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Performing van der Pauw Sheet Resistance Measurements Using the Keithley S530 Parametric Tester

Accurate low voltage measurements are essential to many semiconductor tests. Often, test structures such as contact chains, vias, and metal structures have resistances on the order of tens to hundreds of milliohms. Measuring such small resistances accurately usually requires forcing current and measuring voltage because most source-measurement instruments have limited low-voltage source accuracy. However, even when current is forced through these structures, the resulting voltages are small, necessitating the use of an accurate voltage measuring instrument, such as a digital multimeter (DMM) with at least 6½ digits of resolution.

Van der Pauw Structures

One typical low resistance structure used in semiconductor process monitoring or device characterization is the van der Pauw resistivity structure. In 1958, L. J. van der Pauw of Philips [1] described a technique in which the specific resistivity or Hall Effect of arbitrarily shaped disks can be measured (***Figure 1***). From these measurements on these structures, the resistivity, doping type, sheet carrier density, major carrier mobility, sheet resistance, and line widths can be determined.

In order for the van der Pauw technique to work, the structure must be of negligible and uniform thickness (as compared to the area of the structure), be homogenous in composition, and be symmetrical. More importantly, the contacts must be on the perimeter of the structure and be much smaller than the area of the structure.

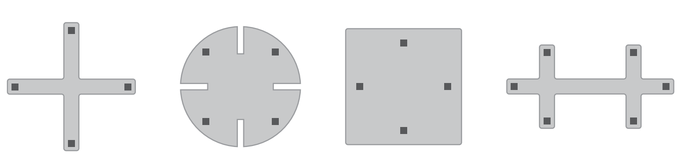

Figure 1: van der Pauw disks.

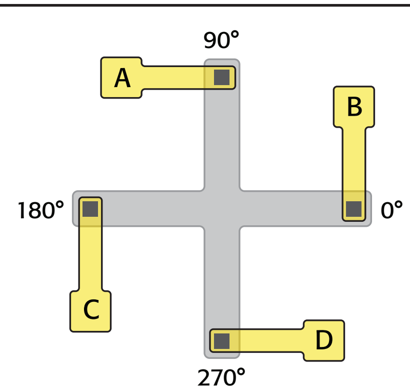

Figure 2: Greek cross

Figure 2 shows one of the most widely used forms of a van der Pauw resistivity structure: the Greek cross. The Greek cross structure yields accurate resistivity data and is easy to design and lay out.

Van der Pauw showed that when the aforementioned conditions are met, the following relation holds:

$$e^{-\left(\pi \frac{d+R_{AB,CD}}{\rho}\right)} + e^{-\left(\pi \frac{d+R_{BC,AD}}{\rho}\right)} = 1$$

where:

$R_{AB,CD}$ is the resistance of the structure when a current is forced through contacts A and exits contact B, and voltage is measured across contacts C-D.

$R_{BC,AD}$ is the resistance of the structure when a current is forced through contact B and exits contact D, and voltage is measured across contacts A-D.

d is the thickness of the structure.

ρ is the resistivity of the material.

In practice, with this knowledge, device designers will use these measurements to extract the parameter sheet resistance. The Greek cross is effectively a two-dimensional structure (a thin film.) The resistance of any material can be shown to be a function of the resistivity of the structure and its volume. This is called the volume resistance. For a two-dimensional structure, the thickness is negligible, and the resistance reduces to a function of the volume resistance times the area. In order to avoid confusion with volume resistance (which is expressed in units of ohms or Ω), sheet resistance is expressed in ohms per square or Ω/□.

When using the Greek cross structure, it can be shown that the sheet resistance (R_S) can be expressed as:

$$R_S = \frac{\pi R}{\ln(2)} \frac{\Omega}{\square}$$

If the structure is known to be homogenous, has contacts that are infinitesimally small in comparison with the rest of the structure, and is perfectly symmetrical, then we can see that we only need to force one current and make one differential voltage measurement in order to extract the sheet resistance. However,

