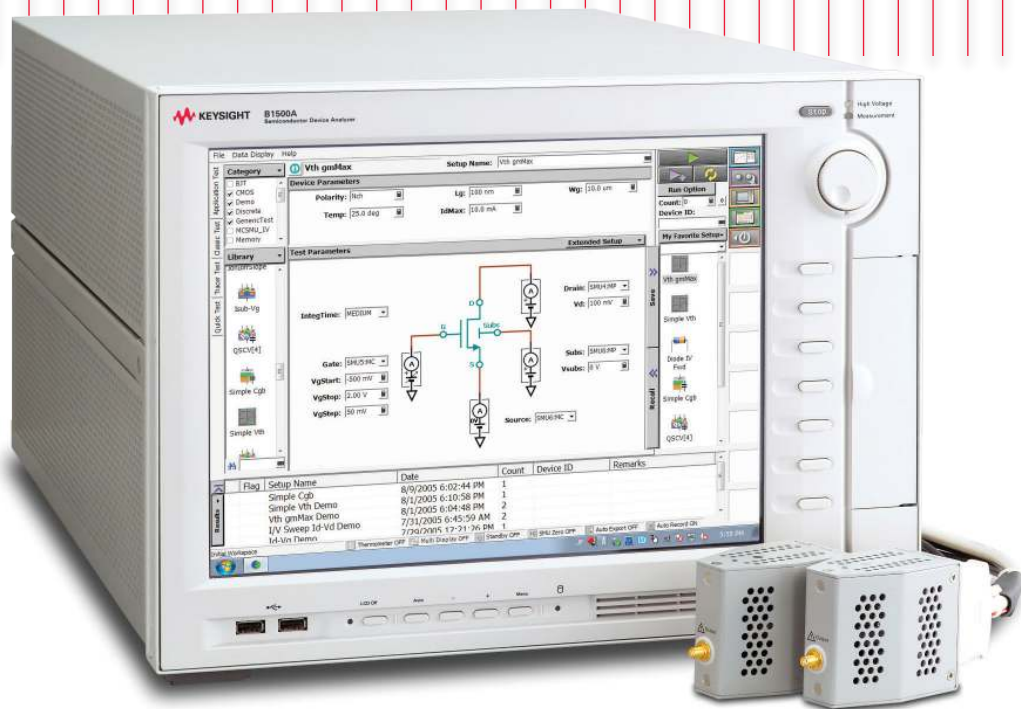


Keysight Technologies

Capacitance Measurement Basics for Device/ Material Characterization

Using Keysight B1500A Semiconductor Device Analyzer

Application Note





Introduction

The capacitance-voltage (CV) measurement has been one of the most important measurements for investigating the characteristics of the materials and the behavior of the devices. Now the importance of the CV measurement is getting higher in the research and development of the next generation materials and devices such as wide band gap devices (GaN/SiC), nano devices, organic devices, MEMS, and so on. The analysis based on the CV measurement is effective for investigating the basic characteristics of the materials and improving the quality of the device.

When performing the CV measurement, it is very common to perform the current-voltage (IV) measurement at the same time. This application note introduces the key points in the CV measurements including the issues, know-hows and tips, especially combined with the IV measurements, which are obtained through the long experience of Keysight in the semiconductor measurements.

The following topics are covered in this application note.

1. CV measurement basic.
2. How to make the cable connections.
3. How to compensate the error.
4. Tips for on-wafer measurement.
5. Keysight solutions for the CV and IV measurement.

The quasi-static CV (QS-CV) measurement is one of important CV measurement techniques for the research and development area, too. It is discussed in the other application note. Refer to it, if you are interested in the QS-CV application.

CV Measurement Basics

This section introduces the basics of the CV measurements for measurement methodology and the cable connections.

Basics of the CV measurement methodology

There are many ways for performing the CV measurement, but the most popular method in below 10 MHz frequency range is the auto balancing bridge type CV meter as shown in Figure 1.

It measures the impedance of the device under test (DUT) Z_x as $Z_x = V_x / I_x$, where V_x is the AC signal voltage applied to the DUT, and I_x is the AC current flowing through the DUT. The CV meter consists of (1) the AC signal source V_x with the DC bias source in the high terminal, (2) the current I_x flowing through the DUT, and (3) the low terminal vector current meter as shown in Figure 1.

