Advanced On-Wafer Device Characterization Using the Summit 10500

Today’s emerging technologies require a higher degree of device characterization than ever before. This application note provides information on how the Summit 10500 Parametric Probe Station enables state-of-the-art DC/CV, LCZ, and high-frequency measurements at fA-, fF-, and GHz-levels. The Summit 10500 is the first integrated on-wafer measurement system for fundamental characterization tasks.
Summary

This application note provides information on advanced, on-wafer device characterization techniques using the Cascade Microtech Summit 10500 Parametric Probe Station. Fundamental Device Characterization Requirements are outlined, leading to a discussion of the probe station features needed for various device characterization measurements at fA-, fF-, and GHz-levels. The Summit 10500 is a state-of-the-art, on-wafer characterization solution for low-current, low-capacitance, and high-frequency measurements.

Next, Connection Diagrams between the probe station and instruments are outlined for various measurements. The Example Applications illustrate the Summit 10500’s ability to make precision measurements for a number of needs. Low-Current and High-Frequency Measurement Fundamentals are then discussed, including topics such as guarding, shielding, ground loops, noise currents, Kelvin probes, and bipolar device measurements. Finally, lists of References and Suggested Equipment and Accessories are provided.

Fundamental Device Characterization Requirements

Before current and next-generation integrated circuits (ICs) can be designed, fabricated, and tested, individual devices must be characterized and modeled. All other activities related to IC design, fabrication, and testing depend on these highly-accurate device models. Consequently, all leading IC manufacturers provide the most accurate and precise equipment to their device characterization teams.

Characterization measurements include the following fundamental requirements:

- **DC tests** Forcing voltages and measuring currents, including very low values in the 10 to 100 fA range. The device under test (DUT) must be shielded from light and noise (EMI, static charges, etc).

- **LCZ tests** Forcing low-frequency AC voltages, and measuring AC currents. Capacitance, inductance, and impedance are calculated from these measurements. Capacitance values of 1 to 10 fF are often measured. Again, the DUT must be isolated from light and stray capacitance.

- **High-frequency tests** Measuring high-frequency and high-speed performance using vector network analysis or time domain reflectometry (TDR). Direct measurement of cutoff frequencies (ft) and other high-frequency parameters is now widely done. As IC speeds increase, additional elements such as diodes, vias, crossovers, power busses, and interconnects need to be characterized at high frequencies.

Because the devices to be characterized are so small, they are generally left together as fabricated on the wafer and electrically contacted on a wafer prober. This approach saves the time and cost of dicing the wafer and packaging the devices for testing within a fixture.

Probe stations are traditionally designed for only one function: either for simple DC testing or for high-frequency characterization. However, stations for DC testing are not designed for advanced, low-level DC/CV or LCZ testing. The stringent requirements for low-level current measurements necessitate a shielded and dark environment for guarded and noise-free
measurements. In addition, air purging around the wafer is often needed to control the temperature and humidity of the test environment.

Until recently, neither isolation, shielding, nor purging has been available as part of an integrated device characterization probe station (although some fixtures can provide some shielding and isolation). Present on-wafer solutions use large, unwieldy dark/shield boxes to enclose the entire probe station. A lid is opened to operate the station and to view the device under test (DUT) through the microscope. But this partial solution does not enable low-level current and capacitance measurements.

Ideally, these characterization requirements should be combined into one unit providing DC, LCZ, and GHz measurement capability with integrated shielding, isolation, and dark. For rapidly-developing technologies, the following probe station functionalities are required for accurate and thorough model development:

- **Electrical performance** The station should make fA-level DC measurements, which are possible if the wafer chuck is biased and isolated. The station must also provide 1 fF LCZ measurements. For GHz characterization, the station should easily measure device S-parameters to 65 GHz or TDR response to 5 ps. The station’s probing environment should eliminate noise caused by static, EMI, dielectric absorption, and triboelectric cable effects.

