Using the 4200A-CVIV Multi-Switch to Make High Voltage and High Current C-V Measurements

APPLICATION NOTE

KEITHLEY
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Introduction

Traditional capacitance-voltage (C-V) testing of semiconductor materials is typically limited to about 30 V and 10 mA DC bias. However, many applications, such as characterizing C-V parameters of LD MOS structures, low interlayer dielectrics, MEMs devices, organic TFT displays, and photodiodes, require higher voltage or higher current C-V measurements. For these applications, a separate high voltage DC power supply, a capacitance meter and bias tees are required to make the measurements.

The 4200A-CVIV Multi-Switch is a four-channel multiplexed switching accessory for the 4200A-SCS that allows users to switch seamlessly between I-V and C-V measurements. It accepts four SMUs, one for each channel, and one 4210-CVU for capacitance-voltage measurement as inputs. Changing the output mode for each of the four channels reconfigures the internal switches of the 4200A-CVIV to route the desired signals to the output terminals.

Beginning with Clarius V1.4, the 4200A-CVIV supports a bias tee on each of its four channels to allow DC biasing of AC signals at the channel outputs. The bias tee modes use the 4210-CVU to measure the capacitance and the 4200 SMUs to sweep the voltage or apply a DC bias of up to ±200 V, or 400 V differential. The bias tees also enable a current limit of up to 100 mA or 1 A, depending on the SMU, either the 4200-SMU or 4210-SMU.

This application note explains the implementation of the bias tee modes of the 4200A-CVIV to make high voltage C-V measurement. It assumes the reader is familiar with making C-V measurements with the Keithley 4200A-SCS using the CVIV.

Bias Tee Theory Overview

A typical bias tee uses a capacitor to isolate the C-V instrument from interfering with DC measurements and an inductor is used in series with the SMU to isolate the SMU from interfering with AC measurements as shown in **Figure 1**.

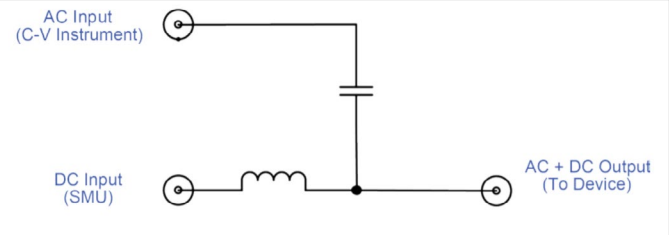

Figure 1: Typical Bias Tee Block Diagram

From the above schematic both the C-V instrument and the I-V measuring instrument (SMU) can be simultaneously connected to one device terminal. This will enable high voltage C-V testing.

Device Connections

All the connections in this application note are made through the 4200A-CVIV. The CVIV could have one 4210-CVU and up to four SMUs connected to it at the same time. Please refer to the 4200A-CVIV Multi-Switch User's Manual for more information.

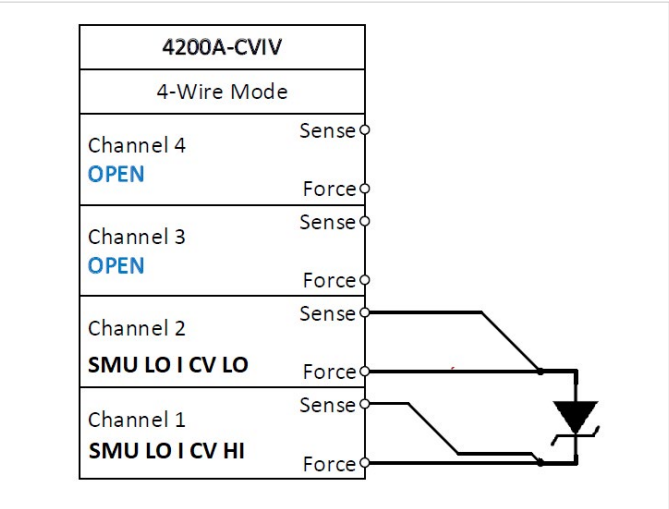

Figure 2: High Voltage C-V Connections for Zener Diode using the CVIV

Figure 2 shows the device connections and 4200A-CVIV settings for a high voltage C-V test on a Zener diode using the bias tee modes. The connections to the Zener diode are made with triaxial cables, Model 4200-TRX-.75 (75cm or approximately 30 inches). These shielded cables are used to ensure that both very low current I-V measurements and high frequency AC measurements can be made with high accuracy. The device can be a packaged part in a test fixture or located directly on a wafer in a probe station.

Configuring High Voltage C-V Measurements Using the Clarius Software

The 4200A-CVIV is controlled using the Clarius software application that comes with the 4200A-SCS Parameter Analyzer. The Clarius software includes a library that contains tests and a project for making high voltage C-V measurements through the 4200A-CVIV. You can easily find these tests and projects in the library by using the key word search and filters.

