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Model 3765 Hall Effect Card

User's Manual

3765-900-01 Rev. A / August 2017

3765-900-01A

KEITHLEY
A Tektronix Company

Model 3765

Hall Effect Card

User's Manual

These are the original instructions in English.

Document number: 3765-900-01 Rev. A / August 2017

Safety precautions

The following safety precautions should be observed before using this product and any associated instrumentation. Although some instruments and accessories would normally be used with nonhazardous voltages, there are situations where hazardous conditions may be present.

This product is intended for use by personnel who recognize shock hazards and are familiar with the safety precautions required to avoid possible injury. Read and follow all installation, operation, and maintenance information carefully before using the product. Refer to the user documentation for complete product specifications.

If the product is used in a manner not specified, the protection provided by the product warranty may be impaired.

The types of product users are:

Responsible body is the individual or group responsible for the use and maintenance of equipment, for ensuring that the equipment is operated within its specifications and operating limits, and for ensuring that operators are adequately trained.

Operators use the product for its intended function. They must be trained in electrical safety procedures and proper use of the instrument. They must be protected from electric shock and contact with hazardous live circuits.

Maintenance personnel perform routine procedures on the product to keep it operating properly, for example, setting the line voltage or replacing consumable materials. Maintenance procedures are described in the user documentation. The procedures explicitly state if the operator may perform them. Otherwise, they should be performed only by service personnel.

Service personnel are trained to work on live circuits, perform safe installations, and repair products. Only properly trained service personnel may perform installation and service procedures.

Keithley Instruments products are designed for use with electrical signals that are measurement, control, and data I/O connections, with low transient overvoltages, and must not be directly connected to mains voltage or to voltage sources with high transient overvoltages. Measurement Category II (as referenced in IEC 60664) connections require protection for high transient overvoltages often associated with local AC mains connections. Certain Keithley Instruments measuring instruments may be connected to mains. These instruments will be marked as category II or higher.

Unless explicitly allowed in the specifications, operating manual, and instrument labels, do not connect any instrument to mains.

Exercise extreme caution when a shock hazard is present. Lethal voltage may be present on cable connector jacks or test fixtures. The American National Standards Institute (ANSI) states that a shock hazard exists when voltage levels greater than 30 V RMS, 42.4 V peak, or 60 VDC are present. A good safety practice is to expect that hazardous voltage is present in any unknown circuit before measuring.

Operators of this product must be protected from electric shock at all times. The responsible body must ensure that operators are prevented access and/or insulated from every connection point. In some cases, connections must be exposed to potential human contact. Product operators in these circumstances must be trained to protect themselves from the risk of electric shock. If the circuit is capable of operating at or above 1000 V, no conductive part of the circuit may be exposed.

Do not connect switching cards directly to unlimited power circuits. They are intended to be used with impedance-limited sources. NEVER connect switching cards directly to AC mains. When connecting sources to switching cards, install protective devices to limit fault current and voltage to the card.

Before operating an instrument, ensure that the line cord is connected to a properly-grounded power receptacle. Inspect the connecting cables, test leads, and jumpers for possible wear, cracks, or breaks before each use.

When installing equipment where access to the main power cord is restricted, such as rack mounting, a separate main input power disconnect device must be provided in close proximity to the equipment and within easy reach of the operator.

For maximum safety, do not touch the product, test cables, or any other instruments while power is applied to the circuit under test. ALWAYS remove power from the entire test system and discharge any capacitors before: connecting or disconnecting cables or jumpers, installing or removing switching cards, or making internal changes, such as installing or removing jumpers.

Do not touch any object that could provide a current path to the common side of the circuit under test or power line (earth) ground. Always make measurements with dry hands while standing on a dry, insulated surface capable of withstanding the voltage being measured.

For safety, instruments and accessories must be used in accordance with the operating instructions. If the instruments or accessories are used in a manner not specified in the operating instructions, the protection provided by the equipment may be impaired.

Do not exceed the maximum signal levels of the instruments and accessories. Maximum signal levels are defined in the specifications and operating information and shown on the instrument panels, test fixture panels, and switching cards.

When fuses are used in a product, replace with the same type and rating for continued protection against fire hazard.

Chassis connections must only be used as shield connections for measuring circuits, NOT as protective earth (safety ground) connections.

If you are using a test fixture, keep the lid closed while power is applied to the device under test. Safe operation requires the use of a lid interlock.

If a screw is present, connect it to protective earth (safety ground) using the wire recommended in the user documentation.

The symbol on an instrument means caution, risk of hazard. The user must refer to the operating instructions located in the user documentation in all cases where the symbol is marked on the instrument.

The symbol on an instrument means warning, risk of electric shock. Use standard safety precautions to avoid personal contact with these voltages.

The symbol on an instrument shows that the surface may be hot. Avoid personal contact to prevent burns.

The symbol indicates a connection terminal to the equipment frame.

If this symbol is on a product, it indicates that mercury is present in the display lamp. Please note that the lamp must be properly disposed of according to federal, state, and local laws.

The **WARNING** heading in the user documentation explains dangers that might result in personal injury or death. Always read the associated information very carefully before performing the indicated procedure.

The **CAUTION** heading in the user documentation explains hazards that could damage the instrument. Such damage may invalidate the warranty.

The **CAUTION** heading with the symbol in the user documentation explains hazards that could result in moderate or minor injury or damage the instrument. Always read the associated information very carefully before performing the indicated procedure. Damage to the instrument may invalidate the warranty.

Instrumentation and accessories shall not be connected to humans.

Before performing any maintenance, disconnect the line cord and all test cables.

To maintain protection from electric shock and fire, replacement components in mains circuits — including the power transformer, test leads, and input jacks — must be purchased from Keithley Instruments. Standard fuses with applicable national safety approvals may be used if the rating and type are the same. The detachable mains power cord provided with the instrument may only be replaced with a similarly rated power cord. Other components that are not safety-related may be purchased from other suppliers as long as they are equivalent to the original component (note that selected parts should be purchased only through Keithley Instruments to maintain accuracy and functionality of the product). If you are unsure about the applicability of a replacement component, call a Keithley Instruments office for information.

Unless otherwise noted in product-specific literature, Keithley Instruments instruments are designed to operate indoors only, in the following environment: Altitude at or below 2,000 m (6,562 ft); temperature 0 °C to 50 °C (32 °F to 122 °F); and pollution degree 1 or 2.

To clean an instrument, use a cloth dampened with deionized water or mild, water-based cleaner. Clean the exterior of the instrument only. Do not apply cleaner directly to the instrument or allow liquids to enter or spill on the instrument. Products that consist of a circuit board with no case or chassis (e.g., a data acquisition board for installation into a computer) should never require cleaning if handled according to instructions. If the board becomes contaminated and operation is affected, the board should be returned to the factory for proper cleaning/servicing.

Safety precaution revision as of June 2017.

Table of contents

Section 1

Introduction

In this section:

Your Hall Effect card

The Model 3765 Hall Effect Card is a 4x5 matrix card designed for use in the Model 3706A System Switch/Multimeter. The 3765 is ideal for switching either current or voltage into a picoammeter or voltmeter.

Figure 1: 3765 Hall Effect Card

The 3765 has low-leakage reed relays with actuation times as low as 1 ms that let you use the 3765 to make accurate, low-current measurement applications. The 3765 output can be connected to the 3706A DMM through the backplane relay. Otherwise, a terminal block is provided to connect to an external DMM or voltmeter.

The 3765 can be operated in either a low- or a high- resistivity mode. In high-resistivity mode, input impedance is greater than 100 TΩ with input bias current less than 50 fA.

WARNING

When an interlock is required for safety, a separate circuit should be provided that meets the requirements of the application to reliably protect the operator from exposed voltages. The digital I/O port of the Model 3765 is not suitable for control of safety circuits and should not be used to control a safety interlock. Bypassing the interlock can result in personal injury or death from electric shock.

System switch / multimeter card compatibility

The following table lists the cards that are compatible with the 3706 and 3706A.

Mainframe System Switch / Multimeter	Compatible plug-in cards
Model 3706	3720, 3721, 3722, 3723, 3724, 3730, 3731, 3732, 3740, 3750
Model 3706A	3760, 3761, 3762, 3765

NOTE

The 3765 is designed for use only with the Model 3706A System Switch / Multimeter. Using the 3765 with the Model 3706 mainframe can cause unpredictable behavior.

Extended warranty

Additional years of warranty coverage are available on many products. These valuable contracts protect you from unbudgeted service expenses and provide additional years of protection at a fraction of the price of a repair. Extended warranties are available on new and existing products. Contact your local Keithley Instruments office, sales partner, or distributor for details.

Series 3700A documentation

Complete documentation for the Series 3700A System Switch/Multimeter instruments is available at the Keithley Instruments website (*http://www.tek.com/keithley*). The following is a list of available documentation.

Document number	Document name	Content description
3700AS-903-01	Series 3700A System Switch/Multimeter Quick Start Guide	Hardware and software requirements, switching card installation instructions, and a brief description of front-panel and remote interface operation
3700AS-900-01	Series 3700A System Switch/Multimeter User's Manual	Information about scanning, reading, writing, and controlling channels
3700AS-901-01	Series 3700A System Switch/Multimeter Reference Manual	Information about controlling the Series 3700A from a remote interface
PA-049	Series 3700A Cables and Connector Kits Installation Instructions	Information about the different cables and connector kits that are used on the Series 3700A cards
PA-955	Series 3700A Screw Terminal Assemblies Installation Instructions	Contains handling and installation instructions for Series 3700A screw terminal assemblies

Contact information

If you have any questions after you review the information in this documentation, please contact your local Keithley Instruments office, sales partner, or distributor. You can also call the corporate headquarters of Keithley Instruments (toll-free inside the U.S. and Canada only) at 1-800-935-5595, or from outside the U.S. at +1-440-248-0400. For worldwide contact numbers, visit the Keithley Instruments website (*http://www.tek.com/keithley*).

General information

General ratings for the Model 3765 are listed in the following table.

Category	Specification
Voltage rating*	30 V
Current rating	100 mA
Input and output connections	Current source input female triaxial cables Sample inputs for female triaxial cables Current monitor female BNC Measurement output spring loaded terminals
Environmental conditions	**Indoor use only** **Operating:** 0 °C to 50 °C (32 °F to 122 °F), 70% relative humidity up to 35 °C (95 °F); derate 3% relative humidity per °C, 35 °C to 50 °C, noncondensing **Storage:** −25 °C to 65 °C (-13 °F to 149 °F) **Altitude:** 0 to 2000 m (0 to 6562 ft) above sea level **Pollution degree:** 2

*Input voltage operating range ±8 V

Specifications

For the most recent instrument specifications, search for the 3765 on the Keithley Instruments website (http://www.tek.com/keithley).

Section 2

Installation and connections

In this section:

Handling precautions

Make sure to handle the Model 3765 carefully. Always grasp the card by the side edges or covers. Do not touch board surfaces, components, or areas adjacent to electrical contacts. Contamination from foreign materials such as dirt, dust, and body oils can substantially lower leakage resistances, degrading card performance.

⚠ WARNING

The information in this section is intended only for qualified personnel. Do not perform these procedures unless you are qualified. Failure to recognize and observe normal safety precautions could result in personal injury or death due to electric shock.

Unpack and inspect the instrument

To unpack and inspect your instrument:

1. Inspect the box for damage.
2. Open the top of the box.
3. Remove the contents accessories and verify that all items are included. You should have received:
   - One Model 3765 Hall Effect Card
   - Cables and connectors (on page 2-4)
4. Inspect the 3765 card for any obvious signs of physical damage.
5. Report any damage to the shipping agent immediately.

Card connectors

You can make signal input and output connections with the triaxial and BNC connectors on the card. The locations for each channel input and the card output are located outside of the card.

Connections are dependent on the application being performed.

Card installation

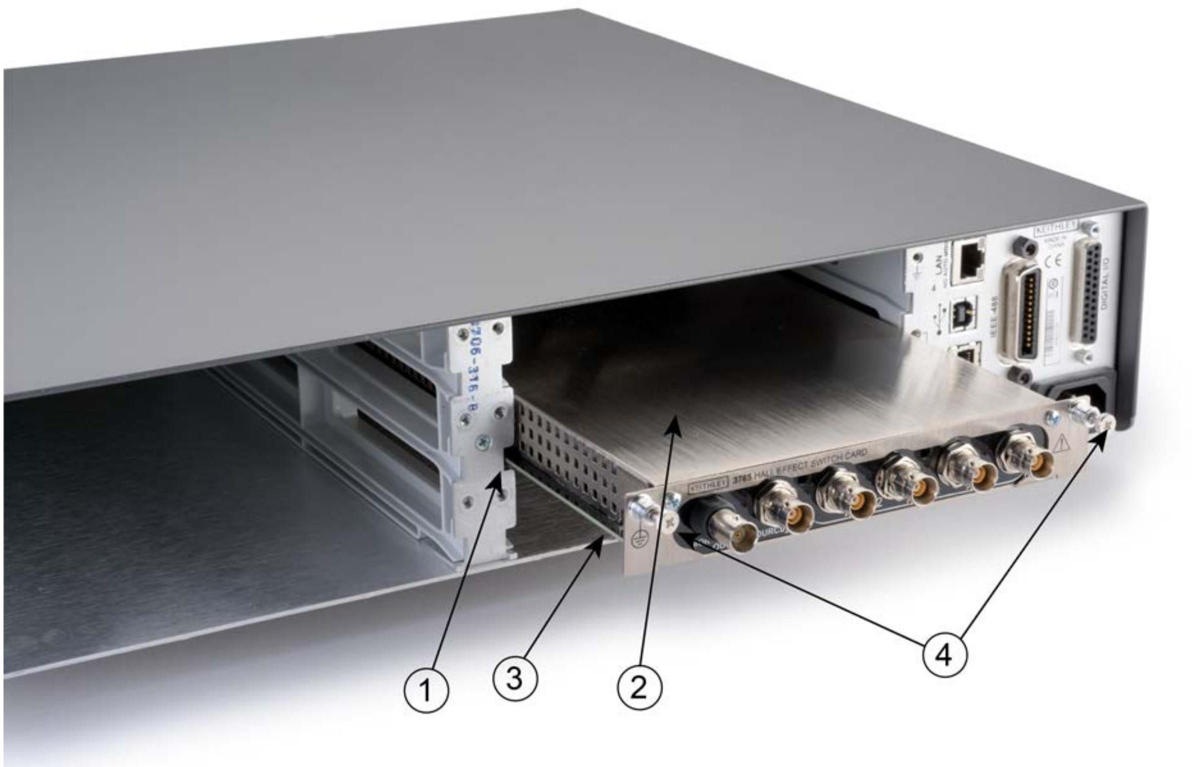
⚠ WARNING

Slot covers must be installed on unused slots to prevent personal contact with high voltage circuits. Failure to recognize and observe standard safety precautions could result in personal injury or death due to electric shock.

To install a switching card into the instrument mainframe:

1. Turn the instrument off and disconnect the power line cord and any other cables connected to the rear panel.
2. Position the instrument so that you are facing the rear panel.
3. Remove the slot cover plate from the desired mainframe slot. Retain the plate and screws for future use.
4. With the top cover of the switching card facing up, align the card's edge into the slot's card guide and slide in the card. For the last ¼ inch or so, press in firmly to mate the card connector to the mainframe connector.
5. On each side of the card, there is a mounting screw. Tighten these two screws to secure the card to the mainframe. Do not overtighten.

Figure 2: Card installation



NOTE

Item shipped may vary from model pictured here.

Item	Description
1	Card guide (part of the mainframe)
2	Card
3	Card edge (part of the card)
4	Mounting screws (part of the card)

Changing guarding and jumper settings is required before connecting the test system for completing most measurements. For more information see 3765 Guarding methods (on page 3-30).

Recommended cables and connectors

Below is a list of recommended cables and connectors for use with the Model 3765 Hall Effect Card.

Keithley model number	Manufacturer number	Description	Application	Supplied
4801	CA-7A (quantity 1)	BNC low-noise cable assembly, 4 ft (1.2 m)	Connect current source to Model 3765 current monitor input	Yes
7078-TRX-10	CA-63-10C2 (quantity 5)	3-lug triaxial assembly, 10 ft (3 m)	Connect sample to Model 3765input. Connect current source to source-in.	Yes
4851	4851-300A (quantity 1)	BNC shorting plug	Shorts Model 3765 current monitor output.	Yes
4802-10	CA-49 (quantity 1)	BNC low-pnoise cable assembly, 10 ft (3 m)	Connects picoammeter directly to sample in bar, 6- and 8-contact samples.	No
7078-TRX	CA-63 (quantity 1)	3-lug triaxial assembly, various lengths	Connects current source directly to sample in bar, 6- and 8-contact samples	No
SC-72-0	Belden 89200101000	Black, 22 AWG (7 x 30) tinned, vinyl nominal outer diameter .094	Connects to ground.	No
SC-72-9	Belden 89200091000	White 22 AWG (7 x 30) tinned, vinyl, nominal outer diameter .094	Connects current source guard to Model 3765 guard terminal.	No
BG-5	Emerson 108-0303-001	Banana plug, black, nylon, 16 AWG wire	Terminates black connecting wires.	No
BG-10-1	Emerson 108-0301-001	Banana plug, white, nylon, 16 AWG wire	Terminates white connecting wires.	No
BG-7	Emerson 108-0253-001	Black double banana plug	Used with BJ-7 when connecting DMM other than 3706A.	No
SC-8	Belden 8737060500	2-conductor cable, twisted pair with shield, 22 AWG (7 x 30), nominal outer diameter .170	Used when connecting DMM other than 3706A.	No
2107		Low-thermal input cable with spade lugs, various lengths	Connects external nanovoltmeter to J7 for ultra-low resistivity measurements.	No
DB-15 male		15-pin standard D-sub cables	Used for bar type sample measurements.	No

Web browser support

Web browser support for the Model 3765 Hall Effect Card is not supported with the 3706A Switch System/DMM.

Section 3

Operation

In this section:

Introduction

This section provides information needed to use the Model 3765 Hall Effect Card with the 3706A system switch mainframe. Once the card is installed in the mainframe, refer to the *Series 3700A System Switch/Multimeter Reference Manual* for additional operating instructions.

Equipment in the test system

Equipment in the test system includes:

Instrument	Description	Recommend Keithley models
Current source	Applies the current to the sample under test.	6221 current source
Picoammeter	Measures the current through the sample under test.	6485 or 6487 picoammeter
Model 3765 Hall Effect Card	Switches and buffers the applied currents and voltages.	
3706A Switch system with DMM	Controls and supplies power to the 3765 and provides measurement.	
Nanovoltmeter	Makes low noise voltage measurements and at high speeds.	2182A nanovoltmeter
IEEE-488 controller	Provides the intelligence to control the instruments in the system.	
Electromagnet	Provides an accurately known magnetic flux for the sample under test. A Hall sensor is sometimes used to measure the magnetic field as well.	
Magnet power supply	Supplies the necessary current for the electromagnet.	
Cryostat	Keeps the sample at the desired test temperature.	
Temperature controller	Controls the cryostat to maintain the desired temperature	

Refer to Recommended cables and connectors (on page 2-4) for a list of recommended cables and connectors for use with the 3765.

Safety hazards

⚠ WARNING

To prevent electrical shock that could cause injury or death, never make or break connections while the equipment is powered on. User supplied lethal voltages may be present on the PC board or the connections. Turn off the equipment from the front panel, disconnect the main power cord, and discharge stored energy in external circuitry before making or breaking cable connections. Putting the mainframe equipment into an output-off state does not guarantee that the outputs are powered off if a hardware or software fault occurs. All wiring must be rated for the maximum voltage in the system. For example, if 300 V is applied to the terminals of the card or instrument, wiring must be rated for 300 V.

Follow these recommendations before and after applying power to the equipment:

1. Do not exceed the 3765 maximum allowable signal level as defined in the specifications.
2. Do not exceed the 3765 maximum common mode voltage of 30 V as defined in the specifications.
3. Make sure the system switch mainframe is grounded through a protective earth-grounded (safety-grounded) receptacle before operation.
4. Turn off all power supplies and discharge any residual energy before installing or removing the 3765 from the system switch mainframe or changing connections.
5. Inspect all cables for wear and defects such as cracks and exposed wires. Make sure that you correct any defects found before operating the instrument.
6. Use only low-noise coaxial cables.
7. Ensure that the mounting screws for the card are securely connected to the system switch mainframe chassis in order to provide the proper chassis protective grounding.
8. Read this manual carefully and adhere to all of the safety precautions listed before operating the instrument.

Channel specifiers

To use the 3765, you need to understand the channel specifiers and the notation style used with the 3765 card.

A channel specifier is a four-digit alphanumeric sequence that specifies channels for use with close and open operations, scans, and channel patterns. The first digit is the slot number of the card in the mainframe. The second digit is the row, and the third and fourth digits are always the column.

A definition for a channel specifier of 1103 is as follows:

Slot	1
Row	1
Column	03

Matrix and test configurations

The following sections discuss a basic van der Pauw resistivity and Hall voltage measurement system and the matrix configuration of the 3765.

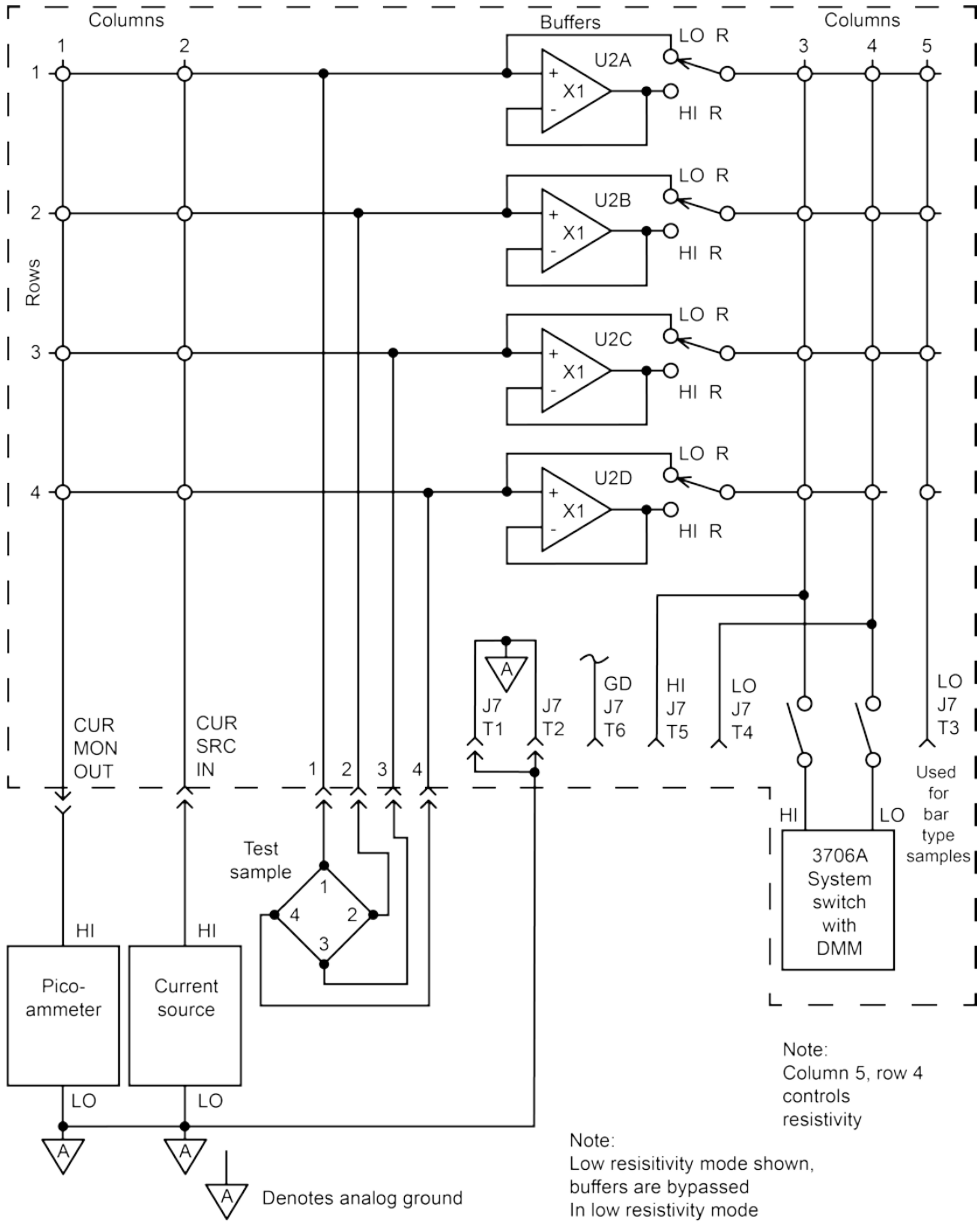
Hall Effect card matrix

The 3765 is organized into a five-by-four matrix, as shown in the next figure. Each intersection of a column and row is called a crosspoint and is designated by a small circle on the diagram. You can connect a row to a column by closing the appropriate crosspoint. The convention used in this manual designates a crosspoint by row and column (row, column). For example, contact 3,4 refers to row 3, column 4 of the matrix.

Source and measurement devices connect to the columns, while the samples connect to the rows. For example, a picoammeter and current source connect to columns 1 and 2 respectively, while the voltmeter is connected to columns 3 and 4. Column 5 is reserved for Hall bar measurements. Contact 4,5 selects low and high resistivity operations.

The four sample inputs are applied to the buffer amplifiers, which have high-input resistance to minimize loading. In low-resistivity mode, these buffers are effectively bypassed by relays. Although not shown on the following diagram, the buffers also provide a driven guard for the four-sample inputs to minimize leakage resistance and capacitance.

Figure 3: 3765 Matrix configuration



When making low resistivity measurements, voltage sensitivity and noise may be critical. A nanovoltmeter may be required to achieve optimal performance. The nanovoltmeter can be connected to J7 (external terminal block) pins 5 and 4.

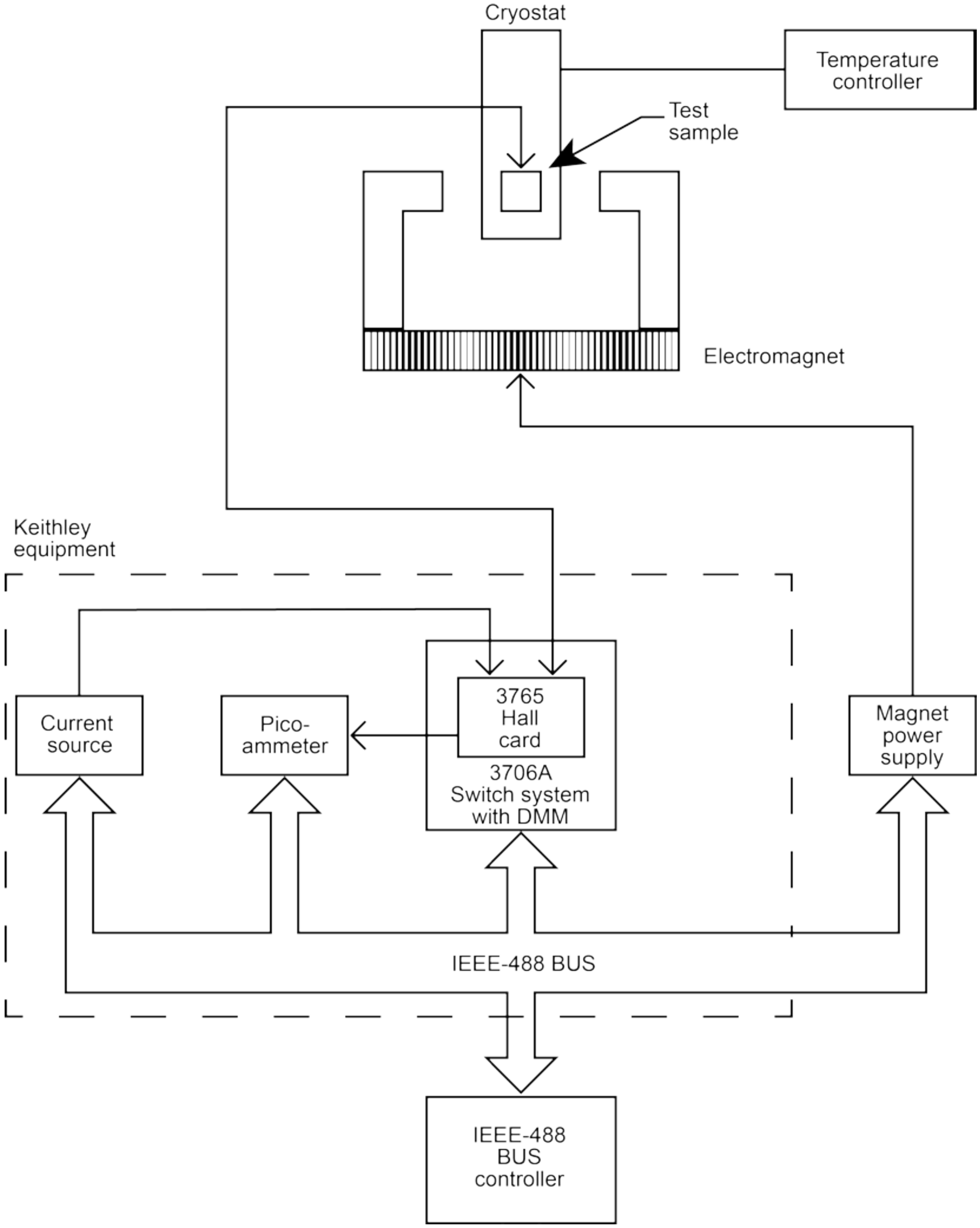
The figure below shows

Applications (on page 4-1) covers measurement methods in more detail.