The high current (Hc) terminal applies the AC measurement signal and the DC bias voltage to the DUT, and the high potential (Hp) terminal senses the actual AC signal applied to the DUT. The low current (Lc) terminal sinks the DUT current through the reference resistor R_r and keeps the Lc potential as close as possible to zero volts (called as virtual ground) with the negative feedback loop consisting of the high gain amplifier (V_r) in the low potential (Lc) terminal and the feedback resistor R_r .

The current flowing through the DUT (I_x) is obtained as V_r/R_r , and the DUT impedance Z_x is obtained as $Z_x = V_x / I_x = R_r (V_x / V_r)$. This is the basic methodology of the auto balancing bridge type CV meter.

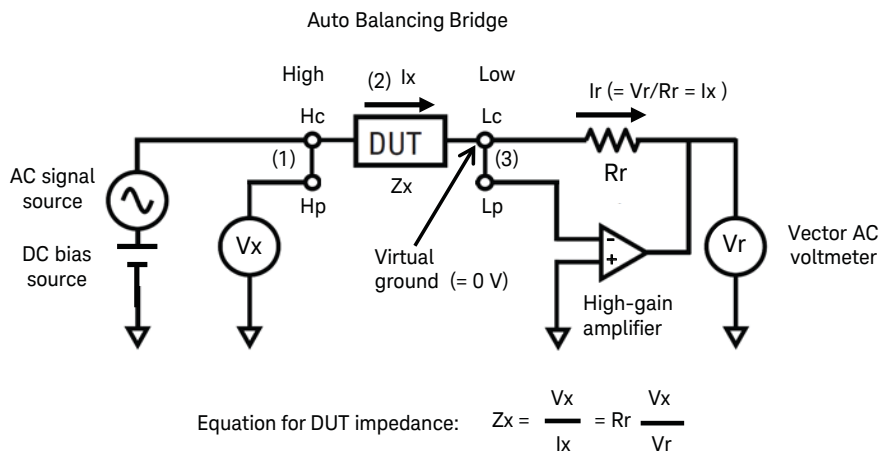


Figure 1. Simplified auto balancing bridge type CV meter block diagram.

Cable Connection to DUT

To perform the accurate CV measurement, you will need to connect the 4 terminals (Hc, Hp, Lc, Lp) correctly to the DUT, and there are several ways of connections. The following describes the most frequently used two types of cabling methods: one is the four terminal pair configuration and the other is the shielded two terminal configuration.

Four terminal pair (4TP) cable configuration

The configuration shown in Figure 2 named as four terminal pair (4TP), which extends the four terminals shown in Figure 1 with the four coaxial cables, provides the best accuracy. Since the two sensing lines, Hp and Lp, are extended to the DUT terminal, the measurement accuracy is maintained, even if there exists an additional stray impedance in the DUT connection, if the standard 4TP cables and fixture are used and a proper error compensation is applied.

Although the 4TP is the best configuration for standalone CV setups, there are the following major issues in conjunction with the IV measurement.

In many cases, there is only one connecting pad for each measurement terminal of the DUT and the connections using the independent Hc/Hp and Lc/Lp lines are not possible. Even if four connection pads are available for Hc/Hp and Lc/Lp connections, it is not easy to set up the 4TP configuration for CV measurement and cabling for IV measurement both together.

Because of these difficulties of the 4TP configuration in the CV and IV test setups, the shielded two terminal configuration shown in the next section is commonly used.

Shielded two terminal (S-2T) configuration:

Shielded two terminal (S-2T) configuration is a popular configuration when both the CV and IV measurements are performed. In this configuration, the 4TP configuration is extended to the closer point of the DUT, and then switched to the S-2T configuration, as shown in Figure 3.

In this configuration, the 4 terminals are reduced to 2 terminals finally similar to the cabling for IV measurement. Therefore, it is easier to integrate with IV measurement setup and flexible for the actual test station that has some limitations such as the number of the pads, probing manipulators layout, and so on. On the other hands, there are some error factors beyond the 4 terminal pair, but those errors of the S-2T section can be compensated in a practical level of accuracy by using the error compensation function and choosing a proper measurement condition as shown in the next section. So the S-2T configuration is considered as the more practical solution.

