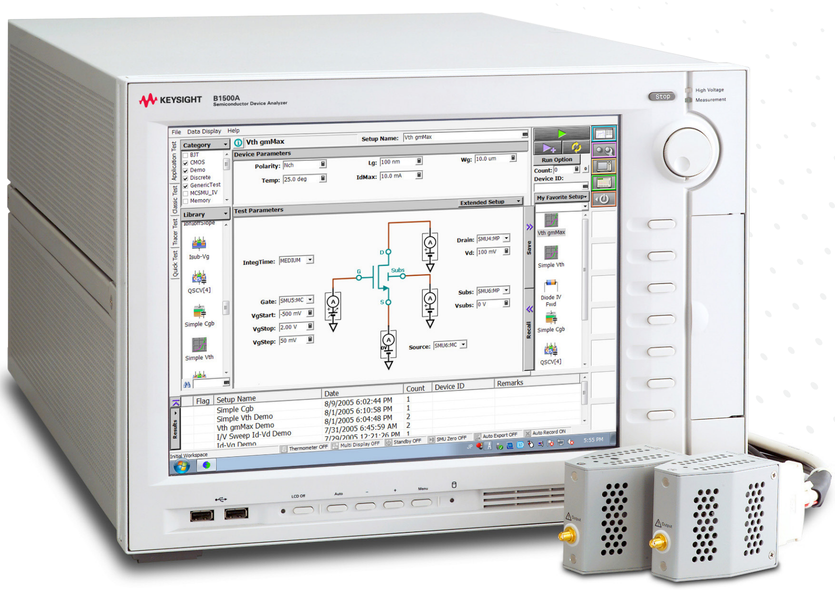
APPLICATION NOTE

How to Perform QSCV (Quasi-Static Capacitance Voltage) Measurement

Using Keysight B1500A Semiconductor Device Analyzer



KEYSIGHT TECHNOLOGIES

Introduction

Recently, the post silicon new devices and materials, such as wide band gap devices (SiC, GaN), nano devices, organic devices and so on, are intensively researched. It is highly demanded to satisfy the requests of high performance, energy saving and cost saving for the next generation products. To introduce it into the market timely with matured quality, it is very important to understand its characteristics and improve the device production processes.

Particularly for MIS/MOS structure devices, the interface status is one of the important evaluations to reduce the defect and improve the device quality for yield and product assurance viewpoints. As well as the silicon technology, the analysis of the interface state is demanded for the new devices and new process technology.

To analyze the interface state, the quasi-static capacitance voltage (QSCV) measurement technique has been the most popular method. The AC signal-based high frequency capacitance voltage (HFCV) measurement (about up to 1 MHz range) is widely used for the new materials and devices characterization, however the interface state analysis cannot be evaluated only by the HFCV measurement, because the slow interface state in-between two materials does not respond to the high frequency AC signal of HFCV. To analyze such slow state traps, the QSCV measurement technique has been widely used, which is effective for capturing a slow frequency behavior as shown in Figure 1. The QSCV measurement uses linear DC ramp sweep or DC step voltage instead of an AC signal, and also needs very low current measurement technique. It is a unique measurement method, and it is very important to understand measurement knowledge and know-hows for performing the measurement appropriately.

This application note discusses the key points in the QSCV measurements including the issues, know-hows and tips when performing the QSCV measurements using the Keysight B1500A Semiconductor Device Analyzer/EasyEXPERT software. The following topics are covered in this application note.

1. Basics of QSCV measurement.
2. Keysight B1500A QSCV solution
3. Set-up and tips for QSCV measurement by the Keysight B1500A

Note: The HFCV measurement which is a counter part of the QSCV measurement is discussed in the other application note. Refer to "Capacitance Measurement Basics for Device/Material Characterization", if you are interested in the HFCV application, too.

