Accurate characterization of modern semiconductor processes requires both current versus voltage (IV) and capacitance versus voltage (CV) measurement. While the need for IV measurement is obvious, the need for CV measurement is less so. To understand why CV measurement is important to the integrated circuit industry, it is worthwhile to review the structure of a MOSFET (metal-oxide-semiconductor field effect transistor). Of course, most modern MOSFET devices do not use metal for the gate material, and some do not use oxide as the gate insulating material; however, the same physical principles apply regardless of the exact materials used. Figure 1 shows a simplified cross-section of an idealized n-channel MOSFET.

When no voltage is applied to the gate, the drain and source regions are isolated from each other and no electrical current can flow. When a sufficiently positive voltage is applied to the gate, channel inversion occurs and the drain and source regions are then connected together (enabling the transfer of electric current). This electrical behavior is the basis for all of the integrated circuit industry.
The gate is separated from the channel region via a thin insulating layer. The first transistors of this type used metal for the gate and oxide for the insulating material, which gave rise to the term metal oxide semiconductor (MOS). Note that the structure of the MOS “sandwich” is very similar to that of a classic parallel plate capacitor. In fact, it turns out that the MOS structure behaves exactly like a capacitor, except that the value of the capacitance depends upon the applied voltage. Depending upon several factors that will not be discussed here, the capacitance versus applied gate voltage plot of a MOSFET will either exhibit high-frequency CV (HFCV) behavior or quasi-static CV (QSCV) behavior. The appearance of these two plots is shown in Figure 2.

From device physics considerations, many of the important physical characteristics of the MOSFET can only be extracted after first plotting the capacitance versus voltage curve of the MOS structure. Typical parameters extracted from this data include gate oxide thickness (tox), substrate impurity concentration (Nsub), flatband capacitance (Cfb), flat band voltage (Vfb), surface charge density (Qss), and threshold voltage (Vth). All of these parameters affect the behavior of the MOSFET device, so understanding their values is important to determining if a semiconductor process is meeting its design targets.

With a basic understanding of the significance of CV measurement to parametric test, it is now important to understand the measurement challenges that CV measurement presents. The first point to comprehend is that capacitance measurement requires an AC signal as opposed to the DC signals used for the IV portion of parametric test. This arises from the fact that capacitance only has significance for AC measurements, as illustrated by the fundamental relationship between capacitance, current, and voltage shown in Figure 3.

The dependence of capacitance measurement on an AC signal (typically a sine wave) introduces several new factors of measurement complexity. The most important single issue is that the length of the cable coming from the capacitance measurement unit (CMU) to the device under test (DUT) has a significant impact on the capacitance measurement. Any measurement cable possesses some innate capacitance per unit length, and this capacitance will distort the total capacitance measured by the CMU unless this distortion is somehow “compensated”. The process of compensation is simply a mathematical operation performed on the measured capacitance values to remove the effects of the cable capacitance.

In addition to compensating for the cable length, there is one other factor that is often ignored by many otherwise experienced engineers. This is the issue of capacitance current return path. Essentially, the CMU will inject current into the capacitor under test, and this current returns to the CMU via the outer ground shield conductor of the CMU BNC cable. However, unless the high and low cables coming from the CMU have their outer ground shields connected together close to the DUT, the return current path is not stable and large fluctuations in the effective cable inductance can occur. These fluctuations affect the capacitance compensation, which in turn affects the accuracy of the capacitance measurement. Therefore, it is also important to have the outer ground shields of the measurement cables connected together close to the DUT, and, unless this is done, the inductance instability will become worse and worse as you measure at higher frequencies.
The source/monitor unit (SMU) utilized for the IV portion of parametric test uses triaxial cables. As the name implies, these cables have three layers: a center force/sense line, a middle guard, and an outer ground shield. The reason that SMUs use triaxial cables rather than BNC cables is as follows. Ultra-low current measurements (down to the femtoamp range) are not possible using BNC cables for the simple reason that no insulator is perfect. Leakage currents between the inner conductor and the outer ground shield of a BNC cable limit these types of cables to measurements of 1 nanoamp or greater. However, the triaxial cable isolates the inner conductor from the outer ground shield via a middle guard shield. The SMU has an active circuit that always keeps the voltage potential of the driven guard the same as that of the inner conductor. Since there is no voltage difference between the driven guard and the inner conductor, by Ohm’s Law there can be no leakage current (the voltage difference = 0 V). Therefore, using triaxial cables current measurements down to even the sub-femtoamp (attoamps) range are possible.

One issue with integrating IV and CV measurements is that these two types of measurement resources (SMU and CMU, respectively) do not use the same types of cables, and hence have incompatible connectors. SMUs use triaxial cables, and CMUs use BNC cables. Since (as already explained) parametric measurements require both types of measurements, this has been an unpleasant problem for engineers involved in parametric test. One solution is to use an external switching matrix, which takes care of converting between the two connector types. However, especially for positioner-based wafer probing setups, a switching matrix adds a lot of expense and complexity. It also introduces additional issues with capacitance compensation (since the user then has to compensate for the additional path length through the matrix).

The Agilent B1500A supports a single-slot, multi-frequency capacitance measurement unit (MFCMU). Besides integrating CV measurement into the device analyzer mainframe, the MFCMU possesses many measurement capabilities not available on comparable external capacitance meters. The MFCMU can measure capacitance at up to 5 MHz, and it also can provide ±25 V of dc bias. In addition, the combination of the MFCMU and SMUs within the same instrument enables these measurement resources to be more tightly coupled. When joined using the B1500A SMU CMU Unify Unit (SCUU), the MFCMU and SMU combination supports capacitance measurement with ±100 V of dc bias.

The B1500A SCUU accepts a cabling fixture that connects to two of the SMUs and to the MFCMU. The cable assembly connects to the SCUU, which is typically located close to the DUT. The outputs of the SCUU consist of two pairs of Kelvin (Force and Sense) triaxial connections, which connect directly to the wafer prober positioners. A Guard Switch Box (GSWB) unit connects to the SCUU via another cable, and the GSWB then connects to the outer ground shields of the wafer prober positioners. Once these simple connections are made, the B1500A software takes care of all of the IV-CV switching, compensation, and capacitance measurement current return path issues. You only have to select an IV or CV algorithm and push a button in order to begin making accurate measurements.