Making Femtofarad (1e-15F) Capacitance Measurements with the 4215-CVU Capacitance Voltage Unit

APPLICATION NOTE

KEITHLEY
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Introduction

Typical semiconductor capacitances are in the picofarad (pF) or nanofarad (nF) ranges. Many commercially available LCR or capacitance meters can measure these values using proper measurement techniques including compensation. However, some applications require very sensitive capacitance measurements in the femtofarad (fF), or 1e-15, range. These applications include measuring metal-to-metal capacitance, interconnect capacitance on a wafer, MEMS devices such as switches, or capacitance between terminals on nano devices. These very small capacitances are very difficult to measure without using the proper instrumentation and measurement techniques.

Using a tool such as the Keithley 4200A-SCS Parameter Analyzer equipped with the optional 4215-CVU Capacitance Voltage Unit (CVU) enables the user to measure a wide range of capacitances, including very low values of capacitance, <1 pF. The CVU is designed with unique circuitry and is controlled by the Clarius+ software to support features and diagnostic tools that ensure the most accurate results. Using this CVU with proper techniques can enable the user to achieve very low capacitance measurements with tens of attofarads (1e-18F) noise levels.

This application note explains how to make femtofarad capacitance measurements using the 4215-CVU Capacitance Voltage Unit. This includes making proper connections and using the proper test settings in the Clarius software for the best results. Further information on making capacitance measurements, including cabling and connections, timing settings, guarding, and compensation, can be found in the Keithley application note, *Making Optimal Capacitance and AC Impedance Measurements with the 4200A-SCS Parameter Analyzer.*

Making Connections to the Device

Making the proper connections to the device under test (DUT) is crucial for making sensitive low capacitance measurements.

For the best results, use only the supplied red SMA cables for making connections from the CVU to the DUT. The red SMA cables have characteristic impedance of 100 Ω. Two 100 Ω cables in parallel have characteristic impedance of 50 Ω, which is standard for high frequency sourcing and measuring applications. The supplied accessories allow connecting to a test fixture or prober with BNC or SMAs connections. Using the supplied torque wrench, tighten the SMA cable connections to ensure good contacts.

The CVU configured for two-wire sensing is shown in **Figure 1**. The HCUR and HPOT terminals are connected to a BNC tee to form CVH (HI), and the LCUR and LPOT terminals are connected to form CVL (LO).

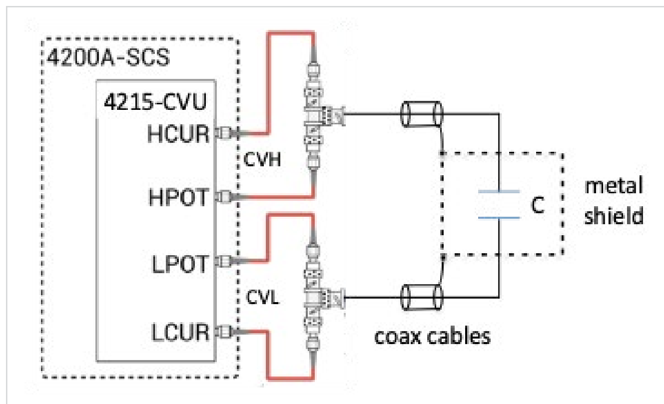

Figure 1. CVU connections for two-wire sensing.

An example of four-wire sensing to the DUT is shown in **Figure 2**. In this case, the HCUR and HPOT terminals are connected to one end of the device, and the LPOT and LCUR terminals are connected to the other end of the device. Four-wire connections to the device facilitate sensitive measurements by measuring the voltage as close as possible to the device.

