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Achieving Accurate and Reliable Resistance Measurements in Low Power and Low Voltage Applications

Low voltage measurements are often associated with resistance measurements of highly conductive semiconductor materials and devices. These tests normally involve sourcing a known current, measuring the resulting voltage, and calculating the resistance using Ohm's Law. Because of the DUT's inherent low resistance, the resulting voltage will be very small and great care needs to be taken to reduce offset voltage and noise, which can normally be ignored when measuring higher signal levels.

However, low voltage measurements may also result from resistance measurements of *non-conductive* materials and components. Electronics are continuing to shrink as consumers demand faster, more feature-rich products in ever-smaller form factors. Because of their small sizes, electronic components of today usually also have limited power handling capability. As a result, when electrically characterizing these components, the test signals need to be kept small to prevent component breakdown or other damage. In resistance measurements, even if the resistance is far from zero, the voltage to be measured is often very small due to the need to source only a small current. Therefore, low level voltage measurement techniques become important, not only for low resistance measurements, but also for resistance measurements of non-conductive materials and components. For researchers and electronics industry test engineers, this power limitation makes characterizing the resistance of modern devices and materials challenging.

There are many factors that make low voltage measurements difficult. Various noise sources can make it difficult to resolve the actual voltage. In

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addition, thermoelectric voltages (thermoelectric EMFs) can cause error offsets and drift in the voltage readings. As mentioned previously, test requirements may limit the maximum current that can be applied, so simply increasing the sourced signal isn't always an option. In other cases, increased test current may cause device heating, changing the device's resistance. The key to obtaining accurate, consistent measurements is eliminating factors that contribute to measurement error. For low voltage measurement applications, such error is composed largely of white noise (random noise across all frequencies) and 1/f noise. Thermoelectric voltages (typically having 1/f distribution), a serious problem in many test environments, are generated from temperature differences in the circuit. This paper discusses techniques to eliminate thermoelectric voltages to allow more accurate resistance measurements, including a three-step delta measurement method for low power/low voltage applications.

Measurement Obstacles

Temperature fluctuations are biggest enemy of low voltage measurements. Any junction of dissimilar metals in a measurement circuit constitutes a thermocouple. Voltage errors occur when there is an opposing junction at a different temperature. ***Figure 1*** illustrates one example of this error.

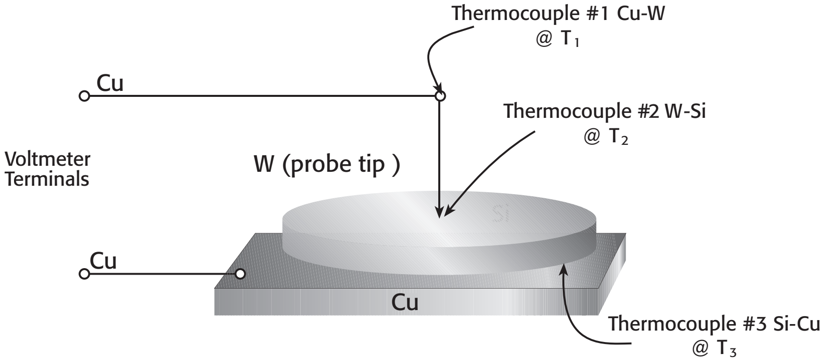

Figure 1. Typical thermocouple scenario. Cu-Si interface where one terminal is one device on wafer and the second terminal is at the substrate connection to a conductive base.

In this example, the device under test is located on a silicon wafer. A tungsten probe makes contact to one terminal of the device. The other terminal is the silicon substrate. A copper base is used to make electrical contact with the substrate. The junctions of differing materials produce three separate thermocouples: at the copper-tungsten interface, at the tungsten-silicon interface, and at the silicon-copper interface. The temperature difference between the two materials at each junction generates a voltage at the voltmeter terminals. The summation of the thermoelectric voltages at each of these junctions is the total error voltage that appears at the voltmeter terminals.

The first step toward reducing measurement error is minimizing the temperature variation in the test environment. This would mean reducing the temperature difference between T_1, T_2, and T_3 in ***Figure 1***. The test setup should be isolated from drafts, air conditioning, and heat sources. The connections should be located as close to each other as possible to minimize temperature differences. Whenever possible, the designer of the setup should use connections made of the same material and select insulators with high thermal conductivity to surround the cables and junctions.