- **Probe types** For fA- and fF-level measurements, the station must accommodate both Kelvin and non-Kelvin DC-guarded coaxial probes. For high-frequency characterization, coplanar probes with bandwidths up to 65 GHz should be compatible. Standard DC needle probes are also required. High-impedance or active probes for unobtrusive node probing may also be used.

- **Dark box** The station must incorporate light shielding, since many devices are light sensitive. Ideally, the probe positioners and station controls should be accessible without disturbing the light-controlled environment.

- **EMI shielding** Measurements as low as 1 fA require integrated EMI shielding to minimize noise.

- **Isolation** Ground loops must be prevented.

- **Environment purging** The station must provide a controlled environment to reduce the effects of changing humidity, temperature, and particle contamination. Ideally, the station should provide the ability to purge with nitrogen or other inert gas to minimize humidity damage to sensitive wafer elements.

- **Easy to use** Mechanical functions should be similar to current probe stations and should operate intuitively.
Description of the Summit 10500 Parametric Probe System

The Cascade Microtech Summit 10500 (Figure 1) provides the necessary features for making fundamental device characterization measurements. The Summit 10500’s key feature is the MicroChamber™ (patents pending), which provides a complete semiconductor measurement environment that shields the chuck and probes from electromagnetic interference (EMI) and light. Standard DC probes, guarded coaxial probes, and high-frequency coplanar probes are optimized for use in this system. The chuck is electrically-guarded to allow accurate, fA-level substrate current measurements.

MicroChamber

The MicroChamber (Figure 1) surrounds the wafer stage, shielding it and the probes from both EMI and light. Sliding metal plates underneath the chuck that eliminate noise from the x-y motors complete the shielding. The MicroChamber and the platen can be electrically isolated from the rest of the station and from earth ground, thus eliminating ground loops. Although the MicroChamber ground safety link is factory-set, connecting the MicroChamber to ground, it can be removed by the user if desired. A more detailed discussion on shielding and ground loops is found starting on page 14.

The top hat (Figure 1) completes the EMI/dark shielding, allowing probes to be inserted through the polymer windows, yet preventing light from entering. Various sized polymer/steel rings surround the microscope objective, allowing the microscope both vertical and horizontal movement without light and EMI leakage. The MicroChamber enclosure shields the wafer chuck, DUT, and probes from EMI, and prevents light from affecting the DUT, yet allows convenient access to the microscope and probe positioners. A convenient wafer loading door allows easy access to the chuck.

The MicroChamber also provides a complete air seal around the wafer chuck, probes, and microscope objective. The system can be purged with nitrogen or inert gas to provide a clean, humidity and temperature-controlled environment. An intake manifold at the rear of the station provides convenient air or gas hookup. The MicroChamber typically evacuates in less than 5 minutes, depending on air flow and pressure.

Guarded chuck

Guarded measurement techniques are required for accurate and rapid current measurements below 1 nA. Because some devices generate low (cf nA) substrate currents that need to be measured, the Summit 10500 provides a guarded chuck assembly, allowing accurate device and substrate measurements at the fA-level. Figure 2 shows the basic design. The chuck is a standard wafer chuck, but is isolated from the guard by $1 \times 10^{13}$ ohms. The guard is also isolated from the shield by $1 \times 10^{13}$ ohms. When the guard is connected in the guarded mode to a source measurement unit (SMU), fA-level currents are accurately measured. The guarded chuck is also optimized to provide low capacitive loading for DC parametric and LCR test instruments. This enhances the test instrument’s settling time and accuracy.

Conventional chucks are typically specified with $1 \times 10^{9}$ ohms isolation (Figure 3). If the chuck is assumed to be biased at -1 volt, a current meter will measure $-1 \times 10^9$ ohms or 1 nA current flowing through the chuck isolation resistor. This is in addition to the current flowing from the DUT. Lower level current measurements of semiconductor devices are limited to about 1 nA when biasing conventional chucks.
In contrast, the Summit 10500's guarded chuck typically has leakage currents of 1 mV/1E13 ohms or 0.1 fA (Figure 4). Most test and measurement instruments with guarded signal lines (like the HP 4142B) have a maximum guard error of 1 mV or less. This means that the voltage difference between the chuck and the chuck guard will be within 1 mV. Further discussion of guarding is found beginning on page 13.