A project titled, *cviv-bias-highv*, contains test modules that perform high-voltage C-V measurements using a 4210-CVU, 4200-SMU or 4210-SMU and a 4200A-CVIV on a Zener diode, MOS capacitor, capacitor, and Schottky diode. A user may use/modify the project, or create a new project to use the Bias Tee modes as long as the *hivculib* user library is used, which will be discussed later. This section will discuss the various bias tee modes that could be used. It will also show how to configure the tests in Clarius as well as using the different modules that are associated with the test. **Figure 3** shows the high voltage C-V project.

Bias Tee modes

Figure 4 shows the various bias tee modes that can enabled in Clarius using the CVIV.

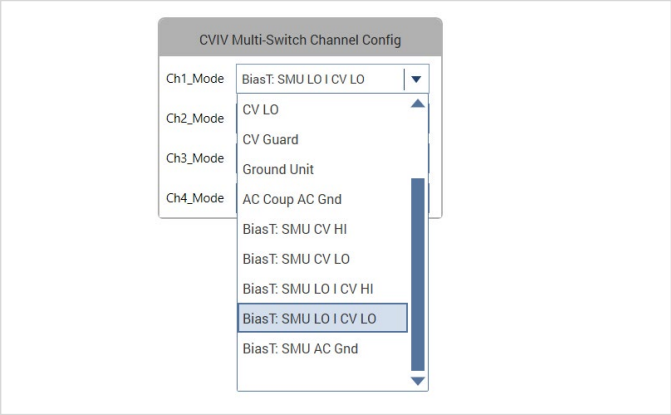

Figure 4: Bias Tee Modes

The bias tee modes of the 4200A-CVIV are described below:

- **BiasT SMU CV HI and BiasT SMU CV LO** – This is the bias tee high-current SMU configuration with a CV HI or LO switching configuration. This combines the DC bias from a 4200-SMU or 4210-SMU with an AC signal from the 4210-CVU through the CV HI or LO

