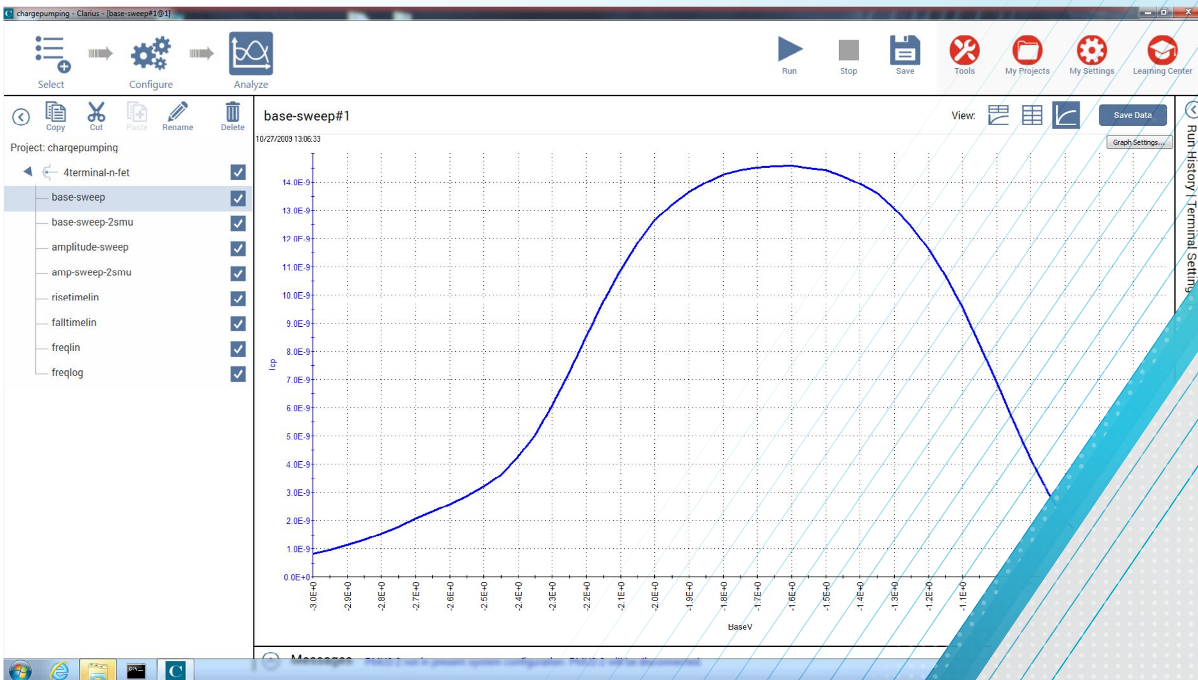
Performing Charge Pumping Measurements with the 4200A-SCS Parameter Analyzer

APPLICATION NOTE



KEITHLEY
A Tektronix Company

Tektronix®

Introduction

Charge pumping (CP) is a well-known measurement technique for analyzing the semiconductor–dielectric interface of MOS structures. Important information about the quality and degradation of a device can be extracted from charge pumping current (I_{CP}) measurement results, including the interface trap density and the mean capture cross section. Pulsing a gate voltage and measuring a DC substrate current simultaneously is the basis for the various charge pumping methods, so a pulse generator and sensitive DC ammeter are required to make these measurements.

The 4200A-SCS Parameter Analyzer offers a complete solution for charge pumping measurements because it contains the necessary hardware to make the sensitive measurements, as well as software to automate the measurements and analyze the results. This system is provided with predefined tests for making most of the common charge pumping tests, such as a pulsed base voltage sweep or a pulsed voltage amplitude sweep. This application note explains how to make charge pumping measurements using the 4200A-SCS with the optional 4225-PMU Ultra-Fast I-V Module (PMU) or 4220-PGU Pulse Generator Unit (PGU).

