APPLICATION NOTE

Considerations for Low Current Measurements in Cryogenic Probe Stations

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Low current measurements—below 1 nA—are critical tools to assess the design and fabrication quality of both established and emerging semiconductor devices. In this context, modification of the device material, growth parameters, or device geometry can lead to undesirable and extraneous current paths in the device. These so-called leakage currents can result from material defects, gate oxide morphology, substrate choice, and electric field profiles and ultimately lead to diminished device performance—most often through excess power dissipation. Because the physical mechanisms behind many of these leakage paths have well-known temperature dependencies, cryogenic probing measurements can be a useful assessment tool to discern the precise mechanism underlying current leakage, especially for new materials and device architectures.

The effect of temperature on device leakage can be seen in the transfer curve of a commercially available, N-type silicon JFET at 300 K and 80 K. Measurements were performed in a Lake Shore Model CPX-VF probe station with triaxial cabling and a grounded sample holder. The device was sourced with a Keithley 4200 Semiconductor Characterization System; at the lowest current range (1 pA) for the source-measure unit (SMU), the 4200 has a 1% ±10 fA accuracy. The picoampere scale subthreshold leakage at room temperature is dramatically reduced to approximately 6 fA by cooling the device below 100 K. Subthreshold leakage in this device likely results from thermally assisted transport across the gate barrier, which is quenched below 100 K. In order to achieve these exceptionally low current (fA) measurement conditions, care must be exercised in all aspects of the measurement apparatus, including measurement unit, cabling, environment, and device fixturing. In this application note, key aspects of low current, cryogenic-temperature probing measurements will be reviewed.

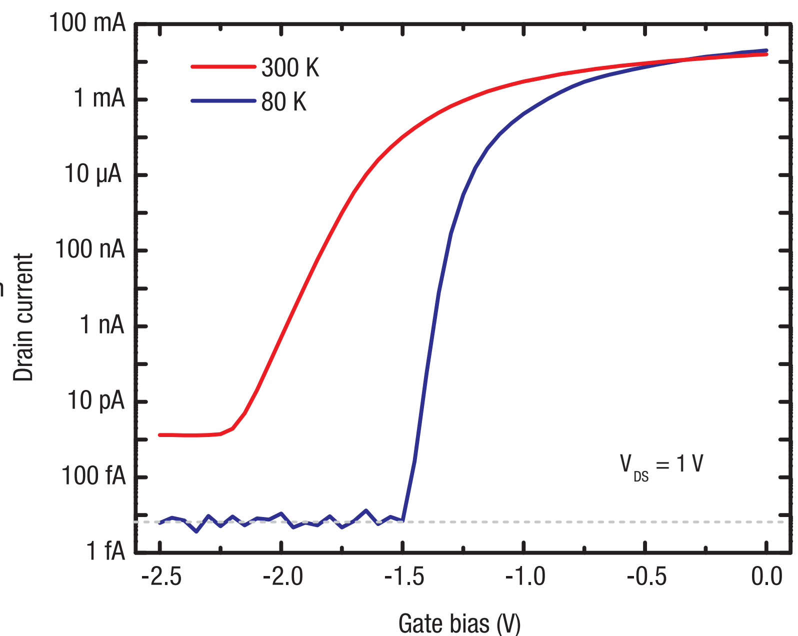

Figure 1. Temperature-dependent subthreshold characteristics of a silicon JFET.

Lake Shore CRYOTRONICS

Cabling and fixturing

Coaxial cables, often referred to as coax or BNC cables, are commonplace in most labs due to their low noise and broad frequency characteristics. The center conductor (or force wire) in a coaxial cable is surrounded by a high resistance insulator, all of which resides inside a conductive shield (Figure 2). In a device measurement, the outer shield of the coaxial cable is connected to ground and the device terminal is attached to the center force conductor. A voltage applied to the force wire will typically cause a current to flow to the device, but as there is a voltage difference between the center conductor and shield, a small cable leakage current (through R_I) will be added to the total measured current. Insulation in high quality coaxial cable has a resistance on the order of 100 GΩ. If the center conductor is biased to 10 V, then a cable leakage current on the order of 100 pA will appear.