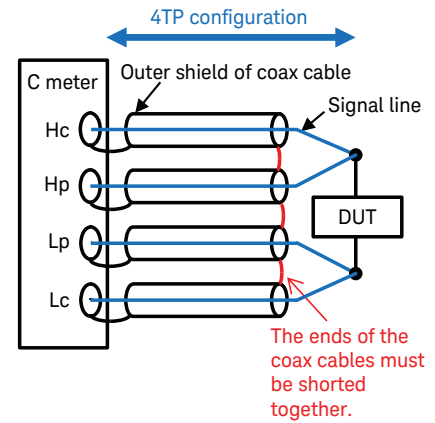


Figure 2. Four terminal pair (4TP) configuration.

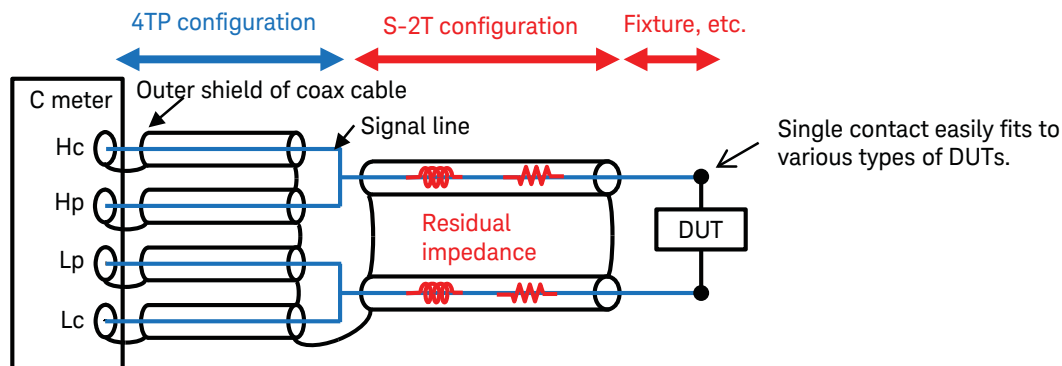


Figure 3. Cable extension using the shielded two terminal (S-2T) configuration.

Key Points/Challenges for Accurate CV Measurement with IV Measurement

This section provides the useful information such as the connection and the error compensation to perform the accurate CV measurement in conjunction with the IV measurement using the S-2T configuration. In addition, the tips for the on-wafer measurement are also discussed.

Challenges to make the S-2T configuration

The S-2T configuration is the practical and accurate configuration when extending cables using the two coaxial cables to the DUT. However, there are some important notes to keep the accuracy. This section explains the key points and challenges to be observed when making the S-2T configuration.

Connect the shield to make the current return path:

The most important point to configure the S-2T is to connect the shield of the extended coaxial cables together to make the current return path as shown in Figure 4(a). This simple connection creates the current return path, which allows the return current flowing in the same magnitude of the measurement signal in the center conductor, but opposite direction and the phase in the outer conductor of the coaxial cable. This return current cancels the magnetic flux generated by the measurement signal flowing in the center conductor, and it shields the magnetic flux inside the coaxial cable in higher frequency test signal.

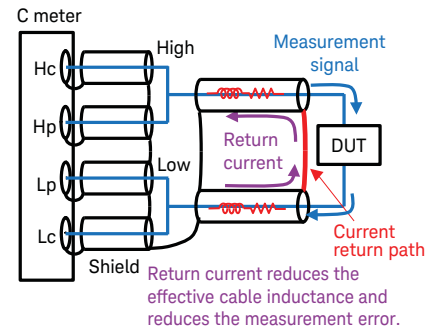
It is easily or mistakenly forgotten to make the return path connection. If the shield is not connected together as shown in Figure 4(b), there is no return current flow and the magnetic flux is formed outside of the cables. The residual cable inductance depends on the area surrounded by the cables, and this increases the residual cable inductance and this inductance also changes when the surrounded area is changed by moving the cables. Both of the increase and the variation of the residual inductance add errors in the measurement accuracy.

The return path generates following two benefits to the measurement stability and the accuracy.

1. Total accuracy is improved. The effective residual inductance of the coaxial cables is reduced to about 1/3 to 1/5 compared to the case where the return path is not connected. This decreases the error added by the extended coaxial cables, and improves the total accuracy.
2. Measurement data is stable. Since the magnetic flux is shielded inside of the coaxial cables, the residual inductance is stable, even if the coaxial cables are moved. Because of this effect, even if the measurement cables are moved, the measurement data keeps the original accuracy at the timing when the error compensation is made.