Charge Pumping Overview

Figure 1 is a charge pumping measurement circuit diagram. Basically, the gate of the MOSFET is connected to a pulse generator, which repeatedly switches the transistor from accumulation to inversion. While the gate is pulsed, a recombination process of majority/minority carriers occurs on the rising and falling edges of the pulses. This causes a current to flow in the opposite direction of the normal drain-to-source current. This induced current is known as the charge pumping current (I_{CP}) and can be measured by connecting a sensitive ammeter to the substrate, or bulk terminal, of the MOSFET.

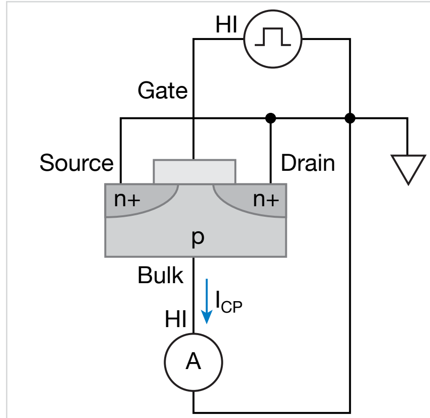


Figure 1. Basic charge pumping measurement circuit

Although several charge pumping methods have been developed, the basic charge pumping technique involves measuring the substrate current while applying voltage pulses of fixed amplitude, rise time, and frequency to the gate of the transistor. The source and drain are either tied to ground or slightly reverse-biased. The voltage pulse can be applied with a fixed amplitude while sweeping the base voltage or with a fixed base voltage while sweeping the amplitude of the pulse.

In the fixed-amplitude/voltage-base sweep, the amplitude and period (width) of the pulse are kept constant while the base voltage is swept from inversion to accumulation. This waveform and the corresponding curve of the charge pumping current shown as a function of the base voltage are both illustrated in **Figure 2**. From the data, it's possible to extract the interface trap density (N_{it}) using this equation:

$$N_{it} = \frac{I_{CP}}{qfA}$$

where:

N_{it} = interface trap charge density (cm^{-2})

I_{CP} = charge pumping current (A)

f = test frequency (Hz)

q = electron charge, 1.6022×10^{-19} C

A = channel area (cm^2)

The interface trap density as a function of band bending can also be extracted from the following equation:

$$D_{it} = \frac{I_{CP}}{qfA\Delta E}$$

where:

D_{it} = interface trap charge density ($cm^{-2}eV^{-1}$)

I_{CP} = charge pumping current (A)

f = test frequency (Hz)

q = electron charge, 1.6022×10^{-19} C

A = channel area (cm^2)

ΔE = the difference between the inversion Fermi level and the accumulation Fermi level [1]

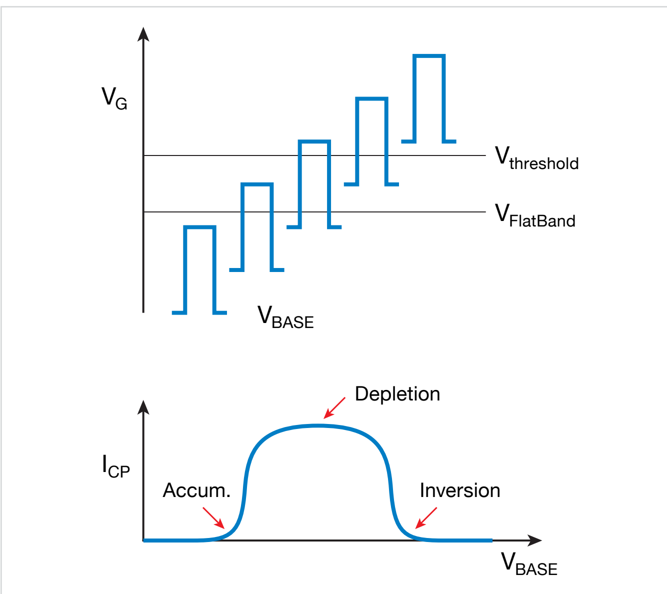


Figure 2. Pulse waveform for fixed-amplitude/voltage-base sweep and corresponding charge pumping current curve

The fixed-base/variable-amplitude sweep method is another common technique for determining the charge pumping current. With this method, the base voltage is kept constant in accumulation and the variable voltage amplitude is pulsed into inversion. As shown in **Figure 3**, as the voltage amplitude (V_{AMP}) of the pulses increases, the charge pumping current saturates and stays saturated.

