User's Manual

Model 7700A

Hall Measurement System

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Chapter 1: Introduction

1.1 General

The Lake Shore 7700A Series Hall effect/electronic transport measurement system (HMS) is designed to measure electronic transport properties of electrically conductive materials. The system consists of the most advanced, integrated hardware and software commercially available. From single field measurements for bulk semiconductors, to variable field measurements for the most demanding compound semiconductor characterization at temperatures from 2 K to 800 K, the Lake Shore Hall effect measurement system is the most flexible, fastest , and precise measurement system available. It is designed and manufactured in the USA.

The 7700A Series systems are easy to operate using the Lake Shore Hall measurement system software. The Hall system software controls the instrumentation during an experiment and determines sample resistance, resistivity, Hall coefficient, Hall mobility, carrier concentration, or current-voltage characteristics. The software controls and varies both temperature and magnetic flux density (field) during measurements. The 7700A Series of electromagnet-based Hall measurement systems consists of the following models:

Model 7704A: HMS with 4 in electromagnet
Model 7707A: HMS with 7 in electromagnet
Model 7712A: HMS with 12 in electromagnet

NOTE

A CE version of the Model 7700A HMS is also available. Additional hardware and processes have been incorporated into the system so that the product meets CE safety requirements for EU countries. These features are mentioned throughout this document. An HMS system that meets CE requirements has a CE mark placed on the back panel of the instrument console.

For your safety, please read the manual and familiarize yourself with the operation of the system before you power up the system.

1.1.1 Hall Effect Measurements

An introduction to Hall effect measurements is included in Appendix A: Hall Effect Measurements.

Hall effect measurements require four or more electrical contacts to the sample. The process for making good electrical contacts varies greatly depending on the sample material and geometry, factors out of Lake Shore control. Formation of adequate electrical contacts is the user's responsibility and can be the most difficult part of the measurement process. Some guidance is given in the sections pertaining to sample mounting in Chapter 4: Sample Modules, and in Appendix B: Electrical Contacts to Semiconductors.

1.1.2 Sample Materials and Applications

Hall effect measurements are the most frequently used means to determine carrier type (electrons or holes), mobility, and carrier density in semiconductor material. Hall effect measurements are used to characterize properties of a wide variety of electronic conductors, including semiconductors, metals, and superconductors, thin films, heterostructures, and bulk materials (single crystal or polycrystalline). Typical semiconductor materials include Si, Ge, GaAs, GaN, AlGaAs, CdTe, HgCdTe, SiC and others. Other samples commonly tested include magnetoresistors, GMR films, high temperature superconductors and magnetic materials.

Measuring transport properties as a function of magnetic flux density (field) or temperature can reveal additional information about the nature of the charge carriers in the material. Information about individual carriers in a material with multiple carriers can be revealed by making variable magnetic flux density measurements of carrier mobility and then applying multi-carrier analysis techniques such as multi-carrier fitting or quantitative mobility spectrum analysis (QMSA®).

In addition, measurements of mobility and density versus temperature give the material scientist insight into the scattering mechanism present . Impurities, light hole states, and other features of the band structure can be inferred from these measurements.

Typical applications for the 7700A series Hall systems include materials research, product development, and quality control.

1.1.3 General Hall Effect Measurement System Features

- Measures Hall voltage, resistance, magnetoresistance, and current-voltage characteristics with one system
- Calculates resistivity, Hall coefficient, carrier concentration and mobility
- Allows contact characterization measuring current-voltage (I-V) curves in most configurations
- Measures samples with resistances ranging from µΩ to hundreds of GΩ (configurations available for this feature)
- Varies temperature and magnetic flux density (field)
- Reduces measurement time with a fully integrated, automated computer data collection system which makes measurements and calculates results
- Displays real-time feedback of processed measurement data in both graphical and/or tabular format as the experiment is taking place
- Controls, monitors, and changes instrument settings throughout the experiment using Hall system software
- Produces more accurate, repeatable measurements by actively monitoring, controlling, and stabilizing magnetic flux density (field). Produces excellent field stability with water cooled magnet coils, feedback control, high quality sensors, and advanced electronics.
- Takes measurements for mobility spectrum analysis using a variable field electromagnet.
- Offers several options for customization

1.1.4 Hall System Software

The 7700A series Hall system uses Windows® XP or VISTA® menu driven, enhanced color-graphic software for system operation, data acquisition and analysis. Real-time feedback of processed measurement data can be displayed in graphical and tabular format. The software controls the operation of the instruments during data acquisition and actively controls the magnetic field throughout a measurement. Hall system software automatically records data for 4-lead van der Pauw structures and 6-lead Hall bar structures and stores data to the hard drive to be used for further processing, analysis, and display.

1.2 System Standard Equipment and Specifications

General specifications about the 7700A series Hall effect measurement system is provided in TABLE 1-1. There is an electromagnet power supply included with the system. You are encouraged to read the included manual for its specifications and installation.

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	System Model Number		
	Model 7704A	**Model 7707A**	**Model 7712A**
Measurement configuration	Refer to section 1.2.4		
Sample holder module	Model 75013 room temperature/77 K; one sided sample cards		
Electromagnet model and pole face sets	EM4-HV, 4 in	EM7-HV, 3 in or 6 in	EM12-HV, 12 in
Shipping dimensions electromagnet	1.29 m × 1.22 m × 0.97 m (51 in × 48 in × 38 in)	0.86 m × 1.22 m × 1.19 m (34 in × 48 in × 47 in)	0.92 × 1.04 × 1.22 m (36 × 41 × 48 in)
Shipping weight electromagnet	215.5 kg (475 lb)	660 kg (1500 lb)	2744 kg (6050 lb)
Installation dimensions electromagnet	0.39 m × 0.84 m × 0.51 m (15.25 in × 33.25 in × 20 in)	0.94 m × 1.02 m × 0.66 m (37 in × 40 in × 26 in)	0.92 m × 0.92 m × 1.22 m (36 in × 36 in × 48 in)
Installation weight electromagnet	201.9 kg (445 lb)	635 kg (1400 lb)	2630 kg (5800 lb)
Electromagnet power supply (MPS)	Model 643	Model 665	Model 668
Shipping dimensions MPS	N/A (mounted in the console)	0.76 m × 0.84 m × 1.52 m (30 in × 33 in × 60 in)	0.76 m × 0.91 m × 1.78 m (30 in × 36 in × 70 in)
Shipping weight MPS	N/A (mounted in console)	340 kg (750 lb)	440 kg (970 lb)
Installation dimensions MPS	0.48 m × 0.31 m × 0.57 m (19 in × 12.2 in × 22.5 in)	1.35 m × 0.60 m × 0.70 m (53.1 in × 23.6 in × 27.6 in)	1.35 m × 0.60 m × 0.70 m (53.1 in × 23.6 in × 27.6 in)
Installation weight MPS	74 kg (163 lb)	260 kg (573 lb)	360 kg (794 lb)
Computer and software	Dell® computer with HDD, CD-ROM, 15 in SVGA flat screen monitor, Windows® XP, Hall software, and National Instruments IEEE-488 USB adapter		
Shipping dimensions computer and console	1.22 m × 0.92 m × 1.32 m (48 in × 36 in × 52 in)		
Shipping weight computer and console	346 kg (763 lb)	272 kg (600 lb)	
Installation dimensions computer and console	0.78 m × 0.96 m × 1.21 m (31 in × 38 in × 48 in)		
Installation weight computer and console	222 kg (488 lb)	148 kg (325 lb)	

All dimensions given as height × width × depth

TABLE 1-1 ***7700A series Hall system general specifications***

1.2.1 Model 7704A HMS with 4 in Electromagnet

FIGURE 1-1 ***Typical Model 7704A HMS***

1.2.1.1 Model EM4-HV Electromagnet (Variable Gap)

One set of pole caps is provided standard with the EM4-HV (4 in) electromagnet.

Air gap	Up to 109 mm (4.3 in) continuously variable
Coil resistance, nominal	0.25Ω per coil (0.5 Ω total wired in series)
Standard pole cap diameter	51 mm (2 in)
Optional pole cap diameter	25 mm, 76 mm, 102 mm (1 in, 3 in, 4 in)
Cooling water	Tap water or closed cooling system
Water flow rate	7.6 L/min (2 gal/min)
Pressure drop	200 kPa (30 psi)
Water chiller cooling capacity	2.5 kW (8,530 BTU/h)
Water inlet temperature	15 °C to 25 °C (59 °F to 77 °F)
Coil over temperature limit	70 °C (158 °F)
Coil spacing, nominal	121 mm (4.75 in)
Coil size-width, nominal	121 mm (4.75 in)
Coil size-diameter, nominal	311 mm (12.25 in)
Current (maximum continuous operating)	±70 A per coil
Voltage, nominal	±35 V
Continuous input power, nominal	2.5 kVA
Lake Shore power supply (suggested)	Model 643

TABLE 1-2 ***Model EM4-HV electromagnet***

1.2.1.2 Model 643 Magnet Power Supply

Refer to the Model 643 MPS User's Manual for complete information. Some important characteristics are given in the following table.

Input				
Wiring and frequency	3-phase, 50 or 60 Hz			
Rating	5500 VA max			
Voltage	204/208 VAC ±10%	220/230 VAC ±10%	380 VAC ±10%	400/415 VAC ±10%
Current	13 A/phase	12 A/phase	7 A/phase	6.5 A/phase
Output				
Voltage	35 V			
Current	70 A			
Load resistance	0.4 Ω to 0.6 Ω			
Load inductance	0 to 1 H			
Ambient conditions				
Air temperature	15 °C to 35 °C at rated accuracy			
Max relative humidity	80% to 31 °C decreasing linearly to 50% at 40 °C (non-condensing)			
Cooling method	Water, tap			
Enclosure				
Type, weight	19 in rack mount, 74 kg (163 lb)			
Dimensions	48.3 cm W × 31.0 cm H × 57.2 cm D (19 in × 12.2 in × 22.5 in)			

TABLE 1-3 ***Model 643 magnet power supply specifications***

1.2.2 Model 7707A: HMS with 7 in Electromagnet

FIGURE 1-2 ***Typical Model 7707A HMS***

1.2.2.1 Model EM7-HV Electromagnet (Variabe Gap)

Two sets of pole caps are provided standard with the EM7-HV (7 in) electromagnet.

Air gap	Up to 178 mm (7 in) continuously variable
Coil resistance, nominal	1.0 Ω per coil (0.5 Ω total wired in parallel)
Standard pole cap diameter	76 mm (3 in)
Optional pole cap diameter	51 mm, 102 mm, 152 mm (2 in, 4 in, 6 in)
Cooling water	Tap water or closed cooling system
Water flow rate	11.4 L/min (3 gal/min)
Pressure drop	220 kPa (32 psi)
Water chiller cooling capacity	5 kW (17,060 BTU/h)
Water inlet temperature	15 °C to 25 °C (59 °F to 77 °F)
Coil over temperature limit	70 °C (158 °F)
Coil spacing, nominal	178 mm (7 in)
Coil size-width, nominal	132 mm (5.2 in)
Coil size-diameter, nominal	445 mm (17.5 in)
Current (maximum continuous operating)	±50 A per coil
Voltage, nominal	±50 V
Continuous input power, nominal	5 kVA
Lake Shore power supply (suggested)	Model 665

TABLE 1-4 ***Model EM7-HV electromagnet (variable gap) specifications***

1.2.2.2 Model 665 Bipolar Magnet Power Supply

Input		
Wiring and frequency	3-phase and ground, 50-60 Hz	
Rating	7.6 kVA max	
Voltage	208 ±10% VAC	400 +6% -10% VAC
Current	21 A/phase with 208/220 VAC between phases	11 A/phase with 380/400 VAC between phases
Customer fuses	25 A, 500 VAC, time lag, each phase	16 A 500 VAC, time lag, each phase
Output		
Voltage	±50 V	
Current	±100 A	
Current stability	±(0.01% of reading + 0.01% of full scale range) under conditions of constant line voltage, load and temperature	
Nominal load	0.5 Ω	
Minimum load	0.25 Ω	
Ambient Conditions		
Air temperature	+10 °C to +30 °C (50 °F to 86 °F)	
Storage and shipping	-10 °C to +50 °C (all remaining water must be removed)	
Max relative humidity	55% ±10% (non-condensing)	
Cooling		
Coolant	Water, tap	
Temperature	+11 °C to +25 °C	
Flow rate	8 L/min (2.1 gpm)	
Inlet pressure	300 kPa to 600 kPa (45 psig to 90 psig)	
Pressure drop at rated flow	0.12 MPa (17 psi)	
Connections	¼ in NPT female thread; ¼ in NPT male to 10 mm (~⅜ in) hose barb included	
Enclosure		
Type, weight	Freestanding rack cabinet with locking wheels and 4 lifting eye bolts; 250 kg (550 lb)	
Dimensions (H × D × W)	1.35 m × 0.7 m × 0.6 m (53.1 in × 27.6 in × 23.6 in)	

TABLE 1-5 ***Model 665 bipolar magnet power supply specifications***

1.2.3 Model 7712A: HMS with 12 in Electromagnet

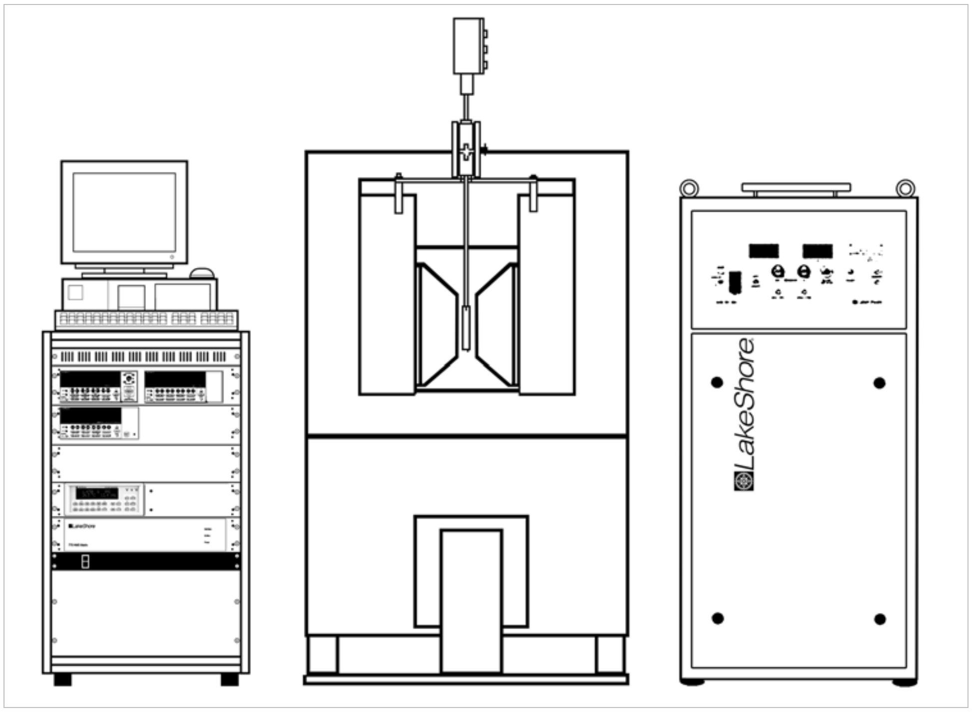

FIGURE 1-3 ***Typical Model 7712A***

Pole diameter	0.30 m (12 in)	
Magnet pole face diameter	0.30 m (12 in)	0.15 m (6 in)
Sample module setup (typical)	(73013 SCSM/Dewar/oven)	(73013 SCSM/Dewar/oven)
Air gap	51 mm (2 in)	51 mm (2 in)
Maximum magnetic induction	1.47 T (14.7 kG)	2.04 T (20.4 kG)
Magnetic field homogeneity over centered 10 cm (4 in) dia circle	±0.05%	±1.6%
Cooling water requirements	Tap water or closed loop cooling system (optional chiller available)	
Inlet temperature	27 °C (81 °F) max	
Supply pressure	205 kPa to 700 kPa (30 to 100 psig) at rated flow	
Flow rate	15 to 23 l/min (4 to 6 gal/min)	
Water chiller cooling capacity	8.5 kW (29,000 BTU/h)	

TABLE 1-6 ***Model EM12-HF electromagnet (fixed gap)***

1.2.4 Model 668 Bipolar Magnet Power Supply

Input		
Wiring and frequency	3-phase and ground, 50-60 Hz	
Rating	15.5 kVA max	
Voltage	208 ±10% VAC	400 +6% -10% VAC
Current	39 A/phase with 208/220 VAC between phases	19 A/phase with 400 VAC between phases
Customer fuses	25 A, 500 VAC, time lag, each phase	16 A 500 VAC, time lag, each phase
Output		
Voltage	±65 V	
Current	±135 A	
Current stability	±(0.01% of reading + 0.01% of full scale range) under conditions of constant line voltage, load, and temperature	
Nominal load	0.5 Ω	
Minimum load	0.35 Ω	
Ambient Conditions		
Air temperature	+10 °C to +30 °C (50 °F to 86 °F)	
Storage and shipping	-10 °C to +50 °C (all remaining water must be removed)	
Max relative humidity	55% ±10% (non-condensing)	
Cooling		
Coolant	Water, tap	
Temperature	+15 °C to +25 °C (59 °F to 77 °F)	
Flow rate	8 L/min (2.1 gpm)	
Inlet pressure	300 kPa to 600 kPa (45 psig to 90 psig)	
Pressure drop at rated flow	0.14 MPa (20 psi)	
Connections	¼ in NPT female thread; ¼ in NPT male to 10 mm (~⅜ in) hose barb included	
Enclosure		
Type, weight	Freestanding rack cabinet with locking wheels and 4 lifting eye bolts; 250 kg (550 lb)	
Dimensions	1.35 m × 0.7 m × 0.6 m (53.1 in × 27.6 in × 23.6 in)	

TABLE 1-7 ***Model 668 bipolar magnet power supply specifications***

1.2.5 Hall System Instrumentation

The 7700A system comes with a standard measurement configuration. The standard instrument configuration of the 7700A system is listed here. Optional instruments for the system are detailed in section 1.4.

- Lake Shore Model 776 Hall matrix card
- Lake Shore Model 475 DSP gaussmeter
- Keithley Model 6220 current source
- Keithley Model 6485 picoammeter
- Keithley 2182A nanovoltmeter

For complete specifications of these instruments, refer to the user manuals. Copies of these manuals are included on the CD distributed with your Hall measurement system.

1.3 Sample Modules

Sample modules are the physical interface between the sample and the measurement instrumentation, and they locate and orient the sample in the electromagnet. Different interchangable sample modules are available for 7700A Series Hall measurement systems. The available sample modules and their key features are described in section 1.3.1 through section 1.3.3.

1.3.1 Model 75013 Sample Card Sample Module (SCSM)

- Plug-in sample cards facilitate sample exchange and storage
- Sample sizes to 60 mm × 60 mm with 4 to 6 contacts
- Triaxial inputs for sample resistances up to 100 GΩ (1×10^{11} Ω)
- Room temperature (RT) operation with magnet poles at 25 mm (1 in) gap for highest field
- Dewar provided for operation at 77 K (-196 °C) with the sample immersed directly in liquid nitrogen or at room temperature; nominal magnet pole gap is 56 mm (2.2 in)
- Temperature monitoring ability with the Model 750TC option
- The CE option sample module has one additional (8-pin) circular connector and interlock pins

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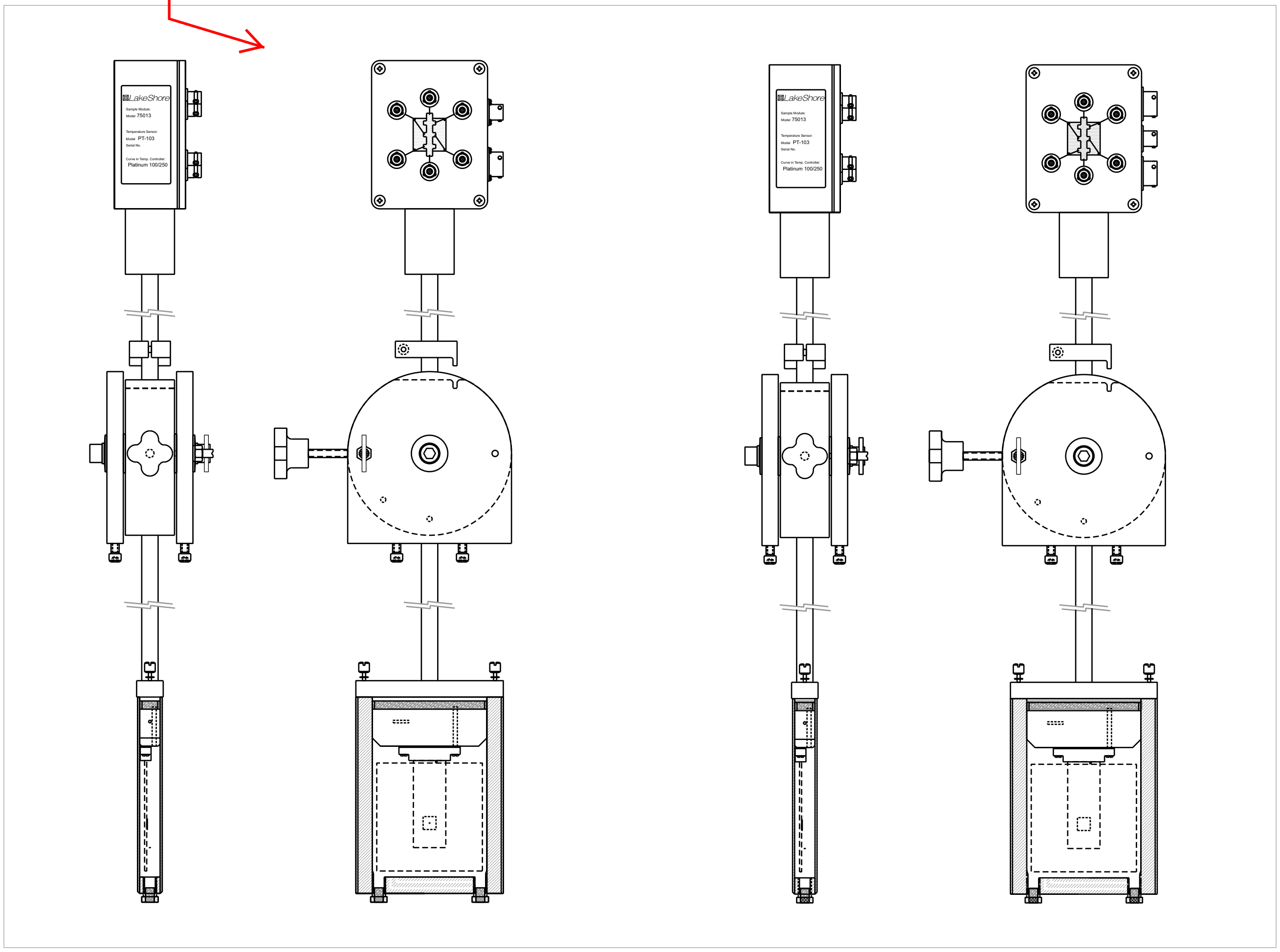

FIGURE 1-4 ***Model 75013 sample card sample module (left shows the standard, right shows the CE option)***

Sample size	12 mm square maximum on a 25 × 75 mm plug-in card (50 provided) or 60 mm square maximum on an 82 × 93 mm plug-in card (10 provided)
Sample structure	Hall bar or van der Pauw
Temperature	Room temperature or 77 K (liquid nitrogen required for 77 K)
Number of contacts	4 or 6 on the sample, 4 additional unassigned contacts

TABLE 1-8 ***Model 75013 sample card specifications***

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1.3.2 Model 75014A Closed Cycle Refrigerator Sample Module (CCR) Option

CCRs provide a variable temperature environment by cooling helium exchange gas. No liquid cryogens are required; therefore, ongoing operating costs are minimal. The sample probe, rotation stage, and hose accessories are provided. The sample is surrounded by helium gas at a pressure slightly above atmosphere, so samples can be changed without breaking vacuum or warming up the CCR. Pump out of the vacuum jacket to 100 Pa (0.1 Torr) is required before cooldown.

The Model 750TC option is required for the Model 75014A and must be ordered separately. Continuous operation for more than one week or at temperatures greater than room temperature requires a dedicated PS-EXT70 turbomolecular pump, which also must be ordered separately. The CE option sample module has one additional (8-pin) circular connector and interlock.

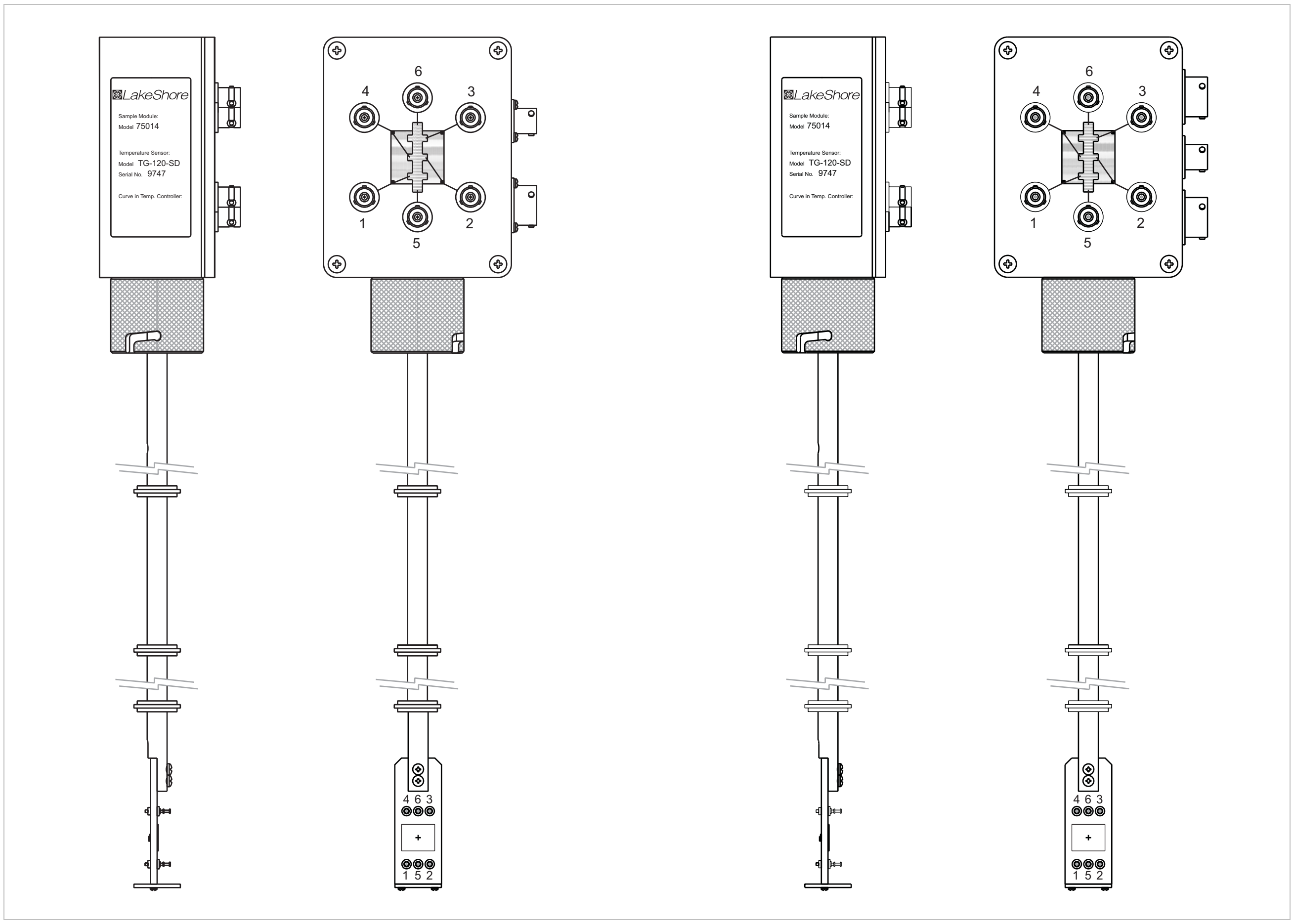

FIGURE 1-5 ***Model 75014A sample card sample module (left shows the standard, right shows the CE option)***

Cryostat	ARS Omniplex with 204SL closed cycle refrigerator and compressor, water cooled (3 L [0.8 gal] per min)
Sample geometry	One 12 mm (0.47 in) diameter maximum; Hall bar or van der Pauw
Temperature range	15 K to 350 K
Number of contacts	6 solder posts provided; 6 additional, unguarded feedthrough pins available

TABLE 1-9 ***Model 75014A sample card specifications***

	Sample module	Compressor
Weight	40 kg (88 lb)	90 kg (200 lb)
Dimensions (h × w × d)	900 mm × 360 mm × 360 mm (36 in × 14 in × 14 in)	514 mm × 432 mm × 508 mm (20.25 in × 17 in × 20 in)

TABLE 1-10 ***Weight and dimensions for the 75014A CCRSM and compressor***

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1.3.3 Model 75016 Oven Sample Module (OSM) Option

The Hall system oven sample module features a heating unit oven body, sample insert, and sample chamber flush/fill unit. The oven body is rigidly mounted to the electromagnet frame and positioned between the electromagnet pole faces. The sample insert attaches through the top of the oven body via a turn locking mechanism. The sample insert makes no contact with the oven body. Because the oven body and sample insert form a vacuum-tight enclosure, the sample heating can be done under an inert gas atmosphere—argon is recommended. The insert has a temperature sensor mounted near the sample location. Electrical contact to the sensor is made through a connector at the top of the sample insert. The CE option sample module has one additional (8-pin) circular connector and interlock.

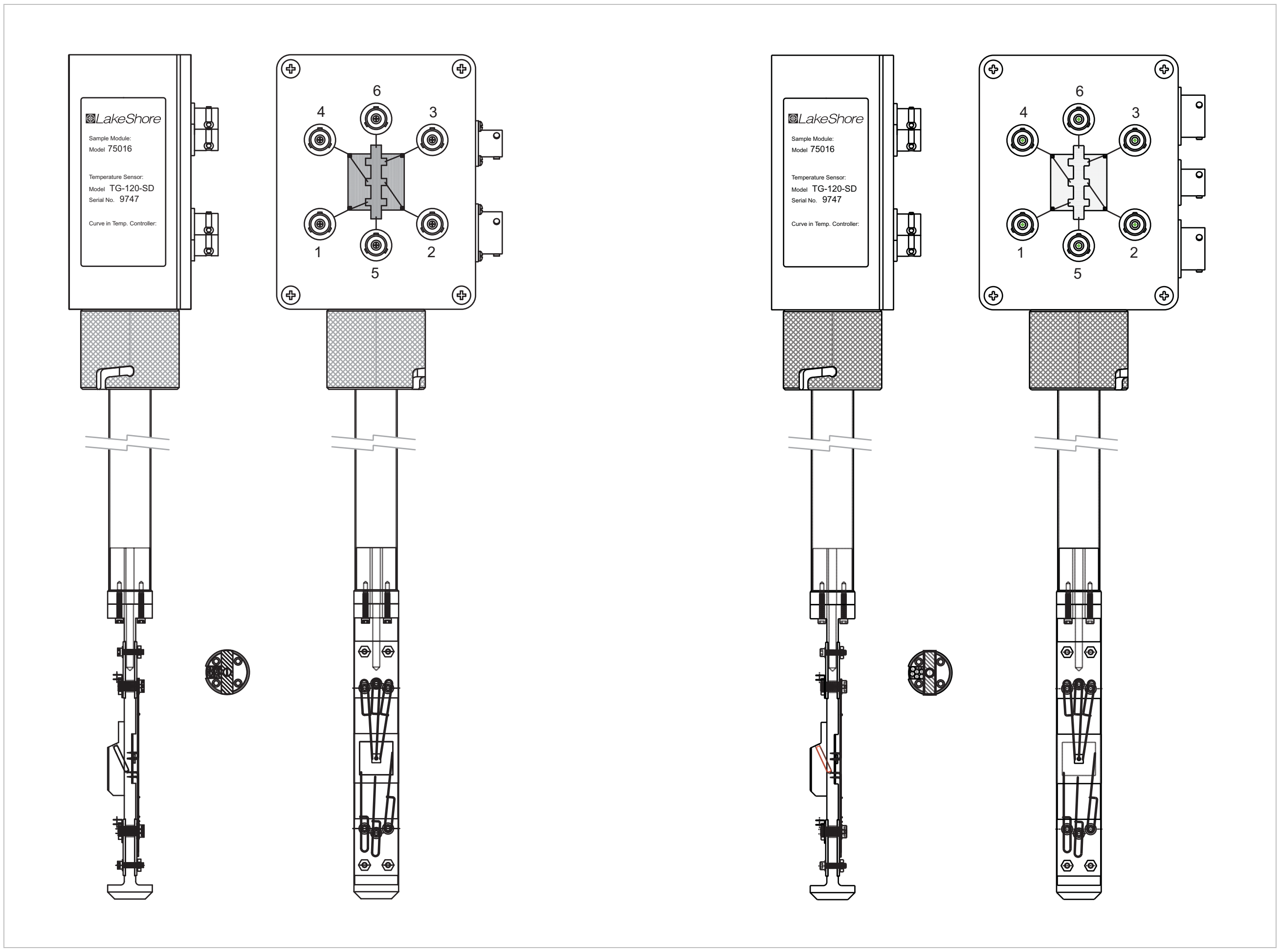


FIGURE 1-6 ***Model 75016 sample card sample module (left shows the standard, rightshows the CE option)***

The Model 750TC option and a mechanical fore vacuum pump (such as the Lake Shore Model PS-E2M) are required and must be ordered separately.

Temperature range	300 K to 800 K
Accuracy	0.4 K to 3 K over temperature range
Sample geometry	14 mm × 17 mm × 1 mm maximum; Hall bar or van der Pauw geometry

TABLE 1-11 ***Model 75016 OSM specifications***

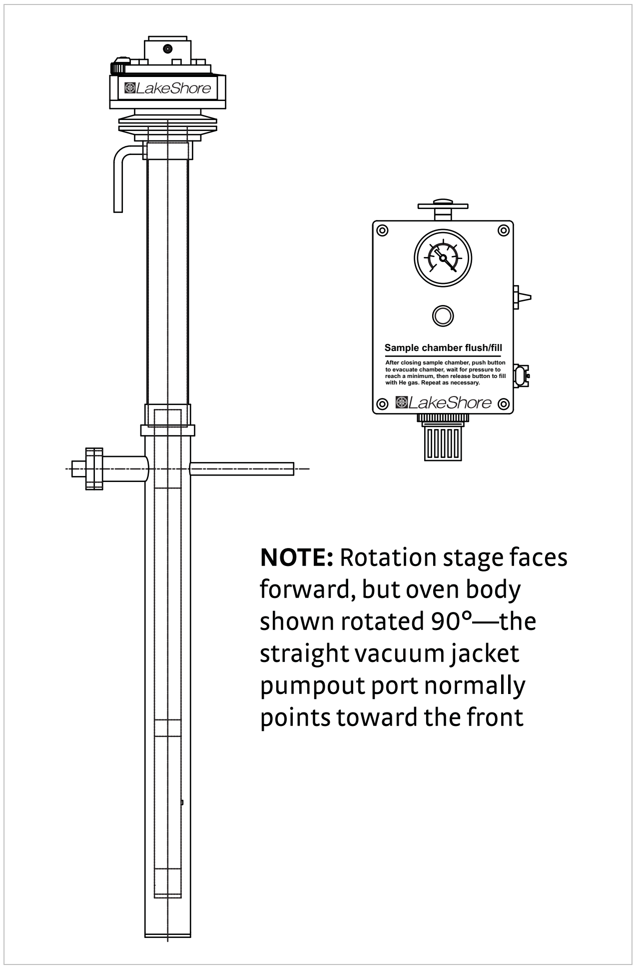


FIGURE 1-7 ***Model 75016 OSM***

1.4 Options

A list of options and systems to which they are applicable is given in TABLE 1-12. Sample module options are explained in section 1.3. Extended descriptions of the individual options are given in the following sections. Other measurement configuration options might be available. Contact Lake Shore regarding your needs.

	Applicable to models	Description
Model 750QMSA	all	Quantitative mobility spectrum analysis software
Model 750TC option	77XX	Adds a Model 340 temperature controller and necessary cables to an existing Model 7700A system at time of purchase or with a field upgrade kit
Model 77020	all	Adds a Model 370 AC resistance bridge for AC current measurements
Model 77021*	all	Adds a Keithley 2400 source meter for contact formation option

**Contact formation option is not available with the CE option*

TABLE 1-12 ***Options availble for the Model 7700A series systems***

1.4.1 Model 750QMSA Software

Our exclusive quantitative mobility spectrum analysis (QMSA®) software pairs with variable field Hall measurements to characterize the mobility spectrum for individual carrier species (electrons and holes) that comprise multilayer or multi-carrier materials (e.g., heterostructures, quantum wells, multiply-doped materials).

Input parameters for the software analysis include Hall coefficient, resistivity, and magnetic field. Output parameters include conductivity spectra as a function of mobility, number of carriers (peaks in the mobility graph), density, mobility, and sign of each carrier.

1.4.2 Model 750TC Temperature Controller Option

The autotuning cryogenic temperature controller is used to measure and control either the closed cycle refrigerator or oven. Only one Model 750TC is necessary whether you require one or both temperature options. The Model 750TC includes a Model 340 temperature controller, connectors, and accessories.

1.4.3 Model 77020 AC Resistance Option

The AC current Hall option is used for the measurement of Hall effect and resistivity in materials with high conductivity (metals) or low mobility (transparent oxides), requiring the measurement of very low voltages. AC measurements are more sensitive than DC measurements.

The AC Hall option, designed for precise, low noise AC resistance measurements on van der Pauw samples with resistances as small as 10 μΩ, incorporates a Lake Shore Model 370 AC resistance bridge. The fully integrated Model 370 uses 4-lead AC measurement for the best possible accuracy with the lowest possible excitation current. AC coupling at each amplifier stage reduces offsets for higher gain and greater sensitivity than DC techniques allow. Phase sensitive detection, an AC filtering technique used in lock-in amplifiers, reclaims small measurement signals from environmental noise.

1.4.4 Model 77021 Contact Blasting Option

The Model 77021 option adds a Keithley Model 2400 sourcemeter for contact formation. This option is not available with the CE-marked system.

1.5 System Measurement Performance

The Model 776 matrix card is a 6 × 5 guarded triaxial matrix switch with 100 V compliance ability. The operational compliance voltage is determined by the Model 6220. By changing the Model 6220 compliance voltage with the HMS configuration utility, the maximum voltage in the system can be set between 7 V to 100 V. The Model 776 provides complete automatic switching between van der Pauw configuration and Hall bar configuration. The Model 776 also automatically removes the Model 6485 current meter for currents larger than 20 mA. The system is designed to measure 100 GΩ resistances, at 100 V with 2% uncertainty.

The ability to make accurate Hall effect measurements is affected by many factors. The ability to measure quantities of common interest, such as resistivity, carrier concentration or mobility, cannot be completely specified because some factors, such as the sample thickness and the uncertainty of the thickness measurement, are user-controlled. Detailed discussions of Hall effect measurements and error sources are given in Appendix A to this manual.

Other than the accuracy of the magnetic flux density, B, Hall effect measurement accuracy is essentially determined by a measured voltage divided by a sourced current.

A computer model of the Hall effect measurement system developed at Lake Shore has been used to determine the ranges within which the system can be used to make accurate measurements. Instrument specifications were used along with the following assumed measurement conditions:

- Maximum power dissipation in the sample of 1 mW
- 295 K sample temperature
- No current leakage to sample holder
- 25 Ω resistance down each lead wire
- Resistivity measurement voltage efficiencies (V_out/V_in) of 0.1 for van der Pauw structures and 0.5 for Hall bar structures
- Zero misalignment voltage in Hall voltage measurements (refer to Appendix A for explanation)

- Hall scattering factor of 1.0 (refer to Appendix A for explanation)
- 1% magnetic flux density (B) uncertainty
- 1% sample thickness (t) uncertainty

The relative accuracy of resistance measurements plots as a function of sample resistance. Current leakage to ground through cabling and instrumentation limits the maximum measurable resistance. Voltmeter sensitivity and the maximum excitation current limit the minimum measurable resistance.

The ability to measure mobility to within an uncertainty of 5% plots as a function of carrier density and sample resistance. Read these plots as showing an envelope within which the mobility can be measured to the stated accuracy. The minimum measurable carrier density is largely a function of the maximum voltage capability of the instrumentation. The maximum measurable carrier density is roughly proportional to the ratio B/t, so large magnetic flux density and thin samples can improve measurement range. Current leakage to ground through the cabling and instrumentation limits the maximum measurable resistance. Voltmeter sensitivity and the maximum excitation current limits the minimum measurable resistance. These plots are calculated assuming no Hall offset voltage. In practice, this can be very difficult to achieve. For low mobility ($\mu < 10$ cm^2/(Vs)), this condition can be nearly impossible to obtain. In this case, the offset voltage and temperature drift of this offset will limit the mobility measurement. See Appendix A for more details.

The performance models have been checked at several points using standard resistors measured in production Hall effect measurement systems. Unfortunately, standards for carrier concentration or mobility measurements do not exist. Uncertainties in these quantities can be referenced to uncertainties in other basic measurements and the sample geometry. Hall measurements have also been performed on wafers purchased from suppliers and samples subjected to round-robbin testing at other laboratories. The system measurement specifications resulted from a combination of modeling and verification. A more complete, but unverified, picture of measurement configuration capabilities can be gained from the following sections.

Resistance range (2% accuracy or better)			Hall measurement (5% accuracy or better)
R max	R min vdP	R min Hall bar	Max carrier density [cm^{-3}]
100 GΩ	0.4 mΩ	0.1 mΩ	3×10^{20}

The maximum measureable carrier density is nearly identical for van der Pauw (vdP) and Hall bar sample geometries

TABLE 1-13 ***Measurement specifications for Hall effect measurement systems***

1.5.1 Resistance Measurements Accuracy

FIGURE 1-8 represents sample resistance measurement accuracy. The measurement conditions for this model include:

- 1 mW maximum power dissipation in the sample
- 100 V maximum excitation or sample output voltage
- 100 mA maximum current
- 295 K sample temperature
- No current leakage to sample holder
- High resistance mode used for sample resistances > 100,000 Ω
- 25 Ω resistance down each lead wire

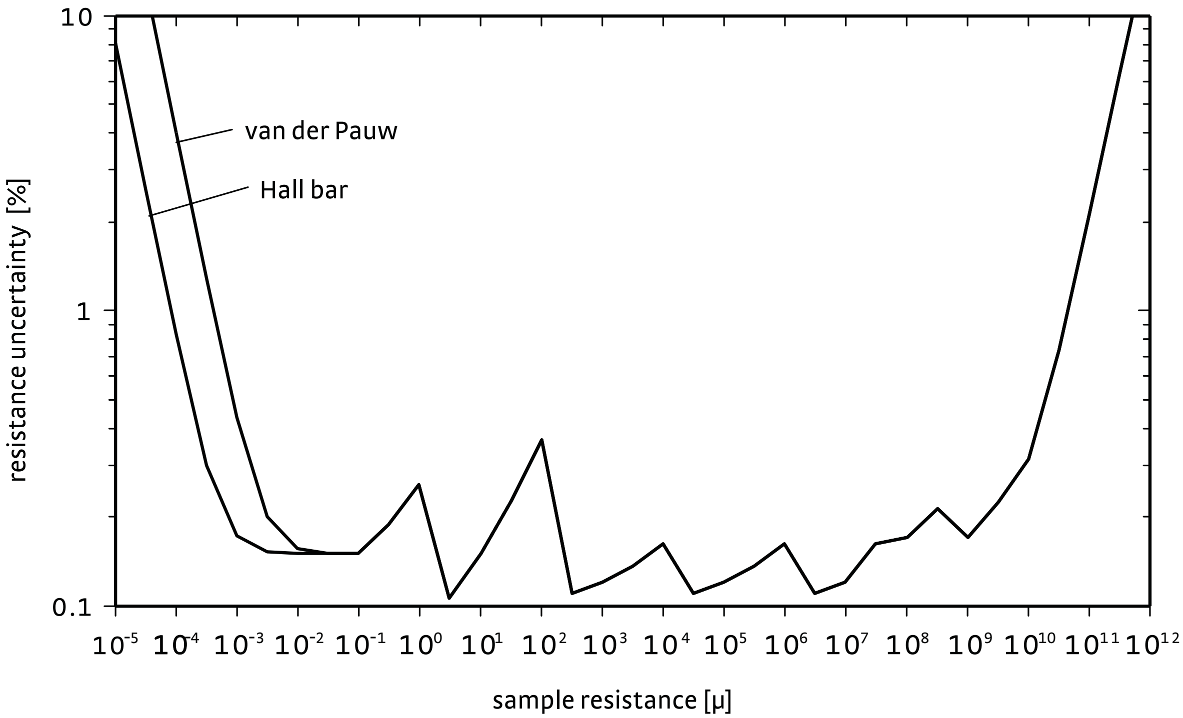


FIGURE 1-8 ***Resistance measurement uncertainty***

FIGURE 1-9 represents the range within which mobility is measured to within an uncertainty of 5% using the -HVWR-HS measurement configuration. The measurement conditions for this model include:

- 1 mW maximum power dissipation in the sample
- 100 V maximum excitation or sample output voltage
  100 mA maximum current
- 295 K sample temperature
- No current leakage to sample holder
- High resistance mode used for sample resistances > 100,000 Ω
- 25 Ω resistance down each lead wire
- Assumed sample resistivity measurement voltage efficiencies (V_out/V_in) of 0.1 for van der Pauw or 0.5 for Hall bar structures
- Zero Hall offset voltage
- Hall factor of 1
- Magnetic flux density (B) and sample thickness (t) uncertainties of 1% each

NOTE **The maximum carrier density is roughly proportional to the ratio B/t, so large magnetic flux density and thin samples can improve the measurement range.**

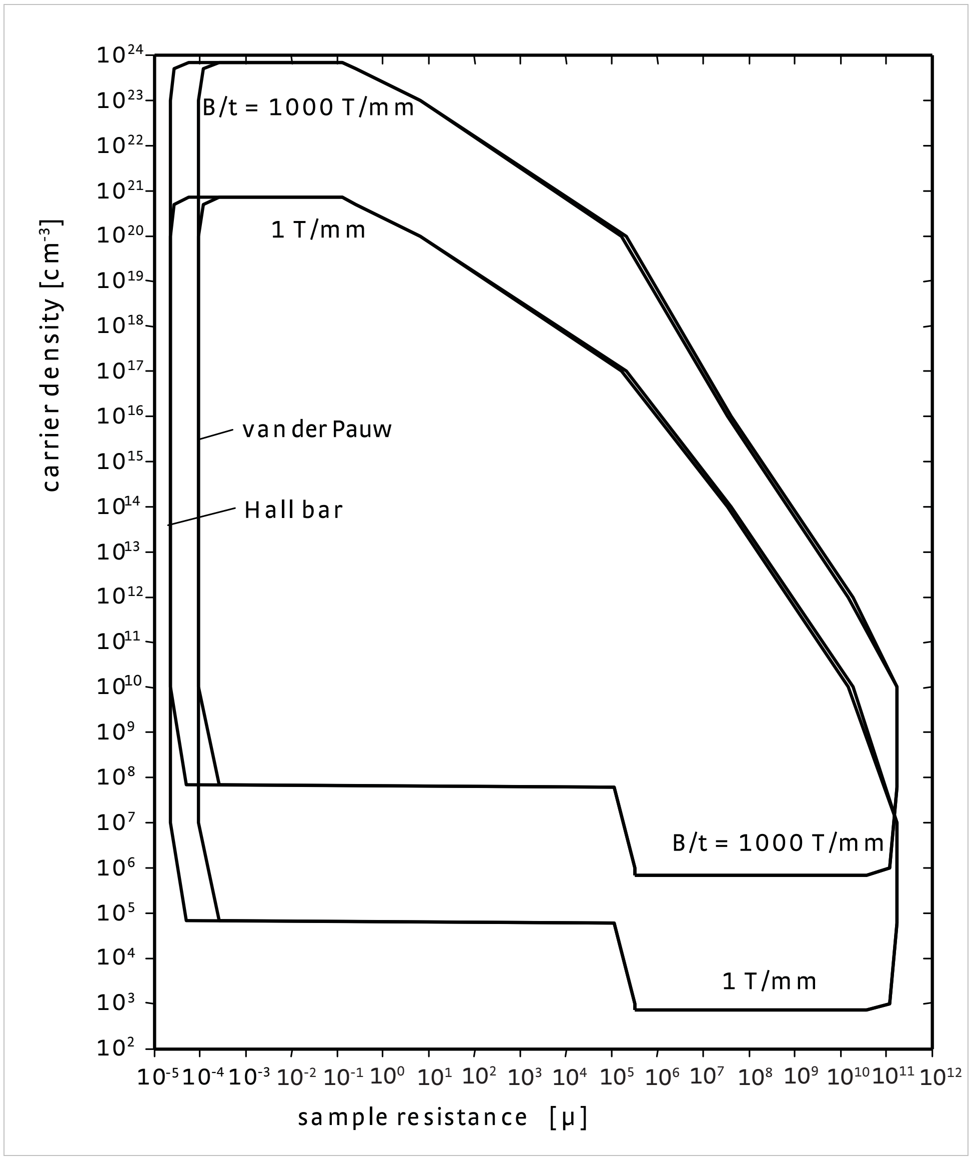


FIGURE 1-9 ***Range within which mobility is measured to within an uncertainty of 5% using the -HVWR-HS measurement configuration .***

1.6 Safety

Observe these general safety precautions during all phases of instrument operation, service, and repair. Failure to comply with these precautions or with specific warnings elsewhere in this manual violates safety standards of design, manufacture, and intended instrument use. Lake Shore Cryotronics, Inc. assumes no liability for the user's failure to comply with these requirements.

Lake Shore equipment protects the operator and surrounding area from electric shock or burn, mechanical hazards, excessive temperature, and spread of fire from the instrument. Environmental conditions outside of the conditions below may pose a hazard to the operator and surrounding area.

