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Measuring the Resistivity and Determining the Conductivity Type of Semiconductor Materials Using a Four-Point Collinear Probe and the Model 6221 DC and AC Current Source

Introduction

Resistivity and conductivity type are fundamental properties of semiconductors and are critical parameters in both materials research and wafer fabrication. A semiconductor's resistivity depends primarily on the bulk doping, but can be modified through device processing. The resistivity can affect a device's series resistance, threshold voltage, capacitance, and other parameters. Measuring a semiconductor material's resistivity is one of the most common electrical tests. Determining the conductivity type (or sign of the majority carrier) of a wafer is common in both research and fabrication. A four-point collinear probe and the appropriate test equipment can be used to determine both resistivity and conductivity type.

This application note explains how to measure resistivity and determine conductivity type of semiconductor materials with a four-point collinear probe and the Model 6221 DC and AC Current Source.

The Four-Point Collinear Probe Method for Measuring Resistivity

The four-point, or Kelvin, probe method is the most common way to measure a semiconductor material's resistivity. Two of the probes are used to source current and the other two probes are used to measure voltage. Using four probes eliminates measurement errors due to the probe resistance, the spreading resistance under each probe, and the contact resistance between each metal probe and the semiconductor material. This technique involves bringing four equally spaced probes into contact with the material of unknown resistance. The probe array is usually placed in the center of the material, as shown in ***Figure 1***.

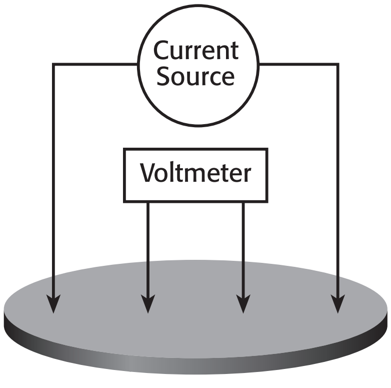

Figure 1. Four-Point Collinear Probe Resistivity Method

The two outer probes source current, while the two inner probes sense the resulting voltage drop across the sample. The volume resistivity is calculated with this equation:

$$\rho = \frac{\pi}{\ln 2} \times \frac{V}{I} \times t \times k$$

where: ρ = volume resistivity (Ω-cm)

V = the measured voltage (volts)

I = the source current (amperes)

t = the sample thickness (cm)

k = a correction factor based on the ratio of the probe spacing to wafer diameter and on the ratio of wafer thickness to probe spacing[1].

The Model 6220 DC Current Source or Model 6221 AC and DC Current Source can be used with a voltmeter, such as the Model 2000 DMM, to measure the resistivity of most normally doped semiconductor materials. Both the Model 6220 and Model 6221 can output a wide range of current from picoamps up to 100mA. For characterizing lower resistance materials, the Model 2000 DMM can be replaced with a Model 2182A Nanovoltmeter. A differential electrometer measurement method must be used for characterizing higher resistance materials.

Measuring High Resistance Semiconductor Materials

Measuring the resistivity of high resistance samples often requires using four isolated probes and the van der Pauw measurement technique. However, if the four-point probe head has very good isolation between the probes, then these measurements may be achievable. This measurement also requires sourcing current with high output impedance and making differential voltage measurements.

Figure 2 is a more realistic circuit representation of a four-point collinear probe measurement setup. This circuit includes a contact or spreading resistance at each probe (r1 through r4), the finite resistance from LO to earth ground of both the current source (R_C) and the voltmeter (R_V), and the input resistance of the voltmeter (R_{IN}). Depending upon the material being measured, the contact resistance (r1, r2, r3, and r4) may be as much as 300× that of the measured resistance (R_2) or more. The high contact resistance means the current source is required to have

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[1] The correction factors can be found in a standard four-point probe resistivity test procedure (such as SEMI MF84-02—Test Method for Measuring Resistivity of Silicon Wafers With an In-Line Four-Point Probe. This standard was originally published by ASTM International as ASTM F 84-67T.)

considerably higher compliance voltage than might be expected and the voltmeter must have a much higher input resistance.