Connecting the shield of the extended coaxial cables together and forming the current return path is very important, but how to connect the shield in the real test environment is a challenge.

(a) Complete S-2T configuration with return path.



(b) Easily mistaken configuration with no return path.

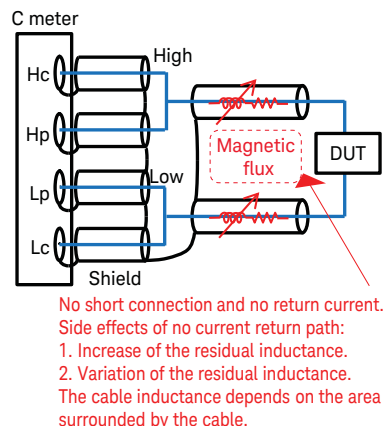


Figure 4. The key of configuring the shielded two terminal (S-2T) configuration.

Reducing the Residual Errors of the Cable Extension

Additional errors of the cable extension:

When the measurement cables are extended using the S-2T configuration, the additional error sources by residual impedance, stray admittance and other factors relating the cable length and the measurement frequency are added as shown in Figure 5. With these additional error sources between the DUT and the C meter, the measured impedance Z_m becomes different from the actual DUT impedance Z_{dut} ($Z_m = Z_{dut} + \text{additional errors} \neq Z_{dut}$). These additional errors by adding the extended cables can be reduced by performing the error compensations. The following section describes how to perform the error compensation and the effect of the compensation.

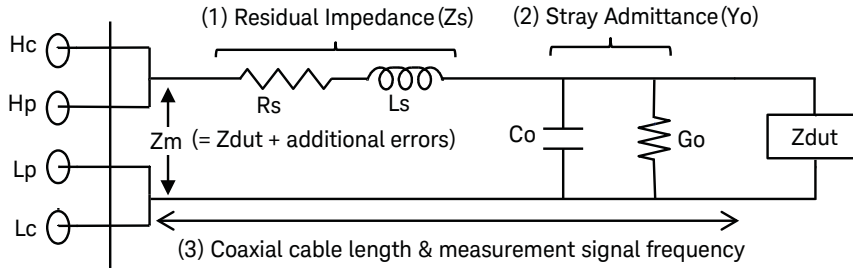


Figure 5. Additional error sources when extending the measurement cable.

Open/Short compensation:

The error caused by the residual series impedance and the stray admittance (or capacitance) can be reduced by performing the open /short compensation.

Open compensation is effective for canceling the stray admittance (Y_o) in Figure 5. As shown in Figure 6(a), the open compensation performs a measurement in the open condition of the DUT terminal. In the open compensation, the series impedance (Z_s) is regarded as zero, and stray admittance (Y_o) is only measured, then it is used to compensate Y_o error factor from Z_m .

Short compensation is effective for canceling the residual series impedance (Z_s) in Fig 5. As shown in Fig6(b), the short compensation performs a measurement by shorting the DUT terminal. Since the stray admittance components are shorted, only the residual series impedance (Z_s) is measured, then it is used to compensate Z_s error factor from Z_m . Short compensation is particularly important for measuring a small impedance (high capacitance) DUT.

After the open/short compensation, the actual impedance of the DUT (Z_{dut}) is calculated from the Z_m and the compensation factors (Z_s and Y_o) as shown in Figure 6(c) and 6(d). The error compensation works very well in the case where the measurement frequency is up to about 1 MHz and the DUT impedance Z_{dut} is much larger than the series impedance Z_s .

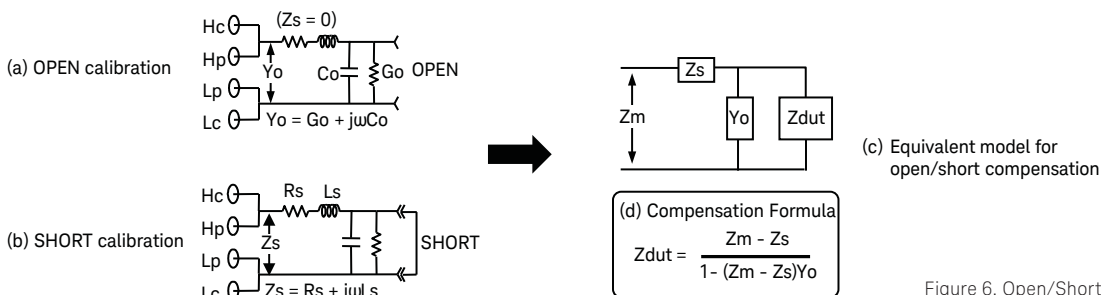


Figure 6. Open/Short compensation.

