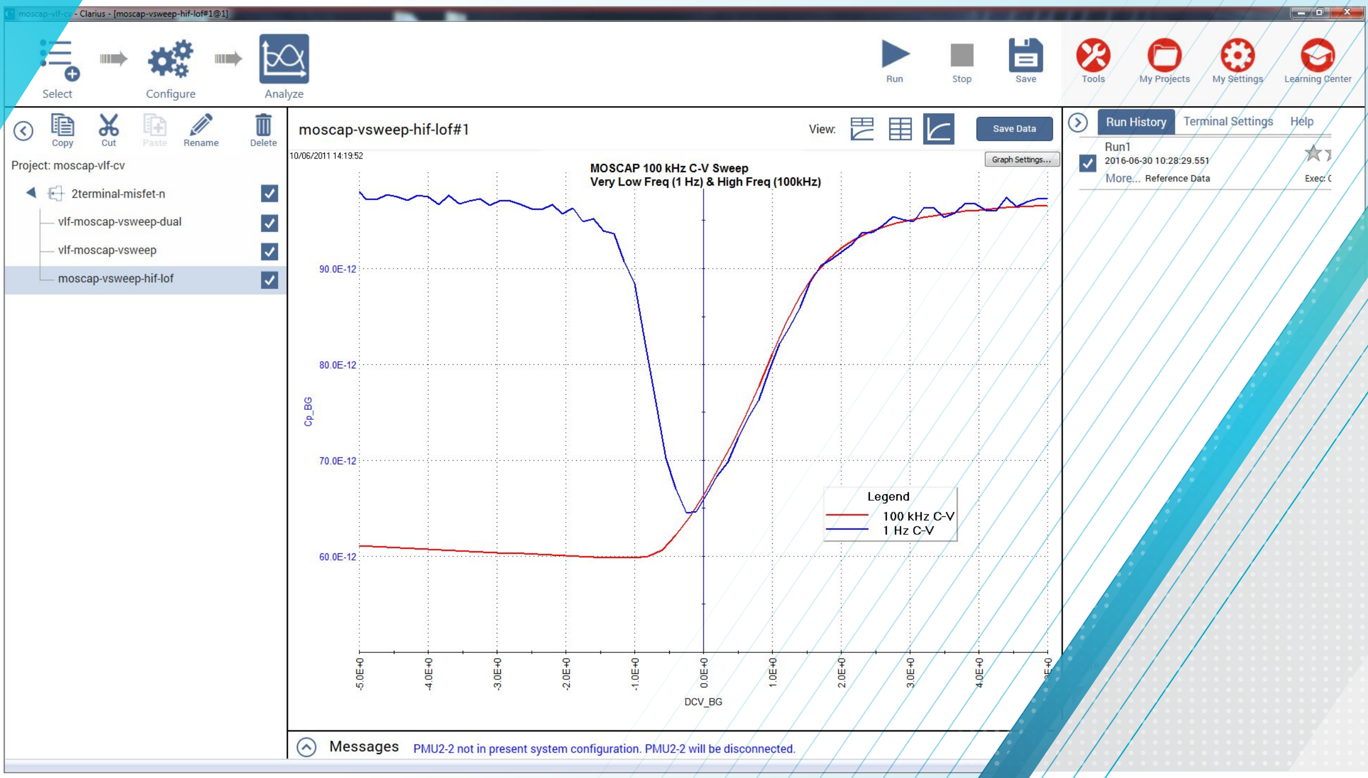
Performing Very Low Frequency Capacitance-Voltage Measurements on High Impedance Devices Using the 4200A-SCS Parameter Analyzer

APPLICATION NOTE



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Introduction

Capacitance measurements on semiconductor devices are usually made using an AC technique with a bridge-type instrument. These AC instruments typically make capacitance and impedance measurements at frequencies ranging from megahertz down to possibly tens of hertz. However, even lower frequency capacitance measurements are often necessary to derive specific test parameters of devices such as MOScaps, thin film transistors (TFTs), and MEMS structures. Low frequency C-V measurements are also used to characterize the slow trapping and de-trapping phenomenon in some materials. Instruments capable of making quasistatic (or almost DC) C-V measurements are often used for these low frequency impedance applications. However, the 4200A-SCS Parameter Analyzer uses a new narrow-band technique that takes advantage of the low current measurement capability of its integrated source measure unit (SMU) instruments to perform C-V measurements at specified low frequencies in the range of 10 mHz to 10 Hz. This new method is called the Very Low Frequency C-V (VLF C-V) Technique.

The VLF C-V Technique makes it possible to measure very small capacitances at a precise low test frequency. This patent-pending, narrow-band sinusoidal technique allows for low frequency C-V measurements of very high impedance devices, up to >1E15 ohms. Other AC impedance instruments are usually limited to impedances up to about 1E6 to 1E9 ohms. The VLF C-V approach also reduces the noise that may occur when making traditional quasistatic C-V measurements.

The 4200A-SCS Parameter Analyzer comes with preconfigured tests and a user library to perform impedance measurements automatically using this very low frequency technique. Because this approach uses the 4200A-SCS's SMU instruments, no additional hardware or software is necessary if low current I-V characterization is already required. This application note describes the VLF C-V technique, explains how to make connections to the DUT, shows how to use the provided software, and describes optimizing VLF C-V measurements using the 4200A-SCS.

Very Low Frequency C-V Technique

Figure 1 is a simplified diagram of the SMU instrument configuration used to generate the low frequency impedance measurements. This configuration requires a 4200A-SCS system with two SMU instruments installed, with 4200-PA preamps connected to either side of the device under test. SMU1 outputs the DC bias with a superimposed AC signal and also measures the voltage. SMU2 measures the resulting AC current while sourcing 0 V DC.

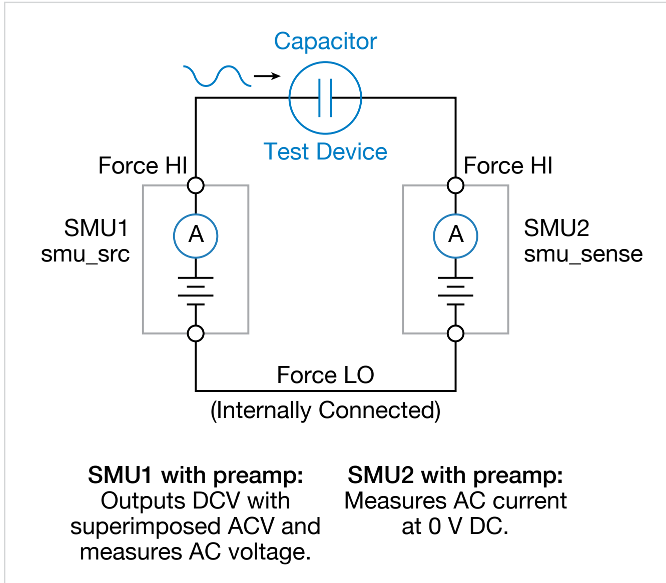

Figure 1. Connections for very low frequency C-V measurements.