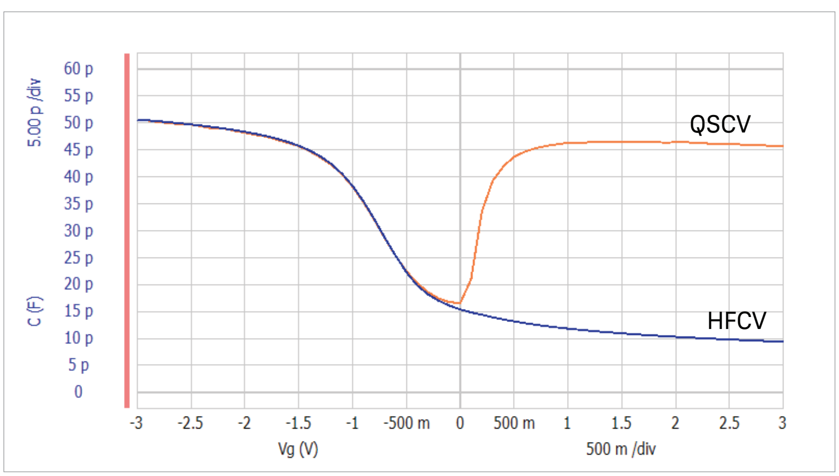


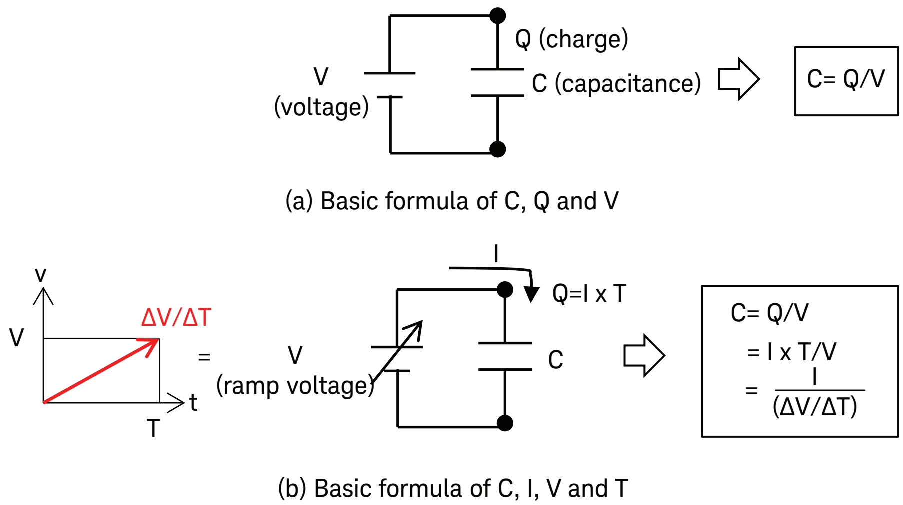
Figure 1. QSCV capture the slow response that cannot be measured by HFCV

Basics of QSCV Measurement

The QSCV measurement seeks the capacitance value by using the basic relationship between current I, voltage V, capacitance C and charge Q as shown in Figure 2. Although they are basically the same, there are two basic formulas, according to the focused variables.

Figure 2(a) shows a basic formula of C=Q/V. From this formula, the capacitance can be obtained as the function of the voltage step and the amount of the charge applied by the voltage to capacitor.

Figure 2(b) shows another formula, which is C=Q/V=IT/V=I/(V/T). The total amount of the charge Q can be expressed by the current integrated for a period of time T as Q= IT. From this formula, the capacitance can be obtained as the function of current I, voltage V and time T. Here, the V/T equals to the voltage ramp rate, so the capacitance can be obtained by the current and voltage ramp rate finally.
In the following sections, two basic QSCV measurement methods by using these formulas are introduced.



(a) Basic formula of C, Q and V

(b) Basic formula of C, I, V and T

Figure 2. Basic formula for QSCV measurement

Linear voltage ramp

The linear voltage ramp method is a traditional measurement method of the QSCV since its start in the late 60's. It uses the linear voltage ramp as shown in Figure 2(b). This has been a very common method, because it simply applies the voltage at a fixed ramp rate (ΔV/ΔT) and measures the current. Unlike the step V method described later, it is not necessary to consider and control the timing precisely for the ΔQ integration.

However, some devices may have the leakage current such as electron tunneling through the gate dielectric or p-n junction. In this case, the leak current is also measured as a part of the current I in the Q= I/(V/T) formula. Because the leak current is not related to the traps, the interface state cannot be analyzed accurately for such devices as the result.

Step voltage method

The step voltage method measures the capacitance by using the formula of C=Q/V as shown in Figure 3. The amount of the charge ΔQ is obtained by the relationship of step voltage ΔV, transient current, and time. The measurement time (integration time) must be set to cover all the transient charge current to obtain the ΔQ accurately. This method is not only limited to single step, but it can be also performed in the voltage sweep and the ΔQ can be obtained in each step.

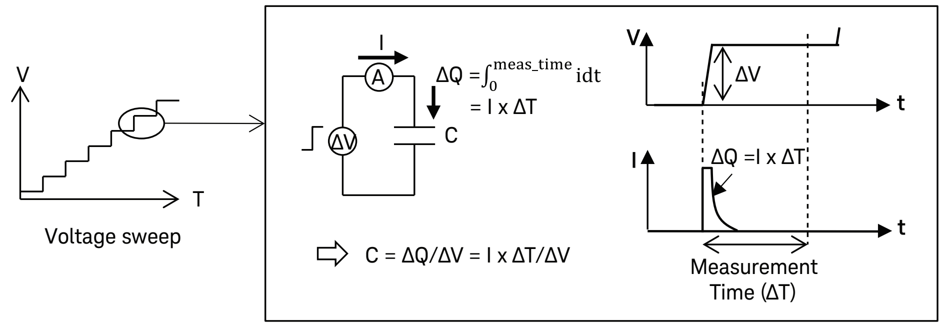
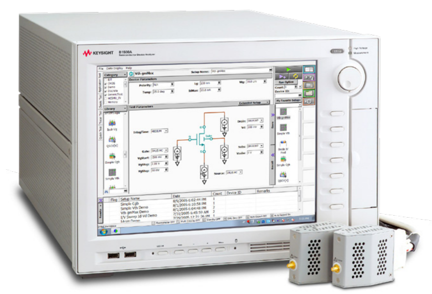


Figure 3. Step voltage QSCV measurement.

