Using the Ramp Rate Method for Making Quasistatic C-V Measurements with the Model 4200-SCS Semiconductor Characterization System

Introduction

Capacitance-voltage (C-V) measurements are generally made using an AC measurement technique. However, some capacitance measurement applications require a DC measurement technique. These are called *quasistatic* C-V (or QSCV) measurements because they are performed at a very low test frequency, that is, almost DC. These measurements usually involve stepping a DC voltage and measuring the resulting current or charge. Some of the techniques used for quasistatic C-V measurements include the *feedback charge method* and the *linear ramp method*. The Model 4200-SCS Semiconductor Characterization System uses a new method, the ramp rate method, which employs two Model 4200-SMUs Source-Measure Units (SMUs) with two Model 4200-PA PreAmps. The optional 4200-PA PreAmps are required because this test involves sourcing and measuring current in the picoamp range. The SMUs are used to source current to charge the capacitor, and then to measure the voltage, time, and discharge current.

The software calculates the capacitance as a function of voltage from the measured parameters and shows the curve on the Model 4200-SCS's display. The software to execute the ramp rate method is included in version 7.1 and higher of the Keithley Test Environment Interactive (KTEI) software. This application note describes how to implement and optimize quasistatic C-V measurements using the Model 4200-SCS and the ramp rate method. It assumes the reader is familiar with making I-V measurements with the Keithley 4200-SCS at the level outlined in the Model 4200-SCS Reference Manual.

Ramp Rate Method

Figure 1 illustrates the basic connection diagram for the ramp rate method. This configuration requires two 4200-SMUs with 4200-PAs connected to either side of the device under test. Because the ramp rate method works over a limited range, the capacitance of the device under test should be in the range of 1pF to about 400pF.

Basically, the ramp rate method works by charging up the device under test to a specific DC voltage using an SMU as a current source. Once the device is charged up, a current of the opposite polarity is forced to discharge the device as the SMU measures voltage as a function of time. A second SMU measures the discharge current. From the measured voltage (V), current (I) and time (t) values, the capacitance (C) is derived as a function of voltage and time:
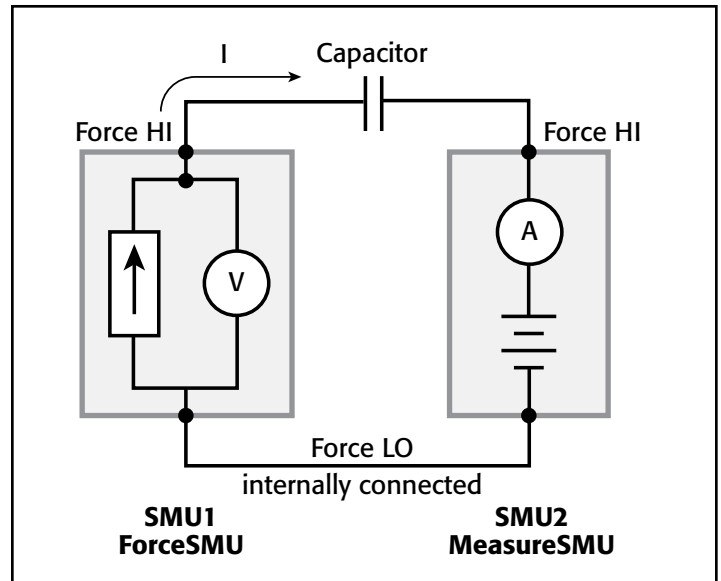

Figure 1. Connections for Capacitance Measurements Using Ramp Rate Method

$$C = \frac{dQ}{dV}$$

$$Q = \int I\,dt$$

The ramp rate method included with the 4200-SCS follows these steps when making QSCV measurements:

1. **Charge the Device:** A precharge current of 100pA is applied to the DUT by an SMU, called *ForceSMU*, until the compliance voltage is reached. The compliance voltage is user specified and is called *VStart*. The polarity of the precharge current is the same as the polarity of the *VStart* voltage. If the precharge current is not sufficient to force the device to *VStart*, then a timeout error will be generated.

2. **Bias the Device for Specified Time Prior to Sweep:** The device is biased at the *VStart* voltage for a user specified time (*PreSoakTime*) prior to the sweep.

3. **Apply Ramp Current to Discharge Device:** Once the device is biased for a specified time, a ramp rate current is applied to the device to discharge the device. The ramp rate current is of the opposite polarity as the precharge current. The value of the ramp current is:

$$I_{ramp} = CVal \times RampRate$$

where:

CVal = the estimated capacitance value input by the user in farads (F).