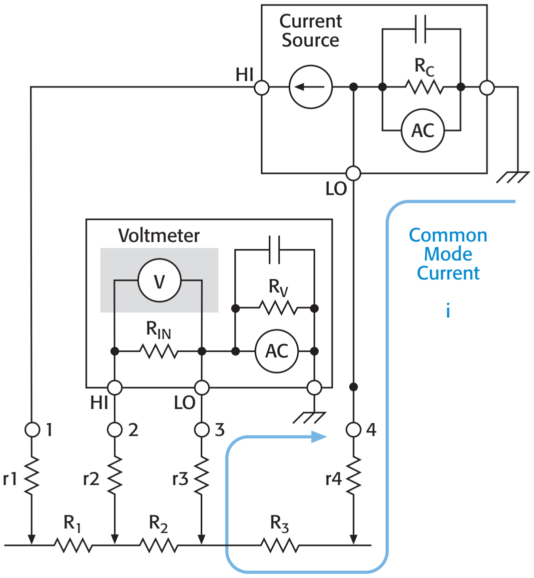

Figure 2. Realistic Circuit of the Four-Point Probe Method

The common-mode current (i) is the result of the imperfect isolation between the LO terminals of the voltmeter and current source to earth ground. As shown in ***Figure 2***, an AC current will flow from the LO terminal of the current source through the sample and to the voltmeter's LO terminal, then back to ground. The resulting voltage drop across r3 will cause erroneous results when the voltmeter measures the voltage drop between probes 2 and 3. As the sample resistance increases, the errors due to the common-mode current become more significant and it becomes increasingly necessary to use a differential voltmeter.

As ***Figure 3*** illustrates, using two electrometers eliminates this common-mode problem. The voltmeter will read the difference between the buffer outputs of the two electrometers, which is equal to the voltage across R_2. The unity-gain buffers have very high input impedance, so little common-mode current will flow through r3, and the value of R_2 can be calculated easily. The buffers can be a pair of JFET op amps or two electrometers with unity-gain outputs.

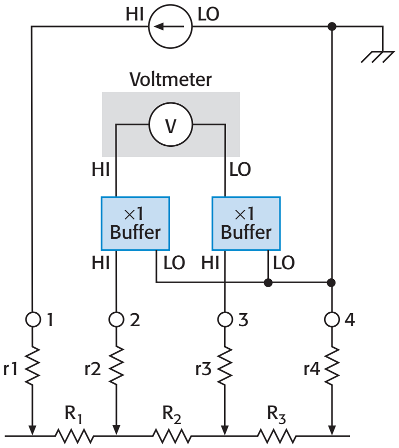

Figure 3. Making Differential Four-Point Probe Measurements

Figure 4 is a schematic of an actual high resistance measurement system, which includes two electrometers (Model 6514s), a DMM (Model 2000), and a current source (Model 6220 or 6221). In this circuit, the electrometers are used as unity-gain buffers. The DMM measures the difference between the outputs of the two electrometers. The settling time of the measurement will be much faster if the electrometers are used in guarded mode. Guarding reduces the effects of the shunt capacitance in the circuit, so the charging time can be much faster. If feasible, triax cables should be used to ensure that guard is connected as close to the material as possible.

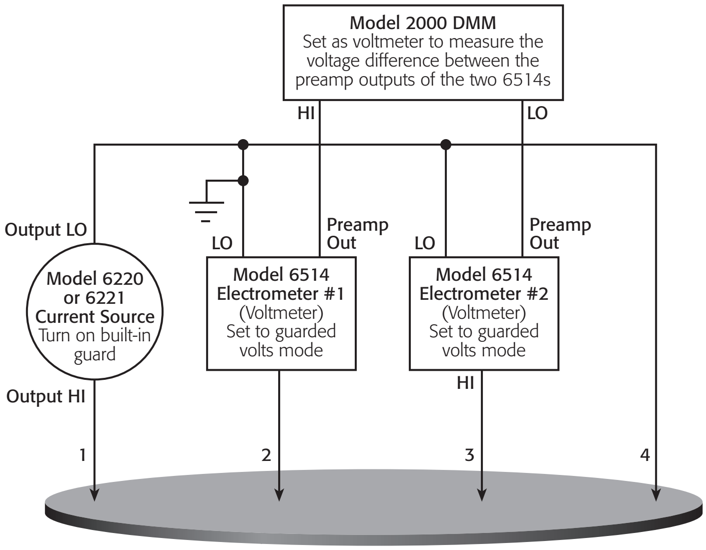

Figure 4. High Resistance Four-Point Probe Measurement System

Both the Model 6220 and Model 6221 have very high output impedance and a built-in guard. Just as with the electrometers, using guarding will reduce the measurement time because the cable capacitance will no longer affect the time constant of the measurement.