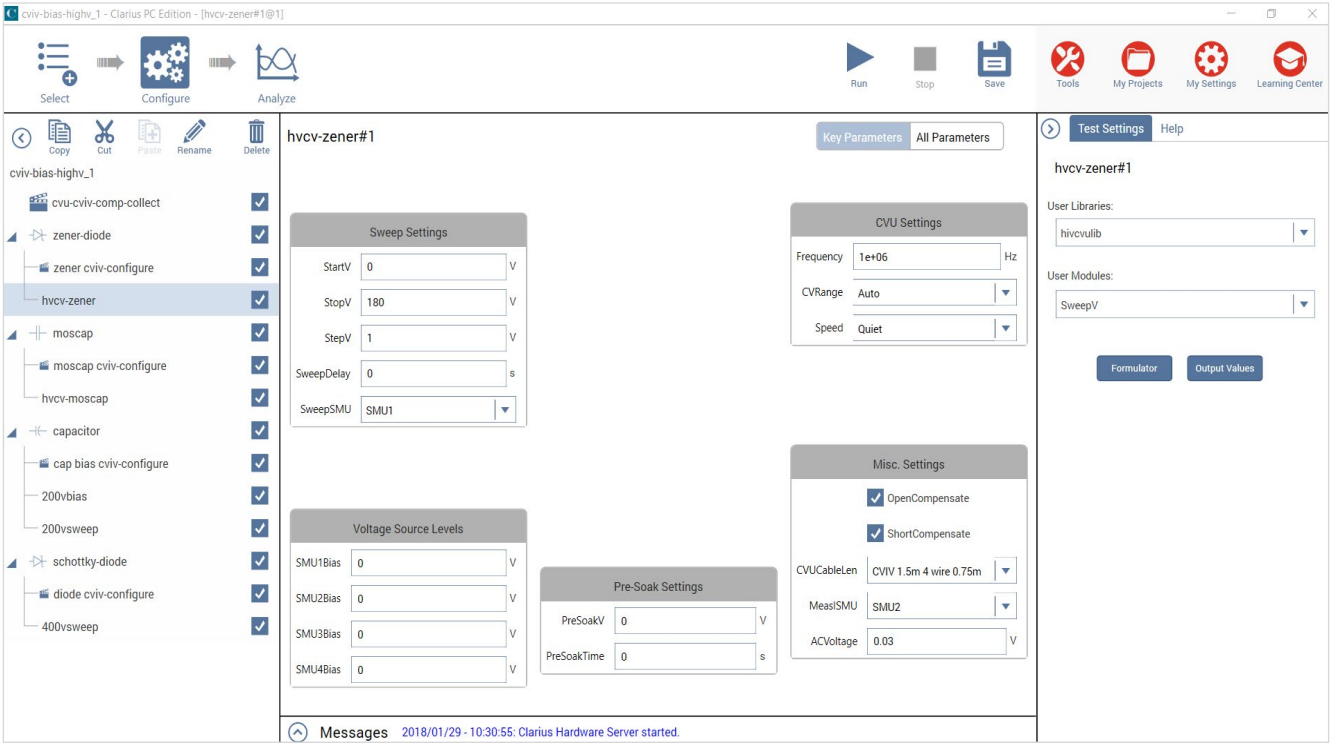

Figure 3: High Voltage C-V Project

of the 4200A-CVIV bias tee circuit. This mode is ideal for performing C-V measurements where a DC bias current of up to 1 A is required, such as when making C-V measurements on a semiconductor device in the on-state. On a two-terminal device, connect both CVU HI or LO and SMU to each output channel as shown in **Figure 5**.

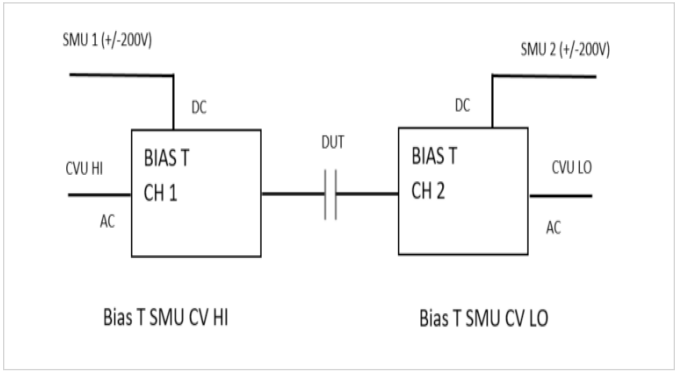

Figure 5: BiasT SMU CV HI or LO Channel Configuration

- **BiasT SMU LO I CV HI and BiasT SMU LO I CV LO** – This is the bias tee low-current SMU configuration with a CV HI or LO switching configuration. This combines the DC bias from a 4200-SMU or 4210-SMU with an AC signal from CV HI or LO through the 4200A-CVIV bias tee circuit. This mode is optimized for use with currents below 100 µA, and is the preferred mode for semiconductors in the off-state. On a two-terminal device, connect both CVU HI or LO and SMU to each output channel as shown in **Figure 6**.

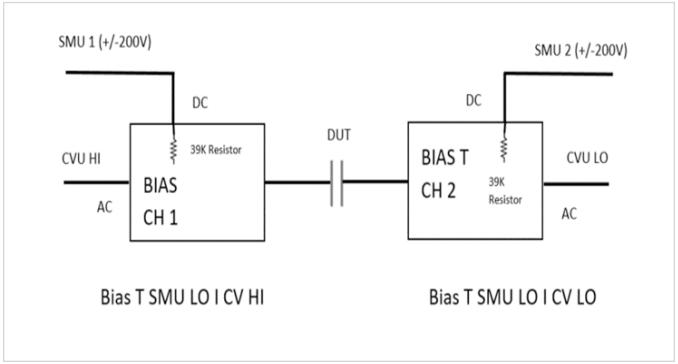

Figure 6: BiasT SMU LO I CV HI or LO Channel Configuration

- **BiasT SMU AC Gnd:** This is the bias tee mode with an AC ground configuration. This combines the DC bias from a 4200-SMU or 4210-SMU with local AC ground through the 4200A-CVIV bias tee circuit. A typical application for this configuration would be when performing C-V measurements on the drain to the source of a MOSFET while applying a DC bias to the gate, just like shown in **Figure 7**. AC signals at the gate would have a ground return path.

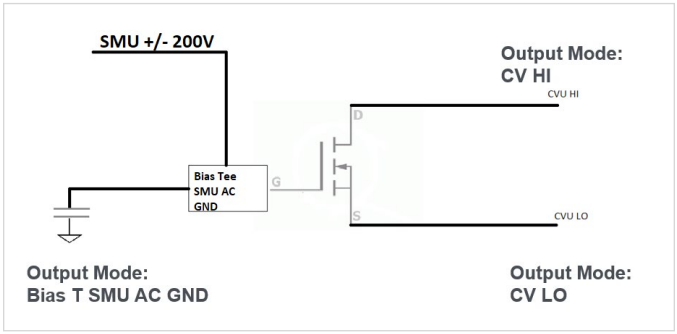

Figure 7: Bias Tee SMU AC GND Channel Configuration

Configuring a Test

Figure 8 shows the project tree for a zener diode test example. *The cvu- cviv- comp-collect* action is added to the project tree to aquire compensation data. Also, the CVIV configuration action, *zener cviv-configure*, is added before device testing to enable the bias tees modes. Both of these actions as well as the *hvcv-zener* test will be explained in details.

