Basics of Low Current Probing

Application Note

Abstract

Useful as a primer for beginners and a refresher for those experienced in making low current measurements, this application note describes the fundamentals of making low current (femtoampere level) measurements using a probe station.

Proper setup, shielding and guarding considerations are discussed. Equipment needs to provide the correct probing environment are described. The application note discusses a series of problem areas typically encountered when doing low current probing and recommendations for solutions to these problems.

Introduction

The need to observe device behavior at femtoampere (fA) levels is being driven by the ongoing reduction in the geometric size of MOSFET devices to increase circuit density, facilitate higher speeds and reduce power consumption. Decreasing the scale of the circuit can help provide the aforementioned improvements; however, tradeoffs in performance will also occur. For this reason, it is necessary to have the tools available to observe the new operating characteristics for comparison with the predicted values. The measurement of current values in the range of 1 to 100 fA is difficult because the quantity of current is so low that many interfering sources exist that are capable of generating this minuscule flow of electrons. To put this into perspective, consider this: 1 fA (1×10^{-15} ampere) is equal to a flow rate of 6,242 individual electrons per second compared to the 6.242×10^{18} electrons per second that defines an ampere. Be forewarned that care and deliberation will be required to setup a system capable of measuring currents down to these delicate levels.

Representative Low Current Measurements

The grounding and shielding techniques needed for low current measurements will be defined for two typical probe contact configurations; *surface to surface* and *surface to substrate.* In the examples to follow, the surface to surface configuration will be represented by MOSFET subthreshold measurements and the surface to substrate measurements by time dependent dielectric leakage observations (TDDL). These configurations are shown in *figure one.* Subthreshold measurements permit the analysis of drain current behavior below the gate turn on voltage. This off state drain current

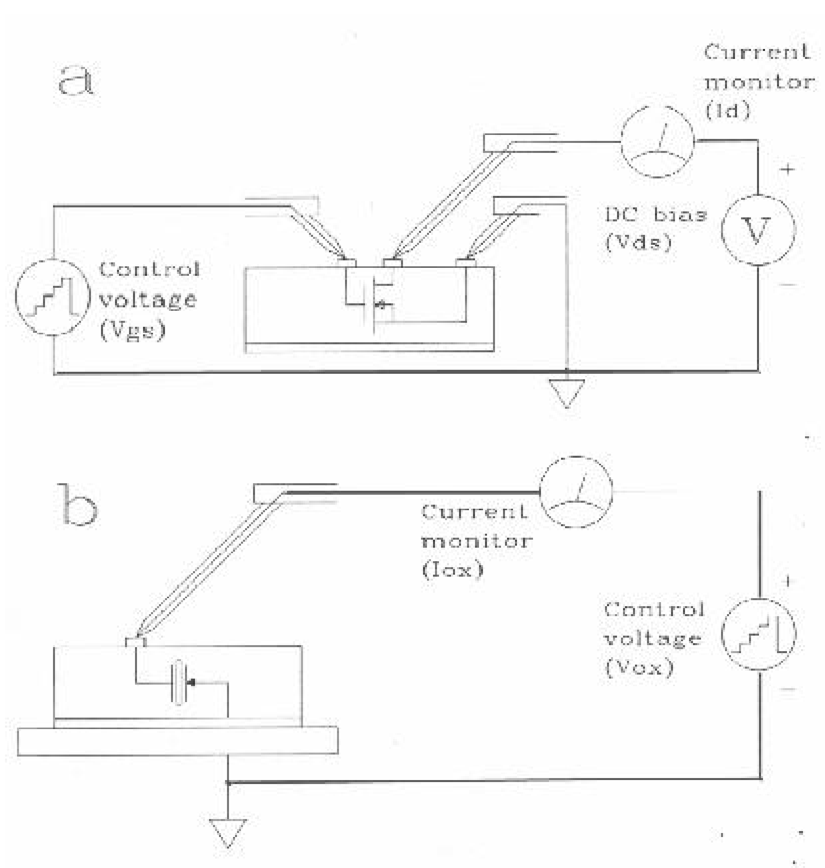

Figure One: *Idealized representations of surface to surface and surface to substrate current measurements for (a): MOSFET subthreshold characterization. (b): Time Dependent Dielectric Leakage characterization. Grounding and shielding requirements and practical SMU connections.*

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A1009492 rev 2 © 10/01

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is typically much less than 100 femtoamperes and will influence DRAM memory refresh requirements. A sub-threshold curve is shown in *figure two*.