Basically, while the voltage is forced, voltage and current measurements are obtained simultaneously over several cycles. The magnitude and phase of the DUT impedance is extracted from the discrete Fourier transform (DFT) of a ratio of the resultant voltage and current sinusoids. This narrow-band information can be collected at varying frequencies (10mHz to 10Hz) to create a complex, multi-element of the DUT. The resulting output parameters include the impedance (Z), phase angle (θ), capacitance (C), conductance (G), resistance (R), reactance (X), and the dissipation factor (D).

Because the very low frequency method works over a limited frequency range, the capacitance of the device under test (DUT) should be in the range of 1pF to 10nF. **Table 1** summarizes the VLF C-V specifications (see Appendix A for complete specifications).

Table 1. Very Low Frequency C-V specifications.

Measurement Parameters	Cp, Gp, F, Z, θ, R, X, Cs, Rs, D, time
Frequency Range	10 mHz to 10 Hz
Measurement Range	1 pF to 10 nF
Typical Resolution	3.5 digits, minimum typical 10 fF
AC Signal	10 mV to 3 V RMS
DC Bias	±20 V on the High terminal, minus the AC signal, 1 µA maximum

Required Hardware for VLF C-V Measurements

To make very low frequency impedance measurements, the following hardware is required:

- 4200A-SCS with Clarius software
- Two SMU instruments (4200-SMU, 4201-SMU, 4210-SMU, or 4211-SMU)
- Two 4200-PA Preamps
- Optional: 4210-CVU or 4215-CVU Capacitance Voltage Unit (CVU) for making high frequency C-V measurements

Making Connections to the Device

To make VLF C-V measurements on a device, connect the DUT between the two Force HI terminals of two SMU instruments (4200-SMU, 4201-SMU, 4210-SMU or 4211-SMU) with 4200-PA Preamps (**Figures 1, 2**). The preamp option is necessary because measuring very high impedances requires measuring very small currents. With the 4200-PAs, currents of <1E-12A can be measured. Because the VLF C-V method requires measuring small currents, it is best to use the triax cables that come with the SMU instruments to make these connections. The method does not support any switching instrumentation between the SMU instrument preamp and the device under test (DUT). One SMU outputs both the DC and AC voltage (SMU1 in **Figures 1 and 2**) and measures the AC voltage. The other SMU instrument measures the AC current (SMU2 in **Figures 1 and 2**). The SMU instrument used to measure the AC current should be connected to the high impedance terminal of the device (**Figure 2**).

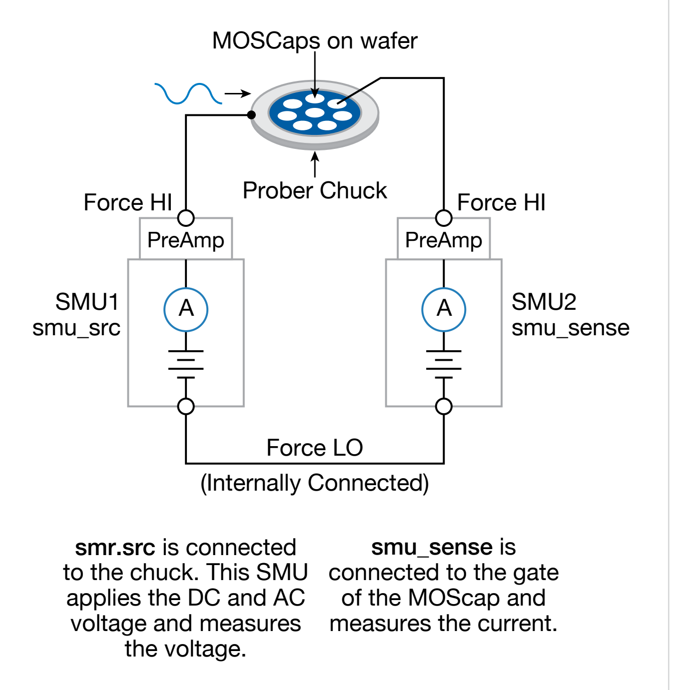

Figure 2. VLF C-V measurement setup for a MOScap on wafer.

An example of a MOSCap circuit connected for VLF C-V measurements is shown in **Figure 2**. Most MOSCaps have only a single pad on the top of the wafer, with the backside of the wafer used as the common contact for all MOSCaps. SMU1 outputs the AC+DC voltage and is connected to the chuck. The SMU that outputs the voltage is known as "smu_src" in the software that is included with the system. The high impedance terminal of the MOSCap is the gate and is connected to SMU2, which is called "smu_sense" in the software.

Using the Clarius Software to Perform VLF C-V Measurements

The system includes a user library called *VLowFreqCV* that contains several user modules that you can use to make low frequency C-V measurements. Clarius includes example tests and projects that are based on these user modules that you can use as templates to develop tests. The example tests and projects are available in the Library.

You can also build custom tests using these user modules. The *VLowFreqCV* User Library contains several modules, listed in **Table 2**, that can be used in a test in a project. To build a custom test, in the Library, select Custom Test and select the option “Choose a test from the pre-programmed library (UTM)”. Select Configure. In the right pane, for the User Library, select *VLowFreqCV* User Library and then select the appropriate User Module.