Load compensation:

When the measurement frequency is much higher than 1 MHz, adding load compensation is effective. Figure 7 shows the relation of the residual impedance Z_s and the DUT impedance (capacitor: $Z_{dut} = 1 / j\omega C$), where R_s and Y_o is set as zero for investigating only the effect of the measurement frequency related terms. The impedance Z_s of the series inductance L_s increases and the impedance of the capacitance (Z_{dut}) decreases as proportional to the increase of the measurement frequency (ω). The ratio of Z_s/Z_{dut} ($= -\omega^2 * L_s * C$) becomes higher with the square of the measurement frequency assuming the DUT is a capacitor.

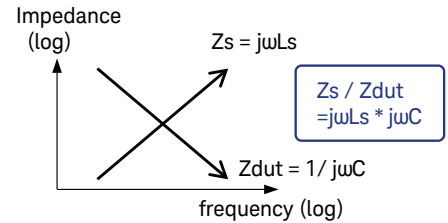
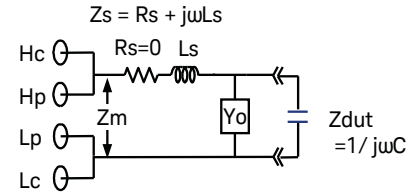


Figure 7. Relation of the residual and DUT impedance

Because of this, if the measurement frequency is increased, the measurement error shows up more rapidly by the square of the frequency once the error becomes noticeable. If the accuracy achieved by the open/short compensation is not enough in a higher frequency range, load compensation is an alternative choice.

The load compensation is performed using the "known impedance standard" (i.e. which value is calibrated, and known) in addition to the open/short compensation. The example of the open/short compensation and the load compensation from 1 kHz to 5 MHz for 2.2 pF, 10 pF and 100 pF capacitors for shielded 2 terminal configurations is shown in Figure 9. The measurement is well compensated up to 1 MHz by performing the open & short compensation. For above 1 MHz, consider to use the load compensation, because the additional error associated by the extended coaxial cable can also be compensated.

In many cases, however, it is very difficult to prepare the suitable known standard in the actual device characterization environment. It is the reason why the measurement frequency is typically used up to 1 MHz, where the measurement error is relatively small even without the load compensation.

