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Instrumentation and Techniques for Measuring High Resistivity and Hall Voltage of Semiconducting Materials

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THE resistivity and Hall mobility of semiconducting materials are fundamental properties investigated during product and process development. For example, the resistivity of a semiconductor device is primarily dependent on bulk doping and can affect capacitance, series resistance, and threshold voltage. Therefore, accurate measurements of these properties are essential. Measurement techniques and instrumentation affect the level of accuracy and difficulty in conducting these tests.

Instrumentation Issues

To maximize accuracy, resistivity is often determined with a four-point probe (Kelvin) technique. Two of the probes are used to source current, while the other two measure voltage. Using four probes eliminates measurement errors due to probe resistance, the spreading resistance under each probe, and the contact resistance between each metal probe and the semiconducting material.

Two common Kelvin techniques in semiconductor measurements are the four-point collinear probe method and the van der Pauw method. There are variations in the instrumentation depending on whether the material has high or low resistivity. The focus of this article is on instrumentation and measurement techniques for high resistivity semiconductor material.

Four-Point Collinear Probe Method for Resistivity

The most common way of measuring the resistivity of a semiconductor material is by using a four-point collinear probe. This technique involves bringing four equally spaced probes in contact with a material of unknown resistance. The probe array is placed in the center of the material, as shown in ***Figure 1***. The two outer probes are used for sourcing current and the two inner probes are used for measuring the resulting voltage drop across the surface of the sample.

Calculations. With the known current and measured voltage, volume resistivity is calculated as follows:

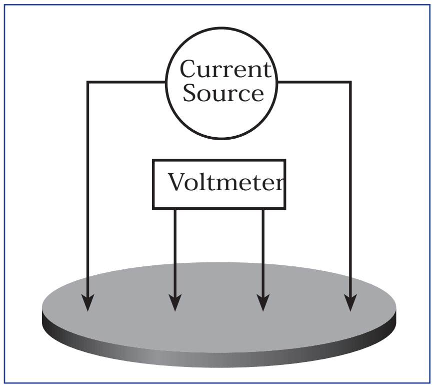

Figure 1. Four-Point Collinear Probe Configuration

$$\rho = [\pi/\ln 2] * [V/I] * t * k$$

where: ρ = volume resistivity (ohm-cm)
V = measured voltage (volts)
I = source current (amperes)
t = sample thickness (cm)
k = a correction factor based on the ratio of the probe to wafer diameter and on the ratio of wafer thickness to probe separation[1].

van der Pauw Resistivity Measurements

The van der Pauw method involves applying a current and measuring voltage using four small contacts on the periphery of a flat, arbitrarily shaped sample of uniform thickness. This method is particularly useful for measuring very small samples because geometric spacing of the contacts is unimportant. Effects due to a sample's size, which is the approximate probe spacing, are irrelevant.

Resistivity derivation. Using this method, the resistivity can be derived from a total of eight measurements that are made around the periphery of the sample with the configurations shown in ***Figure 2***. Once all the voltage measurements are taken, two values of resistivity, ρ_A and ρ_B, are derived as follows:

$$\rho_A = [\pi/\ln 2] * [f_A t] * [(V_1 – V_2 + V_3 – V_4)/(4I)]$$

$$\rho_B = [\pi/\ln 2] * [f_B t] * [(V_5 – V_6 + V_7 – V_8)/(4I)]$$

where: ρ_A and ρ_B are volume resistivities (ohm-cm);
t is the sample thickness (cm);

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[1] The correction factors can be found in standard four-point probe resistivity test procedures such as SEMI MF84-02—Test Method for Measuring Resistivity of Silicon Wafers With an In-Line Four-Point Probe.

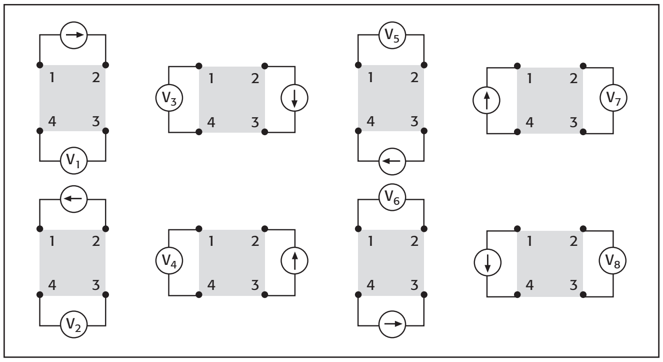

Figure 2. van der Pauw 8-measurement convention

V_1 through V_8 represent the measured voltages;

I is the current through the sample (amperes);

f_A and f_B are geometrical factors based on sample symmetry and related to the two resistance ratios Q_A and Q_B as shown in the following equations ($f_A = f_B = 1$ for perfect symmetry).