Keysight B1500A QSCV Solution

B1500A enables advanced step voltage QSCV measurement



The Keysight B1500A Semiconductor Device Analyzer is widely used in the device characterization, and you can perform QSCV measurement in addition to all the current-voltage (IV) measurement, CV measurement and pulsed measurement in one instrument. The B1500A provides the graphical-user-interface (GUI) for easy-to-test without programming. The B1500A enables you to perform the QSCV measurement easily by using the built-in GUI based application test as shown in Figure 4. The following introduces the detailed features of the B1500A QSCV measurement solution.

The B1500A supports the QSCV measurement by the Source/Monitor Unit (SMU). It enables the advanced step voltage QSCV method by the superior low current measurement down to 0.1 fA resolution and the intrinsic precise timing control. In addition, the B1500A and the application test for QSCV measurement implement the leak and offset compensations applicable to leaky device measurement as described later.

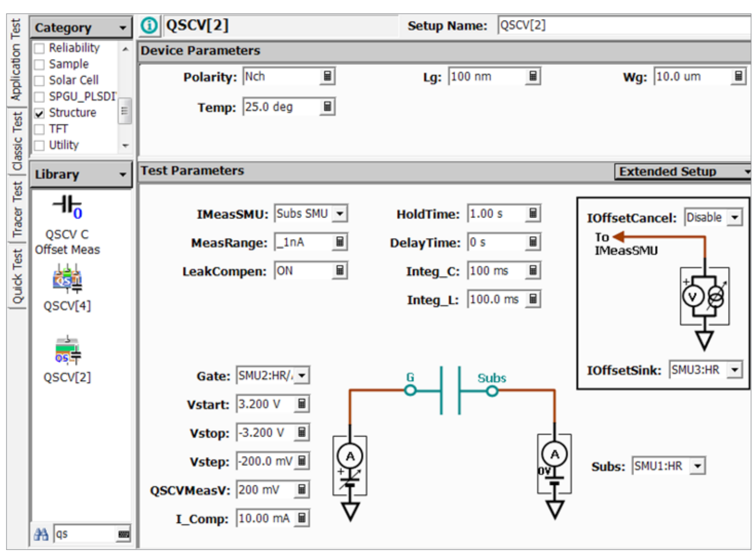


Figure 4. Ready to use QSCV application test

Details of the B1500A step voltage QSCV measurement

The measurement diagram of B1500A QSCV measurement is shown in Figure 5. The basic idea of the B1500A's step voltage QSCV method is the same as Figure 3, but a few more parameters are added to adapt to various devices and to support advanced capabilities. The Figure 5(a) shows the entire CV sweep of QSCV measurement, and Figure 5(b) shows a magnified view of the a sweep step. More details of a QSCV measurement in a step are shown in Figure 5(c).

In the original idea of the voltage step QSCV method as shown in Figure 3, the QSCV measurement is performed by the step voltage of CV sweep. However, in this case, the QSCV measurement parameter (ΔV) is fixed by the CV sweep settings of start V, stop V and number of sweep steps. Typically those parameters are defined by the device operating range from accumulation to inversion, and the number of points to plot the curve. So it limits the freedom to optimize the QSCV measurement parameters.

In the B1500A QSCV measurement, the ΔV of QSCV measurement can be set independently from the step voltage of the CV sweep as shown in Figure 5 (b). Along the CV sweep, any same or different ΔV can be specified for QSCV measurement across each sweep step voltage. At the beginning of the QSCV measurement, the voltage is set to (sweep step voltage Vstep-n - ΔV/2). If necessary, it is possible to place the delay time to wait for the settling of charge current by CV sweep step voltage. Then the QSCV measurement is performed with ΔV from (sweep step voltage Vstep-n - ΔV/2) to (sweep step voltage Vstep-n + ΔV/2), as shown in Figure 5(c). The charge ΔQ induced by the ΔV can be calculated by measuring the current and numerically integrating the area under the current versus time curve precisely inside of the B1500A. As a result, the capacitance at each step can be obtained by the formula of C= ΔQ/ΔV along with any step voltage of CV sweep.