Guarded coaxial probes

Coaxial probes for measuring low-level currents and capacitance values are different than conventional DC needle probes. The center conductor is used for the signal, while the outer conductor is used as either a guard for guarded current/voltage measurements, or as a shield for capacitance measurements. Figure 5 shows the DCP-100 Series Coaxial Probes in both non-Kelvin and Kelvin versions.

When measuring high currents (>100 mA) or small-value precision resistors (<1000 ohms), the Kelvin configuration compensates for voltage drops caused by probe contact resistance and cable resistance. In general, non-Kelvin probes are adequate when dealing with currents less than 100 mA. A variety of guarded non-Kelvin and Kelvin probes are available from Cascade Microtech for the Summit 10500. More information on Kelvin probing is found on page 16.

It is important to extend the outer conductor as close as possible to the probe tip, as this minimizes the fringing fields between the probe tip and the shield, and between multiple probe tips. This is particularly crucial for probes used to measure small capacitance values.
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(<1 001F), where variations in their fringing fields will be measured as changing capacitance values.

When the coaxial probes are used for guarded current measurements, the outer conductor minimizes leakage from the probe center conductor to the shield. Further details on guarding techniques can be found on page 13.

The coaxial probes are connected to the triaxial measurement cables via special triax-to-coax bulkhead adapters. The triaxial cable’s guard and signal lines connect to the coaxial probe cable inside the bulkhead and the shield surrounds the probe cable until it is inside the MicroChamber enclosure. This ensures the signal and guard lines are fully shielded from the instrument all the way to the probe and wafer.

The bulkhead adapters come in single and Kelvin versions to match the coaxial probes. Figure 6 shows a Kelvin bulkhead adapter and probe setup. The bulkhead adapters mount to Cascade Microtech RF and DC probe micropositioners and provide strain relief for the probe cables.

High-frequency probing

Many people use vector network analyzers (VNAs) to measure device S-parameters for extracting ft values and other parameters [1]. These measurements are made with coplanar-waveguide probes (Figure 7) with bandwidths through 65 GHz. The characterization probe station must include features for probe positioning, calibration, and pad parasitic correction.

The Summit 10500 provides extremely rugged RF probe positioners (Figure 1) with x-y-z-axis, and theta probe adjustments. The theta adjust planarizes the coplanar probe contacts to the DUT pads. The arm rigidity prevents cable vibration-induced measurement errors. The integrated cable clamps further control cable movement. Calibration substrates (impedance standard substrate or ISS) mount on the special calibration stages provided inside the MicroChamber.

With the optional VNA Calibration Software, calibration is performed automatically, stepping from standard-to-standard as required. This eliminates a previously tedious task and results in more consistent calibration. Autocal easily achieves 0.3 % calibration accuracy from 0 to 40 GHz when used with Cascade Microtech coplanar probes. The software also includes Pad Parasitic Removal (PPR), a feature that corrects for the silicon substrate bond pad parasitics that can affect measurements by as much as 50%.

Time domain measurements are similarly configured, using instruments like the HP 54120 Series oscilloscopes [2]. The same probes, positioners, cables, and calibration substrate work with the HP 54120 series and similar instruments.

Figure 6. Connections for Kelvin probe use

Figure 7. Coplanar probe contacting impedance standards to calibrate out effects of the instrument, cable, and probe
Connection Diagrams

The Summit 10500 is easily connected to a wide variety of instruments with triaxial and coax cables. This section illustrates some of the important connections. The ground unit adapter included with the Summit 10500 (Figure 8) adapts the standard triaxial pinout to the ground unit (GNDU in the HP 4142 or LO in other instruments) where the force, sense, and shield are contained in one triaxial cable. Either the chuck or a probe can be forced to ground unit potential with this connection.

The MicroChamber ground safety link is set at the factory, connecting the MicroChamber to earth potential. Many measurements (such as low-level DC and capacitance) require that this link be disconnected to prevent ground loops. Ground loops are discussed further on page 14.