Q_A and Q_B are calculated using the measured voltages as follows:

$$Q_A = (V_1 - V_2) / (V_3 - V_4)$$

$$Q_B = (V_5 - V_6) / (V_7 - V_8)$$

Also, Q and f are related as follows:

$$(Q - 1) / (Q + 1) = (f / 0.693) \text{ arc cosh } [(e^{0.693/f}) / 2].$$

A plot of this function is shown in ***Figure 3***. The values of f_A and f_B can be found from this plot using the calculated values of Q_A and Q_B. With the values of f_A and f_B known, ρ_A and ρ_B can be calculated. The average resistivity (ρ_{AVG}) is simply $(\rho_A + \rho_B) / 2$.

Hall Voltage Measurements

Hall effect measurements are important to semiconductor material characterization, because from the Hall voltage the carrier density, mobility, and conductivity type can be derived. With an applied magnetic field, the Hall voltage can be measured using the configurations shown in ***Figure 4***.

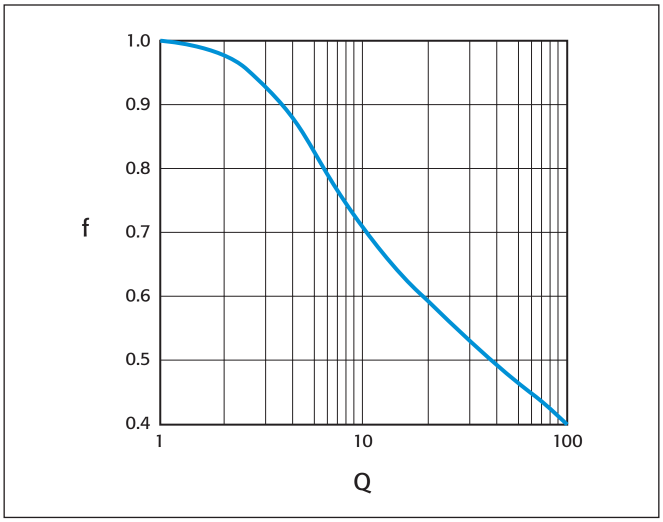

Figure 3. Determining the sample's symmetry factor using an f vs. Q plot.

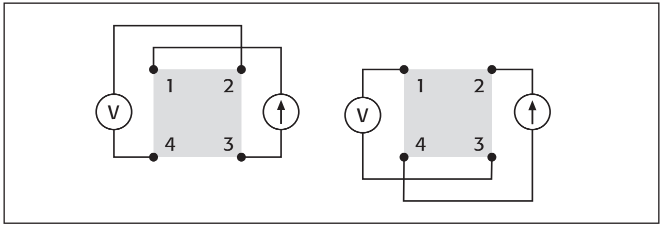

Figure 4. Hall voltage measurement configuration.

Procedure. With a positive magnetic field of known flux, B, applied to the sample, a current is sourced and voltages measured between the sample terminals as follows:

- Constant current is applied between terminals 1 and 3; voltage drop (V_{24+}) is measured between terminals 2 and 4.
- Reverse the current and measure the voltage drop (V_{42+}).
- Apply current between terminals 2 and 4; measure the voltage drop (V_{13+}) between terminals 1 and 3.
- Reverse the current and measure voltage drop (V_{31+}).
- Reverse the magnetic field, B, and repeat the procedure, measuring the four voltage drops (V_{24-}), (V_{42-}), (V_{13-}), and (V_{31-}).

Calculations. From the eight Hall voltage measurements, the average Hall coefficient can be calculated as follows:

$$R_{HC} = \frac{t\,(V_{4-2+} - V_{2-4+} + V_{2-4-} - V_{4-2-})}{BI}$$

$$R_{HD} = \frac{t\,(V_{3-1+} - V_{1-3+} + V_{1-3-} - V_{3-1-})}{BI}$$

where: R_{HC} and R_{HD} are Hall coefficients in cm^3/C;
t is the sample thickness in cm;
V represents the voltages measured by the voltmeter;
I is the current through the sample in amperes;
B is the magnetic flux in V_S/cm^2 ($1\ V_S/cm^2 = 10^8$ gauss)

Once R_{HC} and R_{HD} have been determined, the average Hall coefficient (R_{HAVG}) can be calculated as $(R_{HC} + R_{HD}) / 2$. From the resistivity (ρ_{AVG}) and Hall coefficient (R_{HAVG}), the mobility (μH) can be calculated:

$$\mu H = \frac{|R_{HAVG}|}{\rho_{AVG}}$$

Test Equipment

As described in the previous sections, semiconductor resistivity and Hall effect measurements require a programmable current source and voltmeter for both the four-point collinear probe and van der Pauw methods. For high resistance samples, the current source must have very high output impedance and the voltmeter must have high input impedance. Additionally, in van der Pauw testing, a switching matrix has traditionally been used to automate measurements, because the current source and voltmeter must be switched to all terminals of the sample. However, switches can introduce measurement error with added offset current and loading errors due to insufficient isolation and leakage current of the switching hardware.