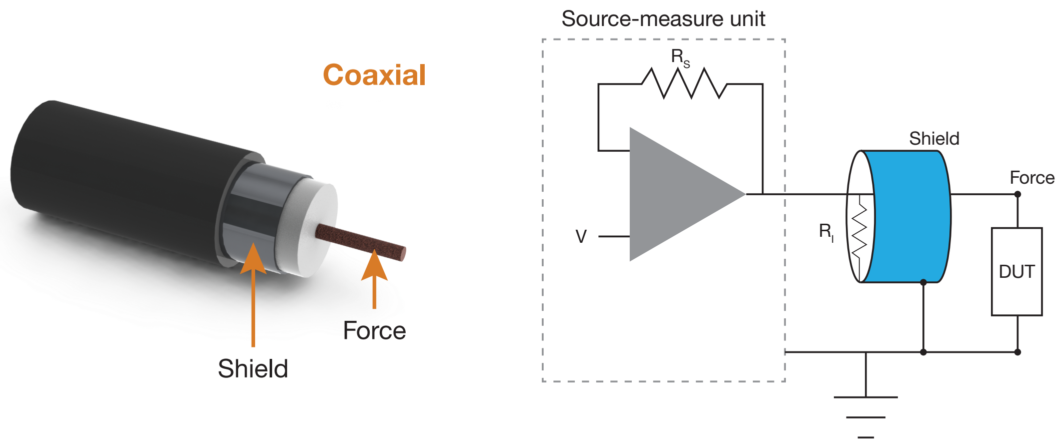

Figure 2. Conductors in a coaxial wire and device measurement layout using a coaxial configuration. Insulation leakage and charging effects in this configuration limit the low-current performance to roughly 1 nA.

Charging current can be an even more detrimental effect for low current measurements with coaxial cable. Typically, device measurements require sweeping the voltage and measuring the corresponding current response. In sweeping the voltage, the cable capacitance will cause a charging current (I_C) given by:

$$I_C = C\frac{dV}{dt}$$

where C is the total cable capacitance—typically on the order of 30 pF/ft. For a measurement with 1 m of cable and a sweep rate of 1 V/s, the charging current is nearly 1 nA. Of course, the charging current could be reduced by slowing the sweep rates, but this would add unnecessary testing time to the device characterization.

Triaxial, or triax, cabling can eliminate both charging and leakage currents encountered with a coax configuration. Triax cable is similar to coax cable except for the addition of an intermediate, concentric guard conductor between the center conductor and outer shield (Figure 3). With modern source-measure units, the guard is driven at the same voltage as the center conductor by a buffer amplifier. Since the guard and force conductor are at the same potential, no leakage current can flow between them. During a swept measurement, the voltage between the force and guard is held constant, which eliminates charging current as well.