The 3706A DMM can measure voltage directly from the 3765 card. Closing the backplane relay 911, routes HI and LO signals onto the backplane; allowing the DMM to measure the voltage.

The 3765 has a 12 V voltage clamp and a 500 μA current limit. This prevents excessive voltages and damage to the card from other cards that are installed in other slots. The current limit circuit adds 2 kΩ to the path resistance. Since the 3706 DMM has input resistance of >10 GΩ on the 100 mV, 1 V, and 10 V ranges, accuracy degradation should be minor. The DMM can be connected to J7 (external terminal block) pins 5 and 4 if accuracy degradation is too significant, but this bypasses the protection network. As another way of bypassing the protection circuitry, connect the DMM through the 3706A rear panel connector or an external DMM. Refer to the next figure for an example. For a figure showing the protection network (voltage clamp), see Configuration with a nanovoltmeter with a protection network (on page 3-7).

Figure 4: Basic Hall system configuration



When making low resistivity measurements, voltage sensitivity and noise may be critical. A nanovoltmeter may be required to achieve optimal performance. The nanovoltmeter can be connected to J7 (external terminal block) pins 5 and 4.

Applications (on page 4-1) covers measurement methods in more detail.

The figure below shows a test system that includes an external DMM or nanovoltmeter along with the protection network (voltage clamp).

Figure 5: Connecting a nanovoltmeter

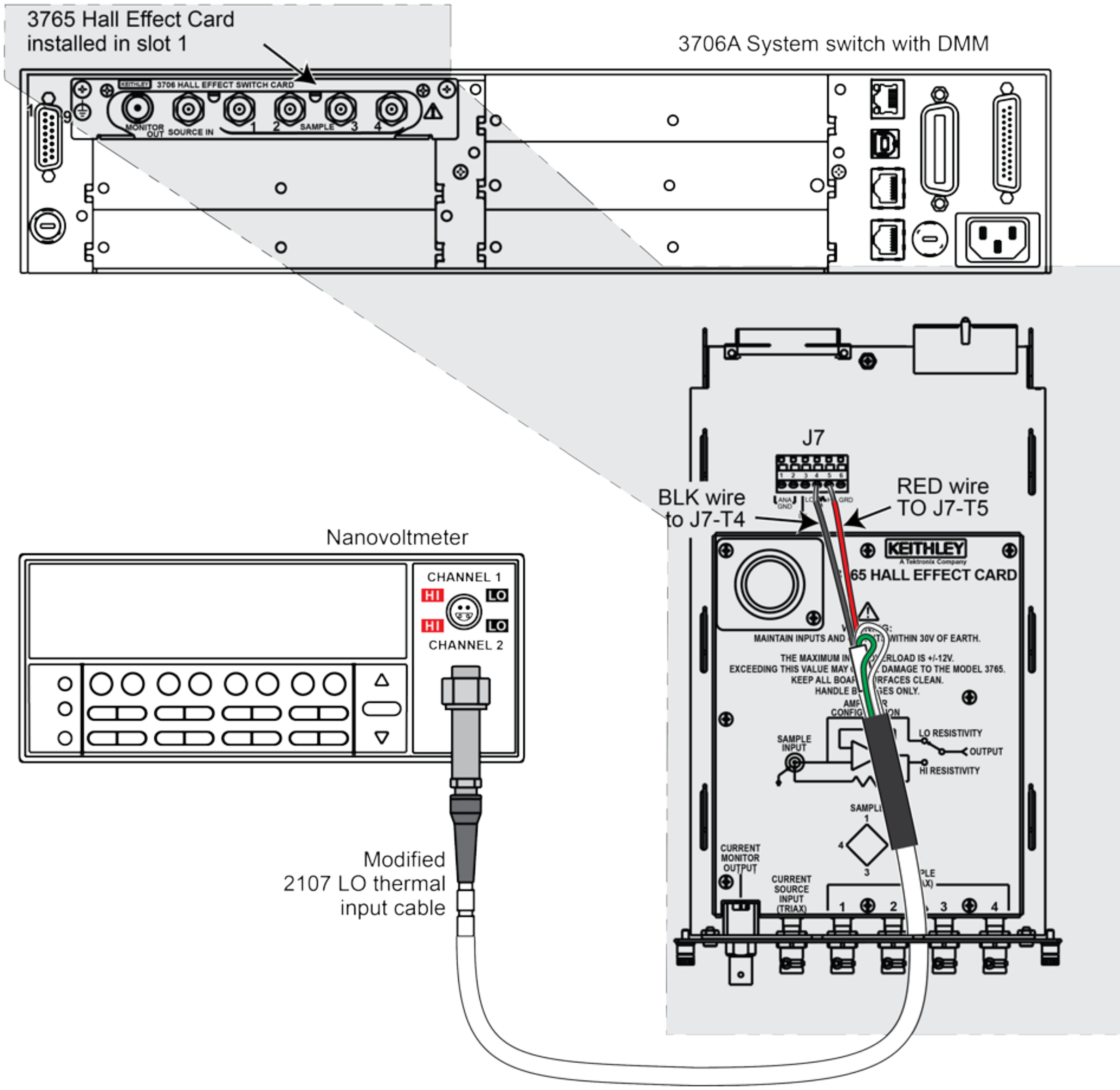
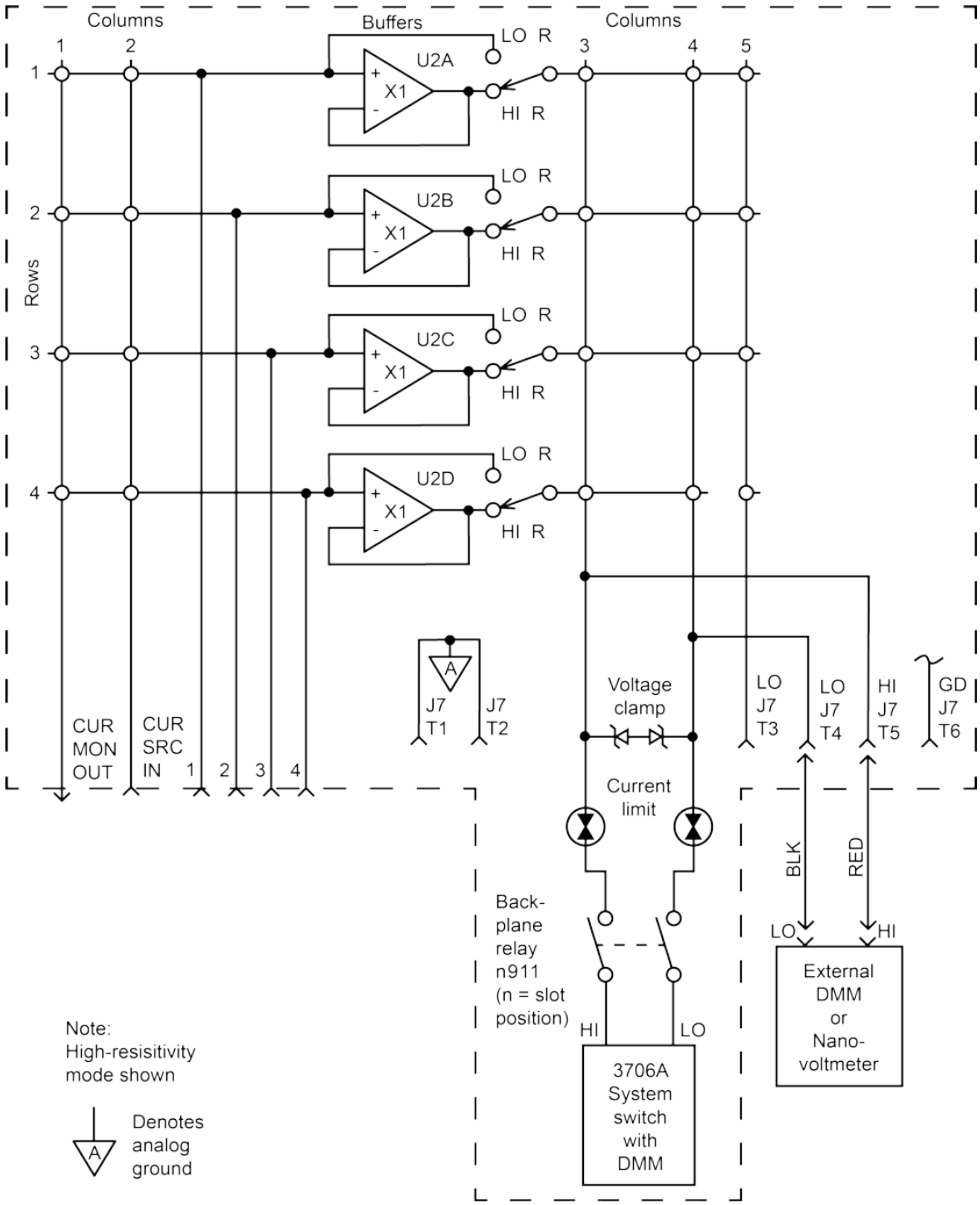


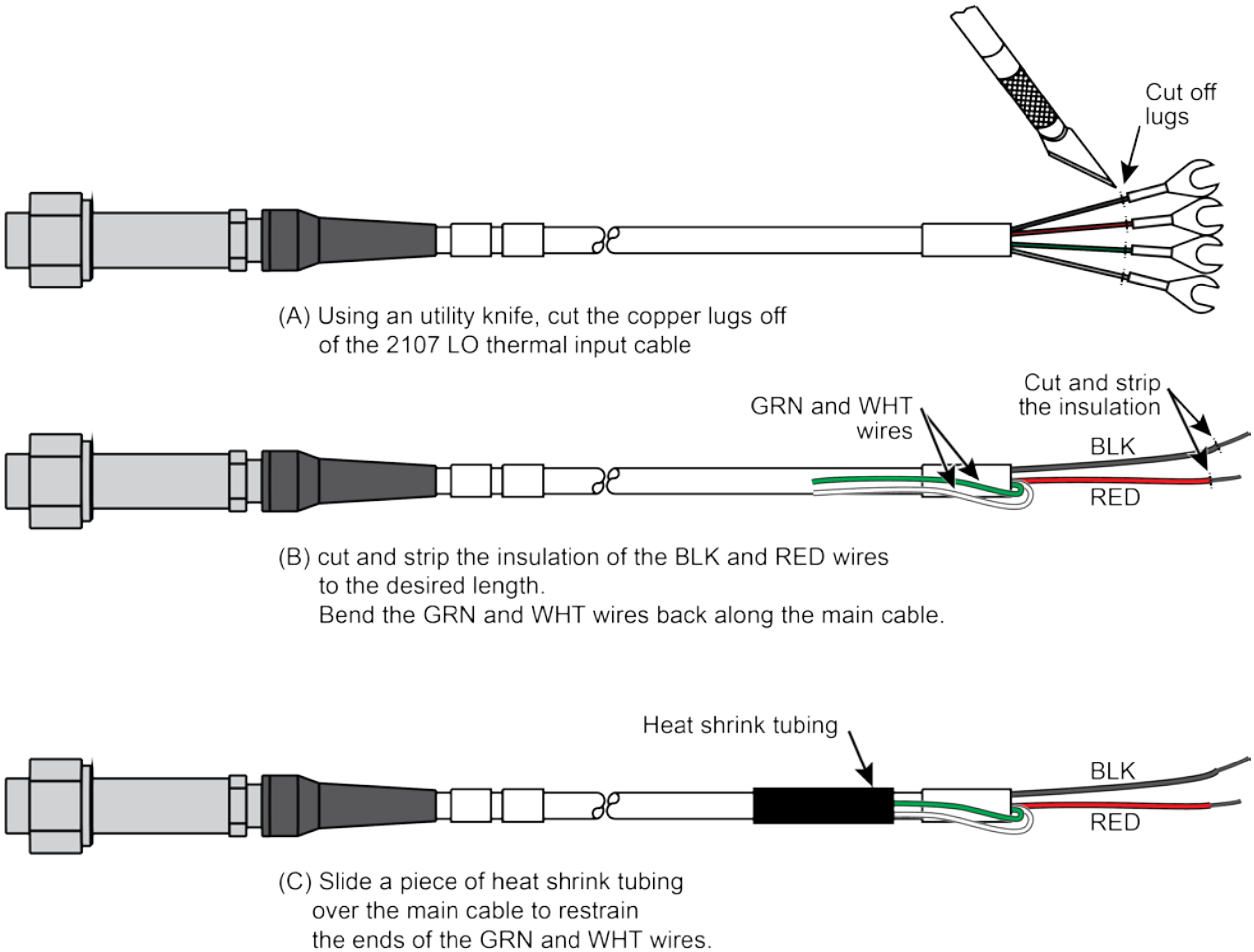
Figure 6: Nanovoltmeter configuration



Cable connection for the nanovoltmeter

The 2107-4, 2107-30, and 2107-50 cables are recommended for making connections when using the nanovoltmeter. Remove the spade lugs and connect the unterminated end to J7 (external terminal block) pins 5 and 4. Preparation of these cables is shown in the figure below.

Figure 7: Cable preparation for the nanovoltmeter



Matrix card channel specifiers

The channels on the matrix cards are referred to by their slot, bank, row, and column numbers.

- **Slot**: The number of the slot in which the card is installed.
- **Row**: The row number is 1 to 4.
- **Column**: Always two digits.

Matrix card examples			
Specifier	**Slot**	**Row**	**Column**
1104	1	1	04
1203	1	2	03
3104	3	1	04

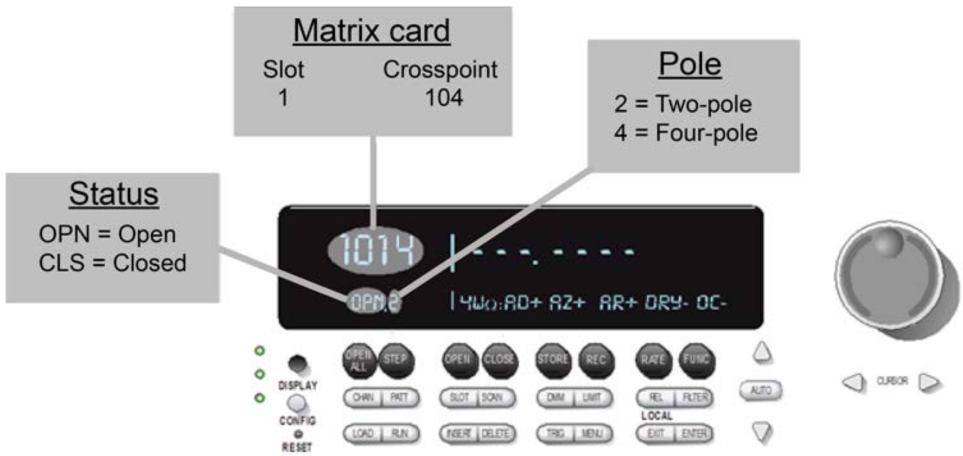
Analog backplane relay channel specifiers

The channels for slots with analog backplane relays are referred to by their slot, backplane, bank, and relay numbers:

- **Slot:** The number of the slot.
- **Backplane:** Always 9.
- **Analog backplane relay**: The number of the backplane relay.

Backplane relay examples			
Specifier	**Slot**	**Backplane**	**Backplane relay**
1911	1	9	1
2911	2	9	1

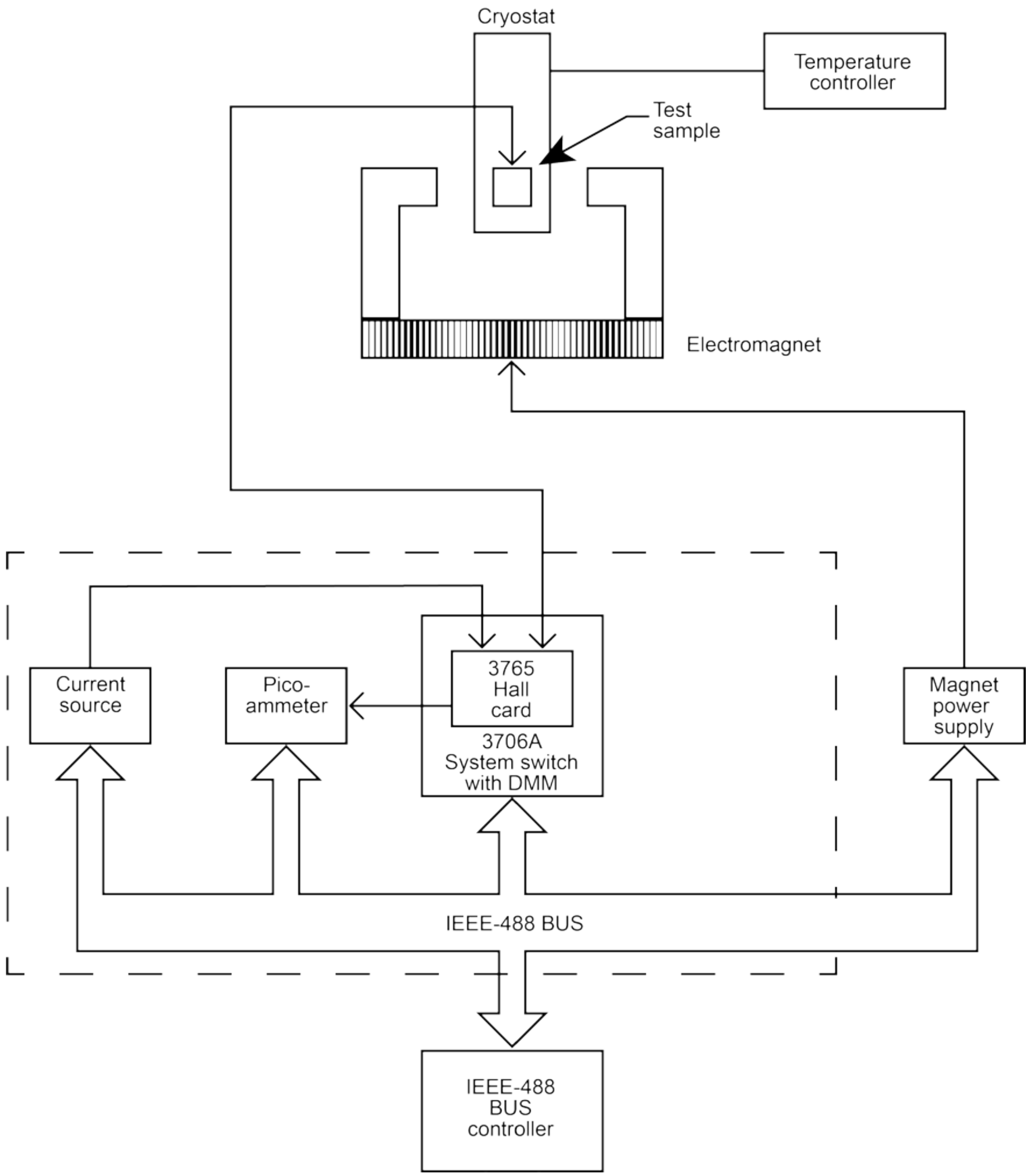
Figure 8: Channel specifiers on display



Test system

The next figure represents a basic configuration of an IEEE-488-based Hall measurement system. A system used primarily for resistivity measurements does not require the electromagnet or magnet power supply.

Figure 9: 3765 IEEE 488 test system



Cable preparation

The necessary cables, wires, and connectors are supplied with the 3765. These cables and wires must be prepared before use as described below.

WARNING

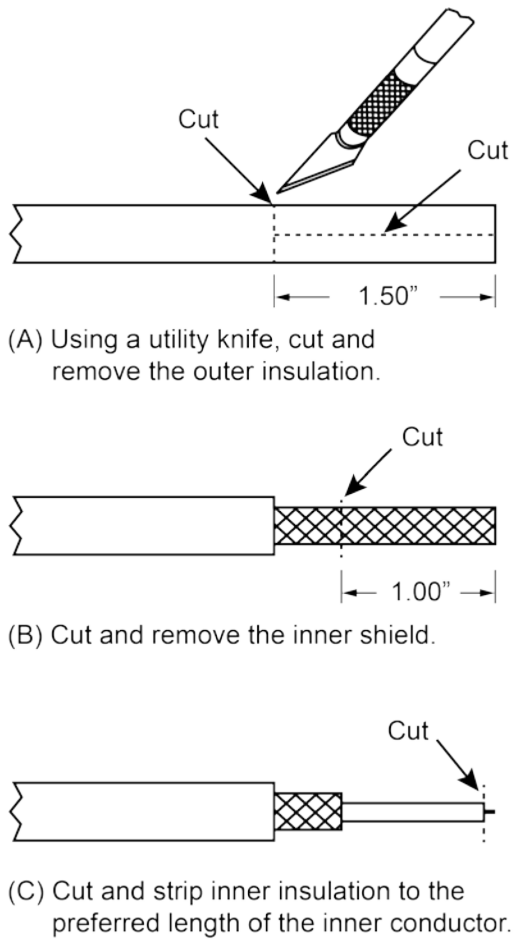
To prevent electrical shock that could cause injury or death, never make or break connections while the equipment is powered on. User supplied lethal voltages may be present on the PC board or the connections. Turn off the equipment from the front panel, disconnect the main power cord, and discharge stored energy in external circuitry before making or breaking cable connections. Putting the mainframe equipment into an output-off state does not guarantee that the outputs are powered off if a hardware or software fault occurs. Precautions must be taken to prevent a shock hazard by surrounding the test device and any unprotected leads (wiring) with double insulation for 1000 volts, Category I.

Triaxial cable preparation

The internal wire conductor must be exposed (stripped) to the proper dimension to ensure correct insertion depth in the connector. Excessive conductor will be exposed if the strip length is too long, which will cause an electrical shock hazard to equipment and personnel.

One end of each 7078-TRX triaxial cable must be prepared as follows before it can be connected to the sample under test. Refer to the figure below.

Figure 10: Triaxial cable preparation



Prepare the 7078-TRX triaxial cable by:

1. Using a utility knife, cut the outer covering of the triaxial cable lengthwise as shown in part A of the previous figure.
2. Cut, strip, and remove the outer insulation about 1 ½ in. from the end of the cable.
3. Cut away the outer shield as far as the insulation is stripped.
4. Carefully strip insulation on the inner shield 1 in as shown in part B of the figure above.
5. After stripping the insulation, cut the shield from the cable as shown in part C of the figure above.
6. Carefully strip the insulation on the inner conductor to the preferred length, then twist the strands together.
7. Connect the cable to the the inputs on the rear panel of the 3765.
8. Connect the unterminated ends of the cable to the DUT.

Coaxial cable preparation

In situations like bar and bridge samples, the picoammeter must be connected directly to the sample using a 4802 coaxial cable.

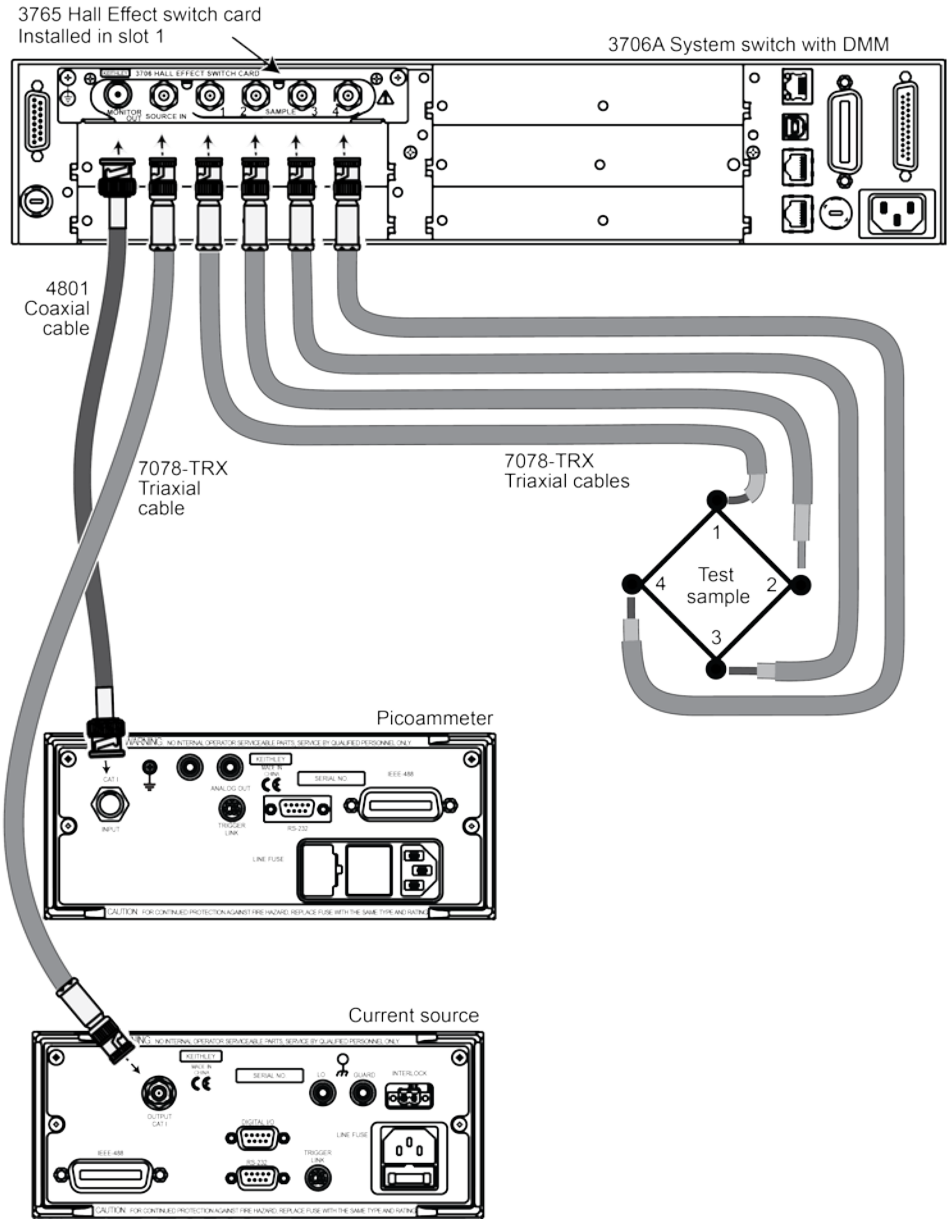
To prepare the 4802 coaxial cable:

1. Cut back the outer insulation about one inch, then remove it.
2. Remove the exposed shield by cutting it back to the insulation.
3. Strip the inner insulation to the preferred length.
4. Twist the strands together.

van der Pauw sample connections

The next figure shows typical connections for measurements made using the van der Pauw method.

Figure 11: Connections for van der Pauw Samples



To make the connections:

1. Connect the current source input connector of the 3765 to the output (Ext) connector of the current source using a 7078-TRX triaxial cable.

NOTE

This setup assumes that the guarded source input configuration is to be used. See Guardng methods (on page 3-30) for more information on guarding.

