Variable Temperature Hall Measurement Systems

The world's resource for variable temperature solid state characterization.
The Variable Temperature Hall Effect Measurement Systems

The variable temperature Hall Effect Measurement System is designed to provide totally automatic measurements of the electrical properties of semiconductor and high temperature semiconductor materials using the van der Pauw measurement technique.

**The Hall Effect**

When a current-carrying conductor is placed into a magnetic field, a voltage will be generated perpendicular to both the current and the field. This principle is known as the Hall effect.

The figure on the right illustrates the basic principle of the Hall effect. It shows a thin sheet of semiconducting material (Hall element) through which a current is passed. The output connections are perpendicular to the direction of current. When no magnetic field is present, current distribution is uniform and no potential difference is seen across the output. When a perpendicular magnetic field is present, a Lorentz force is exerted on the current. This force disturbs the current distribution, resulting in a potential difference (voltage) across the output. This voltage is the Hall voltage ($V_H$).

The ratio of voltage created to product of the amount of current and the magnetic field divided by the element thickness is known as the Hall coefficient; this is characteristic of the material being measured.

The Hall effect is a conduction phenomenon which is different for different charge carriers. In most common electrical applications, the conventional current is used partly because it makes no difference whether you consider positive or negative charge to be moving. But the Hall voltage has a different polarity for positive and negative charge carriers, and it has been used to study the details of conduction in semiconductors and other materials which show a combination of negative and positive charge carriers.

**The van der Pauw Method**

The van der Pauw Method is a technique commonly used to measure the sheet resistance and the Hall Coefficient of a sample. Its power lies in its ability to accurately measure the properties of a sample of any arbitrary shape, so long as the sample is approximately two-dimensional (i.e., it is much thinner than it is wide) and the placement of the electrodes is known.

From the measurements made, the following properties of the material can be calculated:

- The sheet resistance, from which the resistivity can be inferred for a sample of a given thickness.
- The doping type (i.e., if it is a P-type or N-type) material.
- The sheet carrier density of the majority carrier (the number of majority carriers per unit area). From this, the density of the semiconductor, often known as the doping level, can be found for a sample with a given thickness.
- The mobility of the majority carrier.

**Taking Measurements**

The MMR Technologies’ Hall Measurement system requires four ohmic contacts on the sample, on or as close to the sample boundary or edge as possible. It is assumed that the four contact points are infinitely small, composed of the same material, and that leads from these contacts are of the same batch of wires to minimize thermoelectric effects and errors.

Current is then passed between two of the contacts and the resulting voltage is measured between the other two contacts. The measurement functions of the contacts are permuted to allow each contact to serve as both a current supply lead and a voltage measurement lead in combination with each of the other contact points. These measurements, plus the knowledge of the thickness of the sample provide sufficient information to determine the resistivity of the sample. The permutations of the current and voltage leads allow the user to eliminate the thermoelectric EMF and other sources of measurement error. By repeating these measurements in a known magnetic field, the direction of which is automatically reversed by the system as measurements are made, the Hall mobility and carrier concent
characteristics of the material can be determined.

**A Typical Variable Temperature Hall Effect Measurement System**

A typical variable temperature Hall Effect Measurement system includes:
- High-purity high-pressure gas (typically nitrogen or argon)
- A filter/dryer apparatus (cooling stages only) with high-pressure gas lines
- Thermal stage for heating and/or cooling
- MMR’s Programmable Temperature Controller and Hall Effect Measurement Controller
- Vacuum Chamber Equipped with Triax Cables for Data Acquisition
- Magnet setup (may be a permanent magnet or an electromagnet and the required power supplies for operation)
- Vacuum Pump Setup

- Spring Loaded Probes or a Kapton Harness for taking 4-point van der Pauw Measurements
- Computer

The Hall Effect and Seebeck Effect Measurement systems have many common components. It is possible to add on a Seebeck Measurement Option to any Hall Measurement System to broaden the experimental information available from samples of interest.

**Available Temperature Ranges on Thermal Stages**

When the vacuum chamber system is held under a vacuum pressure of at least 8 milliTorr, the following temperature ranges are available on the MMR Technologies’ instruments:
- Room Temperature
- 70K to 580K
- 80K to 580K
- 70K to 730K*
- 80K to 730K
- Room temperature to 730K

* Vacuum assist Joule-Thomson thermal stages require an auxiliary vacuum pump at the thermal stage gas exhaust. These thermal stages are not available on ultra high vacuum or scanning electron microscope systems. Hot stages do not require a filter/dryer setup or high pressure.