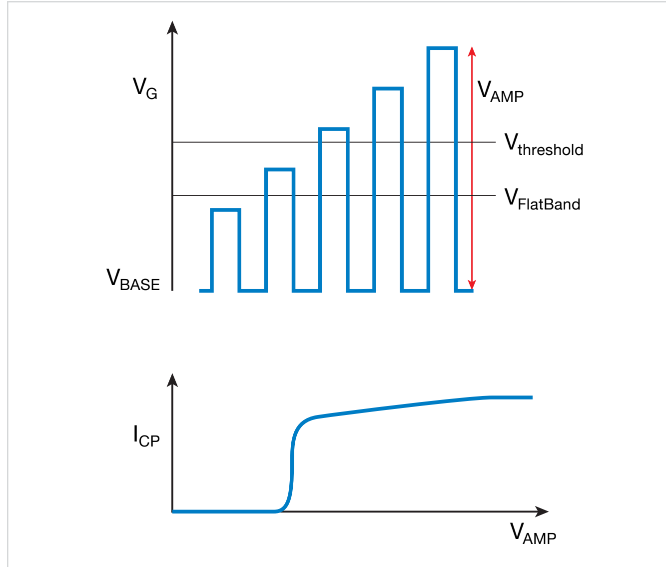


Figure 3. Pulse waveform for fixed-base/variable-amplitude sweep with corresponding charge pumping current curve

Other charge pumping techniques are used in addition to the fixed-amplitude/variable-base sweep and the fixed-base/variable-amplitude sweep. In some cases, the voltage waveform can have various shapes, the rise and fall times can be varied, or the charge pumping current can be measured as a function of frequency.

Hardware Configuration

Figure 4 is the basic circuit diagram for making charge pumping measurements using the 4200A-SCS. For this application, the 4200A-SCS is configured with either a 4220-PGU Pulse Generator Unit (PGU) or a 4225-PMU Ultra-Fast I-V Module (PMU), one or two 4200-SMU Source Measure Units (SMU), and one 4200-PA Preamp.

The pulser (4225-PMU or 4220-PGU) is connected to the gate of the MOSFET in order to apply pulses of sufficient amplitude to drive the device between inversion and accumulation. Depending on the charge pumping method, the PGU or PMU can sweep the pulse amplitude, sweep the base voltage, vary the rise/fall time, and vary the test frequency. The test frequency is usually in the kilohertz to megahertz range.