- Indoor use
- Altitude to 2000 m
- Temperature for safe operation: 5 °C to 40 °C
- Maximum relative humidity: 80% for temperature up to 31 °C decreasing linearly to 50% at 40 °C
- Power supply voltage fluctuations not to exceed ±10% of the nominal voltage
- Overvoltage category II
- Pollution degree 2

Ground Equipment
To minimize shock hazard, connect the instrument console chassis to an electrical ground. Most Lake Shore equipment comes with a three-conductor AC power cable. Plug the power cable into an approved 3-contact electrical outlet or use a 3-contact adapter with the grounding wire (green) firmly connected to an electrical ground (safety ground) at the power outlet. The power jack and mating plug of the power cable meet Underwriters Laboratories (UL) and International Electrotechnical Commission (IEC) safety standards.

Ventilation
The instrument has ventilation holes in its side covers. Do not block these holes when the instrument is operating.

Do Not Operate in an Explosive Atmosphere
Do not operate the equipment in the presence of flammable gases or fumes. Operation of any electrical equipment in such an environment constitutes a definite safety hazard.

Prevent Cooling Water Condensation
Do not operate the power supply when cooling water temperature is lower than the dew point for local atmospheric condition. Condensation on cooling components inside the power supply can cause severe damage to the power supply.

Do Not Touch Hot Surfaces
Oven option outer tube can be hot during operation. Do not touch the tube surface when the option control temperature senser is reading above 100 °C. (Refer to oven section for more information)

Keep Away from Live Circuits
Operating personnel must not remove equipment and instrument covers. Refer component replacement and internal adjustments to qualified maintenance personnel. Do not replace components with power cable connected. To avoid injuries, always disconnect power and discharge circuits before touching them.

Do Not Substitute Parts or Modify Instrument
Do not install substitute parts or perform any unauthorized modification to the instrument. Return the instrument to an authorized Lake Shore Cryotronics, Inc. representative for service and repair to ensure that safety features are maintained.

Cleaning
Do not submerge instrument. Clean only with a damp cloth and mild detergent. Exterior only.

Ground Measurement Module
Before making any measurement and installing the light tight box to the measurement module, connect all six signal cables to the corresponding connectors on the measurement module connector box. Then connect the safety gound connector (8-pins) to the connector box. The measurements will not work properly without the safety ground cable connected.

WARNING **Do not disconnect any cable during measurments. Because an electrical shock hazard can exist if the center pin is exposed.**

Use Light Tight Box or Temperature Option Hardware
Always install the light tight box or install the measurement module into the temperature option before making any measurements. High voltage can present at the sample area during the measurments.

Safe Electrical Practice
Always stop measurement before disconnecting any cables or remove the light tight box from the measurement module. Remove the light tight box from the measurement module before disconnecting any measurement cables. Remove the safety ground cable before removing the measurement cables.

CAUTION **Only connect one measurement module at a time. One may have multiple measurement modules for his sytem. To prevent incorrect measurement and possible damage to the module, only one measurement module should be connected to the cables from the instrument console. Always remove all the cables from one module before connection cables to another module.**

1.6.1 Handling Liquid Helium and Liquid Nitrogen

Helium and nitrogen are colorless, odorless, and tasteless gases. When properly cooled, the gases liquify. Liquid helium (LHe) and liquid nitrogen (LN_2) are used with the Model 7700A. Although not explosive, there are certain safety considerations for handling LHe and LN_2.

Operate all cryogenic containers (Dewars) in accordance with manufacturer instructions. Safety instructions are normally posted on the side of each Dewar. Keep cryogenic Dewars in a well-ventilated place, protected from the weather, and away from heat sources. FIGURE 1-10 shows a typical cryogenic Dewar.

Transfer LHe and LN_2 and operate storage Dewar controls in accordance with manufacturer/supplier instructions. During transfer, follow all safety precautions written on the storage Dewar and recommended by the manufacturer.

WARNING **Liquid helium and liquid nitrogen are potential asphyxiants and can cause rapid suffocation without warning. Store and use in an adequately ventilated area. DO NOT vent the container in confined spaces. DO NOT enter confined spaces where gas may be present unless the area is well-ventilated. If inhaled, remove the person to fresh air. If they are not breathing, give artificial respiration. If their breathing is labored, give oxygen. Get medical attention.**

WARNING **Liquid helium and liquid nitrogen can cause severe frostbite to exposed body parts. DO NOT touch frosted pipes or valves. For frostbite, consult a physician immediately. If a physician is unavailable, warm the affected parts with water that is near body temperature.**

Two essential safety aspects of handling LHe are adequate ventilation and eye and skin protection. Although helium and nitrogen gases are non-toxic, they are dangerous because they replace air in a normal breathing atmosphere. Liquid helium is an even greater threat because a small amount of liquid evaporates to create a large amount of gas. Store and operate cryogenic Dewars in open, well-ventilated areas.

When transferring LHe and LN_2, protect eyes and skin from accidental contact with liquid or the cold gas issuing from it. Protect eyes with full face shield or chemical splash goggles; safety glasses (even with side shields) are inadequate. Always wear special cryogenic gloves (Tempshield Cryo-Gloves® or equivalent) when handling anything that is, or may have been, in contact with the liquid or cold gas, or with cold pipes or equipment. Wear long sleeve shirts and cuffless trousers long enough to prevent liquid from entering shoes.

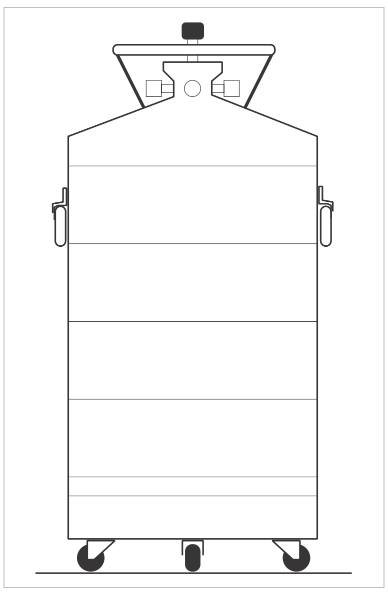


FIGURE 1-10 ***Cryogenic storage Dewar***

1.6.1.1 Recommended First Aid for LHe and LN_2 Exposure

Post an appropriate material safety data sheet (MSDS) obtained from the manufacturer/distributor at every site that stores and uses LHe and LN_2. The MSDS specifies symptoms of overexposure and first aid.

If a person exhibits symptoms of asphyxia such as headache, drowsiness, dizziness, excitation, excessive salivation, vomiting, or unconsciousness, remove to fresh air. If breathing is difficult, give oxygen. If breathing stops, give artificial respiration. Call a physician immediately.

If exposure to cryogenic liquids or cold gases occurs, restore tissue to normal body temperature (98.6°F) by bathing it in warm water not exceeding 105 °F (40 °C). Do not rub the frozen part, either before or after rewarming. Protect the injured tissue from further damage and infection and call a physician immediately. Flush exposed eyes thoroughly with warm water for at least 15 min. In case of massive exposure, remove clothing while showering with warm water. The patient should not drink alcohol or smoke. Keep warm and rest. Call a physician immediately.

1.6.2 Electrostatic Discharge

Electrostatic discharge (ESD) may damage electronic parts, assemblies, and equipment. ESD is a transfer of electrostatic charge between bodies at different electrostatic potentials caused by direct contact or induced by an electrostatic field. The low-energy source that most commonly destroys electrostatic discharge sensitive devices is the human body, which generates and retains static electricity. Simply walking across a carpet in low humidity may generate up to 35,000 V of static electricity.

Current technology trends toward greater complexity, increased packaging density, and thinner dielectrics between active elements, which result in electronic devices with even more ESD sensitivity. Some electronic parts are more ESD sensitve than others. ESD levels of only a few hundred volts may damage electronic components such as semiconductors, thick and thin film resistors, and piezoelectric crystals during testing, handling, repair, or assembly. Discharge voltages below 4000 V cannot be seen, felt, or heard.

1.6.3 Identification of Electrostatic Discharge Sensitive Components

The following are various industry symbols used to label components as ESD sensitive.

FIGURE 1-11 ***Symbols indicating ESD sensitivity***

1.6.4 Handling Electrostatic Discharge Sensitive Components

Observe all precautions necessary to prevent damage to ESDS components before attempting installation. Bring the device and everything that contacts it to ground potential by providing a conductive surface and discharge paths. As a minimum, observe these precautions:

- De-energize or disconnect all power and signal sources and loads used with unit
- Place unit on a grounded conductive work surface
- Technician should be grounded through a conductive wrist strap (or other device) using 1 M series resistor to protect operator
- Ground any tools, such as soldering equipment, that will contact unit. Contact with operator's hands provides a sufficient ground for tools that are otherwise electrically isolated.
- Place ESD sensitive devices and assemblies removed from a unit on a conductive work surface or in a conductive container. An operator inserting or removing a device or assembly from a container must maintain contact with a conductive portion of the container. Use only plastic bags approved for storage of ESD material.

Do not handle ESD sensitive devices unnecessarily or remove them from the packages until they are actually used or tested.

1.7 Equipment Safety Symbols

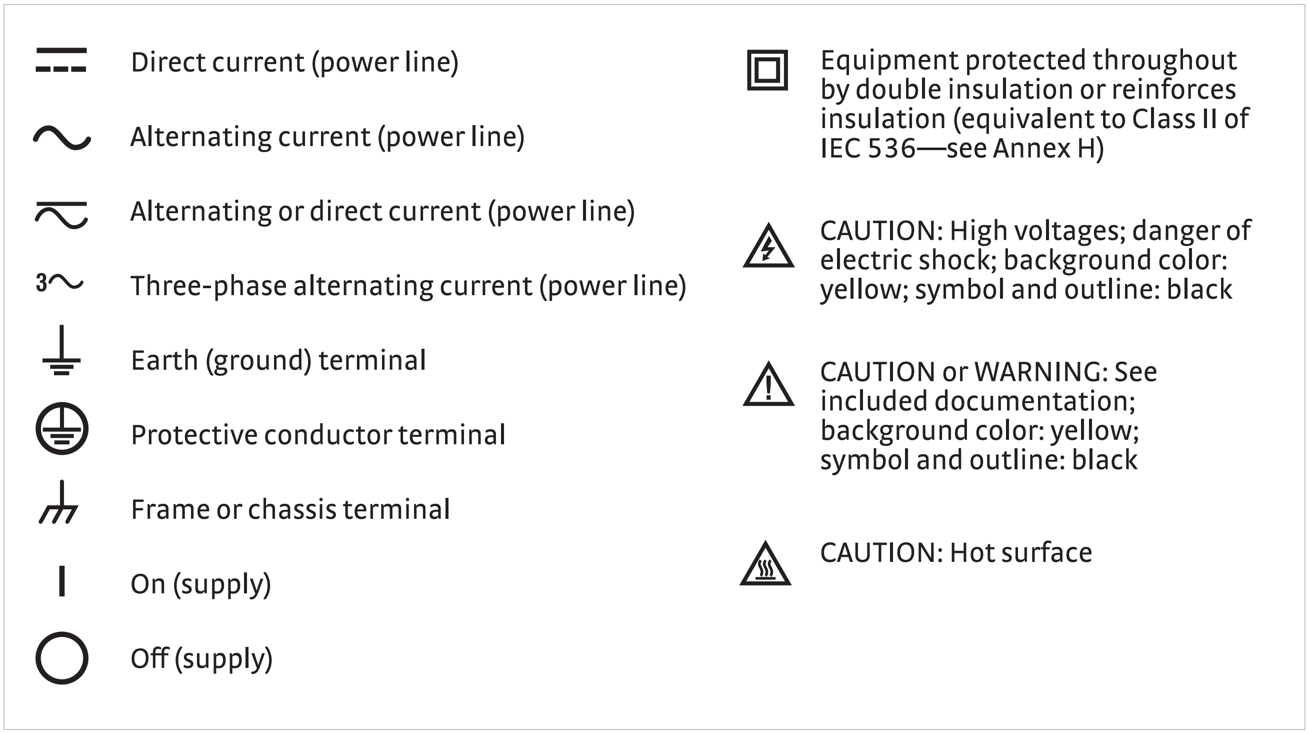


FIGURE 1-12 ***Safety symbols***

Chapter 2: Pre-Installation

2.1 General

This chapter covers preparations to be completed before arrival of the system, as well as other safety and environmental considerations. You are responsible for site preparation and installation of the Model 7700A series Hall measurement system (HMS). If you purchased the installation and training option, you are responsible for ensuring that all requirements are fulfilled as described in section 2.2 through the end of this chapter. You are also responsible for ensuring final electrical and cooling water connections found in section 3.2 through section 3.8 are complete before the installation can be scheduled.

2.2 Site Requirements

Plan the site layout before the system arrives. Use this chapter to guide you in making your decisions concerning physical location, environment, cryogenic storage and access, power, ventilation, safety, and local building, electrical, and safety codes. The measurements in FIGURE 2-1 and FIGURE 2-2 show physical dimensions of the Hall system which will guide you in choosing the installation site. After initial screening, evaluate proposed sites according to space, location, power, and structural integrity.

2.2.1 Space

The physical space should be adequate for system installation, operation, potential expansion, service, and storage of supplies. Space and layout requirements depend on the system selected. A ceiling height of 2.4 m (8 ft) is sufficient to allow for operation of the system.

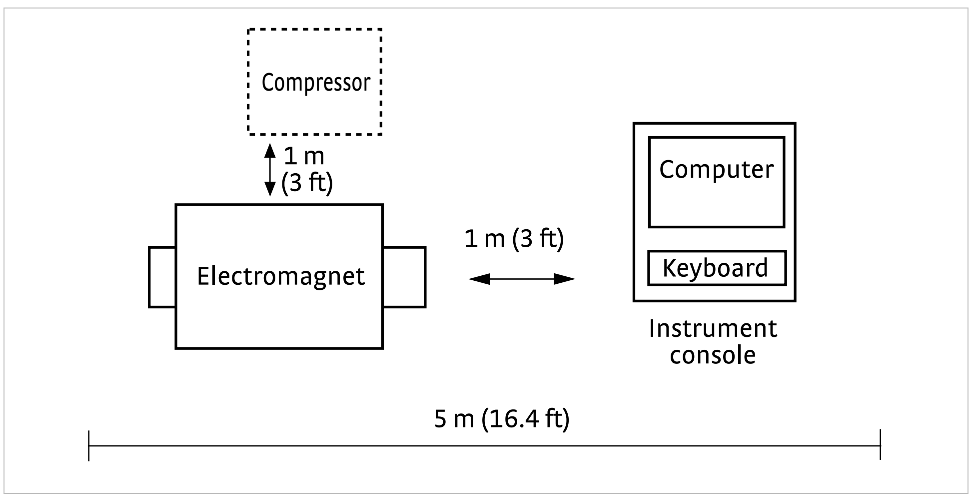


FIGURE 2-1 ***Suggested Model 7704A HMS floor plan***

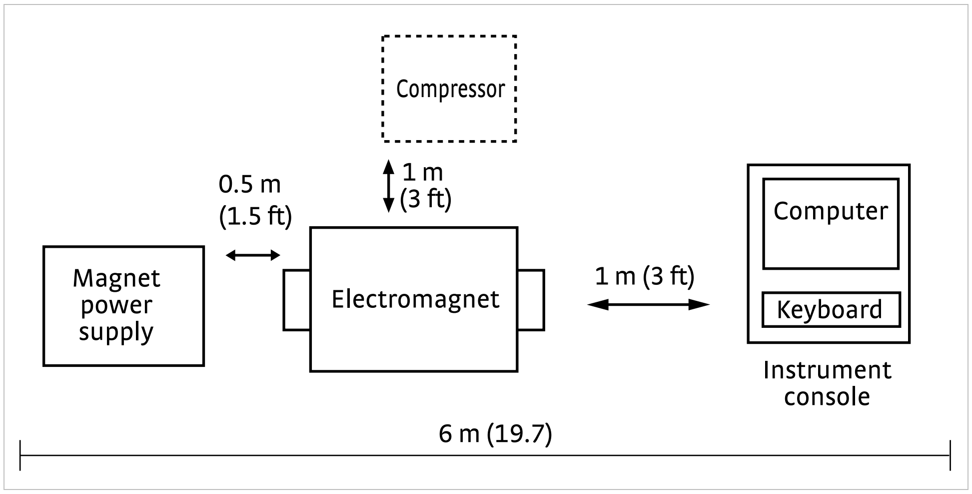


FIGURE 2-2 ***Suggested Model 7707A HMS floor plan***

2.2.2 Location

The location should be convenient for equipment and supply delivery, and it should be close to related work areas for efficient operation. Place the electromagnet in an area free of major vibration from motors, pumps, forklifts, etc., as these things can interfere with measurements. Place the electromagnet as far away as possible from equipment sensitive to stray DC magnetic fields.

WARNING **Ensure that no one with a pacemaker, magnetic implant, or neurostimulator comes near the electromagnet. The electromagnet is unshielded and produces a magnetic field that can disrupt medical implants. Failure to comply could result in injury or death.**

CAUTION **The electromagnets are unshielded and produce a magnetic field that can erase magnetic media, damage watches and affect other instruments.**

2.2.3 Power

Adequate power should be available for system requirements (TABLE 2-1), potential expansion, and wiring for maximum efficiency and economy of operation.

2.2.4 Structural Integrity

The Hall system requires a level floor strong enough to support anticipated loads and free from extraneous vibrations or magnetic fields. Vibrations transmitted to consoles may degrade system performance.

2.3 System Power and Ground Requirements

The AC power source connected to the Model 7700A system must be frequency and voltage regulated and isolated from sources that may generate electromagnetic interference (EMI). Ground fault interrupter (GFI) and transient surge protection circuitry at the AC source are also strongly recommended. In areas where AC voltage is variable, consider a constant voltage transformer. If power outages are a problem, consider an uninterruptable power supply (UPS).

See TABLE 2-1 for a list of system electrical connections. The system includes a plug to mate with the socket on the back of the power supply. You will need to provide an input power cable to the power supply. The instrument console is designed for single-phase 3-wire AC power. The power strip in the instrument console has a 3-conductor power input connector which grounds equipment in the instrument console when plugged into a 3-wire receptacle. Do not use 2-wire (without ground) AC power. If the plug does not mate with available sockets, remove the plug and attach a plug of the correct type with equal or better rating.

The computer and monitor can be placed on top of the instrument console. First place the instrument console top surface on top to provide more room for the keyboard and mouse. The power cords can be plugged inside the instrument console on models with spare internal outlets, or plugged into nearby wall outlets. Alternately, place the computer and monitor on an adjacent table or work surface within limits of the 3 m (10 ft) IEEE-488 cable.

Ground instrument panels and cabinets. The safety ground provides a true ground path for electrical circuitry and, in the event of internal electrical faults such as shorts, it carries the entire fault current to ground to protect users from electrical shock. If the earth ground connection is impaired, render the system inoperative and secure it against any unintended operation. The ground connection is likely impaired if the equipment exhibits any of these conditions:

- Shows visible damage
- Fails to perform the intended measurement
- Has been subjected to prolonged storage under unfavorable conditions
- Has been subjected to severe transport stresses

Do not use an apparatus exhibiting one of these conditions until qualified service personnel verifies its safety. Electromagnetic interference (EMI) is both a natural and man-made phenomena which may, either directly or indirectly, degrade electronic system performance. Natural EMI includes thunderstorms, solar disturbances, cosmic rays, etc. Man-made EMI includes fixed and mobile transmitters, high voltage power lines, power tools and appliances, florescent lights, and other equipment containing motors, heaters, etc. Protect the AC source from EMI. Consider transient surge protectors for lightning protection.

2.4 Cooling Water Requirements

An electromagnet requires cooling water and as such, there are some requirements that you will need to supply for this. The requirements are listed here with explanations following.

- Access to clean cooling water
- A means for controlling the water temperature and flow rate (recirculating chiller)
- One supply line and one return line for water

You will need access to clean cooling water that is clean enough to avoid plugging cooling channels with sediment or deposits such as lime. Cooling with deionized water is not recommended as it can cause erosion of the copper windings.

You will also need a means for controlling the water temperature and flow rate. The electromagnet is provided with a flow switch that will prohibit operation of the power supply if the water flow rate falls below the specification in TABLE 2-1. Control of the water temperature is important when the tap water is cold enough to cause water condensation on the surface of the electromagnet poles, which are made of expensive and easily corroded soft iron. Lack of cooling water temperature control can also cause sample temperature drift when using the Model 75013 sample card sample module without the Dewar or temperature control. Cooling water requirements and input power requirement for the power are summarized in TABLE 2-1 and TABLE 2-2.

A recirculating system can be used to help with each of these conditions (water cleanliness, flow rate and temperature control). A recirculating system is also helpful if you are concerned with the expense incurred with water usage. Recirculating chillers are available from Lake Shore or other sources.

Finally, you will need to provide one supply line and one return line for the cooling water. Garden hose fittings are provided with the system, along with hose barb adapters for connection to the 16 mm (5/8 in) ID tubing. The optional 75014A CCR sample holder module requires additional cooling water for the compressor. Check appropriate manuals to verify water requirements in Table 2-4 and follow any plumbing instructions. The plastic tubing is provided with Swagelok® fittings for connection to the compressor. Any fittings required on the inlet or outlet ends must be provided by the customer.

	Model 7704A	Model 7707A	Model 7712A
Electromagner cooling water requirements	3.8 L/min (1 gal/m) at 2.4 to 4.4 Bar (35 psi to 65 psi)* and 15 °C to 25 °C (59 °F to 77 °F), pressure drop = 0.7 Bar (10 psi)	11.4 L/min (3 gal/m) at 2.4 to 4.4 Bar (35 psi to 65 psi)* and 15 °C to 25 °C (59 °F to 77 °F), pressure drop = 2.2 Bar (32 psi)	15 to 23 L/min (4 to 6 gal/m) at 2 to 7 Bar (30 psi to 100 psi)* and 15 °C to 27 °C (59 °F to 80 °F)
Magnet power supply cooling water needs	6 L/min (1.5 gal/m) at 2.4 to 4.4 Bar (35 psi to 65 psi) and 15 °C to 25 °C (59 °F to 77 °F) *, pressure drop = 1 Bar (15 psi)	8 L/min (2 gal/m) at 2.4 - 4.4 Bar (35 - 65 psi) and 15 - 25 °C (59 - 77 °F) *, pressure drop = 1.2 Bar (17 psi)	8 L/min (2 gal/m) at 2.4 - 4.4 Bar (35 psi to 65 psi) and 15 °C to 25 °C (59 °F to 75 °F) *, pressure drop = 1.4 Bar (20 psi)
Magnet power supply electrical requirements	3-phase with ground (4-wire) Voltages: 400 V +6% -10%, 380 V 10%, 220 V 10%, or 208 V ±10%, 50 Hz to 60 Hz Power consumption is <4.5 kVA. †	3-phase with ground (4-wire) Voltages: 400 V +6% -10%, 380 V 10%, 220 V 10%, or 208 V ±10%, 50 Hz to 60 Hz Power consumption is <7.6 kVA. †	3-phase with ground (4-wire) Voltages: 400 V +6% -10%, 380 V 10%, 220 V 10%, or 208 V ±10%, 50 Hz to 60 Hz Power consumption is <15.5 kVA. †
Instrument console electrical requirements	Electrical requirements: set for 120, 220, 230, or 240 VAC; 1 phase; 50 Hz or 60 Hz; 6 A to 13 A; 1.3 kW maximum Cord: 3.8 m (12.5 ft), or 2.5 m (8.1 ft) for CE option system rated to 15 A; 3-prong U.S. standard male plug or CEE 7/7 plug for CE option system		

** The electromagnet is equipped with a flow switch that inhibits the power supply output if the water flow falls below this specification.*
** If the cooling water is too cold, it can cause condensation and severe damage to the power supply.*
† The customer is responsible for the power cabling between the facility power and the electrical box on the back of the power supply.

TABLE 2-1 ***Cooling water and power requirements***

	Compressor for 75014A CCR sample module (optional)
Room ambient temperature	10 °C to 38 °C (50 °F to 100 °F)
Water inlet temperature	4 °C to 27 °C (40 °F to 80 °F)
Water outlet temperature, max	41 °C (105 °F)
Water inlet pressure	240 kPa to 700 kPa (35 psig to 100 psig)
Water flow, min	2.7 L/min (0.7 gal/m)
Pressure drop at minimum flow	85 kPa (12 psi)
Water supply connections	Plastic tubing (3/8 in OD × 40 ft long) provided, Swagelok® fittings
Water chiller cooling capacity	3.3 kW (11,000 BTU/h)
Power input	Set for a) 208 to 230 VAC, 60 Hz, or b) 220, 230, 240 VAC, 50 Hz; 1 phase; 15 A to 12.5 A; 3 kW
Power cable	3.8 m (12.5 ft), rated to 30 A
Power plug	NEMA L6-30P (2-pole, 3 wire, 30 A, 250 VAC) plug; no plug provided for EU countries

TABLE 2-2 ***Compressor cooling water and power requirements for Model 75014A CCRSM option***

2.5 Other System Requirements

The Model 7700A series Hall systems may have additional requirements that are not provided with the system. Check to make sure these are available when the system arrives.

75013 SCSM (standard)	Liquid nitrogen, see section 4.1 for quantities
	Vacuum pump for occasional evacuation of the Dewar to a pressure of 100 Pa (0.1 Torr) or lower. Rarely required. See full discussion in Chapter 4. Optional valve operator also required for pumpout.
75014A CCRSM (optional)	Helium gas source (99.99% or better) with delivery pressure of 600 kPa to 800 kPa (85 psig to 115 psig).
	Vacuum pump to evacuate the vacuum space to a pressure of 100 Pa (0.1 Torr) or lower. Intermittant operation is possible. See full discussion in section 4.2. Vacuum hose 3 m (10 ft) long is provided with NW 25 fittings (NW 16 on older units).
75016 OSM (optional)	Argon gas source (99.99% or better) with delivery pressure of 600 kPa to 800 kPa (85 psig to 115 psig).
	Vacuum pump with a base pressure of 0.1 Pa (7×10^{-4} Torr) or lower. Continuous, oil-free vacuum pumping is required during oven operation. See full discussion in section 4.3. Vacuum hose 1.8 m (6 ft) long is provided with a NW 25 fitting for connection to the pump.

TABLE 2-3 ***Other gas and vacuum requirements***

2.6 Environmental Requirements

To meet and maintain specifications, operate the system at an ambient temperature range of 18 °C to 28 °C (64.4 °F to 82.4 °F). Operate it within the range of 15 °C to 35 °C (59 °F to 95 °F) with less accuracy. The system is intended for laboratory use. Although no specific humidity or altitude specifications exist, relative humidity of 20% to 80% (no condensation) and altitudes from sea level to 2.4 km (8,000 ft) are generally acceptable.

The system is designed to be used in a laboratory environment; therefore, safety testing is done to laboratory standards. For the CE mark, normal use is defined as: indoor use, altitude to 2000 m, temperature between 5 °C and 40 °C, maximum relative humidity of 80% at 31 °C, and air quality pollution degree 2 (nonconductive pollution of the sort where occasionally a temporary conductivity caused by condensation must be expected).

2.6.1 Ventilation

Place the Hall system in a well ventilated area to avoid the risk of asphyxiation from liquid cryogens. Oxygen content monitor/alarms should be installed near the work site to warn against low oxygen levels if liquid cryogens are used. The air-conditioning system should filter dust and other particulates to reasonable levels. Consult an air-conditioning expert about special filtering if salt air, corrosive gases, or other air pollutants exist.

WARNING

Failure to remove large quantities of vaporized cryogen from the working area can result in a loss of consciousness or death. Vaporizing cryogen displaces oxygen in its vicinity, presenting an asphyxiation hazard. There is a risk of oxygen deficiency if the oxygen level falls below 19.5%.

Chapter 3: Installation and Setup

3.1 General

The 7700A Hall effect system was electrically and mechanically inspected and operationally tested prior to shipment. This chapter covers installation and connection of the electromagnet, power supply, and instrument console. Chapter 4 covers sample module setup. Chapter 5 covers system operation. Study Chapters 4 and 5 before attempting to run the system.

If the customer has paid for final installation and training, the system must be in its final location with all electrical and cooling water connections complete before arrival of the service engineer (section 3.2 through the end of section 3.8).

3.2 Unpacking and Inspecting

Set the pallets on a level surface. Inspect shipping containers for external damage. Make all claims for damage (apparent or concealed) or partial loss of shipment in writing to Lake Shore within five days from receipt of goods. If damage or loss is apparent, notify shipping agent immediately.

Carton Shockwatch® indicators aid in judging the condition of received goods (FIGURE 3-1). A Shockwatch® sticker is also on the pallet under the units. Please accept shipment even if the Shockwatch® is red. Note it on the bill of lading and inspect for damage immediately.

FIGURE 3-1 ***Shockwatch indicator***

Open the crate containing the instrument console first. Cut off the strapping, lift off the lid, and locate the packing list included with the system. Use the packing list to check receipt of all components, cables, accessories, and manuals as the system is unpacked. Inspect for damage. Inventory all components supplied before discarding any shipping materials.

Remove the box from the top of the instrument console. Use four people to lift the instrument console from the pallet. Do not lift the console at the top; always lift from the bottom.

Note how the console was supported on the pallet for future reference. Foam blocks between the instruments support their weight during shipment; if you need to transport the unit, leave them in place.

The second pallet contains the electromagnet. For the Model 7700A with a 7 in electromagnet, a third pallet contains the magnet power supply. Verify receipt of all manuals. If any manuals are missing, contact Lake Shore immediately. Be sure to fill out and send instrument warranty cards.

If there is instrument freight damage, file claims promptly with the carrier and insurance company, and refer to section for return procedures. Advise Lake Shore immediately of missing parts. Lake Shore cannot be responsible for any missing parts unless notified within 60 days of shipment. The standard Lake Shore Cryotronics, Inc. warranty appears in the front matter (immediately behind the title page) of this manual.

3.3 Model 7704A HMS Hardware Installation

This section provides the procedures for installing the electromagnet and the magnet power supply for the Model 7704A HMS. Refer to installation instructions in Chapter 2 of the EM4-HVA user's manual for clarification and additional information for the electromagnet installation. Refer to the Model 643 user manual if you need further information for the magnet power supply installation.

3.3.1 Model EM4-HVA Installation

The Model EM4-HVA electromagnet ships with a stand attached. Move the stand and the electromagnet to its final location. Electrical and coolant connections require rear access.

Verify that the bolted joints did not loosen during shipment. Adjust the screw feet to level the top of the stand.

The Model EM4-HVA normally ships with one set of pole caps with 4 in diameter pole faces. Pole caps necked down to smaller diameter pole faces can produce higher magnetic fields, but with smaller regions of uniform field. If more than one set of pole caps was purchased, use the set with the largest diameter pole faces for initial operation. Leave pole caps backed out for sample module installation (Chapter 4).

CAUTION **Treat the electromagnet pole caps carefully; they are easily damaged. Refer to section 3.3, Pole Caps, in the electromagnet manual. Deep dents or scratches on pole caps can impair magnetic field homogeneity. Wipe pole caps clean with a soft, clean, lint-free cloth lightly oiled with high quality light oil, if it is not nickel plated. The bare iron pole caps are soft and rust easily if not protected from moisture with nickel plating or a coat of oil.**

3.3.1.1 Model EM4-HVA Cooling Water Connections

The electromagnet is configured at Lake Shore with 10 mm (3/8 in) ID tubing and splitters to properly route the water flow through the electromagnet coils so that there is a single inlet and outlet connection to connect to the cooling water system (FIGURE 2-7). Also included on the outlet of the electromagnet is a water safety flow switch. The routing of water through the coils should not be altered and the flow switch should be used.

NOTE **You are responsible for providing the necessary lengths of tubing and connections to your cooling water system.**

You will need to attach the water inlet and outlet hoses. See FIGURE 3-2 for an illustration of these connections.

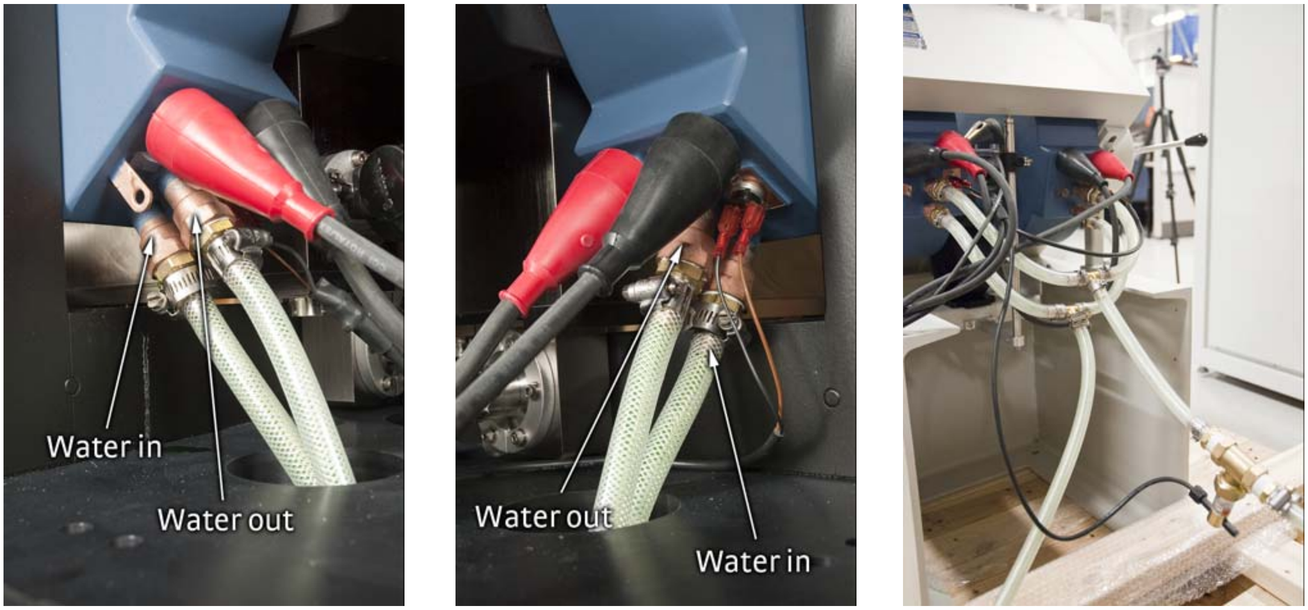


FIGURE 3-2 ***Water connections for a 4 in magnet***

3.3.1.2 Model EM4-HVA Electrical Connections

EM4-HVA magnet current leads are connected in series .

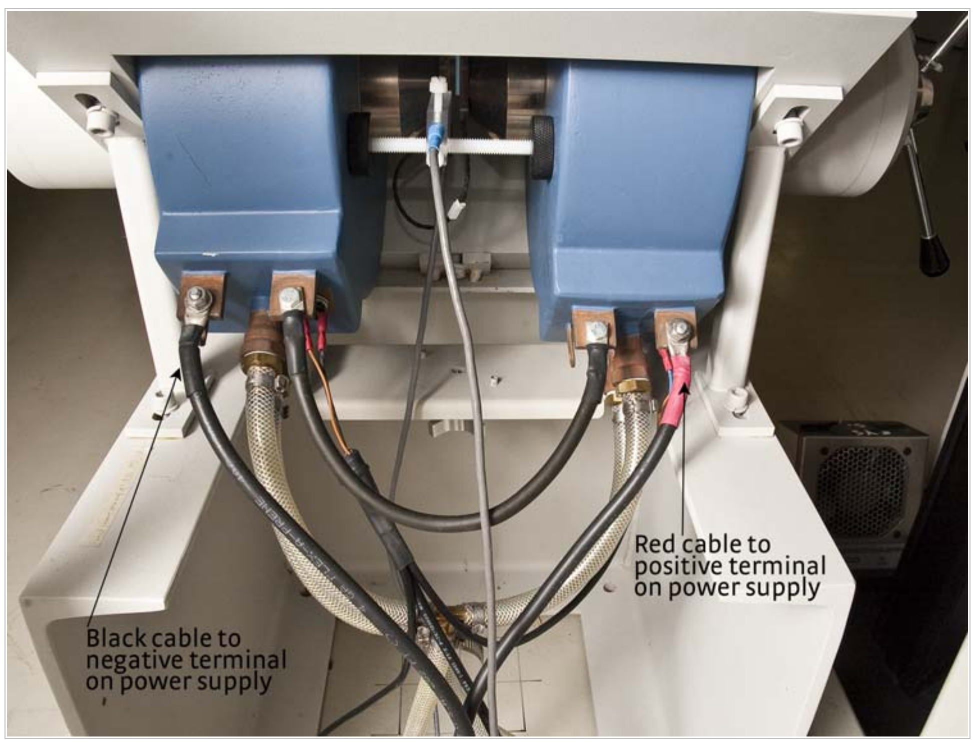


FIGURE 3-3 ***EM4-HVA electromagnet power connections (insulating boots are removed for clarification)***

3.3.2 Model 643 Installation

The Model 7704A HMS uses the Model 643 magnet power supply to supply power to its 4 in electromagnet. This section describes the cooling water connections and the electrical wiring necessary to complete the Model 643 installation.

Refer to the Model 643 electromagnet power supply manual, Chapter 3, to complete the connection of 3-phase power to the Model 643. This should be completed by a qualified electrician adhering to all local codes and standards, prior to the arrival of a Lake Shore representative for installation and training.

3.3.2.1 Model 643 Cooling Water Connections

Supply and return water supply lines are required to cool the magnet power supply. The water connections for the Model 643 are hose barb fittings. Hoses and clamps shown are not provided.

CAUTION **Too cold a supply can cause condensation and severe damage to the power supply. Refer to section 4.2 to avoid water condensation.**

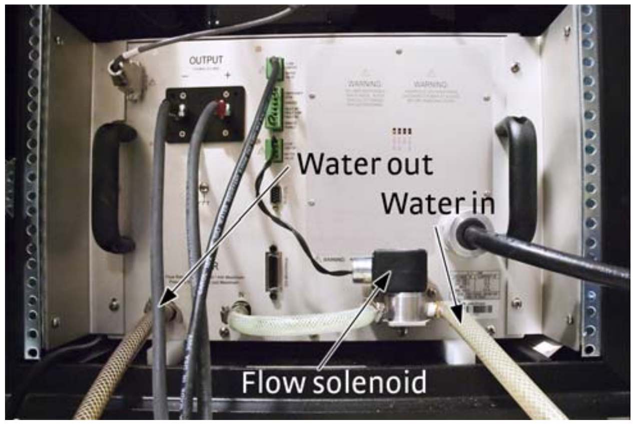


FIGURE 3-4 ***Water connections on the Model 643***

3.3.2.2 Model 643 Electrical Connections

1. Locate the electromagnet current leads on the electromagnet. Uncoil the leads and using the bolts and nuts located on the Model 643 output lugs, connect the positive (red) lead to the positive output and the negative (black) lead to the negative output (FIGURE 3-5). A safety cover is provided to be installed over the power supply output lugs if desired; refer to the Model 643 manual for additional information.

NOTE **The positive and negative power supply output terminals connected to the magnet current leads must be wired properly to maintain the correct magnet field direction.**

2. Locate the fault indicator cable connected to the flow and thermal switches on the electromagnet coils. Connect the green terminal block to the top flow switch location on the Model 643 rear panel (FIGURE 3-5).

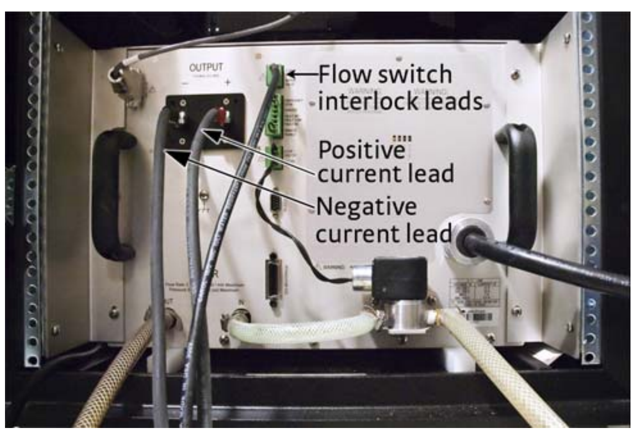


FIGURE 3-5 ***Model 643 electromagnet connections; safety cover removed to show detail***

3.3.3 Connecting the Cooling Water

The Model 7704A HMS can be connected to the cooling water in series, with the electromagnet and power supply sharing a single inlet and outlet flow path from the cooling water system. A block diagram of this setup is shown in FIGURE 3-6. The water flow path should go first to the electromagnet and then to the power supply. Additional hose couplings (not included) may be needed to complete the series flow path. The power supply water flow solenoid is not used in series configuration.

1. Locate the 10 mm (3/8 in) inlet tubing on the electromagnet and connect it to the supply of your facility's water system (FIGURE 3-6).
2. Locate the 10 mm (3/8 in) outlet tubing on the electromagnet and connect it to the inlet to the Model 643 power supply (FIGURE 3-4). The water flow solenoid is connected at the factory; remove the connection from the solenoid to the power supply inlet.
3. Locate the 10 mm (3/8 in) outlet tubing of the power supply and connect it to the return of your facility's water system (FIGURE 3-6).

CAUTION

The cooling water temperature must be above the dew point (the temperature at which condensation will occur) to avoid damage to the Model 643 power supply. Refer to the Model 643 manual section 2.4.4 for additional information.

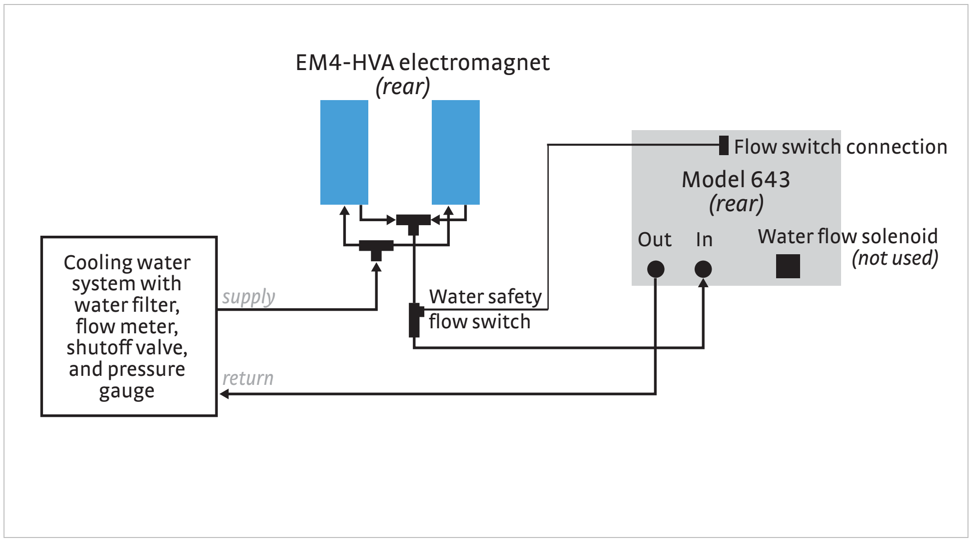


FIGURE 3-6 ***Electromagnet and power supply series cooling water configuration***

3.4 Model 7707A HMS Hardware Installation

This section provides the procedures for installing the electromagnet and the magnet supply for the Model 7707A HMS. Refer to installation instructions in Chapter 2 of the EM7-HV user's manual for clarification and additional information for the electromagnet installation. Refer to the Model 665 users manual if you need further information for the magnet power supply installation.

3.4.1 Model EM7-HV Installation

The Model EM7-HV electromagnet ships with a pedestal stand under the magnet frame. Move the electromagnet assembly to its final location. Electrical and coolant connections require rear access.

Verify bolted joints did not loosen during shipment. The top saddle plate should be level and the entire electromagnet assembly should be solid. If local code requires it, bolt the pedestal stand to the floor.

The Model EM7-HV ships with two sets of pole caps with 3 in and 6 in diameter pole faces. Pole caps necked down to smaller diameter pole faces can produce higher magnetic fields, but with a smaller region of uniform field. The EM7-HV electromagnet normally ships with the 3 in pole face caps installed. Use these for initial operation unless the larger pole faces are required immediately. Instructions for changing the pole caps are given in the user's manual for EM4-HVA and EM7-HV series electromagnets.

CAUTION **The pole caps are heavy and easily dented. Handle them with care. Leave the pole caps backed out for sample module installation (Chapter 4).**

3.4.1.1 Model EM7-HV Cooling Water Connections

The Model EM7-HV comes shipped with the magnet coolant hoses already attached. You will need to attach the facility water inlet and outlet hoses to the garden hose 3/4 in type connections. See FIGURE 3-8 for an illustration of these connections.

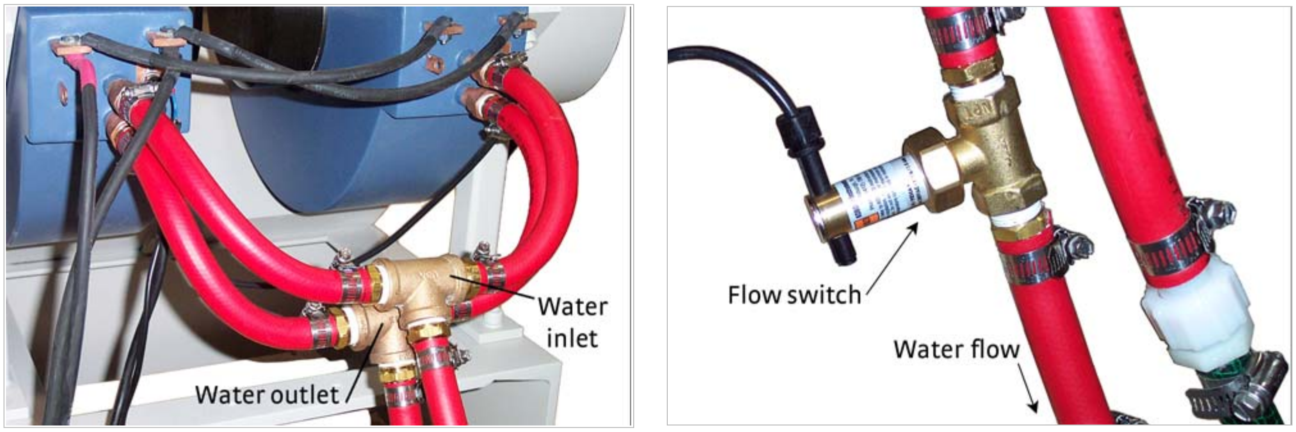


FIGURE 3-7 ***Left: Water connections for 7 in magnet; Right: Flow switch on the water outlet line (switch is closed when water is flowing)***

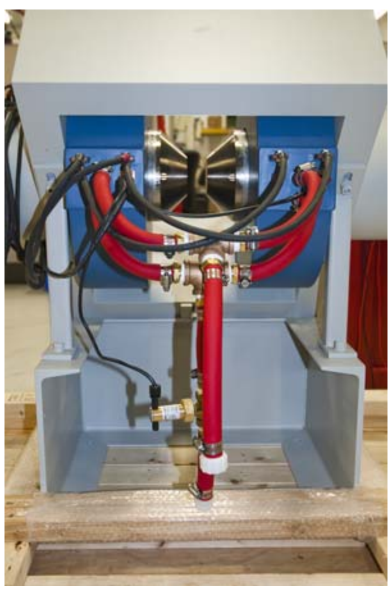


FIGURE 3-8 ***3/4 in type connection***

3.4.1.2 Model EM7-HV Electrical Connections

See FIGURE 3-9 for an illustration of the electrical connections.

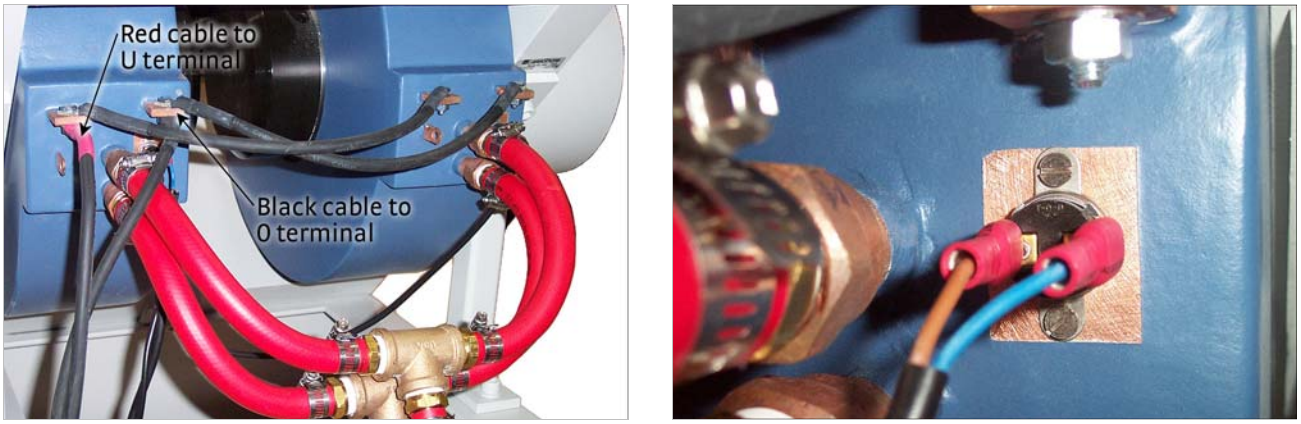


FIGURE 3-9 ***Left: Electrical connections for 7 in magnet; Right: Thermal switch connection***

3.4.2 Model 665 Installation

Per the site preparation instructions (section 2.2), the user is responsible for providing the hookup from the electrical box at the back of the power supply to the electrical service.

3.4.2.1 Model 665 Cooling Water Connections

The water connections for the the Model 665 uses standard 3/8 in hose barb fittings . Hoses and clamps shown are not provided.

FIGURE 3-10 ***Hose barb fittings with customer hoses (not provided) on the Model 665 power supply***

3.4.2.2 Model 665 Electrical Connections

Model 665 wiring is shown in FIGURE 3-11 and described in the following bulleted list.