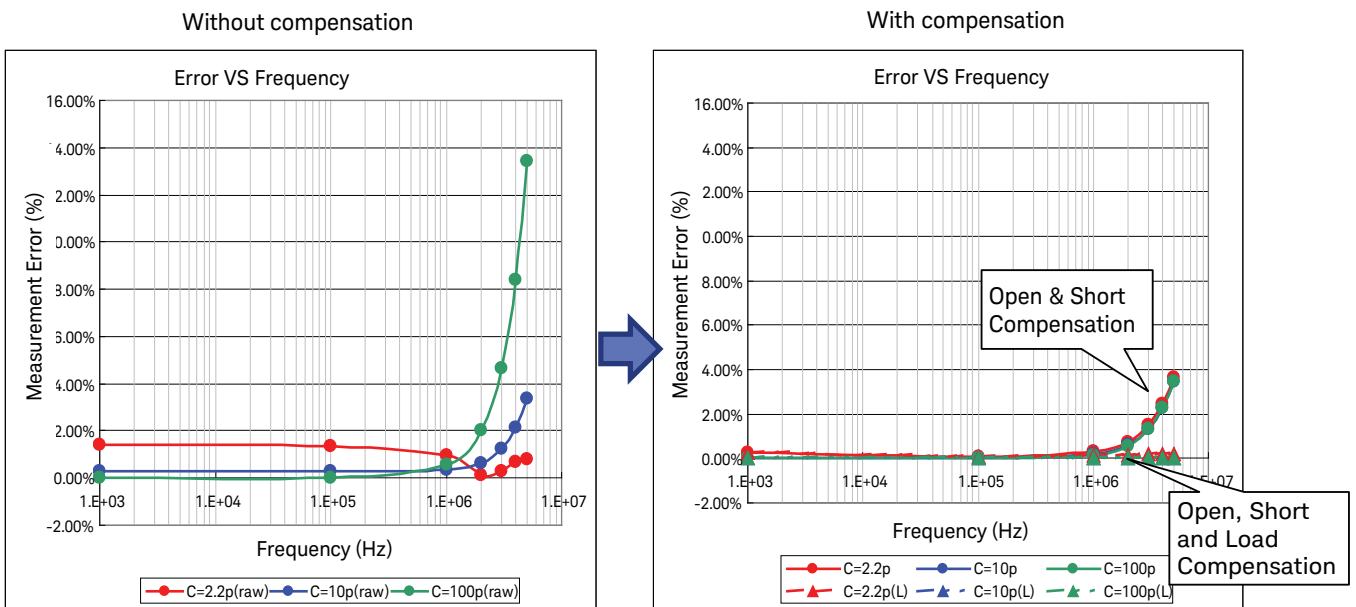


Figure 8. Example of the Open/Short and Load compensation.

Tips for On-wafer Measurement

A wafer prober is often used to characterize the on-wafer devices. When performing the on-wafer CV measurement, the large capacitance of the wafer chuck can introduce the noise and leakage, and they affect the measurement results. However, many of the errors can be reduced by the following actions as shown in Figure 9.

For the on wafer measurement, try the followings to reduce the errors caused by the wafer chuck:

1. Connect the low terminal (CML) to the gate.
2. Use a larger signal level.
3. Use longer integration time (measurement time).
4. Use lower measurement frequency.
4. Shorten the extended cable length of the S-2T configuration.

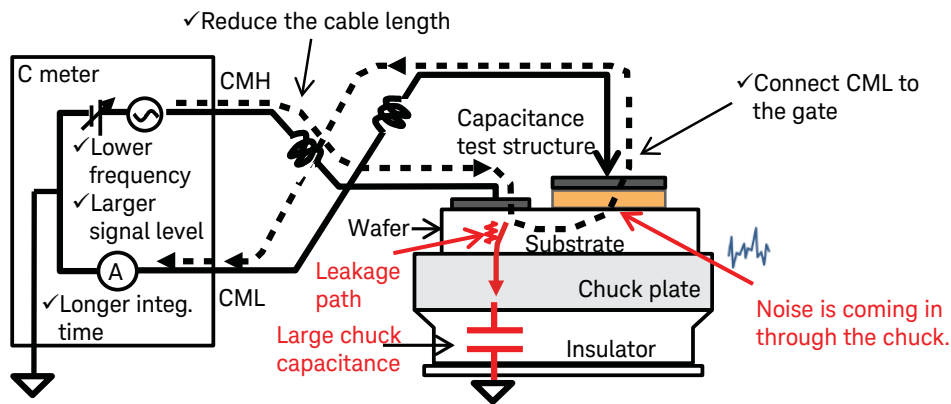


Figure 9. Example of on-wafer CV measurement setup.

The first problem is the noise from the chuck, and it produces problems such as fluctuation in the measurement data, adding offset in the measurement data, and sometimes the unbalancing of auto-balancing bridge making the measurement impossible. The brief reasons why the above actions are effective are described as follows.

- Connecting the low terminal (CML) to the gate prevents the current meter of C meter from being affected by the noise through the chuck. The high terminal (CMH) is low impedance, so connecting it to the chuck is relatively tolerant to the noise.
- Using a larger test signal level and longer integration time improves the noise to signal ratio, and provides more stable measurement results.
- Both connecting the low terminal to the gate and using a larger test signal also improves the auto-balancing bridge stability in the noisy test environment, and contributes to stable measurements.

The second problem is the leakage of measurement signal going out through the large stray capacitor of the wafer chuck, and it increases the measurement error. In simple terms, the measurement signal leakage depends on the ratio of the effective residual impedance of the measurement cables and the impedance of the leakage path which is caused by the similar reason as explained in Figure 8.

- Using a lower measurement frequency, the ratio of the residual impedance of the measurement cables and the leakage path becomes larger, and the measurement signal going out through the leakage path is reduced. Because of this, lowering the measurement frequency improves the measurement accuracy.
- Shortening the length of the extension cable helps also improving the error. The residual impedance of the extended cable is reduced as proportional as the extension cable length, and the error is reduced by the same reason shown above.
- Lowering the measurement frequency improves the error by the square of the frequency reduction, but the improvement by reducing the cable length is roughly linear to the cable length reduction.