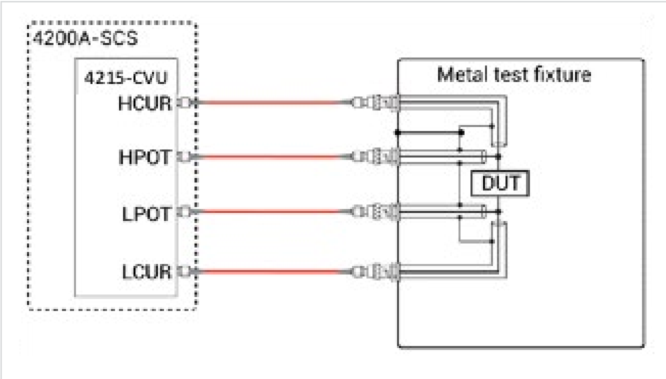

Figure 2. CVU connections for four-wire sensing.

For either two- or four-wire sensing, the outside shields of the coax cables must be connected as close as possible to the device to minimize the loop area of the shields. This reduces the inductance and helps to avoid resonance effects, which can be burdensome at frequencies higher than 1 MHz.

Keep all cables securely mounted to avoid any movement. Any movement that occurs in the time between executing the offset measurements and the actual DUT measurements can slightly change the loop inductance and impact the compensated data.

When measuring very small capacitances, shielding the DUT becomes important to reduce measurement uncertainties due to interference. Sources of interference could be AC signals or even physical movement. The metal shield should enclose the DUT and be connected to the outside shell of the coax cables.

For low capacitance measurements, it is best to use four-wire sensing, however, optimal measurements with two-wire sensing is achievable if the cables are short and compensation is used.

Configuring the Clarius+ Software for Femtofarad Measurements

Setting up the measurements in the Clarius software involves selecting the femtofarad project in the Library, configuring the test settings, and executing the measurements.

Selecting the femtofarad-capacitance Project in the Library

A project for making very small capacitance measurements is included in the Projects Library in the Clarius software. From the Select view, type in “femtofarad” in the search bar. The *femtofarad-capacitance* project will appear in the window as shown in **Figure 3**. Select Create to open the project in the project tree.

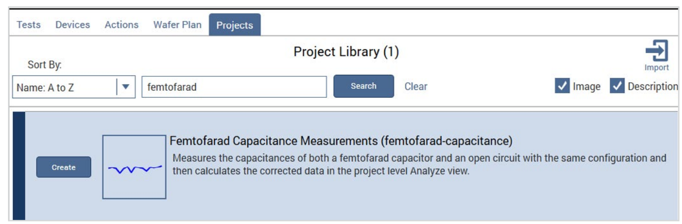

Figure 3. Femtofarad capacitance measurement project in Library.

Configuring the test settings

Once the project is created, the *femtofarad-capacitance* project appears in the project tree as shown in **Figure 4**.

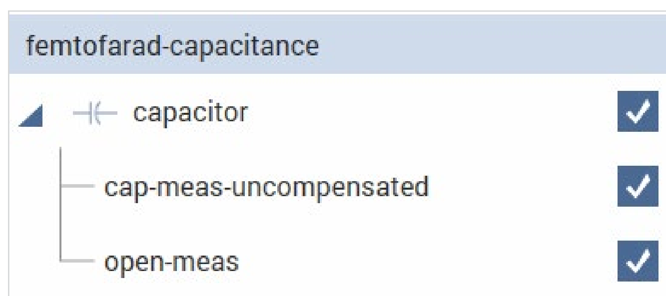

Figure 4. femtofarad-capacitance project tree.

This project has two tests: 1) the *cap-measure-uncompensated* test, which is used to measure the capacitance of the DUT and, 2) the *open-meas* test, which is used to acquire the capacitance of the cabling and connections. Because of the sensitivity of these capacitance measurements, the open circuit measurements are taken with the exact settings used to measure the DUT. The open circuit measurements are then subtracted from the capacitance measurements of the DUT. This method enables good measurement results of extremely low capacitance.

For successful low capacitance measurements, it is important to adjust the measure and timing settings appropriately in the Configure view window. Here are some suggestions for making optimal adjustments:

Measure Settings: Some of the settings that the user can control are the current measure range, AC drive voltage, and the test frequency. These are important to the measurement because they are involved in the equation of determining the device capacitance. The CVU calculates the device capacitance from Iac, Vac, and the test frequency using the following equation:

$$C = \frac{Iac}{2\pi f Vac}$$

where: C = the device capacitance (F)
Iac = AC current measured by the CVU (A rms)
f = test frequency (Hz)
Vac = AC drive voltage (V rms)

By observing the relationship in these equations, the optimal settings for the current measure range, AC drive voltage, and test frequency can be deduced.