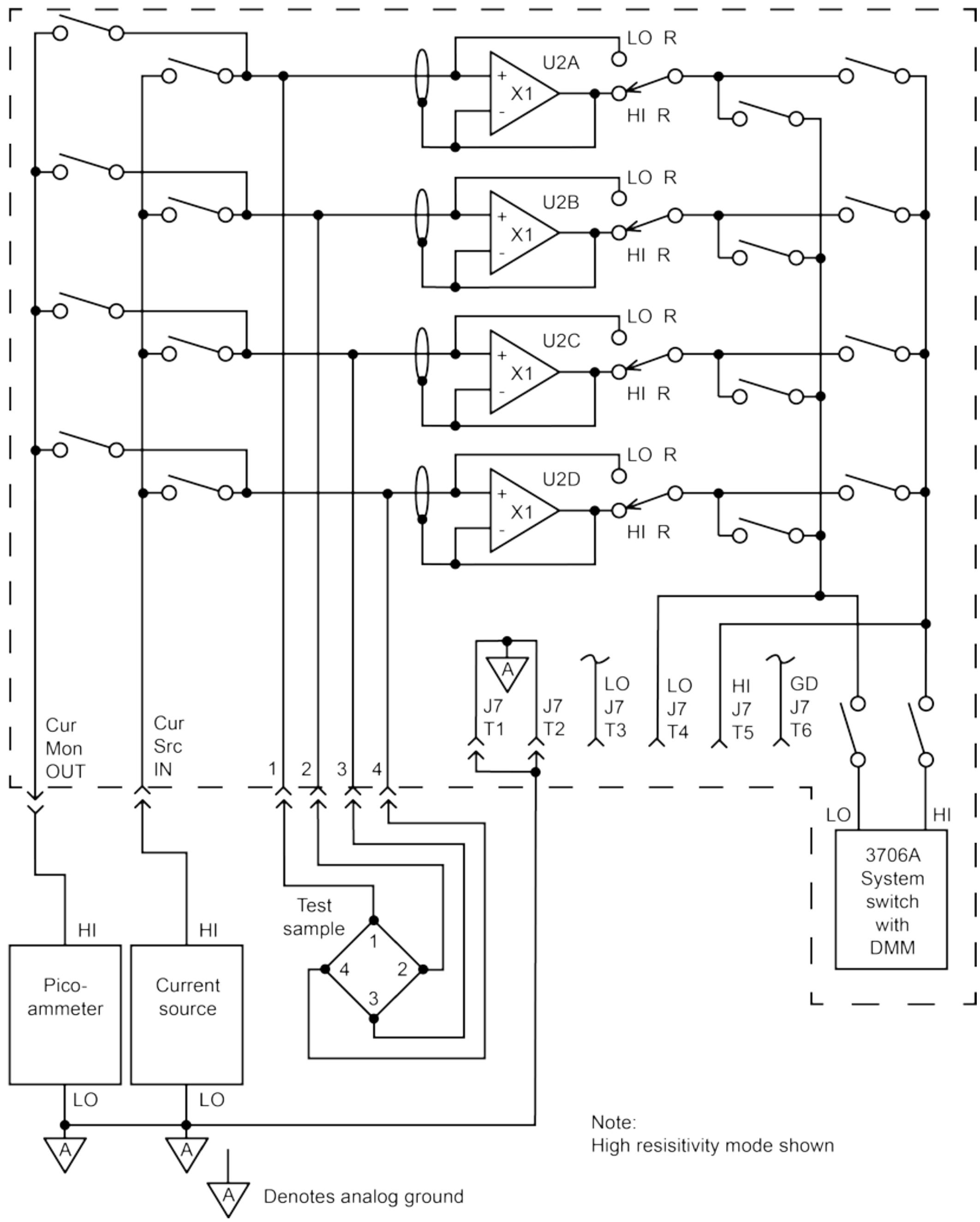
2. Connect the four terminals of the testing sample to the sample inputs using the supplied triaxial cables. See triaxial cable preparation (on page 3-14) for cable stripping instructions.
3. Connect the picoammeter to the current monitor output jack on the 3765 using the supplied BNC 4801 low-noise cable.

NOTE

If no picoammeter is used, use the 4851 shorting plug in the above step. Refer to Hall Effect card matrix (on page 3-4) for a basic Hall system configuration.

For an example of an equivalent circuit, see the next figure.

Figure 12: Equivalent circuit for van der Pauw connections



Bar-type sample connections

The next figure shows typical connections for a measurement made using the bar-type method.

To make the connections:

1. Connect the current source OUTPUT (Ext) connector using a 7078-TRX triaxial cable.

NOTE

This setup assumes that the guarded source input configuration is to be used. See Guarding methods (on page 3-30) for more information on guarding.

2. Connect the four terminals of the testing sample to the sample inputs using the supplied triaxial cables. See triaxial cable preparation (on page 3-14) for cable stripping instructions.
3. Connect the supplied 4802 BNC low-noise cable connector to the picoammeter input and the unterminated end directly to test sample.

NOTE

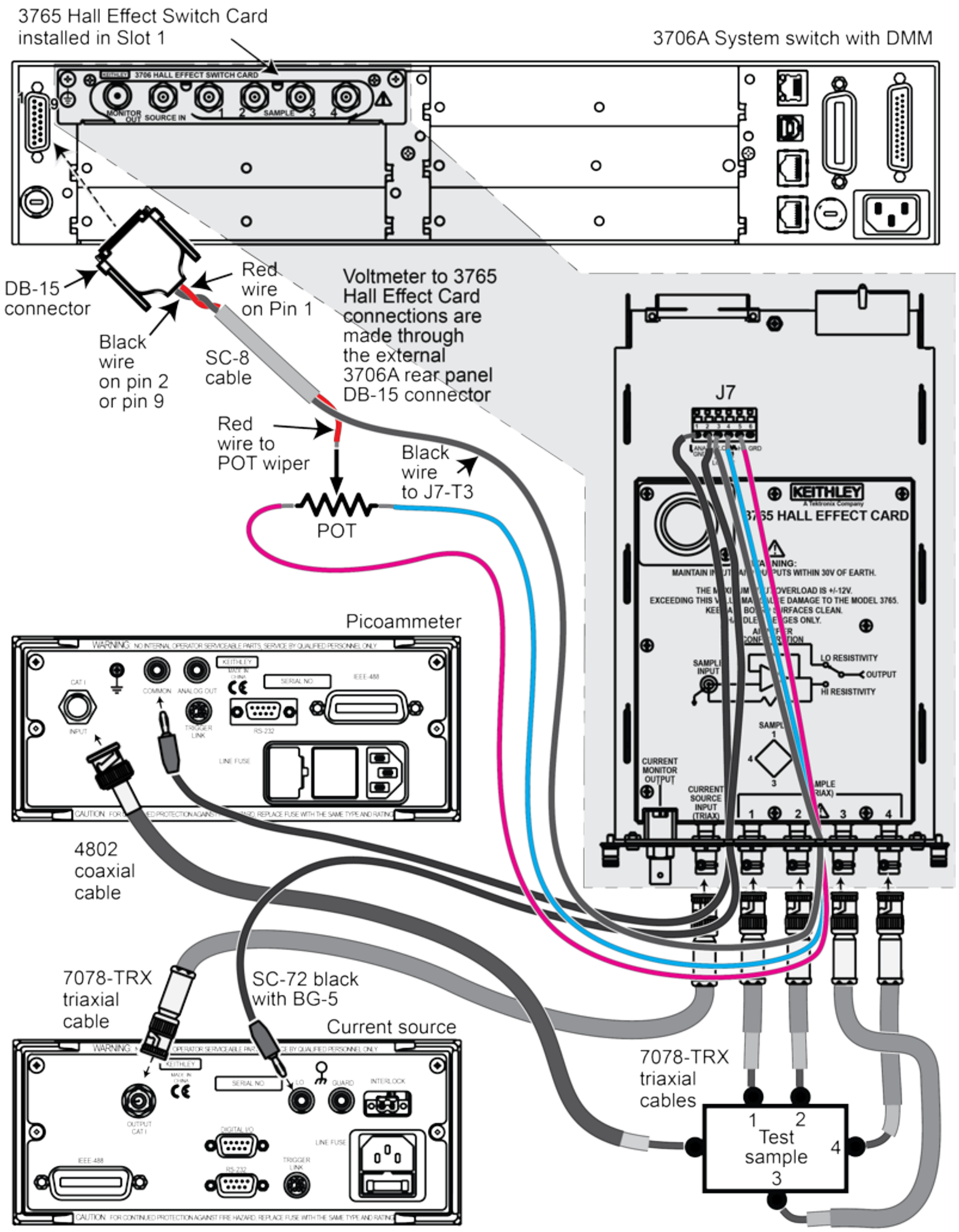
If no picoammeter is used, use the 4851 shorting plug in the above step.

4. Connect a shielded cable (DB-15) to the J7 terminal. See Recommended cables and connectors (on page 2-4) and cable preparation (on page 3-13).
5. Connect the shielded cable to the external voltmeter or the 3706A rear panel connection.

Hall voltage measurements for bar-type samples

Use the basic scheme, shown in the next figure, for Hall voltage measurements on bar-type samples.

Figure 13: Connections for Hall Voltage measurements of Bar Type samples



To make connections:

Connect the sample to the sample inputs, as shown in the next figure. Use the supplied 7078-TRX triaxial cables. See triaxial cable preparation (on page 3-14) for instructions.

NOTE

When programming the current source, you have the option to use the front panel or to do so remotely. See front panel current source programming (on page 3-40) or IEEE-488 bus current source programming (on page 3-40) for more information.

1. Connect a suitable potentiometer between terminals 4 and 5 of the terminal strip. See Determining potentiometer values (on page 4-21) for details on selecting the correct potentiometer value.

NOTE

For the step above, the guard needs to be connected to the center shield of the triaxial cable.

2. Connect a 7078-TRX triaxial cable between the current source connector output and the 3765 current source input connector.

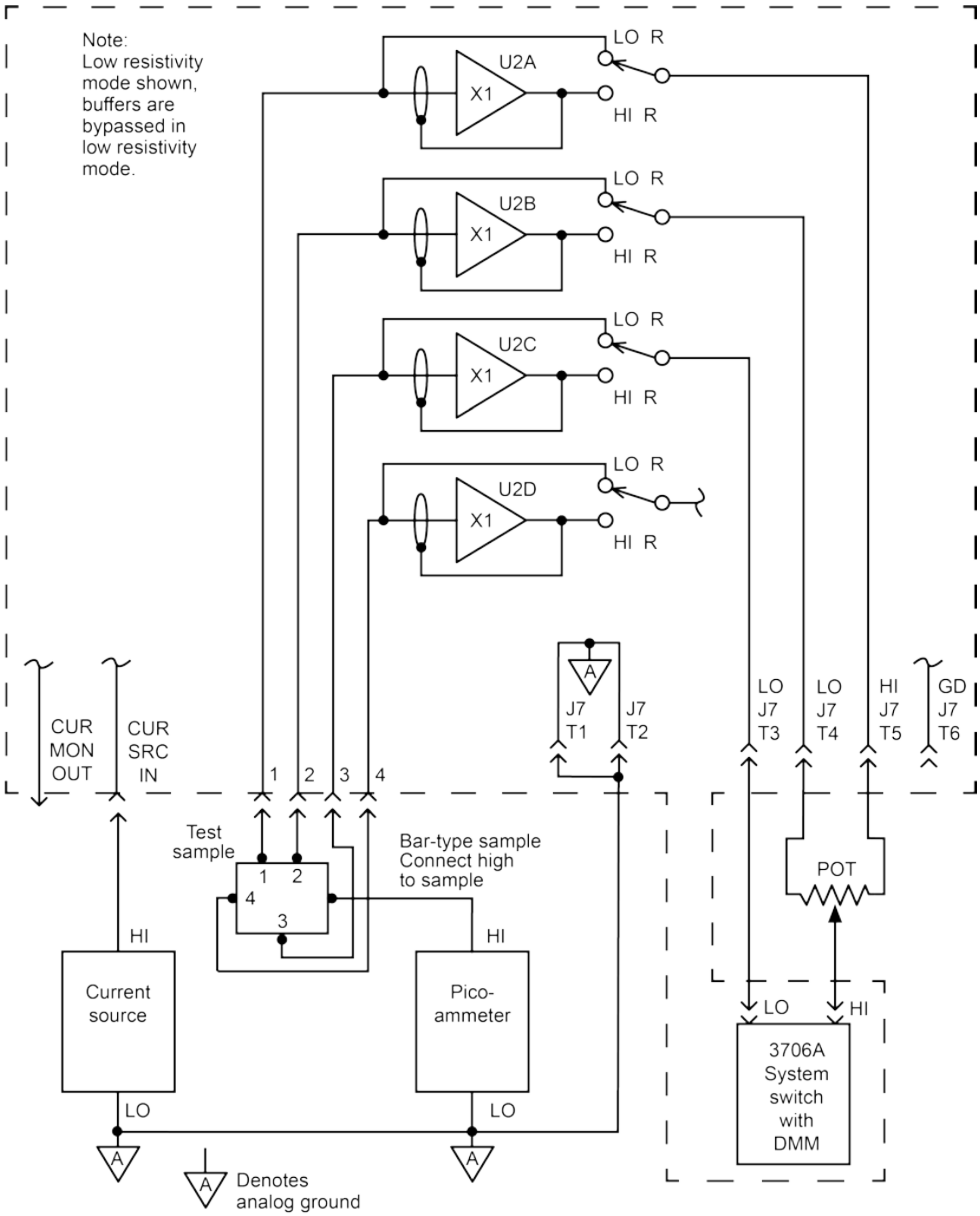
NOTE

This connecting method assumes guarded source input operation. See Guarding methods (on page 3-30) for more information on guarding.

3. Connect the picoammeter HI input terminal directly to the sample under test through a 4802 coaxial cable.
4. Connect a black banana plug wire to the analog ground on the terminal block and to the picoammeter analog output LO.
5. Connect DMM-LO (pin 2 or 9 of DB-15) to the 3706A.
6. Connect DMM-HI (pin 1 of DB-15) to the 3706A.

For an equivalent circuit, see the next figure.

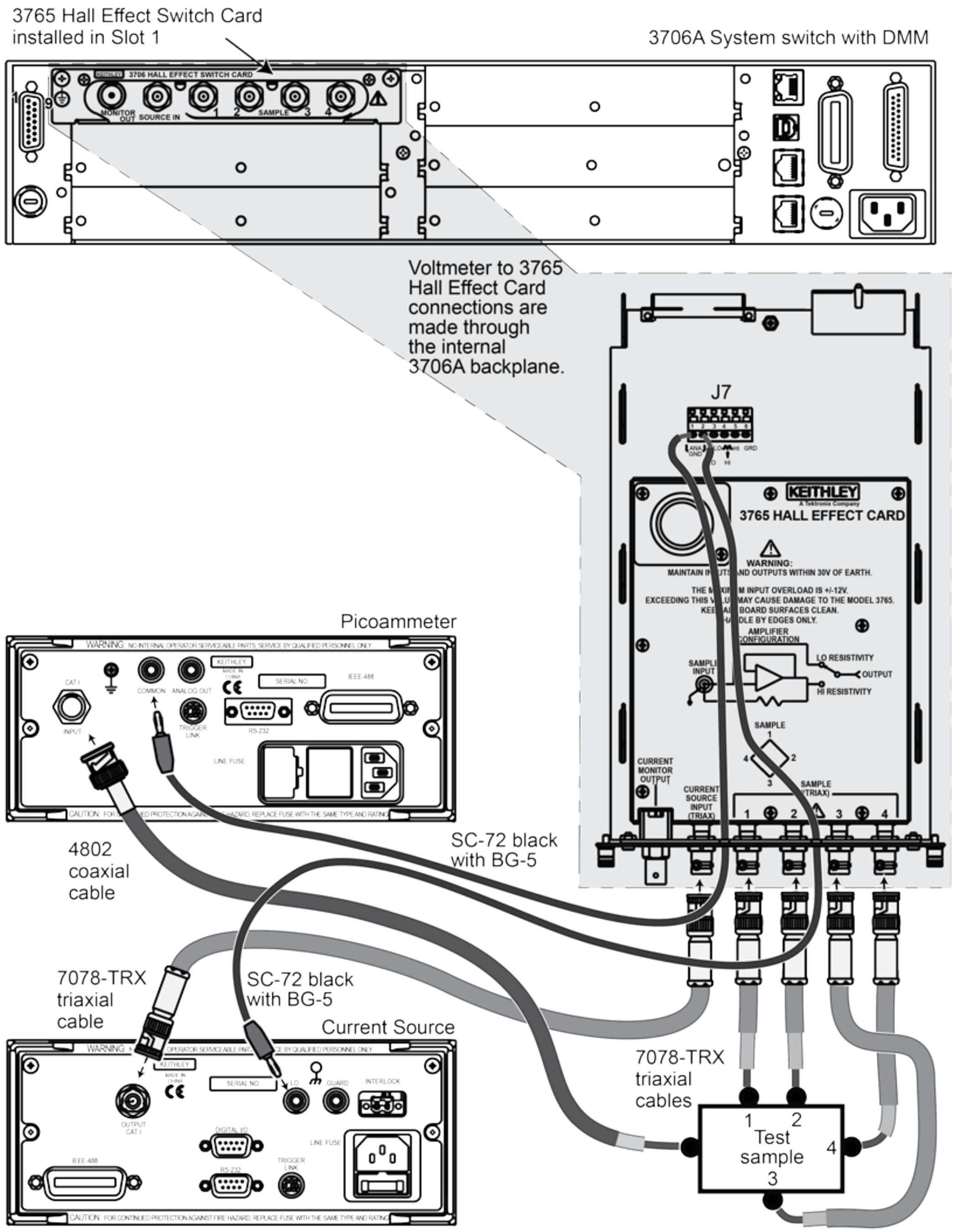
Figure 14: 3765 Hall voltage circuit equivalient



Resistivity connections for bar-type samples

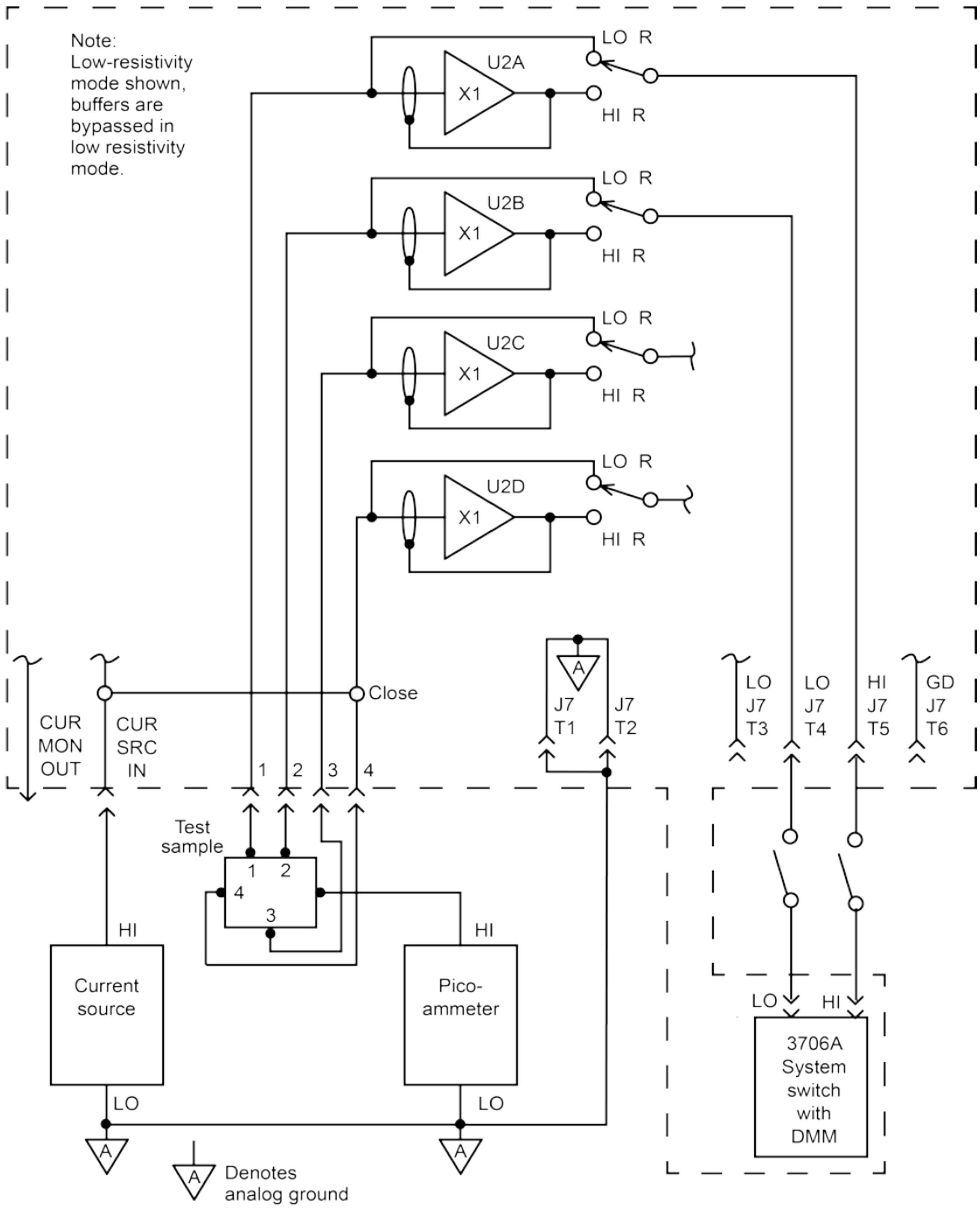
Except for the DMM connection, resistivity connections of bar-type samples are comparable to Hall voltage. As shown in the next figure, DMM-LO (pin 2 or 9 of DB-15) should be connected to terminal 4 of the J7 terminal strip, and DMM-HI (pin 1 of DB-15) should be connected to terminal 5.

Figure 15: Connections for resistivity measurements of bar-type samples



The next figure shows an equivalent circuit of the test configuration.

Figure 16: Resistivity measurements of bar-type samples



Bridge and parallel-piped type sample connections

To make 6- and 8-contact sample connections using the 3765, follow the steps below. Examples of these connections are shown in 6-contact samples (on page 3-26) and 8-contact samples (on page 3-28).

To make the required connections:

1. Connect the required sample terminals to the four sample inputs using the supplied 7078-TRX triaxial cables.
2. Using the supplied 4802 coaxial cable, connect the HI terminal of the picoammeter to the indicated sample terminal.
3. Connect a 7078-TRX triaxial cable to the current source, as indicated. Connect the current source HI center conductor to the sample, as shown in the previous figure.
4. The current source LO and picoammeter LO must be connected together. The connection method depends on whether or not the current input guarding is used. Depending on the the guarding, follow the instructions below. For more information on guarded and unguarded current input see Guarding methods (on page 3-30).
   - Unguarded: Connect the picoammeter analog output LO to the output LO terminal of the current source.
   - Guarded: Connect the picoammeter analog output LO to the output common terminal of the current source. The inner shield should be left floating at the sample end.
5. Regardless of the current input guarding configuration, the current source guard must be connected to the GRD terminal on the 3765 in order to drive the protection circuits on the card.
6. Connect the DMM to the 3765 as indicated on the appropriate diagram. Use the backplane relays to make the connections.

Connections for 6-contact samples are shown in the figures below.

Figure 17: Connections for 6-contact samples

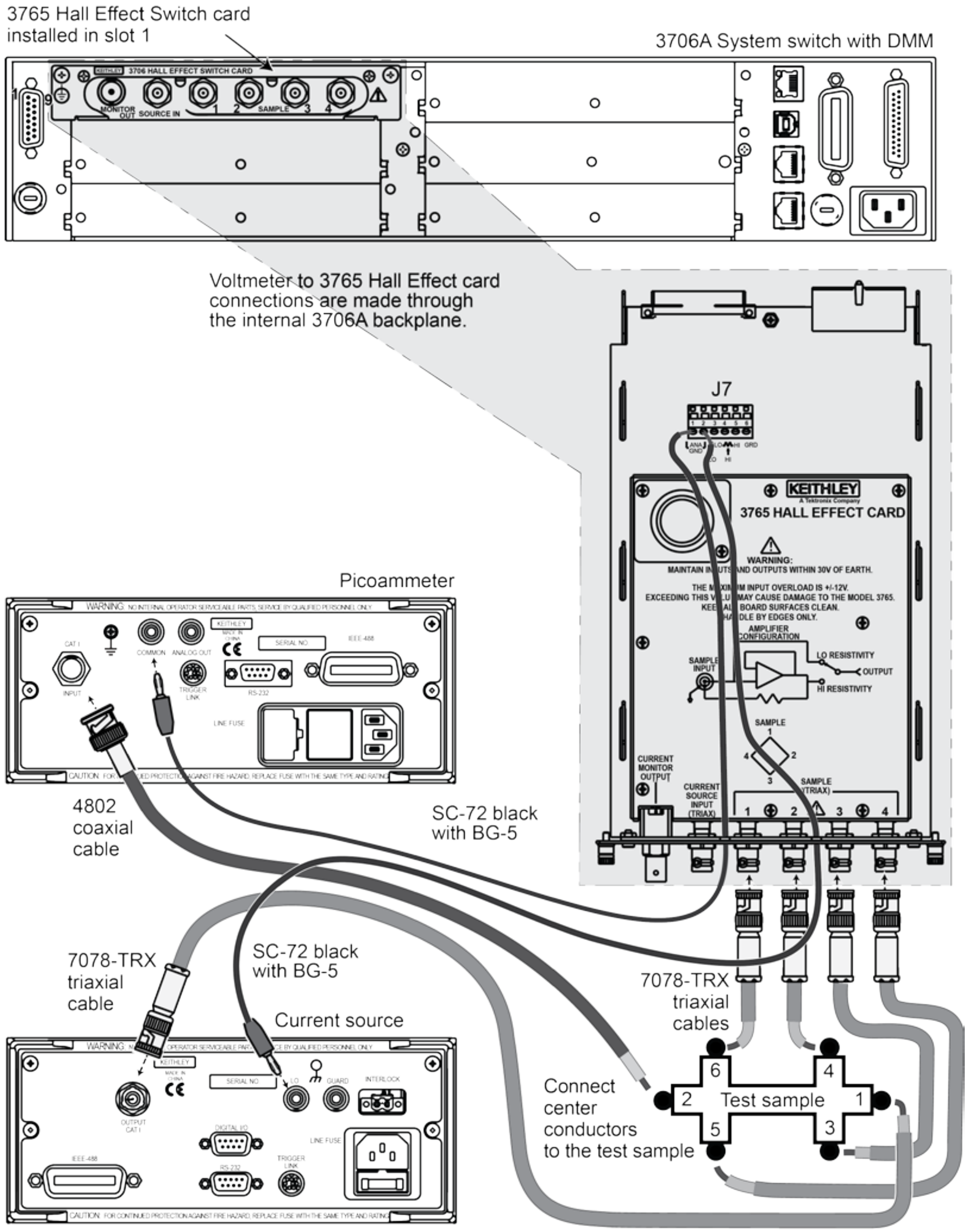
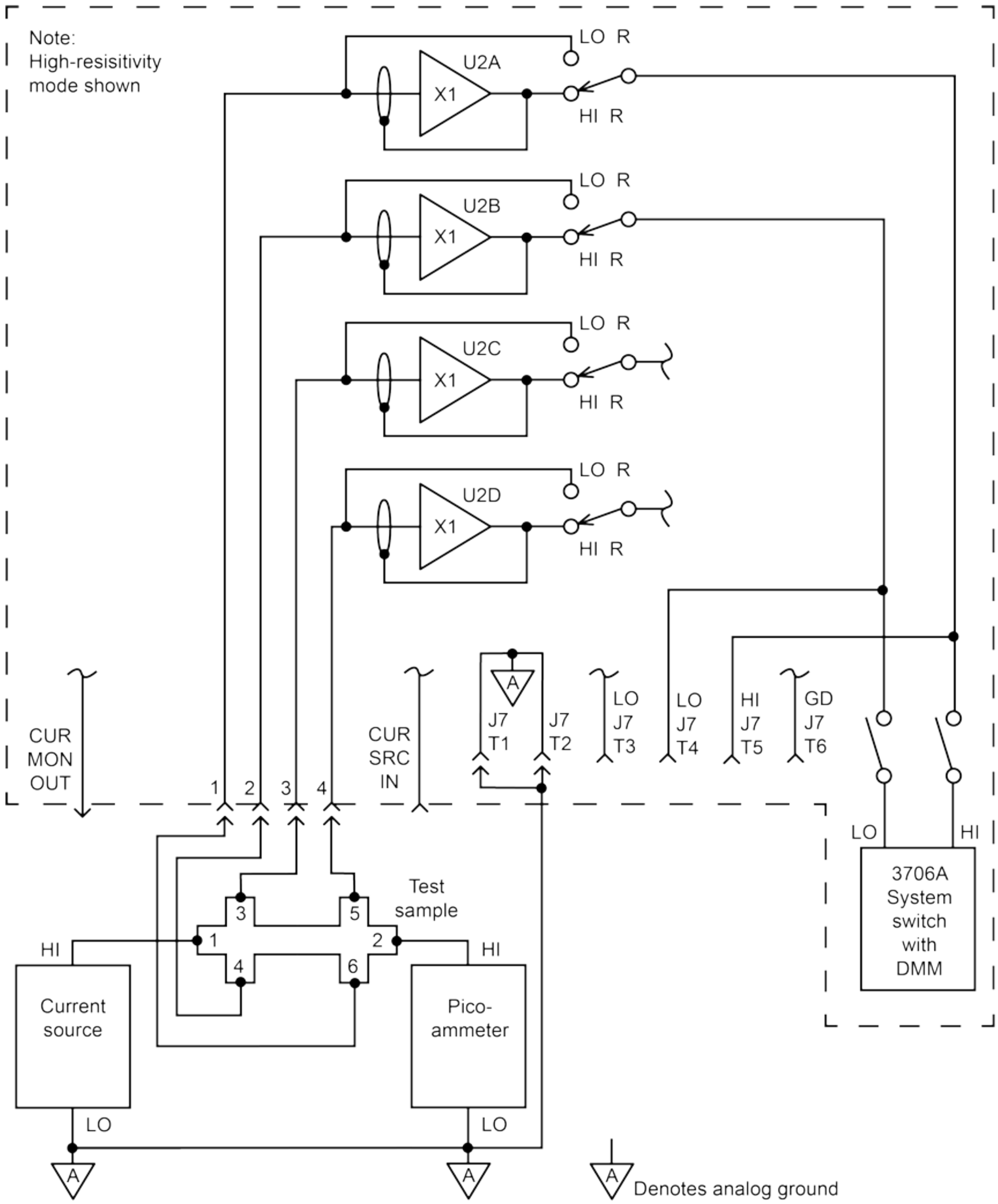


Figure 18: 3765 6-contact sample equivalent circuit



Connections for 8-contact samples are shown in the figures below.