Keysight B1500A's Complete CV and IV Solution

So far, the basic of the CV measurement methodology and tips for accurate CV measurement have been discussed in this application note. They are summarized as follows.

- The impedance is measured by the $Z=V/I$ calculation that is applied and measured by the 4 terminals (Hc, Hp, Lc, Lp).
- When extending the cables from C meter to the DUT, how to connect the 4 terminals is a key point to keep the accuracy of the measurement.
- 4TP is the connection for the best accuracy, but S-2T is the more practical and popular connection applicable to many device/material characterization environments.
- The additional errors in S-2T can be reduced by correctly making the return path and performing open/short compensation.
- For on-wafer measurement, special attention to the connection and setting is required.

However, even if the users have the deep knowledge shown above, the following issues prevent many users to perform accurate CV measurement in the actual integrated environment with the IV measurement.

- Return path is not correctly made due to the difficulty of switching the shield connection between CV and IV measurements.
- Error factors by the extended cables to the DUT are not correctly compensated.

To solve these issues, Keysight introduces the B1500A Semiconductor/Device Analyzer as the complete CV and IV measurement solution. It provides the following capabilities for accurate CV and IV measurement.

- Both the CV and IV measurement capabilities are supported by Source/Measure Unit (SMU) and Capacitance Measure Unit (CMU) in a single instrument.
- CMU supports CV measurement from 1 kHz to 5 MHz.
- Automated switching capability of the connections for CV and IV measurement through the SMU CMU Unify Unit (SCUU).
- Automated return path connection by the Guard Switch Unit (GSWU).
- Open/Short/Load compensation supporting S-2T configuration.

The B1500A enables you to set up the CV and IV measurement applications easily through the graphical user interface (GUI) based application test library as shown in Figure 10. You can perform the CV measurement by just filling in the measurement parameters, and then get the measurement result quickly in either graph or list data format.

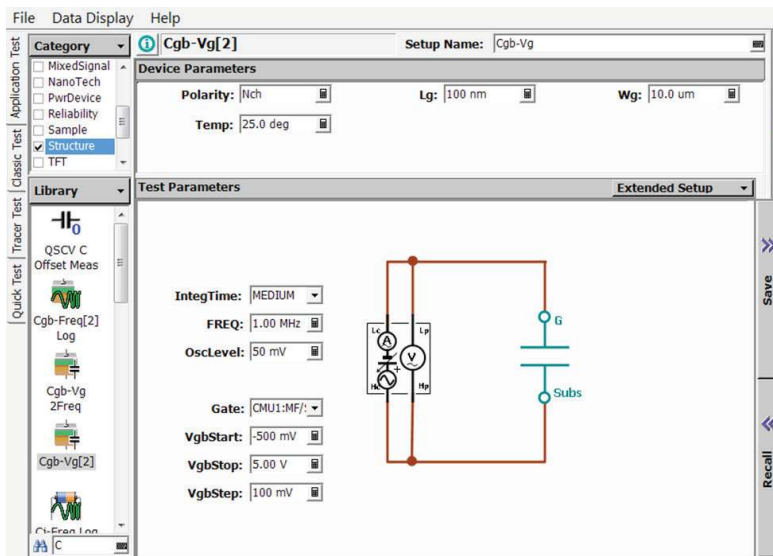


Figure 10. Example setup panel of the B1500A CV application.

To perform accurate CV measurements, the open/short/load compensation is also supported through the GUI as shown in Figure 11.