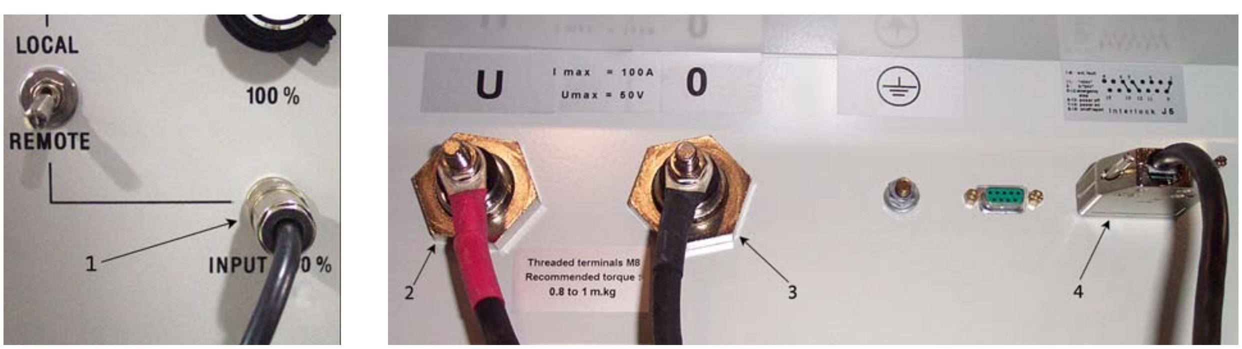


FIGURE 3-11 ***Left: Model 665 front panel connections; Right: Model 665 rear panel connections***

- 1: Remote input 100% —connects to the analog output BNC on the rear panel of the Model 475 gaussmeter.

NOTE **The positive and negative power supply output terminals connected to the magnet current leads must be wired properly to maintain the correct magnet field direction.**

- 2: Power supply output; positive (U)— the wire marked in red goes to the positive terminal of the electromagnet.
- 3: Power supply output; common (0)—the wire marked in black goes to the negative terminal of the electromagnet.
- 4: Interlock —this is the power supply inhibit connector. It is connected to a single water flow and two thermal cutoff switches in series, any of which can inhibit the output of the power supply. A fault can also be caused by detection of internal condensation

3.4.3 Connecting the Cooling Water in Parallel

The Model 7707A HMS needs to be connected to the cooling water in parallel, with the electromagnet and power supply each getting independent inlet and outlet cooling lines. A block diagram of this setup is shown in FIGURE 3-12. Two connections are required from the cooling water system; the required splitters are not included.

1. Locate the 10 mm (3/8 in) inlet and outlet barb connections on the electromagnet (FIGURE 3-7) and connect them to your facility's water supply.
2. Locate the 10 mm (3/8 in) inlet and outlet barb connections on the rear panel of the power supply (FIGURE 3-10) and connect them to your facility's water supply.
3. *Optional*: if the electromagnet water pressure drop is too great to allow flow to the magnet, install a flow proportioning valve in the magnet power supply branch as shown in FIGURE 3-12 to balance the two flow paths.

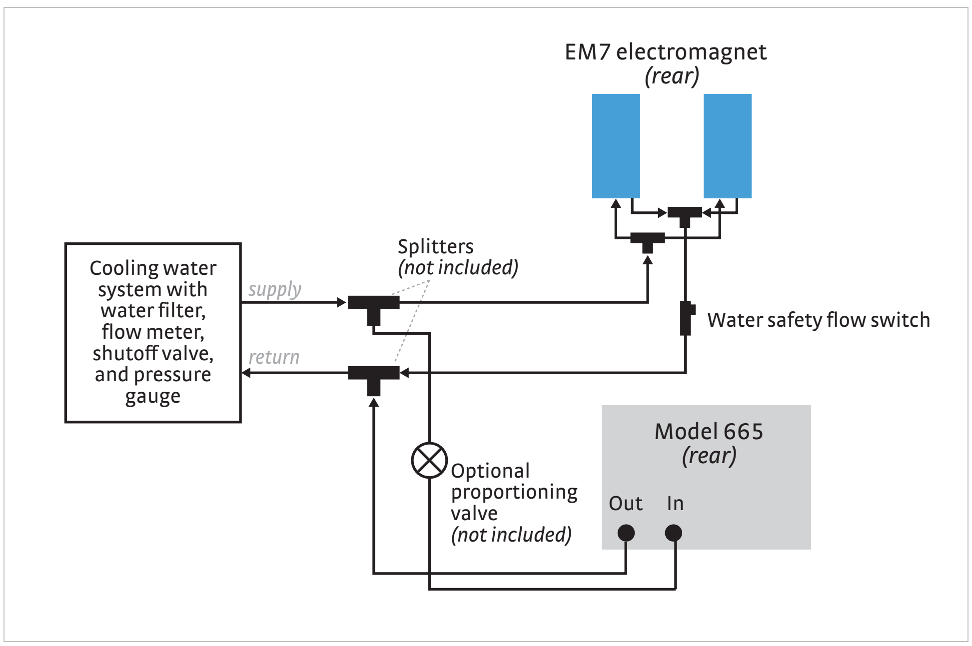


FIGURE 3-12 ***Electromagnet and power supply parallel cooling water configuration***

3.5 Model 7712A HMS Hardware Installation

This section provides the procedures for installing the electromagnet and the magnet power supply for the Model 7712A HMS. Refer to installation instructions in Chapter 2 of the EM7-HV user's manual for clarification and additional information for the electromagnet installation. Refer to the Model 668 users manual if you need further information for the magnet power supply installation.

3.5.1 Model EM12 Installation

Refer to installation instructions in the User's Manual for EM12 Series Electromagnets for clarification and additional information if any of the following instructions are unclear.

The Model EM12 electromagnet ships with a stand under the magnet frame (refer to User's Manual). Move the electromagnet assembly to its final location. Electrical and coolant connections require rear access.

Verify that the bolted joints did not loosen during shipment. The top saddle plate should be level and the entire electromagnet assembly should be solid. Bolt the magnet stand to the floor.

The Model EM12 normally ships with one or two sets of pole caps with customer specified pole face diameters. Pole caps necked down to smaller diameter pole faces can produce higher magnetic fields, but with smaller region of uniform field. The EM12 electromagnet normally ships with pole caps installed as specified by the customer. Use these for initial operation. Instructions for changing the pole caps are given in the User's Manual for EM12 Series Electromagnets.

CAUTION **The pole caps are heavy and easily dented. Handle with care! Leave pole caps backed out for sample module installation (Chapter 4).**

3.5.1.1 Model EM12 Cooling Water Connections

The Model EM12 comes shipped with the certain hoses already attached. You will need to attach the water inlet and outlet hoses. See **FIGURE 3-7** for a reference as to how these are attached.

3.5.1.2 Model EM12 Electrical Connections

See FIGURE 3-9 for a reference as to where these are connected.

3.5.2 Model 668 Installation

The Model 668 installation is similar to that of the Model 665. Refer to the Model 668 user's manual if additional information is needed.

3.5.2.1 Model 668 Cooling Water Connections

The water connections for the Model 668 uses standard 3/8 in hose barb fittings . Hoses and clamps shown are not provided. See FIGURE 3-10 for a reference as to how these are attached.

3.5.2.2 Model 668 Electrical Connections

Per the site preparation instructions (Section 2.2), the user is responsible for providing the hookup from the electrical box at back of the power supply to the electrical service.

3.6 Instrument Console Installation

The instrument console is on casters and moves easily on flat surfaces. If a table top was provided, set it on top of the instrument console. Position the instrument console for easy rear access until installation is complete.

The instrument console contains the Model 475 gaussmeter, the Model 2182A volt meter, the Model 6220 current source, and the Model 6485 current meter. If you ordered the 4 in magnet, the instrument console will also contain the Model 643 power supply. The instrument console is fully assembled, wired and tested at Lake Shore before shipment. There are up to 8 connections from the instrument console to the sample module. This section will describe these connections. A wiring diagram is provided in FIGURE 3-13.

Components of the Model 7704A, 7707A, or 7712A systems connect schematically as shown in FIGURE 3-13. The differences between the systems are the electromagnet size (4, 7, or 12 inch diameter poles) and power supply location (in the instrument console or separate unit).

The Model 776 matrix card is a 6 × 5 guarded triax matrix switch with 100 V compliance ability. The operational compliance voltage is determined by the Model 6220 current source. By changing the Model 6220 compliance voltage with the HMS configuration utility, the maximum voltage in the system can be set to 7 V DC or 100 V DC . The Model 776 provides complete automatic switching between van der Pauw configuration and Hall bar configuration. The Model 776 also automatically removes the Model 6485 current meter for currents larger than 20 mA. The system is designed to measure 100 GΩ resistances, at 100 V with 2% uncertainty.

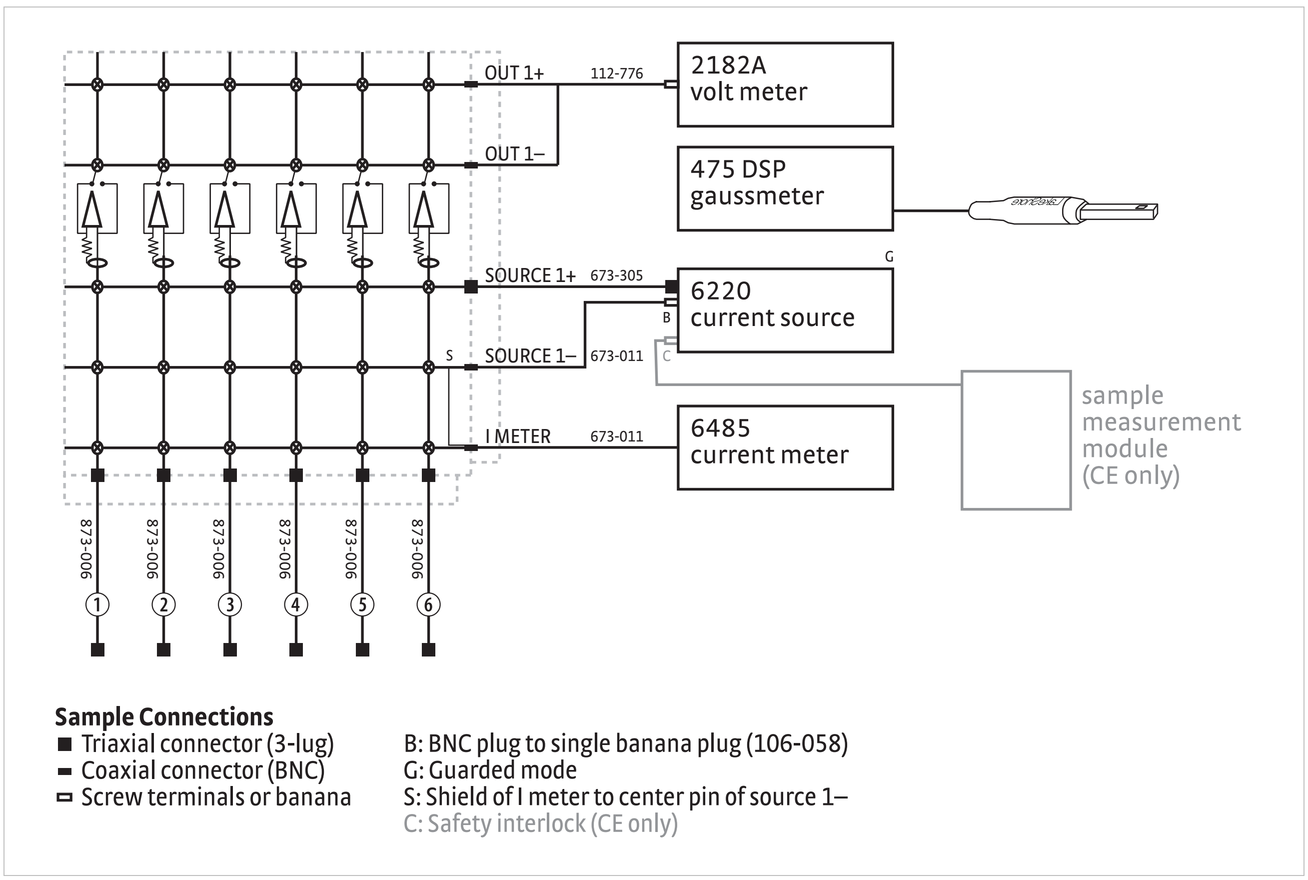


FIGURE 3-13 ***Model 7700A HMS wiring diagram***

3.7 Computer Installation

The computer connections are defined as follows (FIGURE 3-14). The monitor (not shown) also requires input and power connections.

CAUTION

Do not install any third-party software on this computer. Installing other software may cause conflicts with the operation of the 7700A series HMS system and can have unintended consequences. Lake Shore assumes no responsibility for damage to the system as the result of unauthorized software installation.

NOTE

Because of the volatility of the computer market, the computer shown here is a typical representative. Your actual computer may vary in form, but the functions will remain.

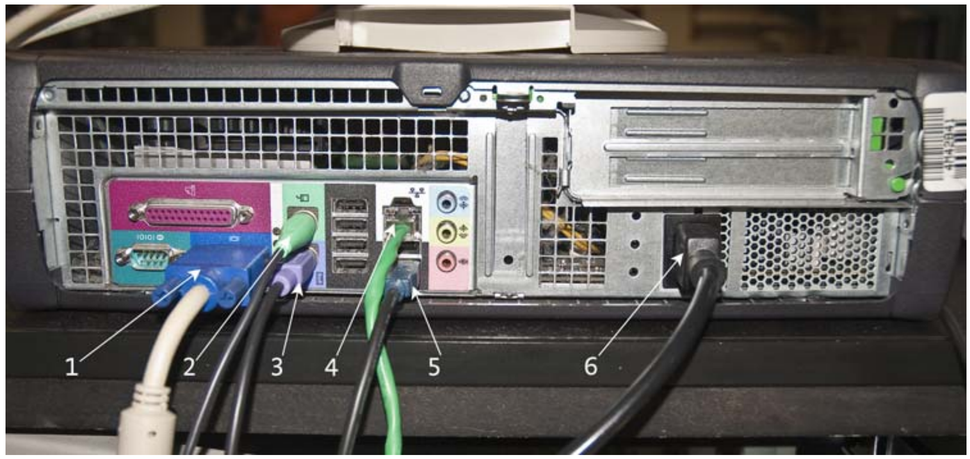


FIGURE 3-14 ***Computer rear panel connections***

1. Monitor: this connector goes to the computer monitor.
2. Mouse: this connector goes to the computer mouse.
3. Keyboard: this connector goes to the computer keyboard.
4. Ethernet: this is the Ethernet connector for your network.
5. USB connector: this is the USB to IEEE dongle. This connection allows communication with all the instruments.
6. Power: this power cord runs inside the instrument console and plugs into the distribution strip. (Also run the monitor power connector to this same distribution strip.)
7. Voltage selection switch: if your computer includes this switch, make sure it matches your local power requirements.

NOTE

While Ethernet is provided with the computer, Lake Shore assumes no responsibility for making the computer communicate with your network.

3.8 Gaussmeter Probe Holder Installation

Use the following procedure to mount the gaussmeter probe holder. It is best to loosely install the assembly first without a probe in the holder, then once the assembly is close to a usable position, place a probe in the holder and make the final adjustments.

1. Place the gaussmeter probe holder assembly at the end of the extruded frame located between the magnet coils. Use the 5⁄32 in hex wrench to mount the holder to the extrusion, as shown in FIGURE 3-15. This screw also provides side to side adjustment of the holder assembly.
2. Use the 3⁄16 in hex wrench to adjust the height and rotation of the post.
3. Use the 3⁄16 in hex wrench to adjust the clear plastic probe holder attached to the post. This screw provides up and down adjustment of the probe holder.

CAUTION

Exercise care when handling the gaussmeter probe; its tip is very fragile. Stressing the probe tip may alter its calibration. Any excess force can easily break the sensor. Broken sensors are not reparable.

FIGURE 3-15 ***Gaussmeter probe holder***

4. Carefully place the gaussmeter probe into the holder. Turn the top screw to hold it in position. Do not over tighten.

CAUTION

Always secure the gaussmeter probe by the body; securing the tip can cause irreparable damage.

5. Do any final adjustments to the probe holder assembly to ensure the probe is in the proper position between the Hall sample module and the magnet pole pieces. Rotate the probe so the flat side is parallel with the pole faces and secure it.

NOTE

To make room for the gaussmeter probe, the gap to the right of the sample enclosure (when viewed from the front of the electromagnet), needs to be about 3 mm to 4 mm (about 1⁄8 in) larger than the gap to the left.

3.8.1 Gaussmeter Probe Orientation

The orientation of the gaussmeter probe is critical to field control. If you are unsure of correct orientation, use this procedure.

1. With the magnet power supply off and local regulation set to zero, place the gaussmeter probe in the electromagnet noting the orientation of the Lake Shore snowflake symbol.
2. Turn the power supply on in local mode. Manually set a positive current of a few amps corresponding to approximately 500 Oe.
3. Read the gaussmeter display in the Hall software to ensure the field reading is positive. If the field reading is negative, reverse the orientation of the probe.
4. When done, reduce current to zero and turn off the power supply.

3.8.2 Changing Probes

An electrically erasable programmable read only memory (EEPROM) is included in each probe. The EEPROM stores specific information that the gaussmeter requires for operation. The information includes serial number, probe sensitivity, and field compensation data.

CAUTION

The probe must be connected to the rear of the gaussmeter before applying power. Probe memory may be erased if connected with power on.

When the instrument is powered up, the probe memory is downloaded to the gaussmeter. This is how the built-in gaussmeter knows which ranges are available and which error correction to apply.

1. Turn the power off
2. Remove the existing probe.
3. Plug in the new probe.

When power is restored, the characteristics of the new probe are downloaded to memory. Normal operation may continue after the new probe offset is nulled using the zero probe operation. If the instrument is powered up with no probe attached, the Hall software will report an error message.

3.8.3 Probe Handling

Although every attempt has been made to make the probes as sturdy as possible, they are still fragile. While taking measurements, be careful not to place pressure on the probe tip.

CAUTION

Care must be exercised when handling the probe. The tip of the probe is very fragile. Stressing the Hall sensor can alter its calibration. Any excess force can easily break the sensor. Broken Hall sensors are not repairable.

When probes are installed on the gaussmeter but are not in use, the protective tubes provided with many probes should be placed over the probe handle and stem in order to protect the tip. The cardboard and foam container that Lake Shore probes are shipped in should be retained for probe storage when the gaussmeter is not in use. For further details on accessories and probes, refer to the Magnetics catalog.

3.8.4 Probe Operation

In the DC mode of operation, the orientation of the probe affects the polarity reading. On a transverse probe, the Lake Shore name printed on the handle indicates the side for positive (+) flux entry.

NOTE

For best results, the instrument and probe should warm up for at least 5 min before zeroing the probe, and at least 30 min for rated accuracy. The probe and the zero gauss chamber should be at the same temperature.

If the exact direction of the magnetic field is unknown, the proper magnitude is determined by turning on Max Hold and slowly adjusting the probe. As the probe turns and the measured field rises and falls, its maximum value is held on the display. Make note of the probe orientation at the maximum reading to identify the field orientation.

3.8.5 Probe Accuracy Considerations

The user must consider all the possible contributors to the accuracy of the reading. Both the probe and gaussmeter have accuracy specifications that may impact the actual reading. The probe should be zeroed before making critical measurements. The zero probe function is used to null (cancel) the zero offset of the probe or small magnetic fields. It is normally used in conjunction with the zero gauss chamber, but may also be used with an open probe (registering Earth's local magnetic field).

NOTE **For best results, the instrument and probe should warm up for at least 5 min before zeroing the probe and at least 30 min for rated accuracy. The probe and the zero gauss chamber should be at the same temperature.**

3.8.5.1 Probe Orientation

Probe readings are dependent on the angle of the sensor (Hall sensor) in relation to the magnetic field. Maximum output occurs when the flux vector is perpendicular to the plane of the sensor. This is the condition that exists during calibration at Lake Shore. The greater the deviation from orthogonality (field perpindicular to the plane of the sensor), the larger the error of the reading. For example, a 5° variance on any one axis causes a 0.4% error, a 10° misalignment induces a 1.5% error, etc.

In the DC mode of operation, the orientation of the probe affects the polarity reading of the gaussmeter. On a transverse probe, the Lake Shore name printed on the handle indicates the side for positive (+) flux entry (FIGURE 3-16).

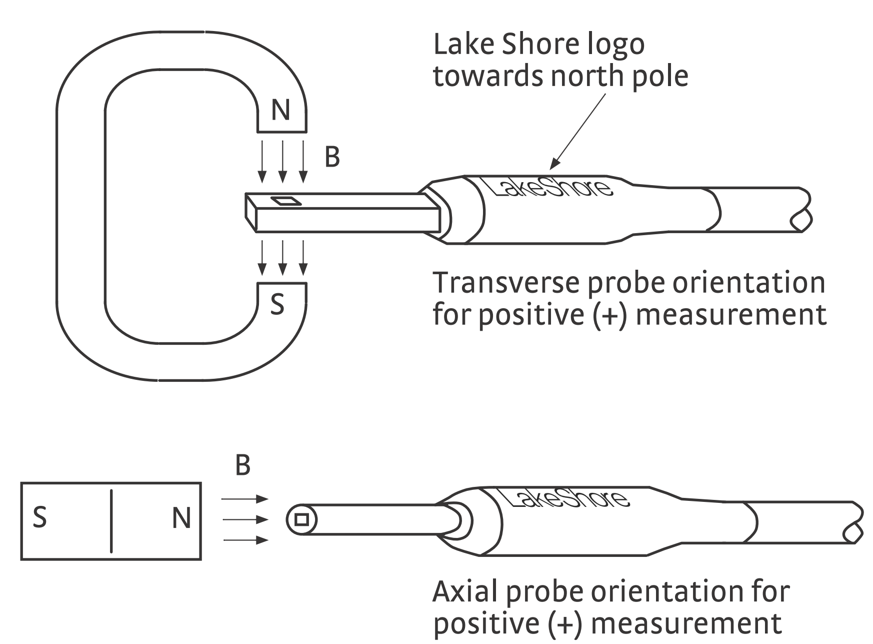


FIGURE 3-16 ***Probe orientation for positive measurement***

NOTE **Use care to ensure the zero gauss chamber does not become magnetized. Using a magnetized chamber to zero a probe can lead to erroneous field readings. It is a good practice to periodically degauss the chamber. A bulk tape degausser (Verity VS250, Data Devices PF211, or equivalent) may be used.**

NOTE **The Model 450 gaussmeter does not read the temperature compensation table stored in the gaussmeter probe.**

Tolerance of instrument, probe, and magnet must be considered for making critical measurements. The accuracy of the gaussmeter reading is better than ±0.20% of reading and ±0.05% of range. Absolute accuracy readings for the gaussmeter and probe is a difficult specification to give, because all the variables of the measurement are difficult to reproduce. For example, a 1° error in alignment to the magnetic field causes a 0.015% reading error. Finally, the best probes have an accuracy of ±0.15%. This implies that the absolute accuracy measurement of a magnetic field is not going to reliably be better than ±0.15% under the best of circumstances, and more likely to be 0.20% to 0.25%.

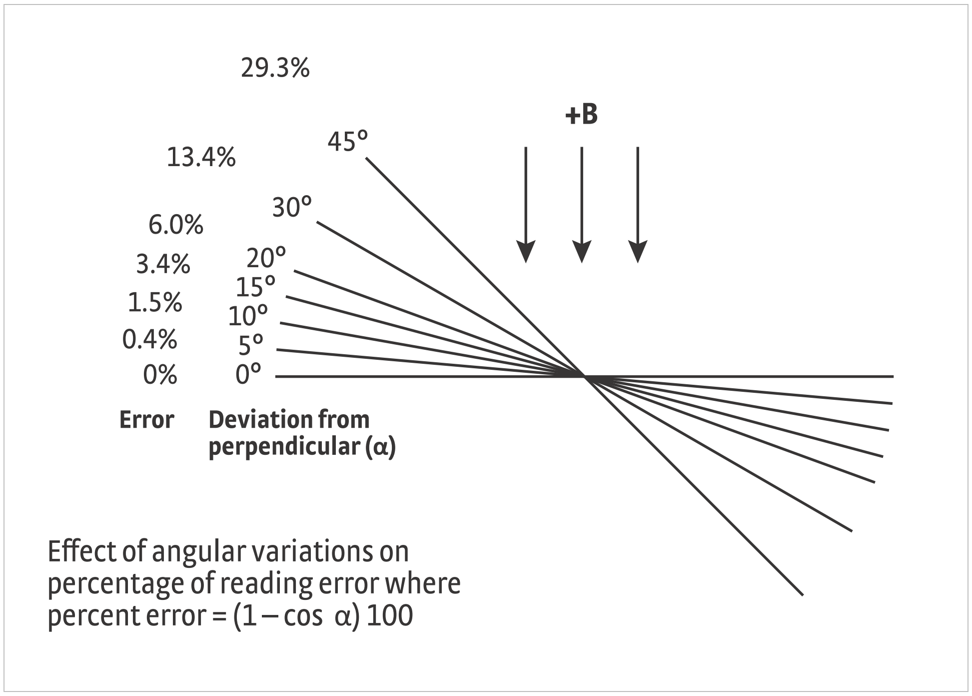


FIGURE 3-17 ***Effect of angle on measurements***

3.9 Installation of Options

This section describes how to install the Model 750TC option.

3.9.1 Model 750TC Temperature Controller Option

The Model 750TC option adds a Model 340 temperature controller to a Model 7700A HMS. To add this option:

1. Remove a blank panel (or panels) to create a 3.5 in high space in the instrument console.
2. Attach the rack mounts to the 340 temperature controller and mount in the rack (refer to the Model 340 User's Manual for more detailed information on mounting the rack).
3. Connect the power cord and IEEE-488 communications cable.
4. Cable connections to specific sample modules are covered in Chapter 4.

3.9.2 Grounding Mounting Base Plate

For the CE option system, the mounting base plate should already be installed on the magnet to support the measurement hardware. A ground cable should be attached between the instrument console and the tap hole located at the rear surface of this plate to complete the safety ground connection.

Chapter 4: Basic Operation

4.1 General

This chapter describes the majority of daily operation. Chapter 5 covers more advanced operation. It is assumed that the system has been installed and set up as described in Chapter 3.

4.2 Avoiding Water Condensation

If the temperature of the cooling water is too cool relative to the air temperature and humidity, condensation can occur. Condensation inside the power supply can cause severe damage. To avoid condensation, the power supply operator must remain cognizant of the ambient air temperature, cooling water temperature, and the relative humidity. Lake Shore defines the limits of these conditions as follows: ambient temperature =18 °C to 28 °C (64 to 82 °F), cooling water temperature = 15 °C to 24 °C (59 to 75 °F), and humidity = 20% to 80% (non-condensing). Knowing the actual state of these conditions, the operator can calculate the dew point, or temperature at which condensation will occur. TABLE 4-1 and TABLE 4-2 are included to aid in dew point calculation.

NOTE

The Model 665 and Model 668 power supplies are equipped with a moisture sensor. This sensor will trigger an external fault that will inhibit the output of the power supply. This fault can also be triggered by the absence of cooling water flow in the magnet.

	% Relative Humidity																		
°C	100	95	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10
32	32	31	31	29	28	27	26	24	23	22	20	18	17	15	12	9	6	2	0
29	29	28	27	27	26	24	23	22	21	19	18	16	14	12	10	7	3	0	—
27	27	26	25	24	23	22	21	19	18	17	15	13	12	10	7	4	2	0	—
24	24	23	22	21	20	19	18	17	16	14	13	11	9	7	5	2	0	—	—
21	21	20	19	18	17	16	15	14	13	12	10	8	7	4	3	0	—	—	—
18	18	17	17	16	15	14	13	12	10	9	7	6	4	2	0	—	—	—	—
16	16	14	14	13	12	11	10	9	7	6	5	3	2	0	—	—	—	—	—

TABLE 4-1 ***Dew point calculation (in degrees Celsius)***

	% Relative Humidity																		
°F	100	95	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10
90	90	88	87	85	83	81	79	76	74	71	68	65	52	59	54	49	43	36	32
85	85	83	81	80	78	76	74	72	69	67	64	61	58	54	50	45	38	32	—
80	80	78	77	75	73	71	69	67	65	62	59	56	53	50	45	40	35	32	—
75	75	73	72	70	68	66	64	62	60	58	55	52	49	45	41	36	32	—	—
70	70	68	67	65	63	61	59	57	55	53	50	47	44	40	37	32	—	—	—
65	65	63	62	60	59	57	55	53	50	48	45	42	40	36	32	—	—	—	—
60	60	58	57	55	53	52	50	48	45	43	41	38	35	32	—	—	—	—	—

TABLE 4-2 ***Dew point calculation (in degrees Fahrenheit)***

For example, determine the actual air temperature and relative humidity. Find the closest air temperature in the left-hand column and the closest relative humidity across the top. If the air temperature is 24 °C (75 °F) and the relative humidity is 35%, the intersection of the two shows a dew point of 7 °C (45 °F). Therefore, for the given conditions, the cooling water must remain above 7 °C (45 °F) to prevent condensation.

4.3 Model 75013: Sample Card Sample Module (SCSM)

The Lake Shore Model 75013 SCSM ships with all 7700A series Hall measurement systems. FIGURE 4-1 shows the standard sample module with components labeled, but without the hardware necessary to mount to a specific electromagnet. The standard unit has one 10-pin connector and one 4-pin connector for temperature measurement and control. For the CE option system, the sample module has an additional 8-pin connector with the connecting cable. TABLE 4-3 provides the CE safety wiring description.

WARNING

High voltage can be present at sample terminals. Always install the light-tight box onto the measurement insert before making measurements, and stop measurements before removing the module.

For the CE option system, an interlock switch is installed in the header of the sample module so that the unit will not operate until the sample enclosure is properly installed, and all the cables are connected.

Instrument console	8-pin cable	8-pin connector	Sample module
Model 6620 interlock terminal	#24 AWG cable	A and G	Interlock switch
	Cable shield	F	Case
Console ground	#16 AWG wire	B	Case
		C	Case
		D	Case
		E	Case
N/A	N/A	H	Not used

Note: Pins B, C, D, and E are connected t othe same wire

TABLE 4-3 ***CE safety wiring description***

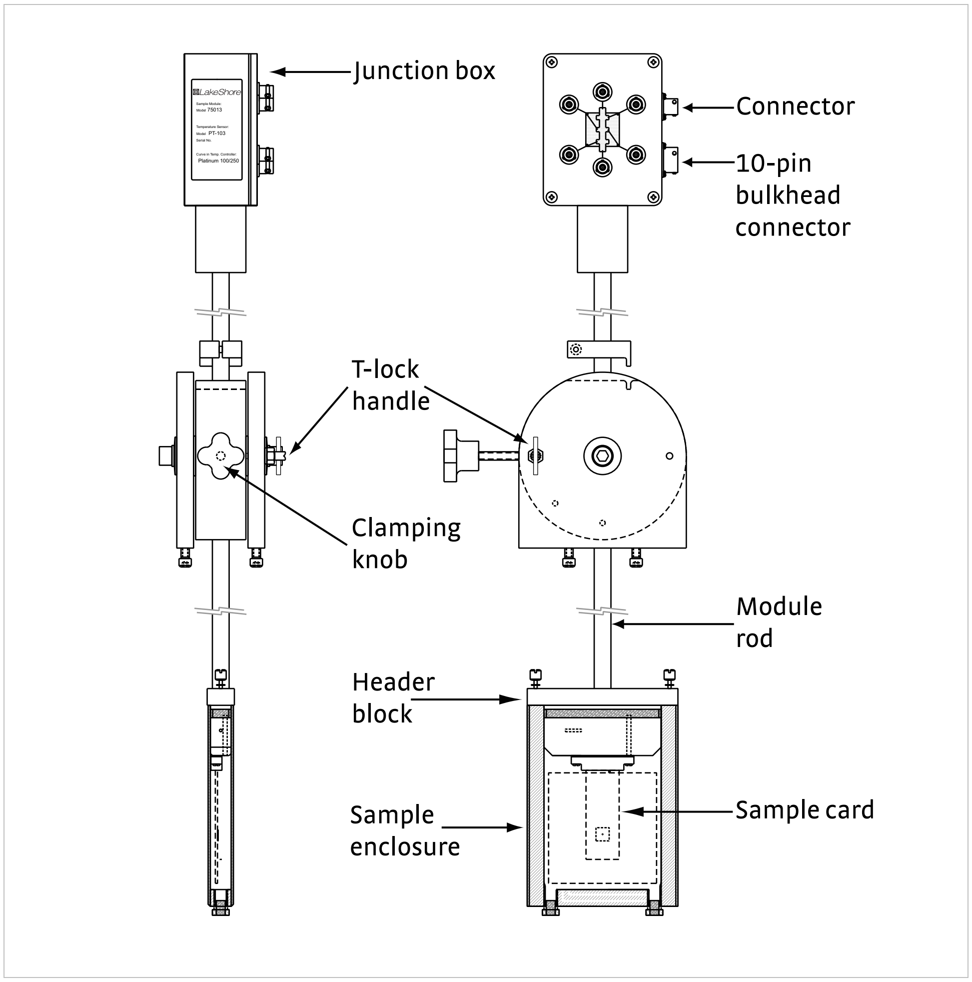


FIGURE 4-1 **Model 75013 SCSM. Left: Side view; Right: Front view**

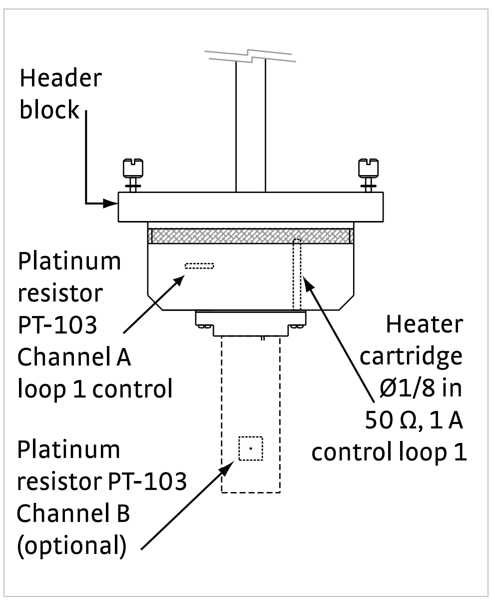


FIGURE 4-2 **Temperature monitoring and control instrumentation in the 75013 SCSM**

4.3.1 Sample Mounting for the Model 75013 SCSM

This section provides step-by-step instructions for mounting a sample for measurement in the Model 75013 SCSM. Contact to the sample is made with either soldered wires or needle probes, depending on the sample card in use.

Each sample card has 20 gold-plated contact fingers. The contact fingers on the front side connect to sample contact pads 1-6 and auxiliary contact pads 7-8. The contact fingers on the back side connect to auxiliary contact pads 9-10 and to the driven shields for signal lines 1-6. Routing the driven shields onto the card minimizes leakage currents, allowing more accurate measurements on very high resistance samples.

Standard sample mounting cards have solder pads where wires from the sample are connected to the card. Soldered contacts are the most reliable, but take more time and effort to make. Samples can be pre-mounted and stored for rapid insertion and measurement in the Model 75013 SCSM.

The prober sample card has tungsten needle probes to contact the sample. Samples contactable with the needle probes can be rapidly mounted and demounted. The contact size and metallurgy can have a significant impact on measurement accuracy. Sample preparation and contacting is the user's responsibility. See Appendix A: Hall Measurement for general Hall effect measurement theory and a discussion of Hall sample geometries. See Appendix B: Electrical Contacts to Semiconductors for references to literature on contact formation. The procedures beginning in section 4.3.1.1 assume that the sample is directly contactable or that contact metallization is already present.

The auxiliary contacts are available for a temperature sensor, heater, light source, sample bias, additional sample contacts, or other use. The auxiliary contacts are not guarded and their use might not be directly supported by the hardware or software supplied.

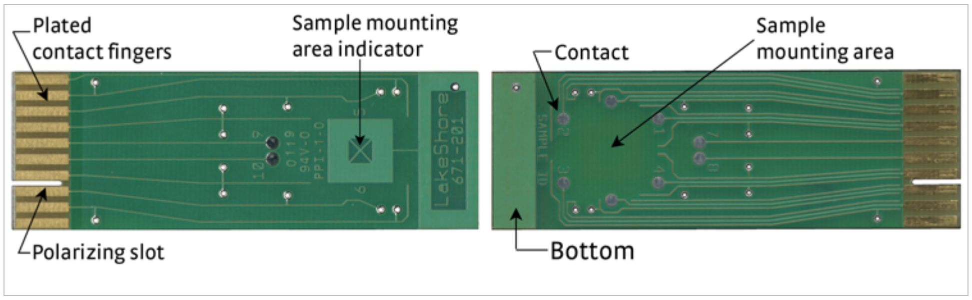


FIGURE 4-3 ***671-201 sample card for nominally 1 cm × 1 cm samples. Left: Back; Right: Front***

Sample mounting materials and tools list

- Sample mounting card (provided by Lake Shore)
- Lead wire (provided by Lake Shore)
- Soldering iron with fine pointed tip
- Indium (provided by Lake Shore), silver paste, conductive epoxy, or other contacting material
- Glass microscope slide
- Magnifying lens
- Tweezers
- Cotton swabs
- Adhesive such as Elmer's® rubber cement (also known as art gum, commonly available at stationary or art supply stores); grease such as silicone vacuum grease may also be used

NOTE **Sample cards are reusable. Do not use permanent adhesive if sample is to be removed from sample card.**

4.3.1.1 Sample Preparation

Much of sample preparation depends on the sample material and type. Develop specific procedures applicable to your samples. These steps are some general guidelines:

1. Select a sample card (large or small with solder contacts, or prober sample card).
2. Verify the sample fits in the sample mounting space. Samples can be cut to size by many methods (scratch and break, diamond sawing, etching), depending on the sample material and form (such as bulk crystal, wafer, thin film).
3. Clean the sample.
4. Pattern the sample or identify contact regions. Refer to Appendix A: Hall Effect Measurement Theory and Practice to determine where to attach leads to sample. Patterning by photolithography or grit blasting might be possible, but are outside the scope of this document.
5. Prepare the contact regions on the sample. Some materials require etching of the surface. Other materials require alloying with a suitable contact metal followed by annealing. Refer to Appendix B: Electrical Contacts to Semiconductors.

4.3.1.2 Mounting the Sample to the Standard Sample Card

Standard sample cards have solder pads where wires from the sample are connected to the card. Soldered contacts are the most reliable, but take more time and effort to make. Samples can be pre-mounted and stored for rapid insertion and measurement in the Model 75013. Pre-mounted samples are included in the box of sample mounting cards provided with each Model 75013. Use these as examples.

4.3.1.2.1 Attaching Leads to a Sample

Attach wire leads to your samples with solder, silver paste, conductive epoxy, wire bonding, spot welding, or other means. Only indium solder lead attachment is covered here. Lead wire (75 µm diameter silver-plated copper) is provided by Lake Shore. Recommended lead wire is 50 µm to 100 µm diameter copper, silver-plated copper, or gold wire. This procedure assumes the sample is directly contactable or that contact metallization is already present.

CAUTION **Applying high temperature during soldering can damage some samples.**

NOTE **Limit the amount of solder on the sample. Place solder on the contact points in small amounts only.**

1. Heat soldering iron. Indium melts at 156.6 °C (313.9 °F), so it does not require a very hot iron.
2. Cut indium or other suitable solder metal and place it on the glass slide.
3. Using a soldering iron, melt solder metal onto the tip of the soldering iron and place a small amount of solder on each contact point on the sample. Refer to Appendix A: Hall Effect Measurement Theory and Practice for contact point locations.
4. Cut the multi-stranded lead wire to the proper length. Length is determined by the distance between the sample, where the lead attachment is made, and the contact on the sample mounting card. Allow enough wire for strain relieving bends.
5. Unravel the cut lead wire into single strands of wire.
6. Using tweezers, place one end of the lead wire at the proper sample contact point. Hold the wire in place with tweezers.
7. Solder the wire to the sample contact point.
8. Repeat for all leads to sample contact points.

4.3.1.2.2 Mounting a Sample on a Sample Card

Be careful not to damage the sample surface. Scratches can alter measurement readings, especially with thin film samples. Lightweight samples often can be lifted by a contact wire, avoiding contact with the sample.

NOTE **Always use tweezers or gloved hands to handle the sample. Oil from your skin can alter measurements on high resistance samples and can alter chemically reactive sample materials.**

1. Select a sample mounting card. Do not touch the gold plated contact fingers at the top of the card. Fingerprints might create electrically conductive paths that can change measurement readings on high resistance samples.
2. Using a wire, stick, or small brush, place a small amount of adhesive in the center of the sample mounting area on the front side of the card. Hold the card up to a light to see the sample mounting area indicator on the back side. The “X” marks the center of the sample mounting area (as well as the tail of the positive magnetic field vector oriented up through the sample).
3. Using tweezers, place the sample in the center of the sample mounting area on the adhesive.
4. Using a cotton swab, press down gently on the sample. Continue pressing down gently for a few seconds and then release. Allow the adhesive to dry if necessary.

4.3.1.2.3 Soldering Leads to Sample Card Contacts

To complete the mounting procedure, solder the other end of the lead (the end not soldered to the sample) to a contact on the sample mounting card. See FIGURE 4-4 or 4-11 for sample mounting card contacts.

1. Using tweezers, bend the lead wire to allow some strain relief. Hold lead wire in place on sample mounting card contact.
2. Solder the lead wire to the sample card contact.
3. Clip the excess lead wire. See FIGURE 4-4.
4. Repeat for all leads to sample mounting card contacts.
5. Write the sample name in the sample ID space on the front side of the card.

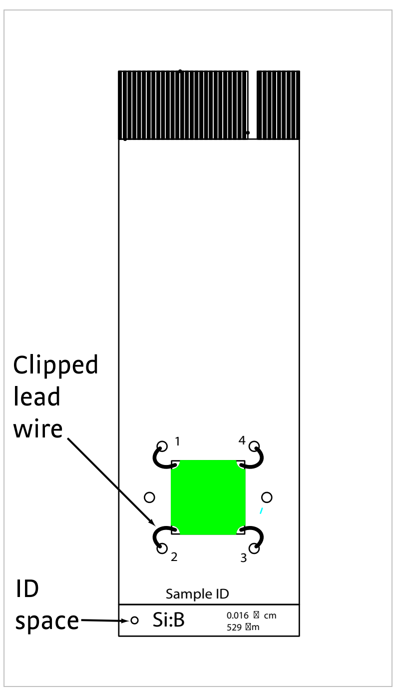


FIGURE 4-4 ***Sample card with mounted van der Pauw sample and leads***

4.3.1.2.4 Sample Removal

To remove a sample mounted to a sample card with rubber cement, gently push the side of the sample with a wooden stick or other soft object to shear it from the adhesive.

CAUTION

Prying the sample up with tweezers or a razor blade can damage the sample. Pushing on the sample with any hard, sharp object can also cause damage.

Remove lead wires from the sample with tweezers and a soldering iron. To reuse a card, remove any adhesive left on the card and remove all leads. Remove adhesive gently to avoid scratching the card. Remove typical “permanent” inks from the card with isopropyl alcohol or acetone.

4.3.1.3 Mounting a Sample to the Prober Sample Card

The prober sample card has tungsten needle probes to contact the sample. Samples contactable with the needle probes can be rapidly mounted and demounted. A prober sample card with a 50 mm (2 in) diameter sample wafer (but only two probers making contact to the sample) is shown in FIGURE 4-5.

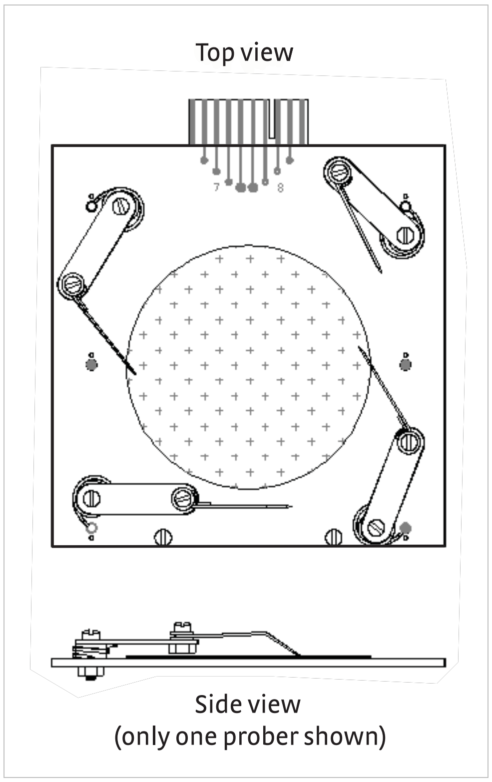


FIGURE 4-5 ***Prober sample card***

Use this procedure to mount samples.

1. Move the probe tips out of the sample mounting region. The probe tips can be picked up and swung out of the way using your fingers or tweezers.
2. Place the sample in the center of the prober card. Hold the card up to a light to see the sample mounting area indicator on the back side. The “X” marks the center of the sample mounting area (as well as the tail of the positive magnetic field vector oriented up through the sample).
3. Pick up one probe tip at a time and place it on the desired contact location on the sample. Some samples might have metallized contact pads.

NOTE

Ohmic contact can be made by direct contact to some semiconducting samples, typically those with higher electrical conductivity. Ohmic contacts can sometimes be formed by running current through the contacts, typically a current significantly higher than the measurement current. Be careful, excessive currents could damage sensitive samples!

The force required to move the prober arms can be changed by tightening or loosening the nylon screws and nuts. The force of the prober on the sample can be adjusted by swinging the probe tip over the edge of the card and then bending the probe needle up or down as required.

Nothing (sample, arms, or probers) should extend beyond the edges of the prober card or they might contact the inside of the sample enclosure.

Heavy samples might require additional support. A small amount of temporary adhesive such as rubber cement could be used. The two nylon screw heads at the bottom of the prober sample card can be used as rests for 75 mm (3 in) diameter wafers. Similar rests could be added as needed.

Accurate van der Pauw measurements require the probes to be as near a sample edge as possible. Some compromise might be necessary if the edge of the sample is not uniform. Symmetrically placed probes on a symmetrical sample generally improve measurement accuracy by minimizing misalignment voltages. For further discussion of this subject, see Appendix A: Hall Effect Measurement Theory and Practice.

4.3.1.4 Using Auxiliary Contacts

The auxiliary contacts shown as numbers 9 and 10 in FIGURE 4-6, are available for a temperature sensor, heater, light source, sample bias, additional sample contacts, or other use. The auxiliary contacts are not guarded and their use might not be directly supported by the hardware or software supplied.

The four auxiliary contacts, numbered 7-10 on the sample card, are connected to the 10-pin bulkhead connector on the junction box (FIGURE 4-1). Wiring assignments are given in TABLE 4-4.

Connector	Pin	Use	Wire R [Ω]
B-1	1	Sample card pad #1	25
B-2	2	Sample card pad #2	
B-3	3	Sample card pad #3	
B-4	4	Sample card pad #4	
B-5	5	Sample card pad #5, I+ for Hall bars	
B-6	6	Sample card pad #6, I– for Hall bars	
B-7	A	Sample card pad #10; "Sensor": temperature sensor (Channel B), V–	8
	B	Sample card pad #9; "Sensor": temperature sensor (Channel B), V+	
	C	Sample card pad #8; "Sensor": temperature sensor (Channel B), I–	
	J	Sample card pad #7; "Sensor": temperature sensor (Channel B), I+	
	D	Heater, 50 , 1 A, in header block (Loop 1), I+	
	E	Heater, 50 , 1 A, in header block (Loop 1), I–	
	G	"Control" temperature sensor (Channel A), V–	
	H	"Control" temperature sensor (Channel A), V+	
	F	"Control" temperature sensor (Channel A), I–	
	K	"Control" temperature sensor (Channel A), I+	
B-8		unused	

TABLE 4-4 ***Sample connection wiring for the 75013 SCSM***

4.3.1.5 Mounting a Temperature Sensor to a Sample Card

A temperature sensor can be mounted to a sample card and electrically connected using the auxiliary contacts shown in FIGURE 4-6 and numbered 9 and 10. Either a 2-wire or a 4-wire temperature sensor can be connected.

The 75013 SCSM is provided with one sample card (P/N 671-201, FIGURE 4-3) with a Lake Shore Model PT-103 platinum resistance temperature sensor mounted on the back side, directly underneath the sample mounting area.

This procedure describes how to mount a PT-103 sensor on a sample card. You can use this procedure as a guideline for mounting a temperature sensor to a sample card.

1. Verify that the sample card is clean and free of defects. Hold the card by its edges. Do not touch the gold plated contact fingers.
2. Apply a small amount of rubber cement to one side of the PT-103 platinum resistor; then center the resistor body over the X located on the back side of a sample card as shown in FIGURE 4-6.
3. Solder the leads to the contact pads numbered 9 and 10.
4. Trim off any excess lead wire. The resistor might need to be held in place with a weight or tape while the rubber cement dries.
5. Cut two lengths of 30 AWG Teflon® insulated wire (Lake Shore type HD-30, or equivalent) 20 mm (¾ in) long. Use a thermal stripper to remove 3 mm (⅛ in) of insulation from each end. Cut it longer if you are mounting the sensor on a larger sample card.
6. Solder one end of one insulated wire to contact pad numbered 9. Solder one end of the other wire to contact pad 10.
7. Push the free ends of the insulated wires through the two holes numbered 9 and 10 in FIGURE 4-6. Solder the other ends of the insulated wires to contact pads 7 and 8 on the front side of the card.
8. If rosin flux was used, clean the contacts of flux residue using isopropyl alcohol scrubbed with a short bristle brush. Rinse with de-ionized (DI) water and blow dry with nitrogen gas.