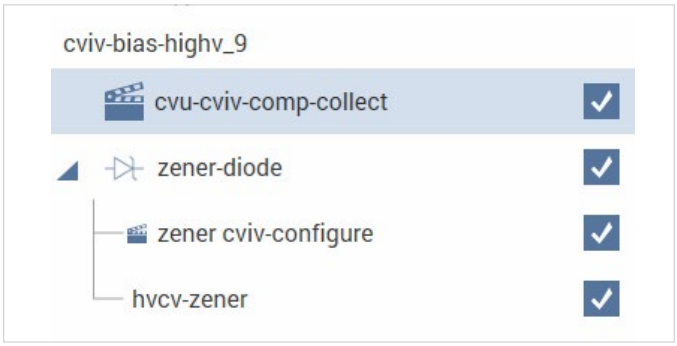

Figure 8: Project Tree

- **CVU CVIV compensation collect (cvu-cviv-comp-collect) – Figure 9** shows the CVU compensation action window. Based on the selected options, the action will collect the compensation data of the CVU instrument connected to the 4200A- CVIV unit. A message box will appear before each selected action to notify the user of the proper setup of the CVIV output connections. This user module also configures the 4200A-CVIV relays and display for each channel. For this device, the BiasT SMU LO I CV HI and BiasT SMU LO I CV LO output configurations were selected. Once the action is completed, the return value should be 0 under the analysis tab. Please refer to the help pane in Clarius for more information.

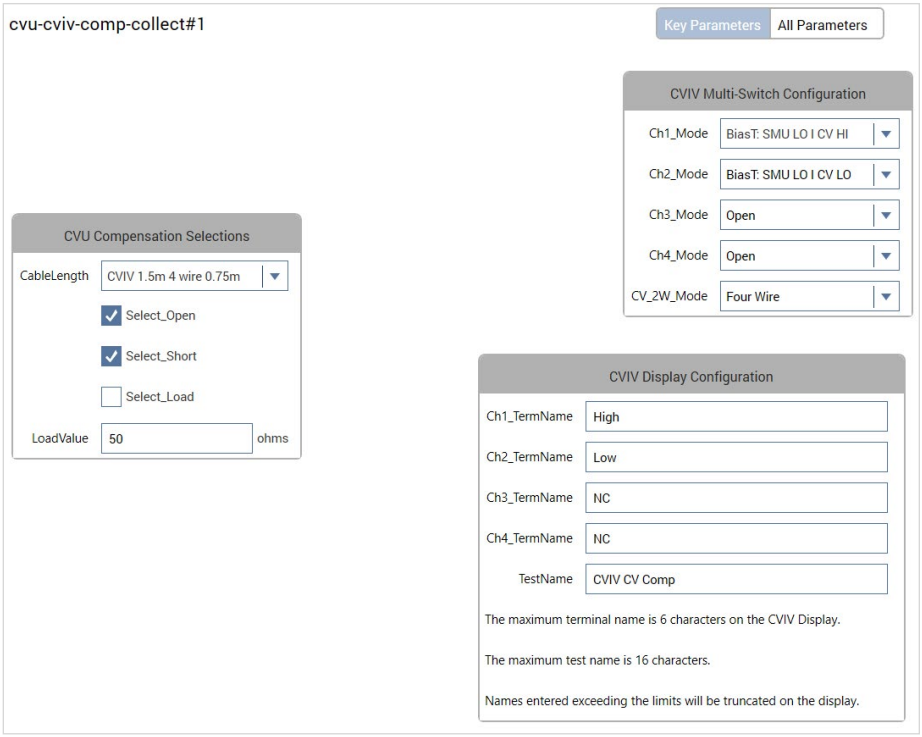

Figure 9: CVU-CVIV-Comp-Collect

- **CVIV Configuration:** The *zener-cviv-configure* action is used to switch the channel output configuration, two-wire/four-wire CVU setting, and the names of the test and channels to be shown on the 4200A-CVIV display. A *cviv-configure* action must be used any time the output configuration of the 4200A-CVIV needs to change. **Figure 10** shows the configurations for this action.