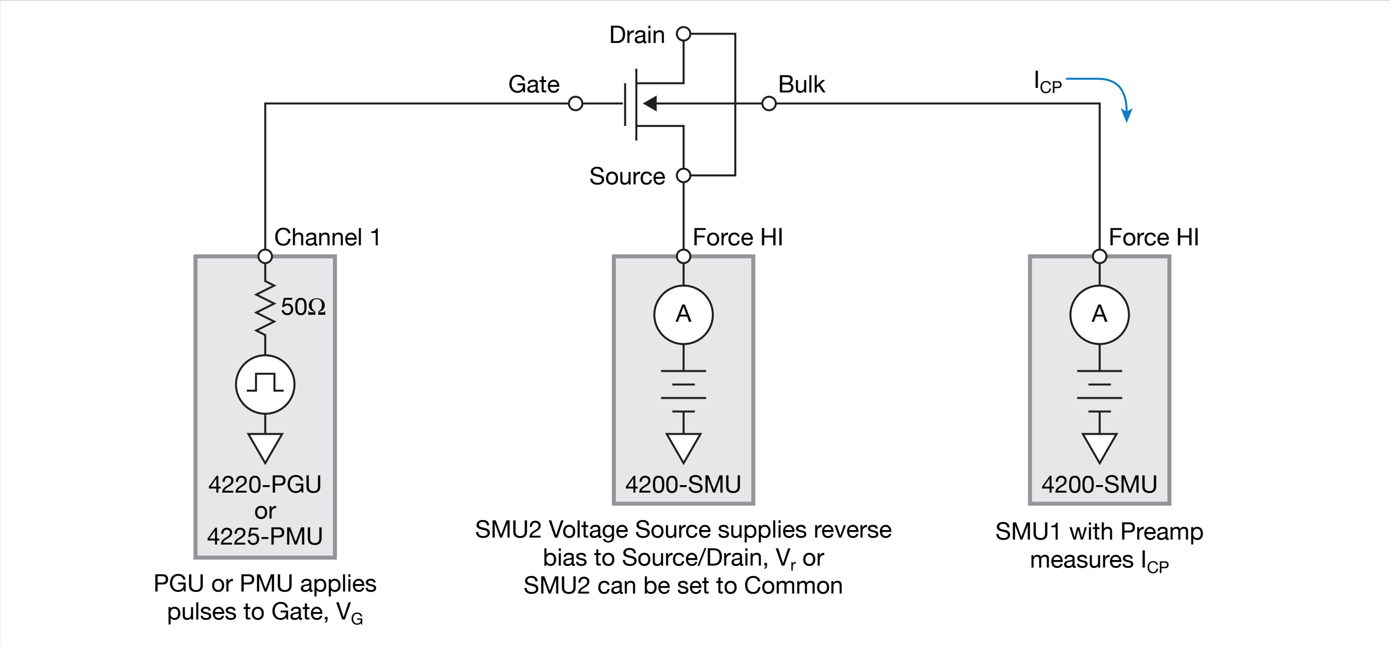


Figure 4. 4200A-SCS configuration for charge pumping measurements

SMU1 is connected to the bulk terminal and measures the resulting substrate current. This charge pumping current (I_{CP}) is often in the nanoamp or picoamp range. For measuring currents of less than one nanoamp, the optional 4200-PA should be used.

The source and drain terminals of the MOSFET are tied together and connected to SMU2, which applies a slight reverse-bias (V_r). If $V_r = 0$, then the source/drain terminals can be connected to the ground unit (GNDU) instead of to SMU2. To prevent oscillations and minimize noise, it is very important to connect the LO (common) terminals of all the SMUs and the pulser (4225-PMU or 4220-PGU) as close as possible to the device. The LO terminal of the SMU is the outside shell of the triax connector. The LO terminal of the PMU and PGU is the outside shield of the SMA cable.

To minimize noise in low current measurements due to electrostatic interference, make sure the device is shielded by placing it in a metal enclosure with the shield connected to the LO terminal of the SMU. Further information on making low current measurements with the 4200A-SCS is available in Keithley Application Note, “Optimizing Low Current Measurements with the 4200A-SCS Parameter Analyzer.”

Using the Clarius Software to Automate Charge Pumping Measurements

The 4200A-SCS includes a project that contains a library of tests used in many of the common charge pumping techniques. The *Charge Pumping Project* is located in the Project Library, which can be found from the Select pane in the Project Library and searching on the phrase “charge pumping.” When this project is opened, a list of the tests is displayed in the Project Tree (**Figure 5**). **Table 1** lists the tests included in the project and a brief description of each test. The individual tests can also be found in the Test Library.