**Ground Unit Adapter**

4142B
GNDU

![Figure 8. Ground adapter details](image)

The Summit 10500 comes with a complete set of standard accessories for interconnecting coaxial and triaxial cables with the system. DC positioners and extra triax adapter kits, cables, and accessories are available from Cascade Microtech. See the *Suggested Equipment* section on page 18.

**HP 4142B Modular DC Source/Monitor** The HP 4142B Modular DC Source/Monitor (Figure 9) is a high-speed, highly accurate computer-controlled DC parametric measurement instrument for characterizing semiconductor devices such as MOSFETs, GaAs devices, op amps, as well as capacitors, insulators, and other components. Together with the Summit 10500, the HP 4142B can be used for on-wafer semiconductor process monitoring, device development, and process development. Its wide measurement range and high resolution affords quick and efficient DC parameter evaluations from ±20 mA to ±1 A, and ±4 µV to ±200 V.

![Figure 9. Hewlett-Packard 4142B Module DC Source/Monitor](image)

Figure 10 shows a common situation, with the chuck at ground unit potential, and one or more probes connected to source measurement units (SMUs). Note that one probe is Kelvin and the other is non-Kelvin. This is the typical configuration for measuring diodes and transistors.
Figure 10. Connection to HP 4142B or similar instrument. Chuck at zero bias, one probe Kelvin, one probe non-Kelvin. Typically used to measure transistors, diodes.

Figure 11 illustrates a more complex situation, with the chuck now guarded and connected to an SMU, similar to a probe. Note that the chuck has Kelvin connections for high-current situations. One probe is connected to the ground unit using the ground unit adapter and is forced to ground unit potential. The other probe is connected to another SMU. Because the chuck is guarded, it is treated as another probe, and very low currents can be measured accurately through the chuck. This configuration is used for measuring substrate currents or with a biased substrate.

Figure 11. Connections to the HP 4142B or similar instrument. Chuck biased and low level substrate can be measured through guarded chuck connections.
HP 4284A Precision LCR Meter  The HP 4284A Precision LCR Meter (Figure 12) is primarily used for component and material measurements. It provides an accurate, high-throughput test solution with 20 Hz to 1 MHz test frequency range and superior test signal performance. In particular, the HP 4284A provides highly accurate on-wafer capacitance measurements with the Summit 10500. This combination can make other device and process material measurements as well.

When measuring capacitance from the top of the wafer to the substrate, the chuck is connected to the HI terminals of the HP 4284A and the probe to the LO terminals (Figure 13). With this connection, the displayed capacitance value in the HP 4284A will not include the parasitic capacitance of the chuck to the MicroChamber. Any variation in the fringing fields from the probe center conductor to the shield, the DUT, or the MicroChamber will show up as changes in measured capacitance. The solution is to extend the probe's outer conductor (which acts as a shield) as close to the probe tip as possible, consistently terminating the electric fields.

Figure 12. The HP 4284A Precision LCR Meter

Figure 13. Connections to the HP 4284A LCR Meter or similar instrument. Chuck is connected to the HI terminals and the probe to the LO.
Example Applications

Figure 14 shows the noise isolation and shielding characteristics of the Summit 10500 system, as measured by the HP 4140B pA meter/dc Voltage Source. A guarded coaxial probe was used to measure the low-level noise floor of the system, which exhibited less than 5 fA variation over the 100 second time period. The MicroChamber and chuck were tied to the shield of the HP 4140B (unbiased), with the chuck, guard, and shield layers shorted together. The HP 4140B has a 11A measurement resolution, and was set up with long integration and filtering at 1 sample per second. Figure 15 illustrates the connections.

Figures 16 and 18 are typical HP 4142B noise floor plots with the Summit 10500. These noise floor examples provide relevant data for determining the limits of device testing methods and for defining expected accuracy for test results. In Figure 16, the chuck is at ground potential, the probe is biased at 1 volt, and current going into the probe is measured. Figure 17 shows the connections.