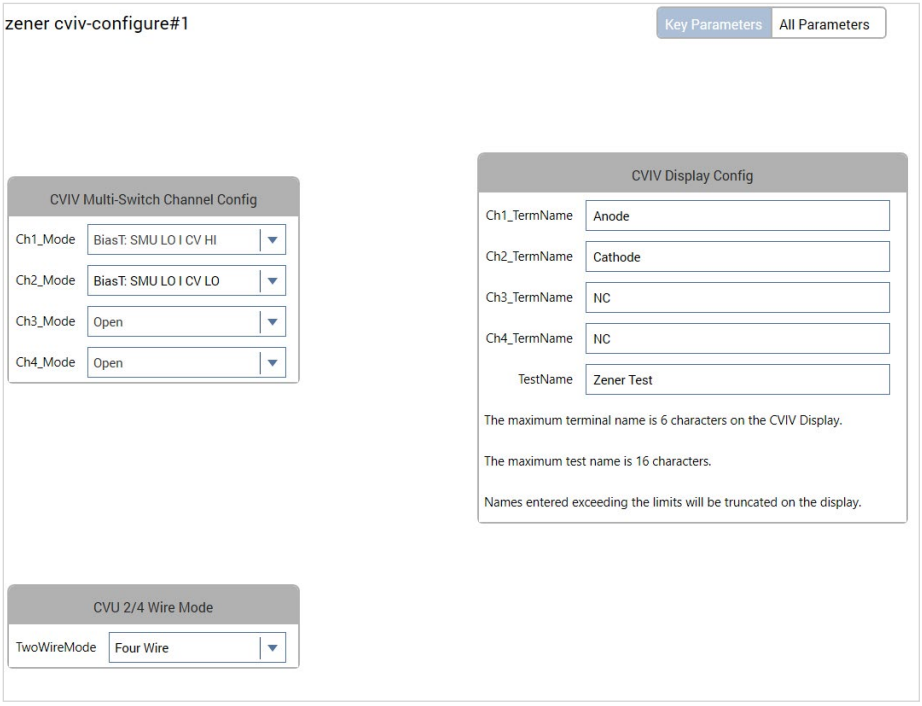

Figure 10: CVIV Configure

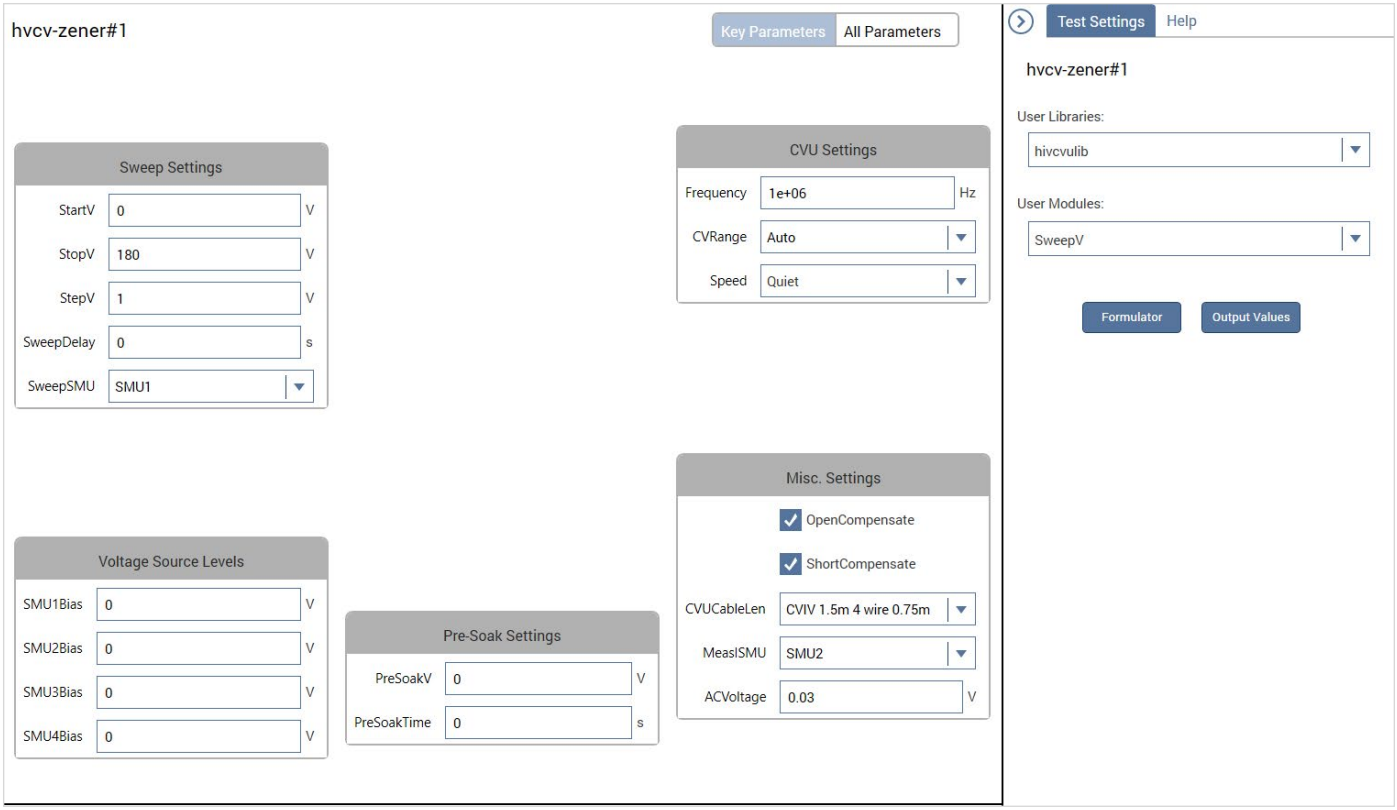

Figure 11: SweepV user Module for High Voltage CV measurement

- **HVCV- Zener Test Module: Figure 11** shows the user test module (UTM) GUI. Using the Clarius Software to Control High Voltage C-V Measurements. *hivcvulib user* library contains two modules, *SweepV* and *CvsT*, for controlling the high voltage C-V measurements. These modules can be used with either one or two bias tee configurations. Using one bias tee, the *SweepV* module allows the user to sweep a DC voltage across the DUT using the 4200-SMU and measure the capacitance using the 4210-CVU. If two bias tees are used with the *SweepV* module, then one SMU is used to sweep the DC voltage and the other SMU is used to apply an offset DC bias (as shown in **Figure 5**). The *CvsT* module provides capacitance measurements as a function of time at a user-specified DC bias. This module can also be used with either one or two bias tees. With one bias tee and one SMU, capacitance measurements can be made with up to 200 V DC bias. With two bias tees and two SMUs, capacitance measurements can be made up to 400 V DC differential. These user modules can be added to a project by selecting a Custom Test from the Test Library. However, a project has already been created that uses these test modules. This project, called *High Voltage C-V Tests (cvu_highv)*, can be found in the Project Library by searching for “high voltage C-V”. This project uses both the *SweepV* and *CvsT* user modules to make measurements on devices.

Setting up the Parameters in the SweepV Module:

The *SweepV* module has settings for the 4210-CVU and up to four 4200-SMUs in the test setup. One SMU is used for the voltage sweep in the C-V measurements. Up to three other SMUs can be used to output a DC bias. One SMU can also be used to measure current.

Here is a description of the input parameters:

OpenCompensate: Once the compensation procedure is performed, it can be enabled in this module by selecting the OpenCompensate parameter in the Key Parameters pane.

ShortCompensate: Once this compensation procedure is performed, short compensation can be enabled in the SweepV module by checking ShortCompensate in the Key Parameters pane.

CVUCableLen: Input the length of the CVU cables. By default, this is set to CVIV 1.5 m 4 wire 0.75 m: 1.5 m references the length of the standard SMA cables that come with the 4210-CVU, Keithley P/N CA-447A. 0.75 m references the standard CVIV output cables. The user may also choose the 2 wire option.