TDDL characterization identifies the behavior of gate oxide leakage under the influence of high electric field stress to thin insulating (e.g. oxide) layers. This behavior is of interest for the reliability of EPROM and flash memory devices because write/erase cycles will cause an increase in leakage current over time. This current will be in the femtoampere range and can influence component leakage and other aspects of device performance resulting in eventual circuit failure. A TDDL curve is shown in *figure three*.

Source Measure Units

Subthreshold and TDDL characteristics are graphically analyzed and both require a voltage for the stimulus or source which produces a current as the response or *measured* value. A *source measure unit* (SMU) is commonly used to facilitate this stimulus and response function. A SMU is capable of being configured to:

- Source current and measure voltage
- Source voltage and measure current

SMUs have two features that facilitate measurement accuracy. When IR drops in the cabling between the SMU and the Device Under Test (DUT) are a concern, remote voltage sensing is available. If leakage paths and stray capacitive charging in the fixturing approach expected DUT current levels, a guard voltage output can be used to minimize the influence of these

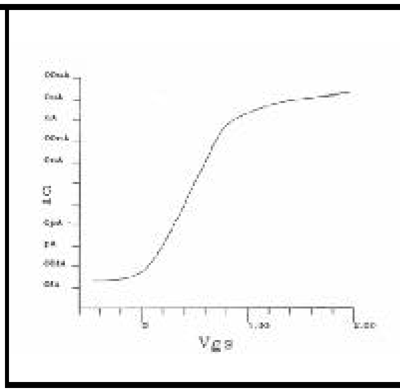

Figure two. *A typical MOSFET sub-threshold characterization curve. Made with a Micromanipulator Model 79 triaxial guarded probe on an unguarded chuck.*

paths. *Figure four* shows the configurations that will be used in the examples to follow.

Factors affecting the Low Level Environment

A number of factors can adversely affect your low level measurements. The very brief descriptions that follow are provided to help you form an intuitive basis for identifying and minimizing either the noise source or the noise coupling mechanism. Use these descriptions to visualize the relationships between noise and signal and to alter your experimental measurement setup to better isolate the noise from the signal. For more detailed information on the mechanisms described, refer to the reference texts listed at the end of this paper.

Remember that the noise coupling mechanisms are best described as "virtual components" in that they will not be obvious or localized as would a lumped equivalent component.

Common impedances

A common impedance is an impedance or current path unintentionally shared by a source of noise and the receiving instrumentation. The noise source causes current to flow through the common impedance. If this common impedance is in parallel with the instrument's input, a noise voltage will be coupled into the measured signal with the relationship:

$$v_{noise} = i_{noise}(Z_{coupling})$$

If the instrument is measuring current, then the current flowing through the common impedance will algebraically sum with the signal current at the connecting node.

Prevention measure: Analyze the grounding scheme and verify it conforms to single point grounding practice. Confirm that current paths between different circuit functions are isolated. Inspect the physical test setup and eliminate all casual, unintended contact between ground conductors that reside in different electrical parts of the circuit.

Incidental mutual inductance

Transfer of a noise voltage can occur through mutually coupled inductances in the noise circuit and the signal circuit. This inductive coupling will have the relationship:

$$v_{noise} = M \frac{di_{noise}}{dt}$$

M is the mutual coupling between the noise circuit and signal circuit and will be influenced by proximity and shared length of noise and signal conductors. v_{noise} is the noise voltage coupled into the signal circuit and is proportional to $\frac{di_{noise}}{dt}$ which is the time derivative of the noise current.

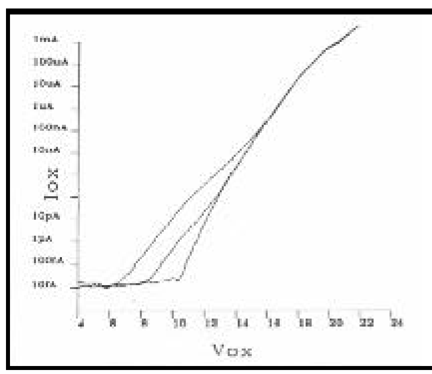

Figure three. *A typical Time Dependent Dielectric Leakage curve family derived from circuit b in figure one.*