**Figure 14.** Noise floor as measured with the HP 4140B pA Meter/dc Voltage Source. (Connections shown in Figure 15.)

**Figure 15.** Connections to the HP4140B

**Figure 16.** HP 4142B noise floor when connected to Summit 10500, chuck at zero bias. (Connections shown in Figure 17.)

**Figure 17.** Connection diagram for noise floor measurement in Figure 16
Figure 18 illustrates the opposite situation, with the probe at ground potential and the chuck biased at -1 volt and guarded. Current going into the chuck is measured and displayed. The system is connected as shown in Figure 19. Both plots display nearly identical results and represent the noise floor of the HP 4142B, around 40 fA.

**Diode measurements** Forward-biased diode measurements are performed for many reasons, including evaluating interface traps and process changes. For many applications, pA and lower-level measurements are required. Figure 20 shows a diode measured with an HP 4142B using the low-power SMU (41421B SMU). The test used 8 power line cycle averages and long integration time. The instrument was connected as in Figure 17. Figure 21 shows the opposite instrument configuration, with the chuck connected to an SMU and the probe at ground unit potential, as in Figure 19. The averaging was 8 power line cycles. With this averaging, the instrument noise floor is typically 40 fA. Note that both measurements are identical above the noise floor, demonstrating the effectiveness of the guarded chuck connection.

![Figure 18. HP 4142B noise floor when connected to Summit 10500, chuck biased at -1 volt. (Connections shown in Figure 19.)](image)

![Figure 19. Connections for noise floor measurement in Figure 18](image)

![Figure 20. Forward biased diode measurement made with HP 4142, chuck at zero bias, current into probe measured.](image)

![Figure 21. Forward biased diode measurement made with HP 4142, chuck biased, probe at zero bias, current into chuck measured.](image)
Gummel plots are widely used in bipolar device characterization. Figure 22 illustrates a typical diode response IV curve in which three stages of $I_b$ are shown. Stage 1 shows the typical voltage drop due to the series resistance of the device. Stage 2 shows the ideal diode response. Finally, Stage 3 illustrates the deviation from ideal diode performance due to features such as recombination currents and interface traps.

![Figure 22. Typical Gummel plot of diode measurement](image1)

Capacitance measurements are affected by the fringing fields from the probe tip to the shield, DUT, chuck, and MicroChamber shield. When measuring capacitance values across a wafer, the fringing fields change at the wafer and chuck edges. Figure 24 shows a measure of this variation, where a single non-Kelvin probe, mounted at the 3 o’clock (East) position on the station, positioned 1/320 inch (0.08 mm) above the bare chuck, measured capacitance to the chuck. At the chuck center, the HP 4284A LCR Meter was zeroed, and measurements were made as the chuck was repositioned under the probe. Note the maximum variation is less than 5 fF, providing superior on-wafer precision for many applications. If greater accuracy is required, the user should restrict the measurements to the center of the wafer, or include local calibration techniques into the measurement sequence. Figure 13 shows the connections for these measurements.

Figure 23 is an example measurement showing $I_b$ and $I_c$ current characteristics as measured with an HP4142B, using three guarded coax probes, and connecting the chuck to ground potential. The low-power SMU (41421B) was used along with 8 power line cycle averages and long integration time. Note the clean response down to the SMU noise floor (40 fA).

![Figure 23. Gummel plot of transistor with chuck at ground](image2)

![Figure 24. Capacitance variation measured across chuck surface, referenced to center of chuck without a wafer](image3)
**High-frequency measurements** are becoming increasingly common in the characterization process. These measurements are easy to make using the HP 8510 or any of the HP 8700 Series Vector Network Analyzers. After mounting the probes, connecting the cables to the VNA, and placing the calibration substrate on its stage, the user performs an auto-calibration with the Summit’s Autocal feature. Autocal controls the chuck and the VNA, moving to the standards on the calibration substrate as required. It then displays a calibration verification plot (Figure 25) showing the calibration quality. If the maximum deviation is less than 0.1 dB, the calibration is acceptable. Typically, the maximum deviation is 0.03 dB. Users can perform a stability check (Figure 26), and repeat this periodically to assure optimum performance. High-frequency measurements are discussed further on page 17.