SweepSMU: This is the number of the SMU that will force the sweep voltage in the C-V sweep.

MeasISMU: The user inputs the number of the SMU that will measure current in the circuit. If the SMU that is measuring current is not the SMU that is used to sweep voltage (SweepSMU), then the current range is set to limited autorange –100 nA range. If the SMU that is measuring current is the same as the SweepSMU, then the current range is set to limited autorange on the 10 µA range. If this is the case, additional sweep delay time needs to be added to ensure a settled reading. It also may be necessary to use PreSoakV and PreSoakTime to charge up the device to the first step in the sweep prior to taking the current measurements.

StartV, StopV, StepV: Input the start, stop, and step size voltages for the C-V sweep.

SweepDelay: The time between steps in the voltage sweep. Allow an adequate delay time to ensure the device reaches equilibrium. If measuring current through the bias tee, additional SweepDelay time may need to be added to ensure optimal results.

PreSoakV: This is the voltage bias output by the SweepSMU prior to the start of the voltage sweep.

PresoakTime: This is the length of the time in seconds for the PreSoakV voltage to be applied to the device. You can verify how much time is required for the device to reach equilibrium by using the *CvsT* module in the *hivcvulib*. This module measures the capacitance as a function of a time while the device is biased with a constant DC voltage. The settling time can be observed from the graph.

SMU1Bias, SMU2Bias, SMU3Bias, SMU4Bias: In addition to an SMU supplying a voltage for the C-V sweep, up to four more SMUs can be used to bias other parts of the test circuit.

Frequency: Test frequency of CVU, which can be set to 10 kHz, 20 kHz, 30 kHz, 40 kHz, 50 kHz, 60 kHz, 70 kHz, 80 kHz, 90 kHz, 100 kHz, 200 kHz, 300 kHz, 400 kHz, 500 kHz, 600 kHz, 700 kHz, 800 kHz, 900 kHz and 1 MHz. For higher capacitance values, the test frequency may need to be lowered through the bias tee to avoid errors due to resonance.

ACVoltage: The amplitude of the AC voltage output of the CVU.

Speed: The speed time can be set as: 0 = FAST, 1 = NORMAL, and 2 = QUIET. The FAST mode has the fastest time but the highest noise. The NORMAL mode is the most common setting, which allows sufficient settling times for most measurements. The QUIET mode ensures high accuracy but a slower settling time. The QUIET mode allows more time for DC settling and provides longer integration time.