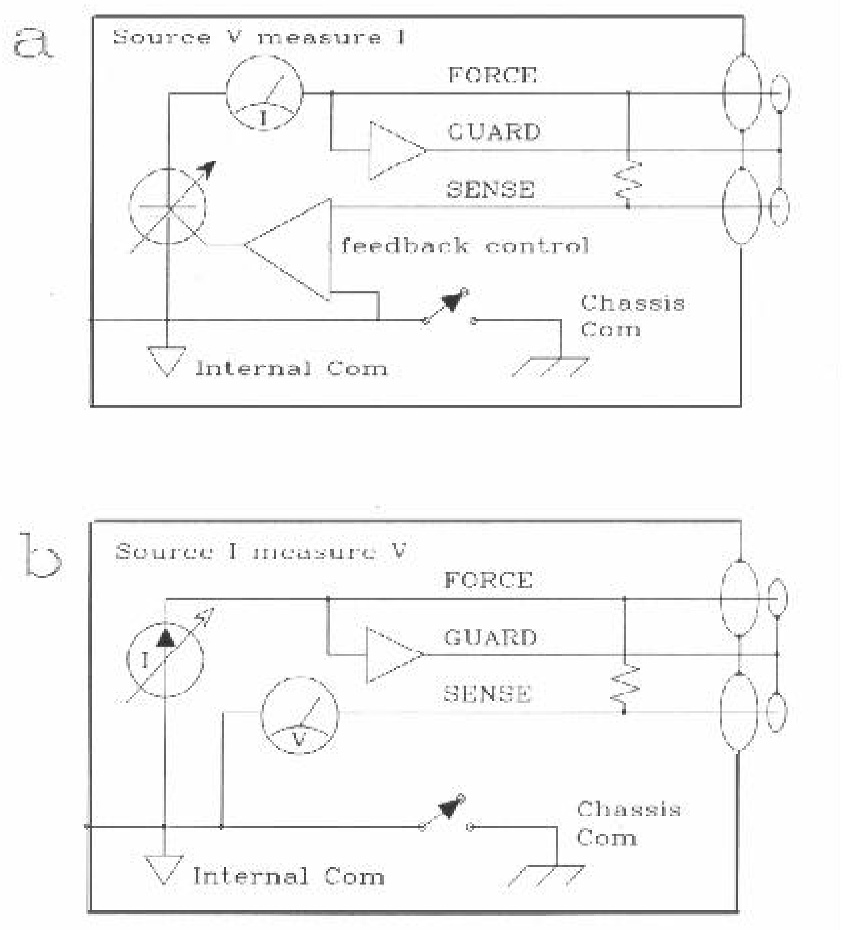

Figure four*. The two generalized basic configurations for Source Measure Units. (a): Source V, measure I. (b): Source I, measure V.*

Prevention measure: Eliminate common runs of conductors and cables, especially conductors not a part of the test signal circuitry. Maintain wide conductor spacing where possible. Isolate circuits with magnetic shielding where practical.

Magnetically coupled noise
Typical noise sources that lend themselves to magnetic coupling are motors, transformers and facility wiring. The coupling mechanism can be expressed as:

$$v_{noise} = 2\pi f B A \cos\theta$$

f is the frequency of the noise signal, *B* is a measure of the noise magnetic field strength, *A* is the area of a closed loop in the signal circuit and θ (theta) is the angle of *B* to the plane of the loop area *A*.

Prevention measure: Remove unnecessary sources of electro-magnetic energy in the area of the test circuit. Eliminate circuit loops. Magnetically shield wires or use twisted pairs.

Incidental capacitive coupling
A source of noise current can be coupled to the measurement circuit via stray capacitance according the relationship:

$$i_{noise} = C_{coupling} \frac{dv_{noise}}{dt}$$

$C_{coupling}$ is the stray capacitance between the noise source and the measurement circuit. This noise current will be proportional to the voltage rise and fall times of the adjacent noise signal and proportional to the amount of stray capacitance between noise conductor and signal conductor. Stray capacitance is inversely proportional to the distance between conductors. If the circuit of interest has a high impedance, it will see a noise voltage. If the impedance is low, a current will be developed.

Prevention measure:
Add distance between unshielded noise sources and the test circuit. Separation of two wires by a distance greater than 40 diameters will provide good electrostatic isolation.

Ensure the test circuit conductors are shielded to redirect capacitively coupled current away from the test circuit to ground. Active guard shields will also provide good protection.