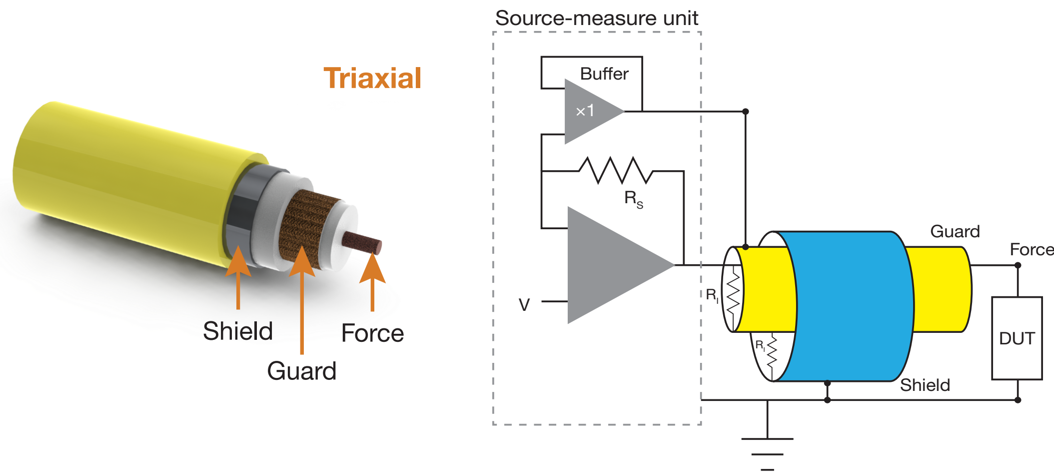

Figure 3. Conductors in a triaxial wire and device measurement layout using a triaxial configuration. The addition of a guard conductor reduces insulation leakage and charging effects in this configuration, leading to fA-scale low-current performance.

Both coaxial and triaxial cabling are offered for the micro-manipulated probe arms in a Lake Shore cryogenic probe station and, depending on the measurement need, users can exchange the cabling in the field. For measurements below 1 nA, Lake Shore recommends the triax cable configuration. In a triax configuration, the probe arm feedthrough and cabling as well as probe blade are fully guarded to the probe tip for excellent low current performance (Figure 4). Leakage current for the probe arm assembly is measured by raising the probe above the sample stage and scanning voltage with a guarded source-measure unit in the Keithley 4200 using a fixed 1 pA current setting. Additionally, Lake Shore offers coaxial and triaxial sample holders which can be used to extend the guard to the sample holder.

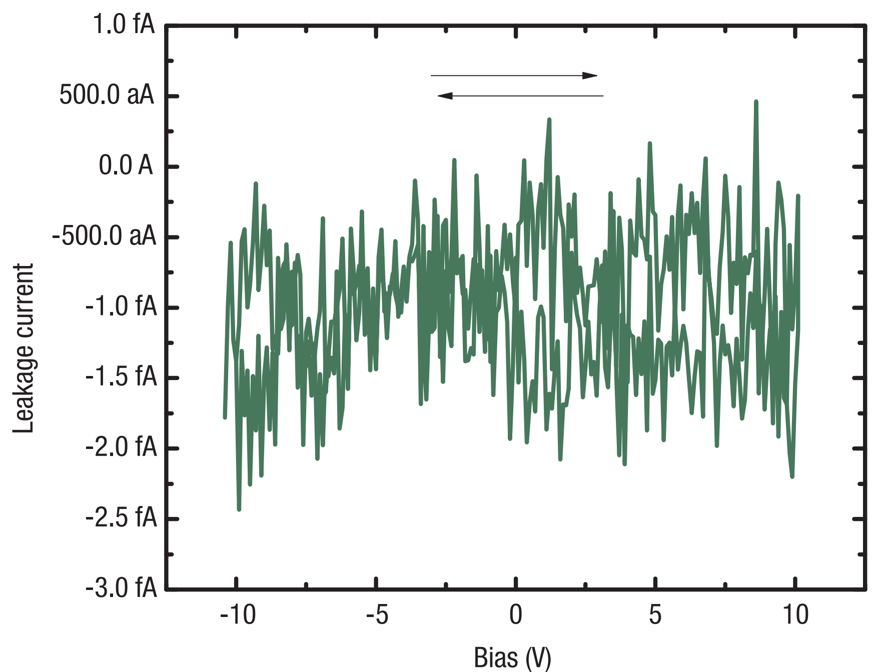

Figure 4. Measured leakage current in a Lake Shore triaxial probe arm assembly, including feedthrough, cable, and probe blade.