CVRange: This is the AC ammeter measurement range of the CVU. The input values are 0 for autorange, 1 µA, 30 µA, and 1 mA ranges.

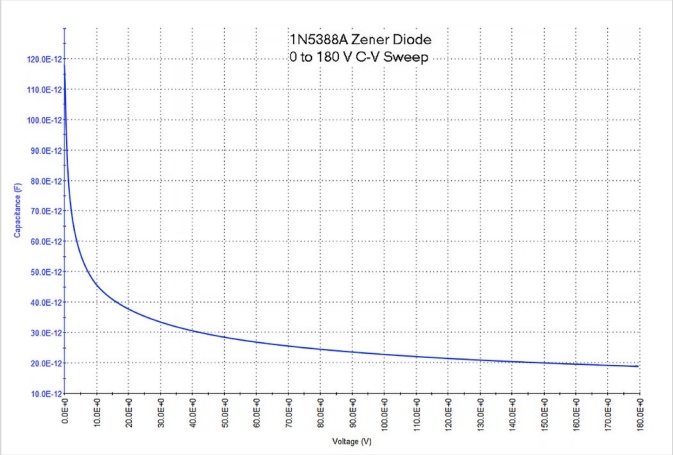

Figure 12: Results of C-V Sweep of Zener Diode

Figure 12 shows the results of the Zener diode sweep. This test is set up to reverse bias the Zener diode from 0 to 180 V in 1 V steps. The capacitance as a function of voltage is plotted in the graph in the Analyze pane.

Setting Up the Parameters in the CvsT Module

This module has settings for the CVU and up to four SMUs in the test circuit. One or two SMUs can be connected to one or two bias tees to output voltage. It is not necessary to specify which SMUs are connected to the bias tees. This is done through the hardware configuration, and then the user inputs in the test the voltage output of those SMUs. Two or three other SMUs can also output voltage in the circuit. One SMU can be used to measure current.

Here is a description of the input parameters for the *CvsT* module:

OpenCompensate: Once the compensation procedure is performed, it can be enabled in this module by selecting the OpenCompensate parameter in the Key Parameters pane.

ShortCompensate: Once this compensation procedure is performed, short compensation can be enabled in the *SweepV* module by checking ShortCompensate in the Key Parameters pane.

CVUCableLen: Input the length of the CVU cables. By default, this is set to CVIV 1.5 m 4 wire 0.75cm, the length of the SMA cables that come with the 4210-CVU, Keithley P/N CA-447A and the cables that come out of the CVIV. The user might also choose the 2-wire option.

MeasISMU: The user inputs the number of the SMU that will measure current in the circuit. The current range is set to limited autorange to the 100 nA range.

SampleCount: Enter the number of capacitance measurements from 1 to 10000.

Interval: This is the time between readings in seconds.

SMU1Bias, SMU2Bias, SMU3Bias, SMU4Bias: Up to four SMUs can be used to bias the test circuit. One or two of these SMUs is connected through a bias tee(s) to supply voltage to the DUT for the C-V measurement.

Frequency: Test frequency of CVU which can be set to 10 kHz, 20 kHz, 30 kHz, 40 kHz, 50 kHz, 60 kHz, 70 kHz, 80 kHz, 90 kHz, 100 kHz, 200 kHz, 300 kHz, 400 kHz, 500 kHz, 600 kHz, 700 kHz, 800 kHz, 900 kHz and 1 MHz. For higher capacitance values, the test frequency may need to be lowered through the bias tee to avoid errors due to resonance.

ACVoltage: The amplitude of the AC voltage output of the CVU.

Speed: The speed time can be set as: 0 = FAST, 1 = NORMAL, and 2 = QUIET. The FAST mode has the fastest time but the highest noise. The NORMAL mode is the most common setting, which allows sufficient settling times for most measurements. The QUIET mode ensures high accuracy but a slower settling time. The QUIET mode allows more time for DC settling and provides longer integration time.

CVRange: This is the AC ammeter measurement range of the CVU. The input values are 0 for autorange, 1 µA, 30 µA, and 1 mA ranges.

Capacitor Testing

Two tests exist in this project for testing capacitors: one applies a constant 200 V bias and the other sweeps the voltage from –200 V to 200 V. To perform these tests, the capacitor is connected to the test system using the bias tee modes as shown in **Figure 5**. High voltage capacitance vs. time measurements can be made using the *200vbias* test, which was created using the *CvsT* module. This module applies 200 V to a 100 pF capacitor, measures the capacitance as a function of time, and plots the data in the graph. The results are shown in **Figure 13**. This module can be used to determine how much settling time to use during an actual C-V sweep.

In *200Vsweep* test, the CVU measures the capacitance while an SMU sweeps the test voltage from –200 V to +200 V. The results of the C-V sweep of the 100 pF capacitor are shown in **Figure 14**.