Charge transfer
If a charged body is brought in proximity to the test circuit, that charge will attract or repel charge in the test circuit and cause momentary electron flow. This will perturb femtoampere measurements. A human body is the typical charge vehicle.

Prevention measure: Limit activity in the area of the test setup during measurements. Provide broad electrostatic isolation by using a metallic light tight enclosure (LTE). Run interconnecting cables between the LTE and SMU behind the test bench away from traffic and AC power cords.

Stray capacitance charging
The voltage supplied by the SMU for subthreshold and TDDL measurements will typically be a stepped sweep of increasing voltage over time. Stray capacitance in the cables and shield surfaces between the SMU and DUT must be charged which will introduce an added current that will swamp the DUT

current as shown in *figure five.* For low current measurements, this will be a major source of error.

Prevention measure: Use an active guarded shield on all cables to keep the differential charging voltage to a very small level. Use probes or probe holders that have guard shielding as close as practical to the probe point. Evaluate the settling time requirement after guarding is in place and be sure to program an adequate measure delay time into the SMU.

Light
Semiconductor devices can be light sensitive. This is especially true for MOSFET devices that rely on minority carriers for conduction. At femtoampere levels, the currents induced by exposure to light will obliterate many measurements.

Prevention measure: Use a light tight enclosure (LTE) to provide a dark environment around the DUT. This serves to block all forms of electromagnetic radiation, not just the visible spectrum.

Intrinsic noise sources
At low femtoampere levels, most coaxial and triaxial cables will show current developed by triboelectric effects caused by flexing or vibration of the cable. Contacts between dissimilar metals as might be found in connectors, crimp joints or solder joints will develop temperature sensitive Seebeck voltages (thermal noise). Moisture combined with chemical residue left over from an assembly process can produce an electrochemical voltage.

Prevention measure: Minimize triboelectric errors by allowing cables to relax after installation. Anchor cables to prevent motion. Prevent Seebeck effect and electrochemical voltages by making connections with similar metals and keeping connectors clean and dry.

Leakage current
All insulation used in cabling, connectors and probes will permit a degree of leakage that can influence femtoampere measurements. Some of this leakage is inherent to the insulating material and additional leakage may sometimes be contributed by contamination during assembly or handling.

Prevention measure: Use an active guarded shield on all cables to keep the differential voltage to a very small level.

Guidelines for successful low level measurements

Pay attention to the details
Because of the very small physical values being observed, many factors can interfere with the desired measurements. Thus it becomes important to review and practice the prevention measures given previously to eliminate problems before they occur.

Diagnose noise sources and minimize their effects
The biggest difficulty related to solving noise problems at femtoampere levels is that analog time domain measurement techniques are not readily available that will permit direct observation of the low level noise. When a noise waveshape can be seen in real time, its behavior can be compared to external events and coupling mechanisms can be deduced and modified to reduce their influence.

Since this luxury probably will not exist, the next best tool will be your parametric tester configured to provide a sampled sweep of *current versus time with a constant source voltage*. When used this way, the filtering and averaging options should be set to minimum to improve its use as a noise diagnostic tool. By observing the sampled noise in this way, possible sources and coupling paths to noise can be identified and altered while observing the effects of the alteration.

System grounds, shields and connections
The ideal grounding, shielding and connection scheme for surface to surface and surface to substrate current measurements are shown in *figures six* and *seven.*

Exploit filtering and averaging available in the instrument
Parametric measurements like subthreshold and TDDL lend themselves to filtering and averaging. Use these features to obtain a clean, nominal representation of these DC characteristics.

Guarding and settling time
The use of a guarded signal path will be a key contributor to successful low current measurements. The driven guard output on a typical SMU will provide a buffered output voltage that follows the source output. Since the voltage difference between the signal path and guard shield will be nearly zero, the leakage current through the isolation will be maintained at very low levels. Charging delay (settling time) of the signal line will be substantially reduced for the same reason. Refer to *figure six* and *seven* for the recommended guard configuration. Compensate for the remaining settling time by adding the appropriate measurement delay to the SMU.