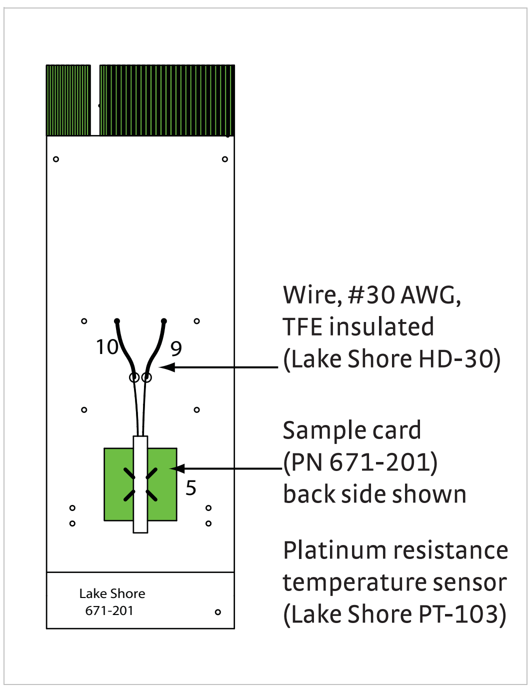


FIGURE 4-6 ***Mounting a platinum temperature sensor on a sample card***

4.3.2 Operation of the Model 75013 SCSM

This section explains the operation of the Model 75013 SCSM, to include inserting and removing a sample card, room temperature operation, and operation with liquid nitrogen.

4.3.2.1 Sample Card Insertion

The Hall voltage is proportional to the cosine of the angle between the magnetic field vector and the normal to the sample plane (which is equivalent to the sine of the angle between the magnetic field vector and sample plane) as shown in FIGURE 4-7. The measurement error introduced in quantities proportional to the Hall voltage (such as carrier concentration, mobility) is tabulated in TABLE 4-5. Holding the sample card parallel to the magnet pole faces (perpendicular to the magnetic field) to within 3 mm (⅛ in) over the 65 mm (2.6 in) exposed length of a small sample card, gives a measurement error of only 0.1%, adequate for many measurements.

	x (mm)							
	1	**2**	**3**	**4**	**5**	**6**	**8**	**10**
$\cos\beta = \sin\alpha$	0.99988	0.99953	0.99893	0.99810	0.99704	0.99573	0.99240	0.98809
error (%)	0.012	0.047	0.107	0.190	0.296	0.427	0.760	1.191

TABLE 4-5 ***Measurement error contributed by a small sample card tilted with respect to the magnetic field. Refer to parameter descriptions. The length, L, was taken as 65 mm.***

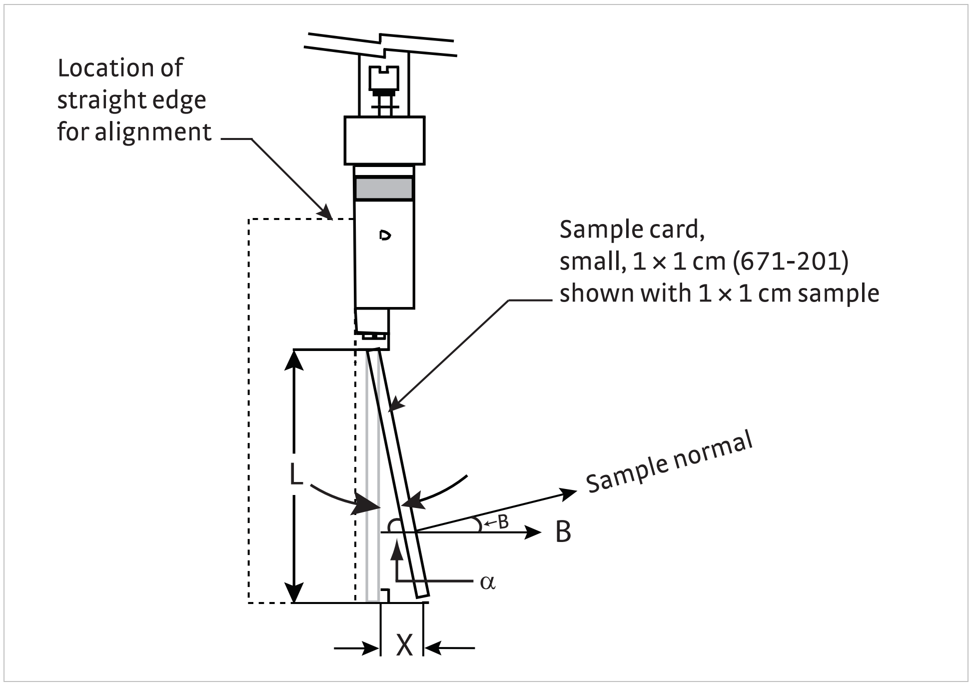


FIGURE 4-7 ***Geometry of a sample card tilted relative to the magnetic field***

WARNING

High voltage can be present at sample terminals. The sample enclosure should be properly installed and all the cables connected before making a measurement.

For the CE option system, an interlock switch is installed in the header of the sample module so that the unit will not operate until the sample enclosure is properly installed and all the cables are connected.

1. Swing the sample enclosure end of the sample module out of the electromagnet and lock it in place at either the 45° or horizontal positions.
2. Remove the sample enclosure.

3. Grasp the sample card by the edges, being careful not to touch the gold-plated contact fingers.
4. Orient the sample card so the mounted sample faces the same direction as the front of the sample module junction box.
5. Align the contact fingers with the card edge connector on the bottom end of the sample module. Check that the alignment key in the card edge connector lines up with the slot in the sample card.
6. Firmly push the sample card straight into the connector.

NOTE

Wiggling the card should be avoided as it can loosen or damage the polarization key in the card edge connector.

7. Check that the sample card protrudes straight out of the connector by holding a straight edge against the side of the header block.

4.3.2.2 Room Temperature Operation

This procedure assumes that you have inserted the sample card into the sample module. The 6 triaxial cables on the sample module have a protective sleeve and a short section of spiral cable wrap and a tie down clamp near the sample end.

1. Locate the tie down clamp near the sample end. Bolt it to the right rear bolt hole on top of the saddles. This positions the cables close to the sample well where they will be attached to the sample module.
2. If you have the CE option system, connect the 8-pin connector cable to the sample module.
3. Insert the sample enclosure into the module and tighten the two thumb screws.
4. Release the T-Lock handle and rotate the sample module rod back to vertical. The index plunger should lock the sample enclosure in place between the magnet poles.
5. Check the location and orientation of the gaussmeter Hall probe.
6. Run the Hall system software (Chapter 5) to perform the experiment.

4.3.2.3 Liquid Nitrogen Temperature Operation

Liquid nitrogen sample module operation (77 K) is similar to room temperature operation.

WARNING

High voltage can be present at sample terminals. Always install the measurement insert into the light tight box before making measurements, and stop measurements before removing the module.

For the CE option system, an interlock switch is installed in the header of the sample module so that the unit will not operate until the sample enclosure is properly installed and all the cables are connected. Do not manually exercise the interlock switch pins. It can be easily contaminated with foreign material that can impair its free movements.

NOTE

The safety interlock switch may prevent measurements from starting, if moisture is present on its surface when the module is cooled with liquid nitrogen. Before installing the sample enclosure, dry any moisture on the measurement components with a clean tissue or air gun.

This procedure assumes that the sample module is not in the Dewar. If the sample module is in the Dewar already, first remove the sample enclosure from the Dewar before rotating to a horizontal position. To do this, hold the sample module rod with your hand, unscrew the clamping knob, lift the sample module rod up until the sample enclosure is out of the Dewar, and tighten the clamping knob until the sample module rod is secured in place.

1. Return the sample module to vertical with the sample enclosure above the magnet gap.
2. Loosen the clamping knob and lower the module rod until the alignment key slides into place. The sample enclosure is now inside the Dewar.

3. Rotate the funnel to the front of the magnet stand.
4. Place the Styrofoam™ cover over the top of the Dewar.
5. Place the rubber transfer hose through the hole in the Dewar cover.
6. Pour liquid nitrogen into the funnel to fill the Dewar. Wait until the liquid stops boiling vigorously and the level stabilizes.
7. Check the location and orientation of the gaussmeter Hall probe.
8. Run the Hall system software to perform the experiment (Chapter 5).
9. Refill the Dewar with liquid nitrogen during the experiment as necessary.

Initial cool down (warm Dewar and sample holder)	Time	5 min to 10 min
	LN_2 consumption	2 L
Subsequent cool downs (cold Dewar, warm sample holder)	Time	5 min
	LN_2 consumption	1 L
Hold time after filling with LN_2	At 77 K: 30 min to 60 min, depending on sample size	
Time to warm sample holder from 77 K to 290 K	In Dewar	5 h to 8 h
	Out of Dewar in 296 K room air	50 min to 80 min
	Out of Dewar with 1000 W hot air gun	10 min to 20 min

TABLE 4-6 ***Dewar specifications for the Model 75013 SCSM***

4.3.2.4 Sample Card Removal

1. Swing the sample enclosure end of the sample module out of the electromagnet and lock it in place at either the 45° or horizontal positions.
2. Remove the sample enclosure.
3. Grasp the sample card by the edges being careful not to touch the gold-plated contact fingers.
4. Firmly pull the sample card straight out of the connector. Wiggling the card should be avoided as it can loosen or damage the polarization key in the card edge connector.

4.4 Model 75014A: Closed Cycle Refrigerator Sample Module (CCRSM) Option

The Model 75014A closed cycle refrigerator sample module (CCRSM) features and specifications are given in Chapter 1. Stable operation at a range of temperatures is made possible by balancing the cooling power provided by a closed cycle refrigerator (CCR) against two heater circuits powered by a temperature controller. An assembly overview is shown in FIGURE 4-9. The Model 75014A consists of these components:

- Omniplex cryostat (see FIGURE 4-10 and TABLE 4-7) modified specifically for this application, including added:
  - Rotation stage
  - Flush-fill unit
  - Mounting base plate
- Sample insert (FIGURE 4-9)
- Compressor for the CCR
- Helium gas lines for the CCR
- Power booster for a Model 340 loop 2 heater output

Also required for operation of the Model 75014A CCRSM, but not provided:
- Model 750TC option
- Vacuum pump
- Helium gas bottle, regulator with 100 psi output

Optional additional equipment:
- Water chiller for the CCR compressor

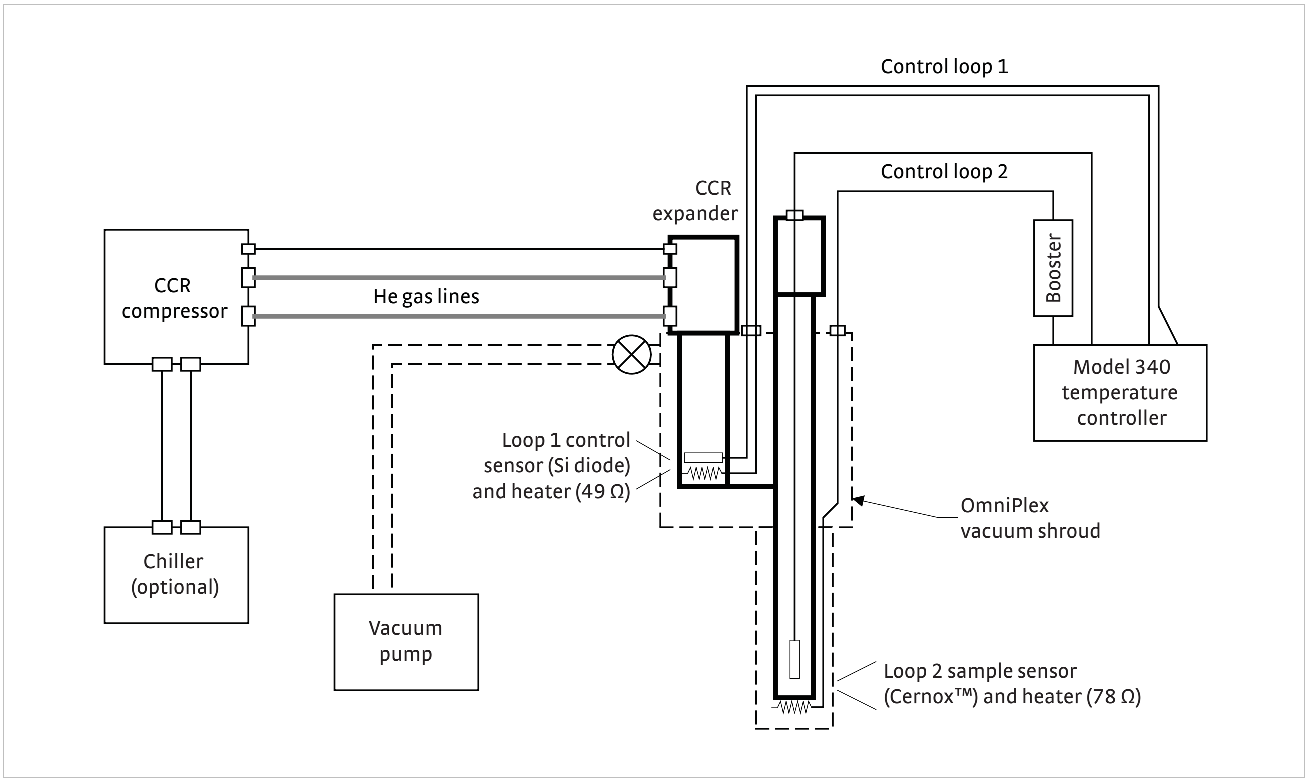


FIGURE 4-8 ***Model 75014A CCRSM operational schematic (the electromagnet and measurement systems are not shown)***

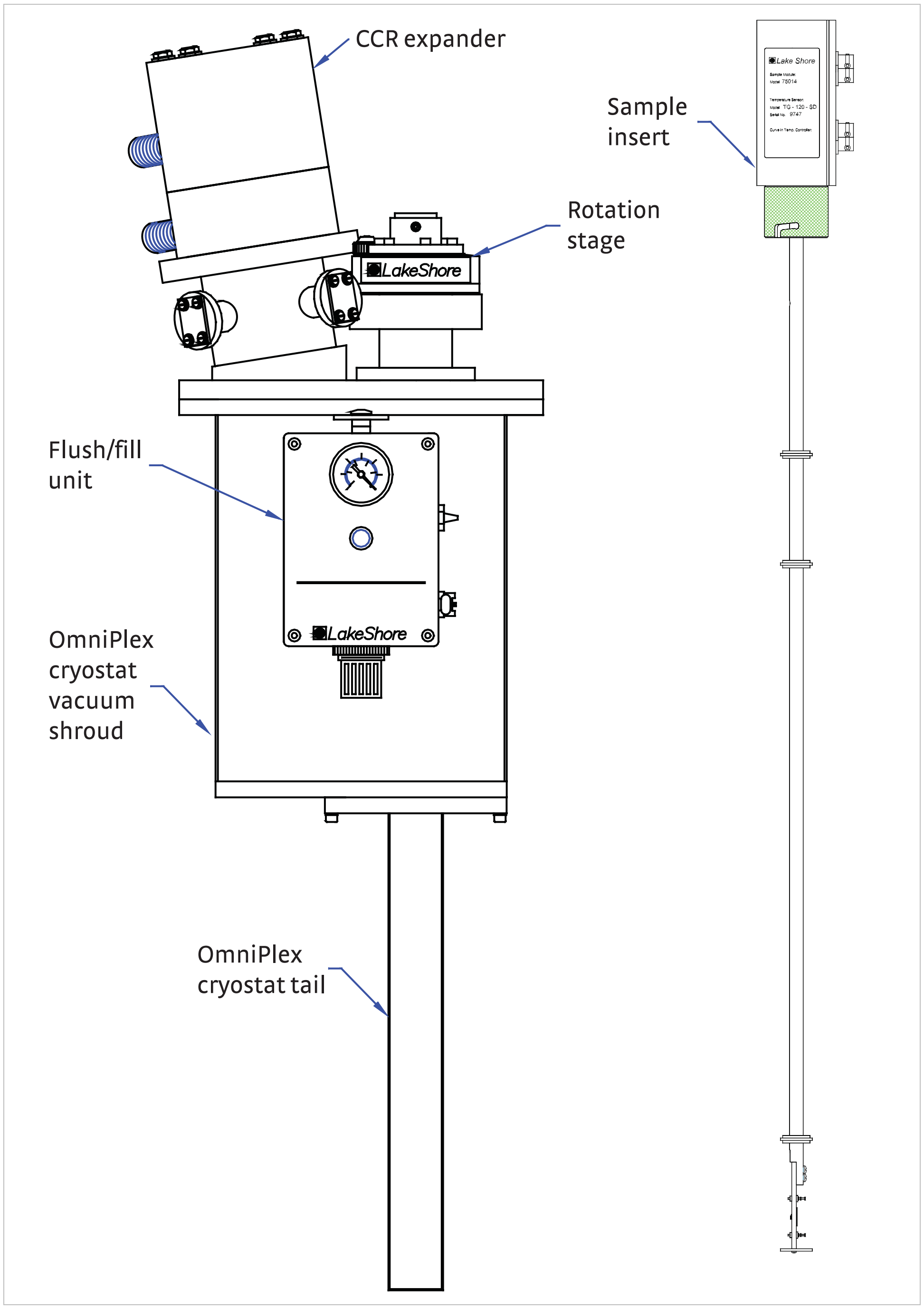


FIGURE 4-9 ***Model 75014A CCRSM assembly overview (view from the front of the magnet): this is a schematic only; your product may vary slightly***

The standard Model 75014A has one 10-pin connector and one 4-pin connector for temperature measurement and control.

The CE sample module has an additional 8-pin connector, and along with the connecting cable, it provides the necessary CE safety requirements. Also, an interlock switch is installed in the quarter turn bayonet of the sample module so that the unit will not operate until the sample enclosure is properly installed and all the cables are connected.

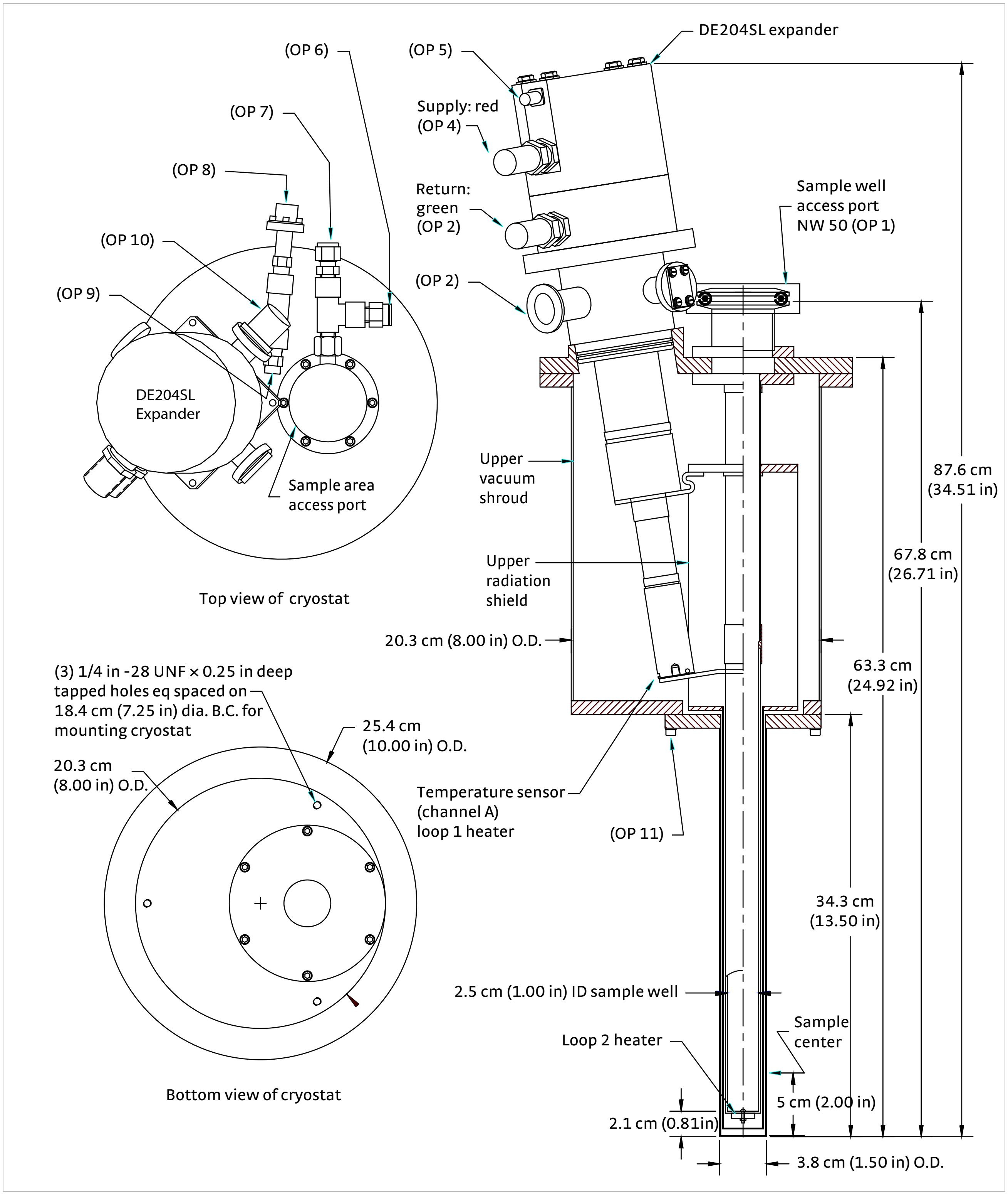


FIGURE 4-10 ***Omniplex cryostat for Model 75014A CCRSM (view from front of electromagnet. Newer units have the expander rotated 90° from the orientation shown, so the connection ports face towards the rear)***

OP-*	Omniplex cryostat
1	Sample well access port, NW 50 flange, 25.4 mm (1.0 in) clear bore
2	Vacuum shroud pumpout port, NW 25 flange
3	Return helium gas connection to compressor (green)
4	Supply helium gas connection from compressor (red)
5	Expander power, 4-pin circular connector, from compressor (blue)
6	Sample well relief valve, 28 kPa (4 psig) cracking pressure
7	Sample well exchange gas inlet, Swagelok® for 6.35 mm (¼ in) OD tube
8	Loop 2 heater (78 Ω), 2-pin circular connector (red)
9	Vacuum shroud relief valve, 28 kPa (4 psig) cracking pressure
10	Loop 1 temperature sensor and heater (49 Ω), 10-pin circular connector (red), see Table 4-12
11	Tail vacuum shroud

**The locations of the connections listed here are shown in FIGURE 4-19*

TABLE 4-7 ***Omniplex cryostat connection point and interface designations***

4.4.1 Connecting the Sample Chamber Flush-Fill Unit

The helium exchange gas sample environment requires a source of helium gas (standard grade) with delivery pressure of 600 kPa to 800 kPa (85 to 115 psig). The customer supplies the helium gas source. A urethane hose 3 m (10 ft) long and 1/8 in ID connects to the flush-fill unit. The other end fits a 1/8 in barb fitting. Use a 1/8 in barb fitting with 1/8 in and 1/4 in NPTM fittings or a quick disconnect to connect to the helium gas source.

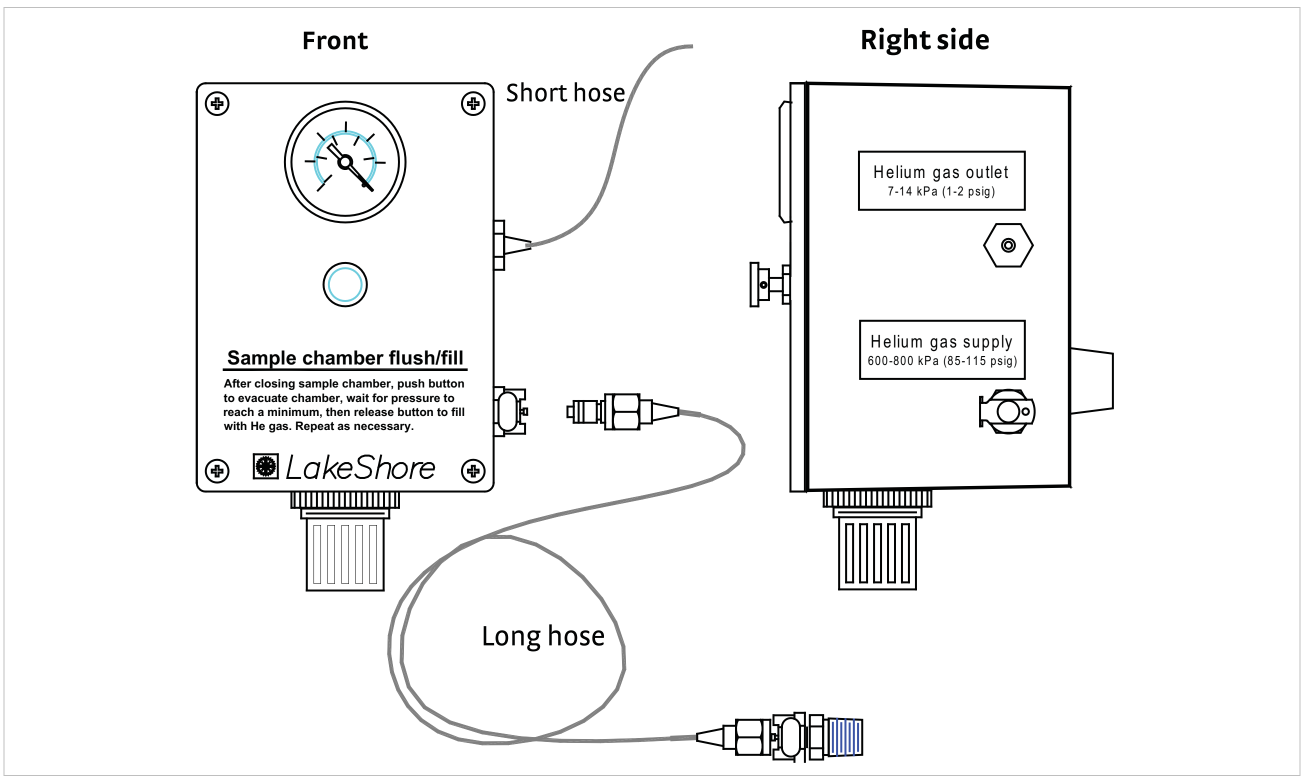


FIGURE 4-11 ***Sample chamber flush fill unit***

1. Attach one end of the 60 cm (24 in) piece of urethane tubing by pushing onto the helium gas outlet hose barb on the side of the flush-fill unit.
2. Install the other end of the urethane hose in the 1/4 in ID Swagelok fitting on the sample well manifold.

3. Remove the 0.75 psig relief valve on the sample well manifold and replace with a relief valve, 4 psig, 1/4 in NPTM (P/N 602-611). Use Teflon® tape to seal the threads.
4. Insert the connector end of the long urethane supply hose into the supply inlet port in the side of the flush-fill unit.
5. Chain a high pressure helium gas cylinder within reach of the supply hose. The pressure regulator must be capable of supplying helium gas at a regulated gauge pressure of 600 kPa to 800 kPa (85 to 115 psi).
6. Connect the free end of the flush-fill supply hose to the pressure regulator on the helium cylinder. A 1/8 in NPTM hose barb (P/N 672-274) is supplied along with a 1/8 in NPTF to 1/4 in NPTM adapter bushing (P/N 209-045). You can also use quick connect fittings.
7. Verify that the sample well plug is in place.
8. Set the helium cylinder regulator pressure in the proper 600 kPa to 800 kPa (85 to 115 psi) range and open any valves to supply helium to the flush-fill unit.
9. Listen for any leaks or hoses popping off. Check for slow leaks by closing the main helium supply tank valve and watching the regulator supply pressure gauge. The pressure should not drop more than 1000 kPa (145 psi) within 10 min and is more typically one tenth this leak-down rate.
10. Correct any leakage problems and open the main supply valve.
11. Stretch a balloon over the relief valve on the sample well manifold.
12. Push the valve button on the front of the flush-fill unit and check that the pressure drops to about -25 mm Hg (-80 kPa).
13. Release the valve button. The sample well should fill with helium gas until the pressure gauge is pegged. If the balloon fills with gas, the sample well pressure regulator sticking out from the bottom of the flush-fill box is set too high. Otherwise, use this regulator to increase the sample well pressure until the balloon just begins to fill, then back off about 1/4 turn.
14. Briefly press the valve button and try to achieve a sample well pressure of -5 mm Hg (-15 kPa). If this pressure can be achieved and the sample well does not refill and pressurize with helium gas, then the sample well regulator is not set high enough. Adjust the regulator setting until a stable pressure of -5 mm Hg is not possible after releasing the valve button, but the balloon does not fill.

14\. The flush-fill unit is now ready for loading of the sample insert.

4.4.2 Sample Mounting with the Model 75014A CCRSM

Mount samples by following the Model 75013 SCSM sample mounting instructions given in section 4.4.2 with the following exceptions:

1. The sample mounting portion of the Model 75014A sample insert is permanently attached, not removable like the sample card used in the Model 75013 SCSM.
2. The sample mounts in the center of a sapphire mounting plate centered between solder posts. Glue the sapphire mounting plate to the G-10 plate with rubber cement. Normally, it should not be removed. The solder posts around the sapphire mounting plate are not numbered, but are laid out in the same pattern and orientation as the numbered triaxial bulkhead connectors on the sample Insert junction box (FIGURE 4-1 and FIGURE 4-9). The figure on the cover of the junction box shows connections to two common sample geometries (van der Pauw square and 1-3-3-1 Hall bar).
3. There is no sample identification space on the Model 75014A sample insert sample mounting plate. If desired, attach a removable note to the sample insert junction box with the sample identification and other relevant information.

4.4.3 Operation of the Model 75014A CCRSM

This section provides instructions for the Omniplex top loading exchange gas cryostat. This module is designed for more sophisticated temperature control.

WARNING

High voltage can be present at sample terminals. Always install the measurement insert into the refrigerator before making measurements, and stop measurements before removing the module.

For the CE option system, an interlock switch is installed in the quarter turn bayonet so that the unit will not operate until the sample enclosure is properly installed and all the cables are connected.

4.4.3.1 Sample Insert Insertion

Use the procedure below in loading the sample insert to avoid contamination or condensation from air.

1. Clean the sample insert of any dust or dirt accumulated on its surface. Verify that the sample insert is completely dry.
2. Ready the sample insert, remove the sample well plug, and carefully insert the sample insert into the module.
3. Twist the sample insert junction box in the rotation stage to fully engage the bayonet lock.
4. Press the valve button on the flush/fill unit two or three times. This removes any air from the sample well and backfills it with helium gas. Any air in the sample well freezes if the temperature is below about 65 K.
5. Set the rotation stage to 0° so the sample is perpendicular to the applied magnetic field.

4.4.3.2 Sample Insert Cable Connections

1. The four or six triaxial sample cables should already have a protective sleeve plus a short section of spiral cable wrap and a tie down clamp near the sample end. Connect the triaxial sample cables to the sample module.
2. Bolt the tie down clamp into the right rear bolt hole on top of the saddles. This strain relieves the cables, but positions them close to the sample well where they will be attached to the sample insert.
3. Connect the 10-pin cable to the sample module.
4. If you have the CE option system, connect the 8-pin connector cable to the sample module.

4.4.3.3 Vacuum Pump Out Procedure

The customer must supply a vacuum pump to evacuate the sample module to a pressure of 100 Pa (0.1 Torr) or lower prior to initial operation. Vacuum pressure gauging must be provided or added to the Omniplex. The Omniplex can be removed and taken to a vacuum pumping station for pumpout.

Pumpout of the vacuum jacket may be required only every few months if the Omniplex is kept cold and the lowest possible temperatures are not required. Pumpout of the vacuum space can be performed during operation of the closed cycle refrigerator (CCR) if a turbo, turbomolecular, cryo, diffusion or other very low ultimate pressure (10-5 Pa [10-7 Torr]) dry vacuum pump is used. Pumping during operation might be necessary for long term (several days) operation to the lowest possible temperatures or for repeated ramping from low to high temperature limits.

Follow this procedure for the initial pumpout. This procedure assumes that you are starting from atmospheric pressure.

1. The Omniplex should be at room temperature for initial vacuum pumpout.
2. Connect the vacuum line to the vacuum valve on the Omniplex vacuum pumpout port (OP 2), but do not open the vacuum valve yet. The vacuum valve is either a plug valve or a diaphragm valve. Use one of these corresponding procedures to prepare the valve:
   - *Plug valve:* seal-off the plug valve Cryolab™ Model SV9-084-5W1 on the NW 25 flange. Remove the retainer ring from inside the vacuum valve body. Push the Cryolab™ valve operator onto the seal-off valve body and tighten in place with a 30.2 mm (1³⁄₁₆ in) wrench kept in the Omniplex tool box. The vacuum hose provided is 13 mm (½ in) ID with NW 16 flange connections. Connect the vacuum hose between the valve operator and the vacuum pump.
   - *Diaphragm valve:* the diaphragm valve has a large black knob and NW 25 flanges. The vacuum hose provided is 25 mm (1 in) ID with NW 25 flange connections. Connect the vacuum hose between the valve operator and the vacuum pump.
3. Open the vacuum valve using one of these corresponding procedures:
   - *Plug valve:* push the Cryolab™ valve handle in, and turn it clockwise to screw into the plug. Pull out on the handle to remove the valve plug.
   - *Diaphragm valve:* turn the large black knob counterclockwise all the way to fully open the valve.
4. Start the vacuum pump, and pump out the Omniplex vacuum space to a pressure less than 1.3 Pa (10 mTorr or 10 µm). If you are using a mechanical vacuum pump which can backstream oil, pump the minimum time necessary to achieve this pressure. Dry pumps can be run longer and the vacuum will be cleaner if the system is pumped for a day or overnight.
5. Close the vacuum valve using one of these corresponding procedures:
   - *Plug valve:* push in the Cryolab™ valve operator handle to insert the valve plug. Rotate the handle counterclockwise to unscrew the handle from the plug. Pull the handle back out. Turn off the vacuum pump and vent the vacuum hose. If desired, remove the valve operator from the valve and replace the retainer ring and dust cap.
   - *Diaphragm valve:* turn the large black knob clockwise all the way to fully close the valve. Turn off the vacuum pump and vent the vacuum hose. If desired, remove the vacuum hose.
6. Monitor the pressure on the vacuum gauge. The pressure should rise slowly and level off at a pressure less than about 13 Pa (or 0.1 Torr or 100 µm). If the pressure rises rapidly above this pressure level, a leak or contamination may exist. Test the system for leaks to isolate the cause of the problem, and repair it. If everything appears normal, proceed to the next step.

NOTE **Dry vacuum pumping can continue until no longer desired, but if you are using a mechanical oil pump, stop pumping before starting the CCR compressor.**

4.4.3.4 Vacuum Cleanup Procedure

Follow this procedure for vacuum cleanup. This procedure assumes that you are starting with the sample module already under vacuum.

1. The Omniplex can be at any temperature for vacuum cleanup, but a dry vacuum pump with low base pressure is required if the Omniplex CCR is operating.
2. Connect the vacuum hose between the vacuum pump and the vacuum valve on the Omniplex (OP 2).

3. Start the vacuum pump and pump out the vacuum line to a pressure less than 1.3 Pa (10 mTorr [10 μm]).
4. Open the vacuum valve using one of these corresponding procedures:
   - *Plug valve:* push the Cryolab™ valve handle in and turn clockwise to screw into the plug. Pull out on the handle to remove the valve plug.
   - *Diaphragm valve:* turn the large black knob counterclockwise all the way to fully open the valve.
5. Pump out the Omniplex vacuum space to a pressure less than 1.3 Pa (10 mTorr [10 μm]). If you are using a mechanical vacuum pump which can backstream oil, pump the minimum time necessary to achieve this pressure. Dry pumps can be run longer and the vacuum will be cleaner if the system is pumped for a day or overnight.
6. Close the vacuum valve using one of these corresponding procedures:
   - *Plug valve:* push in the Cryolab™ valve operator handle to insert the valve plug. Rotate the handle counterclockwise to unscrew the handle from the plug. Pull the handle back out. Turn off the vacuum pump and vent the vacuum hose. If desired, remove the valve operator from the valve and replace the retainer ring and dust cap.
   - *Diaphragm valve:* turn the large black knob clockwise all the way to fully close the valve. Turn off the vacuum pump and vent the vacuum hose. If desired, remove the vacuum hose.
7. Monitor the pressure on the vacuum gauge. The pressure should rise slowly and level off at a pressure less than about 13 Pa (0.1 Torr [100 μm]). If the pressure rises rapidly above this pressure level, a leak or contamination may exist. Test the system for leaks to isolate the cause of the problem, and repair it. If everything appears normal, proceed to the next step.

NOTE **Dry vacuum pumping can continue until no longer desired, but if using a mechanical pump stop pumping before starting the CCR compressor.**

4.4.3.5 Cool Down

To begin the cool down, simply start the compressor. During cooldown, check for condensation on the outside of the Omniplex tail. Condensation indicates that the vacuum is not good enough and the vacuum pumpout must be repeated. The cooldown to 15 K should take about 1 h to 2 h.

4.4.3.6 Sample Insert Removal

Use the procedure below to remove a cold sample insert (FIGURE 4-9) from the Model 75014A CCRSM.

1. Unplug the triaxial BNC cables from the sample insert junction box. If desired, leave 10-pin circular connector in place to monitor the temperature.
2. Twist the sample insert junction box in the rotation stage to release the bayonet lock.
3. Remove the sample insert quickly from the Omniplex sample well.
4. Insert the sample well plug and make sure it seals tightly.
5. Press the flush-fill valve button two or three times to remove the gas (possibly contaminated with air) from the sample well.
6. Wait until the sample insert is dry before removing or mounting samples. If desired, you can blow dry it with a hot air gun, but do not overheat it.

4.5 Model 75016: Oven Sample Module (OSM) Option

The Model 75016 oven sample module (Model 75016 OSM) features and specifications are given in Chapter 1. Stable operation at a range of temperatures is made possible by balancing the cooling power provided by the ambient environment against two heater circuits powered by a temperature controller. An assembly overview is shown in FIGURE 4-13.

WARNING

The outer surface of the oven module around the sample aea can be very hot during opertion. Do not touch the oven outer surface during operation above 400 K.

The Model 75016 OSM consists of the following components:

- Oven body (FIGURE 4-14 and TABLE 4-8)
- Rotation stage
- Flush-fill unit
- Mounting base plate
- Sample insert (FIGURE 4-13)
- Power booster for a Model 340 loop 2 heater output

Also required for operation of the Model 75016 CCRSM, but not included in the option:

- Model 750TC option (only need one Model 750TC for both the CCR and OSM)
- Vacuum pump

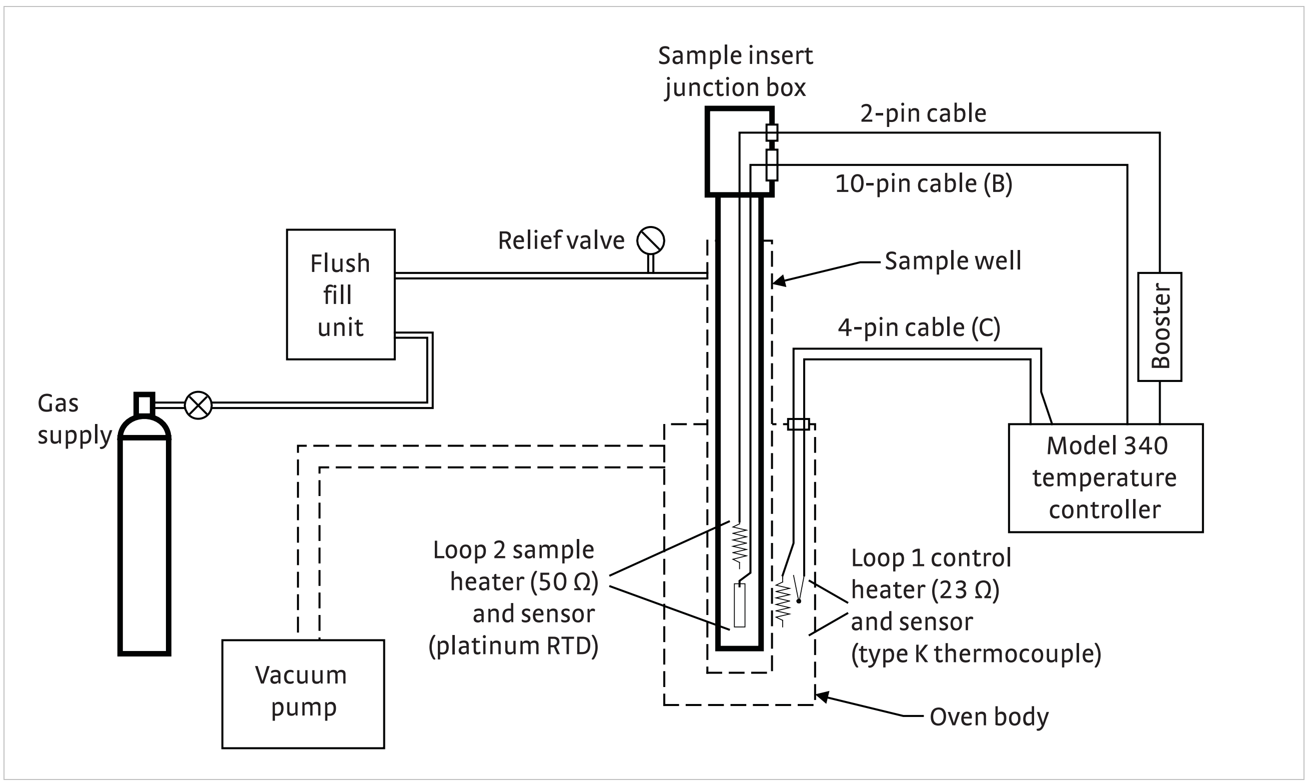


FIGURE 4-12 ***Model 75016 OSM operational schematic (the electromagnet and measurement systems are not shown)***

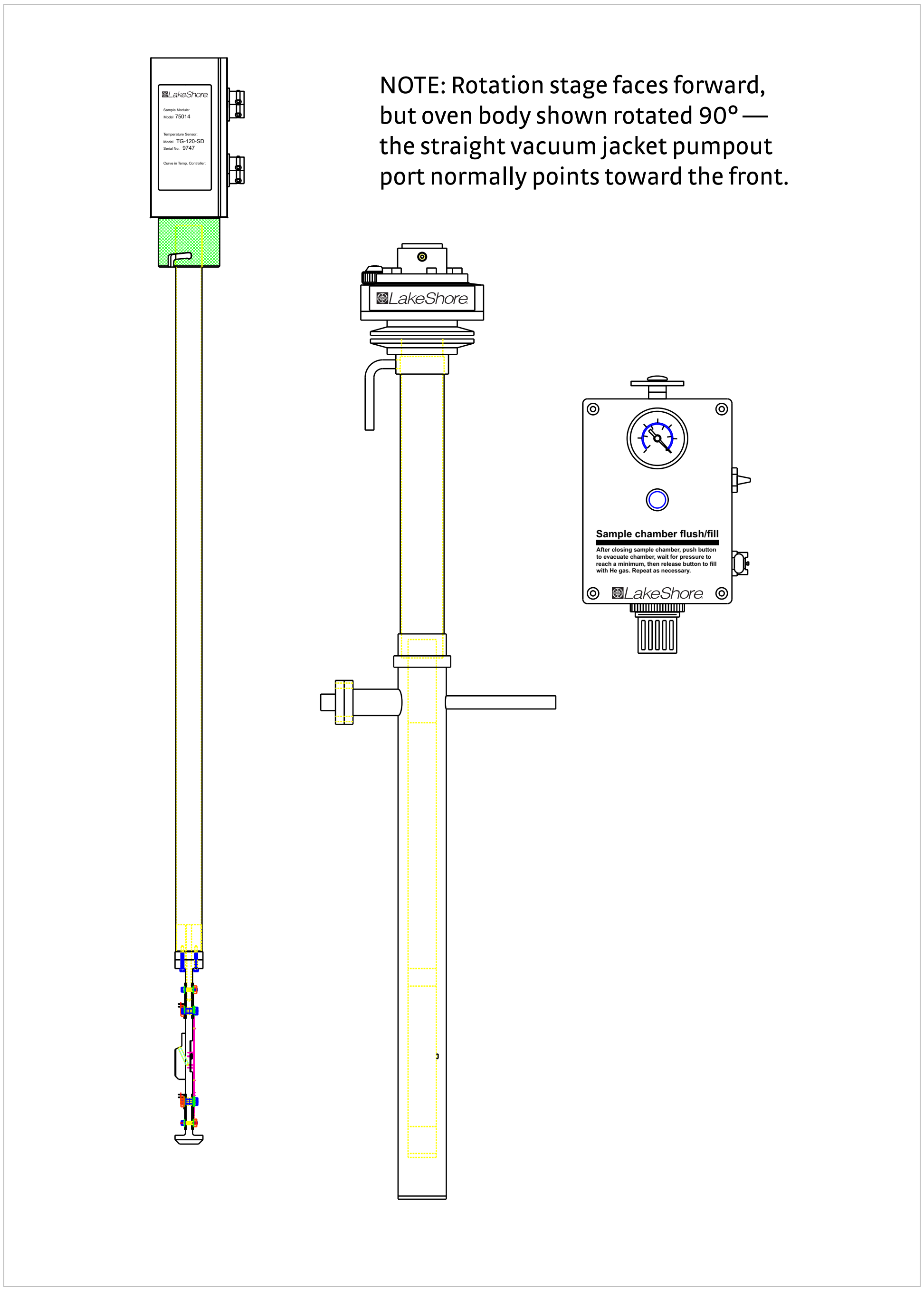


FIGURE 4-13 ***Model 75016 OSM assembly overview (view from front of electrmagnet)***

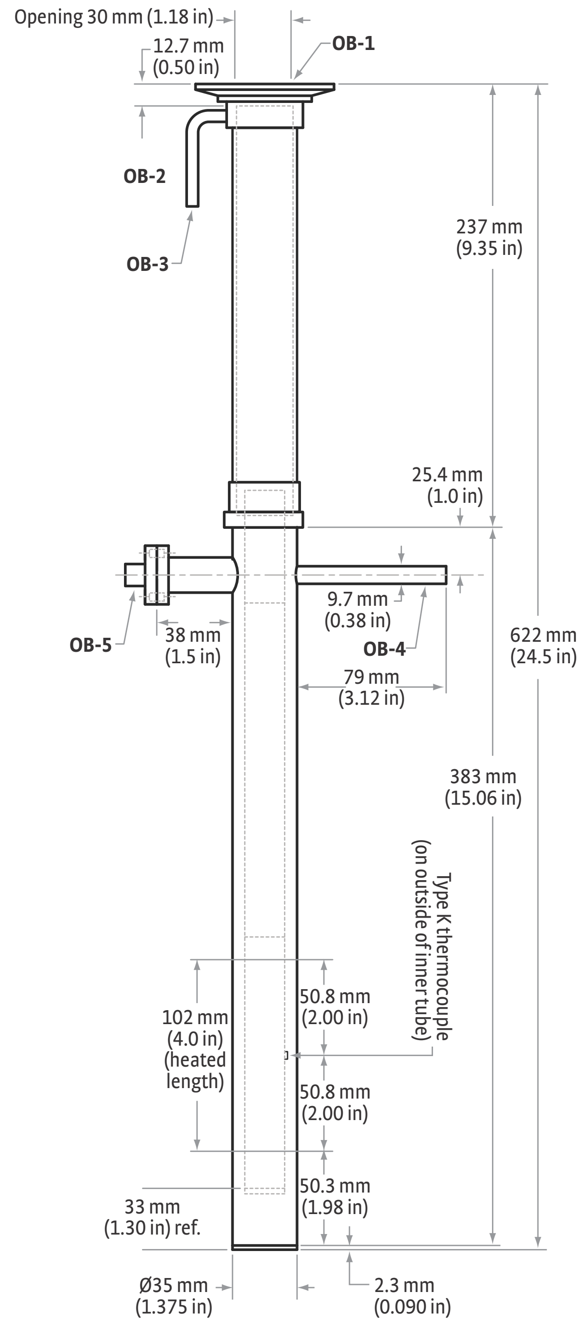


FIGURE 4-14 ***Oven body for the Model 75016 OSM***

The standard sample module has one 10-pin connector and one 4-pin connector for temperature measurement and control.

For the CE option system, the sample module has an additional 8-pin connector and along with the connecting cable it provides the necessary CE safety requirements. Also, an interlock switch is installed in the quarter turn bayonet of the sample module so that the unit will not operate until the sample enclosure is properly installed and all the cables are connected.

OB-*	Oven Body
1	Sample well access port, NW 50 flange, 19.1 mm (0.75 in) clear bore
2	Sample well relief valve, 28 kPa (4 psig) cracking pressure
3	Sample well exchange gas inlet, Swagelok® for 6.35 mm (1⁄4 in) OD tube
4	Vacuum pumpout port, 9.52 mm (3⁄8 in) OD tube
5	Loop 1 temperature sensor and heater (23 Ω), 4-pin circular connector (red)

**The locations of the connections listed here are shown in FIGURE 4-14.*

TABLE 4-8 ***Model 75016 OSM oven body connection point and interface designations***

4.5.1 Connecting the Sample Chamber Flush-Fill Unit

Refer to section 4.5.1 to connect the sample chamber flush-fill unit properly.

4.5.2 Sample Mounting with the Model 75016 OSM

Mount samples by following the Model 75013 SCSM prober sample card sample mounting instructions given in section 4.3.1.3 with the following exceptions:

1. The sample mounting portion of the Model 75016 sample insert is permanently attached, not removable like the prober sample card used in the Model 75013 SCSM.
2. The sample mounts in the center of a sapphire mounting plate that is centered between solder posts. The solder posts around the sapphire mounting plate are not numbered, but are laid out in the same pattern and orientation as the numbered triaxial bulkhead connectors on the sample insert junction box (FIGURE 4-12). The figure on the cover of the junction box shows connections to two common sample geometries (van der Pauw square and 1-3-3-1 Hall bar).

NOTE

There is no sample identification space on the Model 75016 sample insert sample mounting plate. If desired, attach a removable note to the sample insert junction box with the sample identification and other relevant information.

4.5.3 Operation of the Model 75016 OSM

This section provides instructions for using the Model 75016 top loading oven.

WARNING

High voltage can be present at sample terminals. Always install the measurement insert into the oven before making measurements, and stop measurements before removing the module.

For the CE option system, an interlock switch is installed in the quarter turn bayonet so that the unit will not operate until the sample enclosure is properly installed and all the cables are connected.

4.5.3.1 Sample Insert Insertion

Use the procedure below in loading the sample insert to avoid contamination or condensation from air.