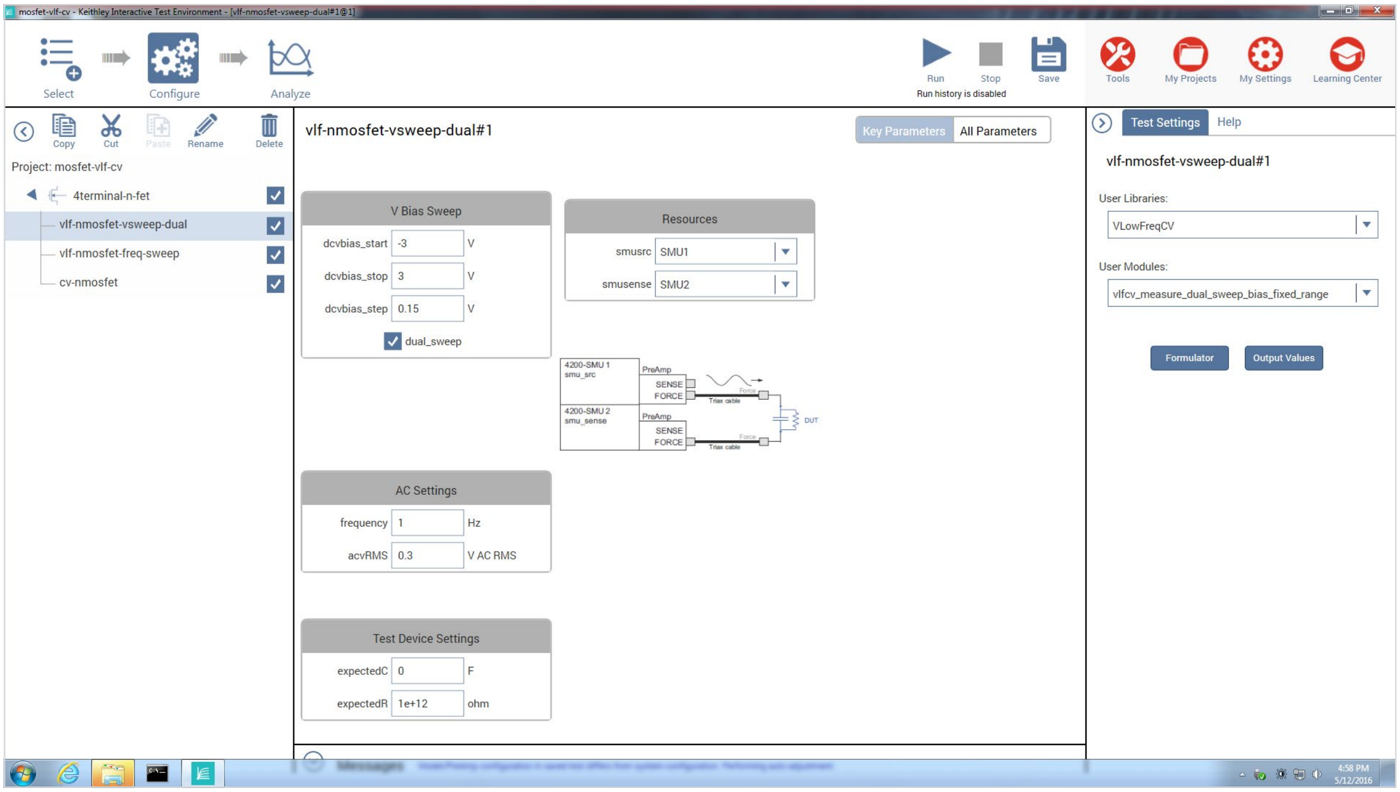

Figure 3. Screen capture of *vlfcv_measure_dual_sweep_bias_fixed_range* user module

Table 2. User Modules in the *VLowFreqCV* User Library.

User Module	Description
vlfcv_measure	Measures C, G, Z, theta, R+jX at a fixed DC bias.
vlfcv_measure_dual_sweep_bias	Measures C, G, Z, theta, R+jX, time while sweeping the DC voltage. Optional dual sweep allows sweeping from dcv_bias_start to dcv_bias_stop, with 1 measure point at dcv_bias_stop, then back down to dcv_bias_start.
vlfcv_measure_dual_sweep_bias_fixed_range	Measures C, G, Z, theta, R+jX, time while sweeping the DC voltage. Measurements are made on a fixed current range which is determined by the expected_C, expected_R and maximum DC voltage. Optional dual sweep allows sweeping from dcv_bias_start to dcv_bias_stop, with 1 measure point at dcv_bias_stop, then back down to dcv_bias_start.
vlfcv_measure_sweep_freq	Measures C, G, Z, theta, R+jX, time at multiple user-specified test frequencies.
vlfcv_measure_sweep_time	Measures C, G, Z, theta, R+jX, time as a function of time.

Once you’ve added a new module to a project, you need to input a few parameters. Many of the parameters are common to all the modules; however, each module has some unique parameters. **Figure 3** illustrates the Key Parameters view of the *vlfcv_measure_dual_sweep_bias_fixed_range* User Module showing all the user-defined parameters. The adjustable parameters for all the modules are listed in **Tables 3 through 6.**

The values of the expected capacitance (expected_C) and the expected parallel resistance (expected_R) determine which current range will be used to make the measurement. However, choosing specific values is generally not required, as setting expected_C = 0 will allow the test routines to estimate the C and R to use.

The simplest module is *vlfcv_measure*. It is used in the *Capacitor VLF C-V Measurement* (*vlf-cap-one-point*) test in the *Capacitor VLF-CV Project.* This test performs a single measurement. The module does not perform any sweeping, but it allows for all test parameters to be controlled (**Table 3**). Note that the maximum voltage possible is a combination of both the AC and DC voltages. The maximum negative DC bias voltage = –20 + (acv_RMS * $\sqrt{2}$). The maximum positive DC bias voltage = +20 – (acv_RMS * $\sqrt{2}$). Use expected_C = 0 to have the routine auto-detect the estimated C and R values.

Table 3. Adjustable parameters in *vlfcv_measure* User Module.

Parameter	Range	Description
smu_src	SMUn	SMU instrument to source DC + AC voltage waveform and measure AC volts: SMU1, SMU2, SMU3…
smu_sense	SMUn	SMU t instrument o measure AC current: SMU1, SMU2, SMU3…
frequency	0.01 to 10	Test frequency in hertz, from 0.01 to 10.
expected_C	1e-12 to 1e-8	Estimate of DUT capacitance in Farads, use 0 for auto-detect of DUT C and R.
expected_R	1e6 to 1e14	Estimate of resistance parallel to DUT, in ohms
acv_RMS	30e-3 to 3	AC drive voltage in volts RMS
dcv_bias	±20 less (acv_RMS * $\sqrt{2}$)	The DC voltage applied to the device

Table 4. Adjustable parameters in the *vlfcv_measure_dual_sweep_ bias_fixed_range* User Modules.

Parameter	Range	Description
smu_src	SMUn	SMU instrument to source DC + AC voltage waveform and measure AC volts: SMU1, SMU2, SMU3…
smu_sense	SMUn	SMU instrument to measure AC current: SMU1, SMU2, SMU3…
frequency	0.01 to 10	Test frequency in hertz, from 0.01 to 10.
expected_C	1e-12 to 1e-8	Estimate of DUT capacitance in Farads, use 0 for auto-detect of DUT C and R.
expected_R	1e6 to 1e14	Estimate of resistance parallel to DUT, in ohms
acv_RMS	30e-3 to 3	AC drive voltage in volts RMS
dcv_start	±20 less (acv_RMS * $\sqrt{2}$)	Starting DC voltage of the sweep
dcv_stop	±20 less (acv_RMS * $\sqrt{2}$)	Stop DC voltage of the sweep
dcv_step	±20 less (acv_RMS * $\sqrt{2}$)	Step size of the DC voltage. Number of steps limited to 512.
dual_sweep	0 or 1	Enter 0 for single sweep; enter 1 for dual sweep

Table 5. Adjustable parameters in the *vlfcv_measure_dual_sweep_freq* user module.

Parameter	Range	Description
smu_src	SMUn	SMU instrument to source DC + AC voltage waveform and measure AC volts: SMU1, SMU2, SMU3…
smu_sense	SMUn	SMU instrument to measure AC current: SMU1, SMU2, SMU3…
frequency	0.01 to 10	Array of Test frequencies in Hertz. Maximum number of entries limited to 512, from 0.01 to 10.
expected_C	1e-12 to 1e-8	Estimate of DUT capacitance in Farads, use 0 for auto-detect of DUT C and R.
expected_R	1e6 to 1e14	Estimate of resistance parallel to DUT, in ohms
acv_RMS	30e-3 to 3	AC drive voltage in volts RMS
dcv_bias	±20 less (acv_RMS * $\sqrt{2}$)	The DC Voltage applied to the device

Table 6. Adjustable parameters in the *vlfcv_measure_sweep_time* user module.