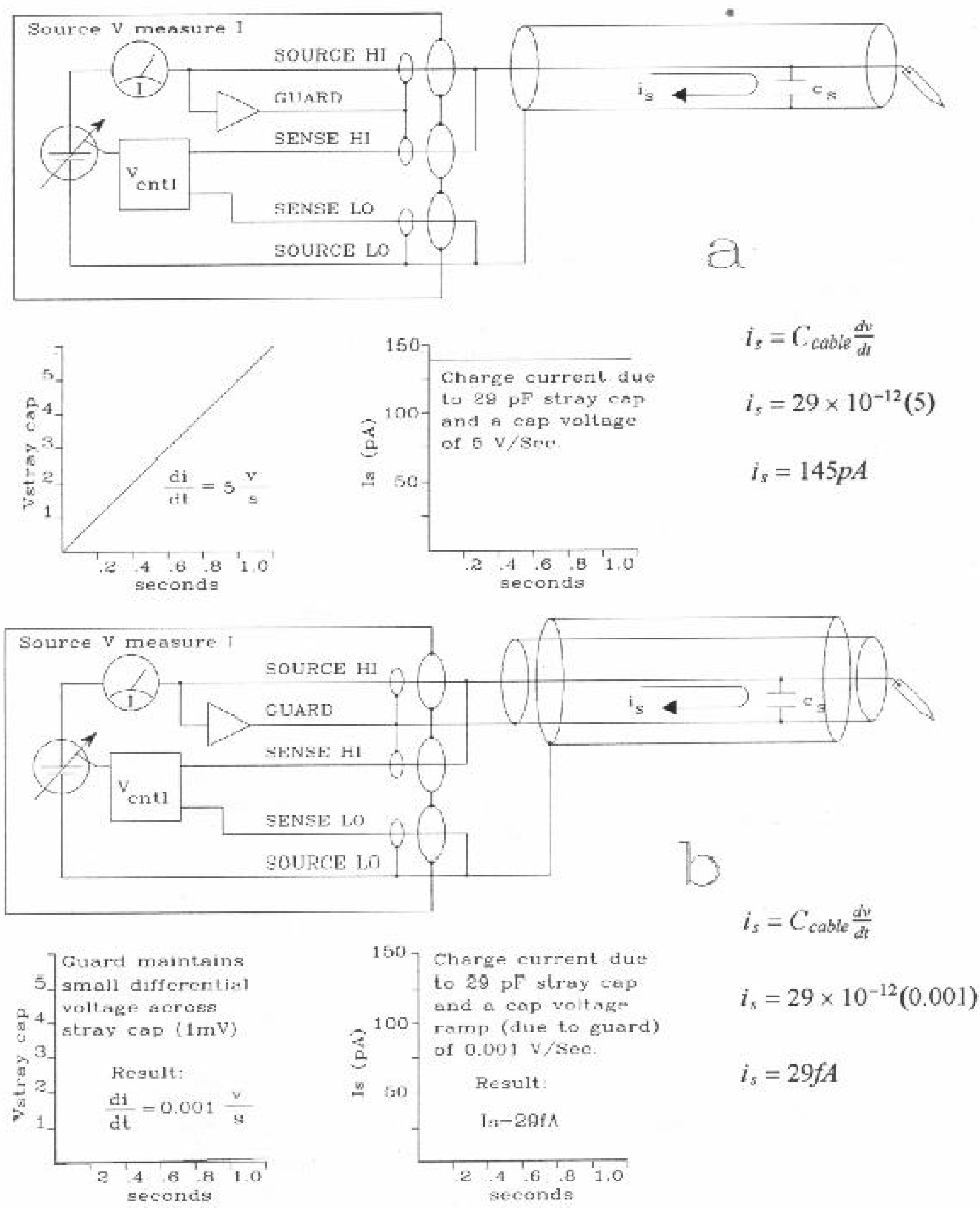

Figure five. The settling time influence of cable (stray) capacitance. Proper connection of the guard from the SMU to the cable shield will significantly reduce or eliminate this source of error. The numerical example shows just how significant a reduction in charge current guarding can make. In this case, charge current is reduced by three orders of magnitude (a reduction of 5,000 to 1)! Similar reduction of leakage current through insulation resistance can also be expected. Reduction of stray capacitance effects in the substrate circuitry is likewise attained by using a guarded (triaxial) chuck.