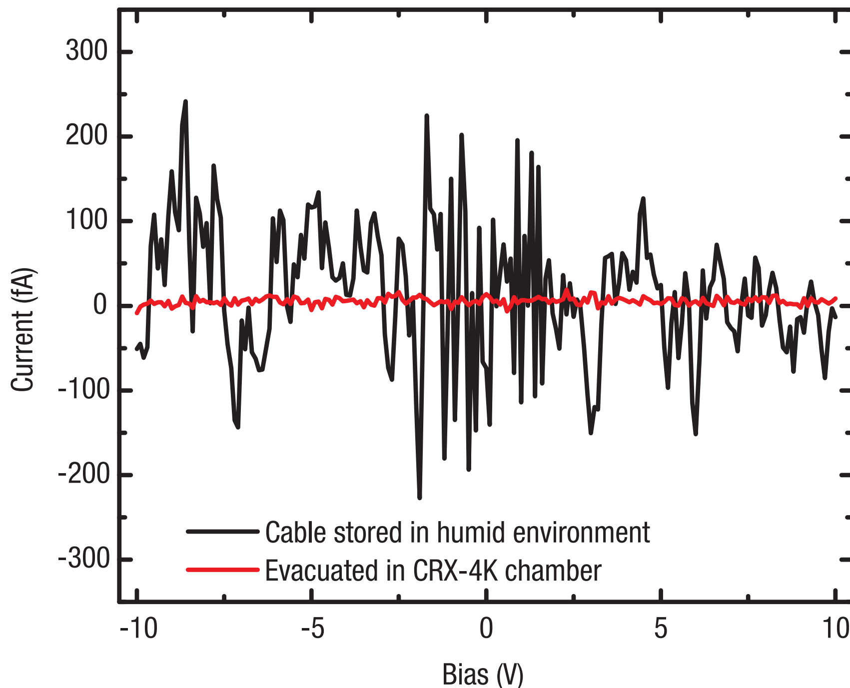

Figure 5. Leakage current for a vapor-saturated and evacuated triax feedthrough and cable. Electrochemical transport limits the current sensitivity of a device measurement and can be avoided by minimizing contamination of probing components as well as evacuating the sample space before each measurement.

Dirty surfaces and humidity

Low current performance of the device or probe station can be compromised by absorbed water and contaminants on cabling, probes, and devices. When a bias is applied, charged contaminants are free to move and can cause background currents. Below is a leakage current plot of a probe assembly that was stored in a humid environment. Measured under ambient conditions, the background current in the assembly could obscure sensitive current measurements. Once the assembly was evacuated in a probe station, low current measurement conditions were restored.

To avoid electrochemical effects, evacuating the probe station chamber—even for room temperature measurements—before any low current measurements is recommended. When not in use, the vacuum chamber of a Lake Shore probe station should be evacuated or purged with dry gas to reduce further contamination. Additionally, nitrile or latex gloves should be worn when handling devices and probe station components, such as replacement probes, to avoid contamination of the probing environment.

Triboelectric, thermoelectric, and piezoelectric effects

Frictional charging (triboelectric), thermal gradients (thermoelectric), and mechanical stress (piezoelectric) in cables or at the device contact can cause background currents that could mask the results of a device measurement. To reduce these charging effects in a probing measurement:

- Before starting device measurements, wait 15 to 30 min after attaching the cables between the source unit and probe station. Any stored charge caused by bending or twisting of cables often dissipates on this time scale.
- During variable temperature measurements, allow sufficient time for the probe arms to come into thermal equilibrium before starting a measurement. In a Lake Shore probe station, thermal stability can be monitored with the probe arm sensor and should vary <1 K/min.
- Do not lay cables on or across the vacuum pump, vacuum connections and, in the case of a closed-cycle system, the compressor unit.
- Avoid kinks or sharp bends in the measurement cabling.

Conclusion

As semiconductor devices are scaled to smaller and smaller sizes, leakage currents can significantly increase the overall power dissipation of these components. Identifying and modeling the various leakage mechanisms is critical in developing next-generation devices for both low- and high-power applications. As several contributors to leakage are thermally activated, cryogenic probing measurements are beneficial for evaluating the physical mechanisms which drive leakage in a particular device architecture. With appropriate attention to cabling and device environment, ultra-low current semiconductor device measurements (critical for evaluating device leakage) were demonstrated in Lake Shore cryogenic probe stations.