Parameter	Range	Description
smu_src	SMUn	SMU instrument to source DC + AC voltage waveform and measure AC volts: SMU1, SMU2, SMU3…
smu_sense	SMUn	SMU instrument to measure AC current: : SMU1, SMU2, SMU3…
frequency	0.01 to 10	Test frequency in Hertz, from 0.01 to 10.
expected_C	1e-12 to 1e-8	Estimate of DUT capacitance in Farads, use 0 for auto-detect of DUT C and R.
expected_R	1e6 to 1e14	Estimate of resistance parallel to DUT, in ohms
acv_RMS	30e-3 to 3	AC drive voltage in volts RMS
dcv_bias	±20 less (acv_RMS * $\sqrt{2}$)	The DC Voltage applied to the device
num_points	1 to 512	Number of points to take as a function of time

Once any test is executed, several test parameters will be returned to the Sheet in the Analyze view and can be saved as an .xls file. These test parameters can also be plotted on the Graph. **Table 7** lists the returned test parameters and their descriptions. From these returned test parameters, more device extractions can be performed using the mathematical functions in the Formulator. Note that the tests return all typical C-V measurement parameters. For example, both Cp-Gp and Cs-Rs are always returned, even if the test device response only matches the parallel (Cp-Gp).

Table 7. Measurements returned for the modules in the *VLowFreqCV* Library.

Returned Test Parameters	Description
Status	Error code from test module execution. Definitions of the returned errors are listed at the bottom of the Definition tab in the UTM Description.
times	Calculated time difference between readings.
dcv_bias	Programmed DC voltage applied to the device.
meas_Cp	Measured capacitance in parallel (Cp-Gp).
meas_Gp	Measured conductance in parallel (Cp-Gp)
meas_freq	Measured test frequency.
meas_Z	Measured impedance (Z-theta).
meas_Theta	Measured phase angle in degrees (Z-theta).
meas_R	Real component of the impedance (R + jX).
meas_X	Imaginary component of the impedance (R + jX).
meas_Cs	Measured AC capacitance in series (Cs-Rs).
meas_Rs	Measured resistance in series (Cs-Rs).
meas_D	Calculated dissipation factor, D.
meas_irange	The SMU instrument current range that the measurement was taken.

Using the Example Tests and Projects in the Library

The Clarius software comes with example tests of very low frequency C-V measurements on various devices. Choose Select to search for the examples in either the Test or Project Libraries. Enter VLF in the search box from either the Test or Project tab. The Tests or Projects will automatically be displayed in the Library. Select the desired Test or Project and add it to the Project tree on the left. Even though the test and projects were created using specific devices, these examples can be used on other devices. Descriptions of the very low frequency C-V projects that can be found in the Project Library are described in the following paragraphs.

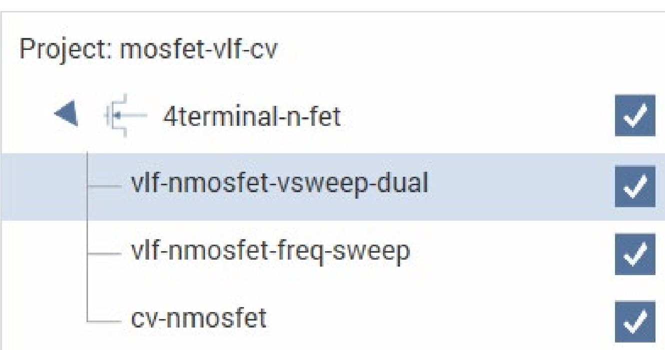

Figure 4. Project tree of *MOSFET VLF-CV* project

MOSFET VLF-CV Project

In the *MOSFET VLF-CV Project*, there are three tests for the n-fet devices, as shown in **Figure 4**. **Figure 6** shows the results of generating a very low frequency dual C-V sweep on an n-MOSFET measured between the Gate terminal and the Drain/Source/Bulk terminals tied together (**Figure 5**). This C-V sweep was generated using the *MOSFET VLF-CV Sweep* (*vlf-nmosfet-vsweep-dual*) test. Tests for measuring capacitance as a function of frequency (*vlf-nmostfet-freq-sweep*), as well as a high frequency C-V test (*cvu-nmostfet*, taken with the CVU) are also included in the project.

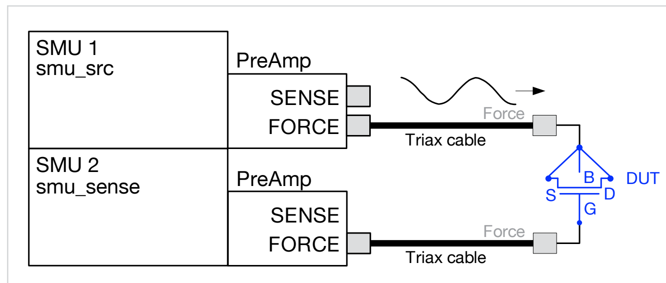

Figure 5. Connection for MOSFET with the gate connected to SMU2 and, with the drain-source-bulk tied together and connected to SMU1 (*smu_sense*).

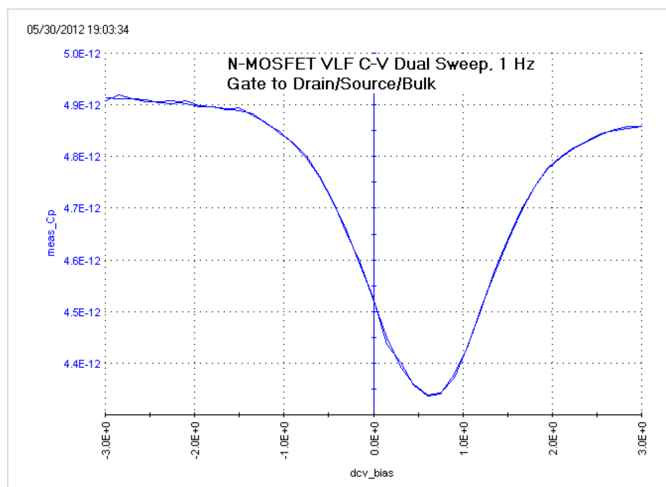

Figure 6. VLF C-V Sweep of an n-MOSFET measured between the gate to drain/source/bulk. This graph is from the *vlf_nmosfet_vsweep_dual* test (user module *vlfcv_measure_dual_sweep_bias_fixed_range*).

Capacitor VLF-CV Project

Using the VLF C-V method, capacitors can be measured in the range of 1 pF to 10 nF, and connections are made as shown in **Figure 7**. The project has four tests for measuring capacitors (**Figure 8**). The *Capacitor VLF-CV C-t Sweep* (*vlf-cap-time*) Test measures the capacitance of a 1pF capacitor as a function of time (**Figure 9**). The results of performing a C-V sweep on a 1 pF capacitor are shown in **Figure 10**. This small capacitance was measured at a test frequency of 1 Hz with capacitance measurement noise levels at less than ±5E-15F. The Formulator can be used to determine the noise and average capacitance readings easily.