Traditional Resistance Measurements

No matter what steps are taken to minimize temperature problems, it's virtually impossible to eliminate them entirely. A standard DC resistance measurement approach doesn't compensate for any of these errors. Resistance is calculated using Ohm's Law; that is, to find the resistance, divide the DC voltage measured across the device by the DC stimulus current (see ***Figure 2a***). The voltage readings will be a sum of the induced voltage across the device (V_R), lead and contact resistance ($V_{\text{lead res}}$), the voltages present from the thermals (V_t), other 1/f noise contributions ($V_{1/f\ \text{noise}}$) and white noise ($V_{\text{white noise}}$). To eliminate lead resistance, use four separate leads to connect the voltmeter and current source to the device. In this way, the voltmeter won't measure any voltage drop across the source leads. However, the errors due to white noise, 1/f noise, and temperature differences will remain (see ***Figure 2b***). Implementing filtering and selecting the appropriate test equipment may reduce white noise and 1/f noise significantly. However, these elements often determine the measurement noise floor. Temperature presents a slightly different challenge because if the temperature changes, the contribution of the Vt term changes, too. With rapidly changing thermoelectric voltages, this term may even exceed V_R, the voltage across the DUT induced by the stimulus.

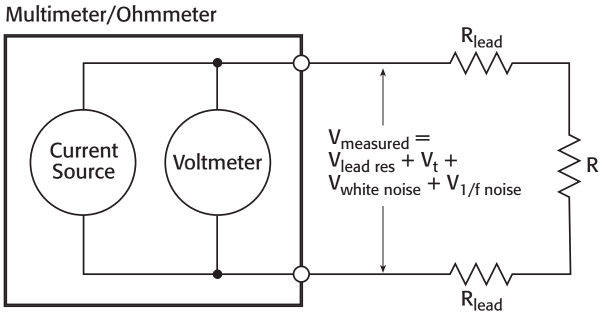

Figure 2a.

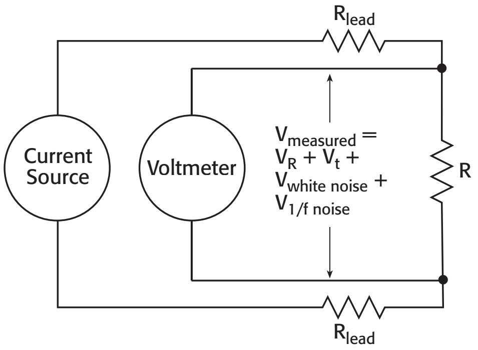

Figure 2b.

The Delta Method of Measuring Resistance

A change in test method is required to improve accuracy and overcome measurement obstacles. A constant thermoelectric voltage may be canceled using voltage measurements made at a positive test current and a negative test current. This is called a delta reading. Alternating the test current also increases white noise immunity by increasing the signal-to-noise ratio.[1] A similar technique can be used to compensate for *changing* thermoelectric voltages (see ***Figure 3***). Over the short term, thermoelectric drift may be approximated as a linear function (see inset of ***Figure 3***). The difference between consecutive voltage readings is the slope–the rate of change in thermoelectric voltage. This slope is constant, so it may be canceled by alternating the current source three times to make two delta measurements – one at a negative-going step and one at a positive-going step. In order for the linear approximation to be valid, the current source must alternate quickly and the voltmeter must make accurate voltage measurements within a short time interval. If these conditions are met, the three-step delta technique yields an accurate voltage readiong of the intended signal unimpeded by thermoelectric offsets and drifts.

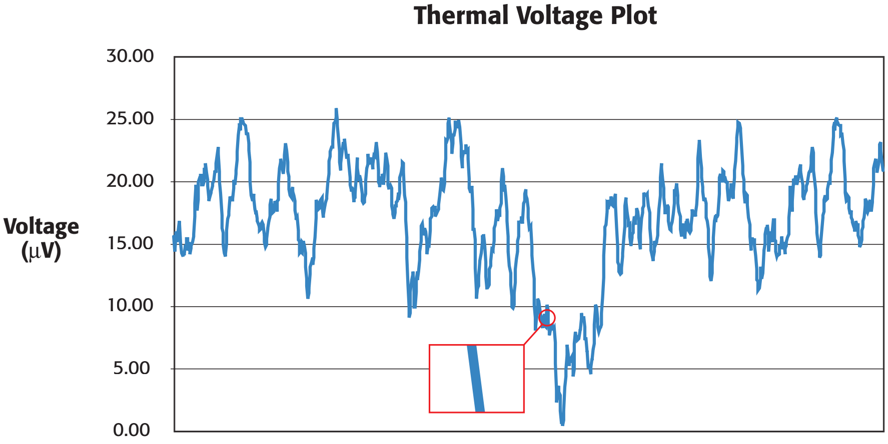

Figure 3.