1. Clean the sample insert to remove any dust or dirt accumulated on its surface. Verify that the sample insert is dry.
2. Ready the sample module, remove the sample well plug, and carefully insert the sample insert.
3. Twist the sample insert junction box in the rotation stage to fully engage the bayonet lock.
4. Press the valve button on the flush-fill unit two or three times. This removes any air from the sample well and backfills it with argon gas.
5. Set the rotation stage to 0° so the sample is perpendicular to the applied magnetic field.

4.5.3.2 Sample Insert Cable Connections

1. The four or six triaxial sample cables should already have a protective sleeve plus a short section of spiral cable wrap and a tie down clamp near the sample end. Connect the triaxial sample cable to the sample module.
2. Bolt the tie down clamp into the right rear bolt hole on top of the saddles. This strain relieves the cables, but positions them close to the sample well where they will be attached to the sample insert.
3. Connect the 10-pin cable to the sample insert.
4. For the CE option system, connect the 8-pin connector cable to the sample module.

4.5.3.3 Vacuum Pump Out Procedure

The customer must supply a vacuum pump to evacuate the sample module to a pressure of 0.1 Pa (7×10^{-4} Torr) or lower prior to initial operation. Vacuum pressure gauging must be provided or added to the oven. The oven must be pumped continuously during operation.

1. The oven should be at room temperature for initial vacuum pumpout.
2. Connect the vacuum line to the oven vacuum pumpout port (OB-4).
3. The other end of the vacuum line has an NW 25 flange attached. Connect the flanged end to a vacuum pump.
4. Start the vacuum pump and pump out the oven vacuum space to a pressure less than 1 Pa (7×10^{-3} Torr). If you are using a mechanical vacuum pump which can backstream oil, a trap must be used. Dry pumps can be run longer and the vacuum will be cleaner.

4.5.3.4 Sample Insert Removal

Use this procedure to remove a sample insert from the Model 75016 OSM.

1. Wait until the sample insert temperature is below 350 K before removing it.
2. Unplug the triaxial BNC cables from the sample insert junction box. If desired, leave the 10-pin circular connector in place to monitor temperature.
3. Twist the sample insert junction box in the rotation stage to release the bayonet lock.
4. Remove the sample insert from the oven sample well.
5. Insert the sample well plug and verify that it seals tightly.
6. Press the flush-fill valve button two or three times to remove the gas (possibly contaminated with air) from the sample well.

4.6 The Configuration Utility

The configuration utility shipped with the system allows for you to change hardware configurations that do not normally need changed. This section describes the use of the configurator to set up the temperature control parameters. The configurator can be run from the HMS start menu under the program section of the system start menu. All the temperature measurement option setups are similar.

4.6.1 Temperature Controller Setup

There are many parameters of the system that determine stability of the temperature control. This section allows you to change the default parameters. This section also allows you to change some default settings of the temperature controller.

FIGURE 4-15 shows the first page of the temperature options. The most useful entry on this screen is the curve number of the sample sensor. For most experiments, the sample sensor is connected to the B input of the Model 340. It is the temperature sensor mounted closest to the sample and is the control sensor for the loop 2 heater.

FIGURE 4-16 shows the second page of the controller setup. On this page, the A channel sensor is defined and the control setup and control limits for both heaters are determined. Also on this page is a check box to determine the state of the heaters when the software exits. To turn the heaters off every time the software exits, select the box. If the box is not selected, the heaters will be left on as the software exits.

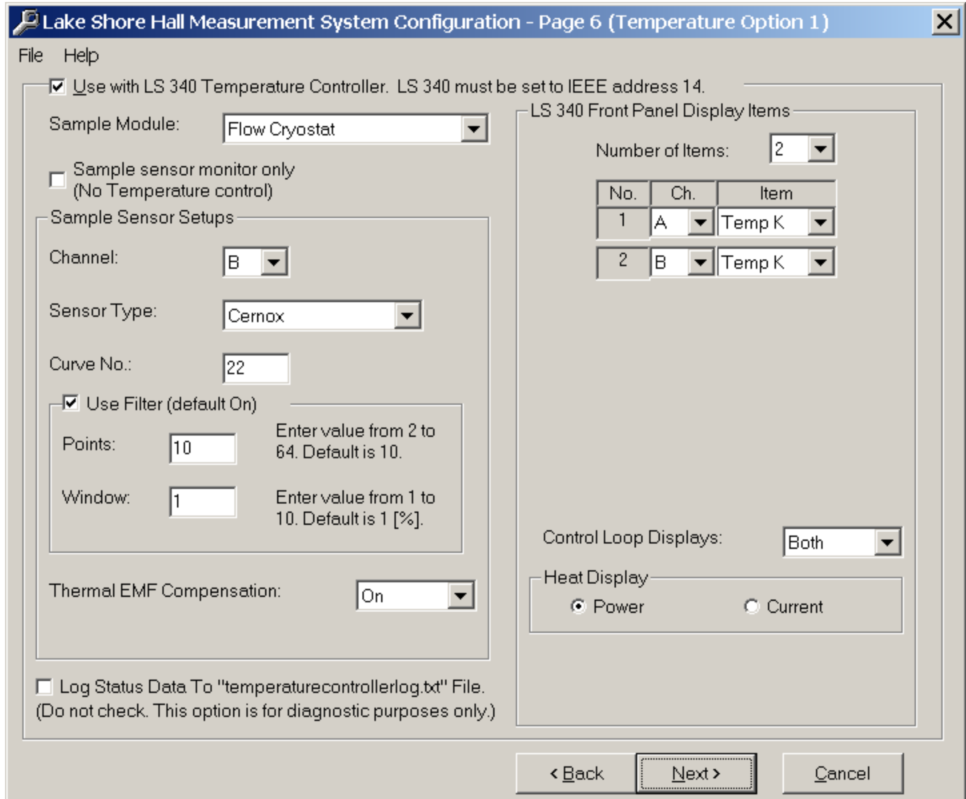


FIGURE 4-15 ***Temperature options***

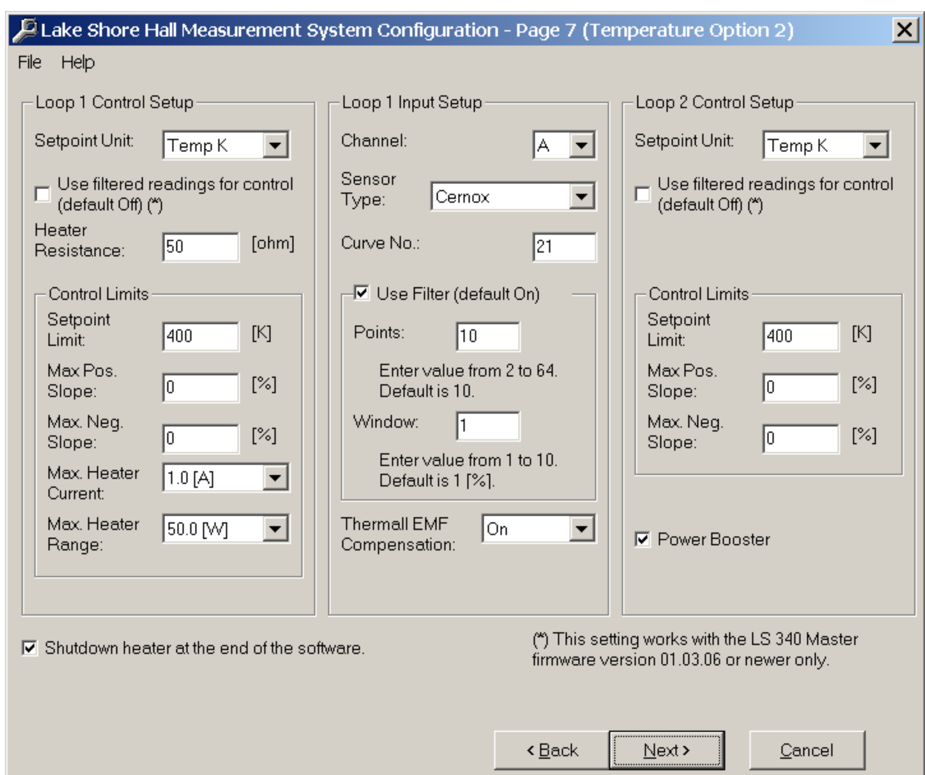


FIGURE 4-16 ***Controller setup***

4.6.2 Understanding How Temperature Settle is Determined

The HMS software is designed to provide a stable temperature environment for the samples using various temperature options and the Lake Shore Model 340 temperature controller. The software has default parameters to determine control and settle criteria. This section describes how the software defines the settle criteria. The next section shows how the users can change the parameters of the control and settle criteria.

Every standard Lake Shore temperature option for the HMS systems has two sensors and two heaters. The first heater, called the loop 1 heater, is always the higher power heater and uses one of the two sensors, called loop 1 control sensor, to control the temperature. The loop 1 control sensor is mounted near the loop 1 heater.

The second sensor, called the sample sensor, and heater, called the loop 2 heater, is mounted near the sample. This smaller heater is used to precisely control the temperature of the sample.

FIGURE 4-17 shows sample sensor temperature during a temperature change. Initially the set point of both loop 1 and loop 2 is changed from the initial temperature to the final set point at a constant rate. This is shown as time t1 to time t2 in the figure. A designated wait time is observed (shown as t2 to t3 in FIGURE 4-17). At this time the temperature drift, time derivative of the sample sensor temperature, is calculated along with the difference between the sample sensor temperature and the final set point. When the drift is less than a specified amount (at time t4 in FIGURE 4-17) and when the difference is less than the temperature band (at time t5 in FIGURE 4-17) the temperature is considered to have settled and a measurement can be obtained.

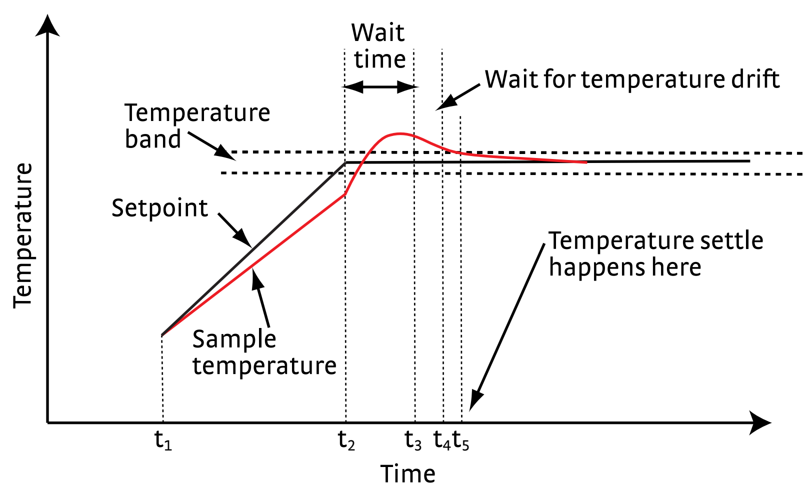


FIGURE 4-17 ***Sample sensor temperature during a temperature change***

4.6.3 How to Change Temperature Control and Settle Parameters

As we have seen from the previous section there are 4 parameters that determine the settle criteria:

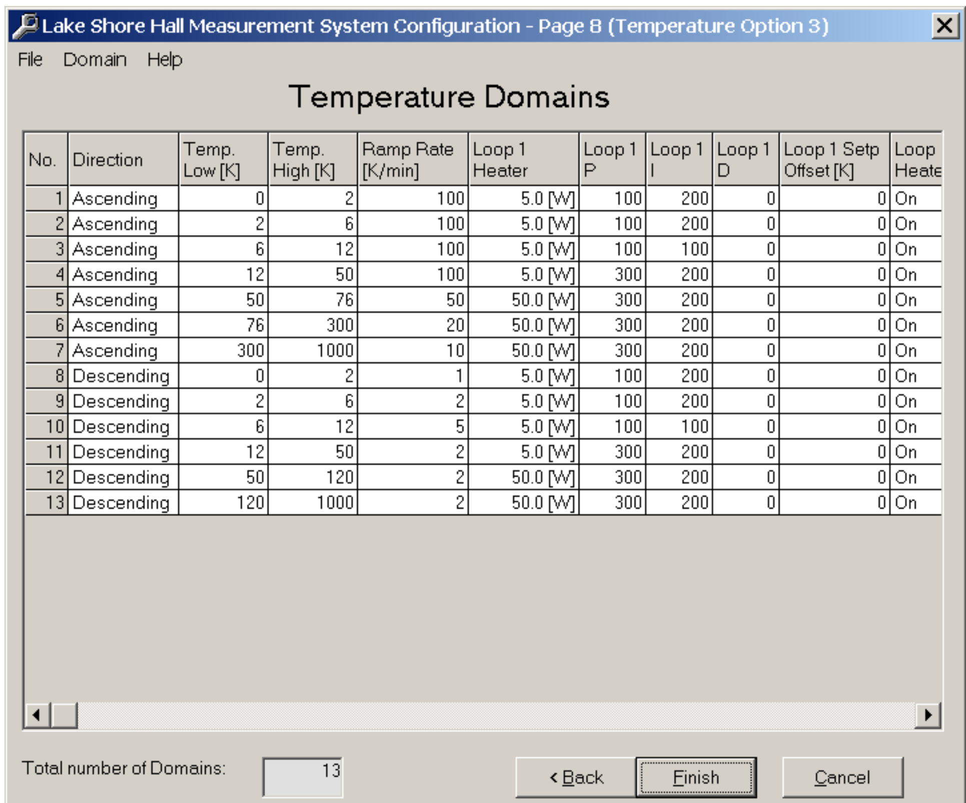
- *Ramp rate:* the rate, in degree/min, that the setpoint changes from the initial set-point to the final setpoint.
- *Settle wait time:* the time, in minutes, to wait after the final setpoint is reached. This value can be zero.
- *Settle temperature drift:* the drift rate, in degree/min. The drift of the temperature must be less than this value for settle to be met. If this value is large (10°/min), then this criteria is essentially not used.

- *Settle temperature band:* when settle criteria is met, the temperature will be within the settle band and the drift will be less than the settle temperature drift. If the temperature band is large (10°) then this criteria is essentially not used.

In addition, there are parameters for the temperature controller. These parameters define how control of the temperature is obtained. These include:

- Loop 1 PID (gain, reset, and rate) values
- Loop 2 PID (gain, reset, and rate) values
- Loop 1 heater range
- The difference between the loop 1 setpoint and loop 2 setpoint.
- The setting of the needle valve to determine the flow through the cryostat.

These parameters depend on temperature. They are maintained by the configuration utility in structures called domains. A domain is defined with a beginning temperature and an end temperature. In addition, different parameters can be defined for ascending (heating) directions and descending (cooling) directions. FIGURE 4-18 shows the domain tables in the configuration utility.



No.	Direction	Temp. Low [K]	Temp. High [K]	Ramp Rate [K/min]	Loop 1 Heater	Loop 1 P	Loop 1 I	Loop 1 D	Loop 1 Setp Offset [K]	Loop Heate
1	Ascending	0	2	100	5.0 [W]	100	200	0	0	On
2	Ascending	2	6	100	5.0 [W]	100	200	0	0	On
3	Ascending	6	12	100	5.0 [W]	100	100	0	0	On
4	Ascending	12	50	100	5.0 [W]	300	200	0	0	On
5	Ascending	50	76	50	50.0 [W]	300	200	0	0	On
6	Ascending	76	300	20	50.0 [W]	300	200	0	0	On
7	Ascending	300	1000	10	50.0 [W]	300	200	0	0	On
8	Descending	0	2	1	5.0 [W]	100	200	0	0	On
9	Descending	2	6	2	5.0 [W]	100	200	0	0	On
10	Descending	6	12	5	5.0 [W]	100	100	0	0	On
11	Descending	12	50	2	5.0 [W]	300	200	0	0	On
12	Descending	50	120	2	50.0 [W]	300	200	0	0	On
13	Descending	120	1000	2	50.0 [W]	300	200	0	0	On

FIGURE 4-18 ***Domain tables in the configuration utility***

To modify a domain click on the domain, the window in FIGURE 4-19 will open.

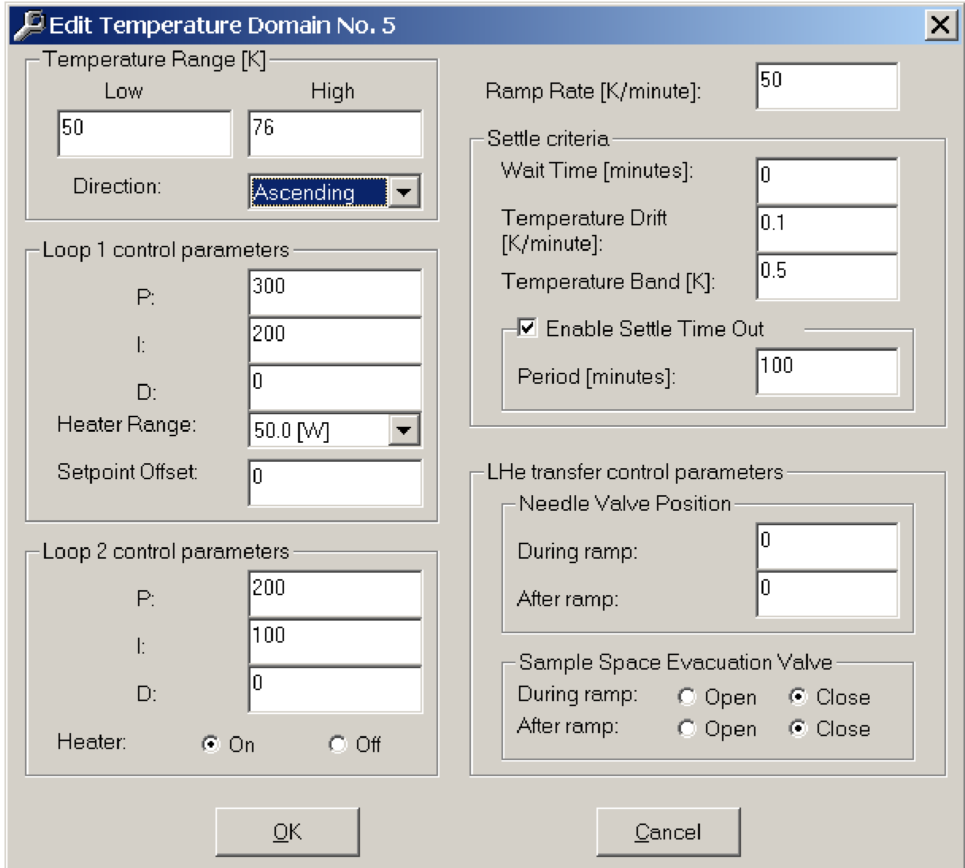


FIGURE 4-19 **Domain edit window**

Chapter 5: Software Operation

5.1 General

The software for the Hall Measurement System (HMS) allows for completely automatic operation of the measurements. It is possible to take a wide variety of measurements using a wide variety of materials. The possible measurements include IV curves, variable field, and variable temperature measurements. The software provides the interface to define setup files and sample definitions, and it records results in a results file. These give the user flexibility in defining measurements and the ability to rerun a setup with different samples, or different setups with the same sample. The HMS software icon is shown in FIGURE 5-1.

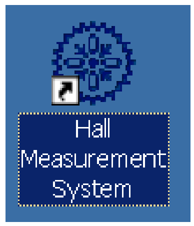


FIGURE 5-1 ***HMS software icon***

5.2 Starting the Software

NOTE

The USB KeyLok dongle must be installed in one of the computer USB ports for the software to work properly. An invalid software key error will be logged in the system log area if the dongle is not present.

When you click on the icon, the software starts and this warning appears:

FIGURE 5-2 ***Initial warning box***

WARNING

High voltages can be present at sample terminals. Always install the light-tight box onto the measurement insert before making measurements, and stop measurements before removing the module. Use caution and read all the safety information in this manual.

Click **OK** to continue. The main HMS screen for the HMS software is shown in FIGURE 5-3 with the major areas identified. Section 5.4.1 describes how to use the main HMS screen.

NOTE

For the Hall system with the CE option, there will be no current delivered to the sample area, thus, the measurement data collected will be invalid if the safety hardware like the light tight box is not used.

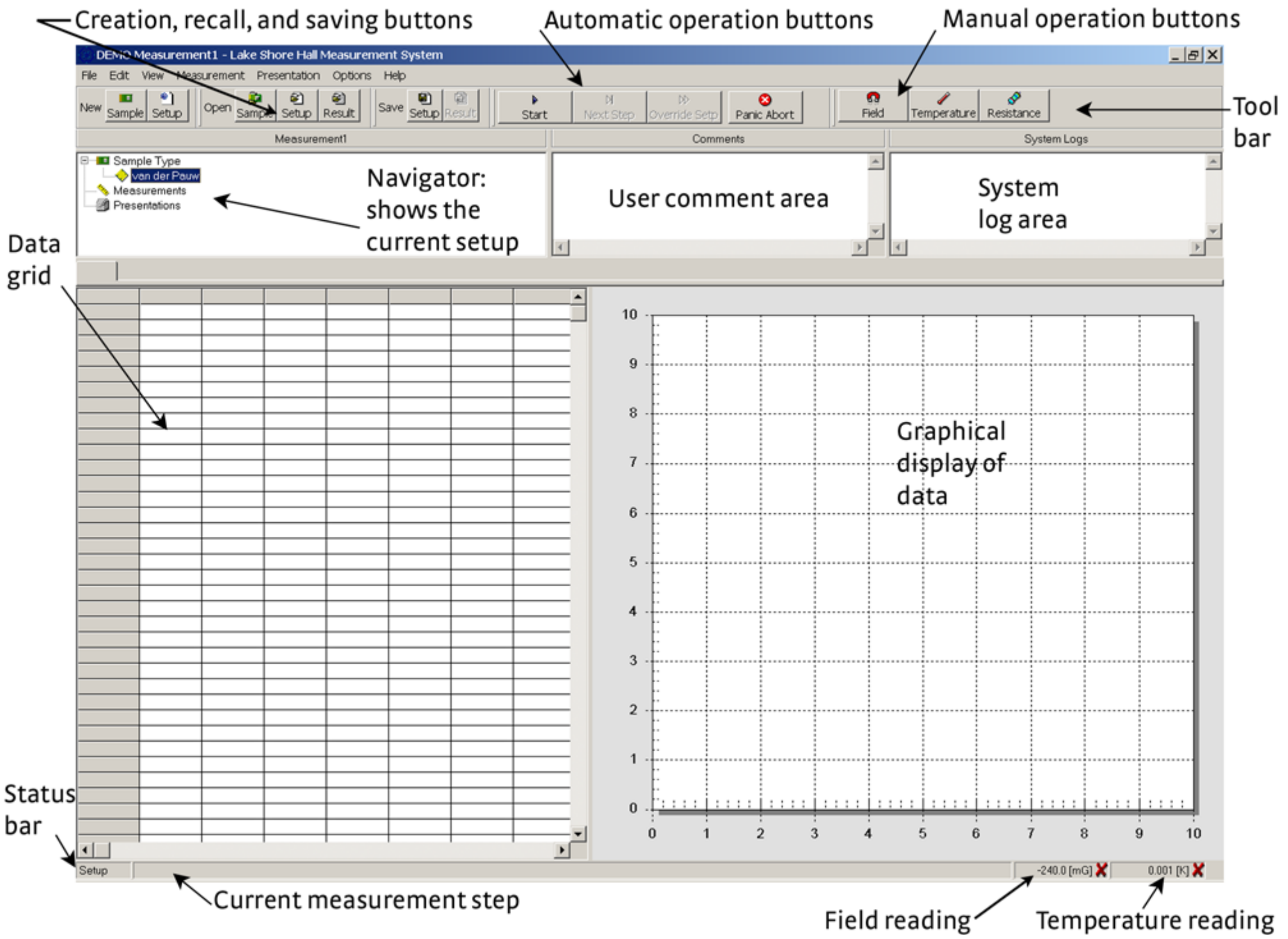


FIGURE 5-3 ***The main HMS screen with major areas identified***

The normal operation is to either define a new sample and new setup to execute, or to recall an existing setup to execute with a new or existing sample. Section 5.3 through section 5.12 will describe the operation of the software.

5.3 The Sample File: Defining Sample Physical Parameters

A sample definition file holds basic sample identification information. You can store sample dimensions, sample geometry, lot tracking, or other information to identify the sample in the sample definition file.

Each sample can have its own sample definition. For a van der Pauw sample the only required information for the sample definition is the thickness. For Hall bar samples, additional geometric values are required depending on the specific Hall bar geometry. Comments entered in the sample definition file are copied into the result file for any measurement this sample is attached to. A Hall factor for the sample can be entered in this file; the default value is 1. For a more complete discussion for the Hall factor see Appendix A.

5.3.1 The Sample File Screen

The sample file screen is divided into components that help you to define your sample. This list describes each component of the sample file screen. FIGURE 5-4 shows an image of the sample file screen.

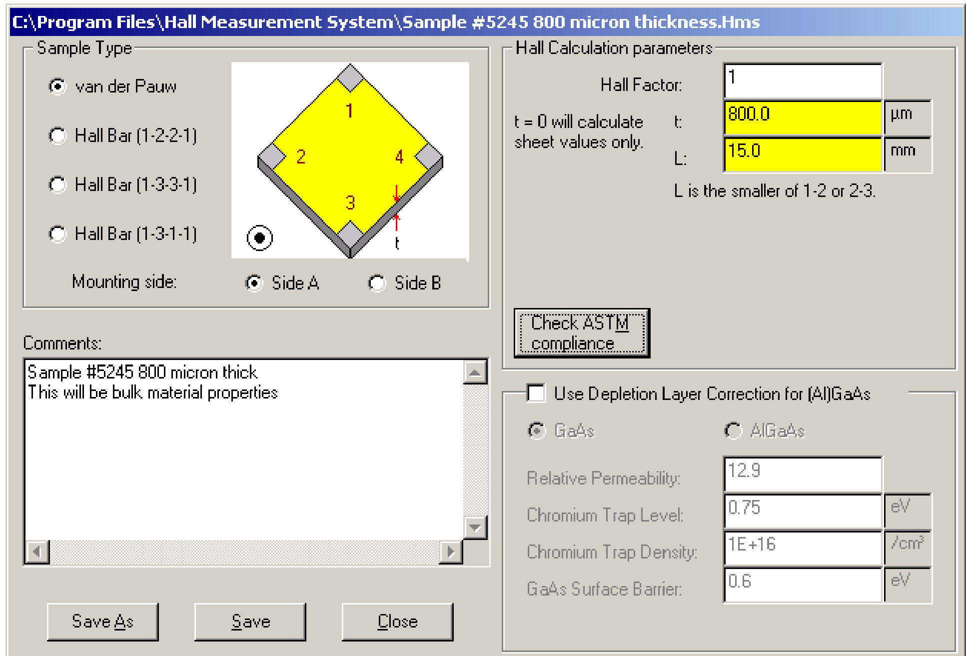


FIGURE 5-4 ***Sample definition screen***

- Sample type: select the sample geometry in this section. Refer to Appendix A for a definition of each type
- Hall calculation parameters: enter the physical parameter in this section. Refer to Appendix A for more information.
- Check ASTM compliance:
  - van der Pauw samples: the requirements are that the thickness is less than 1 mm and the length is greater than 15 × thickness. ASTM compliance check ensures that the assumption of 2D current flow can be met (FIGURE 5-5)
  - Hall bar samples: ASTM compliance check ensures that the error assuming a 1D current flow will be small (FIGURE 5-5)
- Comments: these comments are also saved in the results file for the measurements in which you select this sample file
- Use depletion layer correction for AlGaAs

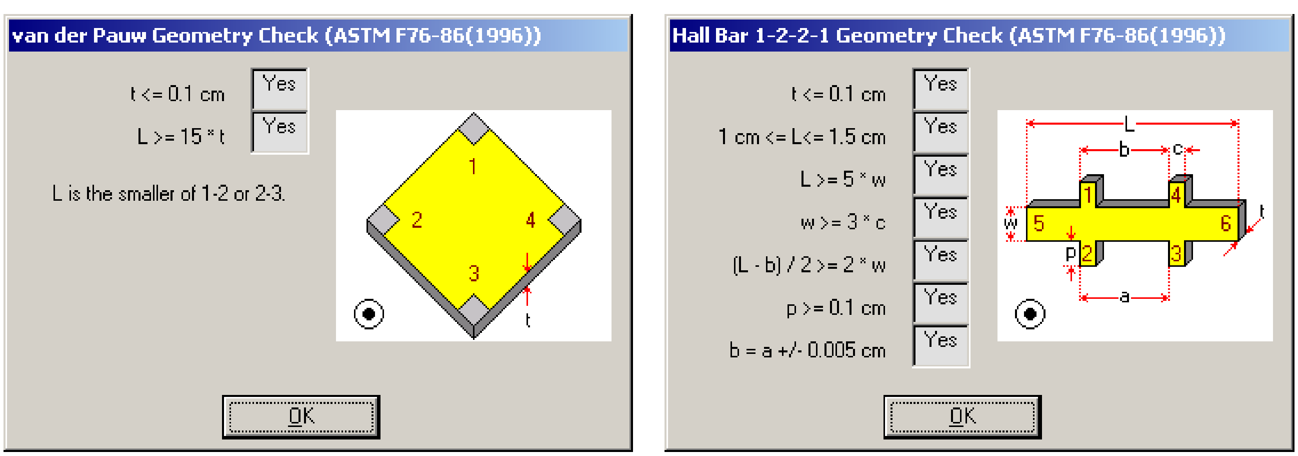


FIGURE 5-5 ***Left: ASTM compliance check window for a van der Pauw sample; Right: ASTM compliance check window for a Hall bar sample***

5.3.2 Default Sample Definition File

The system defines a default sample definition that is used if no sample definition is selected when the setup file is defined. The thickness in the default sample definition is 0. This means that only sheet values of the conductivity and Hall coefficient will be calculated. After a measurement is complete, the thickness can be entered and the results recalculated. At that time the bulk values of the resistivity and Hall coefficient displays.

5.3.3 Defining a Sample Definition File: An Example

Suppose you have ten different samples of a compound semiconductor, each with a different thickness, from bulk material to thin film. You want to measure the mobility of each of the samples to produce a plot of mobility versus thickness. You need to take the measurement at 77 K.

To do this, you will measure the Hall coefficient and resistivity. The mobility is the ratio of the Hall coefficient to the resistivity. To make sure there is no field dependency in the material, measure at five different fields between 2000 G and 10000 G. Since you will be doing the same experiment ten times, on ten different samples, define one setup for the field profile and measurement, and ten sample definitions, one for each sample, each with a different thickness (refer to section 5.3.1. to define a sample file). Each of the samples will be a van der Pauw configuration. FIGURE 5-4 shows the sample definition window for one of the samples. FIGURE 5-5 shows the ASTM compliance check windows for this sample.

5.4 The Setup File: Using the Navigator to Define and Control Measurements

The software is designed to allow the user to define experiments that contain at least one step. A step is a description of all the setup parameters required to perform a measurement. For instance, a step may be to perform an IV curve, or to perform a variable temperature experiment. This information can be stored in a setup file for later use.

For each sample, IV curves should be taken to confirm the quality of the contacts, and resistivity and the Hall coefficient measured at 5 points between 2000 G and 10000 G. To easily create, modify, and store these steps an experiment navigator is included in the software. It uses an Explorer® type interface.

5.4.1 Using the Navigator

Selecting **New Setup** on the menu creates the basic setup in FIGURE 5-6.

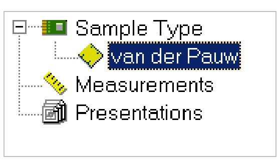


FIGURE 5-6 ***A basic measurement in the navigator***

Right-clicking on **Measurements** brings up the menu of measurements that can be added to the setup (FIGURE 5-7). Measurements that are grayed out are not supported in this configuration of the system.

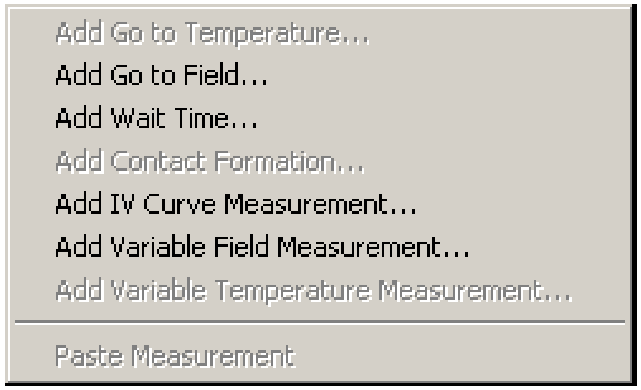


FIGURE 5-7 ***List of available measurements***

Measurement types control the environment of the samples such as the temperature (go to temperature) and the field (go to field). The user can define the measurements performed on the sample, such as add IV curve, add variable field, or add variable temperature. Measurements can be copied to the clipboard and pasted from the clipboard into the navigator. FIGURE 5-8 shows the options which are found by right-clicking any measurement step.

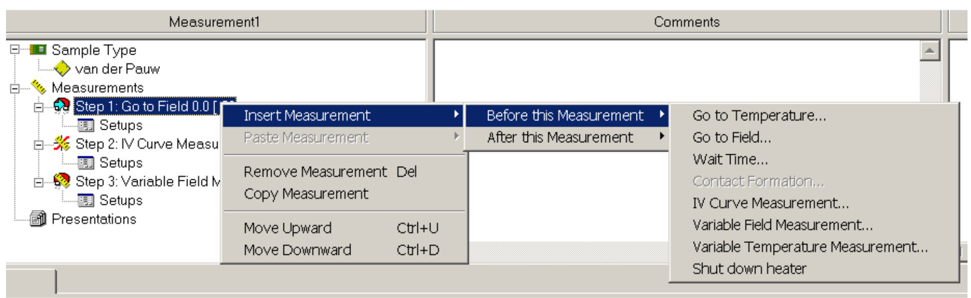


FIGURE 5-8 ***These menus are activated by right-clicking on any measurement step.***

5.4.2 How to Use Scaled Input (Yellow) Boxes

Input boxes with a yellow background are found throughout the software. These boxes are called scaled input boxes. Every yellow box will have a gray label associated with it that contains a unit. By use of numbers and letters, values can be easily and naturally entered over a wide dynamic range. For instance, to enter a current of 1.5 pA, the input would be 1.5p. To enter 1.5 μA use 1.5u. The following lists the acceptable multipliers.

a=10^{-18}
f=10^{-15}
p = 10^{-12}
A = 10^{-10}
n = 10^{-9}
u = 10^{-6}
m = 10^{-3}
c=10^{-2}
space=10^{0}
k = 10^{3}
M = 10^{6}

These designations are case sensitive; enter them exactly as indicated above. For example, to enter a maximum field of 25 kOe, type 25k; to enter 25 MOe, type 25M; to enter 10 minutes, type 10m. Press tab after entering a value to advance to the next field. The displayed base units automatically change to reflect the multiplier. Enter only a value with no multiplier and the units on the right side of this text box scale appropriately.

5.4.3 How to Use the Automatic Operation Buttons

The automatic operation buttons have three states. One is when a the system is idle (FIGURE 5-9), another is during a measurement (FIGURE 5-10), the third is during a temperature or field ramp (FIGURE 5-11).

FIGURE 5-9 ***State of the automatic operation buttons when the system is idle***

FIGURE 5-10 ***State of the automatic operation buttons during a measurement***

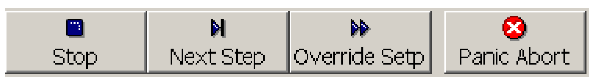


FIGURE 5-11 ***State of the automatic operation buttons during a temperature or field ramp***

In all three states clicking **Panic Abort** will stop all measurements that are in progress, turn off all heaters if temperature control is present, and turn off the magnet power supply output. This is intended to be used only if some major problem has occurred and the measurement must be aborted immediately and loss of data is acceptable.

If the system is in the idle state, clicking **Start** will begin the current setup. If the setup has not been saved, or there is unsaved data from a previous measurement, you will be prompted to save the information.

Clicking **Stop** will halt the current measurement, and ramp the field to 0. All data collected before **Stop** was clicked, is available for viewing and can be saved.

Clicking **Next Step** causes the current step in a setup to be aborted and the next step in the list begins execution. This might be used if a wait time step is included in the measurement, but you wish to skip over the wait.

Clicking **Override Setp** (Override setpoint) is available only during field or temperature ramps. Clicking this button will stop the ramp at its current value and declare that the temperature (or field) has settled to its final value.

5.4.4 Defining a Setup File: An Example

For our samples, we will measure the IV curves at zero field and do a variable field measurement. FIGURE 5-12 shows the navigator after adding these measurements.

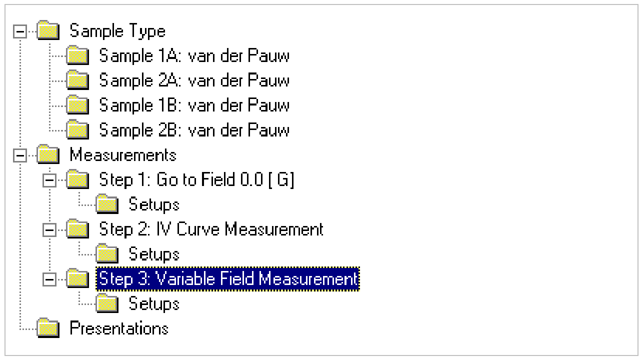


FIGURE 5-12 ***This measurement will measure IV curves at zero field and do a variable field measurement***

Clicking on the setup for each step will allow you to set the parameters for each individual step.

5.5 The Results File

When an experiment is executed the user selects a sample definition. The information in the sample definition is used to calculate the results of the experiment. The results are stored in a results file. The results file contains the sample definition file (section 5.3), the setup file (section 5.4), and the measurement results. This allows the user to recall a result file and re-run the experiment. Or the user can change the physical parameters and recalculate the results of a measurement. The results file also contains the system log file (section 5.6.2.3)

The raw text data for the measurement results is collected in the data grid on the left portion of the main HMS screen. The raw text data contains the instrument readings, contact connections, and the hardware error conditions (section 5.8.6 and section 5.8.7). To access all of the raw text data, use the horizontal scroll bar to navigate across the data grid. The results are graphically displayed as a plot next to the data grid on the main HMS screen, and the plot graphics can be exported as various types of files (section 5.11.1). The text data grid can be saved as a text file (section 5.12).

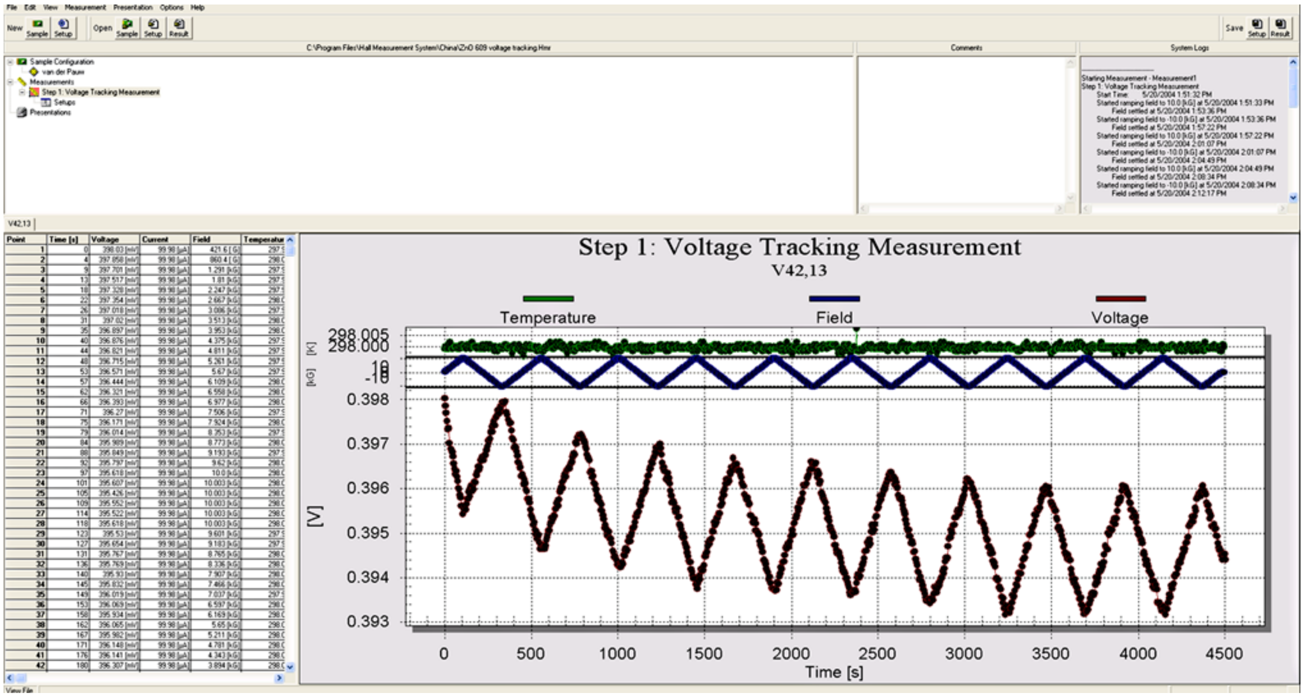


FIGURE 5-13 ***Example of the main HMS screen with results for a voltage tracking experiment***

5.6 IV Curves: Characterizing the Quality of the Contacts on the Sample

IV curves can be used to identify a bad contact on a sample. This experiment applies a current to a pair of contacts and the voltage is read, usually across the same contacts. If the contact is ohmic, the IV curves will be straight lines. The quality of contacts depends on more than just ohmic behavior.

5.6.1 Creating a Setup File for an IV Curve

For a van der Pauw sample, a minimum of two contact pairs should be measured. Typically this could be R12,12 and R34,34. If both of these contact pairs are ohmic then the sample is acceptable. If one or both are non-ohmic then two additional pairs (R23,23 and R41,41) should be measured. If there is only one non-ohmic contact, this procedure uniquely identifies it. With the software, all four configurations (R12,12, R23,23, R34,34 and R41,41) can be measured in a single measurement step.

In the navigator, select IV curve measurement, go to field, and go to temperature. The IV curve setup window to measure four contact pairs is shown in FIGURE 5-14. Executing this single step will generate 4 individual IV curves. By using the go to field and go to temperature steps, IV curves can be run at any temperature and field.

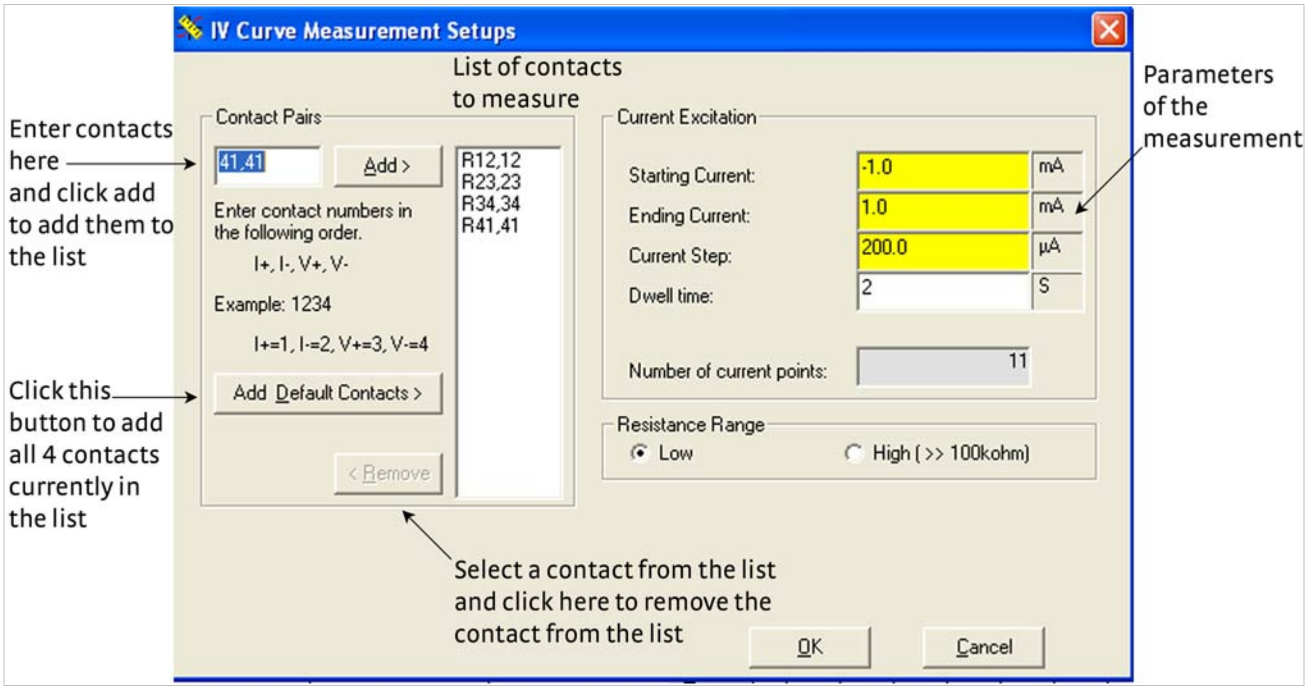


FIGURE 5-14 ***The IV curve setup window to measure 4 contact pairs: executing this single step will generate four individual IV curves. By using the go to field and go to temperature steps, IV curves can be run at any temperature and field.***

5.6.2 Running IV Curves and Obtaining Results

Click on **Start** to begin the measurement. The data will be displayed in real time on both the graphics display and the data grid. When one contact has finished and the next contact begins, the system does not automatically switch displays. Click on any tab in the data grid to display the data.

5.6.2.1 The IV Curve Plot

Plots for the IV curve are made on the plotting chart in the main HMS screen. FIGURE 5-15 shows the IV curve from one of the contacts on a boron doped silicon sample. The contact was 12,12, the best fit straight line has a slope of 16.4 Ω and an intercept of 0.048 V. Since this is a two wire measurement, the 16 Ω includes the resistance of the wires from the matrix switch card to the samples. The correlation coefficient of the fit is 0.998.

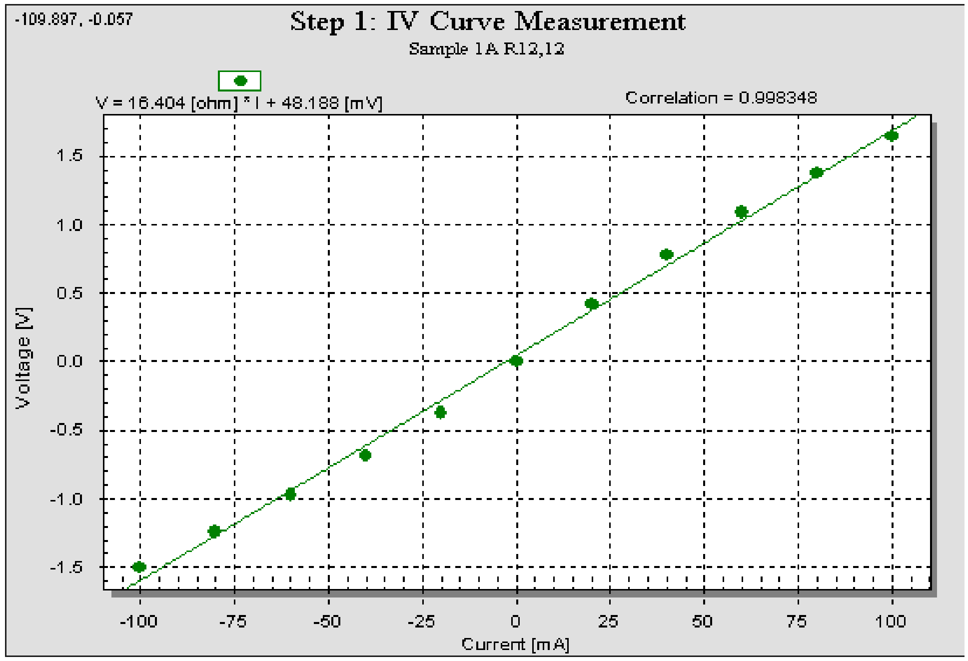


FIGURE 5-15 ***An IV curve for a boron doped silicon sample***

5.6.2.2 The Data Grid for the IV Curve

The main HMS screen includes a data grid that populates as you take a measurement. FIGURE 5-16 shows the data grid from the IV experiment in FIGURE 5-14, with the individual current settings, and voltage and field readings. The resistance values are simply computed from V/I. By clicking on the tabs at the top of the data grid, any of the four measured contacts displays.

R12,12 | R23,23 | R34,34 | R41,41

Point	Current	Voltage	Resistance	Field
1	-100.0 [mA]	-1.502 [V]	15.015358 [ohm]	230.0 [mG]
2	-80.0 [mA]	-1.242 [V]	15.524893 [ohm]	220.0 [mG]
3	-60.0 [mA]	-971.875 [mV]	16.197912 [ohm]	-1.97 [G]
4	-40.0 [mA]	-685.594 [mV]	17.139861 [ohm]	230.0 [mG]
5	-20.0 [mA]	-372.71 [mV]	18.635505 [ohm]	220.0 [mG]
6	0.0 [A]	-2.813 [µV]		-50.0 [mG]
7	20.0 [mA]	422.696 [mV]	21.134806 [ohm]	-1.3 [G]
8	40.0 [mA]	775.919 [mV]	19.397976 [ohm]	-1.22 [G]
9	60.0 [mA]	1.087 [V]	18.109773 [ohm]	220.0 [mG]
10	80.0 [mA]	1.373 [V]	17.167808 [ohm]	220.0 [mG]
11	100.0 [mA]	1.645 [V]	16.451508 [ohm]	60.0 [mG]

FIGURE 5-16 ***The data grid from the IV experiment in figure 5-14.***

5.6.2.3 The System Log File

The system also logs all events during a measurement, and stores them in the system log file. The user has the option to overwrite the system log file for each measurement or to append each measurement onto the existing log file.

```
Starting Measurement - Measurement1
Step 1: IV Curve Measurement
      Start Time:      5/26/2002 3:27:30 PM
      Started measuring Sample 1A: R12,12    5/26/2002 3:27:33 PM
      Started measuring Sample 1A: R23,23    5/26/2002 3:28:00 PM
      Started measuring Sample 1A: R34,34    5/26/2002 3:28:27 PM
      Started measuring Sample 1A: R41,41    5/26/2002 3:28:53 PM
      Time Completed:      5/26/2002 3:29:17 PM
      Elapsed Time:  0:1:47

Total Elapsed Time: 0:1:47
```

FIGURE 5-17 ***System log file for the IV measurement: the start time for each of the contacts is recorded in the system log file***

5.7 Variable Field Experiments: The Setup File

Variable field experiments are used, for instance, to determine the field dependency of magneto-transport properties. Defining the setup file for a variable field experiment involves three main functions, defining the field profile, defining the method and type of transport properties to measure, and defining the current excitation.