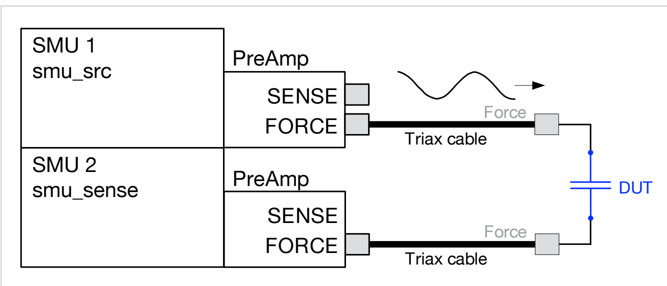

Figure 7. VLF C-V connections for the capacitor. If the test device is on wafer, see the MOSCap diagram (**Figure 2**) for connections.

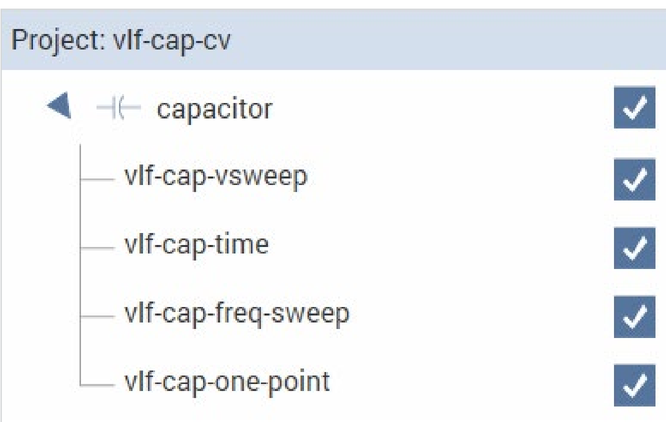

Figure 8. Capacitor tests in the *Capacitor VLF-CV Project.*

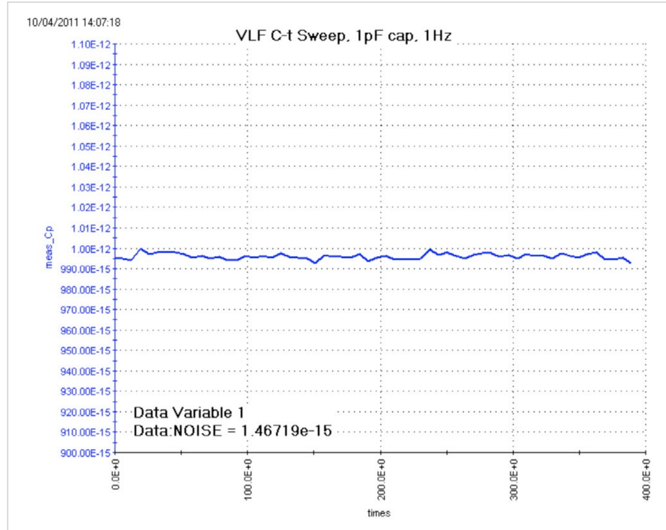

Figure 9. Results of C-t measurements of nominal 1 pF reference capacitor, using VLF capacitance technique at a test frequency of 1 Hz. This graph is from the *vlf-cap-time* test (user module *vlfcv_measure_sweep_time*).

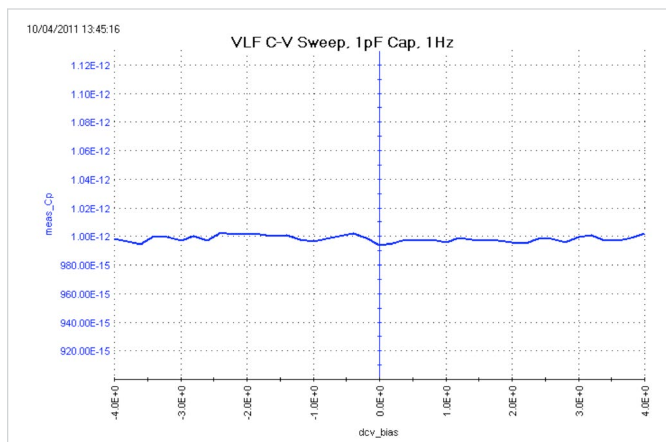

Figure 10. VLF C-V results, at 1 Hz, of a voltage sweep on a 1 pF reference capacitor. This graph is from the *vlf-cap-vsweep* test (*vlfcv_measure_dual_sweep_bias_fixed_range* user module).

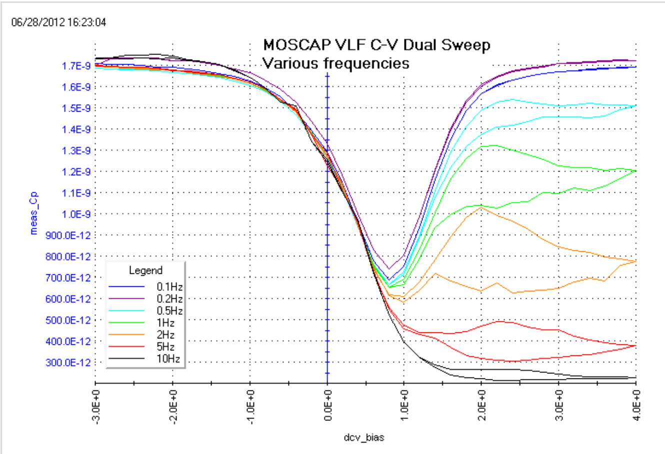

Figure 11. A VLF C-V sweep of a MOScap at various frequences from 100mHz to 10Hz created using the *MOS Capacitor VLF-CV Project*. This graph is from the *vlf-moscap-vsweep-dual* test (*vlfcv_measure_sweep_bias_fixed_range* user module).

MOS Capacitor VLF-CV Project

The MOScap Project has three tests; all are DC bias sweeps with two using SMUs for the VLF C-V test DC bias voltage sweep (*vlf-moscap-vsweep-dual* and *vlf-moscap-vsweep*) and the other using the 4210-CVU or 4215-CVU for higher frequency testing (*cvu-moscap-vsweep*). An example of a MOScap VLF-CV dual sweep generated with various test frequencies ranging from 0.1 Hz to 10 Hz is shown in **Figure 11**. This test was performed on a chuck at room temperature. This sweep is the result of executing the *vlf-moscap-vsweep-dual* test in the project. From the low frequency C-V data, characteristics about the MOScap can be determined. The built-in math functions are helpful in performing the analysis of these devices from the C-V data. The connection diagram for the MOSCap is shown in **Figure 2.** The dual sweep functionality aids in determining any hysteresis behavior in the inversion region of the MOScap device, where frequency dependence is also observed. Note that the SMU instrument measuring the low current is not connected to the chuck. Connecting the sensitive (i.e., low-current measurement) instrument to the chuck will result in noisier measurements.

In addition to the test that generates VLF C-V measurements on the MOScap, the project includes a test to measure high frequency C-V on the MOScap. The high frequency C-V measurements were generated using the CVU, which has a test frequency range of 1 kHz to 10 MHz, with the example data taken at 100 kHz.