Figure 19: Connections for 8-contact samples

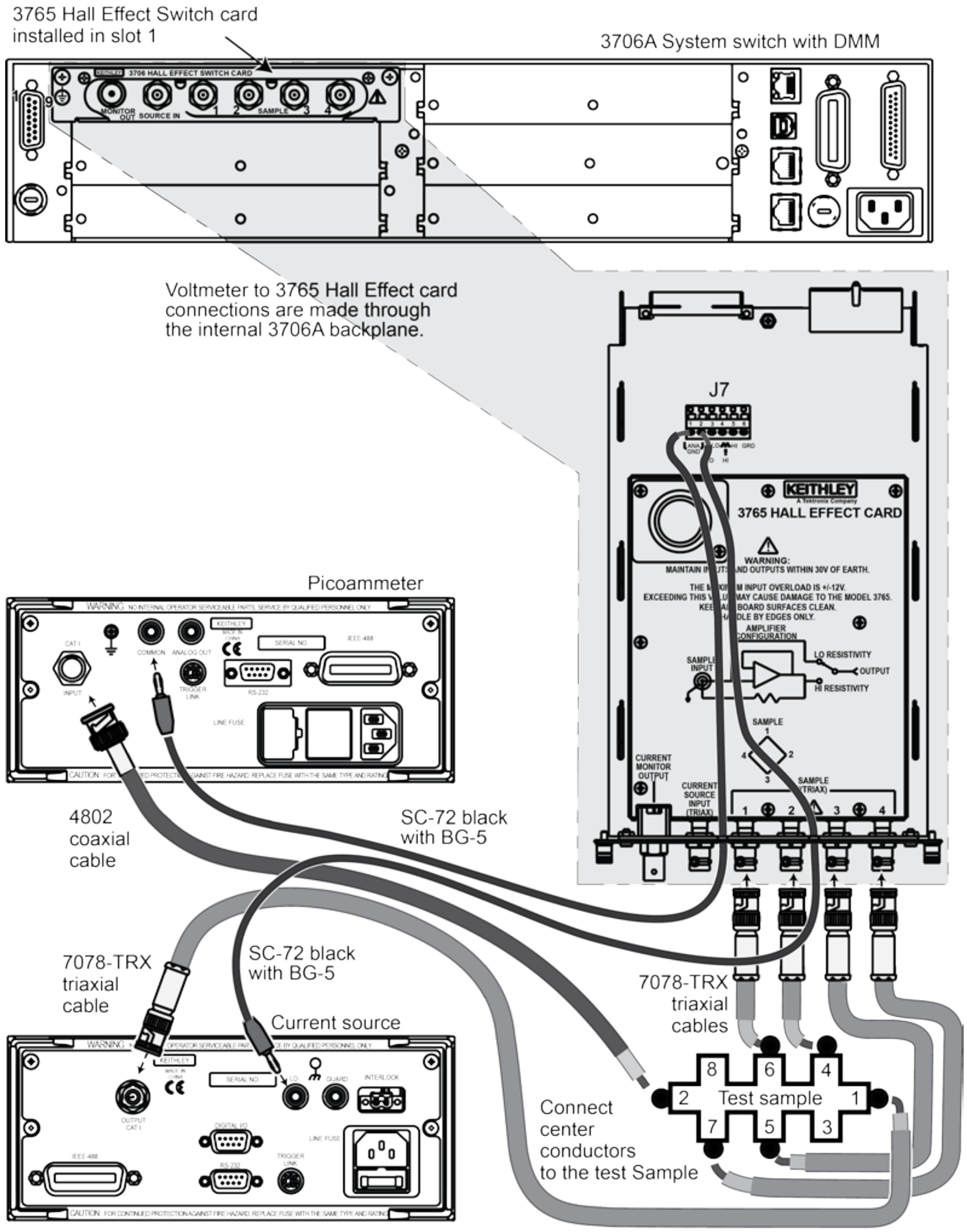
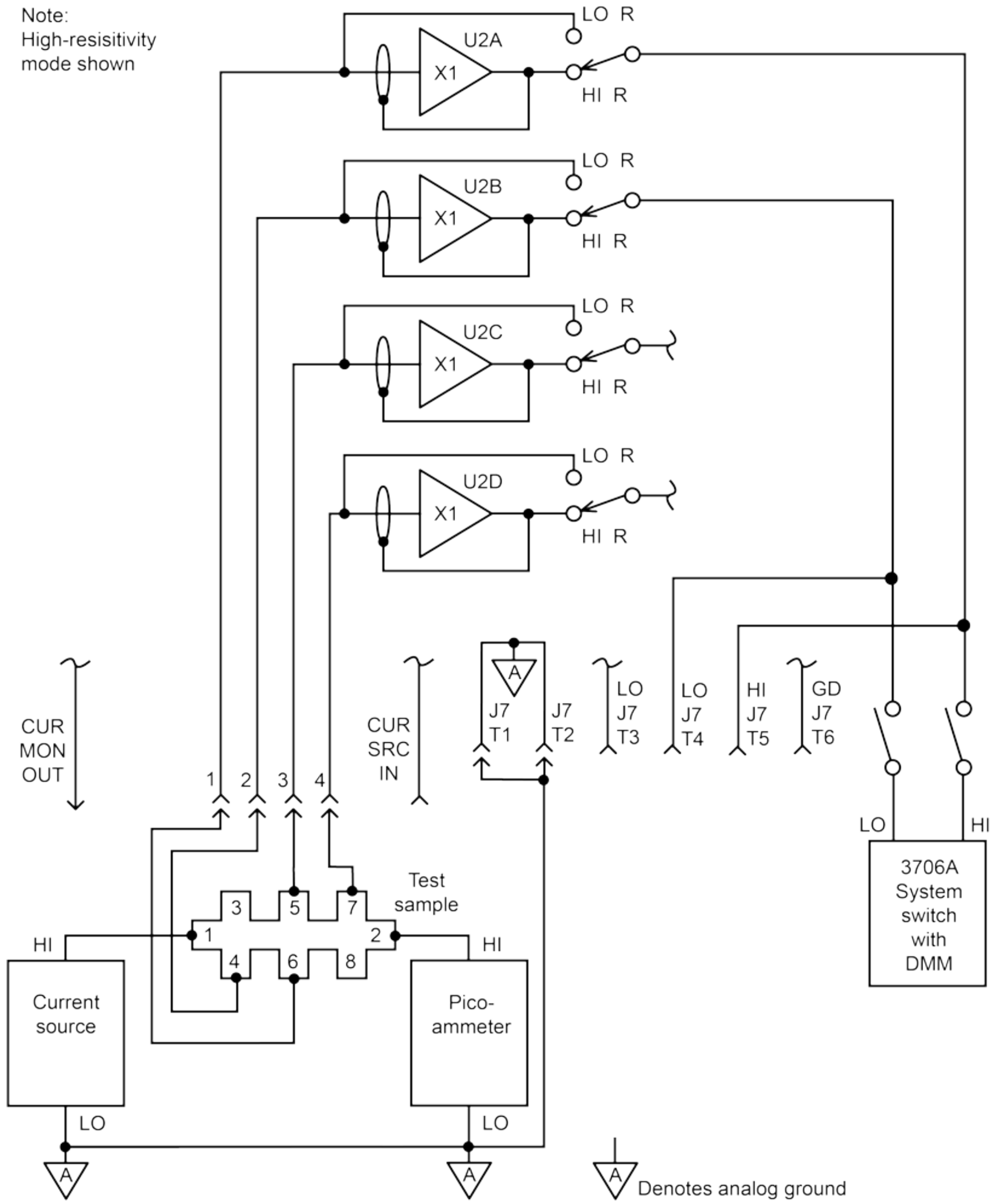


Figure 20: 3765 8-contact sample equivalent circuit



Shorting the current monitor output

To accurately measure the sample excitation current, you can set up a system with a 6485 or similar picoammeter. As an alternative, a system without a picoammeter can be used by placing the 4851 BNC shorting plug on the current monitor output jack in place of the picoammeter connecting cable. This shorting plug is necessary to complete the circuit for the current path. Note that shorting the current monitor output is not necessary for bar, 6-contact, or 8-contact samples because the picoammeter is connected directly to the sample for those measurements. In cases where a picoammeter is not used, short out the current monitor connection on the 3765.

Another situation requiring a BNC shorting plug is when the sample excitation current exceeds the 20 mA measurement capability of the picoammeter. In this case, the picoammeter should be disconnected from the 3765, and the 4851 shorting plug should be connected in its place.

IEEE-488 bus connections

Connect each instrument to the IEEE-488 bus using 7008 IEEE-488 cables. Refer to the instrument instruction manuals for more information.

NOTE

The 7008 IEEE-488 cables are not provided with the 3765.

Guarding methods

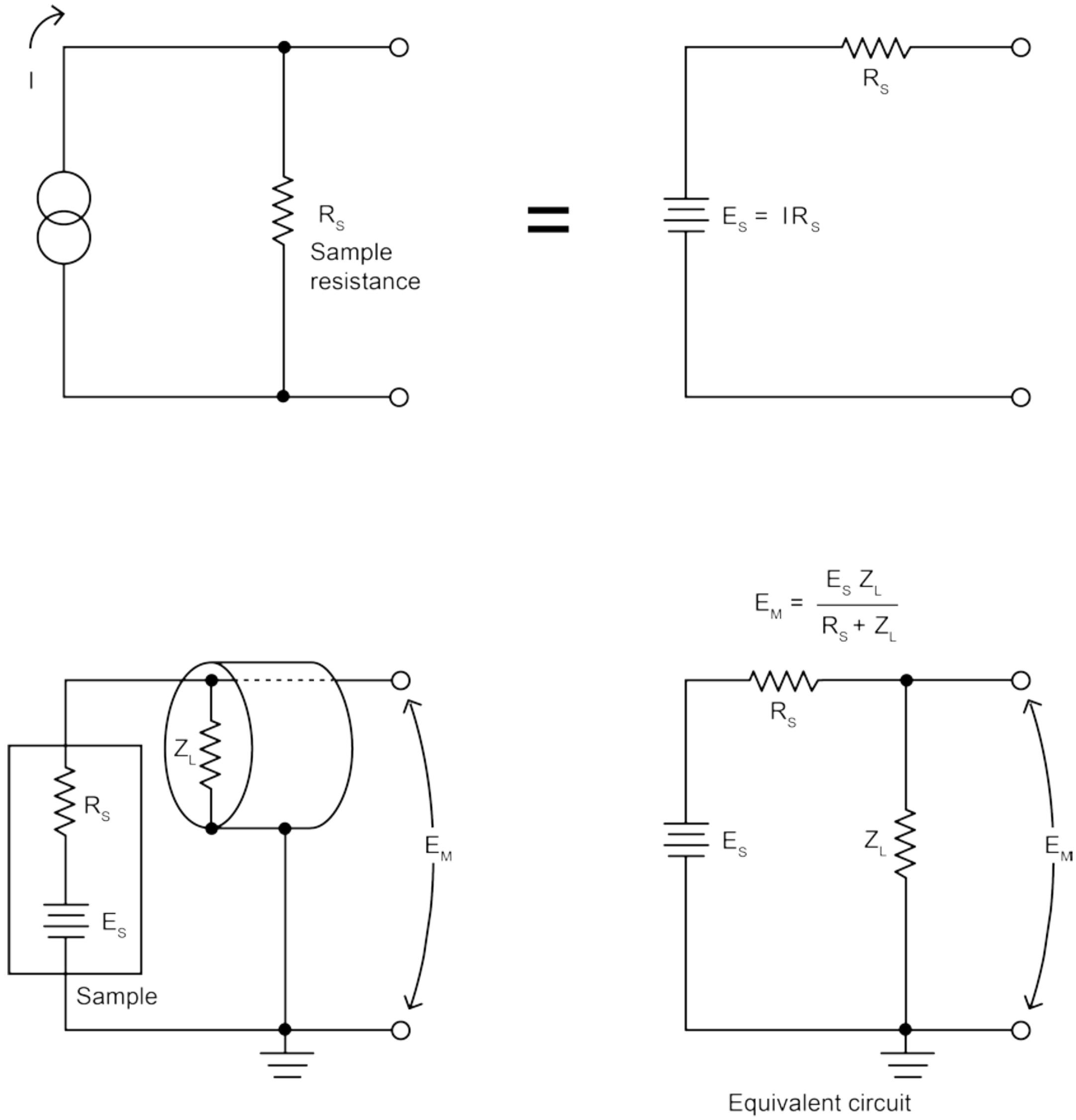
The following sections discuss guarding principles, current source input guarding methods,and sample input guarding.

Guarding principles

Guarding consists of using a conductor driven by a low-impedance source to surround the leads carrying a high-impedance signal. If the output voltage of the low-impedance source is kept at the same potential as the signal, you will notice reduced leakage effects, decreased response time, and lower noise.

To approach guarding, consider the unguarded circuit shown in the next figure. Here, the sample voltage is represented by E_S, while the sample resistance is R_S. The cable leakage impedance is Z_L, and E_M represents the actual measured voltage.

Figure 21: Unguarded circuit example



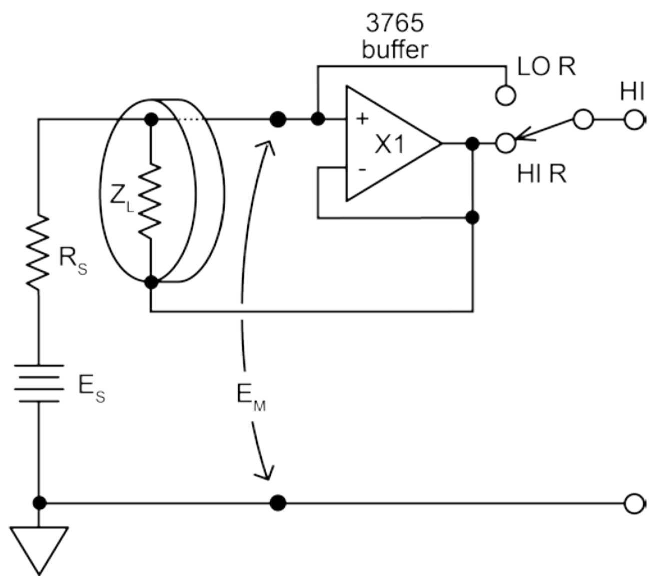
The sample resistance and cable impedance form a voltage divider that attenuates the sample voltage:

$$E_M = \frac{Z_L\ E_S}{Z_L + R_S}$$

To keep the leakage resistance error under 0.1%, the leakage resistance must be at least one thousand times the sample resistance. For low to medium resistivity samples, the leakage resistance is high enough to have minimal effects. However, with high resistivity, leakage resistance errors in unguarded circuits can be intolerably high.

Guarding the circuit minimizes these effects by driving the cable shield at signal potential, as shown in the next figure. Here, the 3765 buffer amplifier, which has high input impedance and low output impedance, is used to drive the inner shield. Since the amplifier has unity gain, the potential across the leakage resistance is zero. Leakage between the inner shield and ground (outer shield) may be considerable, but it is not a concern since that current is supplied by the buffer amplifier rather than by the sample signal voltage.

Figure 22: Guarded circuit example



Guarding reduces the effective cable capacitance, resulting in faster measurements on high-resistivity circuits. Because any distributed capacitance is charged through the relatively low impedance of the buffer amplifier, rather than by the source, guarding shortens the settling times.

As an example, a 10 GΩ resistance is measured through a cable with 200 pF of distributed capacitance. This results in an RC time constant of 2 s. At least ten seconds must be allowed for the circuit to settle to within 1% of the final value. Alternatively, guarding the circuit could result in a reduction in settling time of more than one hundred times.

Current source input guarding

When testing high-resistivity samples, the current source input must be guarded by the driven guard from the current source. The following sections discuss guarded and unguarded operation of the current source input and various connecting methods.

NOTE

After connecting the test system, changing between guarded and unguarded operations is difficult. Guarded mode can be used for all measurements and resistivities.

Guarding jumpers

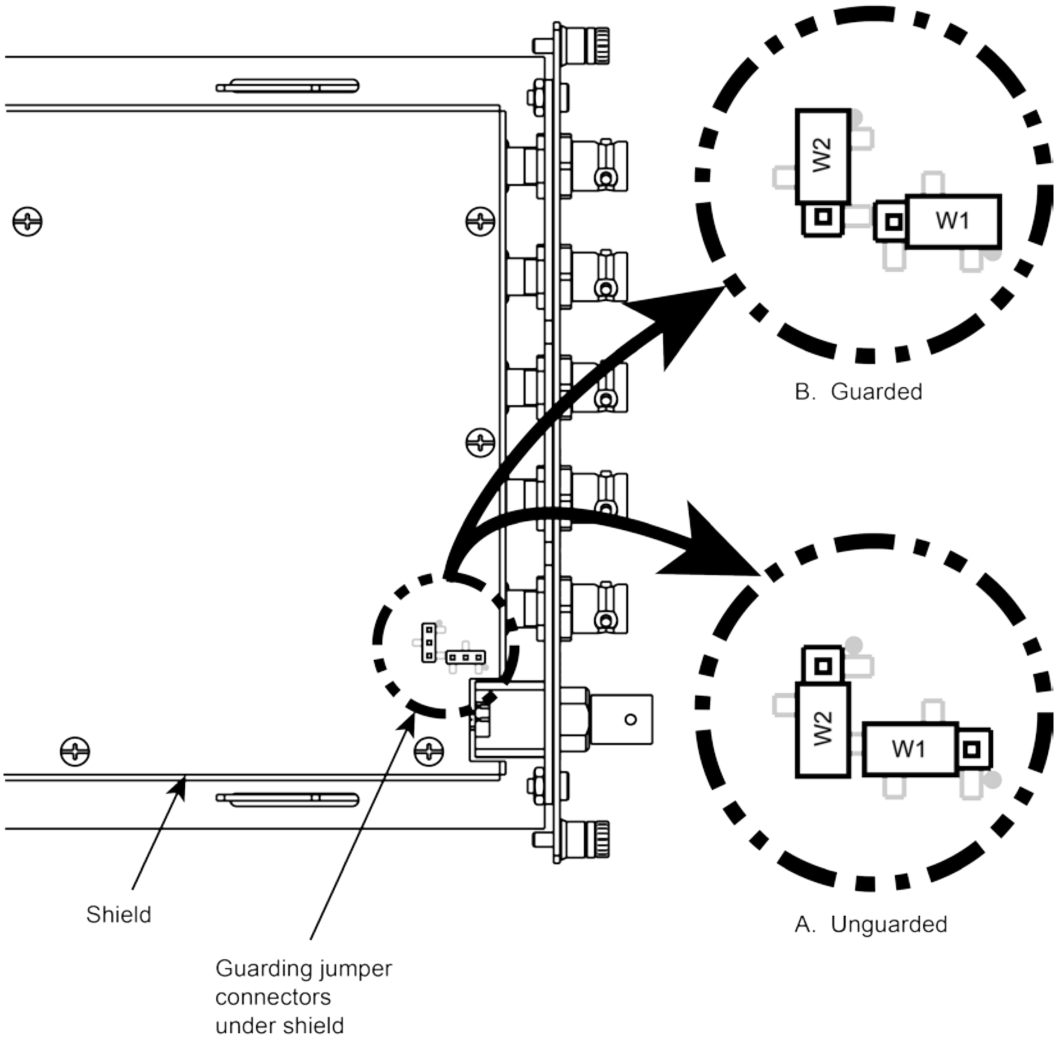
As shown in the next figure, the current source input for either unguarded or guarded operation is set up by two jumpers. The jumper configurations shown at the top of the diagram indicate which of the two configurations apply.

- Unguarded (A): This method can be used only for relatively low resistivity (10^5 Ω or less resistance) samples in low-resistivity mode.
- Guarded (B): This configuration is required with the high-resistivity mode.

NOTE

The current source must be programmed so that the inner shield of the triaxial cables are at guard potential.

Figure 23: Guarding jumpers



Changing jumper settings

The 3765 default setup is for is guarded configuration.

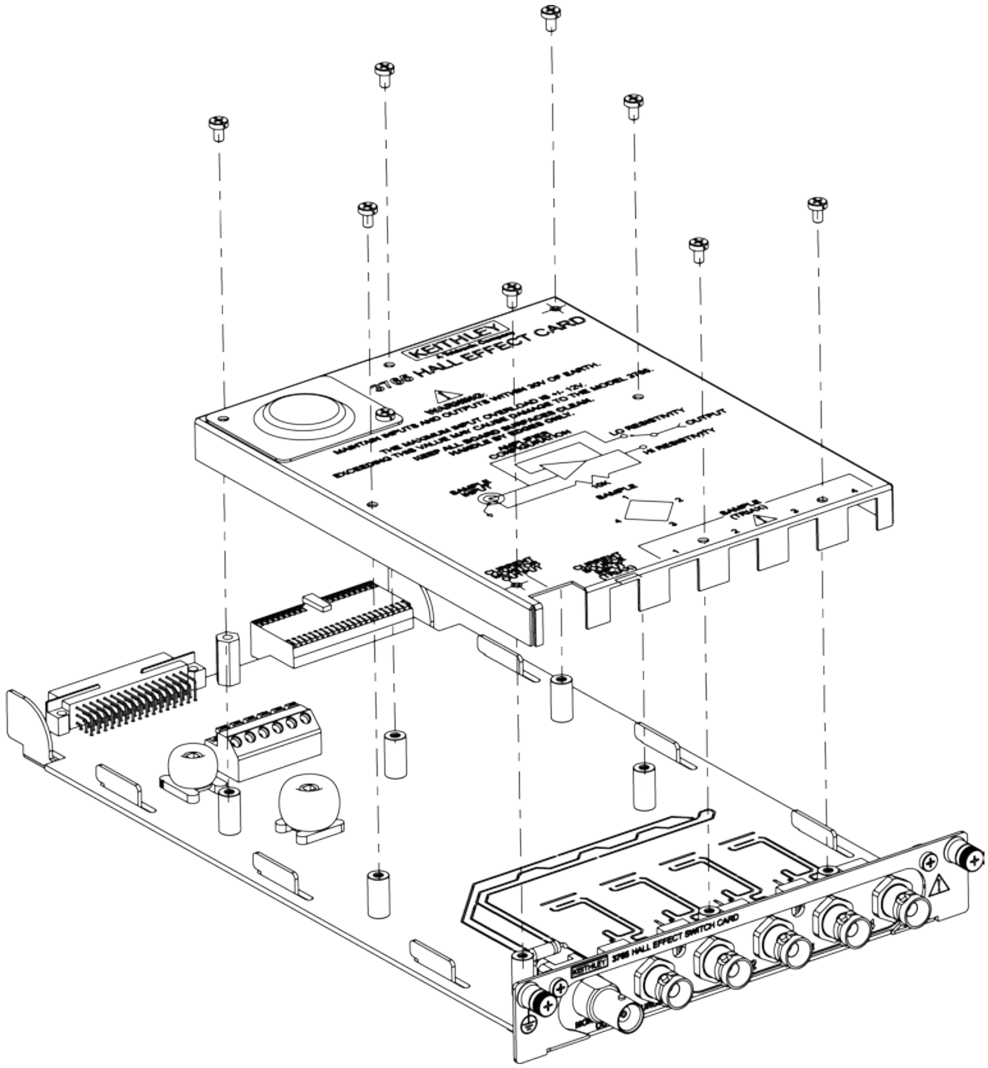
To change or verify the positions of the jumpers:

1. Turn off the 3700A power, and unplug the power line cord.
2. If it is installed, remove the card from the 3700A.
3. Remove the large outer shield.
4. Remove the inner analog shield from the 3765, as shown in the next figure.
5. Place the two jumpers in the necessary positions, as shown in the previous figure. Use a pair of needle-nose pliers to avoid touching the board.
6. Replace the shields and, if necessary, make additional connections as outlined below before installing the card.

CAUTION

Do not touch the board surface or any components on the board as doing so may degrade performance. Handle the board by the edges, and ensure that you are using grounding equipment while handling the board.

Figure 24: Changing jumper settings



Unguarded connections

Use the procedure below to connect the current source to the 3765 using the following figure as a guide. Note that this configuration should only be used with the card in the low resistivity mode, as discussed in Resistivity selection (on page 3-40).

To connect the current source to the 3765:

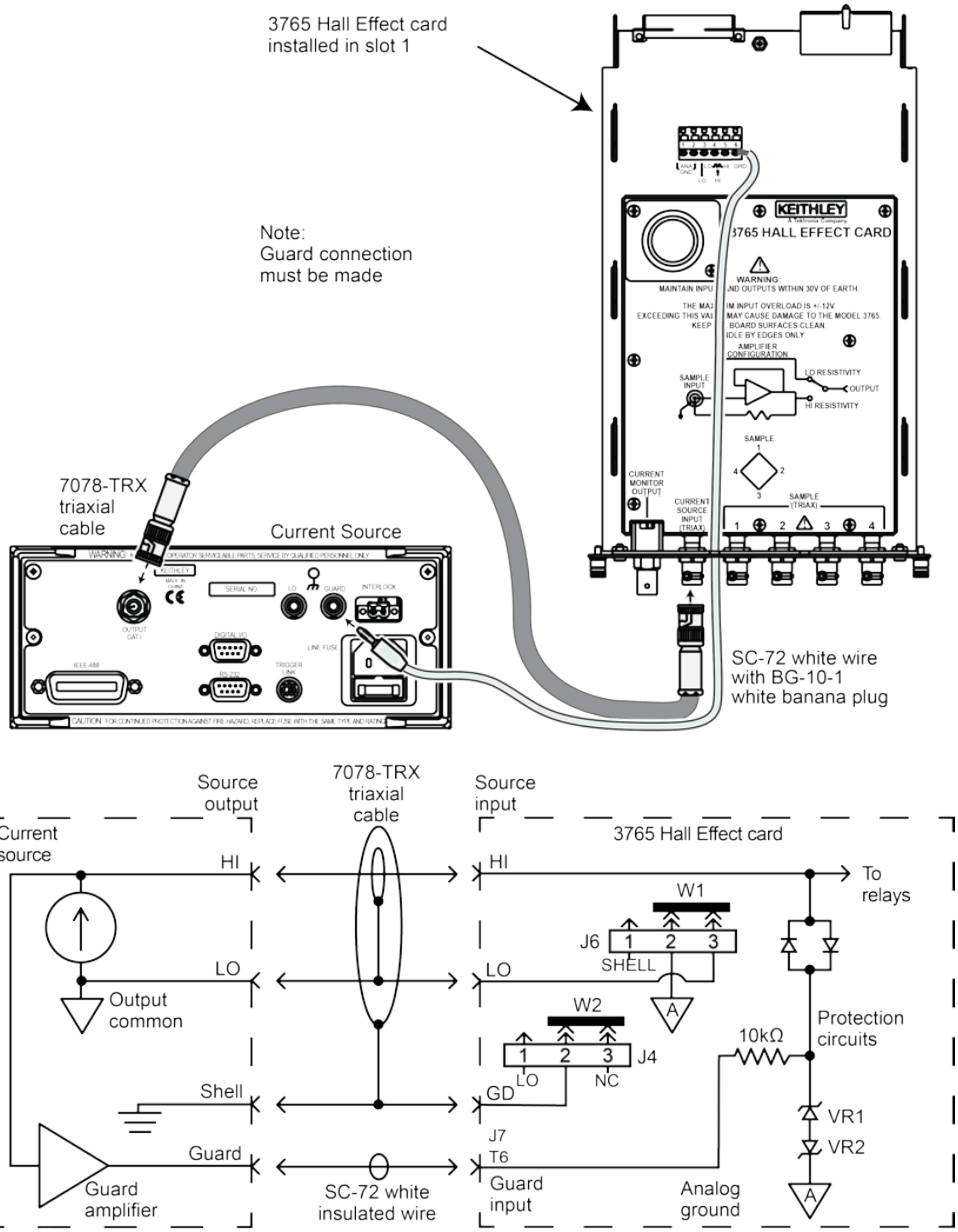
1. Connect the 7078-TRX triaxial cable between the current source output jack and the 3765 current source input.
2. Connect a supplied insulated white wire (with white banana plug) between the current source guard terminal and terminal 6 (GRD) of the terminal block on the 3765.

CAUTION

The current source guard must be connected to the 3765 guard even though the cable itself is not guarded. The current source guard is used to drive the protection circuits in the Hall Effect Card. These circuits protect the source input from damage caused by excessive voltages.

The next figure shows an equivalent circuit of these connections. Current source HI is carried through to input HI using the center conductor of the triaxial cable. Source LO is connected to scanner card analog ground through the inner cable shield, and the outer cable shield connects to the current source chassis only. The current source guard is connected to the guard input on the 3765 in order to drive the input protection circuits.