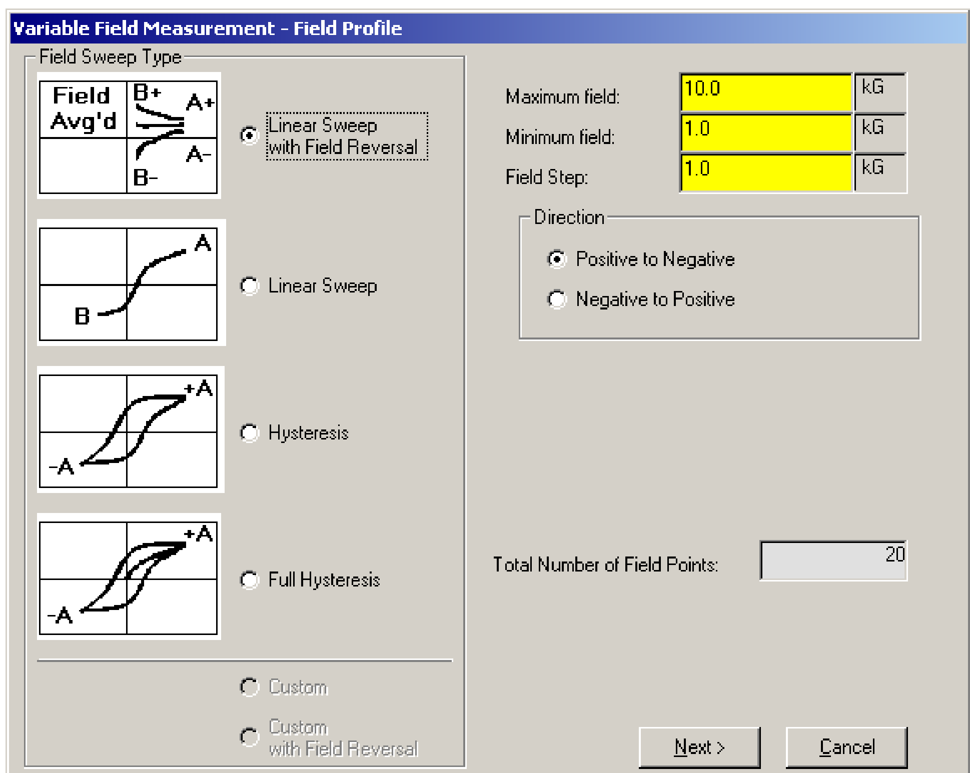


FIGURE 5-18 ***Field profile screen***

5.7.1 Defining the Field Profile for Variable Field Experiments

The field profile starts with defining the field sweep type. For most semiconductor characterizations, linear sweep with field reversal is the preferred method. Linear sweeps are used for M(R) measurements, and hysteresis loops are used to measure the anomalous Hall effect in ferromagnets and dilute magnetic semiconductors.

5.7.1.1 Field Sweep Type

There are four field sweep types in the field profile. The field points defined by the setup depend on the type of field sweep.

- *Linear sweep with field reversal:* for most semiconductor characterization, linear sweep with field reversal is the preferred method. Real world measurement of Hall voltage will always contain a contribution from the resistivity of the material, rather than just the Hall voltage. Since the Hall voltage will change sign when the magnetic field reverses, but the voltage from the resistivity will not change sign, measurements at both positive field and negative field can separate the effect. The field points for this field sweep type consist of the following:
  a. maximum field (+A) to minimum field (+B) by a user-defined field step
  b. minimum field (–B) to maximum field (–A) by the user-defined field step
- *Linear sweep:* this sweep type would be used for magneto-resistance (M(R)) measurements. For these experiments the resistivity, or more typically the four wire resistance, would be measured as a function of field. Often in the case of four wire resistance, the contacts are probes arranged in a linear geometry. No field averaging is done in this case. The field points for this field sweep type consists of: maximum field (+A) to minumum field (+B) by a user-defined field step.
- *Hysteresis:* this sweep type is used to measure the anomalous Hall effect in ferromagnets, ferromagnetic semiconductors, and dilute magnetic semiconductors. Typically in this case field averaging is done with the positive or negative field on the increasing field sweep, and the negative or positive field on the decreasing sweep. This is required because the magnetization of the sample, in addition to the applied field, contributes to the Hall voltage. This method assumes that Mup sweep(H) = -Mdown sweep(-H). For more discussion on the details of resistivity and Hall measurements see Appendix A. The field points for this field sweep type consist of two parts:
  a. maximum field (+A) to negative maximum field (–A) by a user-defined field step
  b. negative maximum field (–A) to maximum field (+A) by the user defined field step
- *Full hysteresis:* a full hysteresis loop is the same as the hysterisis loop, except that the field sweep starts from zero field; therefore, the field points for this field sweep type consist of three parts:
  a. zero field to maximum field (+A) by a user-defined field step
  b. maximum field (+A) to negative maximum field (–A) by the user-defined field step
  c. negative maximum field (–A) to maximum field (+A) by the user defined field step

5.7.1.2 Take Zero Field Resistivity: Do Not Return Field to Zero

This action only becomes available when performing a linear sweep with field reversal. The normal operation of the software is to return the field to zero at the end of each experiment. If this is not desired, check the box on this page. Selecting this box is particularly useful in profiles like go to temperature, do variable field experiment etc. It saves sweeping the field to zero at the end of a step and sweeping to maximum field after the temperature change. This list includes the consequences of not returning the field to zero.

- The user has to specify positive first/negative first for each of the variable field measurements that can be sandwiched by Go to Temps, if he wants to alternate fields.
- The user has to check zero-field resistivity measurements when the field crosses the zero check box on the field profile setup window. Otherwise, like before, it takes Zero-field Resistivity at the beginning of the measurement if it is a Hall & Resistivity type of measurement, and goes back to zero field at the end of the measurement step.
- Mobility grids show ERROR before the field crosses zero at acquisition time, if the Use Zero-field Resistivity to Calculate Mobility check box is selected.
- Until the field crosses zero, the geometry averaged mobility graph shows nothing at acquisition time. Once the field crosses zero, both field averaged and geometry averaged mobility lines are shown, but the field averaged line is not correct.
- The user has to manually click on Re-Calculate at the end of the entire measurement to show valid mobility grids and graphs. The software cannot automatically do this easily.
- This is only available when performing a linear sweep with field reversal.

5.7.2 Defining the Method and Type of Transport Properties

On the second page of the variable field setup, FIGURE 5-19, the measurement type is selected. Measurement can be Hall, resistivity, Hall and resistivity, and four-wire resistance. To get mobility of the sample, both the resistivity and Hall coefficient must be measured. The mobility is reported as the Hall coefficient divided by the resistivity. For simple single carrier samples, this is the Hall coefficient at any field divided by the zero field resistivity.

NOTE

For multi-conduction samples both the resistivity and Hall coefficient depend on magnetic field, and mobility of the material is no longer a well defined term; what is defined is the mobility of each carrier. The mobility of the material, as reported by the measurement, can be calculated as either the field dependent Hall coefficient divided by the zero field resistivity, or divided by the field dependent resistivity. To extract the mobility and density of each carrier from this field dependent measurement requires QMSA software.

5.7.2.1 Current Excitation

Current reversal is used to remove thermal voltages from the measurement. Just like field reversal, reversing the sign of the current will reverse the sign of voltages that depend linearly on the current, but will not change the sign of the thermal EMFs. Normally current reversal should always be used. Turning it off can decrease the measurement time at the expense of accuracy of the measurement.

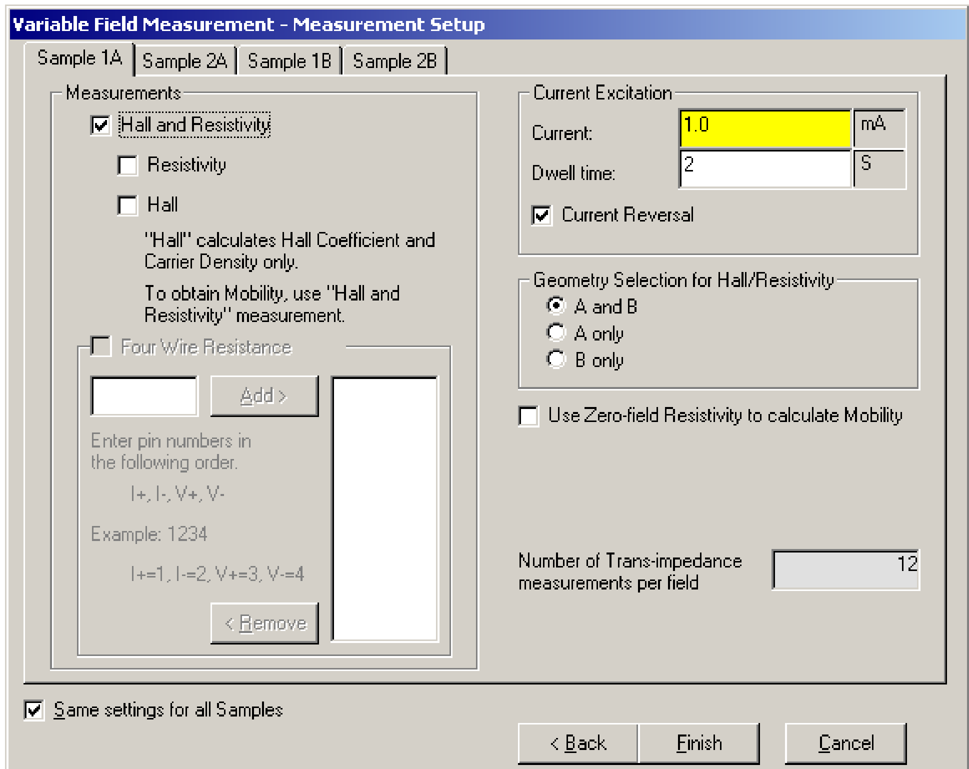


FIGURE 5-19 ***On the second page of the variable field setup the measurement type is selected: Measurement can be Hall, resistivity, Hall and resistivity, and four-wire resistance. In addition the current excitation and, for Hall and resistivity measurements, the geometries used in the measurement can be selected.***

Dwell time is the time the system pauses between changing a current and measuring a voltage. This allows any transients in the system to die out before measuring the voltage. The most common transient is the time to charge the capacitance of the cable connecting the sample to the instrumentation. The equivalent capacitor of the cable is charged through the two wire resistance of the sample. The proper dwell time would be 5 to 6 RC time constants. Typically, for samples less than 10 MΩ, this time is < 1 s.

5.7.2.2 Geometry Selection

For both van der Pauw and Hall bar sample types there are two ways (called geometry A and geometry B) to do many of the measurements. For instance, on a van der Pauw sample the Hall resistance can be measured as R13,24, i.e., the current through contact 1 and 3 and the voltage measured between 2 and 4, or R24,13. Either one of the geometries can be measured or both can be measured and the results averaged. This geometric average removes any errors from non-symmetric samples.

Appendix A contains complete details of the measurement and calculations of resistivity and Hall coefficient for all supported geometries.

5.7.3 Fixed Field Measurements

To define a measurement for a fixed (single) field Hall measurement, select linear sweep with field reversal and set both the maximum and minimum field to the desired fixed field value. As with any setup, this can be saved and recalled any number of times to run the same measurement.

5.8 Variable Field Measurement Results

The resistivity vs. field for a boron doped silicon sample is shown in FIGURE 5-20. The plot shows the zero field resistivity as a single point, the resistivity measured for positive field and negative field and the field averaged resistivity.

5.8.1 Plot Showing Resistivity vs. Field

Silicon is not expected to have any field dependent resistance. The small effect seen in FIGURE 5-20 (about 2 parts per 15,000) is the probability due to thermal effects from self heating. This measurement took 9 min and 12 s.

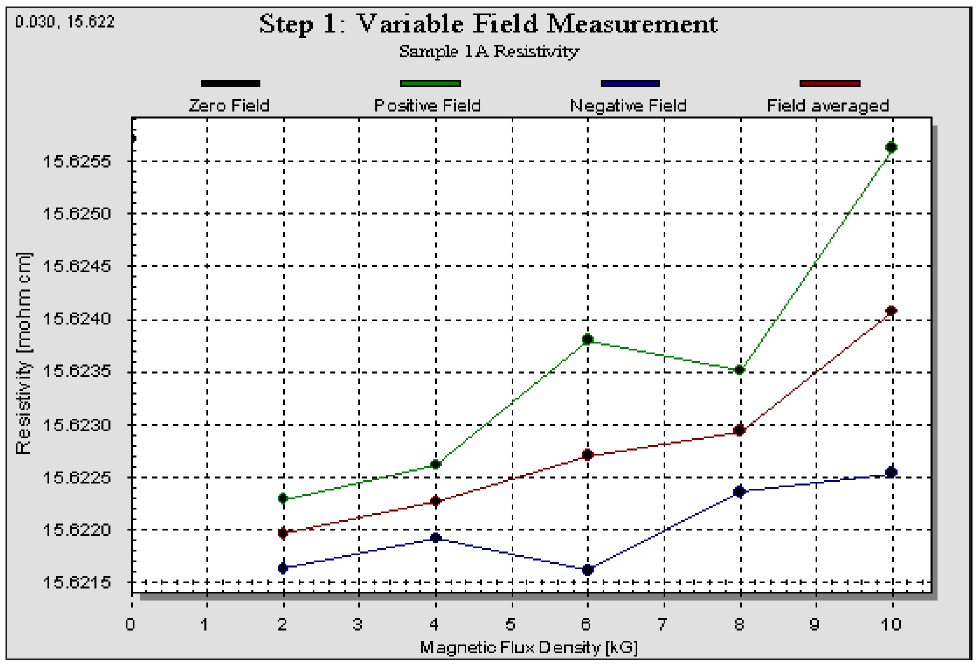


FIGURE 5-20 ***The resistivity vs. field for a boron doped silicon sample***

5.8.2 Data Grid for Resistivity vs. Field

Part of the data grid for the resistivity measurement on SiB is shown in FIGURE 5-21. This shows the measurement at 2000 G. The field averaged resistivity was 15.622 mΩ/cm (as shown in the first column), the corresponding sheet resistivity was 295.311 mΩ/sqr (as shown in the second column). The next columns give the resistivity and sheet resistivity at +2000 G and –2000 G.

For a van der Pauw sample, there are two geometries that can be measured to get the resistivity. Columns three and four in FIGURE 5-21 show the results from geometry A; results from geometry B (columns one and two) can be seen in FIGURE 5-22. Columns five and six in FIGURE 5-21 are the resistivity and sheet resistivity of geometry A. Columns seven and eight show the two resistance measurements which are required to get the resistivity. The solution to the van der Pauw equation is shown in column nine.

Step 1: Variable Field Measurement - Sample 1A Resistivity (Press ESC to Return)

Set Field	Resistivity (Bavg)	Sheet Resistivity (Ba	Resistivity (Gavg)	Sheet Resistivity (Gavg	Resistivity A	Sheet Resistivity A	Resistance A1	Resistance A2	Factor A	Resistivity B
2.0 [kG]										
2.0 [kG]										
2.0 [kG]							65.2293 [mohm]			
2.0 [kG]										
2.0 [kG]										
2.0 [kG]								65.134286 [mohm]		
2.0 [kG]					15.628 [mohm cm]	295.427 [mohm/sqr]			1.E+0	
2.0 [kG]										
2.0 [kG]										
2.0 [kG]										
2.0 [kG]										
2.0 [kG]										
2.0 [kG]										
2.0 [kG]										15.616 [mohm cm
2.0 [kG]			15.622 [mohm cm]	295.317 [mohm/sqr]						
-2.0 [kG]										
-2.0 [kG]										
-2.0 [kG]							65.227163 [mohm]			
-2.0 [kG]										
-2.0 [kG]										
-2.0 [kG]								65.12478 [mohm]		
-2.0 [kG]					15.627 [mohm cm]	295.401 [mohm/sqr]			1.E+0	
-2.0 [kG]										
-2.0 [kG]										
-2.0 [kG]										
-2.0 [kG]										
-2.0 [kG]										
-2.0 [kG]										
-2.0 [kG]										15.617 [mohm cm
-2.0 [kG]			15.622 [mohm cm]	295.305 [mohm/sqr]						
|2.0| [kG]	15.622 [mohm cm]	295.311 [mohm/sqr]								
4.0 [kG]										

FIGURE 5-21 ***Part of the data grid for the resistivity measurement on SiB***

FIGURE 5-22 shows measurement at 2000 G. For a van der Pauw sample, there are two geometries that can be measured to get the resistivity. This shows geometry B results, results from geometry A are in FIGURE 5-21. The first two columns shown here are the resistivity and sheet resistivity of geometry B. Two resistance measurements are required to get the resistivity, these are shown in the next two columns. Finally the solution to the van der Pauw equation is shown in the last column.

Step 1: Variable Field Measurement - Sample 1A Resistivity (Press ESC to Return)

Set Field	Resistivity B	Sheet Resistivity B	Resistance B1	Resistance B2	Factor B
2.0 [kG]					
2.0 [kG]					
2.0 [kG]					
2.0 [kG]					
2.0 [kG]					
2.0 [kG]					
2.0 [kG]					
2.0 [kG]					
2.0 [kG]					
2.0 [kG]			65.266732 [mohm]		
2.0 [kG]					
2.0 [kG]					
2.0 [kG]				65.000197 [mohm]	
2.0 [kG]	15.616 [mohm cm]	295.208 [mohm/sqr]			1.E+0
2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]			65.255042 [mohm]		
-2.0 [kG]					
-2.0 [kG]					
-2.0 [kG]				65.012518 [mohm]	
-2.0 [kG]	15.617 [mohm cm]	295.209 [mohm/sqr]			1.E+0
-2.0 [kG]					
|2.0| [kG]					

FIGURE 5-22 ***Part of the data grid for the resistivity measurement on SiB***

5.8.3 Instrument Readings

The actual instrument readings and contact connections are located in the data grid. Use the scroll bar at the bottom of the data grid to navigate to them. FIGURE 5-23 is an example of the instrument readings and contact connections for a variable field measurement. The first four columns show the connections, current source and voltmeter. This is followed by the current setting, the voltage readings, the calculated V/I and finally the field reading. Here you can see the current reversal and the thermal voltages in the system. This information can be invaluable for understanding and diagnosing measurements that are not giving the expected results.

Step 1: Variable Field Measurement - Sample 1A Resistivity (Press ESC to Return)

Set Field	I+	I-	V+	V-	Current	Voltage	V/I	Field
2.0 [kG]	1	2	4	3	50.0 [mA]	3.248 [mV]	64.957952 [mohm]	2.0 [kG]
2.0 [kG]	1	2	4	3	-50.0 [mA]	-3.275 [mV]	65.500648 [mohm]	2.0 [kG]
2.0 [kG]								2.0 [kG]
2.0 [kG]	2	3	1	4	50.0 [mA]	3.255 [mV]	65.102284 [mohm]	2.0 [kG]
2.0 [kG]	2	3	1	4	-50.0 [mA]	-3.258 [mV]	65.166289 [mohm]	2.0 [kG]
2.0 [kG]								2.0 [kG]
2.0 [kG]								2.0 [kG]
2.0 [kG]	3	4	2	1	50.0 [mA]	3.273 [mV]	65.455483 [mohm]	2.0 [kG]
2.0 [kG]	3	4	2	1	-50.0 [mA]	-3.254 [mV]	65.077981 [mohm]	2.0 [kG]
2.0 [kG]								2.0 [kG]
2.0 [kG]	4	1	3	2	50.0 [mA]	3.257 [mV]	65.133143 [mohm]	2.0 [kG]
2.0 [kG]	4	1	3	2	-50.0 [mA]	-3.243 [mV]	64.867251 [mohm]	2.0 [kG]
2.0 [kG]								2.0 [kG]
2.0 [kG]								2.0 [kG]
2.0 [kG]								2.0 [kG]
-2.0 [kG]	1	2	4	3	50.0 [mA]	3.248 [mV]	64.967936 [mohm]	-1.999 [kG]
-2.0 [kG]	1	2	4	3	-50.0 [mA]	-3.274 [mV]	65.486389 [mohm]	-1.999 [kG]
-2.0 [kG]								-1.999 [kG]
-2.0 [kG]	2	3	1	4	50.0 [mA]	3.256 [mV]	65.113525 [mohm]	-1.999 [kG]
-2.0 [kG]	2	3	1	4	-50.0 [mA]	-3.257 [mV]	65.136035 [mohm]	-1.999 [kG]
-2.0 [kG]								-1.999 [kG]
-2.0 [kG]								-1.999 [kG]
-2.0 [kG]	3	4	2	1	50.0 [mA]	3.273 [mV]	65.451902 [mohm]	-2.001 [kG]
-2.0 [kG]	3	4	2	1	-50.0 [mA]	-3.253 [mV]	65.058181 [mohm]	-2.002 [kG]
-2.0 [kG]								-2.001 [kG]
-2.0 [kG]	4	1	3	2	50.0 [mA]	3.259 [mV]	65.177684 [mohm]	-2.0 [kG]
-2.0 [kG]	4	1	3	2	-50.0 [mA]	-3.242 [mV]	64.847353 [mohm]	-2.0 [kG]
-2.0 [kG]								-2.0 [kG]
-2.0 [kG]								-2.0 [kG]
-2.0 [kG]								-2.0 [kG]
|2.0| [kG]								2.0 [kG]

FIGURE 5-23 ***Actual instruments readings and contact connections***

5.8.4 Plot for the Hall Coefficient vs. Field

FIGURE 5-24 is the Hall coefficient vs. field plot for a boron doped silicon sample. The plot shows the Hall coefficient measured for positive field and negative field and the field averaged Hall coefficient. Silicon is not expected to have any field dependent Hall coefficient. This measurement of the sample took 9 min 12 s.

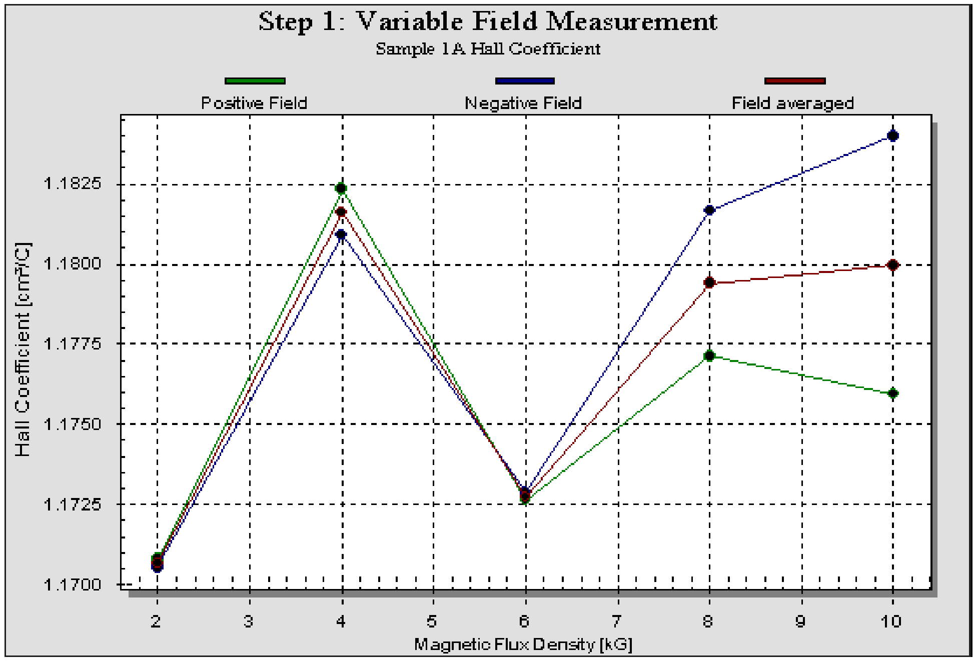


FIGURE 5-24 ***Hall coefficient vs. field for a boron doped silicon sample: the plot shows the hall coefficient measured for positive field and negative field and the field averaged hall coefficient***

5.8.5 Data Grid for the Hall Coefficient vs. Field

Part of the data grid for the Hall coefficient measurement on SiB is shown in FIGURE 5-25. This shows the measurement at 2000 G. The field averaged Hall coefficient was 1.172 cm^3/C, the corresponding sheet Hall coefficient was 22.13 cm^2/C. The next columns give the Hall coefficient and sheet Hall coefficient at +2000 G and –2000 G. The next column shows the Hall resistance (Hall voltage/current). For a van der Pauw sample, there are two geometries that can be measured to get the Hall resistance. The next column is the Hall resistance geometry A, followed by the Hall resistance for geometry B.

Step 1: Variable Field Measurement - Sample 1A Hall Coefficient (Press ESC to Return)

Set Field	Hall Coeff.(Bavg)	Sheet Hall Coeff.(Bavg)	Hall Coeff.(Gavg)	Sheet Hall Coeff.(Gavg)	Hall Resistance (Gavg)	Hall Resistance A	Hall Resistance B
2.0 [kG]							
2.0 [kG]							
2.0 [kG]						610.612188 [μohm]	
2.0 [kG]							
2.0 [kG]							
2.0 [kG]							274.461072 [μohm]
2.0 [kG]			1.171E+0[cm³/C]	2.213E+1[cm²/C]	442.53663 [μohm]		
-2.0 [kG]							
-2.0 [kG]							
-2.0 [kG]						-282.529972 [μohm]	
-2.0 [kG]							
-2.0 [kG]							
-2.0 [kG]							-602.274685 [μohm]
-2.0 [kG]			1.171E+0[cm³/C]	2.213E+1[cm²/C]	-442.402329 [μohm]		
|2.0| [kG]	1.171E+0[cm³/C]	2.213E+1[cm²/C]					

FIGURE 5-25 ***Part of the data grid for the Hall coefficient measurement on SiB***

5.8.6 Instrument Readings for the Hall Coefficient vs. Field

FIGURE 5-26 shows the actual instrument readings and contact connections for all measurements. The first four columns show the connections, current source and voltmeter. This is followed by the current setting, the voltage readings, the calculated V/I and finally the field reading. Here you can see the current reversal and the thermal voltages in the system. This information can be invaluable for understanding and diagnosing measurements that are not giving the expected results. Those entries recorded in red indicate a hardware error condition (section 5.8.7)

Step 1: Variable Field Measurement - Sample 1A Hall Coefficient (Press ESC to Retu

Set Field	I+	I-	V+	V-	Current	Voltage	V/I	Field
2.0 [kG]	4	2	1	3	50.0 [mA]	29.833 [µV]	596.66214 [µohm]	2.001 [kG]
2.0 [kG]	4	2	1	3	-50.0 [mA]	-31.228 [µV]	624.562236 [µohm]	2.0 [kG]
2.0 [kG]								2.001 [kG]
2.0 [kG]	3	1	4	2	50.0 [mA]	10.92 [µV]	218.395252 [µohm]	1.999 [kG]
2.0 [kG]	3	1	4	2	-50.0 [mA]	-16.526 [µV]	330.526892 [µohm]	1.999 [kG]
2.0 [kG]								1.999 [kG]
2.0 [kG]								2.0 [kG]
-2.0 [kG]	4	2	1	3	50.0 [mA]	-12.782 [µV]	-255.638824 [µohm]	-2.0 [kG]
-2.0 [kG]	4	2	1	3	-50.0 [mA]	15.471 [µV]	-309.42112 [µohm]	-1.999 [kG]
-2.0 [kG]								-1.999 [kG]
-2.0 [kG]	3	1	4	2	50.0 [mA]	-32.891 [µV]	-657.815762 [µohm]	-2.0 [kG]
-2.0 [kG]	3	1	4	2	-50.0 [mA]	27.337 [µV]	-546.733608 [µohm]	-1.999 [kG]
-2.0 [kG]								-1.999 [kG]
-2.0 [kG]								-1.999 [kG]
|2.0| [kG]								1.999 [kG]

FIGURE 5-26 ***Actual instrument readings and contact connections for all measurements***

5.8.7 Hardware Error Conditions

On each measurement, the software monitors the hardware and measurement results for certain errors. If an error condition exists, the corresponding data entry is marked in red text. The condition for the error is indicated in the data grid, next to the instrument readings. You can scroll to the right to view them.

The hardware error conditions monitored are:

- Real compliance: this condition occurs when the current source goes into compliance. The requested current could not be delivered.
- Range compliance: for certain hardware configurations the voltmeter is limited to the 10 V range—range compliance occurs when the measured voltage is above 10 V
- Overrange: this condition occurs when the voltage exceeds the meter range setting
- Consistency: this condition occurs when ASTM (F76-86(1996)) criteria are not met. The ASTM criteria specifies certain relationships among the measured voltages and resistances that should be met for a valid measurement. For instance, for a van der Pauw Hall measurement the resistance of the two geometries should agree to within 10% of each other. The software tests all relevant ASTM criteria and marks the measurements that were not met. In FIGURE 5-26, the two geometries are not with 10% of each other.

5.9 Variable Temperature Measurements

The system supports three types of variable temperature measurements. These are:

- Linear spacing: change from a start temperature to an end temperature with a fixed step size. The temperature must settle at each point before taking a measurement.
- 1/T spacing: change from a start temperature to an end temperature with steps that are equally spaced in 1/T. The temperature must settle at each point before a measurement is taken. This is useful for determining an activation energy.
- Quick survey mode: the temperature is changed at a constant rate. Measurements are taken at fixed time intervals or fixed temperature intervals. The temperature changes throughout the measurement, and no settle criteria is used.

These measurements are available if the system is configured for one of three variable temperature options, a closed cycle refrigerator (CCR) for the electromagnet systems, a high temperature oven for the electromagnet system or the superconducting magnet system.

FIGURE 5-27 shows the screen when a variable temperature measurement is selected.

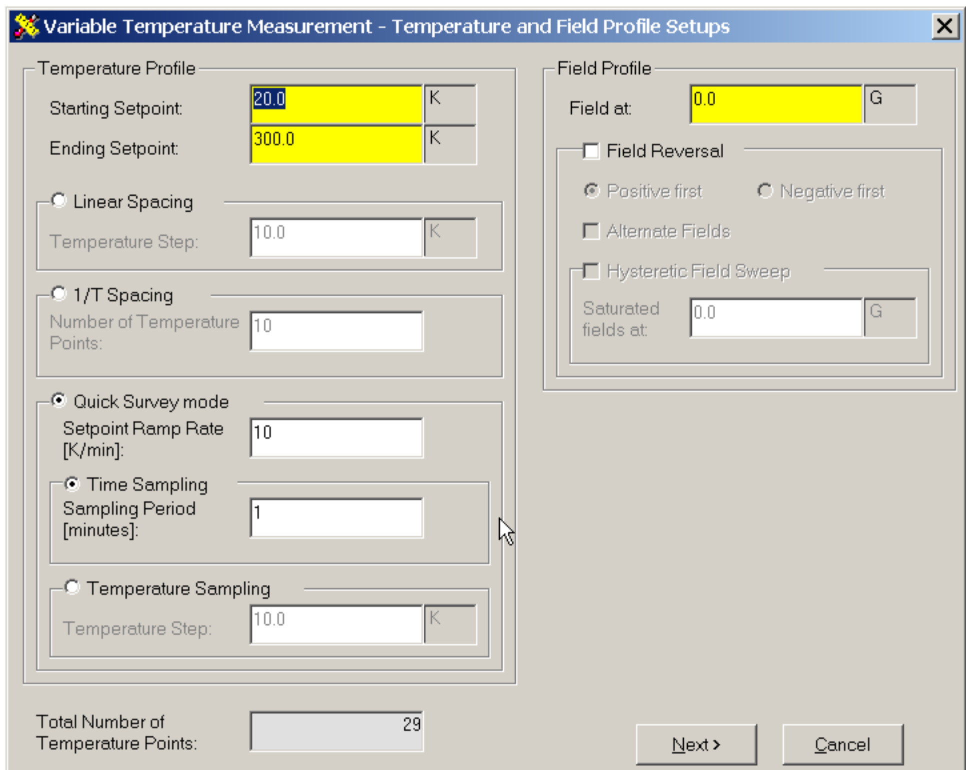


FIGURE 5-27 ***Variable temperature measurement with quick survey mode selected***

CAUTION

Do not input temperatures higher than the sample module is designed for.

5.9.1 Navigator Sequences for the Setup File

If the Hall coefficient is to be measured as a function of temperature, then a magnetic field value must be specified. As described in the variable field section, field reversal should be used to remove stray resistance from the Hall coefficient measurement.

There are several options for controlling the field. This bulleted list shows some examples. The sequences are made with the assumption that field reversal is selected.

- Example 1: this is an example of a navigator sequence for a variable temperature setup file in which the selected field = f.
  Go to temperature t1
  Go to field 0
  Measure 0 field resistivity
  Go to field f
  Measure Hall coefficient and resistivity
  Go to field 0
  Go to temperature t2
- Example 2: this is an example of a navigator sequence for a variable temperature setup file in which alternate fields was selected.
  Go to temperature t1
  Go to field f
  Measure Hall coefficient and resistivity
  Go to field 0
  Measure 0 field resistivity
  Go to field –f
  Measure Hall coefficient and resistivity
  Go to temperature t2
  Measure Hall coefficient and resistivity
  Go to field 0
  Measure 0 field resistivity
  Go to field f
  Measure Hall coefficient and resistivity
- Example 3: this is an example of a navigator sequence for a variable temperature setup file in which a magnetic material is being measured. Hence, the the hysteretic field sweep is used and an additional saturation field (fs) is supplied.
  Go to temperature t1
  Go to field fs
  Go to field f
  Measure Hall coefficient and resistivity
  Go to field –fs
  Go to field –f
  Measure Hall coefficient and resistivity

The second screen of the variable temperature setup is identical to the second screen in variable field setup FIGURE 5-19.

5.10 Voltage Tracking Experiments: Measuring Low Mobility Samples

The voltage tracking experiment is used to measure a voltage as a function of time. This is a very useful diagnostic tool to use when a Hall measurement gives non-repeatable or un-expected results. The Model 7700A HMS voltage tracking mode allows for the synchronous measurement of the Hall voltage while the magnetic field is changing. The method allows you to apply a current to any two contacts on your sample and connect the voltmeter to any two contacts on your sample. Also, if there is a temperature option installed on the system, the magnetic field and temperature can be varied and the voltage is measured continuously and logged into the results file. Temperature drifts are asynchronous with the field change, and they appear as a slow drift on the voltage offset.

There are particular challenges to measuring low mobility materials that are used in organic semiconductors, molecular electronics, organic LEDS and transparent oxides. In these materials, the Hall offset voltage can be orders of magnitude larger than the true Hall voltage. In addition, the temperature coefficient of the offset Hall voltage can be significant. The variation in the offset voltage due to a one degree change of the sample temperature, may change the offset voltage by an amount larger than the change in Hall voltage with a 1 T change in field.

5.10.1 Voltage Tracking Setup

The setup screen from the HMS software for voltage tracking is shown in FIGURE 5-28. The description for each section in the setup screen is given in the bulleted list.

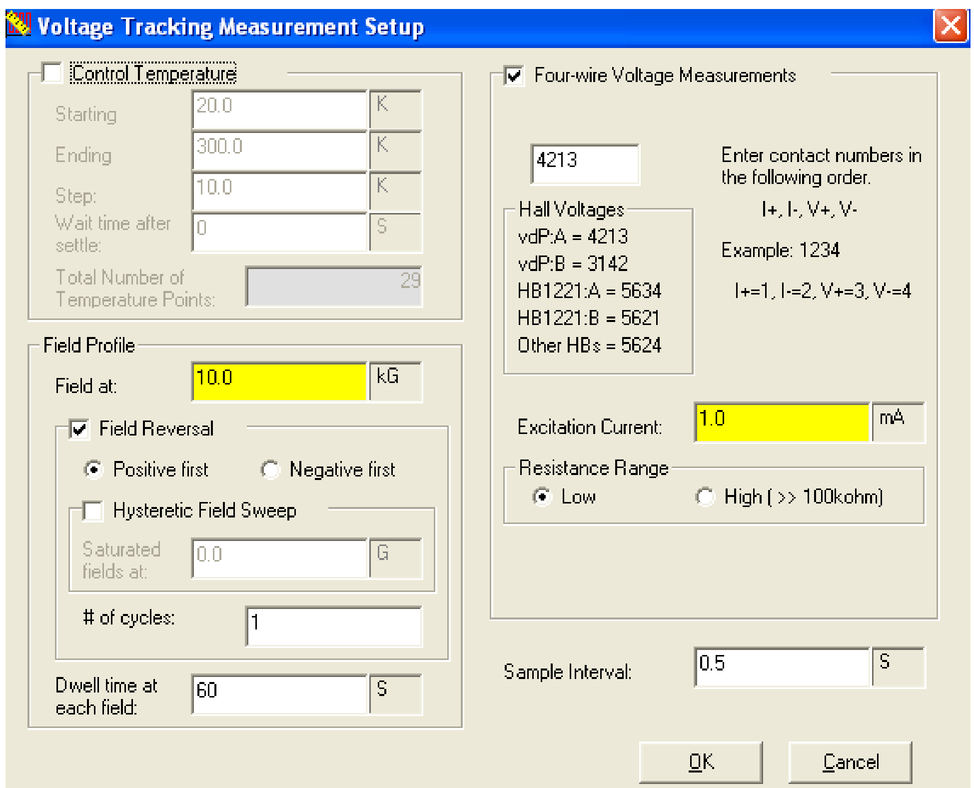


FIGURE 5-28 **Setup screen for voltage tracking**

- *Temperature:* in the temperature section, you can select a number of temperatures for the sample. If the section is unchecked, then the temperature of the systems remains constant during the voltage tracking experiement. Select the start temperature, end temperature, temperature step and wait time. Zero is a valid entry for wait time. After the temperature has settled and the wait time has elapsed the field profile will run.

- *Field profile:* select the desired field value. If field reversal is selected, the measurements are made at both positive and negative field. Selecting hysteretic field sweep means that when the field is changed, the field is first swept to the saturation field of the same sign as the final field. The number of cycles is the number of times the field goes from a plus to a minus value. The dwell time is the amount of time at the field before resuming the sweep. This cycle can be repeated for up to 1000 cycles.
- *Measurement:* the measurement is specified by the measurement configuration, the current, the resistance range and the sample interval. In this measurement, you can specify one four-wire resistance measurement. The current is applied and the voltage measured continuously. The result screen for a ZnO sample is shown in FIGURE 5-29.
- *Time between measurements:* use this section to input the time you would like in between each measurement.

5.10.2 Voltage Tracking Results

FIGURE 5-29 shows an example of a voltage tracking experiment on zinc oxide (ZnO). The top plot shows the temperature of the sample. The second plot shows the magnetic field and the third plot shows the Hall voltage. The offset voltage is approximately 0.99575 V. The amplitude of the Hall voltage oscillation is approximately 0.001 V. The drift of the offset voltage is 0.0003 mV. FIGURE 5-30 is a plot of the temperature coefficient of the resistivity of ZnO. The change is approximately 0.2%/C.

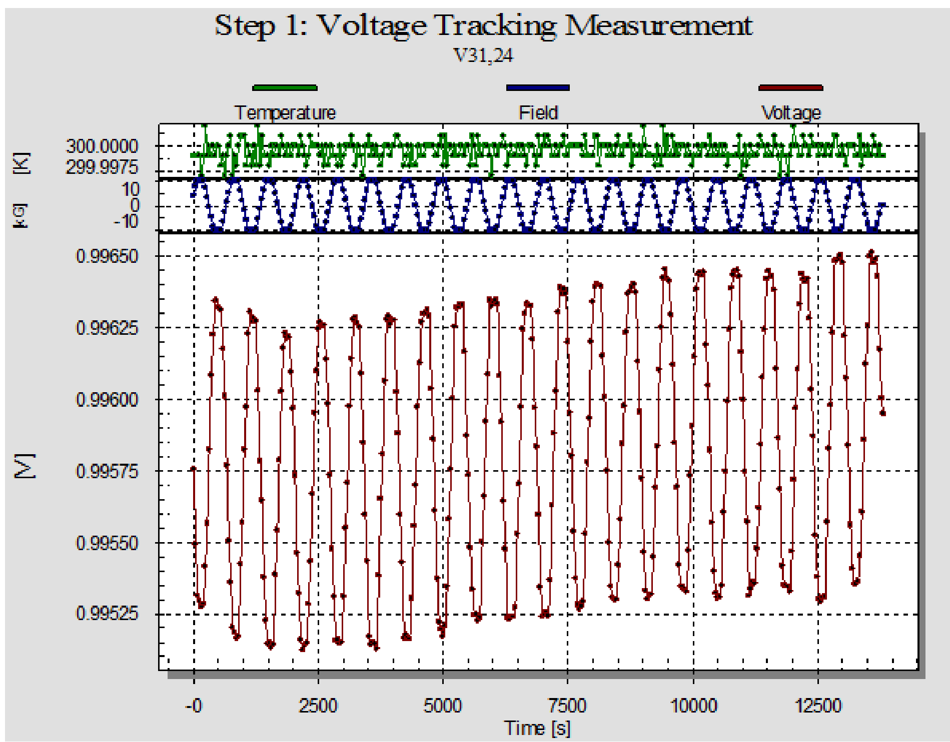


FIGURE 5-29 ***Voltage tracking experiment on ZnO***

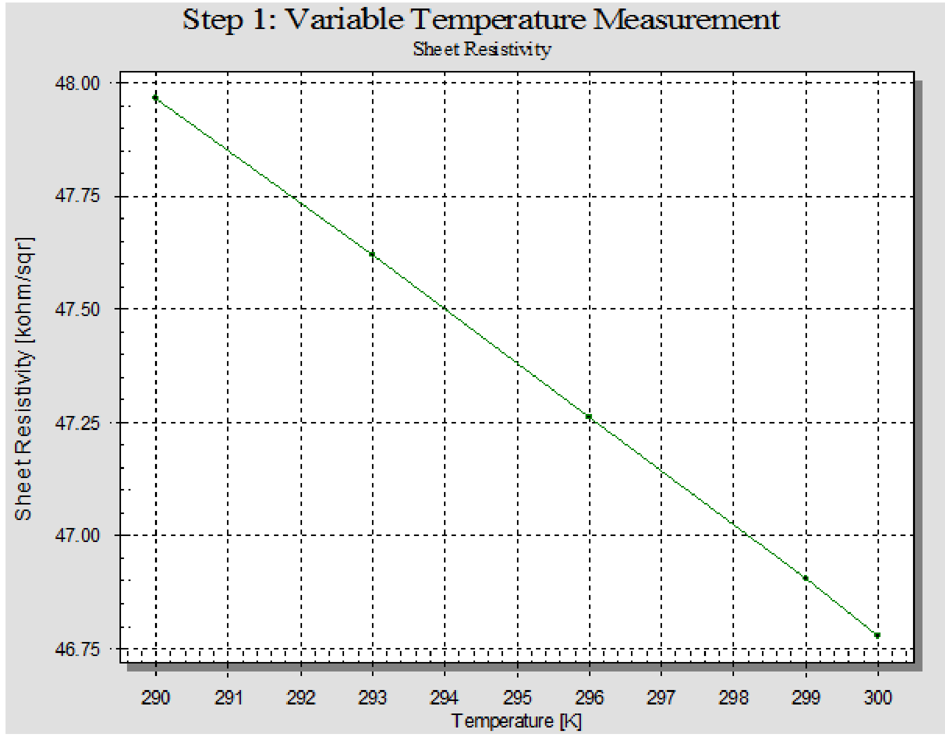


FIGURE 5-30 ***Temperature coefficient of the resistivity of ZnO***

5.11 Advanced Plotting Features

Right clicking on the plot window brings up the menu to customize the appearance of the plots (FIGURE 5-31).

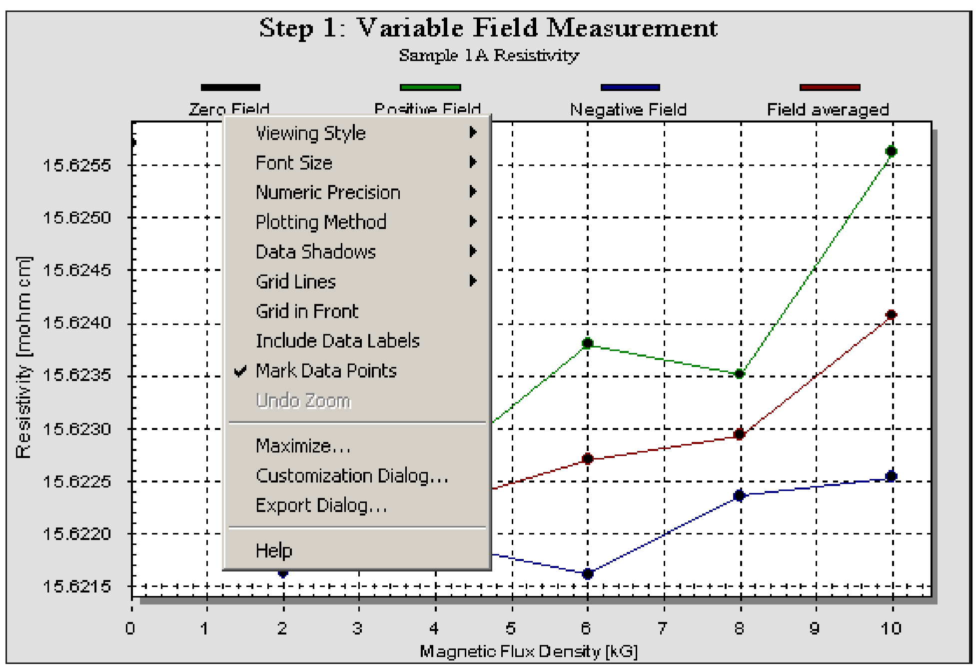


FIGURE 5-31 ***The menu to customize the appearance of the plots***

5.11.1 Exporting the Graphics

A very useful feature here is the export dialog entry which brings up the dialog box in FIGURE 5-32. From here the graphics can be saved in a variety of standard formats.

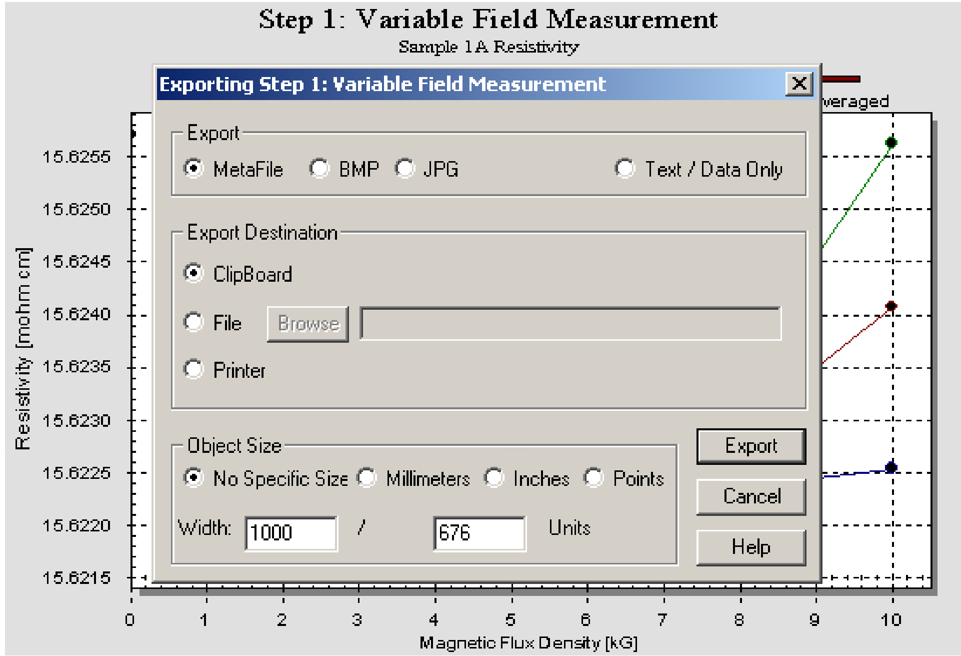


FIGURE 5-32 ***The export dialog box for the plots (the graphics can be saved in a variety of standard formats)***

5.12 Text Output

The software supplies a variety of text output options. The first is to save all the results in a text file. The sample parameters, the measurement parameters and the calculated results are saved as an ASCII text file. Units are provided for all physical parameters.

Additionally the information from the grid can be saved in a text file. Selecting this function gives the user an option to select some or all the columns in the grid. This text file can be imported into Excel® to reconstruct the data grid.