The CVU has three current measurement ranges: 1 μA, 30 μA, and 1 mA. For the lowest capacitance measurements with the least noise, use the lowest current range, the 1 μA range.

The level of the AC drive voltage can affect the signal-to-noise ratio of the measurement. While the AC noise level stays relatively constant, using a higher AC drive voltage generates a larger AC current, thus improving the signal-to-noise ratio. So, it's best to use an AC drive voltage as high as possible. In this project, a 1 V AC drive voltage was used.

For very low capacitance measurements, using a test frequency of about 1 MHz is ideal. With test frequencies much higher than 1 MHz, transmission line effects increase the difficulty in making successful measurements. At lower test frequencies, the measurements will lose resolution since the test frequency and current are proportional. Therefore, noisier measurements will result.

Timing Settings: The timing settings can be adjusted in the Test Settings window. The Speed mode setting enables the user to adjust the measurement window. For very low capacitance measurements, use the Custom Speed mode to set the measurement time to achieve the desired accuracy and noise levels. Basically, the longer the measurement time, or window, the less noisy the measurements will be. The noise is inversely proportional to the square root of the measurement time as shown in the following equation:

$$Noise = \frac{1}{\sqrt{MeasTime}}$$

The noise can be obtained by calculating the standard deviation of the capacitance measurements. This calculation can be done automatically using the Formulator in the Clarius software. The *cap-meas-uncompensated* test automatically calculates the noise and returns the value to the Sheet.

The measurement window can be adjusted using the Custom speed mode in the Test Settings window shown in **Figure 5**.

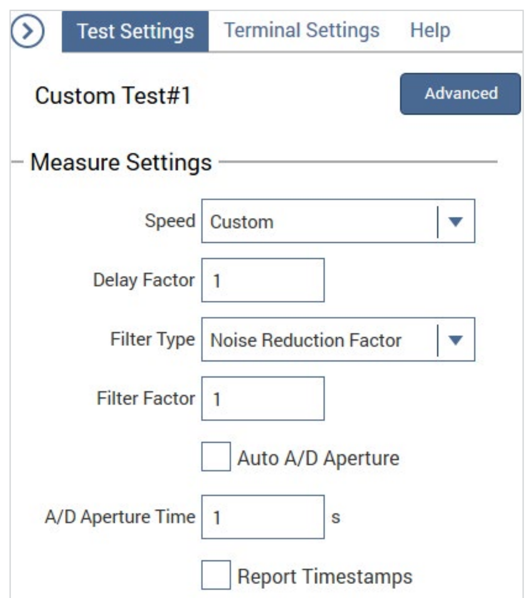

Figure 5. Custom Speed mode in Test Settings window.

The time of the measurement window can be calculated as follows:

*Measurement Window = (A/D Aperture Time) * (FilterFactor² or Filter Count)*

Table 1 lists the CVU noise as a function of the measure window generated with a 1 fF capacitor connected to the terminals of the CVU in a two-wire configuration. The noise was calculated by taking the standard deviation of 15 readings with measurements taken with settings of 0 V DC, 1 MHz, and 1 V AC drive voltage. This data verifies that as the measurement time increases the noise decreases. Notice that measurement times of 1 s and above have noise in the attofarad, or 1 E–18F, range. Experimentation may be required in each test environment to determine the optimal measurement time for a test.

Measurement Time (s)	Noise (rms)
0.001	1.18E-16
0.002	9.90E-17
0.005	9.17E-17
0.01	7.43E-17
0.02	6.84E-17
0.05	2.98E-17
0.1	2.24E-17
0.2	1.49E-17
0.5	1.15E-17
1	6.13E-18
2	5.00E-18
5	3.99E-18
10	2.77E-18

Table 1. Measurement Time vs Noise of 1 fF capacitor.