Figure 25: Unguarded connections equivalent circuit



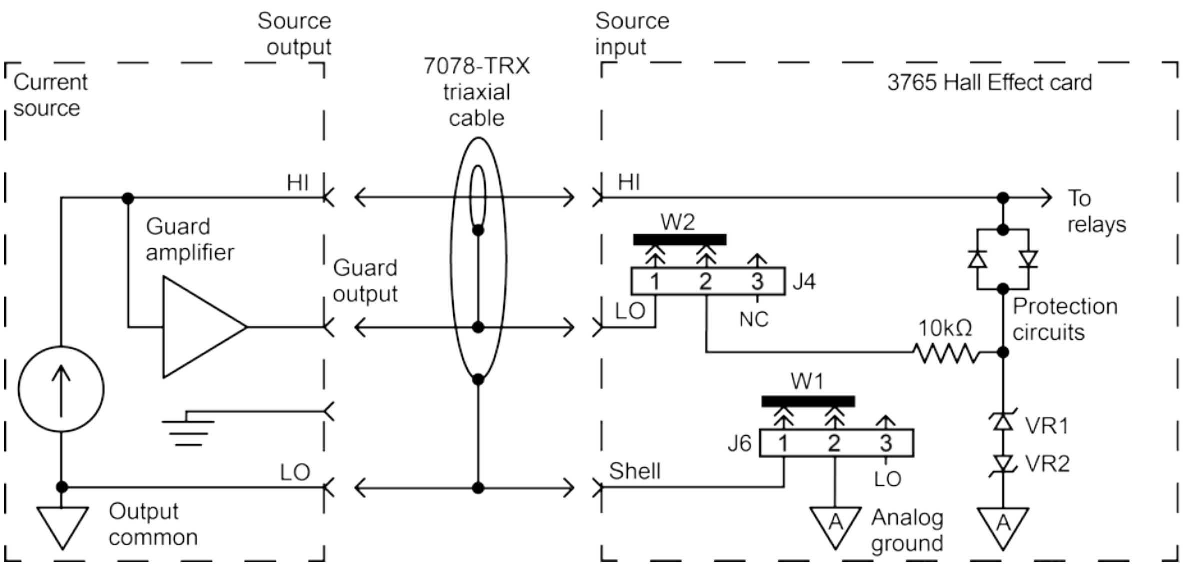
Guarded connections

The current source input should be guarded when the card is in high-resistivity mode. The next figure shows the basic connections, which are outlined as follows.

1. Connect the 7078-TRX triaxial cable between the triaxial end on the adapter and the 3765 current source input.
2. Configure the guard on the current source by either placing the signal LO or guard on the inner shield.

An equivalent circuit is shown in the next figure. Current source output HI is connected to the 3765 input HI through the center cable conductor. Output LO now appears on the outer cable shield and is connected to analog ground in the scanner card.

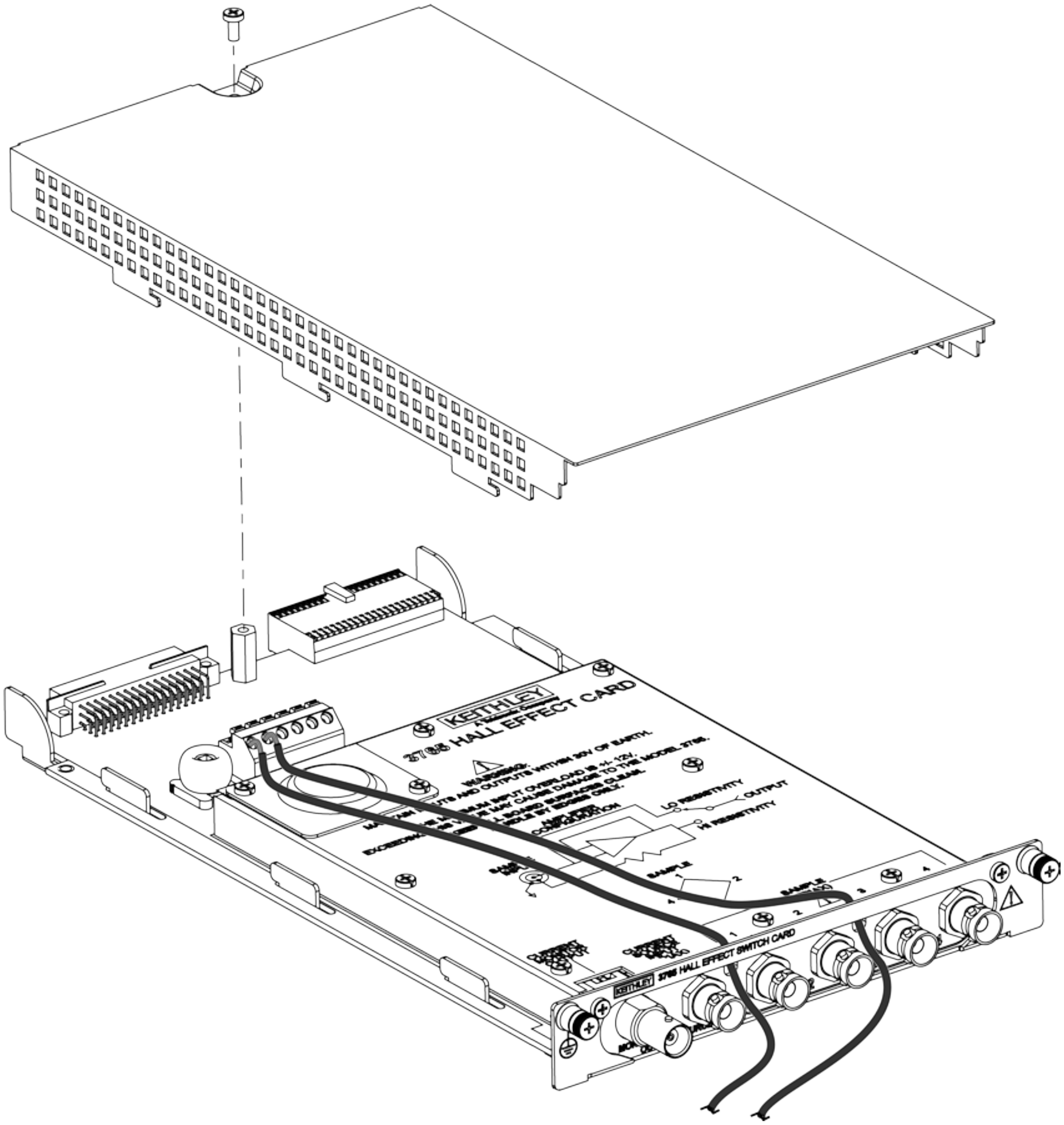
Figure 26: Guarded connection equivalent circuit



Sample input guarding

In order to minimize leakage resistance and capacitance, the input cable shields are guarded by driving the inner shield with the output of the respective buffer amplifier, as shown in the next figure. The outer shield is at analog ground potential, and it is not guarded.The same guard potential also surrounds the contacts of the associated relay in order to minimize leakage effects of the switching circuits. Note that guarding is used for both high- and low-resistivity configurations even though the buffers are effectively switched out of the circuit when the card is configured for low resistivity. Resistivity selection (on page 3-40) covers resistivity mode selection in detail.

Figure 27: Shield removal



Front panel current source programming

The inner shield of the triaxial connector can be connected to output low (to be compatible with the Keithley 220 current source) or cable guard of a current source. Output low is the default connection. The current source output must be off in order to change the inner shield setting.

To check or change the inner shield connection:

1. If the current source output is on, press the **Output** key to turn it off (an “OFF” message is displayed).
2. On the current source, press the **Triax** key to display the Configure Triax menu.
3. Using the cursor controls, place the blinking cursor on **Inner Shield**, and press the **Enter** key to display the Triax Inner Shield options.
4. Place the cursor on output low or guard and press the **Enter** key.
5. Press the **Exit** key to return to the normal display state.

IEEE-488 bus current source programming

To program your current source remotely over the IEE-BUS, input the following SCPI commands on the current source. You cannot input these SCPI commands on the 3706A interface.

CAUTION

Changing the inner shield connection can only be done with the current source output off. Otherwise, an error will occur.

Commands for triax inner shield connection:

`OUTPut:ISHield?`	Query connection for triax inner shield.
`OUTPut:ISHield <name>`	Connect the inner shield to the cable guard or output low. <name> = GUARd or OLOW

As an example, the below SCPI command turns off the current source output and connects the inner shield of the output connector to the cable guard.

```
OUTPut OFF

OUTPut:
ISHield GUARd
```

Resistivity selection

The 3765 may be operated in either the low- or high-resistivity mode, as discussed in the following sections.

Selecting the resistivity setup

The sample inputs can be programmed for low- or high-resistivity by controlling the state of crosspoint 4,5 (row 4, column 5). To select high-resistivity, close crosspoint 4,5; to select low resistivity, open crosspoint 4,5. The table below summarizes these programming states.

Column 5, row 4 state	Resistivity setup
open	low resistivity
closed	high resistivity

Input characteristics

The table below summarizes the input characteristics for low- and high-resistivity setups. In addition to affecting the resistivity setup, selection also affects the input current, noise, and off-set voltages. Note that the input characteristics of the low-resistivity setup are exclusive of the voltmeter, which can also affect the sample under test.

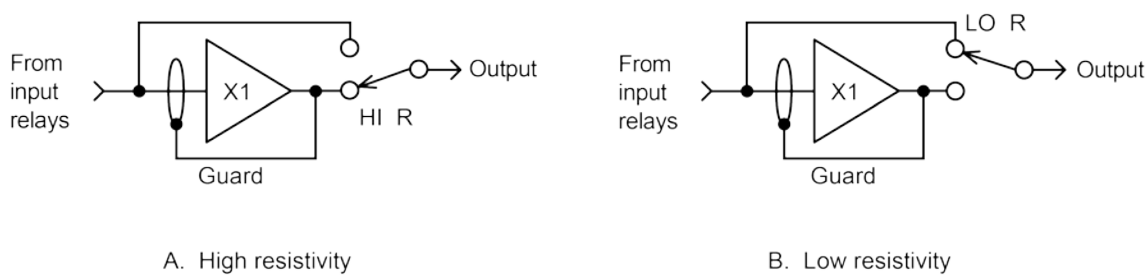
Parameter	Low resistivity setup	High resistivity setup
Input impedance	> 10 GΩ	> 100 TΩ
Input bias current	< 100 pA	< 50 fA
Input bias noise*	< 50 nV peak to peak	< 10 µV peak to peak

*0.1 Hz to 10Hz bandwidth

Equivalent input circuits

The following figure compares the input circuits for low- and high-resistivity setups. With the high-resistivity setup, the signal is routed through the buffer amplifier, which also provides the input circuit guard. In contrast, the signal completely bypasses the buffer amplifier in the low-resistivity mode. However, the guard is is still driven by the buffer amplifier.

Figure 28: Low and high resistivity equivalent circuits



Resistivity setup criteria

The setup depends on the resistivity of the sample under test. Some experimentation may help to obtain the best choice with a particular sample.

For sample resistances above 1 MΩ, input loading can occur due to accuracy degradation. When measuring samples above 1 MΩ, you should always use the high-resistivity setup. For lower sample resistances, however,the best configuration to use is a compromise between noise and gain error performance.

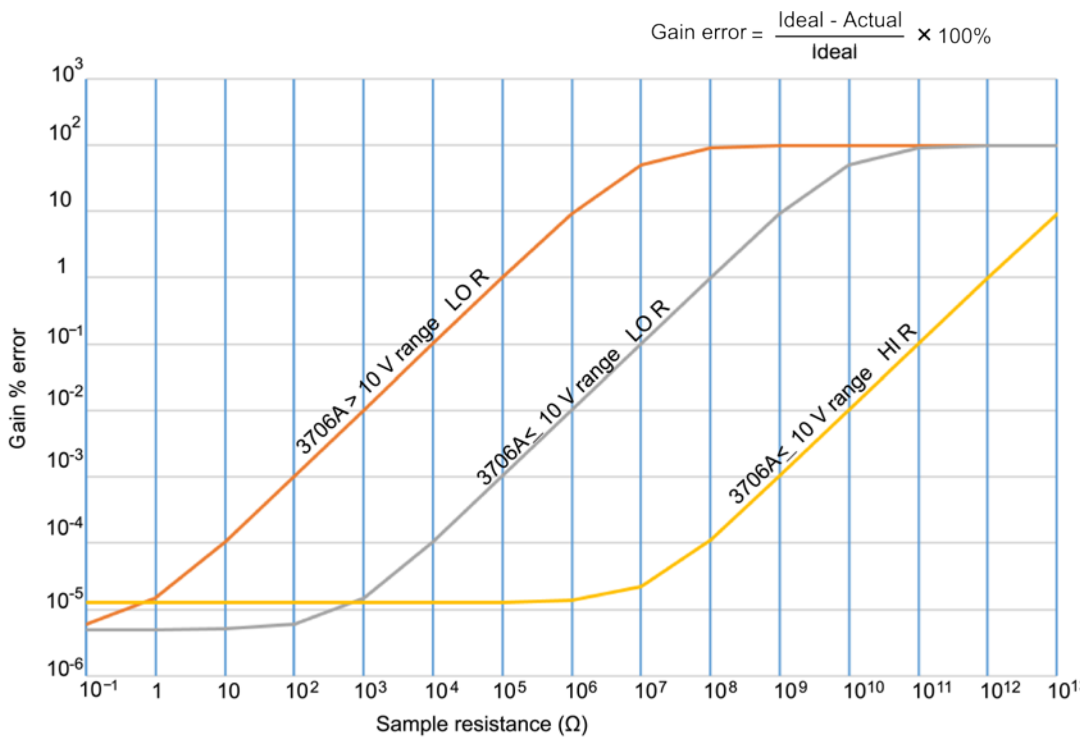
The next figure depicts gain error versus actual sample resistance that is calculated from signal voltage and sourced current. The errors shown do not include possible errors caused by current source uncertainty. Only voltage measurement errors are shown.

Total measurement uncertainty is the sum of gain error and noise uncertainty. The next figure shows the high-resistivity setup should be used for all samples. In fact, you can operate the 3765 exclusively in high-resistivity mode if slight errors caused by noise are tolerable.

NOTE

Hall voltages that are > 5 mV will yield an error due to noise uncertainty of < 0.2%.

Figure 29: Gain error, LO versus HI resistivity setup



The next figure illustrates noise voltage versus actual sample resistance. The tangential lines are theoretical limits given the thermal (Johnson) noise resistance. If the sample temperature is reduced to liquid nitrogen levels (77 K or below), the noise, due to sample resistivity, has improved the limit. Below sample resistances of 10 kΩ, lowering the temperature will not significantly improve the noise performance because the instrument noise dominates at room temperature.

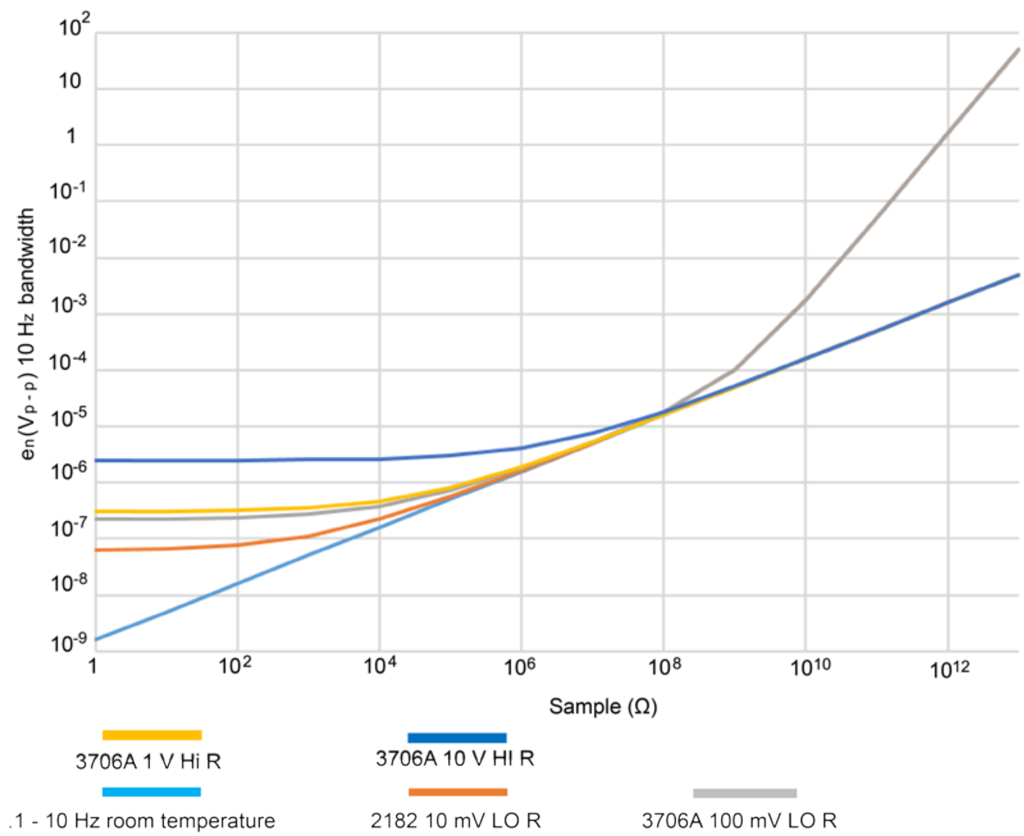
Using the resistivity setup in the resistance range of 10^4 to 10^6 Ω, the next figure shows the best accuracy is achieved if the signal voltage (sourced current, I X R) remains under 3 V.

NOTE

The power dissipated in the sample (V^2 / R) will remain under 1 mW, minimizing problems caused by self-heating and temperature coefficients of the sample.

The signal voltage generated during Hall voltage measurements is typically small, 20 mV or less. If a sample or measurement situation results in small Hall voltages (< 5 mV), and the sample resistance is less than 1 MΩ, you should use the low-resistivity setup. Hall voltages as low as 2 to 4 µV can be measured with less than 2% uncertainty in this mode by using a 2182A nanovoltmeter in place of the 3706A DMM.

Figure 30: Noise performance, LO versus HI resistivity setup



Typical Applications

In this section:

Introduction

This section briefly discusses Hall effect, Hall conventions, and gives some typical measurement examples for the Model 3765. This information is intended as an overview on methods for using the 3765 and associated instruments for measurements. References are included for more detailed information on making van der Pauw resistivity and Hall effect voltage measurements.

Recommended equipment

The table below summarizes the equipment for a Hall voltage measurement and van der Pauw resistivity system.

Equipment	Description	Recommended Keithley model
Model 3706A or external voltmeter	Measures sample voltages and controls the Hall Effect Card	
Current source	Supplies sample current	6221 current source
Picoammeter (optional)	Measures sample current	6485 or 6487 picoammeter
Nanovoltmeter (optional)	Measures voltage	2182A picoammeter
Cryostat	Sets sample temperature	
Magnet (Hall)	Applies magnetic field	
Magnet power supply (Hall)	Supplies magnet power	
Gauss meter (Hall, optional)	Used to measure actual magnetic field strength	

NOTE

In order to make connections using your 3765, you should use recommended cables and connectors (on page 2-4).

Hall Effect Test Suite software

The 3765 has a Hall Effect Test Suite project for the applications in this section. Using the Hall Effect Test Suite, you can easily input the instruments, source settings, measure settings, and test type in the Test Input Parameters window of the Hall Effect Test Suite GUI. You can view test results and progress in real time, save and load test settings, see the results in tabular form, and save the resulting data to a computer in .csv format.

Hall Effect Test Suite installer

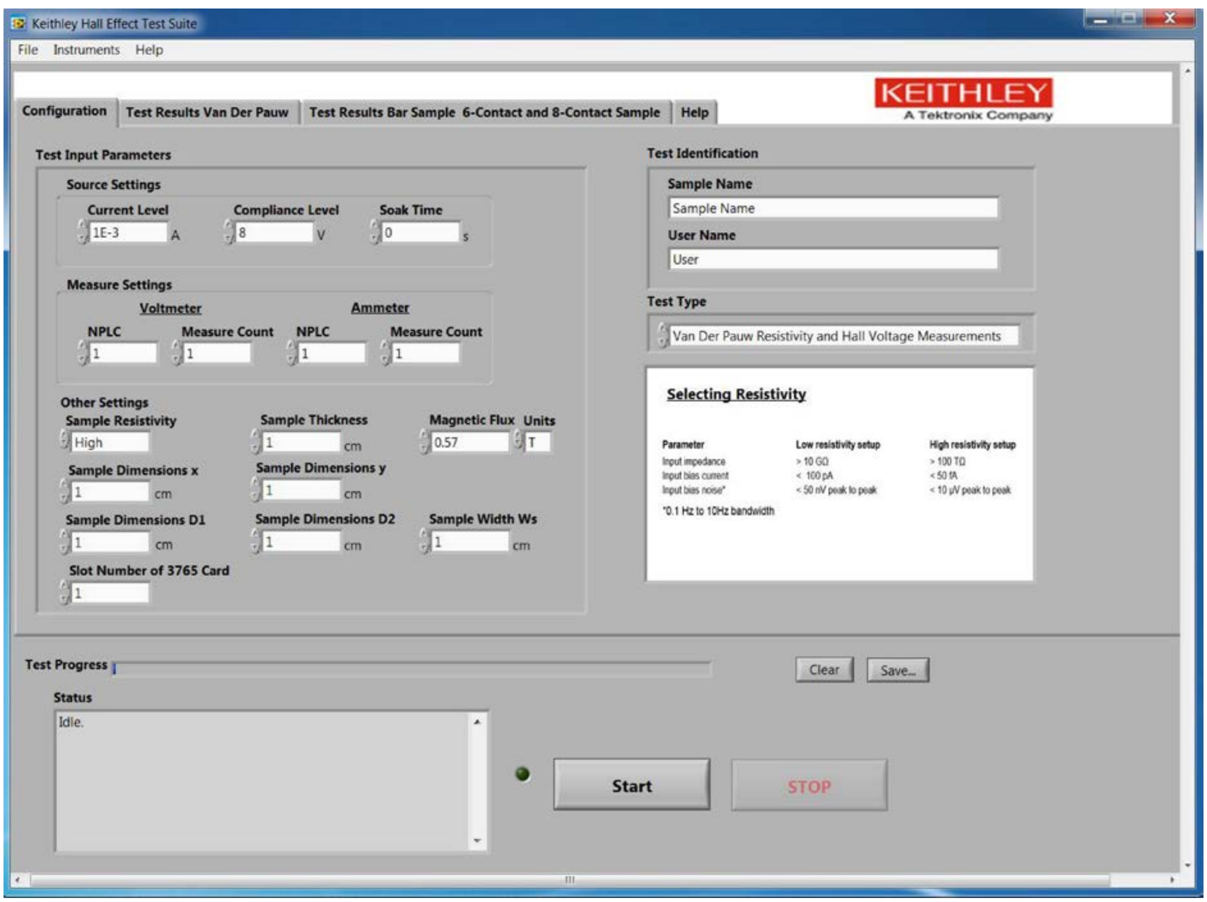
The Hall Effect Test Suite installer can be found at the Keithley Instruments website (*http://www.tek.com/keithley*).

Hall Effect Test Suite overview

The Hall Effect Test Suite GUI consists of the following components.

Configuration	Includes test parameters, test identification, test type, and test progress. This is where all tests are configured.
Test results	Includes read only results and test progress information.
Help	Includes connection diagrams and application information.

Figure 31: Hall Effect Test Suite overview



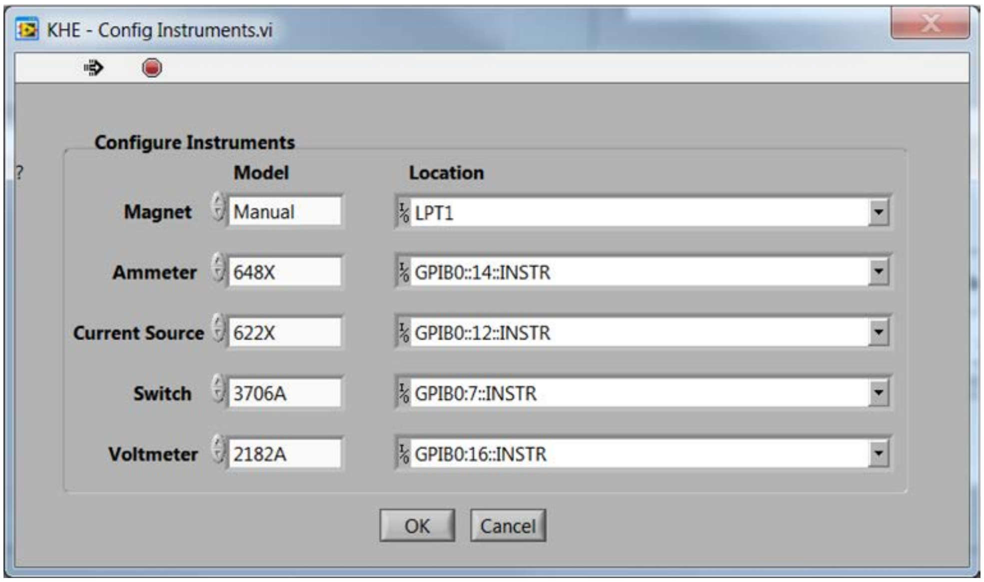
Hall Effect Test Suite instrument configuration

To configure the instruments needed to complete a test:

1. Select **Instruments** from the toolbar.
2. Select **Configure**.
3. Select the model of the instrument you are connecting.
4. Using the list, select the location of the connected instrument.

The next figure is an example of a setup using the Hall Effect Test Suite instrument configuration.

Figure 32: Hall Effect Test Suite instrument configuration



Hall Effect Test Suite test connections

Once the instrument configuration is completed, you must test the connections.

To test the connections:

1. Select **Instruments** from the toolbar.
2. Select **Test Connections**.

You will receive an error message if the specified instruments, from the instrument configuration window, are not connected correctly.

Hall Effect Test Suite test input parameters

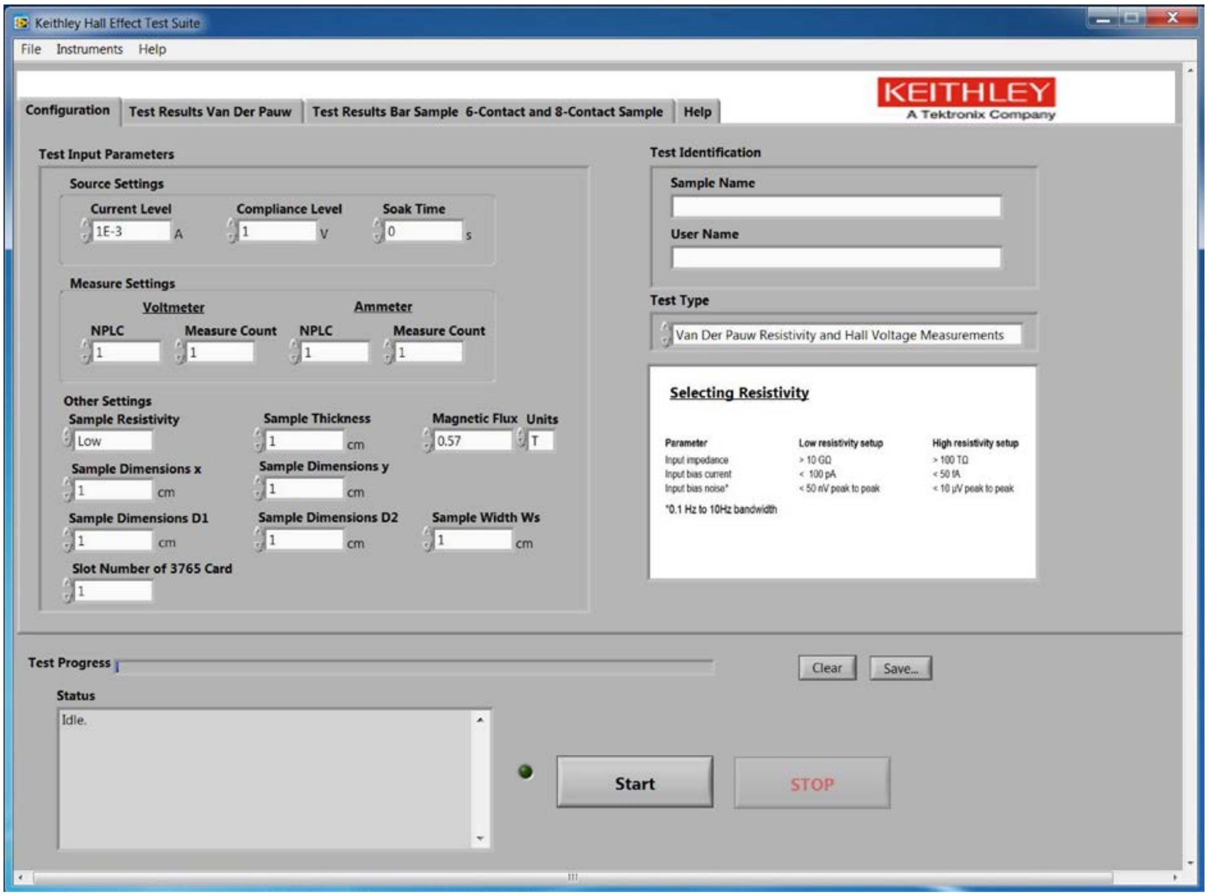
After you have configured the instruments in your test setup and tested the connections, you can run your desired tests.