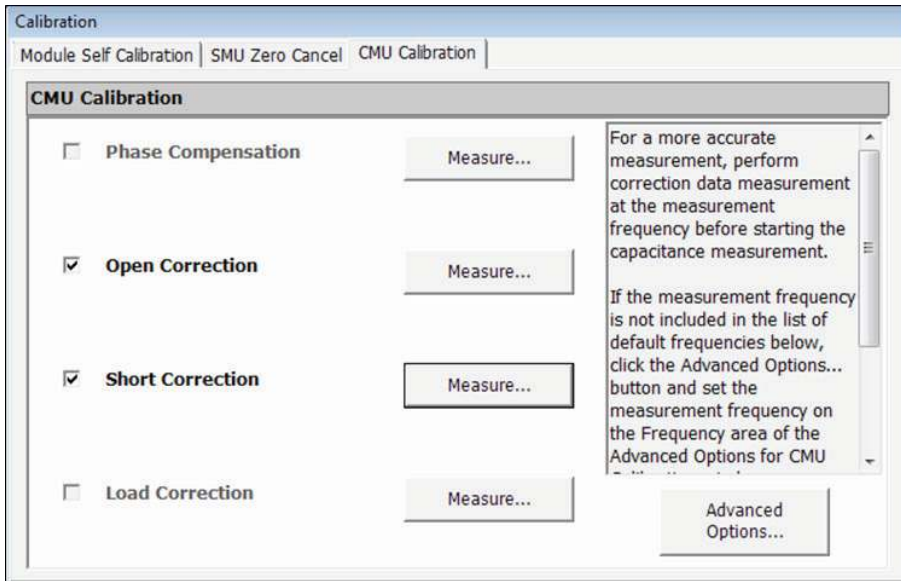
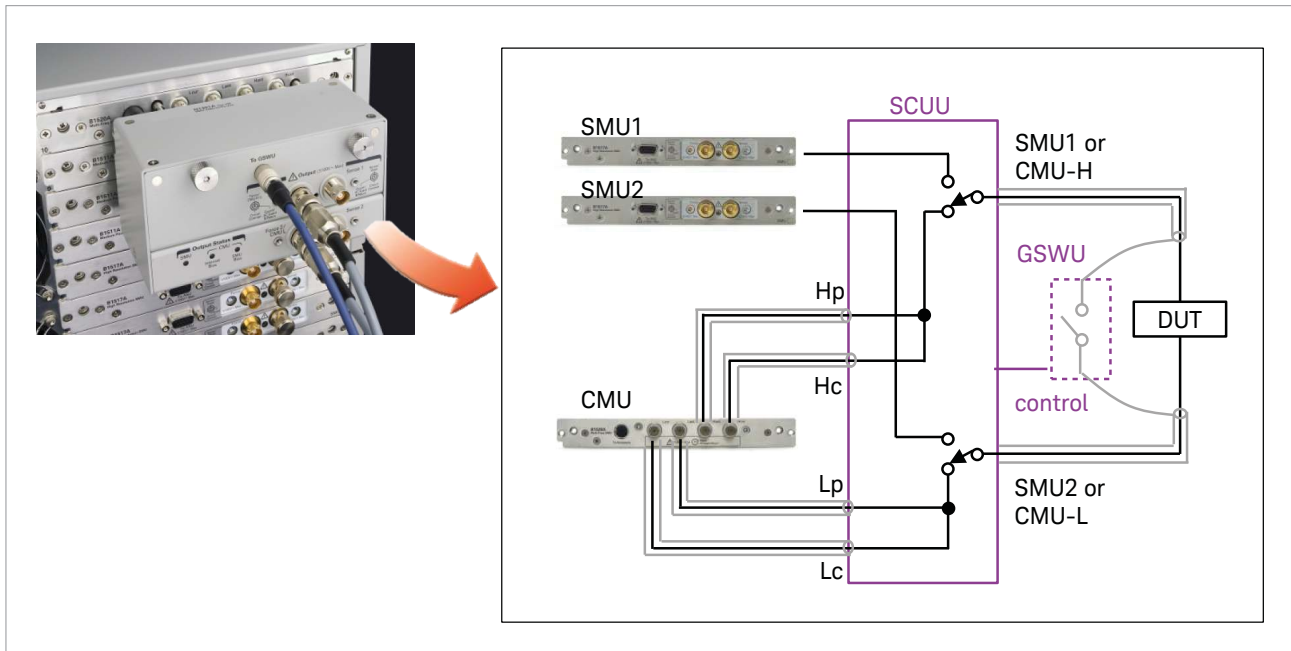


Figure 11. You can perform and select Open/Short/Load compensation.

The unique combination of SCUU and GSWU optimizes the connections between CV and IV measurement to minimize the errors without changing the cables by the user. The detailed circuit diagram of SCUU and GWSU is shown in Figure 12. The unique combination of SCUU and GSWU optimizes the connections between CV and IV measurement to minimize the errors.



Along with more powerful measurement capabilities, including the capacitance versus time (C-t) and the capacitance versus frequency (C-f) measurements, Keysight B1500A resolves your CV measurement challenges and enables you to perform accurate CV and IV characterization on your devices and materials.



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