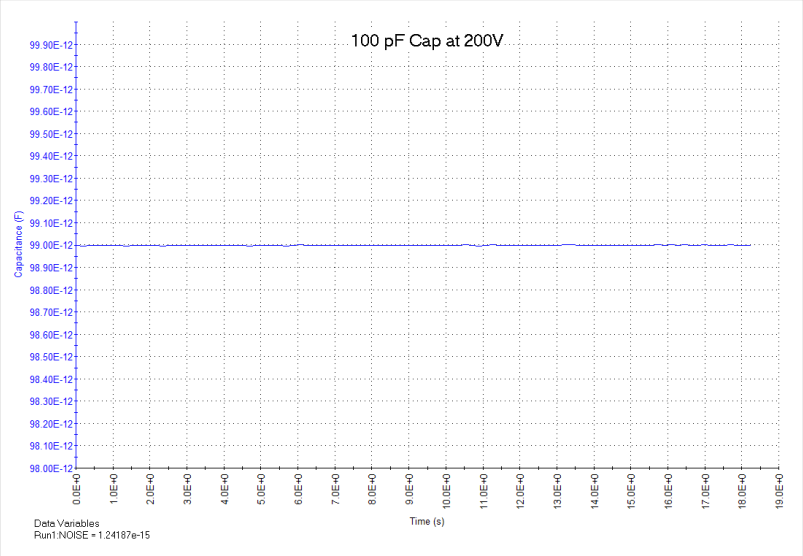

Figure 13: Capacitance vs. Time Measurements

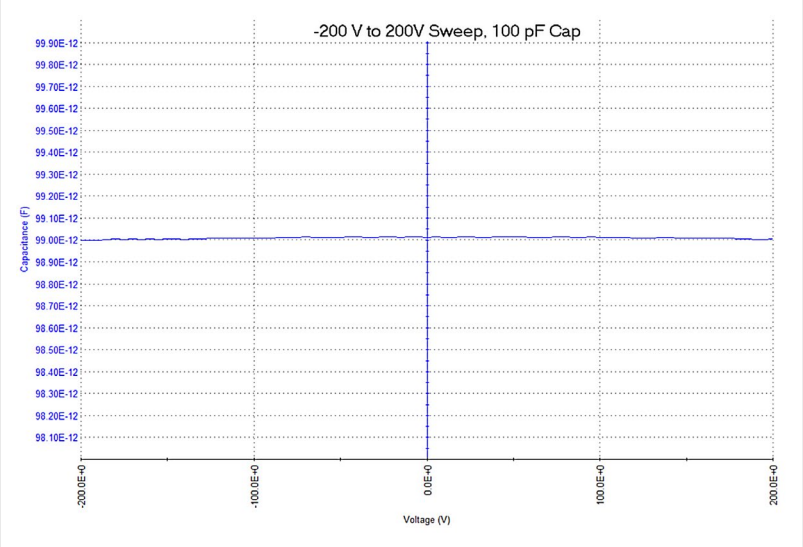

Figure 14: ±200 V Sweep on 100 pF Capacitor

Test System Safety

Many electrical test systems or instruments are capable of measuring or sourcing hazardous voltage and power levels. It is also possible, under single fault conditions (e.g., a programming error or an instrument failure), to output hazardous levels even when the system indicates no hazard is present. These high voltage and power levels make it essential to protect operators from any of these hazards at all times.

Protection methods include:

- Design test fixtures to prevent operator contact with any hazardous circuit.
- Make sure the device under test is fully enclosed to protect the operator from any flying debris.
- Double insulate all electrical connections that an operator could touch. Double insulation ensures the operator is still protected, even if one insulation layer fails.
- Use high reliability, fail-safe interlock switches to disconnect power sources when a test fixture cover is opened.
- Where possible, use automated handlers so operators do not require access to the inside of the test fixture or have a need to open guards.
- Provide proper training to all users of the system so they understand all potential hazards and know how to protect themselves from injury.

It is the responsibility of the test system designers, integrators, and installers to make sure operator and maintenance personnel protection is in place and effective.

Conclusion

Using the 4200A-CVIV bias tee modes allows making C-V measurements with a DC voltage bias of up to ±200 V or 400 V differential and a current output of up to 100 mA or 1 A, depending on the SMU. To achieve the higher test voltage and current, the AC and DC signals are coupled from the 4210-CVU and 4200-SMU (or 4210-SMU) using Bias Tees modes provided in the CVIV. Software that allows making either high voltage C-V sweeps or capacitance measurements at a constant DC voltage is included with the 4200A. Example tests are included for a Zener diode, MOS capacitor, capacitor, and Schottky diode. These tests can be easily modified to measure other devices or new tests can be created by opening a new test in another project. Like C-V measurements in general, high voltage C-V measurements require using appropriate measurement techniques and connections to ensure optimal results.

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