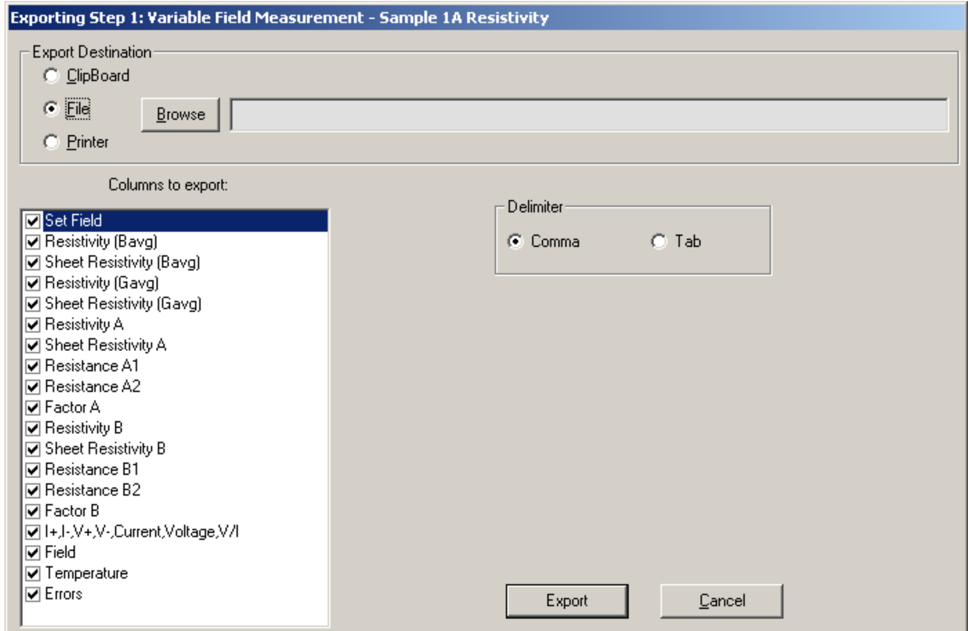


FIGURE 5-33 ***The export grid (for resistivity) dialog box (any or all columns from the grid can be exported to a delimited ASCII test file. This file can be directly imported into Excel to reconstruct the grid).***

5.13 General Information

This software is a true 32-bit implementation using Visual Basic 6.0 for development. It has been tested on Windows 2000 and XP and Vista, which are the only operating systems it should be used with. When sold with a complete system we supply the software on Dell computers, which is the recommended configuration. The software only supports the National Instruments PCI IEEE card and National USB-GPIB-B IEEE.

From the configuration utility the default directory for data files can be set. The directory can be on the local machine or on any mapped network drive.

The software can be installed on other computers without IEEE cards and instruments. From these computers, result can be viewed. Measurement setup and sample definitions files can be created or modified. The only function not available is to run a measurement.

When the system is doing a measurement a second instance of the software can be started, this second copy can view result files on completed experiments.

Chapter 6: Service

6.1 General

This chapter covers maintenance, troubleshooting and field service instructions. Customer service of the product is limited to the information presented in this chapter. Factory trained service personnel should be consulted if the instrument requires repair. Instructions for contacting Lake Shore and arranging product service are in section .

6.2 Line Voltage Selection

CAUTION

Each instrument and equipment in the console is individually adjusted to meet the specific location electrical requirement. The voltage requirement is listed on the label on the rear door of the console. If the system voltage has to be changed, each instrument and equipment in the console needs to be individually adjusted. Please follow each instrument manual provided to change the voltages.

When the instrument or equipment is removed from the system for service, make a note of its line voltage setting. When the item is returned, verify its line voltage setting with the voltage on the note before incorporating it into the system.

When the system is moved to a new location, before connecting the input power cord, verify that the system voltage setting is the same as the facility line voltage. When its necessary, adjust each instrument in the console to the correct voltage. Read each instrument manual provided for detail on voltage adjustment.

6.3 Electrical Ground Connection

All the instrument cases mounted in the electronic console are grounded to the ground lead of the power distribution strip through its input power cable. When you return the unit back to the console, and before turning on the power, verify that the original three conductor power cable is in place.

There is a safety ground cable built into the circular 8-pin connector for connection to the outer case of the measurement insert to the instrument console chassis. Low impedance connections are maintained for safety purposes. This safety ground connection should be reestablished and maintained if any service is performed on the cable or measurement insert.

6.4 Electrostatic Discharge

Electrostatic Discharge (ESD) may damage electronic parts, assemblies, and equipment. ESD is a transfer of electrostatic charge between bodies at different electrostatic potentials caused by direct contact or induced by an electrostatic field. The low-energy source that most commonly destroys Electrostatic Discharge sensitive devices is the human body, which generates and retains static electricity. Simply walking across a carpet in low humidity may generate up to 35,000 V of static electricity.

Current technology trends toward greater complexity, increased packaging density, and thinner dielectrics between active elements, which results in electronic devices with even more ESD sensitivity. Some electronic parts are more ESD sensitve than others. ESD levels of only a few hundred volts may damage electronic components such as semiconductors, thick and thin film resistors, and piezoelectric crystals during testing, handling, repair, or assembly. Discharge voltages below 4000 V cannot be seen, felt, or heard.

6.4.1 Identification of Electrostatic Discharge Sensitive Components

The following are various industry symbols used to label components as ESD sensitive.

FIGURE 6-1 ***Symbols indicating ESD sensitivity***

6.4.2 Handling Electrostatic Discharge Sensitive Components

Observe all precautions necessary to prevent damage to ESDS components before attempting installation. Bring the device and everything that contacts it to ground potential by providing a conductive surface and discharge paths. As a minimum, observe these precautions:

- De-energize or disconnect all power and signal sources and loads used with unit.
- Place unit on a grounded conductive work surface.
- Technician should be grounded through a conductive wrist strap (or other device) using 1 M series resistor to protect operator.
- Ground any tools, such as soldering equipment, that will contact unit. Contact with operator's hands provides a sufficient ground for tools that are otherwise electrically isolated.
- Place ESD sensitive devices and assemblies removed from a unit on a conductive work surface or in a conductive container. An operator inserting or removing a device or assembly from a container must maintain contact with a conductive portion of the container. Use only plastic bags approved for storage of ESD material.
- Do not handle ESD sensitive devices unnecessarily or remove them from the packages until they are actually used or tested.

6.5 Fuse Replacement

Fuses are installed in each instrument. When the fuse needs to be replaced, please read the particular instrument manual for instruction.

6.6 Measurement Insert Interlock Switch Pin Replacement for the CE Option

The Model 75013 safety interlock switch consists of two pogo pins in the header, and a stainless steel block in the light tight box. The safety switch is enabled when the light tight box is installed; thus, pins are electrically shorted across the block. The safety switch must be enabled before measurement can start. The pogo pins should be replaced when their tips become dull or they will have an unreliable connection to the stainless steel block in the light tight box. Refer to FIGURE 6-2 for the location of the pins.

Follow these steps to change the pins:

1. Hold one pin with small needle nose pliers.
2. Pull the pin straight out of its socket.
3. Repeat the steps 1 and 2 to remove the second pin.
4. Use gloved fingers pick up a new pin and slide it into its socket.
5. Use end of a wooden cotton swab against the tip of the pin and apply pressure straight on against the pin until it seats itself in the socket.
6. Repeat the steps 4 and 5 to seat the second pin (FIGURE 6-2).

CAUTION

The pins can be easily damaged. Do not use pliers to handle or install new pins, and do not manually exercise the pins. Side loading force can damage the pins. Dirt also can be wiped into the cavity and preventit from moving freely. Do not reuse the old pins as the process of pulling them out with pliers damages them.

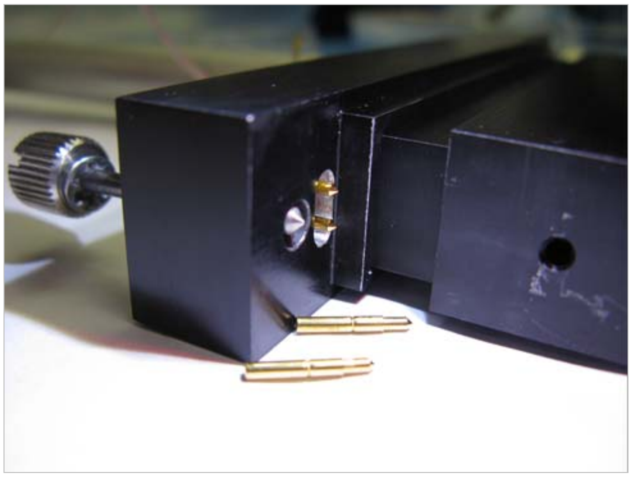
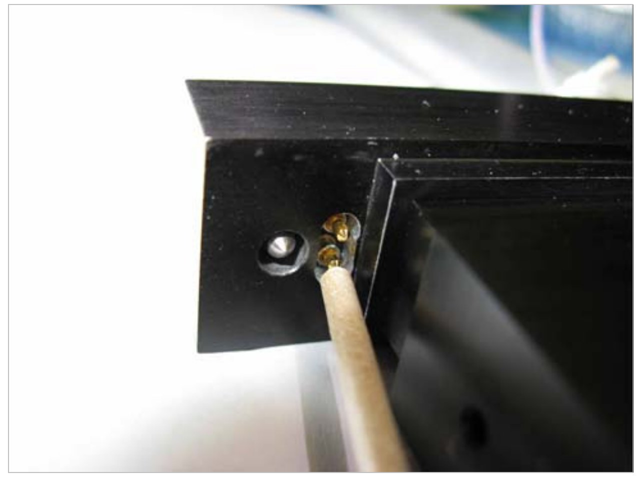



FIGURE 6-2 ***Measurement insert header with interlock pins***

6.7 Pin-Outs

Connector	Pin	Use	Wire resistance
B-1	1	Sample card pad #1	25
B-2	2	Sample card pad #2	25
B-3	3	Sample card pad #3	25
B-4	4	Sample card pad #4	25
B-5	5	Sample card pad #5, I+ for Hall bars	25
B-6	6	Sample card pad #6, I– for Hall bars	25
B-7 (10-pin)	A	Sample card pad #10; temperature sensor B, V–	8
	B	Sample card pad 9; temperature sensor B, V+	8
	C	Sample card pad 8; temperature sensor B, I–	8
	J	Sample card pad 7; temperature sensor B, I+	8
	D	Heater, 50 Ω in header block loop 1, I+	1
	E	Heater, 50 Ω in header block loop 1, I–	1
	G	Control temperature sensor A, V–	8
	H	Control temperature sensor A, V+	8
	F	Control temperature sensor A, I–	8
	K	Control temperature sensor A, I+	8
B-8 (4-pin)		Not used	—
B-10 (8-pin; for CE option only)	A	Safety interlock switch pin	1
	G	Safety interlock switch pin	1
	B	Safety ground	<1
	C	Safety ground	<1
	D	Safety ground	<1
	E	Safety ground	<1
	F	Ground	<1
	H	Not used	—

TABLE 6-1 ***Wire connections for Model 75013 SCSM***

Connector	Pin	Use	Wire resistance
B-1	1	Sample card pad #1	25
B-2	2	Sample card pad #2	25
B-3	3	Sample card pad #3	25
B-4	4	Sample card pad #4	25
B-5	5	Sample card pad #5, I+ for Hall bars	25
B-6	6	Sample card pad #6, I– for Hall bars	25
B-7 (10-pin)	A	Sample card pad #10; temperature sensor B, V–	8
	B	Sample card pad 9; temperature sensor B, V+	8
	C	Sample card pad 8; temperature sensor B, I–	8
	J	Sample card pad 7; temperature sensor B, I+	8
	D	Not used	—
	E	Not used	—
	G	Not used	—
	H	Not used	—
	F	Not used	—
	K	Not used	—
B-8 (4-pin)		Not used	—
B-10 (8-pin; for CE option only)	A	Safety interlock switch terminal	1
	G	Safety interlock switch terminal	1
	B	Safety ground	<1
	C	Safety ground	<1
	D	Safety ground	<1
	E	Safety ground	<1
	F	Ground	<1
	H	Not used	—

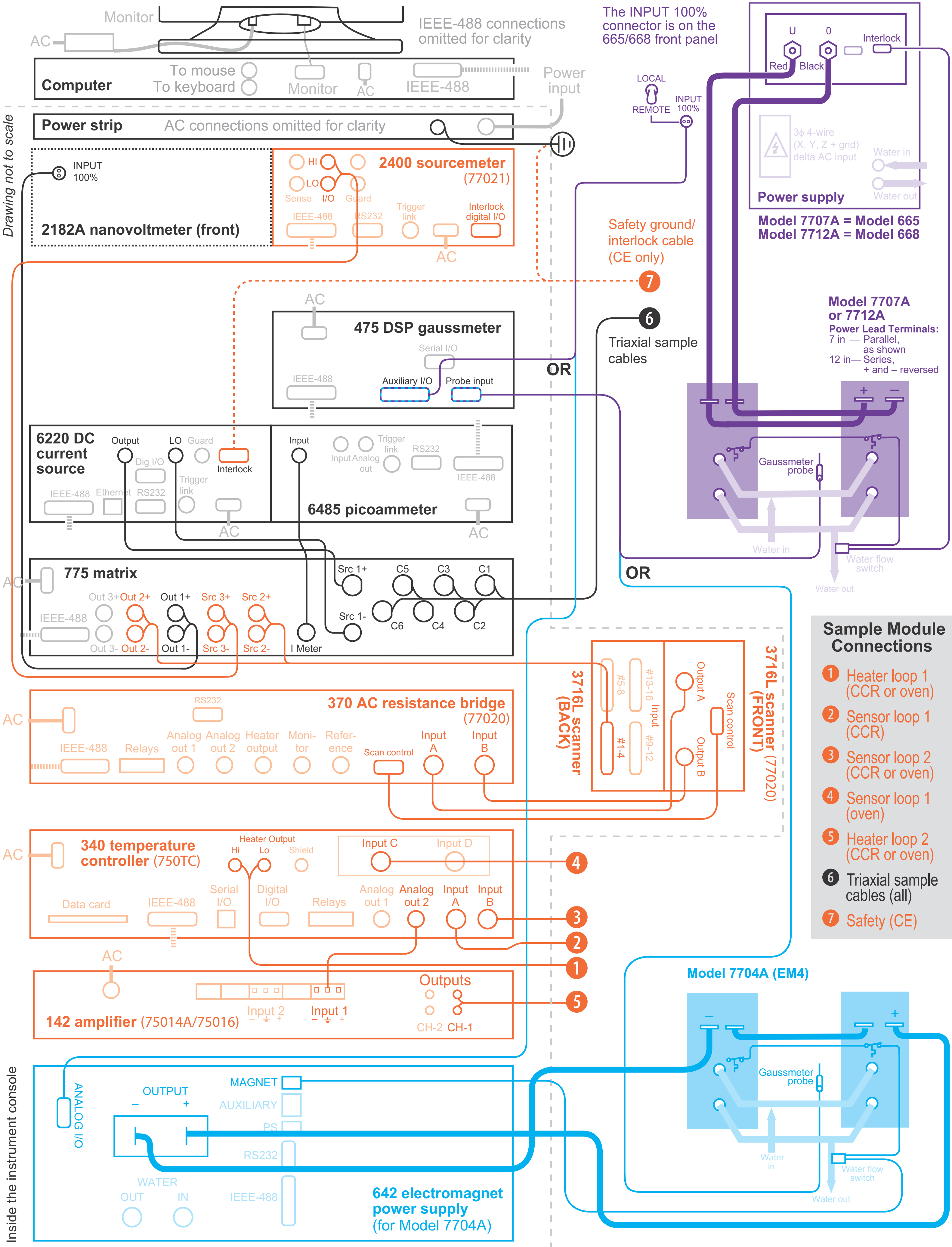
TABLE 6-2 ***Wire connections for Model 75014A CCRSM***

Connector	Pin	Use	Wire resistance
B-1	1	Sample card pad #1	2.5
B-2	2	Sample card pad #2	2.5
B-3	3	Sample card pad #3	2.5
B-4	4	Sample card pad #4	2.5
B-5	5	Sample card pad #5, I+ for Hall bars	2.5
B-6	6	Sample card pad #6, I– for Hall bars	2.5
B-7 (10-pin)	A	Sample card pad #10; temperature sensor B, V–	8
	B	Sample card pad 9; temperature sensor B, V+	8
	C	Sample card pad 8; temperature sensor B, I–	8
	J	Sample card pad 7; temperature sensor B, I+	8
	D	Heater, 50 Ω loop 2 I+	1
	E	Heater, 50 Ω loop 2, I–	1
	G	Not used	—
	H	Not used	—
	F	Not used	—
	K	Not used	—
B-8 (4-pin)		Not used	—
B-10 (8-pin; for CE option only)	A	Safety interlock switch pin	1
	G	Safety interlock switch pin	1
	B	Safety ground	<1
	C	Safety ground	<1
	D	Safety ground	<1
	E	Safety ground	<1
	F	Ground	<1
	H	Not used	—

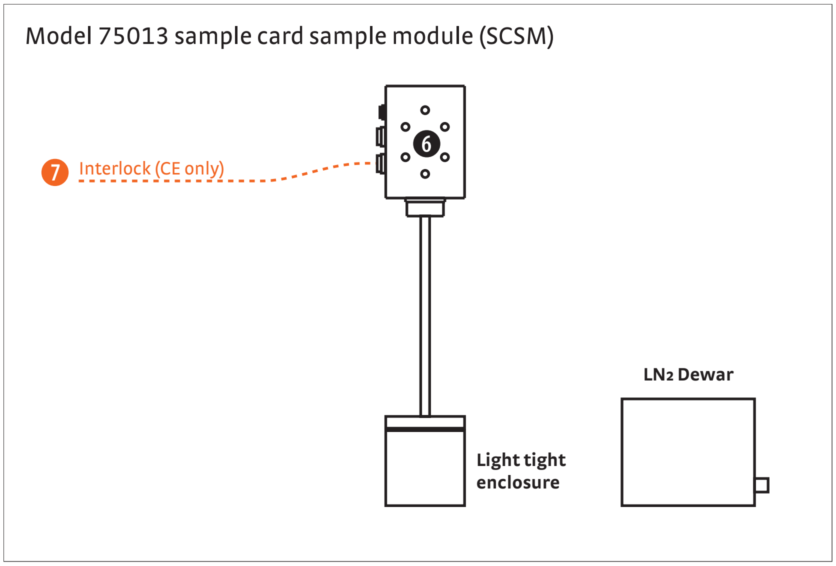
TABLE 6-3 ***Wire connections for Model 75016 OSM***

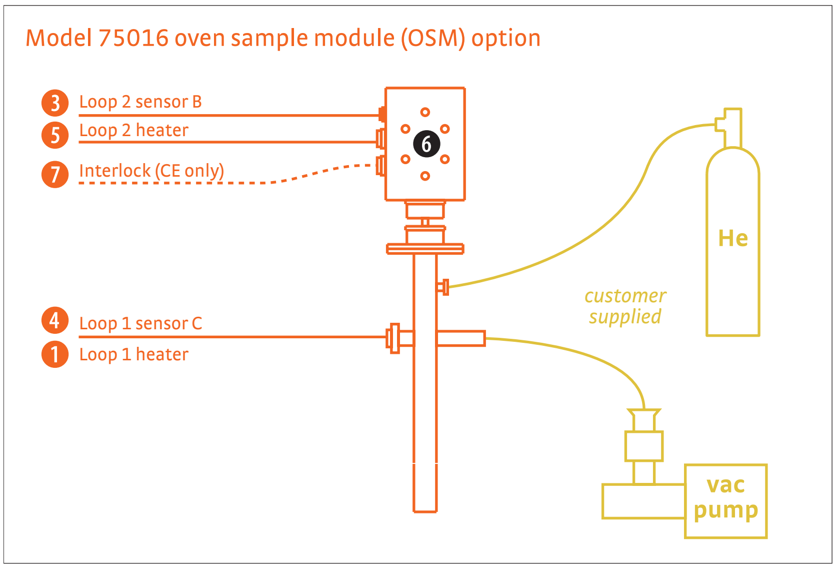
6.8 Wiring Diagram

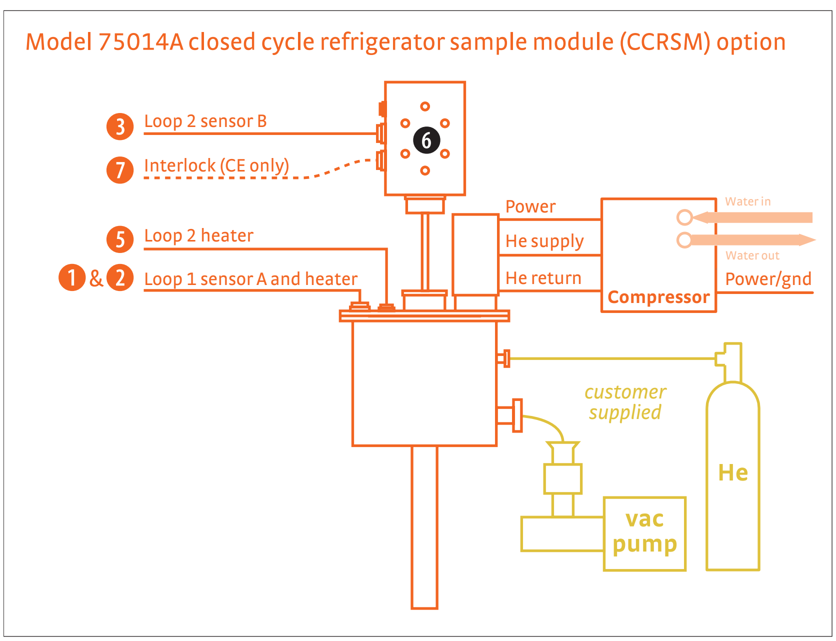
The wiring diagram for the Model 7700A Hall System is provided on the following two pages.

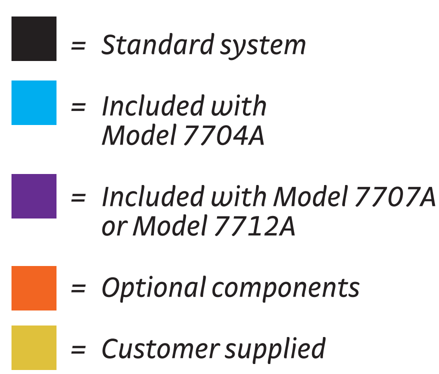


Monitor
AC
IEEE-488 connections omitted for clarity
Computer
To mouse
To keyboard
Monitor
AC
IEEE-488
Power input
Drawing not to scale
Power strip
AC connections omitted for clarity
INPUT 100%
2182A nanovoltmeter (front)
HI
LO
Sense
I/O
Guard
2400 sourcemeter
(77021)
IEEE-488
RS232
Trigger link
Interlock digital I/O
AC
The INPUT 100% connector is on the 665/668 front panel
LOCAL
REMOTE
INPUT 100%
U
0
Red
Black
Interlock
3ϕ 4-wire (X, Y, Z + gnd) delta AC input
Water in
Water out
Power supply
Model 7707A = Model 665
Model 7712A = Model 668
Safety ground/ interlock cable (CE only)
7
6
Triaxial sample cables
AC
475 DSP gaussmeter
Serial I/O
IEEE-488
Auxiliary I/O
Probe input
OR
Model 7707A or 7712A
Power Lead Terminals:
7 in — Parallel, as shown
12 in— Series, + and – reversed
6220 DC current source
Output
LO
Guard
Dig I/O
Interlock
Trigger link
IEEE-488
Ethernet
RS232
AC
Input
Trigger link
Input
Analog out
RS232
IEEE-488
6485 picoammeter
AC
Gaussmeter probe
Water in
Water flow switch
Water out
OR
AC
775 matrix
Src 1+
C5
C3
C1
Out 3+
Out 2+
Out 1+
Src 3+
Src 2+
IEEE-488
Src 1-
C6
C4
C2
Out 3-
Out 2-
Out 1-
Src 3-
Src 2-
I Meter
3716L scanner (BACK)
#5-8
#1-4
#13-16
#9-12
Input
Output A
Output B
Scan control
3716L scanner (FRONT) (77020)
AC
370 AC resistance bridge
(77020)
RS232
IEEE-488
Relays
Analog out 1
Analog out 2
Heater output
Moni-tor
Refer-ence
Scan control
Input A
Input B
Sample Module Connections
1 Heater loop 1 (CCR or oven)
2 Sensor loop 1 (CCR)
3 Sensor loop 2 (CCR or oven)
4 Sensor loop 1 (oven)
5 Heater loop 2 (CCR or oven)
6 Triaxial sample cables (all)
7 Safety (CE)
AC
340 temperature controller (750TC)
Heater Output
Hi
Lo
Shield
Input C
Input D
4
Data card
IEEE-488
Serial I/O
Digital I/O
Relays
Analog out 1
Analog out 2
Input A
Input B
3
2
AC
1
Outputs
5
142 amplifier (75014A/75016)
Input 2
Input 1
CH-2
CH-1
Model 7704A (EM4)
Inside the instrument console
ANALOG I/O
OUTPUT
MAGNET
AUXILIARY
PS
RS232
WATER
OUT
IN
IEEE-488
642 electromagnet power supply (for Model 7704A)
Gaussmeter probe
Water in
Water flow switch
Water out


Model 75013 sample card sample module (SCSM)
7 Interlock (CE only)
6
LN2 Dewar
Light tight
enclosure


Model 75016 oven sample module (OSM) option
3 Loop 2 sensor B
5 Loop 2 heater
7 Interlock (CE only)
6
He
customer
supplied
4 Loop 1 sensor C
1 Loop 1 heater
vac
pump


Model 75014A closed cycle refrigerator sample module (CCRSM) option
3 Loop 2 sensor B
7 Interlock (CE only)
6
Power
Water in
He supply
Water out
5 Loop 2 heater
He return
Power/gnd
1 & 2 Loop 1 sensor A and heater
Compressor
customer
supplied
He
vac
pump


= Standard system
= Included with
Model 7704A
= Included with Model 7707A
or Model 7712A
= Optional components
= Customer supplied

6.9 Technical Inquiries

Refer to the following sections when contacting Lake Shore for application assistance or product service.

6.9.1 Contacting Lake Shore

The Lake Shore Systems Service department is staffed Monday through Friday between the hours of 8:00 AM and 5:00 PM EST, excluding holidays and company shut down days.

Contact Lake Shore Systems Service through any of the means listed below. However, the most direct and efficient means of contacting is to complete the online service request form at http://www.lakeshore.com/sup/serf.html. Provide a detailed description of the problem and the required contact information. You will receive a response within 24 hours, or the next business day in the event of weekends or holidays.

If you wish to contact Systems Service by mail or telephone, use the following:

Lake Shore Cryotronics, Inc.
575 McCorkle Blvd.
Westerville, Ohio 43082 USA
Phone: 614-891-2243 (select the option for service)
Fax: 614-818-1608
e-mail: sysservice@lakeshore.com

6.9.2 Return of Equipment

The HMS is packaged to protect it during shipment. Please use reasonable care when removing it from its protective packaging and inspect the HMS carefully for damage. If it shows any sign of damage, please file a claim with the carrier immediately. Do not destroy the shipping container; it will be required by the carrier as evidence to support claims. Call Lake Shore for return and repair instructions.

All equipment returns must be approved by a member of the Lake Shore Systems Service department. The service engineer will use the information provided in the service request form and will issue a Return Material Authorization (RMA). Once the RMA has been approved, you will receive appropriate documents and instructions for shipping the equipment to Lake Shore.

You will be given an RMA number. This number is necessary for all returned equipment. It must be clearly indicated on both the shipping carton(s) and any correspondence relating to the shipment.

NOTE **The user should retain any shipping carton(s) in which equipment is originally received, in the event that any equipment needs to be returned.**

6.9.3 RMA Valid Period

RMAs are valid for 60 days from issuance; however, we suggest that equipment needing repair be shipped to Lake Shore within 30 days after the RMA has been issued. You will be contacted if we do not receive the equipment within 30 days after the RMA is issued. The RMA will be cancelled if we do not receive the equipment after 60 days.

6.9.4 Shipping Charges

All shipments to Lake Shore are to be made prepaid by the customer. Equipment serviced under warranty will also be returned shipping prepaid by the customer. Equipment serviced out-of-warranty will be returned FOB Lake Shore.

6.9.5 Restocking Fee

Lake Shore reserves the right to charge a restocking fee for items returned for exchange or reimbursement.

Appendix A: Hall Measurements

A.1 General

The model Hall effect system consists of a uniform slab of electrically conducting material through which a uniform current density flows in the presence of a perpendicular applied magnetic field. The Lorentz force deflects moving charge carriers to one side of the sample and generates an electric field perpendicular to both the current density and the applied magnetic field. The Hall coefficient is the ratio of the perpendicular electric field to the product of current density and magnetic field, while the resistivity is the ratio of the parallel electric field to the current density

Experimental determination of a real material's transport properties requires some significant departures from the ideal model. To begin with, one cannot directly measure the electrical field or current density inside a sample. Current density is determined from the total excitation current and the sample's geometry. Electric fields are determined by measuring voltage differences between electrical contacts on the sample surface.

Electrical contacts are made of conductive material, and usually have a higher conductivity than the sample material itself. Electric current therefore tends to flow through the contacts rather than the sample, distorting the current density and electric field in the sample from the ideal. Excitation current flowing through the contacts used to measure voltage differences reduces both current density in the vicinity and the Hall field. If a contact extends across the sample in the same direction as the Hall field, it can conduct current from one side of the sample to the other, shorting out the Hall voltage and leading to an underestimate of the Hall coefficient. Finally, if pairs of contacts used in a voltage measurement are not aligned properly either perpendicular or parallel to the excitation current density, then the voltages measured will not correctly determine the perpendicular or parallel component of the electric field. To minimize these geometrical problems, one must take care with the size and placement of electrical contacts to the sample.

There are also many intrinsic physical mechanisms that alter current density and electric field behavior in a real material. Most of these relate to the thermoelectric behavior of the material in or out of a magnetic field. Some of these effects can be minimized by controlling temperature in the sample's vicinity to minimize thermal gradients across it. In addition, most errors introduced by intrinsic physical mechanisms can be canceled by reversing either the excitation current or the magnetic field and averaging measurements.

A.2 Anomalous Hall Effect

In a Hall effect measurement, there are three Hall voltage (V_H) components,

1) $V_H = (R_H I/t)B\cos(\alpha) + (\mu_o R_s I/t)M\cos(\theta) + (kI/t)M^2\sin^2(\theta)\sin(2\phi)$

where t = film thickness, and the angles α, θ and ϕ are defined in figure A-1. The first term in equation (1) is the ordinary Hall effect (OHE) and arises from the Lorentz force acting on conduction electrons. The OHE depends on the z-component of the B field, and produces an electric field perpendicular to B_z and the current density. The second term is the anomalous Hall effect (AHE) and arises due to spin dependent scattering mechanisms. The AHE depends on the perpendicular component of M, and produces an electric field perpendicular to M_z and the current density. The last term in (1) is the planar Hall effect (PHE), or anisotropic magnetoresistance. The PHE is proportional to the square of the planar component of M, and produces an electric field parallel and perpendicular to the current. The third term in (1) is the component that is perpendicular to the current. Note that all three terms in (1) are inversely proportional to the film thickness t.

A.3 Hall Effect Measurement Theory

Hall effect measurements commonly use two sample geometries: (1) long, narrow Hall bar geometries and (2) nearly square or circular van der Pauw geometries. Each has advantages and disadvantages. In both types of samples, a Hall voltage is developed perpendicular to a current and an applied magnetic flux. The following is an introduction to the Hall effect and its use in materials characterization. A number of other sources are available for further information[1,2,3,4]. Some common Hall bar geometries are shown in FIGURE A-1.

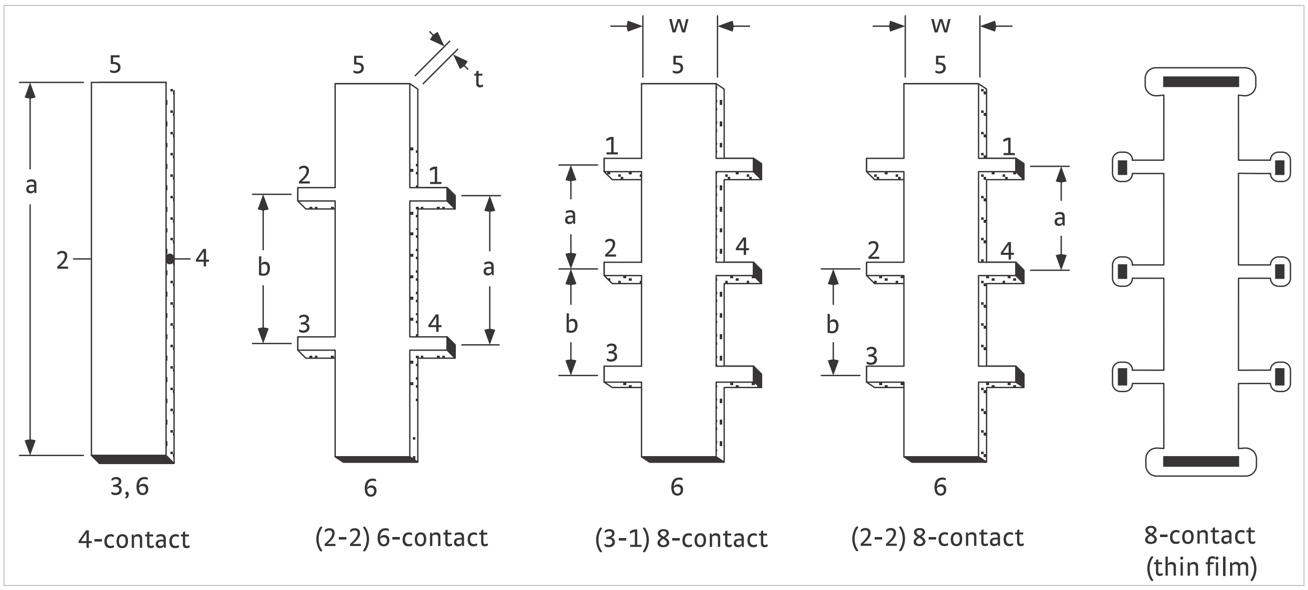


FIGURE A-1 ***Common Hall bar geometries. Sample thickness, t, of a thin film sample = diffusion depth or layer thickness. Contacts are black, numbered according to the standard to mount in Lake Shore sample holders***

A.3.1 Hall Bar Geometry

The Hall voltage developed across an 8-contact Hall bar sample with contacts numbered as in FIGURE A-1 is:

$$V_H = V_{24} = \frac{R_H BI}{t}$$

In this equation, V_{24} is the voltage measured between the opposing contacts numbered 2 and 4, R_H is the Hall coefficient of the material, B is the applied magnetic flux density, I is the current, and t is the thickness of the sample (in the direction parallel to B). This section assumes SI units. For a given material, increase the Hall voltage by increasing B and I and by decreasing sample thickness.

The relationship between the Hall coefficient and the type and density of charge carriers can be complex, but useful insight can be developed by examining the limit $B \rightarrow \infty$, when:

$$VR_H = \frac{r}{q(p-n)}$$

In this equation, r is the Hall scattering factor, q is the fundamental electric charge, p is the density of positive, and n the density of negative charge carriers in the material. For the case of a material with one dominant carrier, the Hall coefficient is inversely proportional to the carrier density. The measurement implication is that the greater the density of dominant charge carriers, the smaller the Hall coefficient and the smaller the Hall voltage which must be measured. The scattering factor r depends on the scattering mechanisms in the material and typically lies between 1 and 2.[1,5]

Another quantity frequently of interest is the carrier mobility, defined as:

$$\mu_H = \frac{|R_H|}{\rho}$$

In this equation, μ_H is the Hall mobility and ρ is the electrical resistivity at zero magnetic flux density. The electrical resistivity can be measured by applying a current between contacts 5 and 6 of the sample shown in FIGURE A-1, and measuring the voltage between contacts 1 and 3, then using this formula:

$$\rho(B) = \frac{V_{13}wt}{I_{56}B}$$

In this equation, w is the width and t is the thickness of the Hall bar, b is the distance between contacts 1-3, and B is the magnetic flux density at which the measurement is taken.

A.3.2 Advantages and Disadvantages of Hall Bar Geometries

The Hall bar is a good geometry for making resistance measurements since about half of the voltage applied across the sample appears between the voltage measurement contacts. For this reason, Hall bars of similar geometries are commonly used when measuring magnetoresistance or Hall mobility on samples with low resistances.

Disadvantages of Hall bar geometries include the following: A minimum of six contacts to make mobility measurements; accuracy of resistivity measurements is sensitive to the geometry of the sample; Hall bar width and the distance between the side contacts can be especially difficult to measure accurately. The accuracy can be increased by making contact to the sides of the bar at the end of extended arms as shown in Figure A-2. Creating such patterns can be difficult and can result in fragile samples.

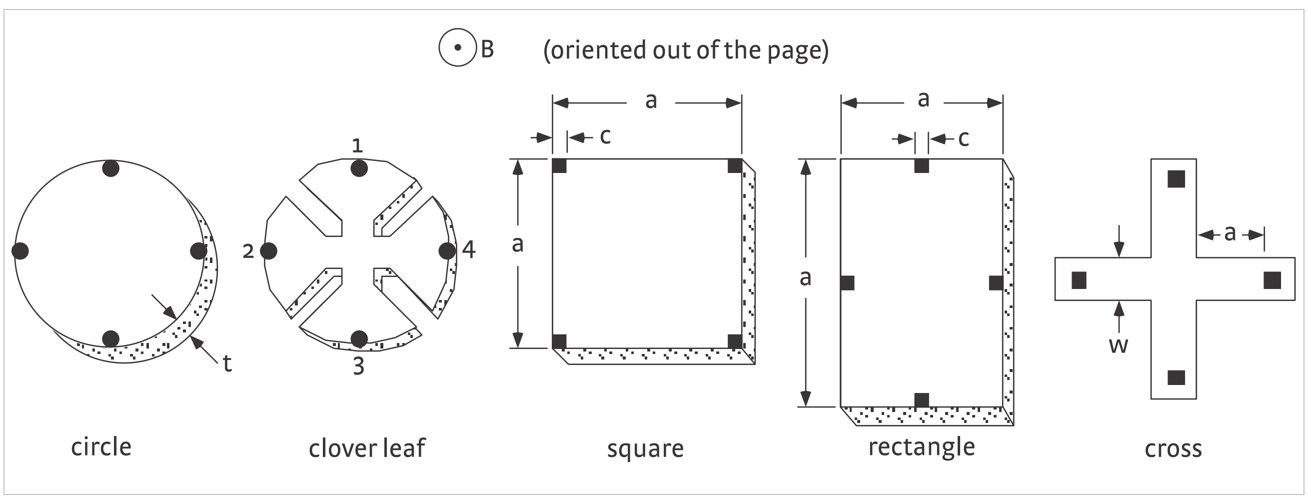


FIGURE A-2 ***Common van der Pauw sample geometries. The cross appears as thin film pattern and the others are bulk samples. Contacts are black.***

A.3.3 Van der Pauw Geometry

Some disadvantages of Hall bar geometries can be avoided with van der Pauw sample geometries (FIGURE A-2). Van der Pauw [5,6] showed how to calculate the resistivity, carrier concentration, and mobility of an arbitrary, flat sample if the following conditions are met:

- The contacts are on the circumference of the sample
- The contacts are sufficiently small
- The sample is of uniform thickness
- The sample is singly connected (contains no isolated holes)

The resistivity of a van der Pauw sample is given by the expression:

$$\rho = \frac{\pi t}{1n(2)} \frac{V_{43}}{I_{12}} + \frac{V_{14}}{I_{23}}$$

In this equation, V_{43} is defined as $V_4 - V_3$ and I_{12} indicates the current enters the sample through contact 1 and leaves through contact 2. Two voltage readings are required with the van der Pauw sample, whereas the resistivity measurement on a Hall bar requires only one. This same requirement applies to Hall coefficient measurement as well, so equivalent measurements take twice as long with van der Pauw samples.

The quantity F is a transcendental function of the ratio R_r, and R_r is defined as the greater of these two:

$$Rr \equiv \frac{V_{43}}{I_{12}} \frac{I_{23}}{V_{14}} \equiv \frac{R_{12,\,43}}{R_{23,\,14}} \quad \text{or} \quad Rr \equiv \frac{I_{12}}{V_{43}} \frac{V_{14}}{I_{23}} \equiv \frac{R_{23,\,14}}{R_{12,\,43}}$$

F is found by solving the equation:

$$\frac{Rr-1}{Rr+1} = \frac{F}{ln(2)} ar\cosh\left\{\frac{\exp[ln(2)/F]}{2}\right\}$$

In this equation, F=1 when R_r=1, which occurs with symmetrical samples like circles or squares when the contacts are equally spaced and symmetrical. The best measurement accuracy is also obtained when R_r =1.

Squares and circles are the most common van der Pauw geometries, but contact size and placement can significantly effect measurement accuracy. A few simple cases were treated by van der Pauw. Others have shown that for square samples with sides of length a and square or triangular contacts of size δ in the four corners, if $\delta/a < 0.1$, then the measurement error is less than 10%[6]. The error is reduced by placing the contacts on square samples at the midpoint of the sides rather than in the corners[7].

The Greek cross shown in FIGURE A-2 has arms which serve to isolate the contacts from the active region. When using the Greek cross sample geometry with $a/w > 1.02$, less than 1% error is introduced[8]. A cloverleaf shaped structure like the one shown in FIGURE A-2 is often used for a patternable thin film on a substrate. The active area in the center is connected by four pathways to four connection pads around its perimeter. This shape makes the measurement much less sensitive to contact size, allowing for larger contact areas.

The contact size affects voltage required to pass a current between two contacts. Ideal point contacts would produce no error due to contact size, but require an enormous voltage to force the current through the infinitesimal contact area. Even with square contacts in the corners of a square sample with $\delta/a < 0.1$, the ratio of the output to input voltage V_{43}, V_{12} is on the order of 1/10. Van der Pauw sample geometries are thus much less efficient at using the available excitation voltage than Hall bars.

A.3.4 Advantages and Disadvantages of Van der Pauw Samples

Advantages of van der Pauw samples: only four contacts are required. There is no need to measure sample widths or distances between contacts. Simple geometries can be used.

Disadvantages of van der Pauw samples: measurements take about twice as long. Errors due to contact size and placement can be significant when using simple geometries.

Mobility spectra: Hall effect measurements are usually performed at just one magnetic flux density, although the polarity is reversed and the voltage readings are averaged to remove some sources of error. The resulting single mobility calculated from the measurements is a weighted average of the mobilities of all carriers present in the sample. Beck and Anderson[9] developed a technique for interpreting magnetic flux-dependent Hall data which generates a mobility spectrum. The result is a plot of the carrier concentration of conductivity as a function of the mobility. The number of peaks appearing in a mobility spectrum indicates the number of distinct charge carriers active in the material. This powerful technique has virtually eliminated the need for destructive testing techniques such as differential profiling. An example mobility spectrum analysis performed on a GaAs/AlGaAs five-quantum-well heterostructure is shown in Figure 2-9 of their paper.

A technique combining mobility spectrum analysis and multi-carrier fitting was developed by Brugger and Kosser[10], yielding some improvement. The development of quantitative mobility spectrum analysis by Antoszewski et al.[2,11,12,13] has produced even greater improvements in capability.

A.4 Sample Geometries and Measurements Supported by IDEAS Hall Software

This section describes common sample geometries useful in the Lake Shore Hall measurement system and formulas used to calculate resistivities, Hall coefficients, carrier concentrations, and mobilities.

A.4.1 System of Units

Hall effect and magnetoresistance measurements commonly use two systems of units: the SI system and the “laboratory” system. The laboratory system is a hybrid, combining elements of the SI, emu, and esu unit systems. Table A-1 lists the most common quantities, their symbols, their units in both systems, and the conversion factor between them.

Quantity	Symbol	SI	=Factor x	Laboratory
Capacitance	C	F	1	F
Carrier concentration	c,n,p	m^{-3}	10^{-6}	cm^{-3}
Charge	q, e	C	1	C
Conductivity (volume)	σ	$(\Omega\ m)^{-1}$	10^{-2}	$(\Omega\ cm)^{-1}$
Current	I	A	1	A
Current density	j	A/m^2	10^{-4}	A/cm^2
Electric field intensity	E	V/m	10^{-2}	V/cm
Hall coefficient	R_H	m^3/C	10^6	cm^3/C
Magnetic induction	B	T (= V s/m^2)	10^4	G
Mobility	μ_H	m^2/V s	10^4	cm^2/V s
Electric potential	V	V	1	V
Resistivity	ρ	Ω m	10^2	Ω cm

TABLE A-1 ***Unit systems and conversions. To use this table, 1 SI unit = (factor) × 1 laboratory unity. For example, 1 T = 10^4 G.***

A.4.2 Nomenclature

The equations below appear twice—once in SI units, once in laboratory units. In all cases, voltages are measured in volts, electric currents are measured in amperes, and resistances are measured in ohms. All other measured quantities appear with their respective unit in brackets. For example, the width of a sample in SI units appears as w[m]. The equations below indicate voltages and currents as follows:

A.4.2.1 Voltage Nomenclature

$V^{\pm}_{ij,\,kl}(\pm B)$ indicates a voltage difference $V_k - V_l$ measured between terminals k and l. Terminal i is connected to the excitation current source and terminal j is connected to the current sink.

The superscript ± indicates the sign of the excitation current supplied by the current source. The symbol $\pm B$ indicates the sign of the applied magnetic induction B, measured in the direction shown on the drawings.

Example: $V^{-}_{56,\,12}(+B)$ indicates a voltage difference measured while a negative current was supplied by a current source at terminal 5 and flowed to terminal 6, in the presence of a positive applied magnetic induction.

A.4.2.2 Current Nomenclature

$I^{\pm}_{ij}(\pm B)$ indicates a current flowing from terminal i to terminal j of polarity given by the superscript ± and with the indicated magnetic field polarity.

A.4.3 Van der Pauw Measurements

The van der Pauw structure is probably the most popular Hall measurement geometry, primarily because it requires fewer geometrical measurements of the sample. In 1958, van der Pauw[13] solved the general problem of the potential in a thin conducting layer of arbitrary shape. His solution allowed Hall and resistivity measurements to be made on any sample of uniform thickness, provided that the sample was homogeneous and there were no holes in it. All that is needed to calculate *sheet* resistivity or carrier concentration is four point contacts on the edge of the surface (or four line contacts on the periphery); an additional measurement of sample thickness allows calculation of volume resistivity and carrier concentration. These relaxed requirements on sample shape simplify fabrication and measurement in comparison to Hall bar techniques.

On the other hand, the van der Pauw structure is more susceptible to errors caused by the finite size of the contacts than the Hall bar. It is also impossible to accurately measure magnetoresistance with the van der Pauw geometry, so both Hall effect and magnetoresistance (i.e. the whole conductivity tensor) measurements must be done with a Hall bar geometry.

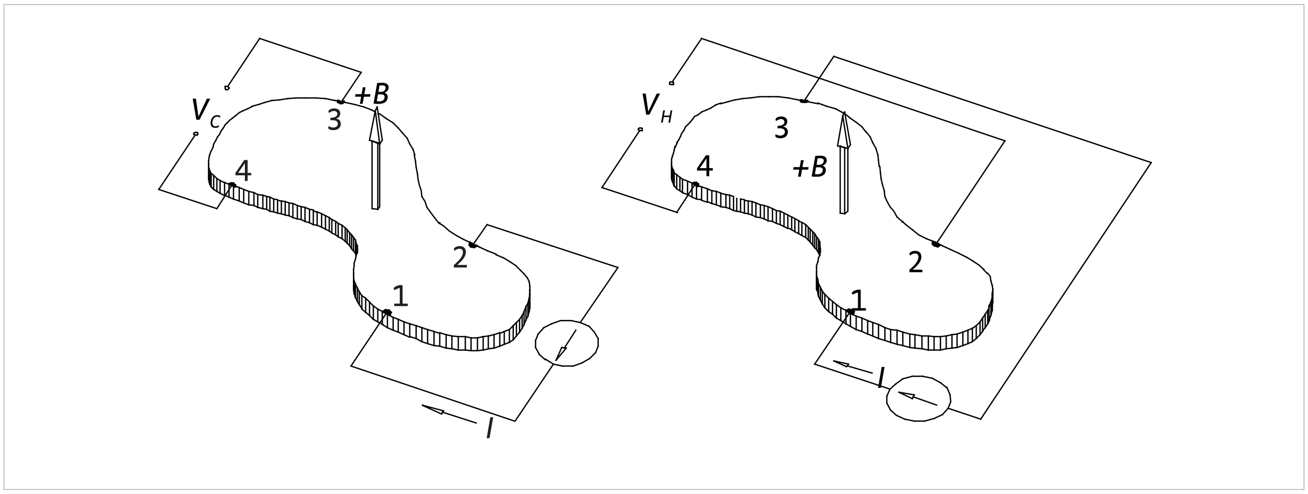


FIGURE A-3 ***Measuring resistivity and Hall coefficient using a van der Pauw geometry***

In the basic van der Pauw contact arrangement, the four contacts made to the sample are numbered counterclockwise in ascending order when the sample is viewed from above with the magnetic field perpendicular to the sample and pointing toward the observer. The sample interior should contain no contacts or holes. The sample must be homogeneous and of uniform thickness.