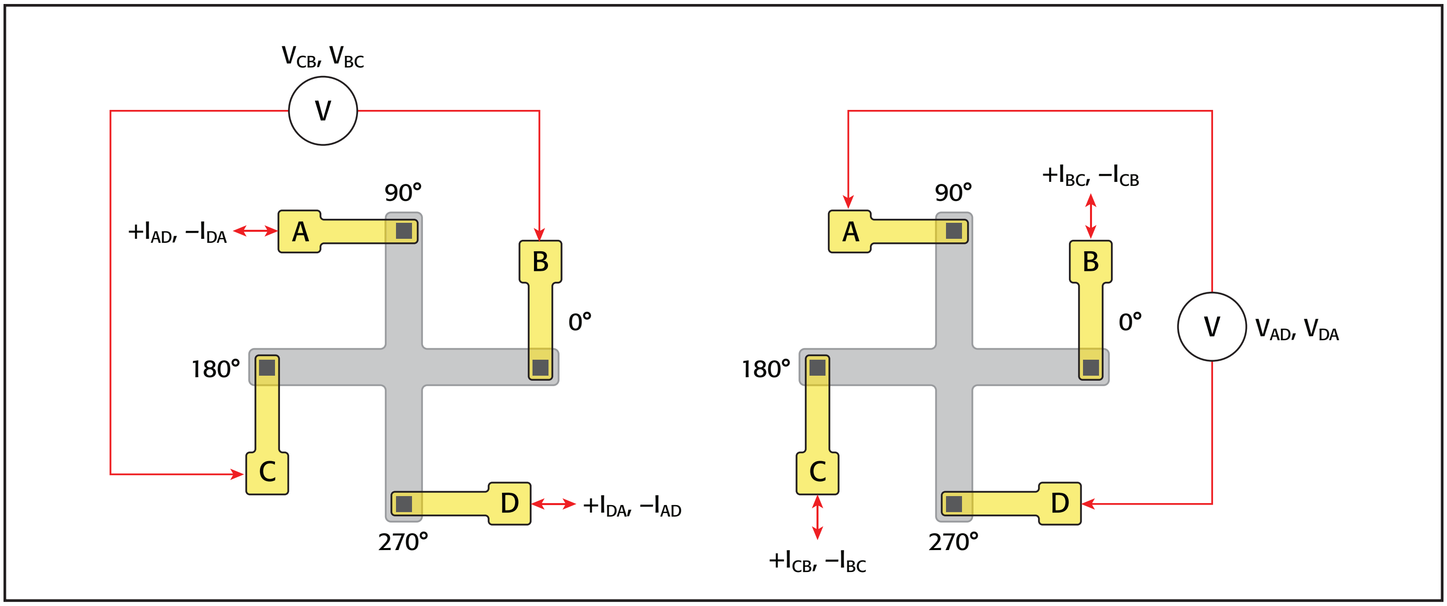

Figure 3: Four DC measurements needed for accurate sheet resistance measurements.

if there is some uncertainty about any of these things or there are thermoelectric EMFs due to the test equipment, then a total of four DC voltage measurements are required to extract an accurate sheet resistance measurement.

If even greater accuracy is needed, then a total of eight DC measurements are required, corresponding to the number of permutations of forcing both positive and negative test currents into each of the four device contacts. In this application note, we will focus on the four-measurement technique.

Measurement Considerations

Van der Pauw resistances are usually on the order of a few ohms. Because these resistances are so small, the ratio of the voltage to the current will be small. More importantly, the voltages will be small. Because it is difficult to source small voltages accurately, it is better to force current and measure the voltage.

The measured voltages may be smaller than a traditional source-measurement unit (SMU) can accurately measure. The best instrument to use when measuring small (<10mV) voltages is a 6½- or 7½-digit digital multimeter (DMM). The 7½-digit DMM option for the Keithley S530 Parametric Test System is suitable for this application.

As mentioned previously, van der Pauw resistances are on the order of a few ohms. This level of resistance is of the same order of magnitude as the system's cable and probe card resistance. This means it is critical to make a Kelvin connection to the device under test. The remote sensing capability of a Kelvin connection will ensure that the small drops caused by the system interconnect will be accounted for.

The accuracy of the voltage measurements can be improved by repeating each measurement by reversing the polarities of the forcing current and the voltage measurement. Reversing these polarities and averaging the resultant measurements will greatly reduce offset voltages due to thermoelectric potentials caused primarily by the test system's switch sub-systems and interconnect.

The magnitudes of the forward and reverse polarity voltage measurements should be close. If these measurements greatly differ, either the structure lacks symmetry, or there is a connection error in the test setup. Therefore, the reverse polarity technique provides another important benefit: it aids in debugging the test setup.

Van der Pauw Resistance Measurement Example

The following example describes how to perform a van der Pauw resistance measurement using the Keithley S530 Parametric Test System. ***Figure 4*** shows a van der Pauw test algorithm and ***Figure 5*** shows the DUT connections.

The commands that can be used to perform the van der Pauw resistance measurement are pretty basic and follow the same basic sequence during each step of the algorithm, as shown in the C language code fragment in ***Figure 6***.