The HI terminals of the Model 6220/6221 and the Model 6514s are three-lug female triax connectors, so it's important to use male triax cables to connect to the instrument. Some four-point probes can be ordered with triax cables. Connect the LO terminals (safety banana jacks on rear panels) from all three instruments to probe 4. Make sure only one of the instruments' LO terminal is connected to earth ground on the rear panel.

Determining Conductivity Type of a Semiconductor Material

There are several methods for determining conductivity type. The *rectification method* is used on high resistivity material; the *thermoelectric method* is used on low resistivity materials. Both methods involve using a four-point collinear probe, an AC current source, and a DC voltmeter.

The Rectification Method. This method involves determining the sign of the majority carrier based on the polarity of a rectified AC signal at the point of contact with the semiconductor material. ***Figure 5*** illustrates this setup. When the four-point collinear probe comes in contact with the wafer, a metal-semiconductor "diode" is created at the interface between each probe and the wafer. An AC current is sourced between the first two probes and a DC voltmeter is used to sense the polarity of the voltage between probes 2 and 3. The metal-semiconductor Schottky "diode" at probe 2 will be either forward- or reversed-biased, depending on the polarity of the current, as well as the conductivity type. As a result, the voltmeter will read a positive voltage for p-type material and a negative voltage for n-type material.

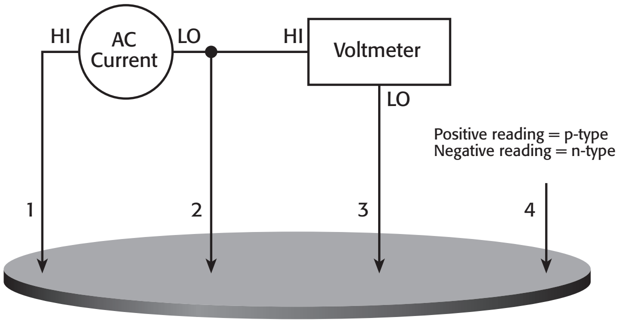

Figure 5. Circuit for Determining Conductivity Type Using the Rectification Mode

To illustrate this concept further, an oscilloscope was placed in parallel with the voltmeter. The oscilloscope produced the waveform shown in ***Figure 6***. Probe 2 was connected to the HI terminal of the scope and probe 3 was connected to the LO terminal. As the trace in Figure 6 indicates, the metal-semiconductor "diode" from the p-type material interfacing with probe 2 is reverse-biased at the top of the waveform and conducting at the bottom of the waveform. For p-type material, the metal-semiconductor junction at probe 2 is reverse-biased when the AC voltage at probe 2 is positive with respect to probe 1 (large and positive voltage). When the AC voltage at probe 2 is negative with respect to probe 1, then the metal-semiconductor junction at probe 2 is forward-biased (small and negative voltage). As a result, the average DC voltage read by the voltmeter between probes 2 and 3 is positive, indicating a p-type material.

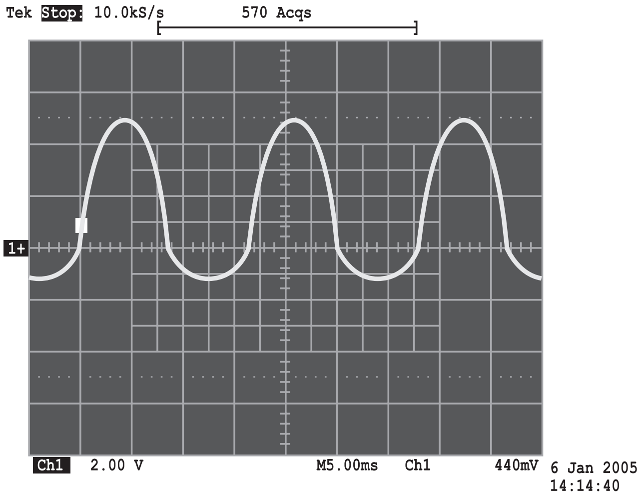

Figure 6. Oscilloscope Trace From P-Type Material

For best results when reproducing this test setup, a line frequency test signal of 60Hz (or 50Hz) from the Model 6221 AC and DC Current Source should be used. Either the Model 2000 DMM or the Model 6514 Electrometer can measure the DC voltage drop. The voltmeter's integration time should be set to 1 PLC (power line cycle).

The magnitude of the AC current will depend on the resistivity of the material, but it should be large enough to forward-bias the diode. This method works well if there is an acceptable rectification action, which occurs for DC voltmeter readings greater than 0.5V. For voltage readings less than 0.5V, the thermoelectric mode should be used.