A.4.3.1 Resistivity

Again, let V^+_{ijkl} indicate a voltage measured across terminals k and l, with k positive, while a positive current flows into terminal i and out of terminal j. In a similar fashion, let R^+_{ijkl} indicate a resistance $R^+_{ijkl} = V_{kl} / I_{ij}$, with the voltage measured across terminals k and l, while a positive current flows into i and out of j. First calculate the two resistivities:

$$\rho_A = \frac{\pi f_A t[m, cm]}{ln(2)}\left\{\frac{V^+_{12,43} - V^-_{12,43} + V^+_{23,14} - V^-_{23,14}}{I^+_{12} - I^-_{12} + I^+_{23} - I^-_{23}}\right\}[\Omega \cdot m, \Omega \cdot cm]$$

and

$$\rho_B = \frac{\pi f_B t[m, cm]}{ln(2)}\left\{\frac{V^+_{34,21} - V^-_{34,21} + V^+_{41,23} - V^-_{41,23}}{I^+_{34} - I^-_{34} + I^+_{41} - I^-_{41}}\right\}[\Omega \cdot m, \Omega \cdot cm]$$

Geometrical factors f_A and f_B are functions of resistance ratios Q_A and Q_B, respectively, given by:

$$Q_A = \left(\frac{R^+_{12,43} - R^-_{12,43}}{R^+_{23,14} - R^-_{23,14}}\right) = \left(\frac{V^+_{12,43} - V^-_{12,43}}{I^+_{12} - I^-_{12}}\right)\left(\frac{I^+_{23} - I^-_{23}}{V^+_{23,14} - V^-_{23,14}}\right)$$

and

$$Q_B = \left(\frac{R^+_{34,21} - R^-_{34,21}}{R^+_{41,23} - R^-_{41,23}}\right) = \left(\frac{V^+_{34,21} - V^-_{34,21}}{I^+_{34} - I^-_{34}}\right)\left(\frac{I^+_{41} - I^-_{41}}{V^+_{41,23} - V^-_{41,23}}\right)$$

If either or is greater than one, then use the reciprocal instead. The relationship between f and Q is expressed by this transcendental equation which can be solved numerically:

$$\frac{Q-1}{Q+1} = \frac{f}{ln2}\cosh^{-1}\left\{\frac{1}{2}\exp\left[\frac{ln2}{f}\right]\right\}$$

The two resistivities ρ_A and ρ_B should agree to within ±10%. If they do not, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do agree, the average resistivity is given by

$$Q_A = \left(\frac{R^+_{12,43} - R^-_{12,43}}{R^+_{23,14} - R^-_{23,14}}\right) = \left(\frac{V^+_{12,43} - V^-_{12,43}}{I^+_{12} - I^-_{12}}\right)\left(\frac{I^+_{23} - I^-_{23}}{V^+_{23,14} - V^-_{23,14}}\right),$$

and

$$Q_B = \left(\frac{R^+_{34,21} - R^-_{34,21}}{R^+_{41,23} - R^-_{41,23}}\right) = \left(\frac{V^+_{34,21} - V^-_{34,21}}{I^+_{34} - I^-_{34}}\right)\left(\frac{I^+_{41} - I^-_{41}}{V^+_{41,23} - V^-_{41,23}}\right).$$

If either Q_A or Q_B is greater than one, then use the reciprocal instead. The relationship between f and Q is expressed by the transcendental equation

$$\frac{Q-1}{Q+1} = \frac{f}{\ln 2}\cosh^{-1}\left\{\frac{1}{2}\exp\left[\frac{\ln 2}{f}\right]\right\},$$

which can be solved numerically.The two resistivities ρ_A and ρ_B should agree to within ±10%. If they do not, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do agree, the average resistivity is given by

$$\rho_{av} = \frac{\rho_A + \rho_B}{2} \quad [\Omega \cdot \mathrm{m}, \Omega \cdot \mathrm{cm}].$$

A.4.3.2 Magnetoresistivity

If desired, calculate the magnetoresistivity as

$$\rho_A(B) = \frac{\pi f_A t[m, cm]}{ln(2)} \cdot \frac{V^+_{12,43}(+B) - V^-_{12,43}(+B) + V^+_{23,41}(+B) - V^-_{23,41}(+B)}{I^+_{12}(+B) - I^-_{12}(+B) + I^+_{23}(+B) - I^-_{23}(+B)} + \frac{V^+_{12,43}(-B) - V^-_{12,43}(-B) + V^+_{23,41}(-B) - V^-_{23,41}(-B)}{I^+_{12}(-B) - I^-_{12}(-B) + I^+_{23}(-B) - I^-_{23}(-B)}[\Omega \cdot m, \Omega \cdot cm]$$

and

$$\rho_B(B) = \frac{\pi f_B t[m, cm]}{ln(2)} \frac{V^+_{34,21}(+B) - V^-_{34,21}(+B) + V^+_{41,23}(+B) - V^-_{41,23}(+B)}{I^+_{34}(+B) - I^-_{34}(+B) + I^+_{41}(+B) - I^-_{41}(+B)} + \frac{V^+_{34,21}(-B) - V^-_{34,21}(-B) + V^+_{41,23}(-B) - V^-_{41,23}(-B)}{I^+_{34}(-B) - I^-_{34}(-B) + I^+_{41}(-B) - I^-_{41}(-B)}[\Omega \cdot m, \Omega \cdot cm]$$

Calculate factors f_A and f_B the same way as at zero magnetic field, and the average magnetoresistivity is:

$$\rho\alpha(B) = \frac{\rho_A(B) + \rho_B(B)}{2}[\Omega \cdot m], [\Omega \cdot cm]$$

This measurement does not give the true magnetoresistance, as defined in terms of the material's conductivity tensor. Van der Pauw's calculation of resistivity is invalid in the presence of a magnetic field, since the magnetic field alters the current density vector field inside the sample. On the other hand, magnetoresistance measurements are routinely performed on van der Pauw samples anyway.

A.4.3.3 Hall Coefficient

Calculate two values of the Hall coefficient by the following:

$$R_{HC} = \frac{t[m]}{B[T]} \cdot \frac{V^+_{31,42}(+B) - V^-_{31,42}(+B) + V^-_{31,42}(-B) - V^+_{31,42}(-B)}{I^+_{31}(+B) - I^-_{31}(+B) + I^-_{31}(-B) - I^+_{31}(-B)}[m^3 \cdot C^{-1}]$$
$$= 10^8 \frac{t[cm]}{B[gauss]} \frac{V^+_{31,42}(+B) - V^-_{31,42}(+B) + V^-_{31,42}(-B) - V^+_{31,42}(-B)}{I^+_{31}(+B) - I^-_{31}(+B) + I^-_{31}(-B) - I^+_{31}(-B)}[cm^3 \cdot C^{-1}]$$

and

$$R_{HD} = \frac{t[m]}{B[T]} \cdot \frac{V^+_{42,13}(+B) - V^-_{42,13}(+B) + V^-_{42,13}(-B) - V^+_{42,13}(-B)}{I^+_{42}(+B) - I^-_{42}(+B) + I^-_{42}(-B) - I^+_{42}(-B)}[m^3 \cdot C^{-1}]$$
$$= 10^8 \frac{t[cm]}{B[gauss]} \frac{V^+_{42,13}(+B) - V^-_{42,13}(+B) + V^-_{42,13}(-B) - V^+_{42,13}(-B)}{I^+_{42}(+B) - I^-_{42}(+B) + I^-_{42}(-B) - I^+_{42}(-B)}[cm^3 \cdot C^{-1}]$$

These two should agree to within ±10%. If they do not, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do, then the average Hall coefficient can be calculated by

$$R_{HAV} = \frac{R_{HC} + R_{HD}}{2}[m^3 \cdot C^{-1}, cm^3 \cdot C^{-1}] .$$

A.4.3.4 Hall Mobility

The Hall mobility is given by

$$\mu_H = \frac{|R_{Hav}|}{\rho_{av}}[m^2 \cdot V^{-1} \cdot s^{-1}, cm^2 \cdot V^{-1} \cdot s^{-1}]$$

where ρ_{av} is the magnetoresistivity if it was measured, and the zero-field resistivity if it was not.

A.4.4 Hall Bar Measurements

Hall bars approximate the ideal geometry for measuring the Hall effect, in which a constant current density flows along the long axis of a rectangular solid, perpendicular to an applied external magnetic field.

A.4.4.1 Six-contact 1-2-2-1 Hall Bar

An ideal six-contact 1-2-2-1 Hall bar geometry is symmetrical. Contact separations *a* and *b* on either side of the sample are equal, with contacts located opposite one another. Contact pairs are placed symmetrically about the midpoint of the sample's long axis.

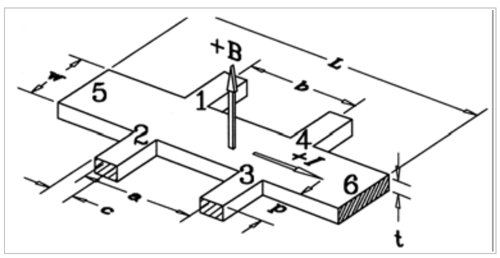


FIGURE A-4 ***Six-contact 1-2-2-1 Hall bar geometry***

This geometry allows two equivalent measurement sets to check for sample homogeneity in both resistivity and Hall coefficient. However, the close location of the Hall voltage contacts to the sample ends may cause the end contacts to short out the Hall voltage, leading to an underestimate of the actual Hall coefficient. While the 1-2-2-1 Hall bar geometry is included in ASTM Standard F76, the contact numbering given here differs from the standard.

A.4.4.1.1 Resistivity

To calculate resistivity at zero field, first calculate

$$\rho_A = \frac{V^+_{56,\,23}(B=0) - V^-_{56,\,23}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \cdot \frac{w[m]t[m]}{a[m]}[\Omega \cdot m]$$
$$= \frac{V^+_{56,\,23}(B=0) - V^-_{56,\,23}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \cdot \frac{w[cm]t[cm]}{a[cm]}[\Omega \cdot cm]$$

and

$$\rho_B = \frac{V^+_{56,\,14}(B=0) - V^-_{56,\,14}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \cdot \frac{w[m]t[m]}{b[m]}[\Omega \cdot m]$$
$$= \frac{V^+_{56,\,14}(B=0) - V^-_{56,\,14}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \cdot \frac{w[cm]t[cm]}{b[cm]}[\Omega \cdot cm]$$

These two resistivities should agree to within ±10%. If they do not, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do, then the average resistivity is given by

$$\rho_{av} = \frac{P_A + P_B}{2}[\Omega \cdot m, \Omega \cdot cm] .$$

A.4.4.1.2 Magnetoresistivity

Magnetoresistivity is typically used in mobility spectrum calculations, but not in Hall mobility calculations. To calculate magnetoresistivity, first calculate

$$\rho_A(B) = \frac{V^+_{56,23}(+B) - V^-_{56,23}(+B) + V^+_{56,23}(-B) - V^-_{56,23}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[m]t[m]}{a[m]}[\Omega \cdot m]$$
$$= \frac{V^+_{56,23}(+B) - V^-_{56,23}(+B) + V^+_{56,23}(-B) - V^-_{56,23}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[cm]t[cm]}{a[cm]}[\Omega \cdot cm]$$

and

$$\rho_B(B) = \frac{V^+_{56,14}(+B) - V^-_{56,14}(+B) + V^+_{56,14}(-B) - V^-_{56,14}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[m]t[m]}{b[m]}[\Omega \cdot m]$$
$$= \frac{V^+_{56,14}(+B) - V^-_{56,14}(+B) + V^+_{56,14}(-B) - V^-_{56,14}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[cm]t[cm]}{b[cm]}[\Omega \cdot cm]$$

These two resistivities should agree to within ±10%. If they do not, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do, then the average magnetoresistivity is given by

$$\rho_{av}(B) = \frac{P_A(B) + P_B(B)}{2}[\Omega \cdot m, \Omega \cdot cm]$$

A.4.4.1.3 Hall Coefficient

First, calculate the individual Hall coefficients

$$R_{HA} = \frac{t[m]}{B[T]} \cdot \frac{V^+_{56,34}(+B) - V^-_{56,34}(+B) + V^-_{56,34}(-B) - V^+_{56,34}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)}[m^3 \cdot C^{-1}]$$
$$= 10^8 \frac{t[cm]}{B[gauss]} \frac{V^+_{56,34}(+B) - V^-_{56,34}(+B) + V^-_{56,34}(-B) - V^+_{56,34}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)}[cm^3 \cdot C^{-1}]$$

and

$$R_{HB} = \frac{t[m]}{B[T]} \cdot \frac{V^+_{56,21}(+B) - V^-_{56,21}(+B) + V^-_{56,21}(-B) - V^+_{56,21}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)}[m^3 \cdot C^{-1}]$$
$$= 10^8 \frac{t[cm]}{B[gauss]} \frac{V^+_{56,21}(+B) - V^-_{56,21}(+B) + V^-_{56,21}(-B) - V^+_{56,21}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)}[cm^3 \cdot C^{-1}]$$

If R_{HA} and R_{HB} do not agree to within ±10%, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do agree, then the average Hall coefficient is given by

$$R_{HA} = \frac{R_{HA} + R_{HB}}{2}[m^3 \cdot C^{-1}, cm^3 \cdot C^{-1}]$$

A.4.4.1.4 Hall Mobility

$\mu_H = \frac{|R_{HAV}|}{\rho_{av}}[m^2 \cdot V^{-1} \cdot s^{-1}, cm^2 \cdot V^{-1} \cdot s^{-1}]$ gives the Hall mobility where $\rho\alpha v$ is the zero-field resistivity.

A.4.4.2 Six-Contact 1-3-1-1 Hall Bar

The ideal 1-3-1-1 Hall bar geometry places contacts 2 and 4 directly across from one another in the exact middle of the sample's length and contacts 1 and 3 symmetrically on either side of contact 2.

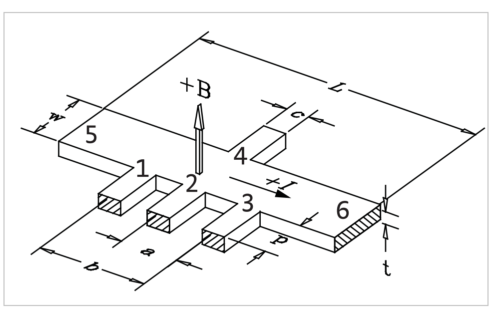


FIGURE A-5 ***Six-contact 1-3-1-1 Hall bar geometry***

This geometry allows no homogeneity checks, but measuring the Hall voltage in the exact center of the sample's length helps minimize the shorting of the Hall voltage via the end contacts. The 1-3-1-1 Hall bar is not included in ASTM Standard F76.

A.4.4.2.1 Resistivity

Calculate the resistivity at zero field by

$$\rho = \frac{V^{+}_{56,13}(B=0) - V^{-}_{56,13}(B=0)}{I^{+}_{56}(B=0) - I^{-}_{56}(B=0)} \frac{w[m]t[m]}{b[m]} [\Omega \cdot m]$$
$$= \frac{V^{+}_{56,13}(B=0) - V^{-}_{56,13}(B=0)}{I^{+}_{56}(B=0) - I^{-}_{56}(B=0)} \frac{w[cm]t[cm]}{b[cm]} [\Omega \cdot cm]$$

A.4.4.2.2 Magnetoresistivity

If desired, calculate the magnetoresistivity by

$$\rho(B) = \frac{V^{+}_{56,13}(+B) - V^{-}_{56,13}(+B) + V^{+}_{56,13}(-B) - V^{-}_{56,13}(-B)}{I^{+}_{56}(+B) - I^{-}_{56}(+B) + I^{+}_{56}(-B) - I^{-}_{56}(-B)} \frac{w[m]t[m]}{b[m]} [\Omega \cdot m]$$
$$= \frac{V^{+}_{56,13}(+B) - V^{-}_{56,13}(+B) + V^{+}_{56,13}(-B) - V^{-}_{56,13}(-B)}{I^{+}_{56}(+B) - I^{-}_{56}(+B) + I^{+}_{56}(-B) - I^{-}_{56}(-B)} \frac{w[cm]t[cm]}{b[cm]} [\Omega \cdot cm]$$

A.4.4.2.3 Hall Coefficient

Calculate the Hall coefficient by

$$R_H = \frac{t[m]}{B[T]} \cdot \frac{V^{+}_{56,24}(+B) - V^{-}_{56,24}(+B) + V^{-}_{56,24}(-B) - V^{+}_{56,24}(-B)}{I^{+}_{56}(+B) - I^{-}_{56}(+B) + I^{-}_{56}(-B) - I^{+}_{56}(-B)} [m^3 \cdot C^{-1}]$$
$$= 10^8 \frac{t[cm]}{B[gauss]} \frac{V^{+}_{56,24}(+B) - V^{-}_{56,24}(+B) + V^{-}_{56,24}(-B) - V^{+}_{56,24}(-B)}{I^{+}_{56}(+B) - I^{-}_{56}(+B) + I^{-}_{56}(-B) - I^{+}_{56}(-B)} [cm^3 \cdot C^{-1}]$$

A.4.4.2.4 Hall Mobility

The Hall mobility is given by, $\mu_H = \frac{|R_H|}{\rho} [m^2 \cdot V^{-1} \cdot s^{-1}, cm^2 \cdot V^{-1} \cdot s^{-1}]$

where ρ is the magnetoresistivity if it was measured, and the zero-field resistivity if it was not.

A.4.4.3 Eight-Contact 1-3-3-1 Hall Bar

The eight contact 1-3-3-1 Hall bar geometry is ideally the most symmetrical of the Hall bars. Two sets of three equally-spaced contacts lie directly opposite one another on either side of the sample with center contacts (numbers 2 and 4) located at the exact center of the sample's length. Voltage measurement connections are made to contacts 1 through 4, while current flows from contact 5 to contact 6. Only six of the eight contacts are used in this measuring procedure. The remaining two (unnumbered) contacts are included to keep the sample completely symmetrical. See FIGURE A-6 for a representation of the eight contact 1-3-3-1 Hall bar geometry.

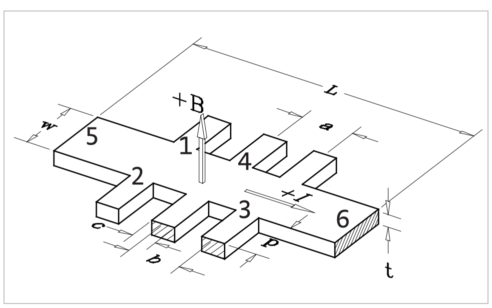


FIGURE A-6 ***Eight contact 1-3-3-1 Hall bar geometry***

The eight-contact Hall bar attempts to combine the homogeneity checks possible with the 1-2-2-1 six-contact geometry and the benefit of measuring the Hall voltage in the center of the sample. It allows two resistivity measurements to compare for homogeneity, but only one Hall voltage measurement. Either the 1-2-2-1 or 1-3-1-1 six-contact measurements can be made using an eight-contact Hall bar, simply by moving the electrical connections to the appropriate points. The eight-contact Hall bar geometry is included in ASTM Standard F76, but the contact numbering given here differs from the standard.

A.4.4.3.1 Resistivity

First calculate the two resistivities

$$\rho_A = \frac{V^+_{56,\,23}(B=0) - V^-_{56,\,23}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \cdot \frac{w[m]t[m]}{b[m]}[\Omega \cdot m]$$
$$= \frac{V^+_{56,\,23}(B=0) - V^-_{56,\,23}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \cdot \frac{w[cm]t[cm]}{b[cm]}[\Omega \cdot cm]$$

and

$$\rho_B = \frac{V^+_{56,\,14}(B=0) - V^-_{56,\,14}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \cdot \frac{w[m]t[m]}{b[m]}[\Omega \cdot m]$$
$$= \frac{V^+_{56,\,14}(B=0) - V^-_{56,\,14}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \cdot \frac{w[cm]t[cm]}{b[cm]}[\Omega \cdot cm]$$

at zero magnetic field.

If these two values disagree by more than ±10%, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do agree, then the average resistivity is given by $\rho_{av} = \frac{\rho_A + \rho_B}{2}[\Omega \cdot m], [\Omega \cdot cm]$.

A.4.4.3.2 Magnetoresistivity

If desired, calculate the two magnetoresistivities

$$\rho_A = \frac{V^+_{56,\,23}(+B) - V^-_{56,\,23}(+B) + V^+_{56,\,23}(-B) - V^-_{56,\,23}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[m]t[m]}{b[m]}[\Omega \cdot m]$$
$$= \frac{V^+_{56,\,23}(+B) - V^-_{56,\,23}(+B) + V^+_{56,\,23}(-B) - V^-_{56,\,23}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[cm]t[cm]}{b[cm]}[\Omega \cdot cm]$$

and

$$\rho_B = \frac{V^+_{56,\,14}(+B) - V^-_{56,\,14}(+B) + V^+_{56,\,14}(-B) - V^-_{56,\,14}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[m]t[m]}{b[m]}[\Omega \cdot m]$$
$$= \frac{V^+_{56,\,14}(+B) - V^-_{56,\,14}(+B) + V^+_{56,\,14}(-B) - V^-_{56,\,14}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[cm]t[cm]}{b[cm]}[\Omega \cdot cm]$$

If these two values disagree by more than ±10%, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do agree, then the average magnetoresistivity is given by

$$\rho_{av}(B) = \frac{\rho_A(B) + \rho_B(B)}{2}[\Omega \cdot m], [\Omega \cdot cm]$$

A.4.4.3.3 Hall Coefficient

Calculate the Hall coefficient by

$$R_H = \frac{t[m]}{B[T]} \cdot \frac{V^+_{56,\,24}(+B) - V^-_{56,\,24}(+B) + V^-_{56,\,24}(-B) - V^+_{56,\,24}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)}[m^3 \cdot C^{-1}]$$
$$= 10^8 \frac{t[cm]}{B[gauss]} \frac{V^+_{56,\,24}(+B) - V^-_{56,\,24}(+B) + V^-_{56,\,24}(-B) - V^+_{56,\,24}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)}[cm^3 \cdot C^{-1}]$$

A.4.4.3.4 Hall Mobility

The Hall mobility is given by

$$\mu_H = \frac{|R_{HAV}|}{\rho_{av}}[m^2 \cdot V^{-1} \cdot s^{-1}, cm^2 \cdot V^{-1} \cdot s^{-1}]$$

where ρ_{av} is the magnetoresistivity if it was measured, and the zero-field resistivity if it was not.

A.5 Comparison to ASTM Standard

The contact numbering and voltage measurement indexing given above differ in several ways from that given in the ASTM Standard F76[15].

To begin, the ASTM contact numbering schemes for the van der Pauw and Hall bar geometries are incompatible with one another. To allow either sample type to be mounted using the same set of contacts, Lake Shore's numbering scheme for Hall bar samples differs from the ASTM scheme.

Second, the ASTM standard is inconsistent with the "handedness" of the van der Pauw contact numbering order with respect to the applied magnetic field. Lake Shore numbered the contacts counterclockwise in ascending order when the sample is viewed from above, with the magnetic field perpendicular to the sample and pointing toward the observer, as shown in FIGURE A-3.

Finally, ASTM assumes that the direction of the excitation current is to be changed by physically reversing the current connections. This technique is not well suited to high-resistance samples using a programmable current source like the Keithley Model 220. This current source (and others like it) has a guarded "high" current output, and an unguarded "low" current return. For proper current source operation, the "high" output lead should be farther from common ground than the "low" return lead, a condition violated half of the time when physically reversing the high and low current leads to the sample. When this condition is violated, leakage current can flow through the voltmeter, leading to possibly serious measurement errors.

To avoid this difficulty, Lake Shore reversed the sign of the programmed current source, while leaving the contacts alone. This requires a more sophisticated notation for voltage measurements:

$V_{ij,kl}^{+-} \pm B$

In this notation, terminal *i* refers to the contact to which the current source output attaches, terminal *j* is the current return contact, terminal *k* is the positive voltmeter terminal, and terminal *l* is the negative voltmeter terminal. The superscript ± refers to the sign of the programmed current, while ±B refers to the sign of the applied magnetic field relative to the positive direction indicated in the figures.

A.6 Sources of Measurement Error

David C. Look gives a good treatment of systematic error sources in Hall effect measurements in the first chapter of his book.[2] There are two kinds of error sources: intrinsic and geometrical.

A.6.1 Intrinsic Error Sources

The apparent Hall voltage, V_{Ha}, measured with a single reading can include several spurious voltages. These spurious error sources include the following:

1. Voltmeter offset (V_o): An improperly zeroed voltmeter adds a voltage V_o to every measurement. The offset does not change with sample current or magnetic field direction.
2. Current meter offset (I_o): An improperly zeroed current meter adds a current I_o to every measurement. The offset does not change with sample current or magnetic field direction.
3. Thermoelectric voltages (V_S): A temperature gradient across the sample allows two contacts to function as a pair of thermocouple junctions. The resulting ther-

moelectric voltage due to the Seebeck effect is designated V_S. Portions of wiring to the sensor can also produce thermoelectric voltages in response to temperature gradients. These thermoelectric voltages are not affected by current or magnetic field, to first order.

4. Ettingshausen effect voltage (V_E): Even if no external transverse temperature gradient exists, the sample can set up its own. The evxB force shunts slow (cool) and fast (hot) electrons to the sides in different numbers and causes an internally generated Seebeck effect. This phenomenon is known as the Ettingshausen effect. Unlike the Seebeck effect, V_E is proportional to both current and magnetic field.
5. Nernst effect voltage (V_N): If a longitudinal temperature gradient exists across the sample, then electrons tend to diffuse from the hot end of the sample to the cold end and this diffusion current is affected by a magnetic field, producing a Hall voltage. The phenomenon is known as the Nernst or Nernst-Ettingshausen effect. The resulting voltage is designated V_N and is proportional to magnetic field, but not to external current. This is the one intrinsic error source which can not be eliminated from a Hall voltage measurement by field or current reversal.
6. Righi-Leduc voltage (V_R): The Nernst (diffusion) electrons also experience an Ettingshausen-type effect since their spread of velocities result in hot and cold sides and thus again set up a transverse Seebeck voltage, known as the Righi-Leduc voltage, V_R. The Righi-Leduc voltage is also proportional to magnetic field, but not to external current.
7. Misalignment voltage (V_M): The excitation current flowing through the sample produces a voltage gradient parallel to the current flow. Even in zero magnetic field, a voltage appears between the two contacts used to measure the Hall voltage if they are not electrically opposite each other. Voltage contacts are difficult to align exactly. The misalignment voltage is frequently the largest spurious contribution to the apparent Hall voltage

The apparent Hall voltage, V_{Ha}, measured with a single reading contains all of the above spurious voltages: $V_{Ha} = V_H + V_o + V_S + V_E + V_N + V_R + V_M$.
All but the Hall and Ettingshausen voltages can be eliminated by combining measurements, as shown in Table B-1.

Measurements taken at a single magnetic field polarity still have the misalignment voltage, frequently the most significant unwanted contribution to the measurement signal. Comparing values of Rh(+B) and Rh(-B) reveals the significance of the misalignment voltage relative to the signal voltage.

A Hall measurement is fundamentally a voltage divided by a current, so excitation current errors are equally as important. Current offsets, I_o, are canceled by combining the current measurements, then dividing the combined Hall voltage by the combined excitation current.

	I	B	V_H	V_M	V_S	V_E	V_N	V_R	V_O
V_1	+	+	+	+	+	+	+	+	+
V_2	–	+	–	–	+	–	+	+	+
$(V_1–V_2)$			$2V_H$	$–2V_M$	0	$2V_E$	0	0	0
V_3	+	–	–	+	+	–	–	–	+
V_4	–	–	+	–	+	+	–	–	+
$(–V_3+V_4)$			$2V_H$	$–2V_M$	0	$2V_E$	0	0	0
$(V_1–V_2–V_3+V_4)$			$4V_H$	0	0	$4V_E$	0	0	0

TABLE A-2 ***Hall effect measurement voltages showing the elimination of all but the Hall and Ettingshausen voltages by combining readings with different current and magnetic field polarities***

A.6.2 Geometrical Errors in Hall Bar Samples

Geometrical error sources in the Hall bar arrangement are caused by deviations of the actual measurement geometry from the ideal of a rectangular solid with constant current density and point-like voltage contacts.

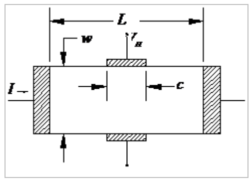


FIGURE A-7 ***Hall bar with finite voltage contacts***

The first geometrical consideration with the Hall bar is the tendency of the end contacts to short out the Hall voltage. If the aspect ratio of sample length to width $l/w = 3$, then this error is less than 1%.[15] Therefore, it's important that $l/w \geq 3$.

The finite size of the contacts affects both the current density and electric potential in their vicinity, and may lead to fairly large errors. The errors are larger for a simple rectangular Hall bar than for one in which the contacts are placed at the end of arms.

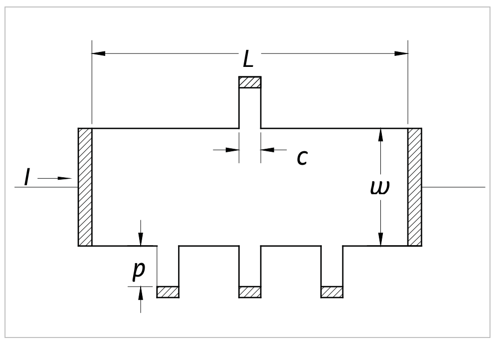


FIGURE A-8 ***Hall bar with contact arms***

For a simple rectangle, the error in the Hall mobility can be approximated (when $\mu B \ll 1$) by[16]

$$\frac{\Delta\mu H}{\mu H} = 1-\left(1^{-\frac{e^{-\pi l}}{2w}}\right)\left(1-\frac{2c}{\pi w}\right).$$

Here, $\Delta\mu_H$ is the amount μ_H must *increase* to obtain a true value.
If $l/w = 3$, and $c/w = 0.2$, then $\Delta\mu_H / \mu_H = 0.13$, which is certainly a significant error.

Reduce the contact-size error to acceptable levels by placing contacts at the ends of contact arms.[17] The following aspect ratios yield small deviations from the ideal:
$p \approx c, c \leq w/3, l \geq 4w$.

A.6.3 Geometrical Errors in van der Pauw Structures

Van der Pauw's analysis of resistivity and Hall effect in arbitrary structures assumes point-like electrical connections to the sample. In practice, this ideal can be difficult or impossible to achieve, especially for small samples. The finite-contact size corrections depend on the particular sample geometry, and, for Hall voltages, the Hall angle θ (defined by $\tan\theta \cong \mu B$, where μ is the mobility). Look[2] presents the results of both theoretical and experimental determinations of the correction factors for some of the most common geometries. We summarize these results here, and compare the correction factors for a 1:6 aspect ratio of contact size to sample size.

A.6.4 Square Structures

The resistivity correction factor $\Delta\rho/\rho$ for a square van der Pauw structure is roughly proportional to $(c / l)^2$ for both square and triangular contacts. At $(c / l) = 1/6$, $\Delta\rho/\rho = 2\%$ for identical square contacts, and $\Delta\rho/\rho < 1\%$ for identical triangular contacts[18]. Hall voltage measurement error is much worse, unfortunately. The correction factor $\Delta R_H / R_H$ is proportional to (c / l), and is about 15% for triangular contacts when $(c / l) = 1/6$. The correction factor also increases by about 3% at this aspect ratio as the Hall angle increases from $\tan\theta = 0.1$ to $\tan\theta = 0.5$.

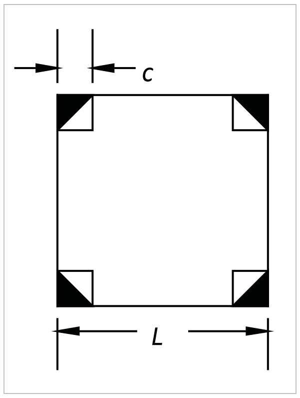


FIGURE A-9 ***Square van der Pauw structure with either square or triangular contacts***

A.6.4.1 Circular Structures

Circular van der Pauw structures fare slightly better. van der Pauw[14] gives a correction factor for circular contacts of

$\frac{\Delta\rho}{\rho} \cong -\frac{1}{16\ln 2}\left(\frac{c}{l}\right)^2$ (per contact), which results in a correction of $\Delta\rho/\rho = -1\%$ for $(c/l) = 1/6$ for four contacts.

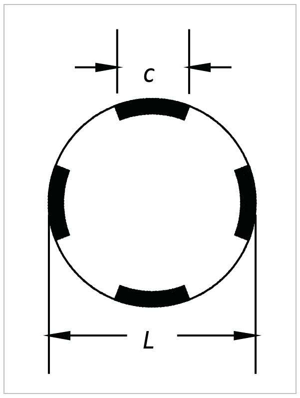


FIGURE A-10 ***Circular van der Pauw structure***

For the Hall coefficient, van der Pauw gives the correction

$\frac{\Delta R_H}{R_H} \cong \frac{2}{\pi^2} \cdot \frac{c}{l}$ per contact.

At $(c/l) = 1/6$, this results in a correction of 13% for four contacts.

Van Daal[19] reduced these errors considerably (by a factor of 10 to 20 for resistivity, and 3 to 5 for Hall coefficient) by cutting slots to turn the sample into a cloverleaf. The clover leaf structure is mechanically weaker than the square and round samples unless it is patterned as a thin film on a thicker substrate. Another disadvantage is that the “active” area of the cloverleaf is much smaller than the actual sample.

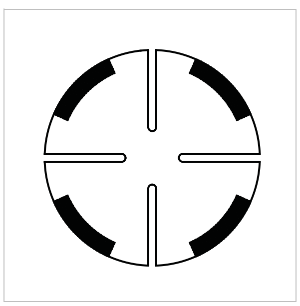


FIGURE A-11 ***Cloverleaf van der Pauw structure***

A.6.4.2 Greek Cross Structures

The Greek cross is one of the best van der Pauw geometries to minimize finite contact errors (see FIGURE A-12 for a representation of a Greek cross structure). Its advantage over simpler van der Pauw structures is similar to placing Hall bar contacts at the ends of arms. David and Beuhler[20] analyzed this structure numerically. They found that the deviation of the actual resistivity ρ from the measured value ρ_m obeyed

$E = 1 - \frac{\rho}{\rho_m} = 0.59 \pm 0.006\exp\left[-(6.23 \pm 0.02)\frac{a}{c}\right]$. This is a very small error: for $c/(c + 2a) = 1/6$, where $c + 2a$ corresponds to the total dimension of the contact arm, $E \cong 10^{-7}$.

Hall coefficient results are substantially better. De Mey[21,22] has shown that $\frac{\mu_H - \mu_{Hm}}{\mu_H} = \frac{\Delta\mu_H}{\mu_H} \cong 1.045 e^{\frac{-\pi a}{c}}$ (four contacts),

where μ_H and μ_{Hm} are the actual and measured Hall mobilities, respectively. For $c/(c+2a) = 1/6$, this results in $\Delta\mu_H/\mu_H \cong 0.04\%$, which is quite respectable.

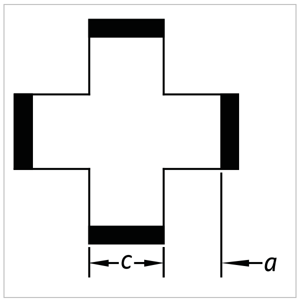


FIGURE A-12 ***Greek cross van der Pauw structure***

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Appendix B: Electrical Contacts to Semiconductors

B.1 General

All direct measurements of the electronic transport properties of a material require adequate electrical contacts between the sample and the measuring instrument. Adequacy depends on the particular measurement performed. Generally, low resistance ohmic contacts are desired.

The word “ohmic” ideally means “obeying Ohm’s Law”, a condition that is technically impossible to achieve in a metal-semiconductor interface1. Ohmic usually means a contact with a small resistance compared to the resistance of the sample being studied, and therefore, insignificant non-linear current-voltage characteristics.

Several parameters describe electrical contacts to semiconductors. The quantity of greatest interest is the contact resistivity or specific contact resistance, denoted by ρc and usually measured in $\Omega \cdot cm^2$. Contact resistivity is the product of the contact resistance R_c and the area A of the contact. Other common contact parameters include the barrier height Φ_B, measured in eV, and the semiconductor doping concentration, measured in cm^{-3}.

Three primary mechanisms govern current transport across a metal-to-semiconductor interface: thermionic emission, field emission, and thermionic-field emission[2]. They differ mainly by the interface potential barrier height and width as determined by the work function of the metal, the semiconductor electron affinity, and the semiconductor doping concentration near the interface.

Thermionic emission is important when both the barrier and doping concentration are low. In thermionic emission, electrons thermally excited to energies above the barrier, pass directly over it. As a result, contact resistance where thermionic emission dominates depends strongly on temperature.

Field emission is important when both the barrier and doping concentration are high. A high doping concentration reduces the width of the carrier depletion region near the semiconductor's surface. This in turn produces a thin barrier that electrons tunnel through directly. A field emission is only weakly dependent on temperature.

Thermionic-field emission is important when both barrier and doping concentration are moderate. In thermionic-field emission, electrons are thermally excited part way up the potential barrier, at which point they tunnel the rest of the way through. Thermionic-field emission is moderately temperature-dependent. Typically, some sort of thermionic-field emission is the most likely transport mechanism.

There are several methods of contact deposition: applying metal-bearing paints and pastes, melting metals directly on the semiconductor surface, evaporation, sputtering, molecular beam epitaxy, ion-implantation, and others. Once deposited on the semiconductor, the contact may be thermally annealed by conventional oven, laser or electron beam, or rapid thermal annealing/processing (RTA or RTP), in which halogen lamps rapidly heat the semiconductor to the annealing temperature, and hold it there for a short time (typically 10 s to 30 s).

This appendix discusses methods of making electrical contacts to a variety of semiconductor materials. In most cases, it indicates contact materials, method of deposition and annealing, contact resistivity and doping concentration, and references to original publications.

B.2 Silicon

Much effort has been made to produce reliable, small, low-resistance contacts to silicon for VLSI electronics. Gildenblat and Cohen[3] give an excellent review of the art and include the following reference table for silicon contacts. Cooke gives an additional review of LPCVD metallization techniques.

B.2.1 Making Electrical Contacts to Silicon

Contact resistivities are minimum values reported in the references. Usually, these were obtained with the highest dopant concentration employed. Conventional sintering typically involves a furnace anneal at 400 °C to 450 °C for 30 min to 60 min. All surfaces are assumed to be (100) unless indicated otherwise.[3]

Metallization	Semiconductor type	Sintering conditions	$\overline{\rho}_c$ (Ω•μm²)	Comments	Reference
Aluminum	p+	Conventional	3700	(111) Si	4
	p+	Conventional	26	(111) Si	5
	n–	Conventional	410000	(111) Si	4
	n+	Conventional	100	(111) Si, high doping	6
	n+	Conventional	<120	(111) Si	7
	n+	Conventional	100	(111) Si	8
	n+	Conventional	400	—	9
	n+	Conventional	<60	—	10
	n+	E-beam	310	—	11
	n+	Laser, e-beam	104-1000	—	12, 13, 14
	n+	Conventional	100	Polysilicon	15
	p+	Conventional	300	(111) Si	7
	p+	Conventional	<100	Ion beam deposition	16
	p+	Hallogen lamp	15	—	17
	p+	E-beam	110	—	11
	p+	Conventional	20	Polysilicon	15
Al-Si alloys	p+	Conventional	15	0.9% Si in alloy	18
	n+	Conventional	90	—	18
	n+	Conventional	70	1% to 2% in Si	10, 19
	n+	Conventional	<200	1% in Si	19
	p+	Conventional	<500	—	10, 19
PtSi	n+	Conventional	5000	Al overlayer	20
	n+	Conventional	20	Al overlayer	21
	n+	Conventional	4	Al overlayer	22
	n+	Conventional	5	Mo overlayer	23
	n+	CW laser	<100	Ti overlayer	24
	p+	Conventional	10000	Al overlayer	20
	p+	Conventional	7	Al overlayer	22
	p+	Conventional	10	Patterning by liftoff	25
	p+	Conventional	7	Mo overlayer	5
Pd_2Si	n–	Conventional	400	—	26
	n–,p+	Conventional	63, 68	Both (100) and (111)	5
$MoSi_2$	n–	Conventional	400	—	26
$CoSi_2$	n–	Laser	<50	—	28
	p+	Laser	700	—	29

TABLE B-1 ***Electrical contacts to silicon***

Metallization	Semiconductor type	Sintering conditions	$\bar{\rho}_c$ (Ω•μm²)	Comments	Reference
$TiSi_2$	n–	Laser	100	—	30
	n–	Laser	<150	—	31
	n–	Laser	15	—	32
	p+	Laser	<40	—	31
	p+	Laser	100	—	32
$TiSi_{1,86}$	p+	—	<50	—	31
	n–	—	<30	—	31
Tungsten	n–	Laser	20	Selective deposition	33
	p+	Laser	25	Selective deposition	33
WTi	p+	Laser	20	Al overlayer	34
	n–	Laser	7	Al overlayer	34
	n–	E-beam	17	—	11
	p+	E-beam	13	—	11
Molybdenum	p+	Conventional	440	—	4
	p+	Conventional	600	—	35
	p+	Conventional	5	Sintered at 650 °C	36
	n–	Conventional	8000	—	4
	n–	Conventional	800	—	35
	n–	Conventional	<100	—	37
	n–	Conventional	2	Sintered at 650 °C	36
Mo_xNi_{1-x}	n–	Conventional	<350	—	38
	p+	Conventional	<150	—	38
$Fe_{45}W_{36}$	p+	Conventional	110	—	39
	n–	Conventional	10	—	39
Nickel	n–, p+	Conventional	200	—	35
Vanadium	p+	Conventional	520	—	4
	n–	Conventional	7300	—	4
Cobalt	n–	Conventional	14000	—	4
	p	Conventional	780	—	4
Chromium	p	Conventional	400	—	35
	n–	Conventional	300	—	35
TiN, HfN	p	Conventional	<10	Solar cell type Si	40

TABLE B-1 ***Electrical contacts to silicon***

B.3 Gallium Arsenide and Other III-V Compounds

Electrical contact to gallium arsenide has grown due to the popularity of GaAs in the electronic industry, particularly for electrooptical and high-speed digital applications which exploit other III-V compounds as well. In his book, David Look reviews a variety of techniques to contact GaAs and closely related compounds[41]. A more recent article by T. C. Shen, G. B. Gao, and H. Morkoç[2] discusses the emerging role of rapid thermal annealing/processing in contacting GaAs, and electrical contacts to several other III-V compounds.

Semiconductor	Carrier Conc. (10^{18} cm^{-3})	Metallization	Preparation	ρ_c ($10^{-6}\,\Omega \cdot cm^2$)	Ref.
n-GaAs	2.2	Au/Pd/Ge	Evap. surf. heater, 450 °C, 30 s	0.5	42
	2.2	Au/Ge/Ni	Evap. surf. heater, 450 °C, 30 s	0.4	42
	5	Ni/AuGe	Evap., laser, 40 ns	56	43
	5	Ni/AgGe	Evap., laser, 40 ns	95	43
	1	Au/Ni/AuGe	Evap. surf. heater, 320 °C, 60 s	15	44
	10	Ni/Au/Ge	Evap. no alloying	0.2	45
	1.8	AuGe/Ni	Evap., laser, 20 ns	1.5	46
	2	Au/Pd	Electroless dep., furnace, 350°C, 2 min	8	47
	100	Au/Cr	Evap. no alloying	2.5	48
	0.5	WSix	Evap. RTA, 800°C, few s	1	49
	0.3	In	Evap. surf. heater, 350°C, 15 s	12	50
	0.15	In/Pt	Evap. surf. heater, 400°C	2	51
	2	Au/In	Electroless dep., furnace, 350°C, 2 min	15	47
	low 10^{18}	Ge/Pd, Pd/Ge	Furnace, 325 °C to 375°C, up to 30 min, or RTP	~1	42,52
	low 10^{18}	Si/Pd	RTP	~1	53,54
	1	MoGeW	RTP	0.3 mm1	55
	4	MoGeW	RTP	0.4	56
	3.5 x 10^{13} cm^{-22}	MoGeInW	RTP	0.5 mm	57
	3.5 x 10^{13} cm^{-2}	GeInW	RTP	0.5 mm	58
	3.5 x 10^{13} cm^{-2}	NiInW	RTP	0.3 mm	58
	6.6 x 10^{13} cm^{-2}	NiInW(Si)	RTP	0.1 mm	59
	6.6 x 10^{13} cm^{-2}	NiInW(Ge)	RTP	0.3 mm	59
	3.5 x 10^{13} cm^{-2}	NiInW	RTP	—	60
	0.01	Au/WSi2/Ge **Au/$W_{40}N_{40}$** **Ge/Ni**	RTP	50	61
	0.1	Au/W/Pd/Ge	RTP	~5	62
	0.1	Au/W/Mo/ Ge	RTP	~5	62
	1	W-In	RTP	3	63
	1	NiGe(Au)W	RTP	0.16 Ω mm	64
	3.5 x 10^{13} cm^{-2}	W/Ni/InAs	RTP	0.4 Ω mm	65
	6 x 10^{13} cm^{-2}	WInTe	RTP	5	66
	3.5 x 10^{13} cm^{-2}	W/Ni/InAs /Ni	RTP	0.4 Ω mm	65
	—	Pd/In	RTP	~2	67

TABLE B-2 ***Electrical contacts to III-V compound semiconductors***

Semiconductor	Carrier Conc. (10^{18} cm^{-3})	Metallization	Preparation	ρ_c ($10^{-6}\,\Omega \cdot cm^2$)	Ref.
p-GaAs	4	Au/Pd	Electroless dep., furnace, 250°C, 2 min	200	47
	2	Ag/TiN/Pt/ Mg	Evap., furnace, 450°C, 30 min	100	68
	1	Ag/W/Pt	Evap., furnace, 400°C, 30 min	300	69
	100	Ni/AuZn	Evap., furnace, 450°C, 2.5 min	10	70
	—	Si/Ni/Mg/Ni	RTP	0.7	71
p-AlGaAs	10-100	AuBe, Pt/Ti	RTP	—	72
n-InGaAs	—-	Au/Cr	Evap., no alloying	2.2	73
	15	Au/Pt/Ti	Evap., no alloying	0.05	74
	1.8	Al	Evap., no alloying	0.5	75
	1	Ni/Au-Sn/Ni	—	0.04	76
	30	Al	—	0.48	75
p-InGaAs	—	Au/Cr	Evap., no alloying	82	73
	1	Ni/AgZn/Ti	Evap. furnace, 400°C, 2 min	11	77
	1	Ni/Au-Zn/Ni	—	20	76
n-InAlAs/ InGaAs	1	Au/Ag/Au/ Ge/Ni	Evap., furnace, 480°C, 60 s	0.8	78
n-AlGaAs /GaAs	3	Au/Ni/AuGe	Evap. 500°C, 50 s	0.1	79
p-InGaAsP	5	AuBe	—	0.49	80
	20	Pt/Ti	—	1	80
	23	Pd/Ge	Solid-phase epitaxy	2.3	81
p-GaSb	1	Au-Zn	Furnace	10	82
n-InP	—	Ni/Zn/Au, Ni/Hg/ Au, InPd	Electroless dep.	—	83
	2	AuGe/Ni/Au	Si-implanted, RTP	0.2	84
	—	Pt/Ti	RTP >400°C	0.8	85
	0.8	Au/Sn/In	400°C, 2 min	300	86
	0.8	Ni/AuGe/Ni	350°C 2 min after AuGe, 400°C 1 min after Ni	2.3	86
p-InP	1	Au/Cr/AuBe	RTP	10	87
	0.9	Au/Zn 90/10	400°C, 2 min	110	86
p-InAs	10	Pt/Ti	Zn-doped, RTP, 450°C, 30 s	0.099	88
n-GaN	—	Al	Evap. no annealing	0.01-0.1	89
n-GaN	—	Au	Evap. 575°C, 10 min	0.01-0.1	89
	0.1	Al/Ti	Evap., RTA 900°C, 30 s	8	90
	5	InN/GaN	Superlattice, InN cap, no annealing	60	91
n- & p- AlN	—	Al, Pt, Au	Sputtering	—	92

TABLE B-2 ***Electrical contacts to III-V compound semiconductors***

B.4 Diamond (Carbon)

Semiconducting diamond is gaining popularity thanks to its unique combination of electronic and physical properties, including high breakdown voltage, high thermal conductivity, low dielectric constant, and radiation hardness. Tachibana and Glass[93] and by Das et al.[94] review the art of making both ohmic and Schottky contacts to diamond.

There are several methods to produce ohmic contacts on diamond: roughening or damaging the surface, welding noble metal/transition metal alloys, ion implantation, in situ doping with B during CVD film growth, solid-state diffusion doping, and deposition of carbide-forming metals.

Metallization	Doping	Preparation	A	Ref.
Ag Paint	Natural	Mechanical roughening	—	95
Colloidal Graphite	Natural	Mechanical roughening	—	96
W point probes	Natural	Mechanical roughening	—	97
Au(99%)-Ta(1%)	Natural	Welding: e-beam and joule heating	—	95-97
Au(90%)-Ta(9%)-Al(1%)	Natural	Welding: e-beam and joule heating	—	95-97
Pd-Ta	Natural	Vacuum brazing	—	98
Pt-Au-Ta	Natural	Vacuum brazing	—	98
Au, Ag, Cu	B, 3×10^{16} cm^{-3}	35 keV ion implantation at 200°C, annealed at 1200°C, etched	36 Ω cm	99
Au/Ti	B, 10^{20} cm^{-3}	Ion implantation at 200°C	10^{-5} to 10^{-6} Ω cm2	100
	B,3×10^{20} cm^{-3}	In situ vapor-phase doping	10^{-4} Ω cm^2	101
Ti	B, 10^{19} cm^{-3}	Solid state diffusion, cBN at 1400°C, 20 s to 60 s in Ar	—	102,103
Ti, Mo, Ta	Natural	Carbide formation, annealing at >400°C	10^{-5} Ω cm^2	96,**104-108**
Al/Si	B, 4.9×10^{21} cm^{-3}	Annealed 450°C	2.3×10^{-7} Ω cm^2	109
Ti-Au	B, 4.9×10^{20} cm^{-3}	Annealed 450°C	14×10^{-5} Ω cm^2	109
TiWN-Au	B, 4.9×10^{20} cm^{-3}	Annealed 450°C	6.6×10^{-5} Ω cm^2	109

TABLE B-3 ***Electrical contacts to diamonds***

B.5 II-VI Materials

Wide and narrow bandgap II-VI compounds are increasingly sought for optoelectronic applications ranging from IR to UV wavelengths. HgCdTe is a "gapless" semiconductor used in IR detectors. ZnTe is a wide bandgap semiconductor that can be heavily doped with N, making it a potentially attractive material for blue and UV optoelectronics. ZnSe is the focus of considerable effort in the area of blue and UV semiconductor lasers, but it is extremely difficult to produce ohmic contacts to this material110.

Material	Carrier Concentration (cm-3)	Metallization	Process	pc (Ω· cm2)	Reference
HgCdTe	~10^{15}	Au	Ar presputter, evap.	~1×10^{-4}	111
	4×10^{14}	Sn/In	Evap.	1×10^{-5} - 1×10^{-5}	112
p-ZnTe	3×10^{19}	Au/Pt/Ti/N	E-beam evap., 120°C	1.1×10^{-6}	113

TABLE B-4 ***Electrical contacts to II-VI compound semiconductors***

B.6 Silicon Carbide

Like diamond, silicon carbide is potentially useful for high-power, high-speed, and high-frequency devices, due to its large bandgap, high breakdown field and high thermal conductivity. However, ohmic contacts to this material have not been studied extensively.

Material	Metallization	Process	pc (Ω· cm2)	Reference
SiC	Cr and alloys	ohmic to p-type	—	114
	Al	—	—	115
	Ti	sputter, 300°C, 30 min	9.2×10^{-3}	116
	TiSi2	450°C, 390 min	1×10^{-4}	116
	WSi2	450°C, 120 min	3×10^{-4}	116

TABLE B-5 ***Electrical contacts to silicon carbide***

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