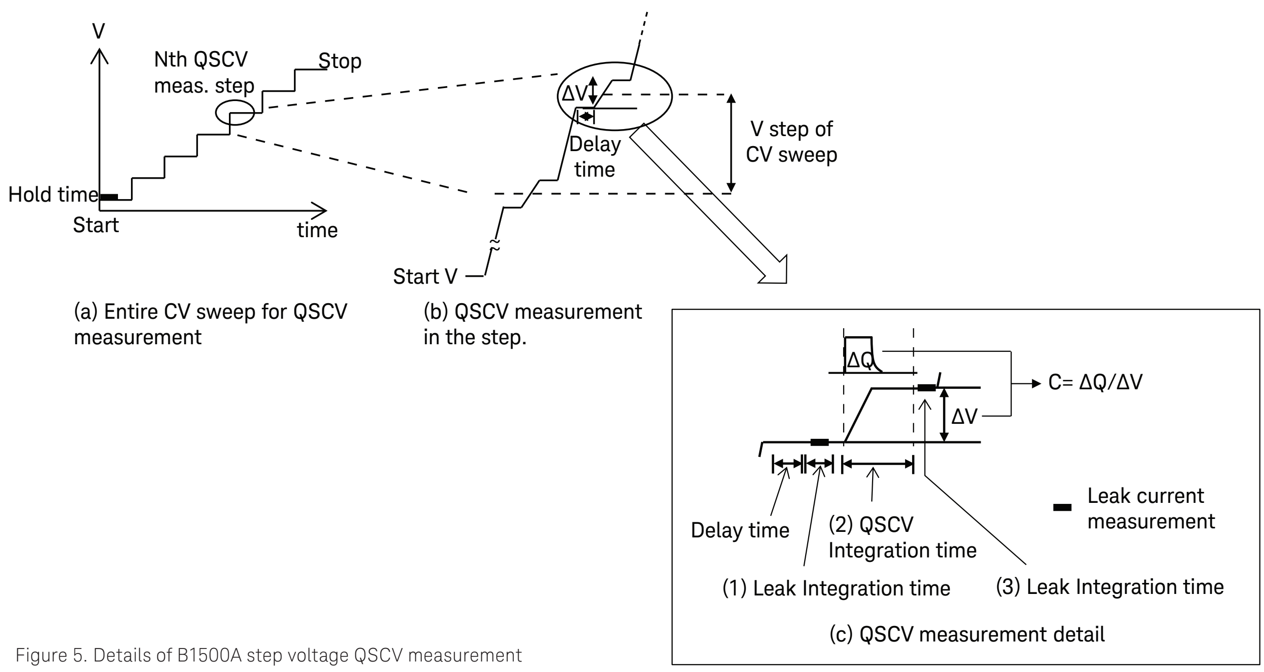


Figure 5. Details of B1500A step voltage QSCV measurement

Details of the B1500A advanced capabilities

Leakage current compensation:

If the device has the leakage current such as electron tunneling through the gate dielectric or p-n junction, it cannot be distinguished from the charge current for QSCV measurement. To reduce the error caused by those leakage currents, the B1500A QSCV measurement provides the advanced feature to compensate the leakage current. It measures the leakage current before and after the QSCV measurement as shown in figure 5(c), and then subtracting out the leakage current before calculating the ΔQ for the capacitance.

Since the above leakage current compensation is made by using the same current range which measures the QSCV current, the compensated maximum leak current is limited to the QSCV measurement current range. If the leak current is large, the leak current cannot be fully compensated. If the higher current range is used for the large leakage current, the QSCV measurement accuracy tends to be degraded. To resolve this challenge, the B1500A provides another leakage current compensation capability (I offset cancelation) by using additional SMU. This additional SMU is connected in parallel to force the current to cancel the large leak, enables to perform QSCV measurement in the appropriate range even with the large leak. It can be set up as shown "IOffsetCancel" in the center-right of figure 6.

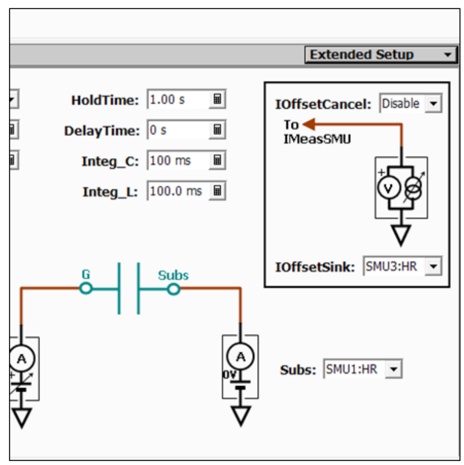


Figure 6. I offset cancel capability

QSCV offset compensation:

Offset capacitance and the leakage current can be the error (or parasitic) factors for QSCV measurement as shown in Figure 7. As well as HFCV measurement, stray capacitance between the measurement terminals is regarded offset capacitance (Coffset) to be compensated. In addition, the QSCV method calculates the capacitance from the charge current, so the leakage current (I_leak) without device is also contributed to the capacitance calculation. Unless these are appropriately compensated, the QSCV result can include some measurement errors.

The B1500A supports both of these measurements to determine the offset capacitance and the leakage current while the test terminal is open. The I-leak offset current is also converted to offset capacitance C(I_leak) using the QSCV measurement parameters, and generates total offset capacitance Cmo in addition to Coffset. The Cmo is stored and automatically subtracted from subsequent QSCV measurements (Cm), and you can get the compensated result.

The offset measurement GUI is shown in Figure 8. The current measurement SMU (IMeasSMU) and the current measurement range (MeasRange) have to be the same for accurate Coffset compensation.

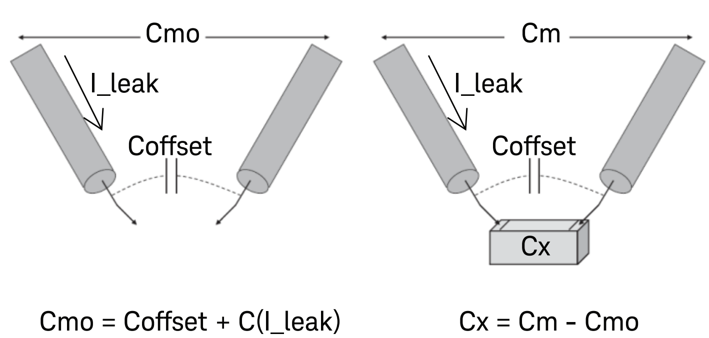


Figure 7. offset capacitance compensation.