RampRate = user input slope of stimulus voltage (dV/dt) in V/s.

4. **Simultaneously Trigger SMUs to Take Measurements:** The SMU that is the *ForceSMU* measures voltage (V1, V2, T3 … Vn) and time (T1, T2, T3 … Tn). The SMU that is the *MeasureSMU* measures the current (I1, I2, I3 … In). The voltage, time, and current measurements are made until the opposite polarity of the *VStart* voltage is reached.

5. **Calculate Voltage, Time, and Capacitance Output Values:** In real time, parameters are extracted from the measurements and will appear in the Sheet or Graph. These parameters are V_{out} = voltage, T_{out} = time, and C_{out} = capacitance, and are calculated as follows:

$$V_{out} = \frac{(V2 + V1)}{2} \text{ (the average of two measured voltages)}$$

T_{out} = T2 (the time when the second measurement is made)

$$C_{out} = \frac{I2}{(dV/dt)}$$

where dV = V2 – V1 and dT = T2 – T1.

How to Make QSCV Measurements Using the KITE Software

The system's software includes a module to make quasistatic C-V measurements using the ramp rate method. This module, *meas_qscv*, located in the *QSCVulib* user library, can be opened up as a UTM from within a project.

Setting up the Parameters in the *meas_qscv* Module

Once you've opened the module up into a project, you need to input a few parameters. The adjustable parameters for the *meas_qscv* module are listed in *Table 1*.

Table 1. List of Adjustable Parameters in *meas_qscv* Module

Parameter	Range	Description
ForceSMU	1–8	SMU number that will force current through capacitive load. This SMU must have a preamp.
MeasureSMU	1–8	SMU number that will measure current. This SMU must have a preamp.
VStart	–200 to 200	Starting and ending voltages (V) for C-V sweep.
CVal	1E–12 to 400E–12	Approximate capacitance of device under test in Farads (F).
RampRate	0.1 to 1	Slope of stimulus voltage (dV/dt) in V/s.
PreSoakTime	0 to 60	Additional time delay in seconds to allow DUT, fixture, and cables to charge up.
TimeOut	10 to 60	Time allowed in seconds to charge up prior to time out.

Here's a more detailed description of the input parameters:

ForceSMU: The SMU that will force current to the device under test and measure the voltage as a function of time. This SMU must have a preamp because it will be sourcing current in the picoamp range.

MeasureSMU: The SMU that will measure the current flow in the circuit. This SMU must have a preamp because it will be measuring current in the picoamp range.

VStart: This is both the starting and ending voltage of the C-V sweep because the C-V sweep is always symmetrical about 0V.

CVal: Enter at least the approximate maximum capacitance value of the device under test. This value is used to determine the magnitude of the source current to charge the device.

RampRate: The slope of the stimulus voltage in V/s. If the ramp rate is too fast, there will not be enough data points in the sweep. If the ramp rate it too slow, the readings may be noisy. Some experimentation may be needed to find the optimal setting for a particular device.

PreSoakTime: The length of time in seconds to apply the *VStart* voltage to the device prior to the start of the C-V sweep. Specify sufficient time for the device to charge up and reach equilibrium.

TimeOut: The amount of time allowed to charge the device to the *VStart* voltage until the test module times out. In some cases, such as when a device is shorted, the device may not reach the *VStart* voltage; this parameter enables the module to stop automatically and generate an error message. By default, this is set to 10 seconds.

Executing the Test

The *meas_qscv* module can be opened up in a project using a UTM (User Test Module). However, Keithley has already created a project called qscv that makes quasistatic C-V measurements using this module. It can be found at the following address on the Model 4200-SCS's hard drive:

C:\S4200\kiuser\Projects_CV

The project tree for the *qscv* project is shown in *Figure 2*.

This project contains a UTM called *CVsweep* for making C-V measurements on a MOSFET device. The Definition Tab of *CVsweep* UTM is shown in *Figure 3*.