To compare the results of both low and high C-V measurements on one graph, the data can be copied from one test module into another. Just select and copy the C-V measurements from the Sheet of one test module and then paste the data into the columns of the CALC Sheet of the other test module. The data in the CALC Sheet can be selected on the graph to plot. To do this, make sure to check the “Enable Multiple Xs” box in the Graph Definition window. An example showing both the low and high frequency C-V measurements on one graph is shown in **Figure 12.**

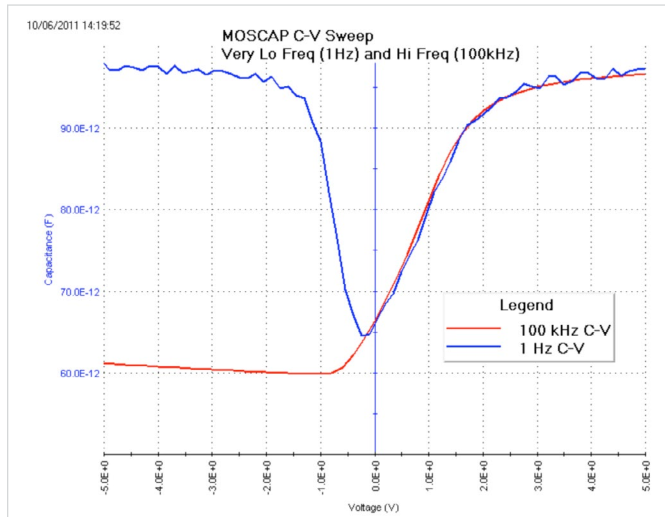

Figure 12. This graph is from the *moscap-vsweep-hif-lof* test, showing the high frequency data from the CVU card along with the VLF C-V data from the *vlf-moscap-vsweep* test.

R-C Circuit VLF-CV Project

Some devices can be modeled as a parallel RC combination (connection diagram in **Figure 13**). The parallel resistance is usually the leakage resistance of the device. In the *R-C Circuit VLF-CV Project*, there are two tests for the RC device: one is the test for a VLF C-V DC bias sweep (*vlf-1nf-1gohm*) and the other tests sweeps votage and measures current using an SMU (*smu-vsweep*). **Figure 14** shows the results of performing a low frequency sweep on a 1.5 nF and 1 GΩ parallel combination. From the bias voltage and the resistance (1/Gp) of the device, the current can be calculated in the Formulator and displayed on the graph. Excessive leakage current can cause erroneous results if the current exceeds the maximum current range for the particular RC combination. To determine the DC leakage current of an unknown DUT, use the *smu-vsweep* test, as described in the section titled “Testing a Device with VLF C-V.”

More information about making optimal measurements is described in the next section of this note.

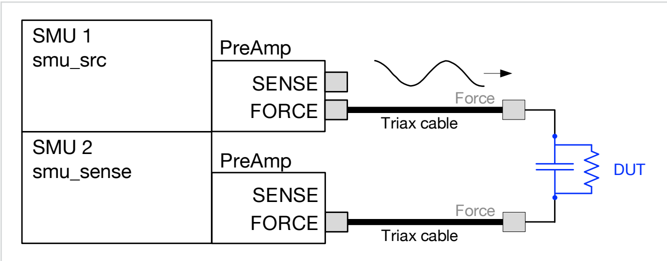

Figure 13. Connection diagram for parallel RC test device.

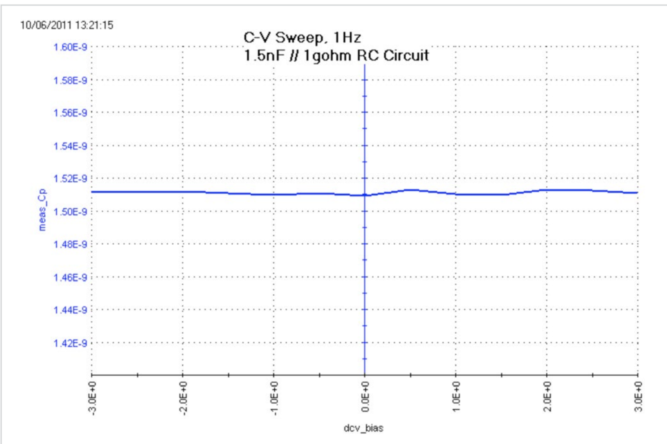

Figure 14. Results of measuring parallel RC combination of 1.5nF capacitor and 1GΩ resistor. This graph is from the *vlf-1nF-1gohm* test (*vlfcv_measure_dual_sweep_bias_fixed_range* user module).

Testing a Device with VLF C-V

Dissipation Factor

The parallel resistance of the device under test is a key aspect that determines the quality of the capacitance measurement because it causes additional DC current to flow, which reduces measurement accuracy. This parallel resistance at a given frequency is otherwise expressed as D, the dissipation factor. Here is the equation for the simple parallel model.

$D = \text{Reactance/Resistance} = 1/\omega RC = 1/2\pi fRC$

where:

f is the test frequency, in Hz

R is the parallel resistance of the test device, in Ω

C is the capacitance of the test device, in farads

Guidance for measurement performance across a range of D values is shown in **Table 8**. As the table shows, higher D values reduce the accuracy of the reported C measurement.

Table 8. VLF C-V typical accuracy vs. D and current measure range for the sense SMU instrument.

	0.01 D	0.1 D	1 D	10 D
1 μA	0.6 %	1.6 %	Not Recommended	Not Recommended
100 nA	1.4 %	10 %	Not Recommended	Not Recommended
10 nA	0.7 %	4 %	6 %	Not Recommended
1 nA	0.4 %	2 %	2.6 %	3 %
100 pA	0.8 %	0.6 %	0.6 %	2 %

"Not Recommended" means that the typical error is >10%. For details on specific capacitance and frequency values, see the VLF C-V Typical Specifications in Appendix A.

If the device is purely capacitive (very low to almost no leakage current, a D <0.1), then just connect the DUT as shown in **Figure 7** (or **Figure 2** if the DUT is on a wafer). After connection, run the desired test(s). However, if the device type is new, or its electrical characteristics are unknown, then use the following procedure. This procedure provides a guideline for determining reasonable parameter values for unknown test devices using the parallel (**Figure 13**). It also provides guidance for evaluating results.

Setup

1. Connect the DUT as shown in **Figure 2**. The connection must be direct with the supplied triax cables. No switching or 4225-RPMs may be in the cable path from the SMU instrument Preamp to the DUT. The VLF C-V method utilizes low current measurements, so ensure that appropriate shielding and guarding are used. Use triax cable and eliminate, if possible, or minimize any unshielded or unguarded cable runs. For on-wafer measurements, use triax probe manipulators and guarded probe arms.

2. Open one of the example very low frequencyy tests or project examples in the Library.

Initial Screening of DUT characteristics

3. Choose the SMU instrument IV sweep, *smu-vsweep* test, *R-C Circuit VLF-CV Project*. Choose voltage start and stop values for the sweep that match the desired minimum and maximum DC bias voltages to be used for

VLF C-V tests. This test will help determine if the DUT leakage is too high for repeatable, accurate results.