Examining this technique in detail reveals how it reduces measurement error. An analysis of the mathematics for one three-step delta cycle will demonstrate how the technique compensates for the temperature differences in the circuit. Consider the example in ***Figure 4***:

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[1] For more details, refer to the “Reducing Resistance Measurement Uncertainty: DC Current Reversals vs. Classic Offset Compensation” white paper.

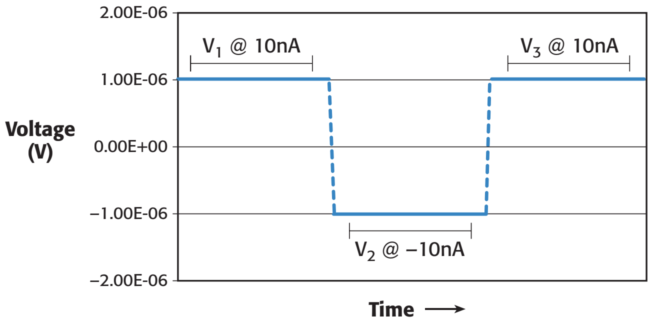

Figure 4a (No thermoelectric voltages shown)

Test current = ±10nA
Device = 100Ω resistor

Ignoring thermoelectric voltage errors, the voltages measured at each of the steps are:

$V_1 = 1\mu V$
$V_2 = -1\mu V$
$V_3 = 1\mu V$

Let's assume the temperature is linearly increasing over the short term in such a way that it produces a voltage profile like that shown in ***Figure 4b***:

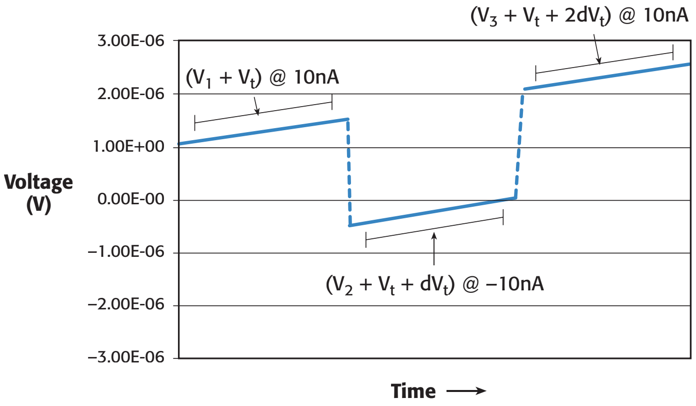

Figure 4b (Thermoelectric voltage error included)

where V_t = 100nV and is climbing 100nV with each successive reading.

As ***Figure 4b*** shows, the voltages now measured by the voltmeter include error due to the increasing thermoelectric voltage in the circuit; therefore, they are no longer of equal magnitude. However, the absolute difference between the measurements is in error by a constant 100nV, so it's possible to cancel this term. The first step is to calculate the delta voltages. The first delta voltage (V_a) is equal to:

$$V_a = \text{negative-going step} = \frac{(V_1 - V_2)}{2} = 0.95\mu V$$

The second delta voltage (V_b) is made at the positive-going current step and is equal:

$$V_b = \text{positive-going step} = \frac{(V_3 - V_2)}{2} = 1.05\mu V$$

The thermoelectric voltage adds a negative error term in V_a and a positive error term in the calculation of V_b. When the thermal drift is a linear function, these error terms are equal in magnitude. Thus, we can cancel the error by taking the average of V_a and V_b:

$$V_f = \text{final voltage reading} = \frac{(V_a + V_b)}{2} = \frac{1}{2}\left[\left(\frac{(V_1 - V_2)}{2}\right) + \left(\frac{(V_3 - V_2)}{2}\right)\right] = 100\mu V$$

The delta technique eliminates the error due to changing thermoelectric voltages. Therefore, the voltmeter measurement is the voltage induced by the stimulus current alone. As the test continues, every reading is the average of the three most recent A/D conversions, so a moving average filter is embedded in this three-step delta technique. The moving average filter further enhances white noise immunity by reducing the spread of the data. The three-step delta method clearly offers significant advantages over other DC resistance measurement techniques in overcoming error due to changing temperature.