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**Figure 18. Calibration verification plot.**

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**Figure 19. Calibration stability plot.**
Low-CURRENT
Measurement Fundamentals

Guarding
Guarding reduces leakage in cables, probes, wafer chucks, and other test fixtures. First, look at an unguarded circuit in Figure 27. The instrument is forcing voltage (V) and measuring the current with an ammeter (A). Meter A, however, will measure the current flowing into the DUT in addition to the cable leakage current V/R amps. If R = 1E11 ohms and V = 10 volts, then the leakage is 10/1E11 = 100 pA; too high for many applications. If the room’s ambient humidity increases, the leakage goes up. This is unacceptable for many characterization tasks.

Figure 27. Unguarded circuit example

unity gain buffer (1 mV error)

Figure 28. Guarded circuit example
With the guarded circuit (Figure 28), a low output impedance unity gain buffer drives the guard shield. Typically, the voltage difference between the center conductor and the guard is less than 1 mV.

The leakage becomes 1 mV/R = 1 mV/1E$^{11}$ or 10 fA, an improvement by 4 orders of magnitude. Also, note that the leakage is now independent of center conductor voltage. Rather it depends only on the leakage resistance and the guard voltage offset. Additional benefits from guarding include faster settling time and less sensitivity to cable noise. Note that the leakage current from the guard to shield is 10V/1E$^{11}$ or 100 pA. This is inconsequential because the buffer is designed to source this current.

**Ground Loops**

Measurement noise often arises from ground loops. When an instrument and a probe station are both connected to a common ground bus (such as main AC power ground), a ground loop can be formed (Figure 29). A small voltage ($V_0$) often exists between the two grounds and will cause currents to flow around the loop, resulting in noisy measurements.

![Figure 29. Ground loop caused by multiple grounding connections within system](image)

A typical situation occurs when the probe station and the instrument are plugged into different power circuits. When power line currents flow, a small voltage difference exists between individual ground points, giving rise to ground loop currents unless a single ground point is used. Even if there is no voltage difference between ground points, any magnetic field intersecting a loop induces a voltage difference and ground loop current will flow.

Grounding the instrument and the probe station at one point solves this problem, as shown in Figure 30. The Summit 10500 MicroChamber and platen are electrically-isolated for this reason, allowing the instrument to define the ground point and potential.

![Figure 30. Solving ground loops by connecting system ground at one point only](image)

**Shielding**

When considering electrical interference and shielding, it helps look at three different categories: electrostatic interference, magnetic interference, and high-frequency electromagnetic interference.

**Electrostatic Interference** Electrostatic interference is usually observed when hand or body movements near an experiment cause variations in the measurement. A highly-conductive enclosure improves this problem by completely encapsulating the experiment (in this case the wafer chuck and probes). The Summit 10500's MicroChamber and top hat accomplish this by surrounding the chuck with a metallic structure. Sliding metal plates beneath the chuck allow chuck movement while still providing shielding.

Users still encounter this effect, however, if measuring low-level currents from the chuck when an unconnected probe is positioned in the top hat over the chuck. The probe conducts the electrostatic signals generated by body movements to the chuck, where they are measured as current variations. This problem is solved by connecting the probe or by removing it from the top hat.
Magnetic Interference Changing magnetic fields or conductors moving through a magnetic field can generate error voltages and error currents (Figure 31). Error voltages, developed when a field passes through a circuit enclosing a specified area, are described by:

\[ E_B = \mathbb{A} \oint \frac{\partial B}{\partial t} \ dA \]

where \( B \) is the magnetic field intensity and \( \frac{\partial B}{\partial t} \) is the rate of change with time over the area enclosed by the circuit.

![Figure 31. Voltages generated by magnetic fields](image)

To solve this, first restrain all conductors and cables so they do not move. Then shield the experiment with a high-magnetic permeable material. The Summit 10500's MicroChamber is constructed primarily of 1/4 inch steel, providing a high degree of magnetic-field shielding.