When a thermal stage is used within an ambient pressure setup, with a well controlled atmosphere, the following temperature ranges** are available using the appropriate thermal stage setup:
- -10 °C to 200 °C (using nitrogen gas) or -30 °C to 200 °C (using argon gas)
- -10 °C to 350 °C (using nitrogen gas) or -30 °C to 350 °C (using argon gas)
- Room temperature to 350 °C

** These are the maximum temperature ranges under ideal conditions like a glove box where there is no humidity and a dry, clean gas environment.

**MMR Technologies’ Unique Temperature Controller**

MMR Technologies’ offers a unique Programmable Temperature Controller that is exclusively intended for use with our patented cryogenic cooling and thermal stage systems. This controller provides accurate temperature measurement, precise and very stable temperature control and easy-to-use data acquisition functions over the temperature range from 70K to 730K. Controlled cycling, temperature ramping and changing temperature operation under software control gives the user a valuable tool for solid state characterization studies.
MMR Technologies offer a turnkey solution with their Programmable Temperature Controller and their Hall Measurement Controller. The two controllers work together, operated by the Hall Measurement software to provide an integrated temperature control both of the overall sample area and the small required temperature gradient.

**The Circuit Breakout Box**

The temperature controller and the unique temperature stages can work together with a Circuit Breakout Box - enabling direct electrical connections between the sample surface and extra pins available on the thermal stage. This gives an expanded flexibility to the system through up to 4 external BNC connection options.

**The Filter/Dryer Setup**

A filter-dryer system is necessary to remove both the water and the other condensable contaminants to ensure optimal performance of the Joule Thompson refrigerators. Failure to use one of these systems in conjunction with your cooling system will ultimately result in a loss of cooling capacity, reduction in the temperature range the microminiature refrigerator can obtain, clogging in the channels of the glass refrigerator, and ultimately damage to these channels that may not be repairable.

There are two types of filter/dryer systems available from MMR Technologies: Model F2115 and Model F2105. These systems are designed to work with the company’s line of microminiature Joule-Thomson refrigerators.

There are a number of applications for the filter-dryers from MMR Technologies, including:

- Suitable for drying argon, nitrogen, hydrogen, helium, and many other gases to a Dew Point below -75 °C.
- Use of this dryer with the MMR line of microminiature refrigerators allows continuous operation of the refrigerators for up to hundreds of hours without clogging.
- The dryer may be used to provide point-of-use, dry gas at a purity level, previously attainable only with dryers of much greater cost.

*** For more detailed information on the two types of filter dryer systems, please refer to the data sheets or the technical support bulletin TSB003. These are available by contacting sales@mmr-tech.com.

**The Vacuum Chamber and Connections for Four-Point Measurements**

The Hall System Dewar or vacuum chamber has been designed to facilitate rapid and simple measurements of resistivities, carrier densities, and mobilities of semiconductor materials over a range of temperatures. The sample is mounted in an evacuated dewar or vacuum chamber on a thermal stage which is cooled by a microminiature Joule-Thomson thermal stage and heated by a computer controlled heater. When used with MMR Technologies’ programmable temperature controller, the thermal stage will provide controlled cycling and temperature measurements over the range of 70K to 730K.

There are two ways of making connections with the sample surface:

- Spring Loaded Probes (image to the left)
- Wire Bonding to a Kapton Harness (image on the next page)
The spring loaded probe assemblies provide the electrical access to the sample under study without the use of wire bonding or soldered connections. This is particularly useful when the sample is to be studied at temperatures that are above the melting point of many common solders. The spring loaded probe assemblies additionally enable faster sample exchange.

The Kapton harness method of making electrical contacts using wire bond or solder is advantageous when the sample surface is sensitive to scratching, or when there is very low resistivities and electrical contact through touch (like with the spring loaded probes) is challenging to obtain. Use of the Kapton harness is also particularly useful when non-square geometry is desired in the sample measurements.

The Hall vacuum chamber has a built in Hall sensor, located directly under the sample that is being measured. This enables the measurement of the magnetic field experienced by the sample to be measured through the MMR electronics, and to be taken into account during calculations. This also allows the Hall Measurement Controller, when coupled with an electromagnet, to control both the magnetic field strength and direction automatically during experiments.

### The Magnets and Electromagnets

There are three magnet systems offered by MMR Technologies. All three models will work as a part of a turnkey solution with the MMR Technologies Hall controller and software. These magnets provide both low field and high field options, and offer solutions for a range of budget needs and sample measurement needs. To increase the mobility of carriers within a sample, moving to a stronger magnetic field can increase successful measurements and reproducibility, while reducing noise.