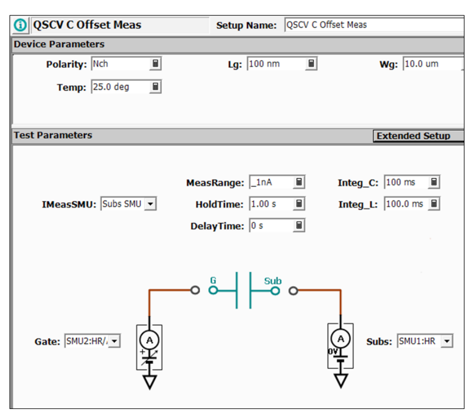


Figure 8. offset capacitance measurement GUI.

Parameters in the application test

In the B1500A QSCV application test, you can control the following parameters in the GUI in Figure 9.

– CV sweep setup parameters:
  Start V, Stop V, Step V: CV sweep parameters. Refer to Figure 5.
  I_comp: Current compliance of SMU.
  HoldTime: Wait time before starting the CV sweep at the first bias voltage. Refer to figure 5(a).

– QSCV measurement setup parameters:
  IMeasSMU: SMU to measure the charge current for QSCV.
  MeasRange: Current range of SMU to measure the charge current for QSCV.
  Integ_C: Integration time for ΔQ for QSCV. Refer to Figure 5(c).
  QSCVMeasV: Step voltage ΔV for QSCV. Refer to Figure 5(c).
  DelayTime: Delay time before starting the QSCV measurement at each CV sweep step. Refer to Figure 5(c).

– Leakage current compensation setup parameter
  LeakCompen: Switch to enable/disable the leak compensation.
  Integ_L: Integration time for leakage current measurement.

– I offset cancelation capability
  IOffsetCancel: Switch to enable/disable the I offset cancel capability
  IOffsetSink: Specify the SMU to connect in parallel to the "IMeasSMU"

In the following section, the setup method of these parameters is discussed.

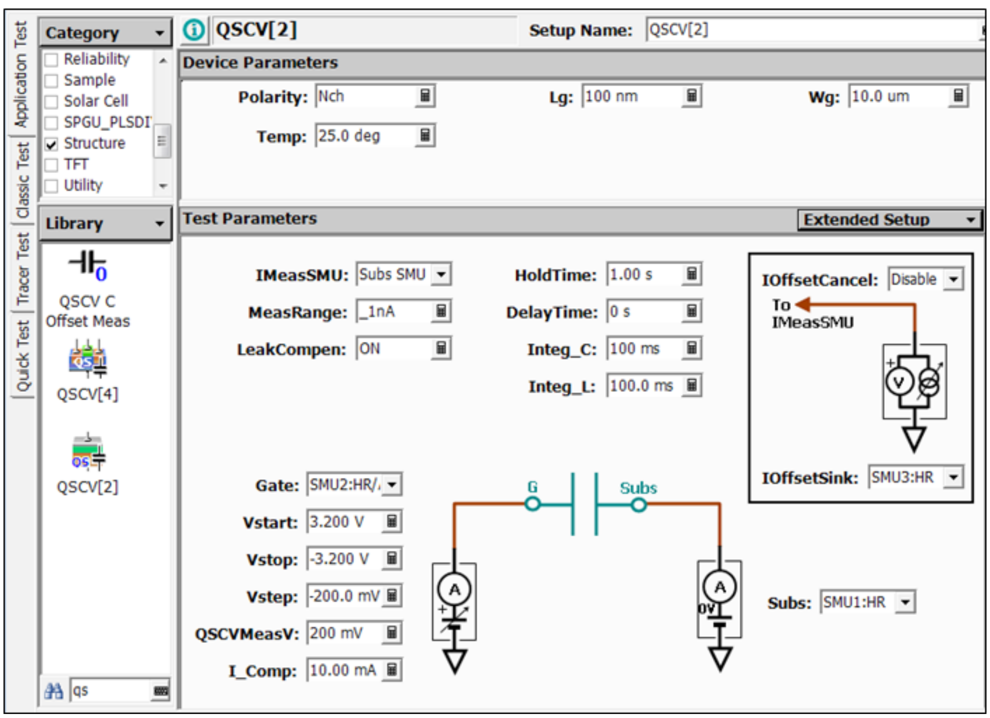


Figure 9. GUI and setting parameters for QSCV measurement

Set-up and Tips for QSCV Measurement by the B1500A

This section provides several useful information to setup QSCV parameters and tips for accurate measurement to meet in various situations. There is a deep relation between the integration time setting, current range setting, leakage current setting and the capacitance value in the QSCV measurement, and the explanation starts from these relations.