The use of multiple Source Measure Units (SMUs) that can source and measure both current and voltage is one approach that eliminates these switching issues. For testing high resistance materials, use

SMUs that have very high input impedance voltmeters and current sources with high output resistance. These multi-SMU systems speed up measurements by automatically switching the current source and voltmeter between the terminals of the sample according to a programmed test sequence.

Automated test systems are available with integrated SMUs that can provide good performance and accurate results without the need for a switching matrix or other external instruments. Since no external switching is required, this eliminates leakage and offsets errors caused by mechanical contacts. The system software may include a four probe resistivity application that takes the user through all the steps required to set up the test, collect data, and do the necessary calculations.

Systems of this type are often called parameter analyzers or semiconductor characterization systems. Keithley's Model 4200-SCS is an example of this type of system.

Four-point Probe Resistivity Instrumentation. At least three SMUs and a grounding unit are required to make resistivity measurements using the four-point collinear probe method. Interactive programming is used to create and run the test sequence on the sample. ***Figure 5*** illustrates how to configure the Keithley Model 4200-SCS's SMUs for this type of measurement.

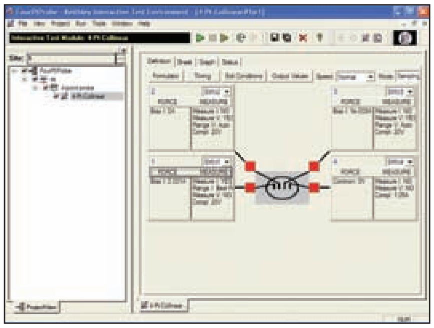

Figure 5. SMU configuration for the four-point collinear probe method using a Keithley Model 4200-SCS.

SMU1 is used to source current between the outer two probes. SMU2 and SMU3 are used to measure the voltage drop between the two inner probes. SMU4 is configured as the common terminal. Depending on measurement system design, the user may write the test program, or use an interactive test generation module to create the setup (***Figure 5***) and run the test sequence on the sample, which is treated as a four-terminal device.

SMU1, SMU2, and SMU3 are configured for the source current/measure voltage mode, even though SMU1 will be used to source current, and SMU2 and SMU3 are used to measure voltage. In general, the current source range determines the input impedance of the SMU as a voltmeter. The lower the current range, the higher the input impedance, and the better the accuracy. To avoid loading errors when measuring voltage drops across high resistance samples, SMU2 and SMU3 are configured to measure voltage with the source current to zero amps on a low current range.

Most automated test systems of the type described here provide mathematical functions that facilitate resistivity calculations. For instance, in the Keithley Model 4200-SCS, the Formulator function allows the user to type in the formula for sheet and volume resistivity, and from the data sets, calculate the voltage difference (V_{diff}) between SMU2 and SMU3. The sheet resistivity is $R_{sheet} = 4.532 (V_{diff}/I_{applied})$, and the volume resistivity is $R_{sheet} * t$, where t is the sample thickness.

The constant 4.532 is a geometric correction factor for probe spacing and sample diameter. It allows for the fact that current does not flow in a straight line between the outer probes, but rather in an arc-like path.

van der Pauw Instrumentation. The same type of instrumentation used in the four-point collinear probe method can be used for van der Pauw measurements. However, preamps are required with the SMUs for high resistance samples. To limit the magnitude of the voltage drops, the output of the current source must be very small. If separate instruments are used, this requires a differential electrometer with a very high input impedance to minimize loading effects and leakage currents. (A differential electrometer isn't required with a Keithley Model 4200-SCS because its preamps have very high shunt resistance ($>10^{16}\Omega$) on the 1pA and 10pA source ranges.)

Four different SMU test configurations are required, with test currents flowing in opposite directions for the eight measurements shown in ***Figure 2***. One SMU applies the test current (positive and negative values), and two others are used as high impedance voltmeters with a test current of zero amps. (For very high resistance measurements, use a lower current range.) The fourth SMU is set to common. The source current value is the same for all four test configurations. This value is based on the expected sample resistance, and is set so that the voltage difference will not exceed ~25mV.

Typically, test system software performs van der Pauw resistivity calculations in a manner similar to the four-point collinear probe calculations. However, the average voltages from each of the four test configurations are used to calculate the resistivity on a sub-site calculation worksheet. The thickness, coefficients, and correction factors also are inputs on the calculation worksheet for the resistivity equations.

Hall Voltage Measurements. The test equipment setup to measure Hall voltage is very similar to the setup for measuring resistivity. The difference is the location of the current source and voltmeter terminals. The procedures and calculations were presented earlier. (See ***Figure 4***.) If the user-supplied electromagnet has an IEEE-488 interface, a module can be written to control the electromagnet with the SMU test system.