To run the tests:

1. Fill in **Sample Name** and **User Name** under Test Identification.
2. Set the necessary settings for your application under Test Input Parameters.
3. Set the **Test Type** using the arrows.
4. Select **Start**.

Below is an example of the Hall Effect Test Suite information completed before the test is run.

Figure 33: Hall Effect Test Suite input parameters



Saving and loading settings

Test settings and configurations are savable using the Hall Effect Test Suite.

To save your settings:

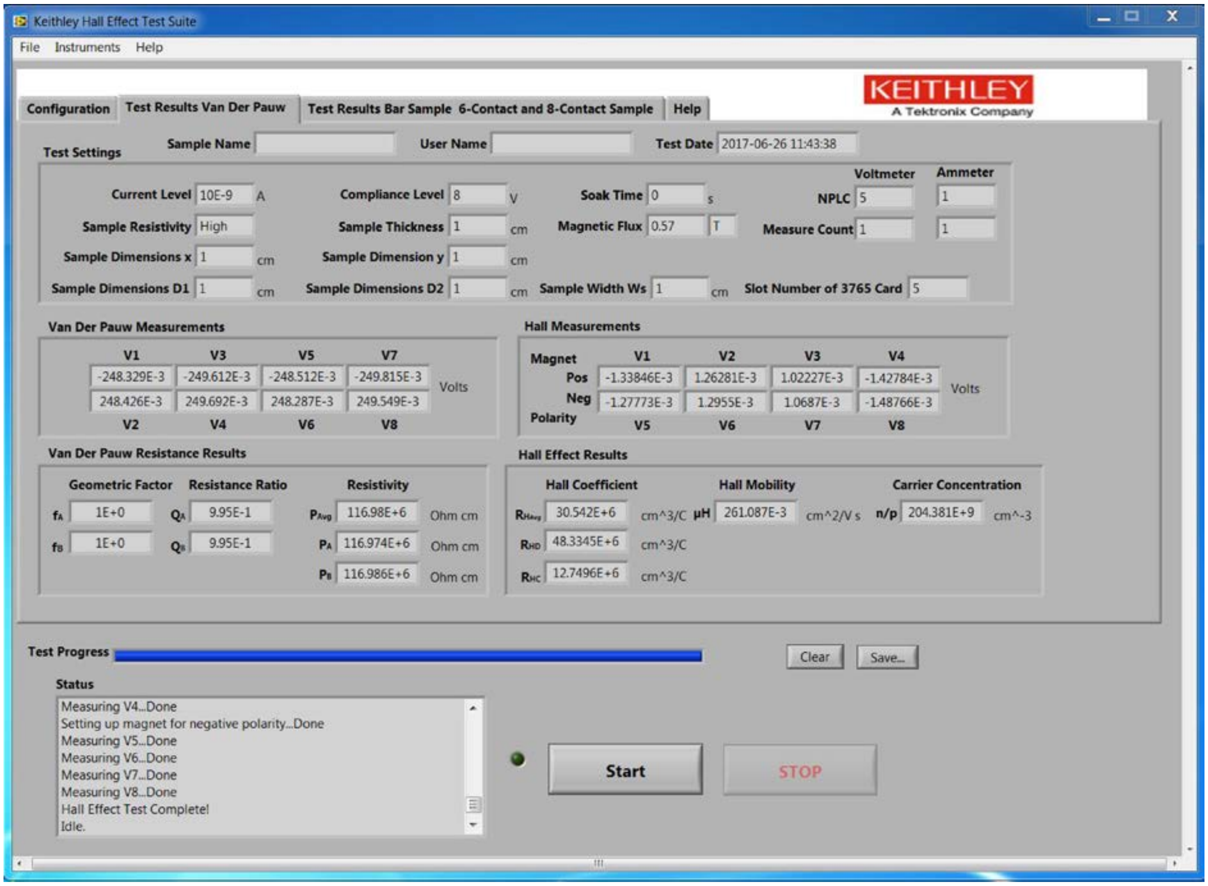
1. Select **File**.
2. Select **Save Settings**.
3. Name the file and save location.

The file is saved in a .xml file that can be loaded when needed.

Hall Effect Test Suite sample results

An example of test results is shown below. This graphic illustrates the given results for a van der Pauw test using the Hall Effect Test Suite.

Figure 34: Hall Effect Test suite sample results



Conventions and principles

The following paragraphs discuss Hall effect sign and sample terminal conventions, basic Hall effect principles, and van der Pauw resistivity.

Measurement units

The table below summarizes generally accepted units of measure.

Quantity	Symbol	Units
Sample dimensions	L, t, w, d	cm
Potential difference	V	V
Charge	q	C
Carrier concentration	n, p	cm^{-3}
Drift mobility	μ	cm^2 / Vs
Hall mobility	μ_H	cm^2 / V s
Current density	J	A / cm^2
Hall coefficient	R_H	cm^3 / C
Electric field	E	V / cm
Magnetic flux density	B	gauss
Resistivity	ρ	Ω - cm
Hall voltage	E_H	volts
Charge of electron	e	coulombs, C
Conductivity	σ	1 / Ω - cm

Hall voltage sign conventions

The next two figures show the sign conventions for n-type and p-type materials.

Figure 35: Hall effect sign conventions for n-type materials

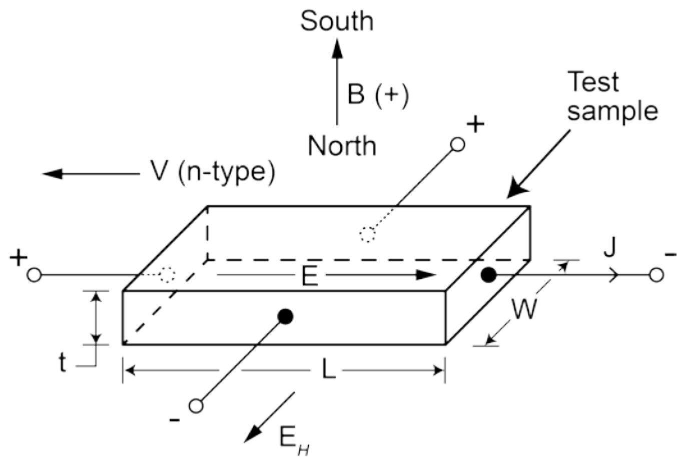
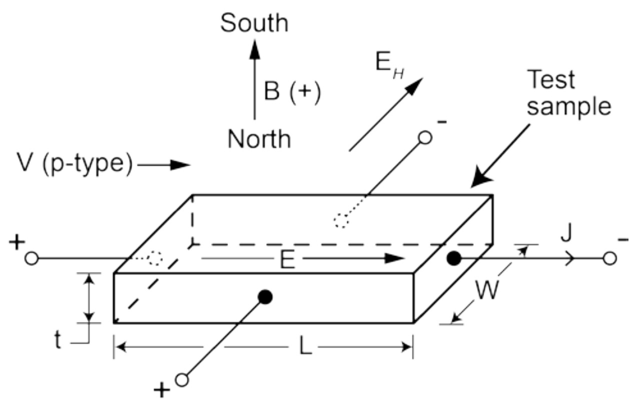


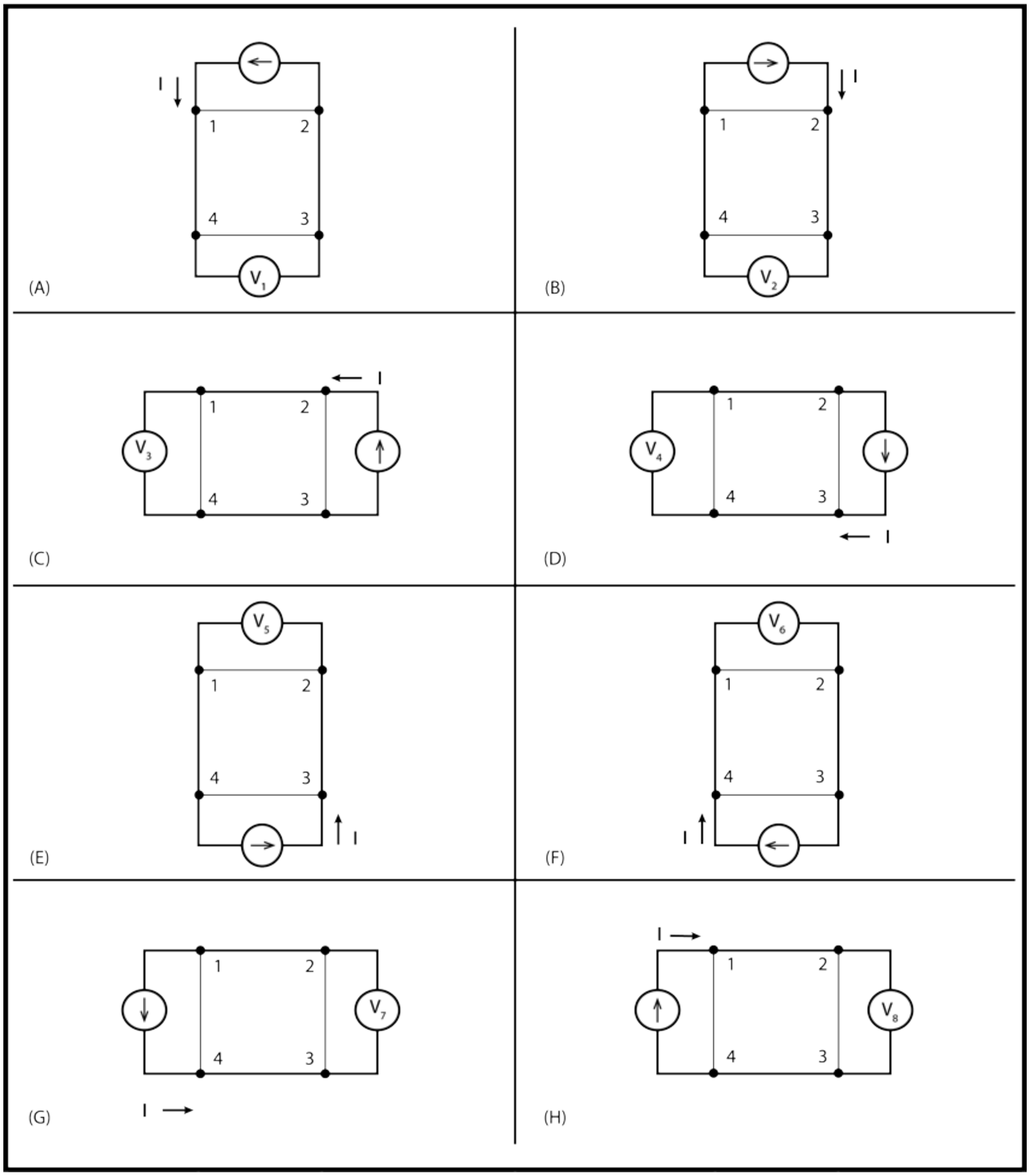
Figure 36: Hall effect sign conventions for p-type materials



Terminal conventions

In the case of van der Pauw resistivity measurements, a current is applied between two terminals, while the voltage is measured between the two opposite terminals, as shown in the next figure. A total of eight such measurements are taken with each possible terminal and current convention. In this manual, these voltages are designated V_1 through V_8, and are covered in detail in van der Pauw resistivity measurements (on page 4-10).

Figure 37: Resistivity measurement conventions



The connections for Hall voltage measurements are shown in the next figure. Current is applied and voltage is measured across the diagonal of the sample. Eight measurements are necessary, both with positive and negative current and positive and negative magnetic flux. These voltages are designated V_1 through V_8, as discussed in Hall voltage measurements (on page 4-34).

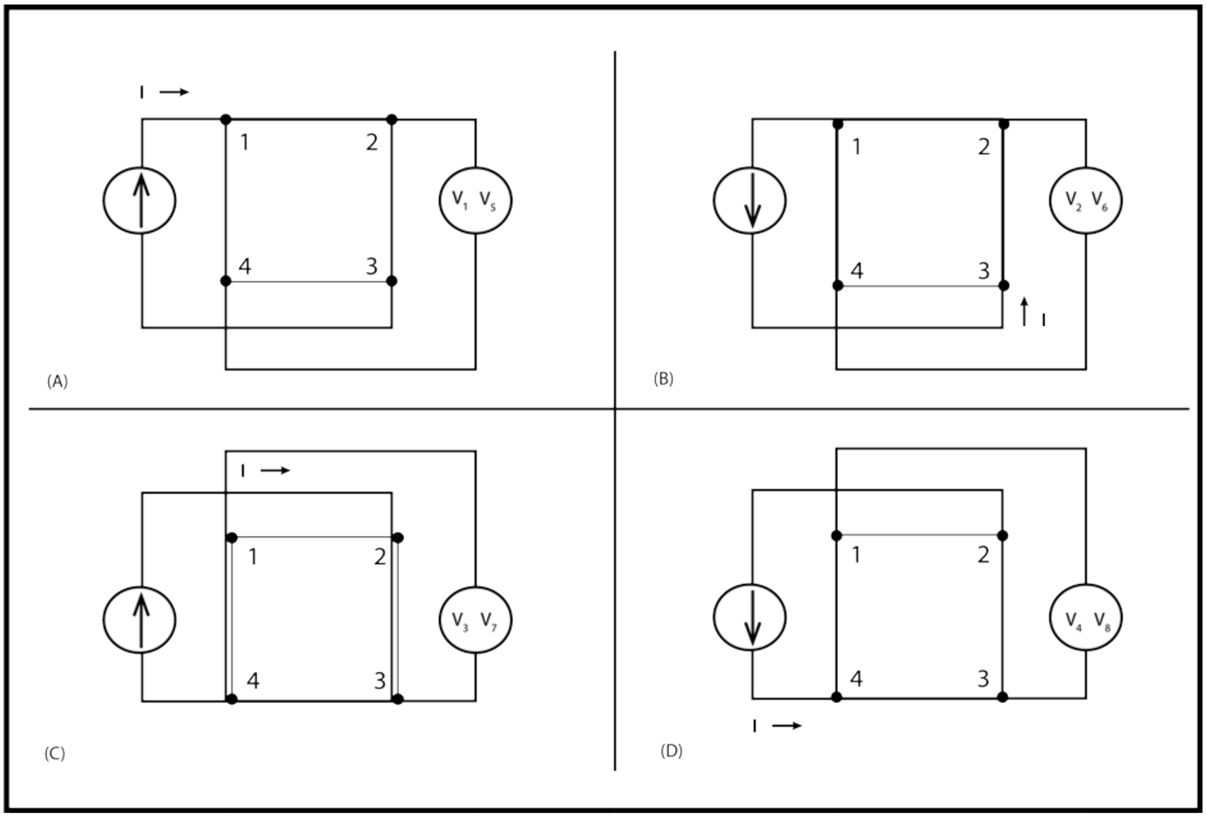
NOTE

Oftentimes additional measurements are taken with no flux applied.

These voltages are designated V_1 through V_8, as discussed in Hall voltage measurements (on page 4-34).

Conventions used for bar and bridge specimens are similar, and are covered in Measuring bar-type samples (on page 4-18) and Measuring bridge and parallel-piped type specimens (on page 4-30) respectively

Figure 38: Hall voltage measurement conventions



Basic Hall Effect principles

For the following discussion, refer to the basic sample configuration shown in the previous figure, Hall effect sign conventions for n-type materials.

If a current, I = J / A, is applied across the length of the sample, voltage is developed across that sample. If a magnetic field, B, is subsequently applied, normal (perpendicular) to the current, the carriers are displaced from their normal paths, and a voltage, E_H, is developed. This voltage is known as the Hall voltage.

Once the Hall voltage is known, it can be defined as follows:

$$R_H = \frac{E_H}{JB}$$

Where:

- R_H is the Hall coefficient.
- E_H is the Hall voltage.
- J is the current density.
- B is the magnetic flux density.
- n is the carrier concentration.
- q is the carrier charge.
- µ is the drift mobility.
- A is the cross sectional area (cm^2). A = tw

Once the Hall coefficient is known, carrier concentration and mobility can be calculated when derived from the measured resistivity.

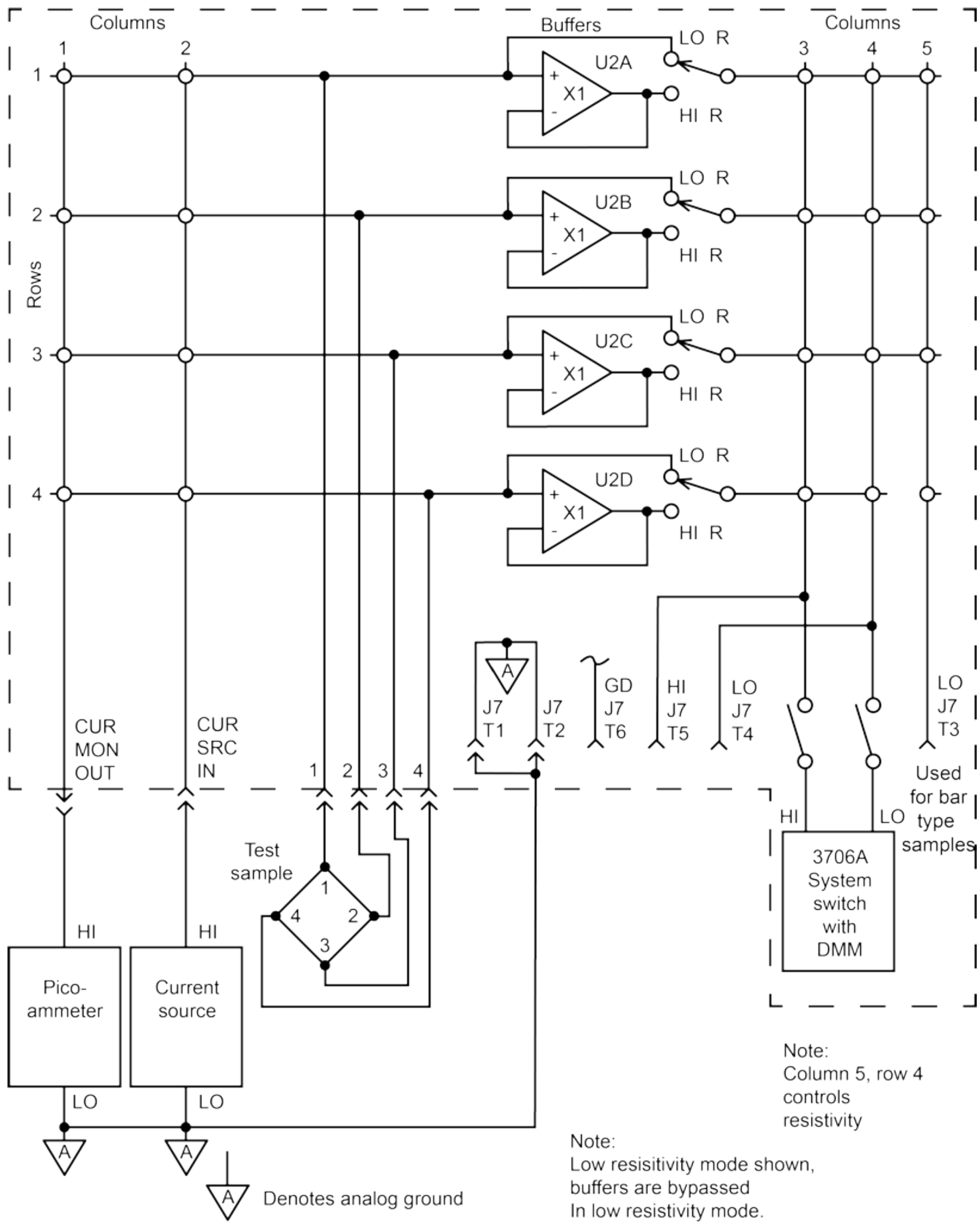
van der Pauw resistivity measurements

The following paragraphs describe basic test configuration, test procedures, and calculations necessary to make resistivity measurements using the van der Pauw method.

van der Pauw resistivity measurement test configuration

The figure below shows the basic test configuration for making resistivity measurements.

Figure 39: Measurement configuration for resistivity and Hall voltage measurements



van der Pauw resistivity measurement test procedure

Use the following procedure to measure parameters necessary to calculate sample resistivity. The procedure assumes that the sample has been stabilized at the desired operating temperature and will remain at that temperature throughout the tests.

To calculate sample resistivity:

1. Turn on all the instruments, and allow them to warm up for the prescribed period for rated accuracy.
2. Set the DMM and picoammeter to autoranging. The DMM must be using the DCV function.
3. Close relay 911 to route signal on the back plane so the DMM voltmeter can measure the signal.
4. Program crosspoint 4,5 to select low or high resistivity. This crosspoint should be open for low resistivity, and it should be closed for high resistivity.
5. Program the current source current to the desired value in the range of 500 fA to 100 mA. The maximum current that can be used will depend on the resistance of the sample.

NOTE

The maximum 3765 input voltage is ±8 V. In order to maintain proper sign convention for the measured voltage, program only positive currents.

6. Close the crosspoints necessary to measure V_1, as indicated in the next table.
7. Enable the REL function on the DMM and picoammeter.

NOTE

The REL function on both the DMM and the picoammeter takes a reading and subtracts it from all subsequent readings.

8. Press **Output On** to turn on the current source.
9. Measure V_1 by noting the reading on the DMM. Also, note the current measured by the picoammeter.
10. Turn off the current souce output and open the crosspoints.
11. REL the DMM and picoammeter.
12. Measure and record the remaining voltages (V_2 through V_8) listed in the next table by closing the appropriate crosspoints. Be sure to open the crosspoints from the previous measurement before closing crosspoints for the present measurement.

Voltage designation	Crosspoints closed (row, columns)*				Current applied between	Voltage measured between
V_1	2,1	1,2	3,3	4,4	2-1	4-3
V_2	2,2	1,1	3,3	4,4	1-2	4-3
V_3	2,2	3,1	4,3	1,4	3-2	1-4
V_4	3,2	2,1	4,3	1,4	2-3	1-4
V_5	3,2	4,1	1,3	2,4	4-3	2-1
V_6	4,2	3,1	1,3	2,4	3-4	2-1
V_7	4,2	1,1	2,3	3,4	1-4	3-2
V_8	1,2	4,1	2,3	3,4	4-1	3-2

*Only those crosspoints shown can be closed for a specific measurement, except 4,5 which controls the input configuration for low- or high-resistivity samples.

van der Pauw resistivity measurement resistivity calculations

Once the voltages and current through the sample have been measured, the resistivity can be calculated as follows. Two values of resistivity, ρ_A and ρ_B, are computed as follows:

$$\rho_A = \frac{1.1331\ f_A\ t_S}{I}\ (V_2 + V_4 - V_1 - V_3)$$

$$\rho_B = \frac{1.1331\ f_B\ t_S}{I}\ (V_6 + V_8 - V_5 - V_7)$$

Where: ρ_A and ρ_B are resistivities in ohm-cm.

- t_s is the sample thickness in cm.
- V_1- V_8 represent the voltages measured by the DMM (see the previous table).
- I is the current through the sample in amperes, as measured by the picoammeter.
- f_A and f_B are geometrical factors based on sample symmetry and are related to the two resistance ratios Q_A and Q_B as shown below ($f_A = f_B = 1$ for perfect symmetry).

Q_A and Q_B can be calculated using the measured voltages from the previous table as follows:

$$Q_A = \frac{V_2 - V_1}{V_4 - V_3}$$

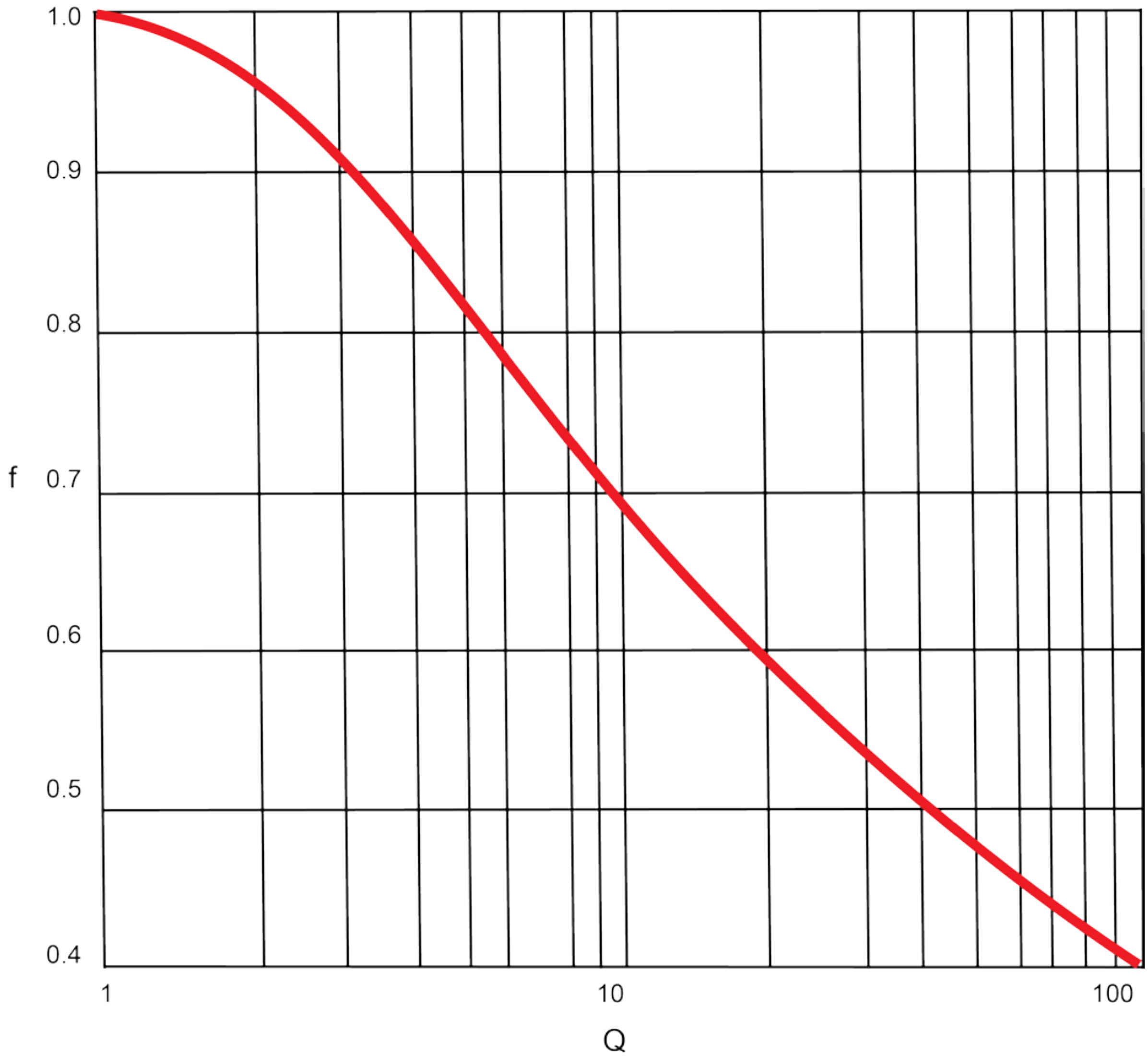
$$Q_B = \frac{V_6 - V_5}{V_8 - V_7}$$

$$\frac{Q_A - 1}{Q_A + 1} = \frac{f_A}{0.693}\ \mathrm{arc\,cosh}\ \left({}^1/_2\ e^{\frac{0.693}{f_A}} \right)$$

$$\frac{Q_B - 1}{Q_B + 1} = \frac{f_B}{0.693}\ \mathrm{arc\,cosh}\ \left({}^1/_2\ e^{\frac{0.693}{f_B}} \right)$$

A plot of this function is shown in the figure below.