Executing the Measurements

Once the hardware and software are configured, the measurements can be executed. Ideally, the 4200A-SCS should be warmed up for at least one hour prior to taking measurements.

Follow these four steps to take compensated measurements and repeat the results.

1. **Measure the Capacitance of the Device.** Select the *cap-meas-uncompensated* test in the project tree. In the Configure view, adjust the test settings based on the device and application. Run the test.

2. **Measure the Open Circuit.** Select the *open-meas* test in the project tree. Adjust the test settings to be exactly like the test settings in the *cap-meas-uncompensated* test including the number of data points and voltage steps. Disconnect only the CVH (HCUR and HPOT) cables. Make sure the unterminated cables are capped. Run the open test.

3. **Analyze the Results.** Select the *femtofarad-capacitance* project in the project tree and select Analyze view. A screen capture displaying the compensated 1 fF measurements is shown in **Figure 6**.

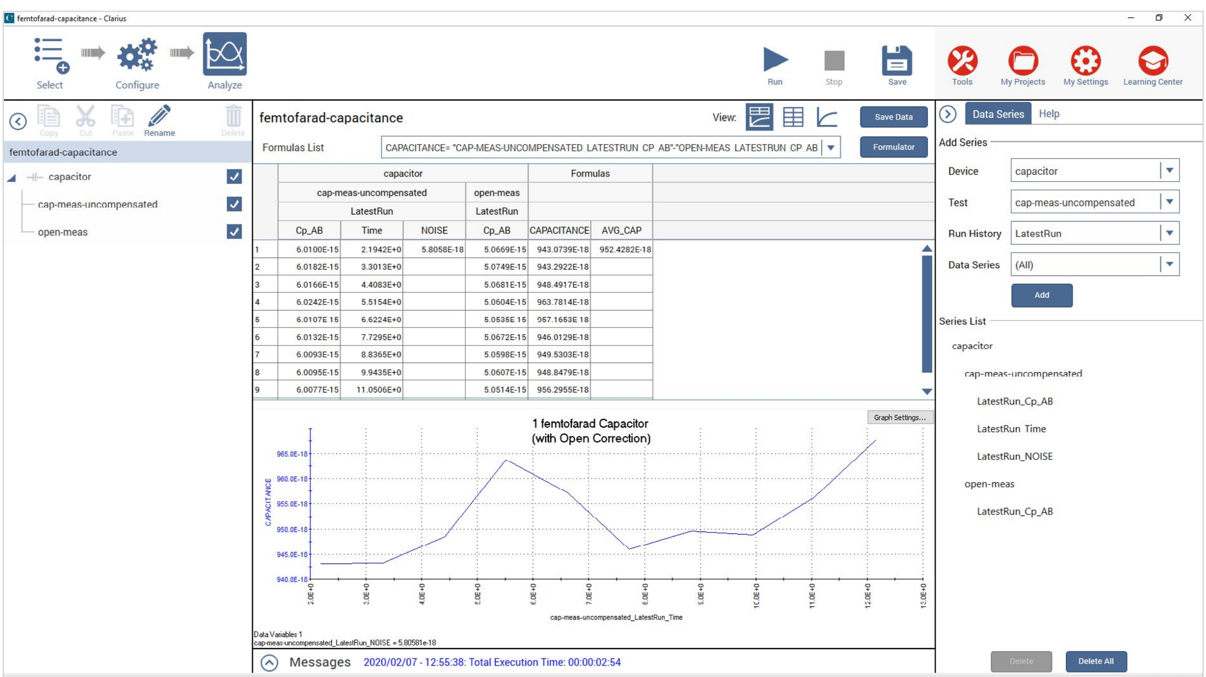

Figure 6. Screen capture of the Analyze view Sheet and Graph showing 1 fF measurement.