Other DC resistance measurement techniques include a two-step current reversal and offset compensation, a subset of the two-step method. The two-step method calculates an average based on only the first delta (V_a) of the three-step method. Offset compensation is really a subset of the two-point delta method where the current is alternated between some positive value and zero. The offset compensation method will commonly be found in digital multimeters where the test current can't be programmed or reversed. Although this two-point technique sufficiently compensates for constant thermoelectric error voltages, it's inadequate when the temperature is changing.

The three-step delta technique is the best choice for high accuracy resistance measurements. ***Figure 5*** compares 1000 voltage measurements of a 100Ω resistor made with a 10nA test current taken over approximately 100 seconds. In this example, the rate of change in thermoelectric voltage is no more than 7µV/sec. The two-step delta technique fluctuates with the thermoelectric error voltage ±30Ω around the true resistance value. Thus, for any one measurement, there could be an error of up to 30%, which doesn't provide much confidence in the measurement's integrity. In contrast, the three-step delta technique is "tightly packed" around the average—the measurement is unaffected by the thermoelectric variations in the test circuit. It's important to note that both these measurements can be completed in the same test time. In addition, the speed of the three-step delta method permits additional digital averaging of the data, so it has lower noise than data taken with the two-step delta technique.

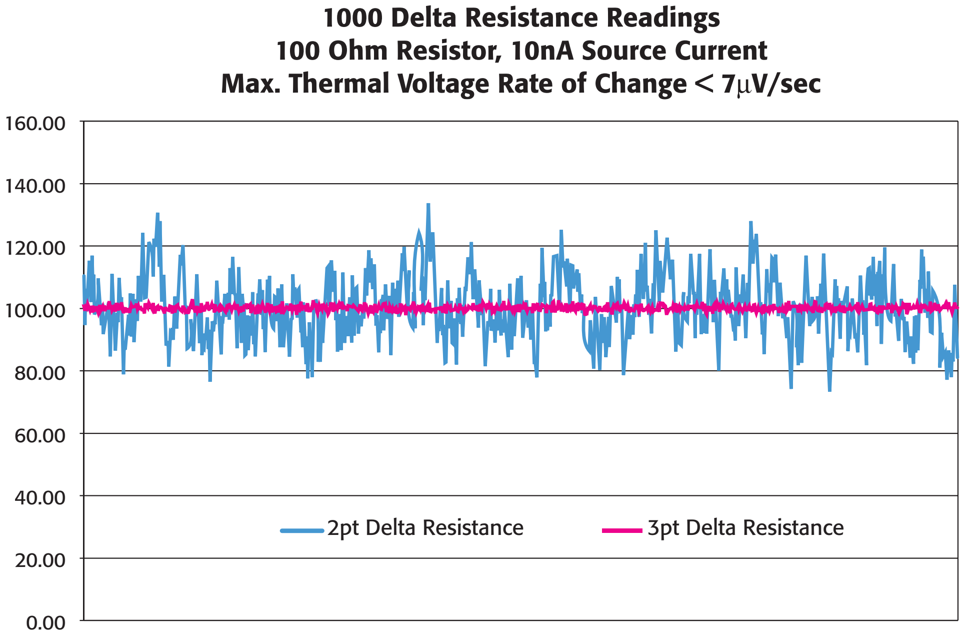

Figure 5.

Equipment Requirements

Selecting appropriate measurement equipment is critical to the three-step delta method. Keithley has designed the Models 6220 and 6221 Current Sources and the Model 2182A Nanovoltmeter to perform resistance measurements using the three-step delta technique. Pairing either of the current sources with the nanovoltmeter creates a user-friendly solution that can be operated like a single instrument and that meets the accuracy and repeatability requirements of low power and low voltage applications. By understanding how the equipment affects the measurement, the researcher or test engineer can also minimize white noise and 1/f noise.

The success of the three-step delta method depends on the linear approximation of the thermal drift when this drift is viewed over a short time interval. This approximation requires the measurement cycle time to be faster than the thermal time constant of the test system, which imposes certain requirements on the current source and voltmeter used.