4. Run the *smu-vsweep* test. Review the results on the graph or in the Sheet. For best results, the maximum current should be <±1 µA. If the current >±1 µA, reduce the bias voltages until the current <±1 µA. Note these voltages for later testing. These voltages may need to be adjusted again as described later in this procedure.

5. Next, choose the *vlf-cap-freq-sweep* test, *Capacitor VLF-CV Project*. Enter the desired test frequencies, using just five to ten points to span the desired frequency range. If only one test frequency is desired, use the single point test *vlf-cap-one-point* instead. Use the default expected_C = 0 and expected_R = 1E+12. Use acv_RMS = 0.3V and dcv_bias = 0.0V. This test will help determine the dissipation factor D of the DUT.

6. Run the *vlf-cap-freq-sweep* test. Review the results in the Sheet. Review the value(s) in the meas_D column. If |meas_D| <1, then the results are reasonable for the test frequencies and DC bias values that had <±1 µA with the *smu_vsweep* test. If |meas_D| <10 then results should be reasonable for dcv_bias = 0V. If |meas_D| >10, then this present implementation of VLF C-V may provide unacceptable results or results with fairly large errors (**see Table 8**). Note that reasonable values with a low D value at dcv_bias = 0 may provide larger errors as the DC bias is increased.

VLF C-V Characterization of DUT

7. Configure the desired test, such as the bias sweep *vlf-cap-vsweep* (**Table 4**) or frequency sweep *vlf-cap-freq-sweep* (**Table 5**) in the *Capacitor VLF-CV Project*. Use the voltage values determined in the previous step. As stated earlier, using expected_C = 0 will perform an auto-detect of both the C and R values. For the other parameters, follow the description in the table corresponding to the test (**Tables 3** through **6**).

8. Run the test. Because of the Run History feature, repeating the test keeps the old data, allowing for comparison across multiple tests. The test parameters used for each run are in the Settings tab of each Run History. For unknown or new devices, review the measurements to ensure that the results are reasonable by evaluating the data in the Sheet as well as the plotted values.

   a. Review the plotted data, noting the overall shape and Y-axis values.

   b. Check the status returned from the test. Status = 0 means that the routine did not detect any errors, but the validity of the data must still be assessed; go to the next step. If there is a non-zero status value, refer to the **Table 9** Error Codes to see the explanation and troubleshooting suggestions.

   c. In the Sheet, check the current measurement range used. The column meas_irange, located on the right side of the Sheet, shows the current measure range used for each point. If this range is 1E-6 (1 µA) or lower, skip to the next step. If any of the measure range values is 10E-6 (10 µA) or larger, the results for these rows are suspect. Change the DC bias voltage to reduce the current measure range used for the test. For example, when running a voltage bias sweep, reduce the start and stop voltage used, for example from ±5 V to ±2 V, and re-run the test. Verify that the new test uses a meas_irange 1E-6 (1 µA) or lower, then compare the results to the previous run taken with the 10 µA range. Generally, the results with the 1 µA range are more accurate.

   d. If the Y-axis scale shows the maximum of 7E22 or 70E21, then an overflow has occurred on one or more measurements in the test. Review the data in the Sheet, in the meas_Cp column, for entries of 70E21 or 7E22. There are a few causes of the overflow:

      i. If the overflow values are only at the start and end of the test, consider reducing the range of sweep values to omit the sweep points that cause the overflow values. Another option is to specify appropriate values for expected_C and expected R. Before choosing values for expected_C and expected_R, let's briefly explain how these values affect the test. If the overflow values are most or all of the rows in the meas_Cp column, it is possible that an incorrect measure range was used for the test. This means that the current measure range used for the test was too small for the test parameters and DUT. The measure range used for the test is contained in the meas_irange in the Sheet. The current measure range for the sense SMU instrument is based on the expected_C and expected_R values.

ii. To change the current measure range for a test, supply an expected_C value that is larger than the meas_Cp value. Review the values in the meas_Cp column and choose a representative, non-overflow value and use it to calculate the expected_C = 2 * chosen meas_Cp value. To choose a value for expected_R, review the meas_Gp column for a representative value. Set expected_R = 1/(2 * chosen meas_Gp).

e. If one or more of the meas_Cp values is negative:

i. Ensure that the DUT connections are good.

ii. The D may be too high, or the DC current leakage is too high compared to the capacitance.

1. Review the Sheet for meas_D and meas_irange values. If D > ~10 and or meas_irange is ≥10 nA, the results may have a larger error.

2. Consult **Table 8**. Compare the current measure range (in the meas_irange) column to the corresponding row in **Table 8**. Note that the higher D values are more difficult to test.

3. Try one or more of the following adjustments: a) reduce the DC bias voltage; b) increase the acv_RMS = 0.3 V; c) increase the test frequency.

4. If the meas_Cp values seem noisy or inconsistent, append several tests with identical parameter values and review the data. If the results are different across each run, this indicates that the system is operating at or near the noise floor, which means that the capacitance value of the test device is small, or the test device has a higher D value (**Table 8**).

5. If none of these adjustments provides reasonable results, try a higher frequency C-V test using the CVU, if available.

9. Add tests, such as the capacitance vs. time (test *vlf-cap-time*) or more DC bias sweeps at additional test frequencies. Recall that data may be saved in .xls or .csv file formats by using the Save Data button in the Analyze pane.

Table 9. VLF C-V error codes and descriptions.