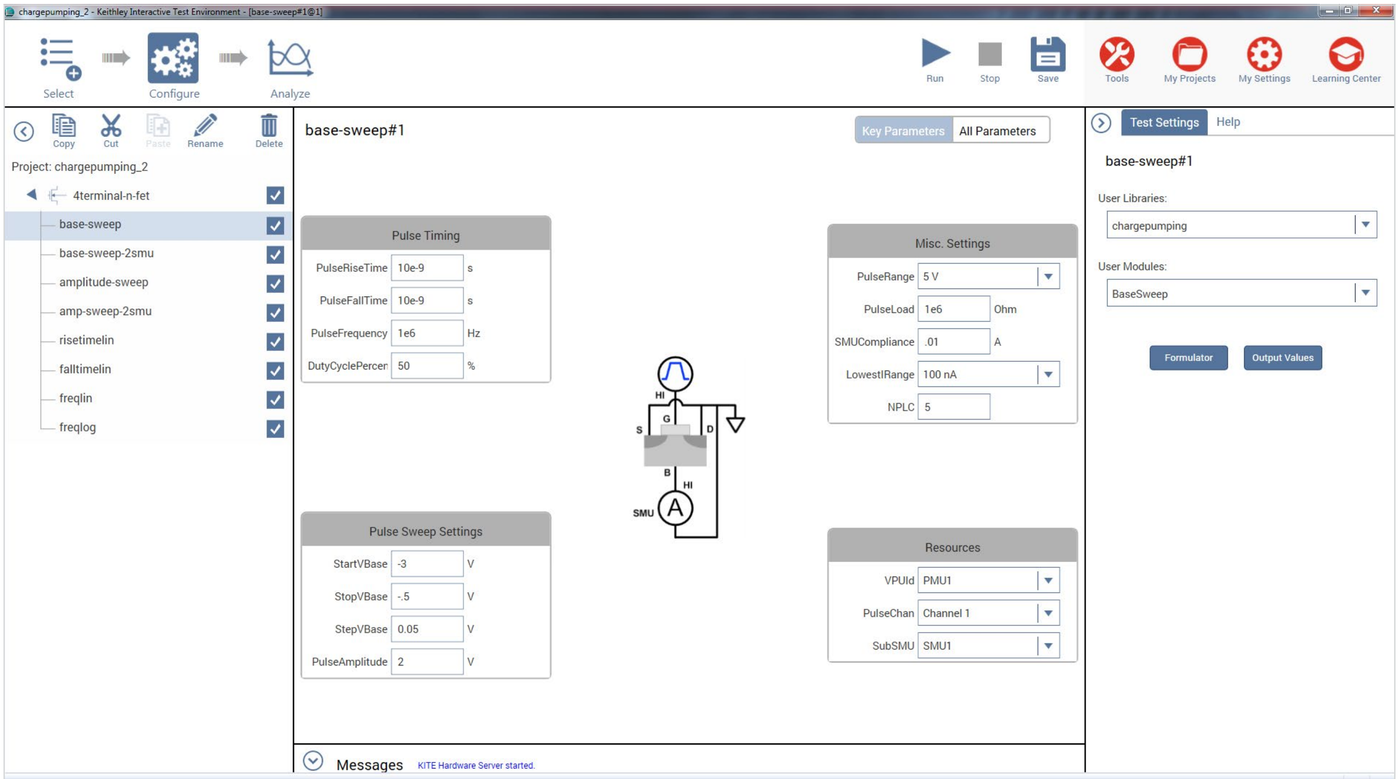


Figure 5. The *Charge Pumping Project*

Table 1. *Charge Pumping Project* Tests

Tests	Description
BaseSweep	The base voltage of the waveform is swept while the amplitude of the pulse is kept constant. The resulting charge pumping current is measured and graphed as a function of the base voltage. The source/drain terminals are tied to ground.
BaseSweep_2SMU	Same as *BaseSweep* test, except it adds a second SMU to apply a DC voltage bias to the source/drain terminals.
AmplitudeSweep	The amplitude of the pulse is swept while the base voltage is kept constant. The charge pumping current is measured and graphed as a function of the pulse amplitude voltage. The source/drain terminals are tied to ground.
AmplitudeSweep_2SMU	Same as *AmplitudeSweep* test, except it adds a second SMU to apply a DC voltage bias to the source/drain terminals.
RiseTimeLin	Performs a linear sweep of the rising transition time of the pulse. I_{CP} is measured and graphed as a function of the rise time. The source/drain terminals are tied to ground.
FallTimeLin	Performs a linear sweep of the falling transition time of the pulse. I_{CP} is measured and graphed as a function of the fall time. The source/drain terminals are tied to ground.
FreqLin	With the amplitude, offset voltage, rise/fall times constant, the I_{CP} is measured as a function of a linear sweep of the test frequency. The source/drain terminals are tied to ground.
FreqLog	With the amplitude, offset voltage, and rise/fall times constant, the I_{CP} is measured and graphed as a function of a log sweep of the test frequency. The source/drain terminals are tied to ground.