The current source must alternate quickly in evenly spaced steps, which helps make a fast measurement cycle time possible. The current step spacing guarantees the measurements are made at consistent intervals so the thermoelectric voltage change remains constant between these measurements.

The voltmeter must be tightly synchronized with the current source and capable of making accurate measurements in a short time interval. Synchronization favors hardware handshaking between the instruments so that the voltmeter can make voltage measurements only after the current source has settled and the current source doesn't switch polarity until after the voltage measurement has been completed. The measurement speed of the voltmeter is critical in determining total cycle time; faster voltage measurements mean shorter cycle times. For reliable resistance measurements, the voltmeter must maintain this speed without sacrificing low noise characteristics.

The Models 6220/1 Current Source and the Model 2182A Nanovoltmeter combine to return as many as 48 delta readings per second at an integration time of 1PLC (16.67ms at 60Hz power line frequency, 20ms at 50Hz power line frequency). These two instruments are coupled by means of the Keithley Trigger Link bus so the test can be run completely independent of a computer.

In low power applications, the current source must be capable of outputting low values of current so as not to exceed the maximum power rating of the device. This ability is particularly important for moderately high and high impedance devices. Models 6220 and 6221 Current Sources can output currents as small as 100fA. Pairing either of these current sources with the Model 2182A Nanovoltmeter permits accurate measurements with 1nV sensitivity.

The test current may be increased without violating the device power rating by using a pulsed current source. The Model 6221 differs from the 6220 in its ability to perform pulsed delta measurements.[2] The Model 6221 may output pulses as short as 50µs with amplitude ranging from 100fA to 100mA.

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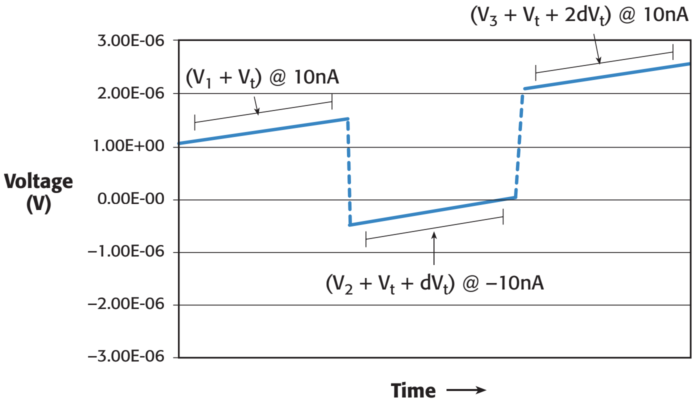
[2] Please see the datasheets for the Models 6220 and 6221 Current Sources for additional differences.

Conclusion

Thermoelectric EMFs are often the dominant source of error in low resistance/low power resistance measurements. This error may be almost completely removed using a three-point current reversal technique. To implement this measurement technique, the Keithley Model 6220 or 6221 Current Source, paired with the Model 2182A Nanovoltmeter, produces faster and lower noise measurements than other resistance measurement techniques. This improvement means it's no longer necessary to take extreme care to minimize thermally induced voltage noise in the wiring of resistance measuring systems, greatly simplifying the measurement process.

Appendix – Detailed Three-Step Delta Calculations



$$V_a = \text{negative-going step} = \frac{(V_1 + V_t) - (V_2 + V_t + dV_t)}{2} = \frac{(V_1 - V_2 - dV_t)}{2}$$

$$= \frac{(V_1 - V_2)}{2} - \frac{dV_t}{2}$$

$$V_b = \text{positive-going step} = \frac{(V_3 + V_t + 2dV_t) - (V_2 + V_t + dV_t)}{2} = \frac{(V_3 - V_2 + dV_t)}{2}$$

$$= \frac{(V_2 - V_3)}{2} + \frac{dV_t}{2}$$

$$V_f = \text{final voltage reading} = \text{average } (V_a, V_b) = \frac{(V_a + V_b)}{2} = \frac{(V_1 + V_3 - 2V_2)}{4}$$

For linear devices, $|V_1| = |V_2| = |V_3| = V_R$ = voltage across resistor induced by stimulus current.

Thus: $V_1 = \dfrac{1}{4}(4V_R) = V_R$

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