Figure 40: Plot of f versus Q



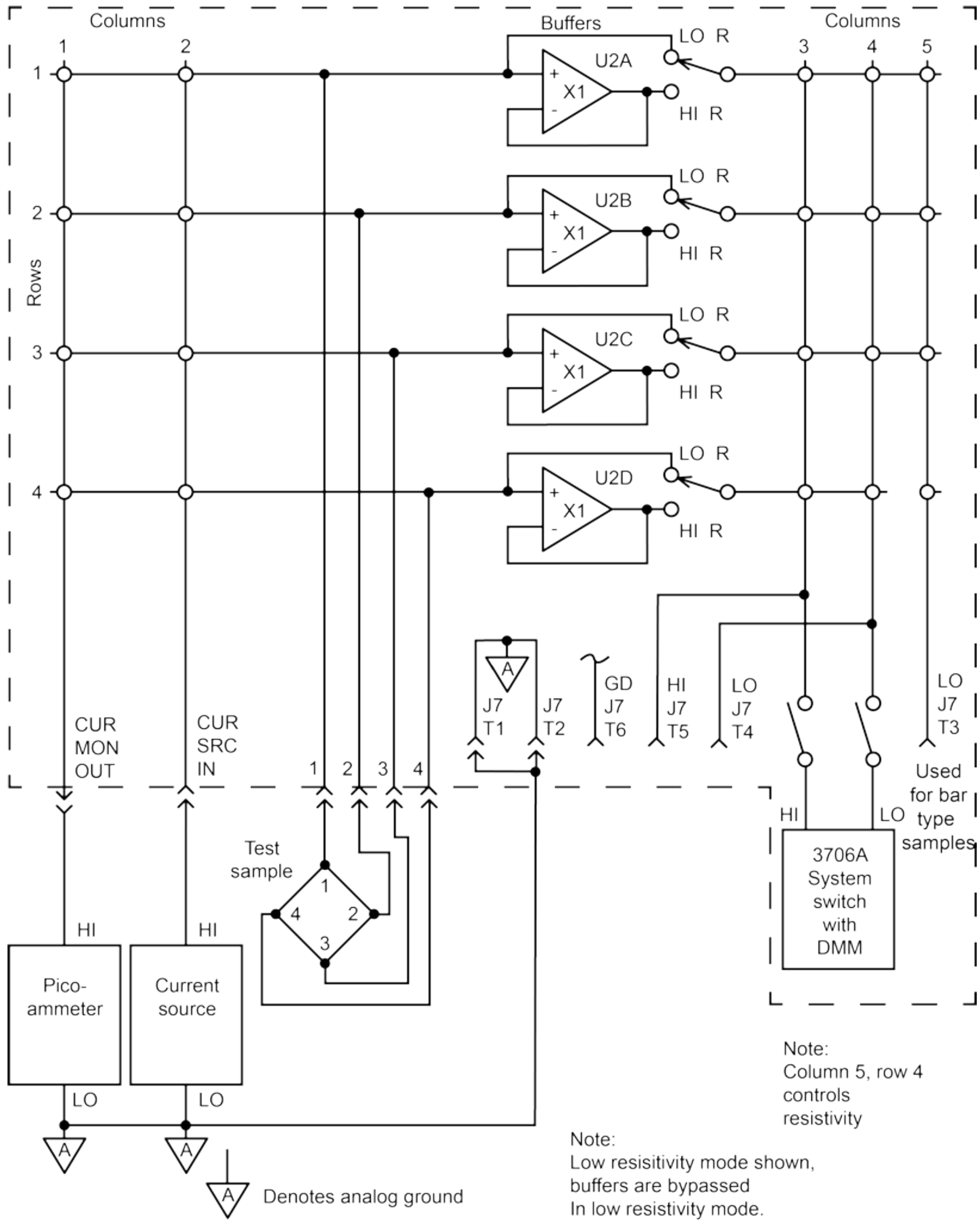
Hall voltage measurements

The following paragraphs discuss Hall voltage measurements on van der Pauw type samples.

Hall voltage measurement test configuration

The sample test configuration can be used to measure the parameters necessary to calculate Hall coefficients. In addition to the equipment shown, a suitable magnet or electromagnet will be necessary to generate the required magnetic field.

Figure 41: Measurement configuration for resistivity and Hall voltage measurements



Hall voltage measurement test procedure

Use the procedure below to measure data that is necessary to calculate Hall coefficients. Note that the sample should be stabilized at the desired temperature before and during the tests. Also, the flux density magnitude must be kept constant during the measurements.

To calculate Hall coefficients:

1. Turn on all the instruments, and allow them to warm up for the prescribed period for rated accuracy.
2. Place the DMM and picoammeter in autoranging and the DMM in DCV function.
3. Close relay 911 to route signal on the back plane so the DMM can measure the signal.
4. Program crosspoint 4,5 to select low or high resistivity. This crosspoint should be open for low resistivity, and it should be closed for high resistivity.
5. Program the current source current to the desired value in the range of 500 fA to 100 mA. The maximum current that can be used will depend on the resistance of the sample.

NOTE

The maximum 3765 input voltage is ±8 V. In order to maintain proper sign convention for the measured voltage, program only positive currents.

6. Close crosspoints 1,2; 3,1; 4,3; and 2,4.
7. REL the DMM and picoammeter.

NOTE

The REL function on both the DMM and the picoammeter takes a reading and subtracts it from all subsequent readings.

8. Turn on the current source output by pressing the **Output On** key.
9. Turn on the magnetic field, and set it to the desired positive flux density (+B). Measure and record the value of +B.
10. Measure the voltage V_1 by noting the DMM reading.
11. Note and record the current being measured by the picoammeter.
12. Measure and record V_2 through V_4, as listed in the table below by closing the appropriate crosspoints. Be sure to open crosspoints from the previous measurement and turn off the current source output.
13. After closing the next crosspoints, REL the DMM and enable REL on the picoammeter before turning on the current source output.
14. Reverse the magnetic flux and adjust it to the same magnitude used for positive flux; measure and record the flux value.
15. Measure V_5 through V_8 listed in the table below, now with negative flux (-B).
16. Open all crosspoints by pressing the **Open All** button on the scanner.
17. Turn off the current source output after the measurements are complete.

Voltage designation	Flux	Crosspoints closed (row, columns)*				Current applied between	Voltage measured between
V_1	+B	2,1	3,1	4,3	2,4	3-1	2-4
V_2	+B	3,2	1,1	4,3	2,4	1-3	2-4
V_3	+B	2,2	4,1	1,3	3,4	4-2	3-1
V_4	+B	4,2	2,1	1,3	3,4	2-4	3-1
V_5	-B	1,2	3,1	5,	2,4	3-1	2-4
V_6	-B	3,2	1,1	4,3	2,4	1-3	2-4
V_7	-B	2,2	4,1	1,3	3,4	4-2	3-1
V_8	-B	4,2	2,1	1,3	3,4	2-4	3-1

*Only those crosspoints shown can be closed for a specific measurement, except 4,5 which controls card input configuration for low or high resistivity samples.

NOTE

Channel 911 routes voltage onto the backplane so the DMM can measure it.

Hall voltage measurement coefficient calculations

Once the voltages are measured, two Hall coefficients, R_{Hc} and R_{HD} can be calculated as follows:

$$R_{HC} = \frac{2.5 \times 10^7 \, t_s}{BI} (V_2 - V_1 + V_5 - V_6)$$

$$R_{HD} = \frac{2.5 \times 10^7 \, t_s}{BI} (V_4 - V_3 + V_7 - V_8)$$

Where:

- R_{H_C} and R_{H_D} are Hall coefficients in cm^3/C
- t_s is the sample thickness in cm.
- B is the magnetic flux density in gauss.
- I is the current measured by the picoammeter in amperes.
- V_1- V_8 are the voltages measured by the DMM.

NOTE

R_{H_C} and R_{H_D} should be within 10% of one another, or the sample is not sufficiently uniform. V_1 and V_6 are measured with a negative magnetic field, -B. V_2 and V_5 are measured with +B.

Once R_{H_C} and R_{H_D} have been calculated, the average Hall coefficient, $R_{H_{AVG}}$ can be determined as follows:

$$R_{H_{AVG}} = \frac{R_{H_C} + R_{H_D}}{2}$$

Hall voltage measurement mobility calculation

Once the Hall coefficient and resistivity are known, the Hall mobility can be calculated as follows:

$$\mu_H = \frac{|R_{H_{AVG}}|}{\rho_{AVG}}$$

Where:

- μ_H is the the Hall mobility in cm^2 / Vs
- $R_{H_{AVG}}$ is the average Hall coefficient in cm^3 / C.
- ρ_{AVG} is the average resistivity in ohm - cm.

Measuring bar-type samples

The following paragraphs discuss procedures and test configurations for measuring resistivity and Hall voltage measurements on bar samples.

Bar-type measurement test configuration

The following two figures show the general test configurations for making resistivity and Hall voltage measurements. The two setups are similar except for the way the voltmeter is connected. Using the first figure for resistivity measurements, the voltmeter is connected between terminal 5 and 4 of the terminal block. For Hall voltage measurements, a suitable potentiometer is to be connected between terminals 5 and 4 while the voltmeter is connected between the wiper of the pot and terminal 3 of the block.

Figure 42: Test configuration for Hall voltage measurements of bar-type samples

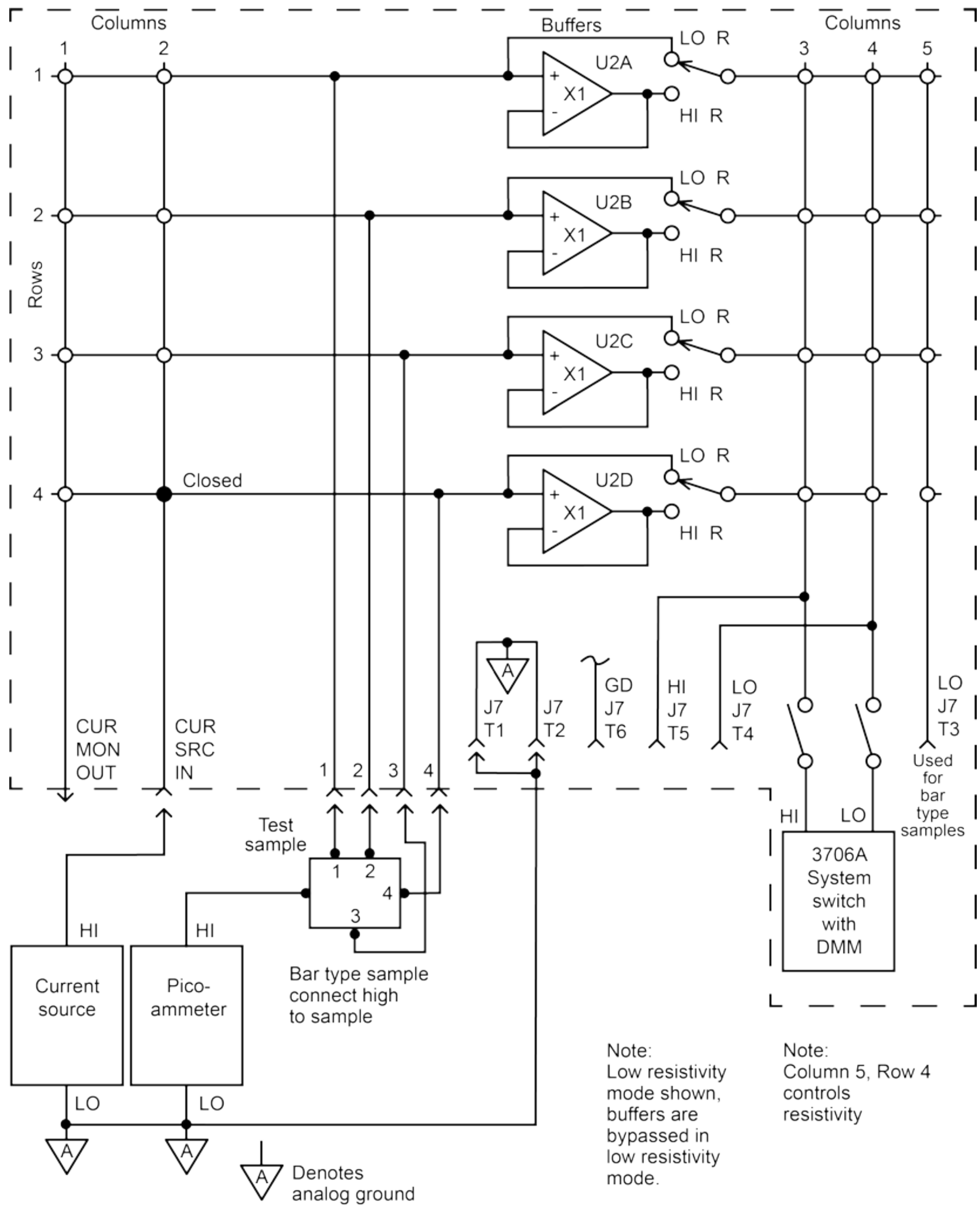
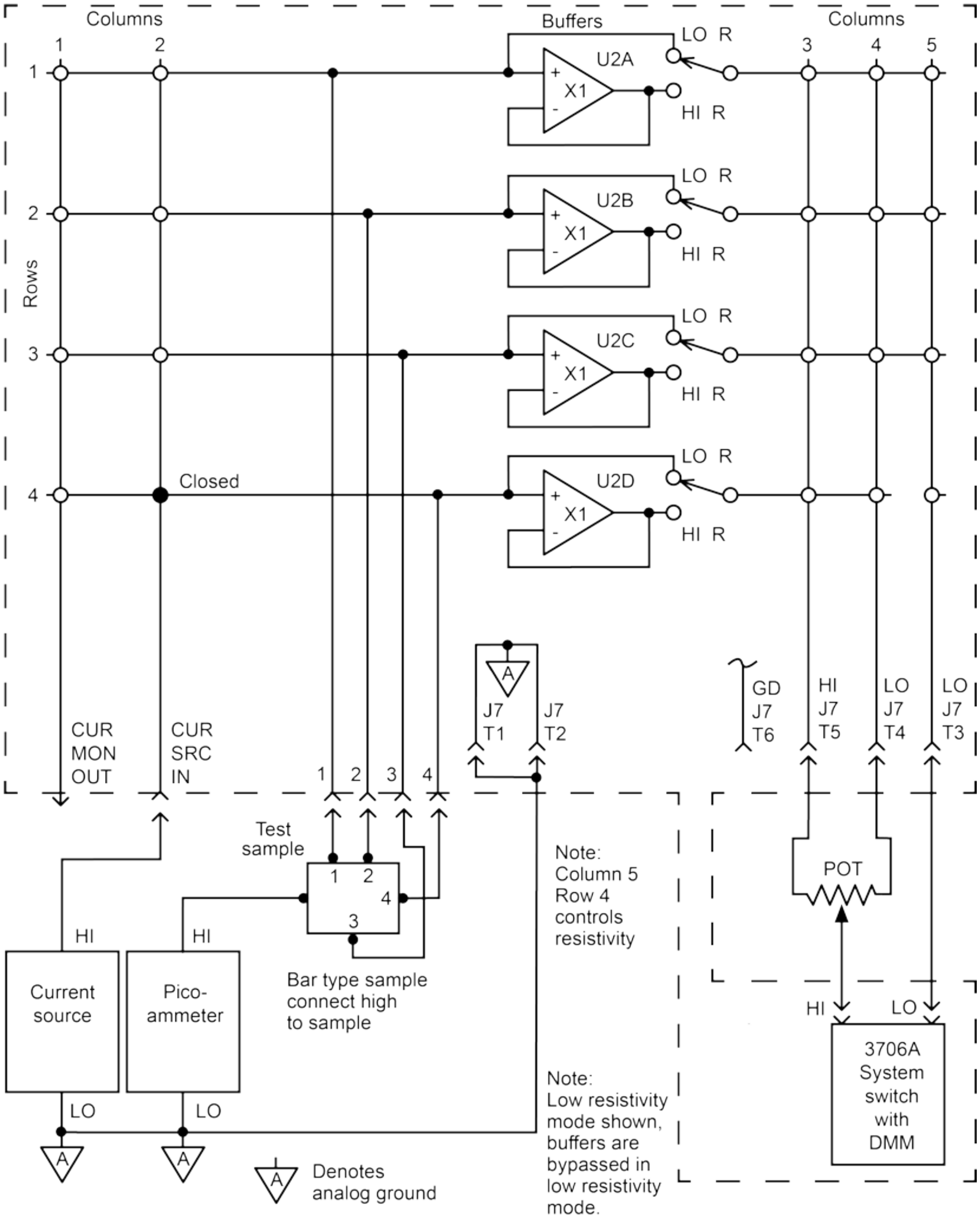


Figure 43: Test configuration for Hall voltage measurement of bar samples



The crosspoints that must be closed depend on whether resistivity or Hall voltage measurements are to be taken. The Crosspoint configurations for bar measurements (on page 4-27) table summarizes which crosspoints to close for each type of measurement.

Determining potentiometer values for bar-type measurements

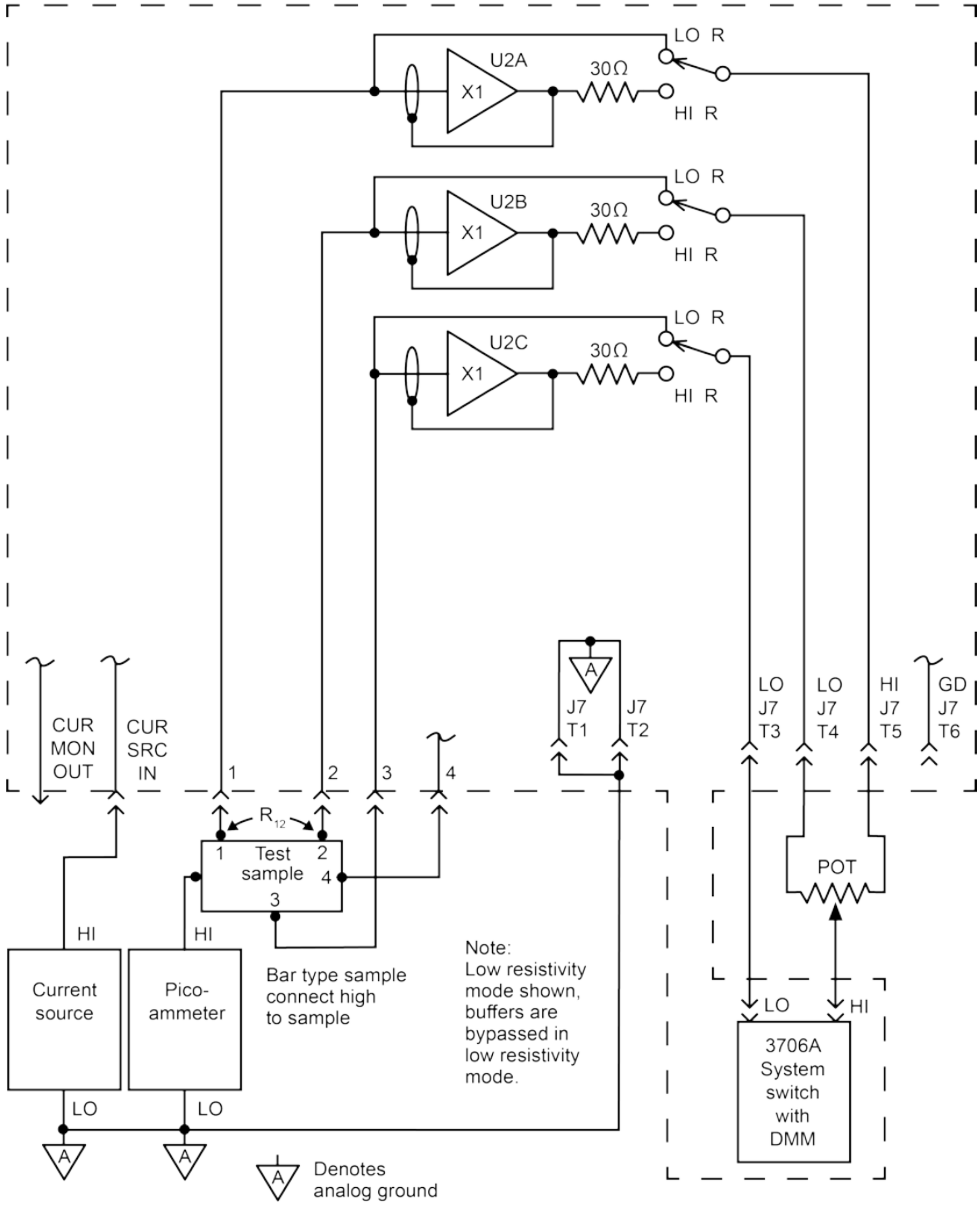
The loading effects of the DMM and potentiometer can affect the accuracy of both low- and high-resistivity measurements. The table below summarizes recommended potentiometer values along with nominal errors.

Resistivity mode	**R_{12}***	**DMM range**	**Recommended Rp***	**Additional error introduced by Rp (E)**
LO	Up to 1 kΩ	100 V	200 kΩ	1%
LO	Up to 10 kΩ	100 mV, 1V	1 MΩ	1%
HI	All	All	50 kΩ	0.25%

*The DMM range values change depending on the voltmeter used.

An equivalent circuit of the card and sample for this discussion is shown in the figure below.

Figure 44: Hall bar equivalent circuit



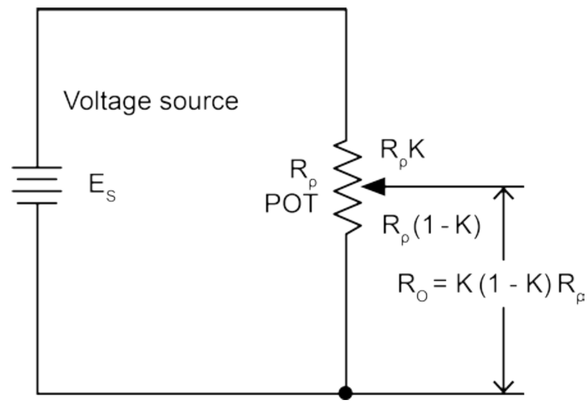
Measuring high resistivity of bar-type samples

In order to minimize loading errors, the equivalent resistance seen by the buffers must be as low as possible; also, the DMM input resistance must be substantially higher than the equivalent resistance seen at its input. The worst case condition occurs when the potentiometer wiper is at the center of its adjustment range (R=½). For example, in the equivalent circuit of the following figure, assume that R_ρ has a value of 200 kΩ. In this case, $R_O = ½ (½) R_\rho = ¼ R_\rho = 50$ kΩ

NOTE

For the above example, R_O is resistance output.

Figure 45: Equivalent potentiometer circuit, high resistivity



Measuring low resistivity of bar-type samples

For the low-resistivity setup, and for values significantly less than the values listed for R_{12} in the table above, better accuracy can be obtained by using a different value for R_P than that shown in the table. Using the equivalent circuit shown in the following figure, the relationship between the error, E, R_P, and R_{12} is given as follows:

$$E\% \cong \frac{R_\rho}{4R_{IN}} + \frac{R_{12}}{R_\rho} \text{ x } 100\%$$

Where: R_ρ = potentiometer value

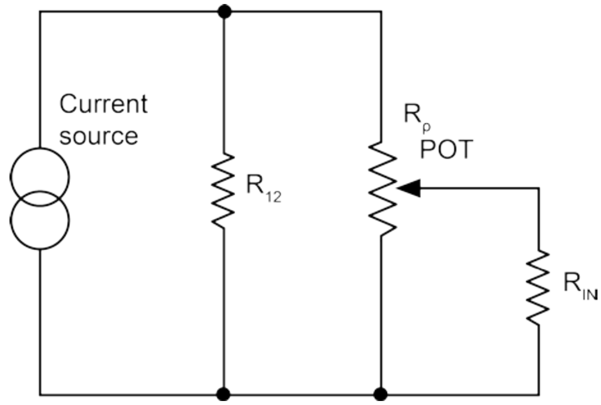
R_{IN} = Input resistance of the DMM ($R_{IN} = 10^9$ for range, 100 mV, 1 V, 10 V, of 3706S. 10 M or 100 V).

NOTE

These values change depending on the voltmeter used.

Note that this approximation is valid for E < 10%.

Figure 46: Equivalent potentiometer circuit, low resistivity



Bar resistivity measurements

Use the basic procedure below to make the necessary measurements to determine resistivity of bar-type samples. This procedure assumes that the sample temperature is held to the constant necessary temperature throughout the test.

To determine resistivity of bar-type samples:

1. Turn on all the instruments, and allow them to warm up for the prescribed period for rated accuracy.
2. Place the DMM and picoammeter in autoranging mode. The DMM must be in the DCV function.
3. Close relay 911 to route the signal on the backplane so the DMM can measure the signal.
4. Program crosspoint 4,5 to select low or high resistivity. This crosspoint should be open for low resistivity, and it should be closed for high resistivity.
5. Program the current source to the preferred value in the range of 500 fA to 100 mA. The maximum current that can be used depends on the resistance of the sample.

NOTE

The maximum 3765 input voltage is ±8 V. In order to maintain proper sign convention for the measured voltage, and to minimize common-mode errors, program only positive currents.

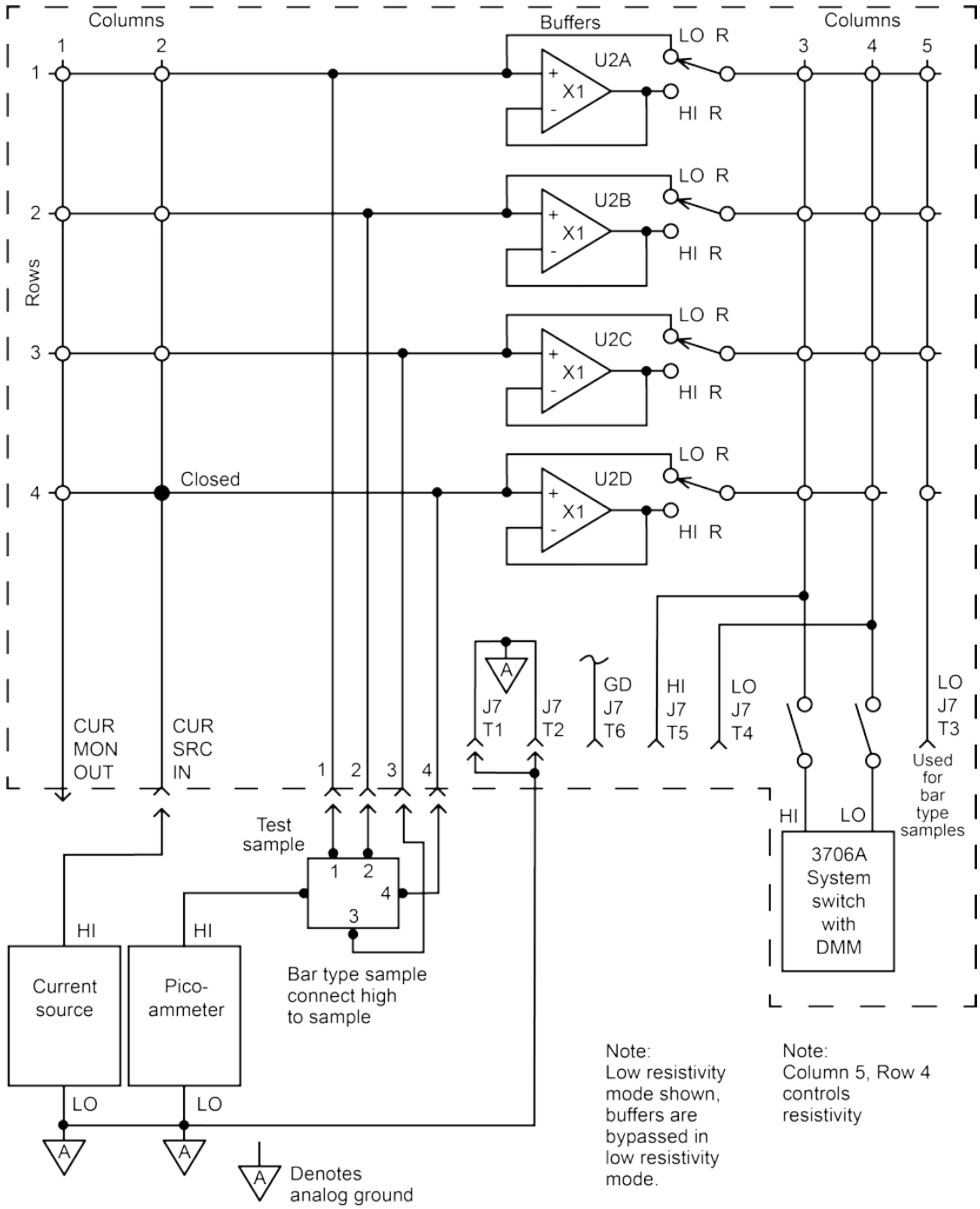
6. Close crosspoints 4,2; 1,3; and 2,4 by programming the scanner.
7. REL the DMM and picoammeter.

NOTE

The REL function on both the DMM and the picoammeter takes a reading and subtracts it from all subsequent readings.

8. Turn on the current source output by pressing the **Output On** key.
9. Note and record the voltage (VR) and (IR) current readings on the DMM and picoammeter.
10. Open all crosspoints by pressing the **Open All** button on the scanner and turn off the current source output after measurements are complete.

Figure 47: Test configuration for Hall voltage measurements of bar-type samples



Hall voltage measurements of bar-type samples

The following procedure assumes that the sample is held stable at the preferred temperature throughout the tests, and that the applied magnetic flux is also held constant at the desired density.