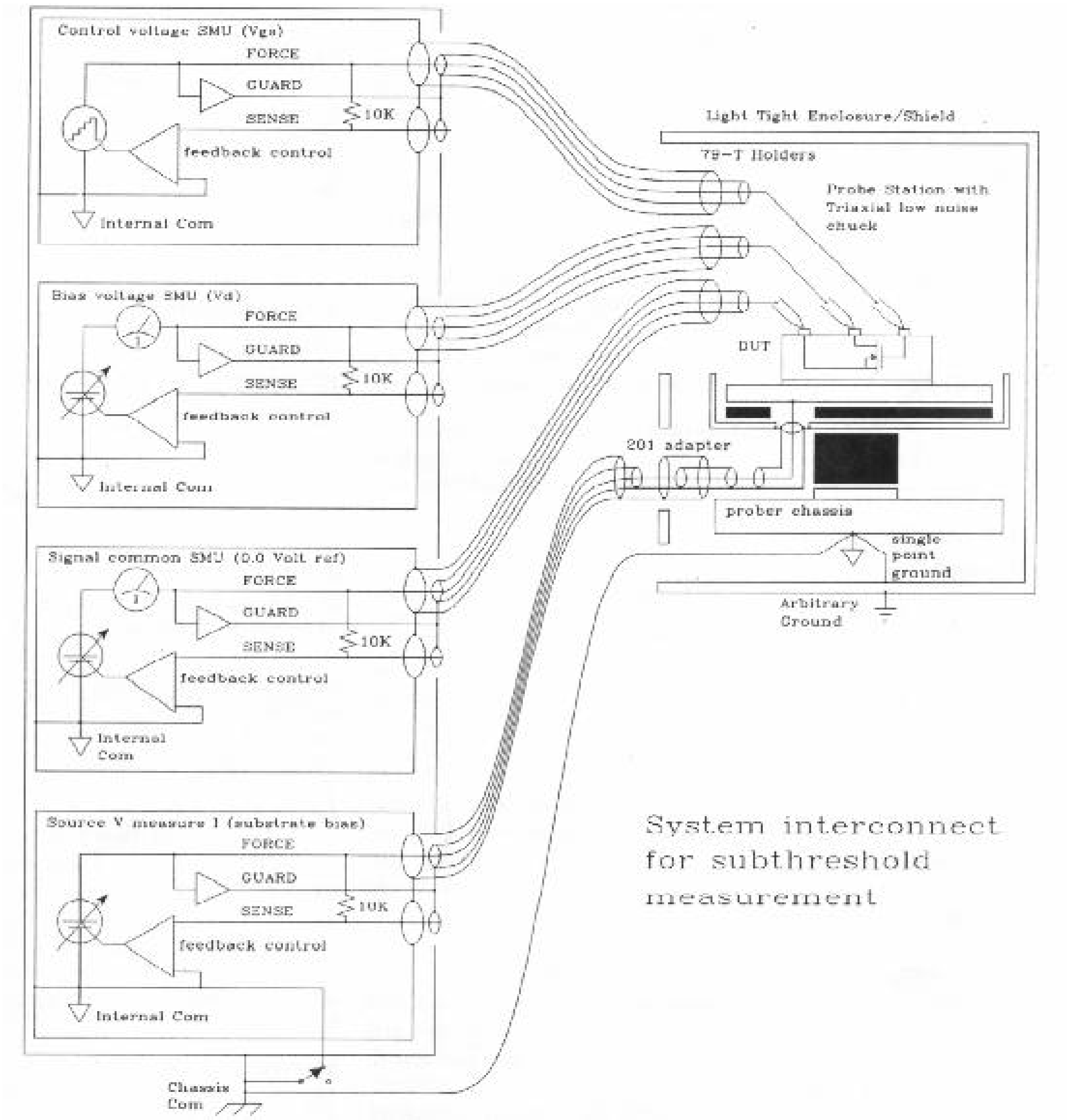

Figure six. Shielding, grounding and guarding scheme for low current surfact to surface measurements with a parametric tester having an internal common reference.

Cable Isolation and noise

Femtoampere current measurements will require very high resistive isolation and guarding between the signal path and all conductors at the reference potential. Specify cabling designed for low leakage such as cable insulated with virgin PTFE (Teflon) insulation. Most cabling will generate some degree of intrinsic noise especially when the cable is flexed or vibrated, but most of this will subside after the motion stops. Cable designated as low noise is specifically manufactured to minimize triboelectric effects. When evaluating cables for leakage and intrinsic noise, allow the cable to relax into a limp position before making a leakage measurement. This requirement for a relaxed and motionless cable also applies when making real measurements. Note that the noise settling time could vary from seconds to tens of minutes depending on the cable type and characteristics.