The user selects the desired test and then inputs the appropriate values for the test parameters displayed in the Configure pane. The parameters vary depending on the particular test, but they usually include the magnitude of the pulse, sweep values, rise/fall times, test frequency, and duty cycle. Specific information on these tests, including the input parameters, can be found on the right-hand side of the screen or in the Learning Center.

After the hardware and software have been configured, the measurement can be executed by selecting Run at the top of the screen. In the Analyze pane, the measurements are displayed in the graph and the sheet. The results can be saved in a worksheet as an .xls, .txt, or .csv file.

The graph from executing the *BaseSweep* test is shown in **Figure 6**. This test measures the charge pumping current as a function of the base voltage.

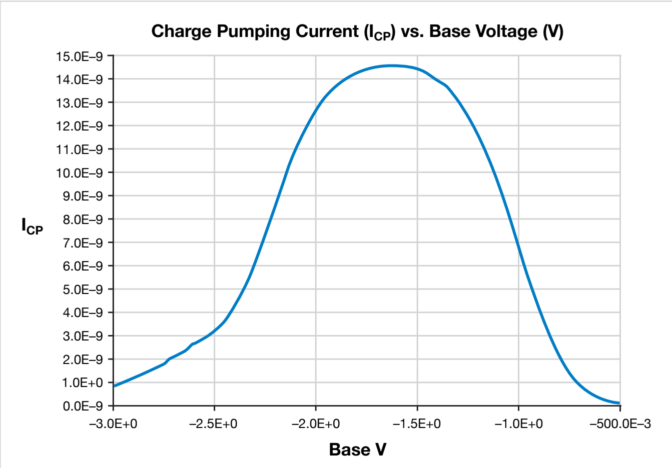


Figure 6. Graphical results of *BaseSweep* test

From the Configure pane, the input parameters of a test can be updated and the measurements can be repeated. Each time the test is repeated, the data is stored in Run History. Multiple test results can be viewed on the graph at one time by selecting the appropriate Run History check boxes of the tests to view. **Figure 7** shows the test results of measuring the charge pumping current as a function of the base voltage at increasing test frequencies from 1 MHz to 6 MHz.

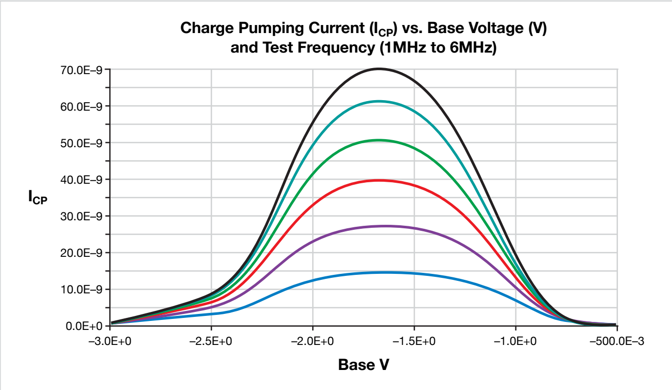


Figure 7. Charge pumping current measurement results at multiple test frequencies

The *AmplitudeSweep* test is another common charge pumping test. It measures the charge pumping current as the amplitude of the pulse is swept. The base voltage is kept constant. The resulting charge pumping measurements are shown in **Figure 8.**