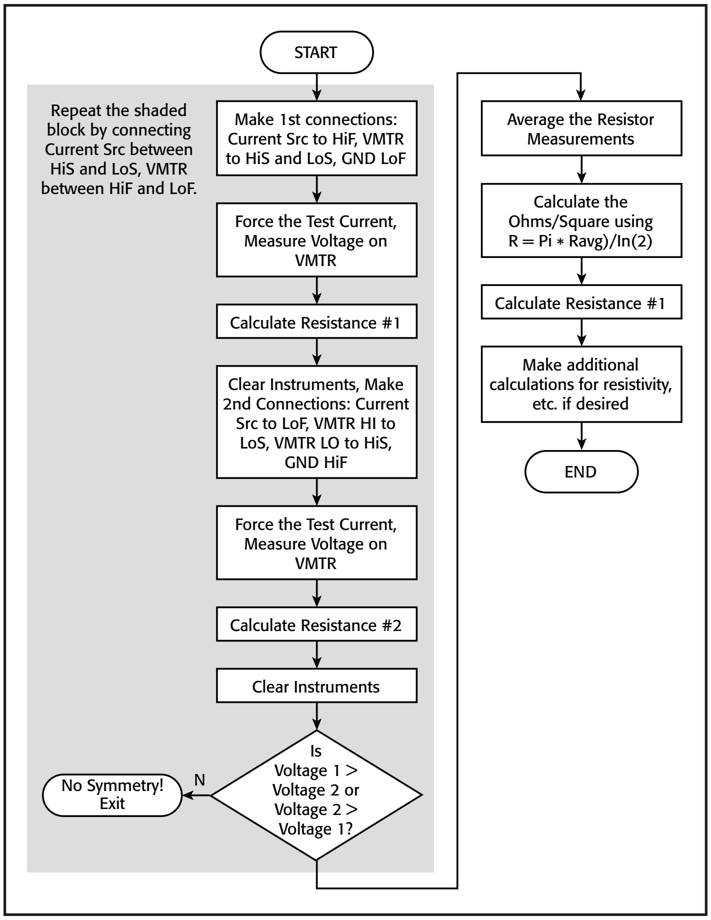

Figure 4: Testing flow chart.

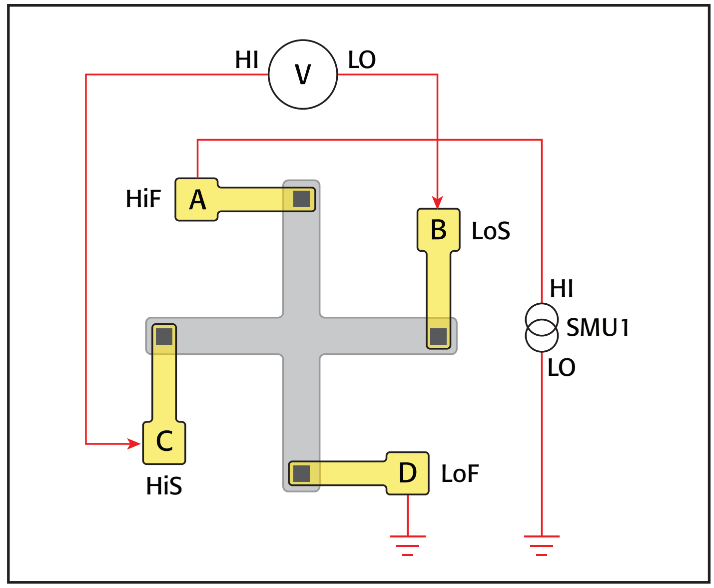

Figure 5: Instrument connections.

```
double PI = 3.14159;
double R1, R2, R3, R4, Ravg;
//Make the DUT connections
conpin(SMU1, hif, 0); // Connect the SMU to the Hi Force DUT terminal
conpin(VMTR1, his, 0); // Connect the DMM to the Hi Sense DUT terminal
conpin(VMTR1L, los, 0); // Connect the DMM to the Lo Sense DUT terminal
conpin(lof, GND, 0); // Connect the Lo Force DUT terminal to GND
forcei(SMU1, itest); // Force the test current
measv(VMTR1, &vmeas1); // Make the forward differential voltage measurement
devint();

//Now repeat the measurement for the reverse polarity
conpin(SMU1, hif, 0); // Connect the SMU to the Hi Force DUT terminal
conpin(VMTR1L, his, 0); // Connect the DMM LOW to the Hi Sense DUT terminal
conpin(VMTR1, los, 0); // Connect the DMM HI to the Lo Sense DUT terminal
conpin(lof, GND, 0); // Connect the Lo Force DUT terminal to GND
forcei(SMU1, -itest); // Force the test current (negative)
measv(VMTR1, &vmeas2); // Make the reverse differential voltage measurement
devint();

Ravg = ((vmeas1/itest) + (vmeas2/itest))/2;
Rs = (PI * Ravg) / ln(2);
```

Figure 6: C language code fragment.

As you can see, only a few basic S530 instrument commands are required to perform the measurement: `conpin`, `forcei`, `measv`, and `devint`. The accuracy of the measurement can be improved by substituting `intgv` for `measv` and taking integrated voltage measurements. The measurements can be further improved by rotating the instrument connections 180° around the structure (i.e., connecting the high of the current source to the LoF terminal, the high of the DMM to the lo sense terminal, etc.) and averaging the four resistance measurements.

Conclusion

This application note has described how van der Pauw resistance measurements can be performed using the SMU and DMM option of the Keithley S530 Parametric Test System. For further information on this measurement and on the S530 Parametric Test System DMM option, consult the user documentation provided with the test system or contact a local Keithley applications engineer.

References

1. Van der Pauw, L. J. "A Method of Measuring Specific Resistivity and Hall Effect of Discs of Arbitrary Shape." Philips Research Reports 12.1 (1958): 1-9. Print.

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