In this UTM, SMU1 (*ForceSMU*) and SMU2 (*MeasureSMU*) are used to make the C-V measurements. The *VStart* value is set to 4V, so this will generate a voltage sweep from –4V to 4V. The approximate capacitance value is 10pF, so this was entered as the *CVal* parameter. This *CVal* capacitance value will be used to determine the ramp rate current. If this number is too low (for example, 1E–12 instead of 10E–12), then the capacitance measurements will appear noisy. The *RampRate* value was set to 0.7V/s. In this case, a *RampRate* that is larger (1V/s) will produce
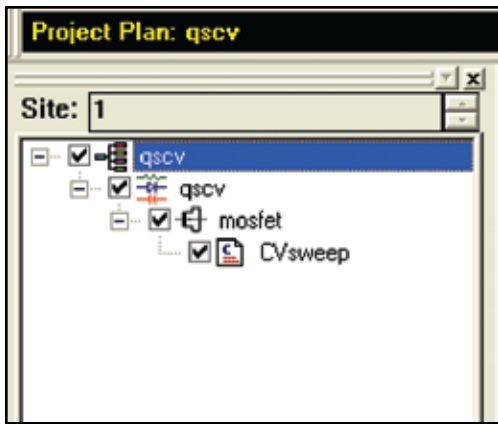
Figure 2. Project Tree for *qscv* Project

Figure 3. Definition Tab of *CVsweep* UTM of *qscv* Project

Figure 4. C-V Sweep of MOSFET device

a somewhat quieter curve but will have fewer data points. A *RampRate* that is smaller (0.1V/s) will produce a much noisier curve with lots of data points. You will need to experiment in order to determine the optimal settings for a particular device under test.

Once the device is connected to the two SMUs and the UTM is created with the desired input parameters, the C-V sweep can be executed. The results of such as sweep are shown in *Figure 4*.

Optimizing Measurements

When making quasistatic C-V measurements using the ramp rate method, 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.

Because using the ramp rate method involves sourcing and measuring picoamp-level current, low current measurement techniques must be implemented. Use the triax cables that come with the 4200-SCS, which are shielded and will allow making a guarded measurement. To reduce noise due to electrostatic interference, make sure the device is shielded by placing it in
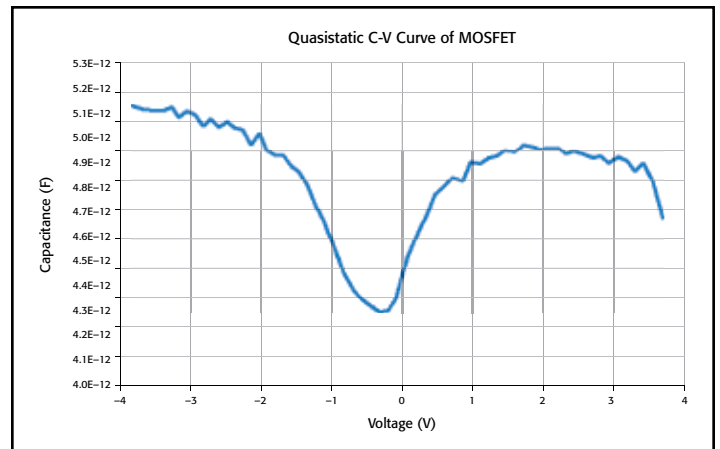
a metal enclosure with the shield connected to the Force LO terminal of the 4200-SCS. Detailed information on low current measurement techniques can be found in Keithley's *Low Level Measurements Handbook*.

The parameter settings in the *meas_qscv* module that will most affect the measurements are *CVal* and *RampRate*. *CVal* is the approximate value of the device under test. If you input a value that is larger than that of the actual device, then the *RampRate* will be larger and there will be fewer data points. Conversely, if the capacitance value entered is smaller than the actual device capacitance, the *RampRate* will be lower and there will be more data points in the curve. Use the largest *RampRate* possible, but ensure the device curve appears settled. However, if the *RampRate* is too fast, there may not be enough points in the sweep.

To reduce the noise level of the curve, the moving average (MAVG) function in the Formulator can be used. Try using a moving average of three readings to see if this helps. Do not set the moving average number so large so that you lose the shape of your C-V curve.

To subtract the offset due to the cables and probe station, generate a C-V sweep using the *meas_qscv* module with the probes up or with an open circuit in the test fixture. Using the Formulator, take an average of the readings. Subtract this average offset value from capacitance measurements taken on the device under test.

Conclusion

Quasistatic C-V measurements can be made with the 4200-SMUs using the ramp rate method. This technique is implemented in software in the *meas_qscv* module of the *QSCV_uslib* user library of the 4200 KITE software. Using low level measurement techniques and choosing the appropriate parameter settings in the software will ensure optimal results.

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