Notice the most recent capacitance and open measurements appear in the Sheet along with the noise calculation. The Data Series from all the tests in the project tree appear on the right-hand side of the screen. As shown in **Figure 7**, the Series List of the Latest Run measurements from the *cap-meas-uncompensated* and *open-meas* tests are selected. This means that each time the test is executed, the latest data will be populated in the Sheet.

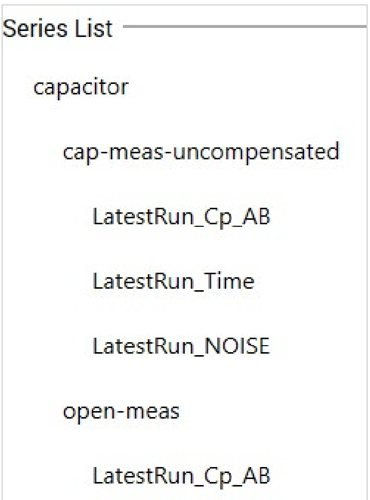

Figure 7. Data Series from tests.

A formula has been set up in the Formulator that automatically calculates the compensated capacitance measurements by subtracting the *open-meas* test data from the *cap-meas-uncompensated* test data in the Project level Analyze view Sheet. The graph displays the compensated capacitance as a function of time. The CAPACITANCE column in the Sheet lists the compensated measurements along with the average capacitance of all the readings. **Figure 8** shows the Latest Run Sheet data with the capacitance measurements (Cp-AB), time, noise, open measurements, compensated measurements (CAPACITANCE), and average capacitance (AVG_CAP).

	capacitor				Formulas	
	cap-meas-uncompensated			open-meas		
	LatestRun			LatestRun		
	Cp_AB	Time	NOISE	Cp_AB	CAPACITANCE	AVG_CAP
1	6.0100E-15	2.1942E+0	5.8058E-18	5.0669E-15	943.0739E-18	952.4282E-18
2	6.0182E-15	3.3013E+0		5.0749E-15	943.2922E-18	
3	6.0166E-15	4.4083E+0		5.0681E-15	948.4917E-18	
4	6.0242E-15	5.5154E+0		5.0604E-15	963.7814E-18	
5	6.0107E-15	6.6224E+0		5.0535E-15	957.1653E-18	
6	6.0132E-15	7.7295E+0		5.0672E-15	946.0129E-18	
7	6.0093E-15	8.8365E+0		5.0598E-15	949.5303E-18	
8	6.0095E-15	9.9435E+0		5.0607E-15	948.8479E-18	
9	6.0077E-15	11.0506E+0		5.0514E-15	956.2955E-18	
10	6.0222E-15	12.1576E+0		5.0544E-15	967.7908E-18	

Figure 8. Test data shown in the Analyze view Sheet.

4. **Repeating the measurements.** The measurements can be repeated from the project level by selecting Run. The compensated readings will automatically be calculated. However, the *open-meas* test must be unchecked as shown in **Figure 9**. Acquired open measurements should be repeated periodically if the data appears to move unexpectedly. This could indicate temperature variations or cable movements.

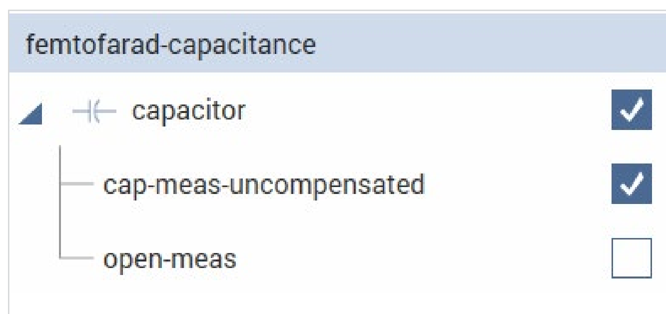

Figure 9. Uncheck the *open-meas* test to repeat measurements from the project level Analyze view.

Conclusion

Femtofarad level capacitances can be measured with the 4215-CVU using the Library project, proper connections, and appropriate measurement techniques and settings. Using the 4215-CVU with the appropriate measurement window can enable noise levels in the tens of attofarads range and below.

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 3086
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

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