#### 5000 Gauss (0.5 Tesla) Permanent Magnet

The M25 Permanent Magnet is a low cost, low field magnet system (left). This compact bench top magnet provides a 5000 Gauss field between flat 2.5 inch by 1.66 inch pole pieces with a 0.78 inch gap. The Hall vacuum chamber slides into the pole gap of the magnet, and a measurement can be taken in one field direction. The MMR Technologies' Hall Measurement software prompts the user to remove the chamber and to insert it in the opposite direction when a reversed direction field measurement is required.

#### 5000 Gauss (0.5 Tesla) Electromagnet and Power Supplies

The MK50 Electromagnet is our variable low field magnet system (below). This compact, air or water cooled, bipolar bench top system provides a reversible field of 5000 Gauss with a 20 mm face diameter pole pair and 0.75 inch gap. The size of the gap can be adjusted if necessary to accommodate other chambers or devices.

The MK50 electromagnet is coupled with the MPSK-50 bipolar power supply. This power supply is capable of providing 12 Amps of current at 36 volts (400 Watts). It is continuously controllable over both the current and voltage range windows, and is controlled by the MMR Technologies’ Hall Measurement software and the Hall Measurement Controller.

With the MPSK-50, field reversal of the electromagnet is automatic and measurements can be done with either sign or at zero field.

This electromagnet is air cooled but has water cooling ports as an option for...
temperature stability over long experimental setups.

**14,000 Gauss (1.4 Tesla) C-Frame Electromagnet and Power Suppliers**

This high field electromagnet is supplied with a 38 mm face diameter pole pair to provide the highest possible field versus current values. It may be operated with currents up to 40 amps at 20 volts (800 Watts) when coupled with the MPS150 Magnetic Power supplies from MMR Technologies. Higher current operation is possible, but this requires power supplies from alternate vendors. For high current operation, or lengthy experiments, the M150 electromagnet must be operated with a recirculating chiller.

The MPS-150 power supplies are high powered operational amplifiers with full 4-quadrant, bipolar operation. The voltage and current outputs can be made to vary smoothly and linearly through the entire plus and minus ranges, passing smoothly through zero with no polarity switching.

The MPS-150 power supplies enable easy software controlled field reversal and measurements can be done with either sign or at zero field.

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**Performance Behavior for the Hall System**

The van der Pauw and Hall Effect Measurement System can measure the following properties:

**Sheet Resistance**

Sheet resistance is a measure of resistance of thin films that are nominally uniform in thickness. It is commonly used to characterize materials made by semiconductor doping, metal deposition, resistive paste printing, and glass coating. From the sheet resistance, the resistivity can be inferred for a sample of a given thickness.

**Doping Type of the Major Carrier within the Material**

Extrinsic semiconductors with a larger electron concentration than hole concentration are known as n-type semiconductors. The phrase ‘n-type’ comes from the negative charge of the electron. In n-type semiconductors, electrons are the majority carriers and holes are the minority carriers. N-type semiconductors are created by doping an intrinsic semiconductor with donor impurities. In an n-type semiconductor, the Fermi energy level is greater than that of the intrinsic semiconductor and lies closer to the conduction band than the valence band.

As opposed to n-type semiconductors, p-type semiconductors have a larger hole concentration than electron concentration. The phrase ‘p-type’ refers to the positive charge of the hole. In p-type semiconductors, holes are the majority carriers and electrons are the minority carriers. P-type semiconductors are created by doping an intrinsic semiconductor with acceptor impurities. P-type semiconductors have Fermi energy levels below the intrinsic Fermi energy level. The Fermi energy level lies closer to the valence band than the conduction band in a p-type semiconductor.

Carrier mobility is most commonly measured using the Hall effect. The result of the measurement is called the “Hall mobility” (meaning “mobility inferred from a Hall-effect measurement”).

Consider a semiconductor sample with a rectangular cross section where a current is flowing in the x-direction and a magnetic field is applied in the z-direction. The resulting Lorentz force will accelerate the electrons (n-type materials) or holes (p-type materials) in the (−y) direction, according to the right hand rule and set up an electric field y. As a result there is a voltage across the sample, which can be measured with a high-impedance voltmeter. This voltage, \( V_{H} \), is called the Hall voltage. \( V_{H} \) is negative for n-type material and positive.

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1 Alternate power supplies may not be compatible to be operated as a turnkey system with the MMR Technologies’ Hall Controller and software.
for p-type material.

**Sheet Carrier Density of the Majority Carrier**

The sheet carrier density of the majority carrier is the number of majority carriers per unit area. From this the charge density and doping level can be found for a sample with a given thickness.