Measurement Considerations and Sources of Error

For successful resistivity measurements, possible sources of errors should be considered and steps taken to minimize them. These errors fall into three categories: those arising from the test procedures, those associated with resistivity calculations, and those external to the measurement system, including those related to the sample material and its handling.

Carrier Injection. To prevent minority/majority carrier injection from influencing resistivity measurements, the voltage difference between the two voltage sensing terminals should be kept at less than 100mV (ideally 25mV) since the thermal voltage, kT/q, is approximately 26mV. Therefore, the output of the test current source should be kept to as low as possible without having detrimental affects on measurement precision.

Measurement Settling Time. When testing high resistivity material, adequate time must elapse after a current stimulus is applied to allow the material's voltage response to settle to a stable value. This elapsed time, the current source sweep delay, can be established by sourcing current into two terminals of the sample and measuring the voltage difference between the other two terminals. The settling time is then determined by graphing the voltage difference versus the time of the measurement (***Figure 6***). This may require a few hundred time-stamped readings, typically with a sweep time of one second. Once the settling time has been determined, use this time as the sweep delay for the voltage measurements.

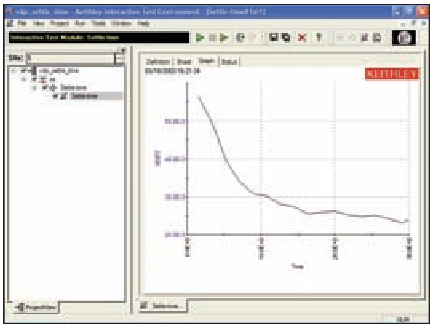

Figure 6. Differential voltage vs. time graph for determining measurement settling time on a very high resistance sample.

Sample Geometry. Volume resistivity calculations require an accurate value for the sample thickness. Moreover, to get realistic sheet resistivity estimates, correction factors based on the ratio of the sample diameter to the probe spacing (D/s), and ratio of sample thickness to probe spacing (t/s), are required. For $t/s \leq 0.3$, no thickness correction is required (i.e., the correction factor is unity). When $D/s > 200$, the diameter correction factor is 4.532. This correction factor decreases as D/s decreases. Comprehensive sets of correction factors can be found in standard four-point probe resistivity test procedures, such as SEMI MF84-02—Test Method for Measuring Resistivity of Silicon Wafers With an In-Line Four-Point Probe.

Light Exposure. Currents generated by photoconductive effects in semiconductor materials can degrade measurements, especially on high resistance samples. To prevent this, the sample should be placed in a dark chamber.

Temperature. Thermoelectric voltages due to temperature gradients may also affect measurement accuracy. Temperature gradients may result if the sample temperature is not uniform. Thermoelectric voltages may also be generated from sample heating caused by the source current. Heating from the source current will more likely affect low resistance samples, since a higher test current is needed to make the voltage measurements easier. Temperature fluctuations in the laboratory environment may also affect measurements. Since semiconductors have a relatively large temperature coefficient, temperature variations in the laboratory may need to be compensated for by using correction factors.

Leakage Current. For high resistance samples, leakage current may degrade measurements. The leakage current is due to the insulation resistance of the cables, probes, and test fixturing. Leakage current may be minimized by using good quality insulators, by reducing humidity, and by using guarding.

A guard is a conductor connected to a low impedance point in the circuit that is nearly at the same potential as the high impedance lead being guarded. For example, when using the Keithley Model 4200-SCS, the inner shield of its triax connector is a guard terminal. Using triax cabling and fixturing ensures that the high impedance terminal of the sample is guarded. A guard connection also reduces measurement time since the cable capacitance will no longer affect the time constant of the measurement. The guard should be run from the measuring instrument to as close as possible to the sample.

Electrostatic Interference. Electrostatic interference occurs when an electrically charged object is brought near an uncharged object. Usually, the effects of the interference are not noticeable because the charge dissipates rapidly at low resistance levels. However, high resistance materials do not allow the charge to decay quickly and unstable measurements may result. The erroneous readings may be due to either DC or AC electrostatic fields.

To minimize the effects of these fields, an electrostatic shield should enclose the sensitive circuitry. The shield is made from a conductive material and is always connected to the low impedance (FORCE LO) terminal of the SMU. The cabling in the circuit must also be shielded, so it's best to use low noise shielded triax cables.

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Mary Anne Tupta is a senior applications engineer at Keithley Instruments, Inc., headquartered in Cleveland, Ohio. She earned a Bachelor of Science degree in physics/electronic engineering and a Master of Science degree in physics from John Carroll University in Cleveland. She has assisted Keithley customers with instrument applications since 1988.

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