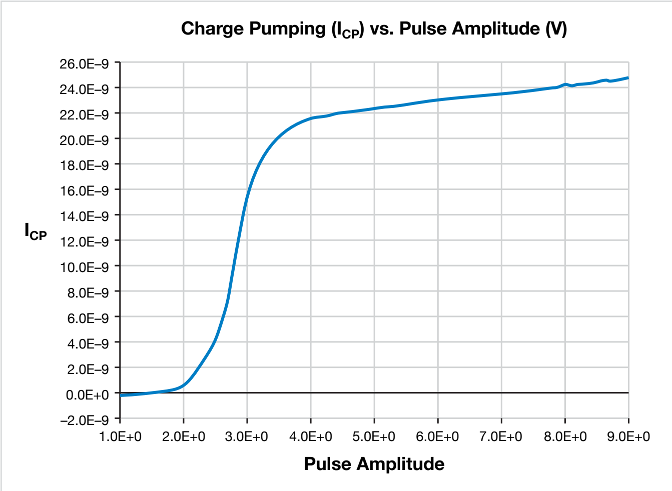


Figure 8. Charge pumping current as a function of pulse amplitude

Simple analyses, such as extracting the interface trap density, can be performed on the data using the built-in Formulator function. To activate this function, sekect the Formulator button on the right side of the screen in the Configure pane. As an example, enter the formula for D_{it} as shown in **Figure 9**. The resulting D_{it} value can also be plotted in the graph.