High-Frequency Electromagnetic Interference Shielding that suppresses both electrostatic and magnetic fields often provides effective high-frequency electromagnetic shielding. Additional shielding is recommended, however. Even small openings in the shield should be closed with electrically conductive gasketing and other conductive materials. The Summit 10500 is constructed with these shielding features.

Noise Currents Noise currents are caused by several phenomena, including triboelectric effects and electrochemical effects. Triboelectric currents are generated by charges created at the interface between a conductor and an insulator due to friction. In Figure 32, for example, as a cable is bent, free electrons rub off the dielectric and create a charge imbalance, thereby causing a current flow and noisy measurements. Users can easily observe this effect by bending a cable while measuring sub-pA currents. Noise is reduced when cables are restrained, preventing them from moving. Low-noise cables are available for the more critical measurements.

![Figure 32. Triboelectric effects can generate noise in cables.](image)

Noise currents also occur from electrochemical effects (Figure 33) when ionic chemicals and water create small currents between conductors. Probe cards or similar fixtures that contaminated by a person handling with bare hands are common examples. Sodium ions (from NaCl) are transferred, and with moisture from the ambient air, the NaCl ionizes into Na⁺ and Cl⁻. To remove the contaminants carefully clean all fixtures used in low current (nA) applications with high-purity Freon or methanol.

![Figure 33. Electrochemical effects can generate noise on test fixtures.](image)
Kelvin Probes

The Kelvin configuration compensates for voltage drops caused by probe contact resistance and cable resistance. Figure 34 shows a non-Kelvin probe connection, where it is desired to accurately measure resistor $R$ connected to probe pads $P$. The SMU forces a current $I$ through the resistor and measures voltage $V$. Note that voltage $V$ also includes the voltage drop of the probe contact resistance and the voltage drop across the probe center conductor from the sense line up to probe tip. When one calculates the value of the resistor equals $VI$, significant errors can result (depending on the currents and voltages involved) because the additional voltage drops are not associated with the resistor.

Figure 34. Non-Kelvin example.

$R_m = R_1 + R_2 + R_x$

Figure 35 shows the equivalent Kelvin connections. In this case, the force and sense lines are brought up to the pads, eliminating these errors. Note that these probes are also guarded up to the probe tips as well, so they can be used to make very low-level measurements with no loss of accuracy.

Figure 35. Kelvin example.
High-Frequency Measurement Fundamentals

Measuring Small Bipolar Device S-parameters

As device frequencies exceed 10 GHz, most characterization teams directly measure high-frequency performance using a VNA and Cascade Microtech coplanar probes [1]. After calibrating the probes, cables, and VNA up to the probe tips, the measurement is straightforward. Application routines available in the Summit 10500 optional VNA Calibration Software calculate and display H21 for immediate display of f1-values. There are two fundamental problems with small bipolar device measurements. The first involves compensating for pad and interconnect parasitics, particularly when measuring minimum-size devices. The other problem is selecting the input signal going into the base to avoid overdriving the device.

Pad parasitic removal Figure 36 shows a typical layout so that ground-signal-ground probes can contact the DUT. As devices get smaller, the capacitive parasitics associated with the pads and interconnects are larger than the capacitive parasitics of the device. In most cases, only the device characteristics are desired, not the pad/interconnect characteristics. The Summit's VNA Calibration Software includes a Pad Parasitic Removal (PPR) routine that removes the pad/interconnect parasitics from the DUT measurement. First, the user measures a "dummy" device (Figure 36) that has the same pad and interconnect layout without the device present. The user then measures an actual device layout, and the routine subtracts the pad/interconnect parasitics, leaving the response of just the DUT, as shown in Figure 37. This is described in more detail in [1,3].

As devices become smaller (1×1 μm emitters and less) the pad parasitics are much larger than those of the DUT. For example, a 4×4-mil pad capacitance is typically 400 fF, and a 2×2-mil pad is typically 100 fF. The capacitance associated with very small devices is now on the order of 20 fF, giving rise to significant errors after pad parasitic removal. Careful thought at the layout stage assures accurate results. Please remember to conform to the layout rules [4] and to call a Cascade Microtech applications engineer with your questions.