The Thermoelectric Voltage Method. For highly doped (low resistivity) materials, the voltage developed between probes 2 and 3 becomes too small and the rectification mode no longer works well. For this case, the thermoelectric voltage method determines the conductivity type by the polarity of the thermoelectric (or Seebeck) voltage that is generated by a temperature gradient on the material. ***Figure*** 7 is a circuit diagram of this setup.

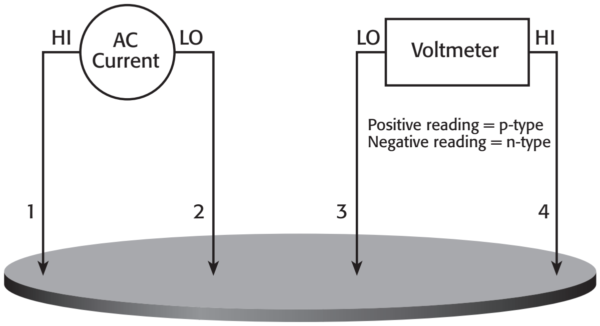

Figure 7. Diagram of Thermoelectric Voltage Method

With this method, an AC current flows between probes 1 and 2 and causes joule heating of the semiconductor. The Seebeck voltage is generated between probes 3 and 4 by the diffusion of thermally generated carriers from the hot region of the material to the cold region. This diffusion creates a non-equilibrium carrier concentration in the cold region, which generates an electric field, opposing further diffusion. This diffusion of carriers from the hot probe (probe 3) to the cold probe (probe 4) continues until the generated electric field is sufficient to overcome the tendency of the carriers to diffuse. For example, in p-type material, the thermally generated holes diffuse to the cold probe, building up a positive space charge, which prevents further diffusion. As a result, the cold probe (4) is more positive than the hot probe. Thus, for p-type material the voltmeter will read a positive voltage. Conversely, the voltmeter will read a negative voltage for n-type material.

Sources of Error and Measurement Considerations

Measuring resistivity successfully requires considering several potential sources of error, especially for high resistance materials.

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

  Building an electrostatic shield to enclose the sensitive circuitry can minimize the effects of these fields. The shield is made from a conductive material and is always connected to the low impedance terminal of the instrument. The cabling in the circuit must also be shielded.

- **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. Using good quality insulators, reducing humidity, and using guarding can minimize leakage current.

  A guard is a conductor connected to a low impedance point in the circuit that is at nearly the same potential as the high impedance lead being guarded. Both the Model 6220/6221 and the Model 6514 can be configured to operate in guarded mode. Refer to the instrument's instruction manual for further information on guard setting and connections. This guard should be run from the instruments to as close to the sample as possible. Using triax cabling and fixturing will ensure the high impedance terminal of the sample is guarded. The guard connection will also reduce measurement time, because the cable capacitance will no longer affect the time constant of the measurement.

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

- **Temperature.** Thermoelectric voltages may also affect measurement accuracy. Temperature gradients may result if the sample temperature isn't uniform. Thermoelectric voltages may also be 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 be able to make the voltage measurements easier. Temperature fluctuations in the lab environment may also affect measurements. Semiconductors have a relatively large temperature coefficient, so the use of correction factors may be necessary to compensate for temperature variations in the lab.

Test System Safety

Many electrical test systems or instruments are capable of measuring or sourcing hazardous voltage and power levels. It is also possible, under single fault conditions (e.g., a programming error or an instrument failure), to output hazardous levels even when the system indicates no hazard is present. These high voltage and power levels make it essential to protect operators from any of these hazards at all times.

Protection methods include:

- Design test fixtures to prevent operator contact with any hazardous circuit.
- Make sure the device under test is fully enclosed to protect the operator from any flying debris. For example, capacitors and semiconductor devices can explode if too much voltage or power is applied.
- Double insulate all electrical connections that an operator could touch. Double insulation ensures the operator is still protected, even if one insulation layer fails.
- Use high reliability, fail-safe interlock switches to disconnect power sources when a test fixture cover is opened.
- Where possible, use automated handlers so operators do not require access to the inside of the test fixture or have a need to open guards.
- Provide proper training to all users of the system so they understand all potential hazards and know how to protect themselves from injury.

It is the responsibility of the test system designers, integrators, and installers to make sure operator and maintenance personnel protection is in place and effective.

For Further Reading

W. A. Keenan, C. P. Schneider, and C. A. Pillus, "Type-All System for Determining Semiconductor Conductivity Type," *Solid State Technology*, 51-56, March 1971.

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