Typical steps for successful QSCV measurement setups

The step voltage QSCV test setup can be made easier if the measurement starts from the DC and HFCV measurement as shown in Figure 10. The B1500A supports the seamless measurement among the IV and QSCV measurement by SMU and HFCV measurement by the CMU (Capacitance Measurement Unit) with the optional SCUU (SMU CMU Unify Unit) as shown in Figure 11. This enables you to perform accurate HFCV and QSCV measurement quickly and effortlessly. Through the DC and HFCV measurements, the following useful information can be obtained for QSCV measurement.

- **DC measurement to know leakage current:**
  DC leakage current information is useful for determining the minimum QSCV measurement range. It can also be useful for determining if the DC leak compensation function is used.
- **HFCV measurement to know maximum capacitance value:**
  If the capacitance value can be known roughly in advance, you can set the various parameters such as QSCV measurement range, step voltage and integration time smoothly. This is described later in detail.

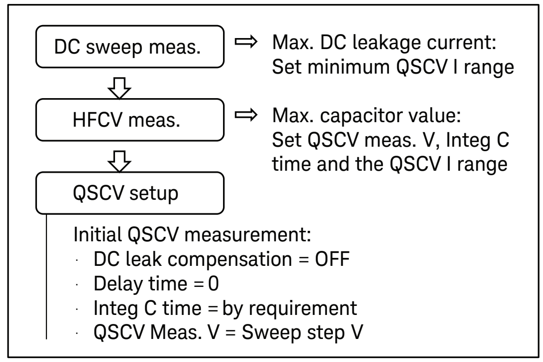


Figure 10. Typical QSCV test setup flow.

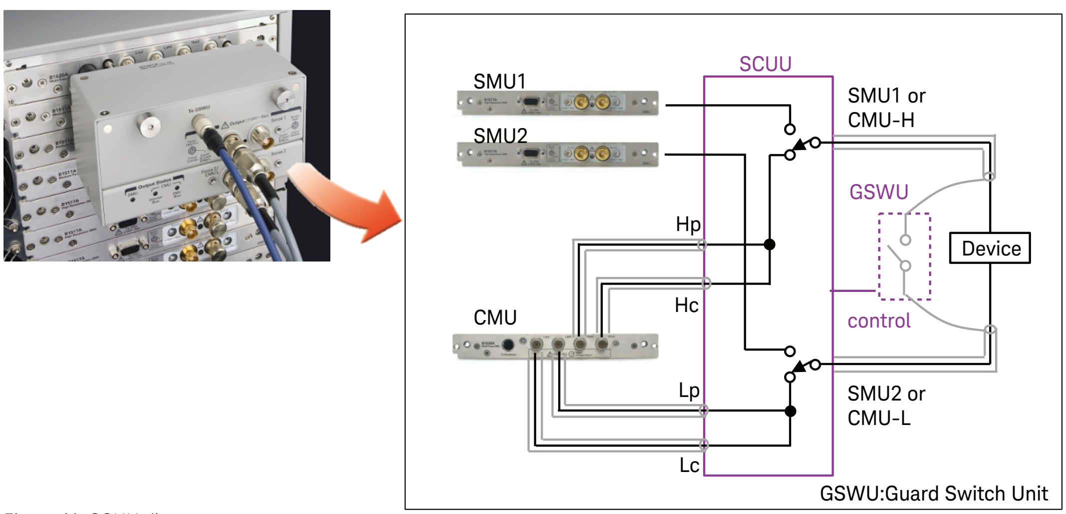


Figure 11. SCUU diagram

How to set the QSCV measurement parameters

The following section provides the information how to set the measurement parameters appropriately. For the details, refer to the graph of maximum measurement value in "QSCV Maximum Measurement Value and Accuracy" of the EasyEXPERT user's guide. That graph shows the maximum capacitance value by the combination of the parameters such as the range, step voltage and integration time.

- **Set longer QSCV integration time than the graph of maximum measurement value:**
  The graph of maximum measurement value in the user's guide shows the measurement limitation of the maximum capacitance that can be measured at the combination of parameters, as shown in Figure 12 and 13 as the examples. According to your capacitance value, this graph provides the good starting point of C integration time (Integ_C) at specific ΔV. For example, if the 1 nF capacitance is measured at 0.1 V step, the graph shows the 100 ms as the minimum C integration time. So set the C integration time larger than this value. If the QSCV measurement fails, the compliance state "C" or overflow status "V" is shown in the data status, and then try a longer integration time.

- **Start the measurement range equal to or larger than 1 nA range:**
  The 1 nA and higher ranges allow larger capacitance measurement, so it is recommended to start from 1 nA range. As shown in the Figures 12 and 13, the maximum capacitance value is a function of ΔV as well as C integration time. If the ΔV is from 0.1 V to 0.2 V, the 1 nA range allows up to 10 nF, but 10 pA/100 pA allows up to 10 pF approximately at 1 s C integration time. If the capacitance is known small appropriately for 10 pA/100 pA ranges, of course those ranges can be used. After starting the parameter combination on this graph, and then adjust those parameters according to the device characteristics.