To measure Hall voltage:

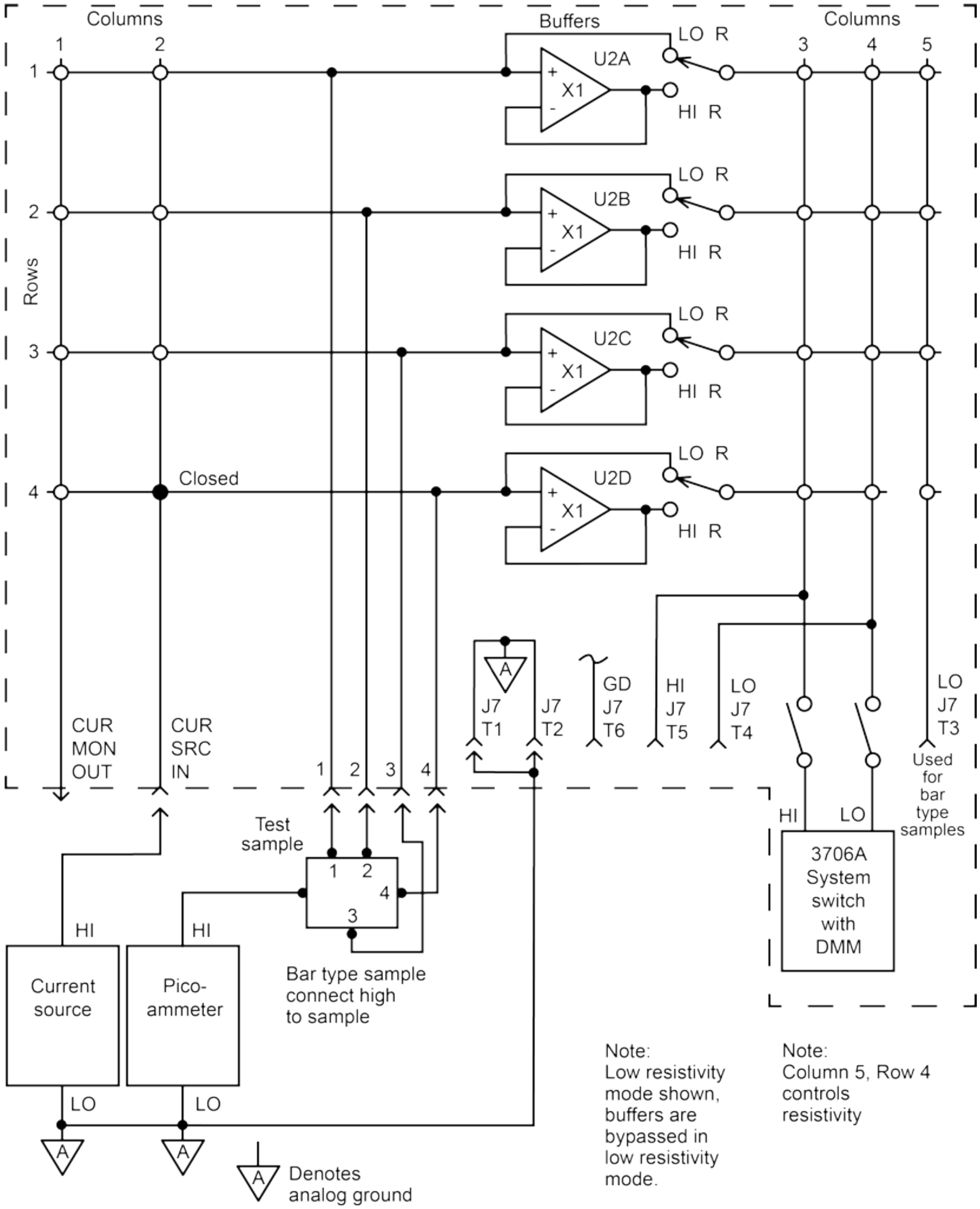
1. Turn on all instruments and allow them to warm up sufficiently.
2. Select the DCV function on the DMM, and set both the DMM and the picoammeter to autoranging.
3. Program crosspoint 4,5 for the preferred resistivity setup. This crosspoint should be open for low resistivity, and it should be closed for high resistivity.
4. Program the current source to the needed (positive) current.
5. Program the scanner to close contacts 4,2; 1,3; 2,4; and 3,5.
6. REL the DMM and picoammeter.

NOTE

The REL function on both the DMM and the picoammeter takes a reading and subtracts it from all subsequent readings.

7. Turn on the current source output by pressing the **Output On** button.
8. With no magnetic field applied, adjust the potentiometer for a reading of 0 V on the DMM.
9. Turn on the magnetic field and adjust it for the desired intensity.
10. Note and record the DMM voltage (V_H) as well as the sample current (I_H) measured by the picoammeter.
11. Open all crosspoints by pressing **Open All** on the scanner and turn off the current source output after all measurements are complete.

Figure 48: Test configuration for Hall voltage measurements of bar-type samples



Crosspoint configurations for bar measurements

Measurement	Closed crosspoints (row, column)			
Resistivity	4,2	1,3	2,4	
Hall voltage	4,2	1,3	2,4	3,5

Calculations for bar-type samples

Bar-type resistivity calculations

The resistivity of the sample is related to the voltage measurements as follows:

$$V_R = \rho I_R \frac{x}{yt}$$

Where:

- V_R is the voltage measured by the DMM.
- ρ is the resistivity in ohm-cm.
- I_R is the current in amperes measured by the picoammeter.
- x and y are the sample dimensions shown in the following figure in cm.

Bar-type Hall voltage calculations

The magnetic field, B, generates a Hall voltage, V_H, as follows:

$$V_H = \frac{R_H I_X B_Z}{t}$$

The Hall coefficient is:

$$R_H = \frac{1}{n|e|}$$

Then:

Equation 1: Equation 26

$$V_H = 6.25 \times 10^{10} \frac{IB}{nt}$$

Where: V_H is the voltage measured by the DMM in volts.

e is the charge of the electron, 1.602×10^{-19} C.

I is the current in amperes measured by the picoammeter.

B_Z is the magnetic flux density in gauss.

t is the sample thickness in cm.

n is the carrier concentration in electrons / cm^3 (substitute p for hole carrier concentration in ρ type materials).

μ is the drift mobility.

Bar-type mobility calculations

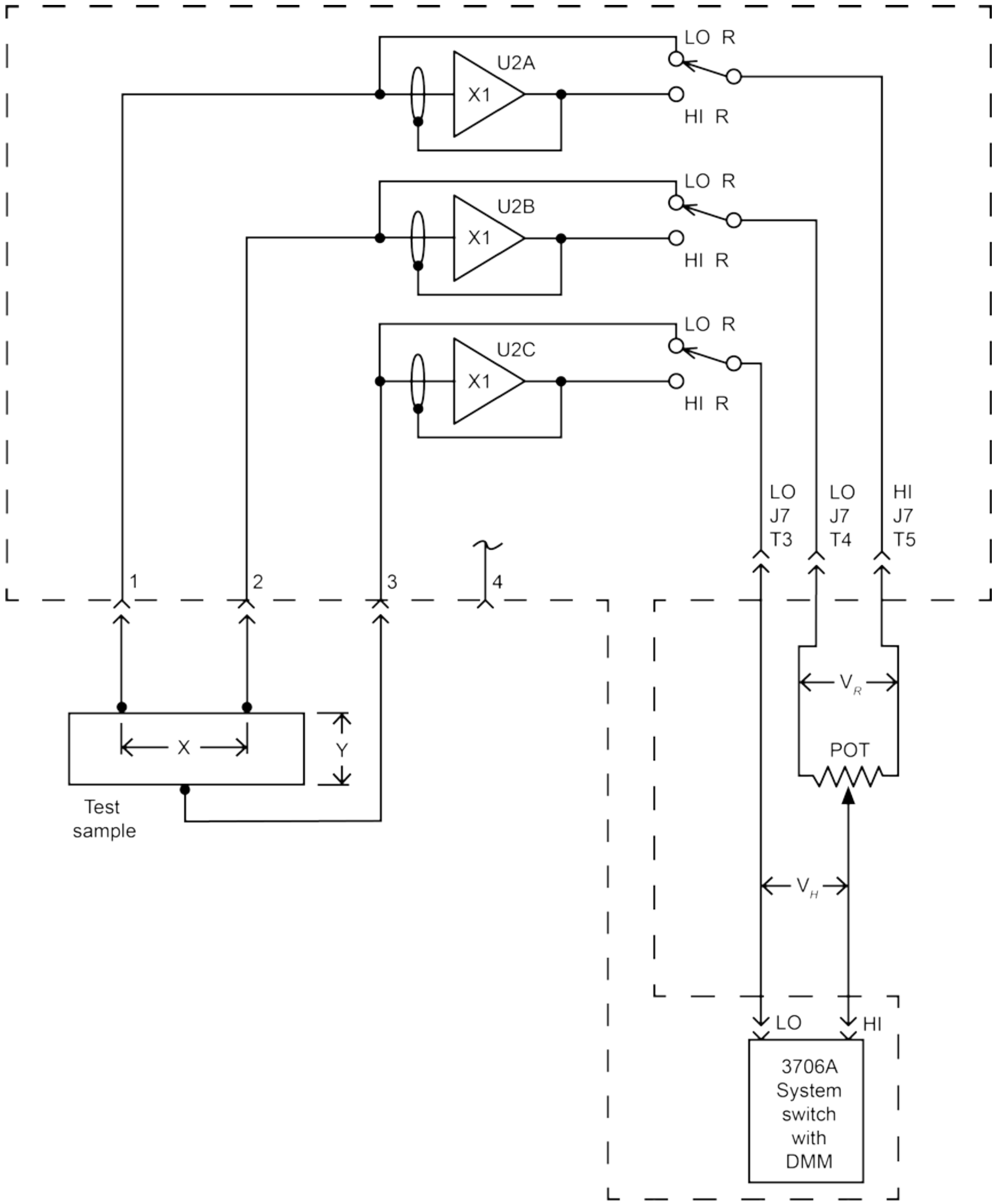
Once the resistivity and Hall voltages are known, the mobility, μ, can be determined as follows:

$$\mu = 10^8 \frac{xV_H}{yBV_R}$$

Where:

- μ is the mobility in cm^2 / Vs.
- x, y are the sample dimensions in cm (the following figure).
- B is the magnetic flux density in gauss.
- V_R is the voltage measured by the DMM (van der Pauw).
- V_H is the Hall voltage measured by the DMM.

Figure 49: Bar sample dimensions



Measuring bridge and parallel-piped-type specimens

The fundamental procedures for measuring 6- and 8-contact bridge and parallel-piped-type specimens are discussed in the following paragraphs.

Bridge and parallel-piped-type test configurations

The first of the following figures shows the test setup for 6-contact specimens, and the setup for 8-contact samples is shown in the second figure. In both cases, four sample contacts are connected to the sample inputs on the 3765. The current source and picoammeter must be connected directly to the sample itself.

Figure 50: Connections for a 6-contact sample

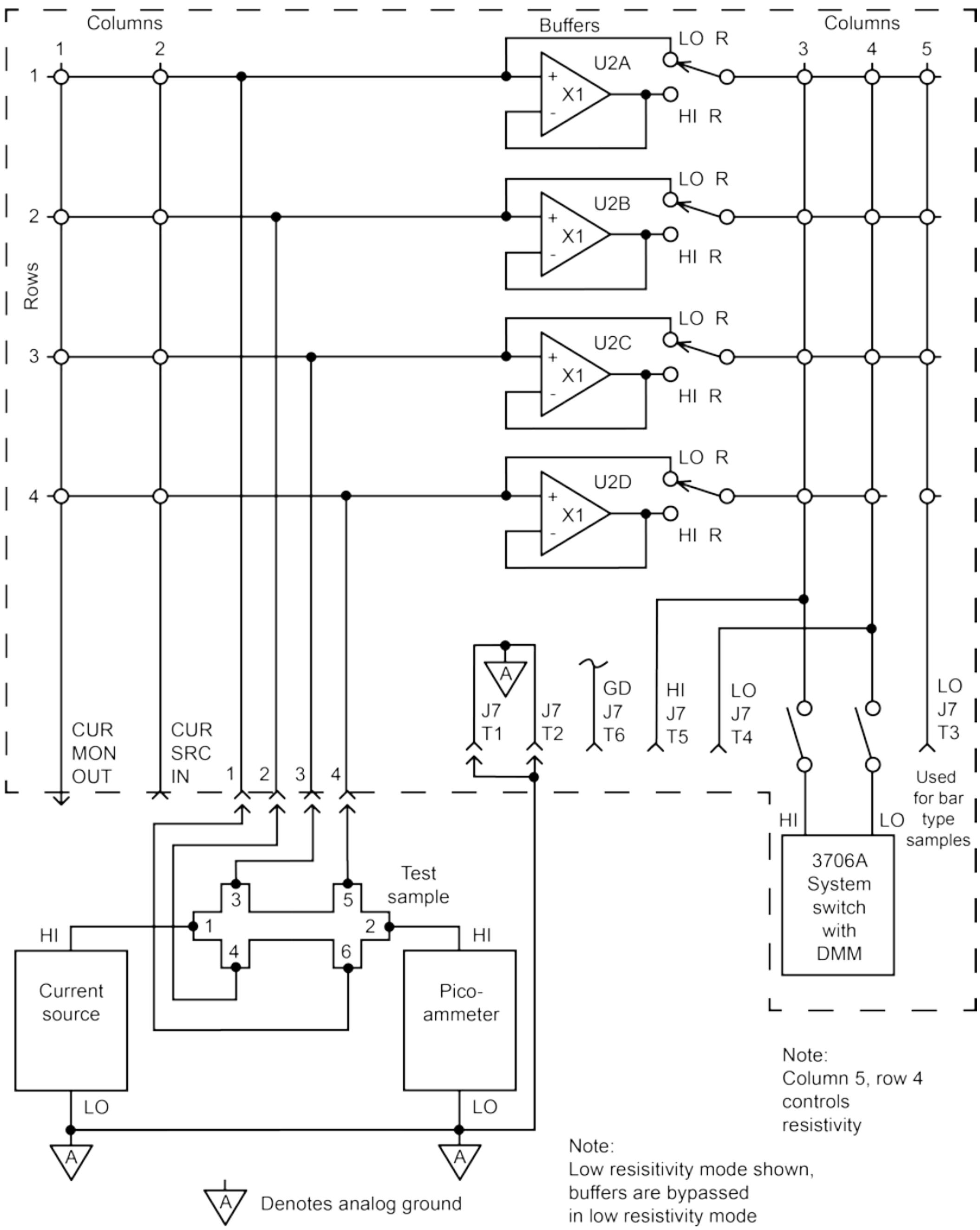
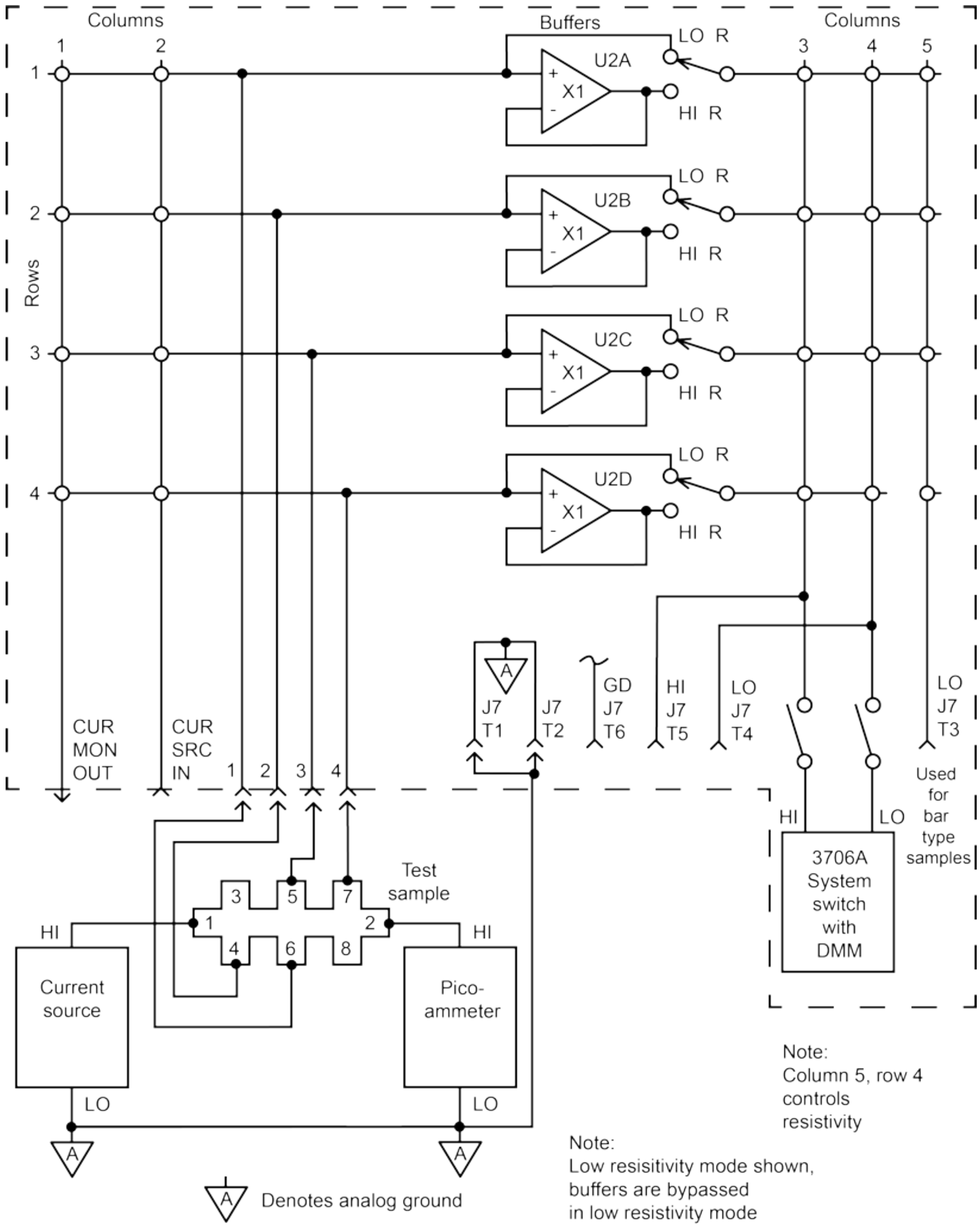


Figure 51: Connections for an 8-contact sample



Bridge and parallel-piped-type resistivity measurements

Use the basic procedure below to measure parameters for 6- and 8-contact specimens. As always, the sample should be stabilized at the needed temperature both before and during the tests.

To measure the 6- and 8-contact specimens:

1. Turn on all the instruments, and allow them to warm up for the prescribed period for rated accuracy.
2. Place the DMM and picoammeter in autoranging mode. Be sure the DMM is in the DCV function.
3. Close relay 911 to route signal on the backplane so the DMM voltmeter can measure the signal.
4. Program crosspoint 4,5 to select low or high resistivity. This crosspoint should be open for low resistivity, and it should be closed for high resistivity.
5. Program the current source to the needed positive current value in the range of 500 fA to 100 mA. The maximum current that can be used depends on the resistance of the sample; remember that the maximum 3765 input voltage is ±8 V.
6. Close the appropriate crosspoints for the sample by programming the scanner (see the table below).
7. REL the DMM and picoammeter.

NOTE

The REL function on both the DMM and the picoammeter takes a reading and subtracts it from all subsequent readings.

8. Turn on the current source output by pressing the **Output On** key.
9. Note and record the voltage (V1) and current readings on the DMM and picoammeter.
10. Turn off the current source output, open the presently closed crosspoints, and close the second set of crosspoints listed in the next table.
11. Enable REL on the picoammeter then turn the current source output back on. Measure the voltage V_2.
12. Program the current source for a negative current of the same magnitude as is presently programmed.
13. Note the picoammeter current reading and compare it to the one obtained in step 8. If the current magnitudes are not exactly the same, reprogram the current source, as necessary, so that the magnitude of the current is as close as possible to that obtained in step 8.
14. Repeat steps 6 through 11 and measure V_J and V_4 by closing the crosspoints indicated in the appropriate table (the next table).
15. Open all crosspoints by pressing the **Open All** button on the scanner.
16. After the measurements are complete, turn off the current source output.

Voltage designation	Crosspoints closed (row, column)		Current between*	Voltage between
V_1	2,3	1,4	2-1	6-4
V_2	3,3	4,4	2-1	5-3
V_3	2,3	1,4	1-2*	6-4
V_4	3,3	4,4	1-2*	5-3

*Reverse current by programming source for opposite polarity.

Bridge and parallel-piped-type Hall voltage measurements

The following procedure assumes that the sample is held stable at the needed temperature throughout the tests and that the applied magnetic flux is also held constant at the desired flux density.

To take Hall voltage measurements:

1. Turn on all instruments, and allow them to warm up.
2. Select the DCV function on the DMM, and set both the DMM and the picoammeter to autoranging.
3. Close relay 911 to the route signal on the backplane so the DMM voltmeter can measure the signal.
4. Program crosspoint 4,5 for the needed resistivity. This crosspoint should be open for low resistivity, and it should be closed for high resistivity.
5. Program the current source to the necessary positive current.
6. Program the scanner to close the first set of contacts listed in the tables below.
7. REL the DMM and picoammeter.

NOTE

The REL function on both the DMM and the picoammeter takes a reading and subtracts it from all subsequent readings.

8. Turn on the current source output by pressing the **Output On** button.
9. Turn on the magnetic flux and adjust it to the preferred positive value (+B).
10. Note and record the DMM voltage (V_1) as well as the sample current measured by the picoammeter.
11. For 6-contact specimens only, measure the voltage V_2, as indicated in the first table below.
12. Reverse the current source polarity and note the current reading from on the picoammeter. If necessary, reprogram the current source so that the magnitude of the measured current is as close as possible to that measured in step 10.
13. Measure the remaining voltage(s) as indicated in the tables below using steps 6 through 12 of the above procedure.
14. Reverse the magnetic flux and repeat steps 10 through 13.
15. Open all crosspoints by pressing the **Open All** button on the scanner.
16. After the measurements are complete, turn off the current source output.

Voltage designation	Flux polarity	Crosspoints closed (row, column)		Current between*	Voltage between
V_1	+ B	1,3	4,4	2-1	5-6
V_2	+ B	2,3	3,4	2-1	3-4
V_3	+ B	1,3	4,4	1-2	5-6
V_4	+ B	2,3	3,4	1-2	3-4
V_5	- B	1,3	4,4	2-1	5-6
V_6	- B	2,3	3,4	2-1	3-4
V_7	- B	1,3	4,4	1-2	5-6
V_8	- B	2,3	3,4	1-2	3-4

*Reverse current by programming source for opposite polarity.

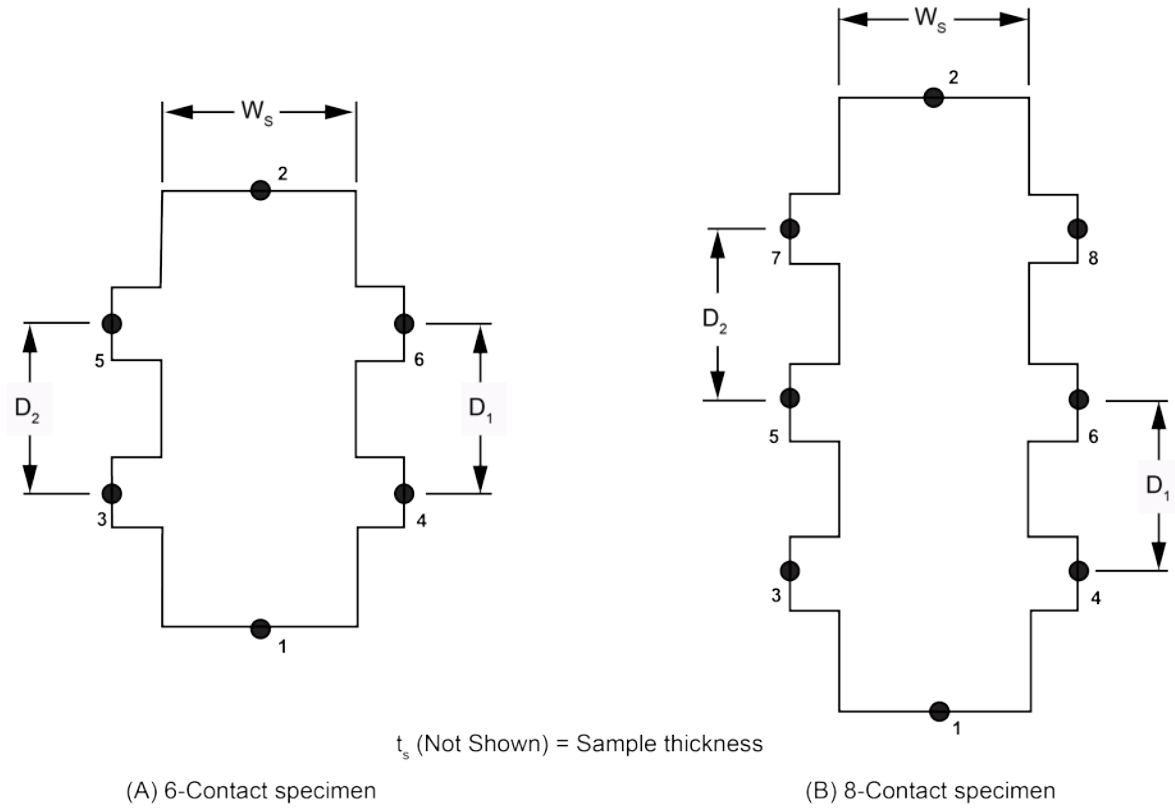
Voltage designation	Flux polarity	Crosspoints closed (row,column)		Current between*	Voltage between
V_1	+B	1,3	3,4	2-1	5-6
V_2	+B	1,3	3,4	1-2	5-6
V_3	-B	1,3	3,4	2-1	5-6
V_4	-B	1,3	3,4	1-2	5-6

*Reverse current by programming source for opposite polarity.

Bridge and parallel-piped-type measurement calculations

Once the necessary measurements are made, resistivity, Hall voltage, and Hall mobility calculations can be made from the data and 6- and 8-contact dimensions, which are outlined in the figure below.

Figure 52: Sample dimensions necessary for calculations



Bridge and parallel-piped-type resistivity calculations

Two resistivity values, P_A and P_B can be calculated as follows:

$$\rho_A = \frac{w_s\, t_s}{2ID_1}\ (V_1 - V_3)$$

and,

$$\rho_B = \frac{w_s\, t_s}{2ID_2}\ (V_2 - V_4)$$

Where: ρ_A and ρ_B = resistivity in ohm × cm

- w_s is the sample width in cm.
- t_s is the sample thickness in cm.
- D_1 and D_2 are the sample dimensions in cm.
- I is the current measured by the picoammeter in amperes.
- V_1 - V_4 are the voltages measured by the DMM.

Once ρ_A and ρ_B are known, the average resistivity, ρ_{AVG},can be computed as follows:

$$\rho_{AVG} = \frac{\rho_A + \rho_B}{2}$$

NOTE

In the above equation, ρ_{AVG} is also given in ohm - cm.

Bridge and parallel-piped-type Hall voltage calculations

For 6-contact samples, two Hall coefficients, R_{H1} and R_{H2} can be calculated as follows:

$$R_{H_1} = \frac{2.5 \times 10^7 t_s}{BI} (V_1 - V_3 + V_7 - V_5)$$

and

$$R_{H_2} = \frac{2.5 \times 10^7 t_s}{BI} (V_2 - V_4 + V_8 - V_6)$$

Where:

- R_{H1} and R_{H2} are the Hall coefficients in cm^3 / C.
- t_s is the sample thickness in cm.
- B is the magnetic flux density in gauss.
- I is the current in amperes measured by the picoammeter.
- V, -V_8 are the voltages measured by the DMM from the table in Hall voltage measurements.

From these two coefficients, the average Hall coefficient, R_{HAVG} can be computed in the following manner:

$$R_{H_{AVG}} = \frac{R_{H_1} + R_{H_2}}{2}$$

Note that R_{HAVG} is in units of cm^3 / C.

For 8-contact samples, only a single coefficient, R_{H1} is needed.

$$R_H = \frac{2.5 \times 10^7 t_s}{BI} (V_1 - V_2 + V_4 - V_3)$$

Where: R_H is the Hall coefficient in cm^3 / C.

- t_s is the sample thickness in cm.
- B is the flux density in gauss.
- I is the current measured by the picoammeter in amperes.
- V, $-V_4$ are the voltages from the table in Hall voltage measurements measured by the DMM.

NOTE

R_{HC} and R_{HD} should be within 10 percent of one another, or the sample is not sufficiently uniform. V_1 and V_6 are measured with a negative magnetic field, -B. V_2 and V_5 are measured with +B.

Bridge and parallel-piped-type Hall mobility calculations

The Hall mobility, μ_H, can be computed from the Hall coefficient and average resistivity of the specimen as follows:

$$\mu_H = \frac{|R_{H_{AVG}}|}{\rho_{AVG}}$$

Where:

- μ_H is the Hall mobility in cm^2 / Vs.
- $R_{H_{AVG}}$ is the average Hall coefficient in cm^3 / C.
- ρ_{AVG} is the average resistivity in ohm - cm.

For 8-contact samples, substitute R_H for $R_{H_{AVG}}$ in the above equation.

Index

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