**Mobility of the Majority Carrier**

The electron mobility characterizes how quickly an electron can move through a metal or semiconductor, when pulled by an electric field. In semiconductors, there is an analogous quantity for holes, called hole mobility. The term carrier mobility refers in general to both electron and hole mobility in semiconductors. Only the mobility of the majority carrier can be determined in a sample.

Semiconductor mobility depends on the impurity concentrations (including donor and acceptor concentrations), defect concentration, temperature, and electron and hole concentrations.

**Specifications for the Variable Temperature Hall Systems**

Operating Temperature Range: Available between 70K and 730K (Joule-Thomson Thermal Stage)*

Dimensions of Vacuum Chamber: 2.5 in wide x 6.0 in long x 0.75 in high (at sample end)
Weight of the Vacuum Chamber: 16 oz (454 grams) with thermal stage mounted
Sample Mounting Surface Size: 10 mm x 12 mm
Standard Window Material: Fused Silica
Maximum Sample Weight Allowed: No more than 5 grams
Working Distance: 12 mm
Four-Point van der Pauw Measurement Dimension Configurations: Spring Loaded Probe Spacing: 0.1 in, 0.2 in, 0.3 in (5.25 mm, 10.5 mm, 15.75 mm Kapton Harness Space: not applicable
Electrical Connections: Triax connectors.
Current source range : 1\(^{12}\) to 0.1 Amps
Voltage measurement range: 0.1 to 2.4 Volts
Resistance (or resistivity) range:** Typical range is 10\(^{4}\) Ohm*cm to 10\(^{13}\) Ohm*cm (dependent on sample thickness)
Carrier concentration range:** Approximate range is 10\(^{14}\) cm\(^{-3}\) to 10\(^{20}\) cm\(^{-3}\) (dependent on sample thickness)
Mobility range:** Approximate range is 1 cm\(^{2}\)/volt*sec to 10\(^{7}\) cm\(^{2}\)/volt*sec (dependent on magnetic field strength)
Sample Thickness: 0.001-2000 micrometer
Types of Samples Measurable: Thin Films, Quantum Dots, Solar Cells, Colloidal Nanorods, etc
Semiconductors including GaN, AlN, Bn, SiC, ZnO, CdTe, etc
High Temperature Superconductor Samples
Temperature Controller Requirements: MMR’s Programmable Temperature Controller
Temperature Accuracy: < 0.5K at 80K; */- 0.5K between 80K and 400K; < 1.5K from 400K to 730K
Temperature Stability: */- 0.05K
Temperature Resolution: 0.01 K
Filter/Dryer Requirements: Either the standard filter dryer or the reversible filter dryer system if operation below room temperature is required.
Vacuum Requirement: For operation outside of room temperature, 8 milliTorr of vacuum pressure is a minimum requirement.

* For more information, please refer to the product data sheets for the Joule-Thomson thermal stages.

** For more information, please refer to the Measurement Range of the MMR Technologies Hall System Application note. Measurement ranges can be increased one to two orders of magnitude by varying the sample geometry (length to width ratio), sample thickness, and magnetic field strength.
Features and Benefits

The variable temperature Hall and van der Pauw Measurement systems are noted for their unique benefits and features, making these systems easy to use and valuable additions to research facilities:

♦ Modular - you can build the systems up over time to meet your budget and experimental needs.
♦ Two Sizes of Systems Available:
  ♦ Bench-top Configuration: small and compact in size
  ♦ Large High Field Magnets: powerful measurement systems with the largest range of samples possible
♦ Excellent temperature setability, stability, and reproducibility.
♦ Absence of mechanical, acoustic, or electrical noise.
♦ Fast cool down and warm up times, with frost free operation.
♦ Wide range of operation: 70K to 730K
♦ Non-magnetic electrical feedthroughs facilitate electrical connections directly to samples on the thermal stage.
♦ Low cost of operation: $0.50/hour
♦ On the Joule-Thomson stages there are no liquid cryogens to handle.
♦ Very low power consumption - less than 12 watts on any stage.
♦ Seebeck Add-On Option Available to expand your measurement capabilities.
♦ Three Magnet Options Available - Low and High Field Systems

Applications

MMR Technologies Variable Temperature Hall Measurement system is one of the more valuable instruments for solid state characterization. There are many possible applications for these systems, including but not limited to:

♦ Hall effect devices:
  ♦ Immune to dust, dirt, mud, water
  ♦ Better for position sensing
♦ Hall sensors:
  ♦ Can easily detect stray magnetic fields
  ♦ Work well as electronic compasses
♦ Hall effect current transducers:
  ♦ High accuracy, environmentally hardy, low power consumption
  ♦ Ideal solution for solar energy management
♦ Electrical Measurements
♦ Material studies

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