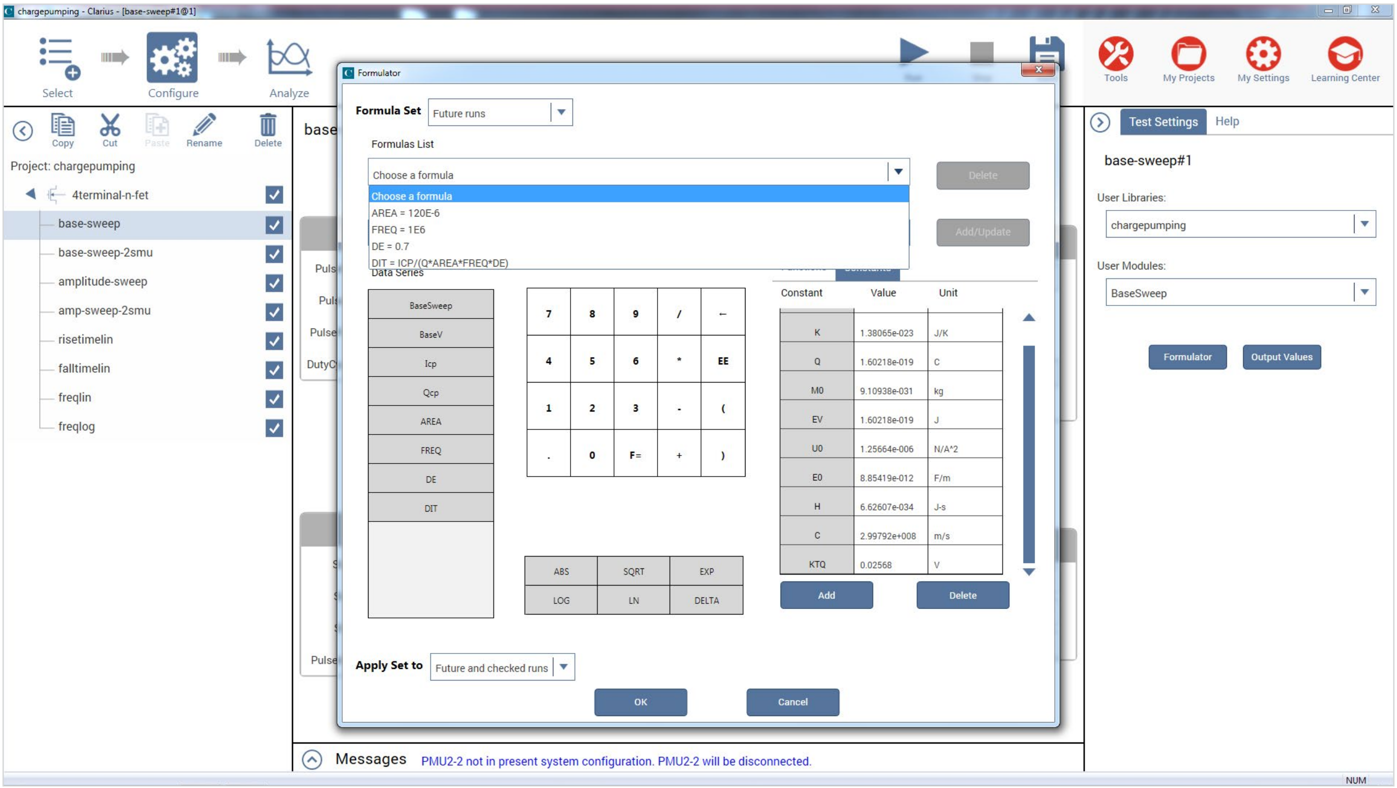


Figure 9. Entering formulas in the Formulator function

Conclusion

The 4200A-SCS is the ideal tool for characterizing interface properties of gate dielectrics. With the built-in pulse generator, 4225-PMU or 4220-PGU, and the Clarius software, the user need not do any programming, which simplifies measurement and analysis. When equipped with the 4225-PMU, the 4200A-SCS is a powerful tool for performing many tests commonly required in DC and ultra-fast I-V electrical characterization of devices, including the charge pumping application detailed here. The 4225-PMU is not simply a pulse generator; it can also measure current and voltage and be used for transient I-V (waveform capture) applications.

References

1. G. Groeseneken, H.E. Maes, N. Beltran, and R.T. De Keersmaecker, "A Reliable Approach to Charge-Pumping Measurements in MOS Transistors," *IEEE Trans. Electron. Dev.*, Vol. ED-31, pp. 42-53, 1984.

Contact Information:

Australia* 1 800 709 465

Austria 00800 2255 4835

Balkans, Israel, South Africa and other ISE Countries +41 52 675 3777

Belgium* 00800 2255 4835

Brazil +55 (11) 3759 7627

Canada 1 800 833 9200

Central East Europe / Baltics +41 52 675 3777

Central Europe / Greece +41 52 675 3777

Denmark +45 80 88 1401

Finland +41 52 675 3777

France* 00800 2255 4835

Germany* 00800 2255 4835

Hong Kong 400 820 5835

India 000 800 650 1835

Indonesia 007 803 601 5249

Italy 00800 2255 4835

Japan 81 (3) 6714 3010

Luxembourg +41 52 675 3777

Malaysia 1 800 22 55835

Mexico, Central/South America and Caribbean 52 (55) 56 04 50 90

Middle East, Asia, and North Africa +41 52 675 3777

The Netherlands* 00800 2255 4835

New Zealand 0800 800 238

Norway 800 16098

People's Republic of China 400 820 5835

Philippines 1 800 1601 0077

Poland +41 52 675 3777

Portugal 80 08 12370

Republic of Korea +82 2 565 1455

Russia / CIS +7 (495) 6647564

Singapore 800 6011 473

South Africa +41 52 675 3777

Spain* 00800 2255 4835

Sweden* 00800 2255 4835

Switzerland* 00800 2255 4835

Taiwan 886 (2) 2656 6688

Thailand 1 800 011 931

United Kingdom / Ireland* 00800 2255 4835

USA 1 800 833 9200

Vietnam 12060128

*** European toll-free number. If not accessible, call:** +41 52 675 3777

KEITHLEY
A Tektronix Company

Find more valuable resources at TEK.COM

070716 SBG 1KW-60634-0