Error Code	Description	Explanation and Troubleshooting Recommendation
0	Test executed with no errors	No software or operational errors were detected.
-16001	smu_src is out of range	Specified SMU instrument is not available in the chassis. For example, if SMU5 is entered, but there are only four SMU instruments in the 4200 chassis, then this error will occur. Modify SMU instrument string to an available SMU instrument number: SMU1, SMU2, SMU3 …
-16002	smu_sense is out of range	Specified SMU instrument is not available in the chassis. For example, if SMU5 is entered, but there are only four SMU instruments in the 4200 chassis, then this error will occur. Modify SMU instrument string to an available SMU number: SMU1, SMU2, SMU3 …
-16003	Frequency is out of range.	Ensure that the test frequency is within the range of 10mHz to 10Hz, inclusive
-16004	acv_RMS is out of range	Make sure that the RMS voltage is within the range of 0.01V to 3.0V, inclusive
-16005	dcv_bias is out of range	Modify the DC or AC voltage bias to ensure that the ±20V maximum is not exceeded. Maximum negative voltage = –20 + (AC voltage *) Maximum positive bias voltage = 20 – (AC voltage * √_2)
-16006	hold_time is out of range	This error is unused for the *VLowFreqCV* routines.
-16007	delay_time is out of range	This error is unused for the *VLowFreqCV* routines.
-16008	Too few points per period	This error indicates that the test was aborted by the operator.
-16009	Output array sizes are not equal, or are larger than 4096.	Make sure all output array sizes are the same value and are not greater than 4096.
-16010	Over range indication detected.	Current measurement over-range occurred and returned values are set to 7E22 (70E21). Troubleshooting: Review the value in the meas_CP column of the Sheet, looking for the overflow values (7E22 or 70E21). Follow the process given in **Step 8d**.
-16011	Results array size is less than the number of points in the sweep.	Increase the size of all output arrays to be equal to the number of points in the sweep.
-16012	Could not collect enough data to perform measurement.	Cannot estimate expected_C or expected_R. This error occurs only when expected_C = 0. Input a estimated non-zero value for expected_C. Review the meas_Cp values in the Sheet for non-overflow values. Set estimated_C = 2 * non-overflow meas_Cp
-16013	Unable to allocate memory.	This error is unused for the *VLowFreqCV* routines.
-16014	Current range is out of range.	This error is unused for the *VLowFreqCV* routines.
-16015	Irange_sense and expected_C cannot be 0 at the same time	This error is unused for the *VLowFreqCV* routines.
-16016	expected_C is out of range	expected_C must be 0 (auto-detect C) or between 1E-15 and 1E-3, inclusive.
-16017	This test requires preamp is connected to smu_sense	Make sure preamp is connected to each SMU used in the test. If reconnecting preamps, run run KCON and choose “Update PreAmp and RPM Configuration” in the Tools menu.
-16018	Invalid start, stop, step DC bias sweep values.	Correct the values for the voltage bias sweep. dcv_bias_step cannot be 0, unless dcv_bias_start = dcv_bias_stop. If dcv_bias_start = dcv_bias_stop, then dcv_bias_step must = 0.
-16019	Output array sizes are less than number of points in sweep.	Increase the size of all output arrays to be equal to the number of points in the sweep.
-16020	Invalid combination of start, stop, step dc bias sweep values.	Correct the values for the voltage bias sweep. dcv_bias_step cannot be 0, unless dcv_bias_start = dcv_bias_stop. If dcv_bias_start = dcv_bias_stop, then dcv_bias_step must = 0.

Guidelines for Making Optimal Measurements and Troubleshooting Techniques

When making high impedance, very low frequency C-V measurements using the SMU instruments, various techniques must be used to optimize measurement accuracy. These techniques include implementing low current measurement practices and choosing the appropriate settings in the software.

Implementing Low Current Measurement Techniques

Because using the very low frequency impedance measurement method involves measuring picoamp to femtoamp current levels, low current measurement techniques must be implemented. Use the triax cables that come with the 4200A-SCS, which are shielded and will allow making a guarded measurement, if necessary. To reduce the noise due to electrostatic interference, make sure the device is shielded by placing it in a metal enclosure with the shield connected to the Force LO terminal of the 4200A-SCS. Detailed information on low current measurement techniques can be found in Keithley's Low Level Measurements Handbook. Also, ensure that the triax cable is directly connected to the DUT or probe pins; do not use any switching matrix or 4225-RPM in the SMU instrument signal path.

Choosing the Correct "expected_C" and "expected_R" Values

In most cases, expected_C should be 0 and the expected_R = 1E12 (both are the default values). When expected_C = 0, the VLF C-V routine will determine estimated values for both C and R of the device under test. The estimated R and C values determine the SMU instrument measurement range. If these values are chosen incorrectly, measurement errors or measurement range overflow may result (see **Table 9**, error code -16010 for more information). However, in some cases, entering a non-zero estimated capacitance for expected_C may provide better results for higher D devices or larger DC bias tests. To calculate a value of expected_C, multiply a non-overflow value from the meas_Cp column by two and enter this value into the test definition expected_C.

To determine if a device is compatible with the present VLF C-V approach, measure the DC resistance of the DUT, performing an I-V test using the *smu-vsweep* test, *R-C Circuit VLF-CV Project*. Use the same test voltages in the I-V sweep that will be used in the impedance measurements. Additionally, performing a single measurement (test *vlf-cap-one-point*) or frequency sweep (test *vlf-cap-freq-sweep*) at a DC bias of 0 V will determine the D of the device. Refer to "Testing a Device with VLF C-V" and **Table 8** for additional information.

Conclusion

The 4200A-SCS contains a tool for performing very low frequency C-V measurements using the SMU instruments and preamps. This method enables the user to perform low capacitance measurements at a precise test frequency in the range of 10 mHz to 10 Hz. The Clarius software included with the system enables the user to execute these low impedance measurements easily and extract important parameters about the DUT. When combined with the 4210-CVU or 4215-CVU Capacitance Voltage Unit, the 4200A-SCS offers the user a single system that can perform both high and low frequency measurements.

Appendix A

Very Low Frequency C-V Typical Specifications

MEASUREMENT FUNCTIONS

Measurement Parameters: Cp+Gp, Cp+D, Cs, Rs+Cs, R+jX, Z, theta, frequency, voltage, time.

Connector Type: Two triax (female) connectors.

TEST SIGNAL

Frequency Range: 10 mHz to 10 Hz.

Minimum Resolution: 10 mHz

Signal Output Level Range: 10 mV rms to 3 V rms.

DC BIAS FUNCTION

DC Voltage Bias:

Range: ±20 V[1].

Resolution: 0.5 mV.

Accuracy: ±(0.02% + 1.5 mV).

Maximum DC Current: 1 µA.

SWEEP CHARACTERISTICS

Available Test Types: Linear bias voltage sweep (up or down), frequency list sweep, sample (time), single point

Maximum Number of Measurement Points: 512.

INCLUDED LIBRARIES

- C-V, C-t and C-f modules
- Includes test and projects for:
  - Capacitor
  - MOSCAP
  - nMOS FET
  - R-C circuit

REQUIRED HARDWARE and SOFTWARE

- 4200A-SCS
- Two SMU instruments, 4200-SMU, 4201-SMU, 4210-SMU or 4211-SMU, with Pre-amplifiers (4200-PA)

TYPICAL MEASUREMENT ACCURACY[2]

Frequency	Measured Capacitance	C Accuracy @ 300 mV rms[1]	C Accuracy @ 30 mV rms[1]
10 Hz	1 pF	10%	13%
	10 pF	10%	10%
	100 pF	5%	5%
	1 nF	5%	9%
	10 nF	5%	5%
1 Hz	1 pF	2%	2%
	10 pF	1%	2%
	100 pF	2%	1%
	1 nF	2%	1%
	10 nF	2%	2%
100 mHz	1 pF	2%	3%
	10 pF	2%	2%
	100 pF	2%	2%
	1 nF	1%	2%
	10 nF	2%	1%
10 mHz	1 pF	5%	10%
	10 pF	1%	2%
	100 pF	1%	1%
	1 nF	1%	1%
	10 nF	2%	2%

NOTES

1. ±20 V maximum includes the DC Bias and the AC Test Signal peak voltage. Maximum negative bias voltage = –20 + (AC voltage * $\sqrt{2}$). Maximum positive bias voltage = 20 – (AC voltage * $\sqrt{2}$).
2. Test device must have dissipation factor D_X <0.1. All data shown for DC Bias voltage = 0 V.

All specifications apply at 23°C ±5°C, within one year of calibration, RH between 5% and 60%, after 30 minutes of warmup.

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