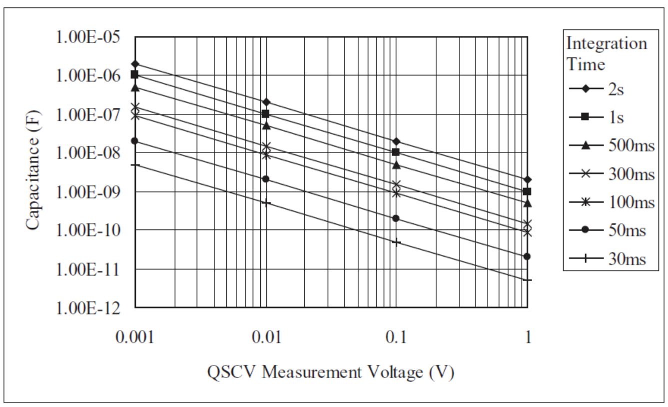


Figure 12. Maximum measurement value by parameter combination (1 nA range).

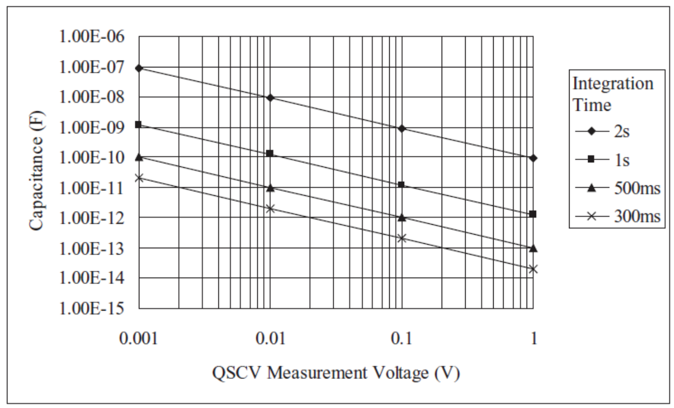


Figure 13. Maximum measurement value by parameter combination (10 pA and 100 pA ranges).

- **Additional notes to measure the device with slow interface state:**
  When measuring the device with slow interface state, pay more attention to the C integration time. Due to the slow interface state, the value of device capacitance can be shifted during the measurement, and the charge current is slowly settlled down. To characterize the device with accurate ΔQ, it is important to integrate the charge current enough by the end of the settling, which has its time constant. To integrate the charge current by settling within about 5 %, the C integration time needs to be longer than approximately three times the time constant of the QSCV response, in the time constant matter. For most cases, the integration time from 5 s to 10 s is enough at maximum, in case the leak compensation is disabled.

  When the leak compensation is enabled for a leaky device, adjusting the C integration time becomes more important to fully integrate the charge current. If a longer C integration time is necessary, adjusting the L integration time sometimes provides better results. To obtain a satisfactory result, it may be necessary to adjust the parameters by try and error of repeat measurements by comparing the data.

  When the CV sweep step is larger than the ΔV of QSCV measurement, adjust the delay time as well. The charge current of slow state caused by the CV sweep might not be settled down yet at the QSCV measurement.

How to use the leak compensation

The step voltage QSCV test setup can be made easier if the measurement starts from the DC and HFCV measurement as shown in Figure 10. The B1500A supports the seamless measurement among the IV and QSCV measurement by SMU and HFCV measurement by the CMU (Capacitance Measurement Unit) with the optional SCUU (SMU CMU Unify Unit) as shown in Figure 11. This enables you to perform accurate HFCV and QSCV measurement quickly and effortlessly. Through the DC and HFCV measurements, the following useful information can be obtained for QSCV measurement.

- **Enable the leak compensation for leaky device:**
  The QSCV measurement is very susceptible to the leakage current of the device, and it is important to know the level of the leakage current. Figure 14 shows the comparison of the QSCV measurements and the HFCV measurment made on a varicap diode with the same sweep condition. The QSCV measurements are made in two different conditions; one is leak compensation ON and the other is OFF condition. The device shows leakage current as shown in the graph, and the QSCV curves show quite different results. The QSCV curve measured under the leak compensation ON data correlates well to the reference HFCV measurement curve. As you can see this example, the leak current compensation function is very useful especially when measuring the leaky device.

  Normally, the measurement can be started from the leak compensation OFF, and then try ON according to the measurement result. If the device is known as leaky device, set the leak compensation ON from the beginning.

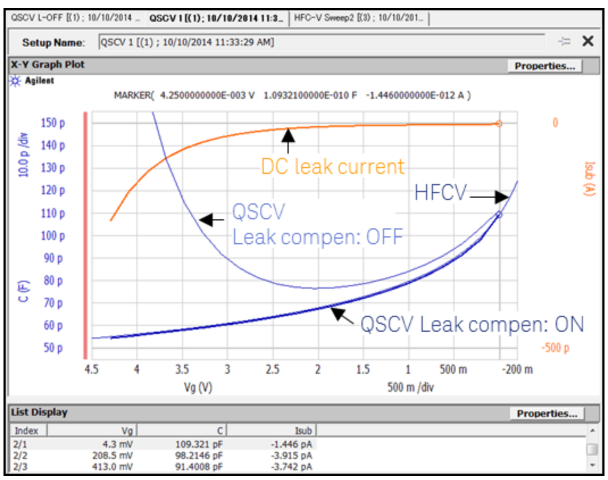


Figure 14. The effect of leak compensation and the correlation with the HFCV measurement.