Selecting proper signal levels The most common error made while measuring small bipolar devices is to overdrive the DUT into the nonlinear region. At DC, most devices exhibit current gains in excess of 100, which roll off to less than unity as the test frequency is increased. The trick is to select a signal level that does not saturate the DUT at low frequencies, while still providing enough signal at high frequencies for the VNA to operate properly. The user can raise the lowest frequency to around 1 GHz, where the gain is already rolling off. Users can also use a power slope, providing more power at higher frequencies and less at lower frequencies.

![Figure 36](image)

Figure 36. Typical layout for high frequency probing small devices. The "dummy" is used for removing the pad parasitics from the measurement.

![Figure 37](image)

Figure 37. Typical H21 plot of 2×3 μm bipolar transistor, showing the effect of removing the pad parasitics.
References


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Suggested Equipment and Accessories

This section outlines the suggested equipment and accessories for low-current, low-capacitance, and high-frequency characterization measurements.

**Summit 10500 Parametric Probe Station**

The Summit 10500 Semi-Automatic Parametric Probe Station includes the following standard hardware and accessories:

- Summit 10000 Series base station, including
  - Base plate
  - Linear z-axis platen lift
  - Platen
  - Controller unit
  - Driver unit
  - 14" color monitor
  - Keyboard
  - Joystick
  - Installation tools and instructions
- MicroChamber enclosure
- Wafer chuck
  - Specify nickel or gold plating
- Vacuum manifold (6 outlets)
- Electrical manifolds, left and right (banana jack connections)
- Triaxial interface panel (8 triax hookups and ground safety link)
- Optics bridge mount
- Operating manual
- Measurement cable kit, including
  - 4 triaxial cables for interface panel-to-positioner connection, 0.5 m (20 in.)
  - 4 triax-to-BNC inline adapters for 4-terminal CV setup
  - 1 BNC coax cable (safety interlock) 1.5 m (60 in.)
- Ground Unit Adapter Kit, including
  - 2 triax-to-triax cables for ground unit adapter, 25.4 cm (10 in.)
  - 1 triax adapter box (SMU ground unit adapter)
Optional Accessories
These accessories are available from Cascade Microtech:

**DCM-200 Series Micropositioners**
- **DCM-208-ML** Magnetic base, left
- **DCM-208-MR** Magnetic base, right
- **DCM-208-VL** Vacuum base, left
- **DCM-208-VR** Vacuum base, right

**RF positioners**
- **103-752** West positioner (two-port configuration)
- **103-753** East/West positioner
- **103-754** North/South positioner

**Bulkhead adapters**
- **104-346** Dual triax bulkhead adapter for DCM-200
- **104-249K** Dual triax bulkhead adapter for DCM-200 (Kelvin)
- **104-030** Dual triax bulkhead adapter for RF positioner
- **104-030K** Dual triax bulkhead adapter for RF positioner (Kelvin)

**DCP-100 Series Coaxial Probes**
- **DCP-100** Single line coaxial probe
- **DCP-100K-25** Kelvin coaxial probe, 25 µm pitch
- **DCP-100K-50** Kelvin coaxial probe, 50 µm pitch
- **DCP-100K-xxx** Kelvin coaxial probe, custom pitch

**Miscellaneous**
- Various DC and RF cables, adapters, and connectors

**Suggested equipment for high-frequency measurements:**
All are available from Cascade Microtech
- VNA Calibration Software (including Autocal and Pad Parasitic Removal features)
- WPH-Series High-Frequency Microprobes (multiple frequency ranges available)
- Impedance Standard Substrates (providing metrology-grade calibrations with Cascade Microtech microprobes)
- Flexible, high-frequency RF cables
- Contact substrates (to check probe contact and setup planarity)

Call your local sales office or the factory directly at (503) 626-8245 for questions regarding parametric probing issues or for information on the equipment listed above. Our system application engineers can help you configure your system for the best results.
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Alliance Technologies—Metrics™ Software for data collection, analysis, and display