Cleanliness

Avoid touching insulation between two conductors such as might be found around connectors, probes, shields and guards. Oils or contamination on your fingers could cause an increase in leakage current.

Application of Micromanipulator products for low level measurements

Probing stations
The probing stations best suited for low current measurements are the 8060, the 8065 and the 8860 stations. The chassis is configured with a single point grounding scheme to minimize current generated by Seebeck voltages in the chassis. These stations also have the feature of providing isolated, independent electrical access to the chuck surface and chuck guard when used with the triaxial chuck (see *figure seven*).

Low noise enclosures
The 7000-LTE and 8800-LTE provide both a dark environment and electromagnetic shielding from external sources of noise. A key advantage to completely enclosing the probe station is that access to the wafer, probe and probe holder is convenient when compared to local, wafer only shielding.

The low noise chuck
The 8800-EVS-LN8 chuck is shown schematically in *figures six* and *seven*. This chuck will provide very high isolation to ground (with or without guarding) and is configured to permit the application of a guard voltage to isolate the substrate circuitry from the effect of leakage and stray capacitance charging.

Probe holders with replaceable tips
Probes suitable for low current measurements are:
- 79-XXXX-T-02
- 79-XXXX-T-03

These probe holders have triaxial cabling which permits the use of the inner shield as a guard within close proximity to the replaceable probe tip.

For applications where currents at higher levels as well as low levels are of interest, a Kelvin type triaxial probe holder should be used to compensate for IR drop in the source voltage cable. The part number for the Kelvin triaxial probe holders are:
- 79-XXXX-DT-02
- 79-XXXX-DT-03

Also suitable for low current probing (but with the caution noted below) are the following:
- 79-XXXX-F-02
- 79-XXXX-F-03
- 79-XXXX-R-02
- 79-XXXX-R-03

These probe holders have coaxial cabling and should be used with a Model 101 adapter (or equivalent). This adapter will route the inner shield from triaxial cabling to the probe shield so that it will continue the guard down to the vicinity of the probe tip.

Caution: The guard voltage will be accessible at the BNC connector body. A potential shock hazard exists with the use of these probe holders especially if the guard voltage exceeds thirty volts. Isolate and insulate these connectors and only handle the connector if the guard voltage is off.

44 series probes
All 44 series probes are coaxial. The particular advantage of this style of probe is an integral shield that extends to within 0.1 inches of the probe tip. Use this style of probe with 49-14 coaxial cables and a Model 101 adapter to extend the guard shield to the probe shield. The following versions of 44 probes are appropriate for low current measurements:
- 44-XXXX-V-NA

Caution: The guard voltage will be accessible at the BNC connector body and at the exposed probe shield. A potential shock hazard exists with the use of these probe holders especially if the guard voltage exceeds thirty volts. Isolate and insulate these connectors and only handle the connector or probe if the guard voltage is off.

Cables and adapters
Generic, triaxial cables intended for low noise applications are suitable for use in these low current applications. When adapters are required to connect BNC connectors to triaxial connectors, adapters that connect the triax inner shield to the BNC shield should be used. The adapters available from Micromanipulator are:
- Model 101 triax male to BNC female adapter
- Model 201 triax female to BNC male adapter

The 101 adapter is useful for connecting coaxial probes to triaxial cables. The 201 adapter will connect the triaxial chuck properly to triaxial cable through the chuck BNC connector.
- 44-XXXX-V-NA

Caution: The guard voltage will be accessible at the BNC connector body and at the exposed probe shield. A potential shock hazard exists with the use of these probe holders especially if the guard voltage exceeds thirty volts. Isolate and insulate these connectors and only handle the connector or probe if the guard voltage is off.

Application Note

Summary

The need exists for low current measurements in the range of 100 to 1 fA due to the continuing trend toward decreasing geometric scale. Instruments are now available that can resolve down to 1 fA or below and engineers involved in process and design are ready to make use of this technology. The factors that affect the low current environment are well known and can be modeled as "virtual components." These models will help the visualization of noise sources and noise coupling mechanisms when trying to deduce and eliminate error sources in the test system. Because noise at the femtoampere level is difficult or impossible to see in real time, the best measure against this source of error is prevention.

Further Reading

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Acknowledgments

Special thanks to the following people for sharing their knowledge, experience and time:

Lee Stauffer; Keithley Instruments, Inc.
Jim Forst; The Micromanipulator Co., Inc.
Dan Harrison; The Micromanipulator Co., Inc.