- **Set appropriate integration time for the leak measurement:**
  The parameter of Integ_L is the integration time for the leak current measurement. The leak current is subtracted from the charge current during the C integration time at each CV sweep step. This feature provides the accurate QSCV data by eliminating the effect of leak current for leaky device, but it could add the unexpected error by noise from the device and SMU, unless it is appropriately set up.

  Obviously the unstable leak current measurement results in unstable QSC data, because the leak current is subtracted from the charge current of QSCV measurement. From this viewpoint, the leak measurement must be accurate enough and low noise relatively to the QSCV charge current measurement. Hence, it is recommended to use the 1 PLC (power line cycle) averaging for the integration time for leak current (Integ_L). Using the PLC multiplied integration time can reduce the power line oriented noise drastically.

How to reduce the noise in the QSCV measurement

- **Increase ΔV for QSCV measurement:**
  When the measurement data is noisy, try to use larger ΔV. Since the amount of charge and its transient current are defined by the ΔV, larger ΔV induces larger charge current and it improves the signal to noise ratio. The ΔV of 100 mV or 200 mV would be a good starting point for the QSCV measurement for most of cases.

- **Use the SMU at gate for QSCV measurement:**
  To measure the MOS/MIS cap, two SMU are used in the QSCV measurements as shown in Figure 15. SMU 1 is connected to the gate and SMU 2 is connected to the substrate. To reduce the noise, it is recommended to use the SMU at gate site for the current measurement for QSCV. The gate side is usually high impedance and less affected by the noise from the measurement environment.

- **Choose the SMU to sweep the voltage:**
  Whichever SMU connected to the gate or substrate can be a voltage sweep source. However, it is important to note that the effect of the stray capacitance Cg or Cs, as shown in Figure 15. In Figure 15(a), the voltage is swept and the charge current is also measured at gate side. In addition to the charge current to the device, the charge current (Is) into the stray capacitance (Cg) is also measured. This can be a measurement error. In Figure 15(b), on the other hand, there is no charge current into the stray capacitance (Cg), because the voltage remains the same at the gate side. Although these stray capacitance components can be cancelled by the offset capacitor compensation, it is recommended to choose the SMU to sweep the voltage carefully. In general, it is recommended to measure the QSCV at gate and sweep the voltage at substrate, as shown in Figure 15(b).

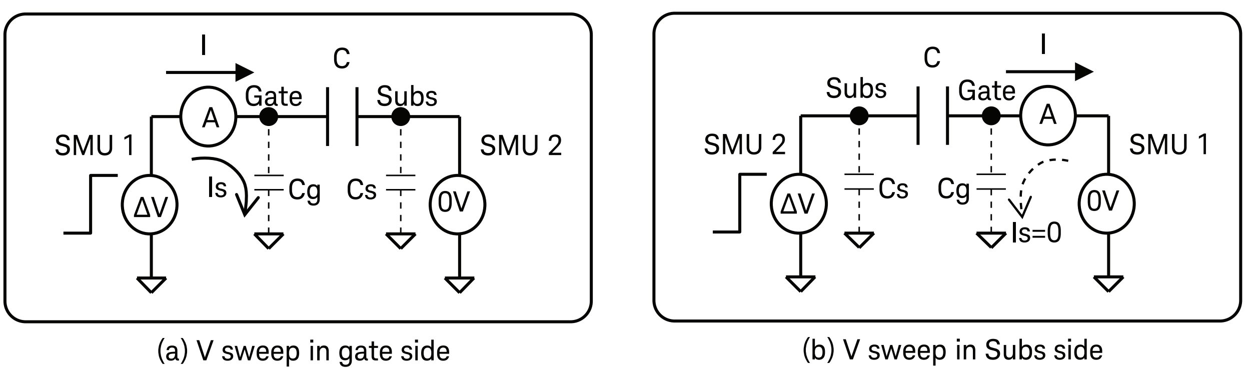


Figure 15. Effect of the charge current into stray capacitance

Conclusion

The QSCV measurement is important application for evaluating new materials and devices and improving their performance and quality, as well as IV and HFCV measurement. The advanced QSCV measurement feature of B1500A enables wide range of materials and devices with the flexibility of various settings as discussed above.

The B1500A provides all of the IV, CV and QSCV measurement and switching capabilities in the combination with the optional SCUU. The SCUU enables the B1500A to perform the IV and QSCV measurement by SMU and HFCV measurement by the CMU without changing the connection manually. The B1500A provides the total solution for QSCV and other fundamental IC/CV characterizations for various materials and devices.

B1500A now supported in Windows 10

B1500A PC platform has been renewed. It includes Windows 10 OS, faster CPU, 8 GB of memory and a solid state drive (SSD). The latest PC platform enables you to perform your software tasks easily while improving your total computing performance. Windows 10 upgrade option is also available.

For more detail: https://literature.cdn.keysight.com/litweb/pdf/5991-3327EN.pdf