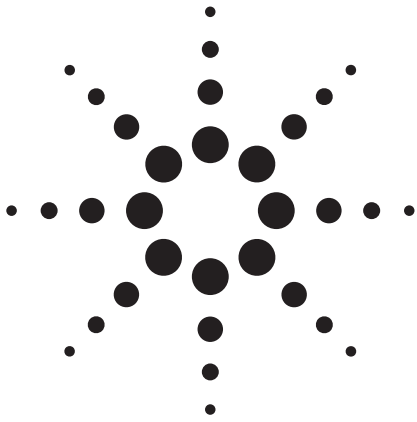


Accurate and Efficient C-V Measurements

Application Note E5250A-3



Agilent E5250A Low Leakage Switch Mainframe

Introduction

For next generation ULSI development, precise characteristics evaluation of semiconductors during device development, process development, and circuit design phase is essential. As well as IV measurement, C-V measurements are very important to determine the oxide thickness. Other important parameters such as substrate impurity concentration can also be calculated from C-V measurement results.

Also, improvement of test productivity is mandatory for faster IC development.

This application note explains how to perform accurate and efficient C-V characteristics measurements of multiple devices by changing connections using the Agilent E5250A Matrix Switch.

Difficulties in Device Characterization

On Test Element Groups (TEG), there are various devices. They are for dc characteristics measurements and for C-V measurements. So, to improve test efficiency, it is necessary to automate the changing of measurement

instrument connections and multi-probing on the wafer. A switching matrix is required to automate switching measurement instruments and test devices.

Until now, there has been no suitable switching matrix for precise low current measurements and accurate capacitance measurements. Using existing switching matrices, the performance of measurement instruments was sacrificed. C-V measurement results included big error due to the residual impedance in the extension cables and matrices. It was also difficult to compensate for the measurement error.

For precise testing, you had to perform IV and/or C-V measurements on separate probing stations. There was no adequate matrix available to combine these into one probe station.

Therefore, the biggest issue was that measurement productivity was lowered because you had to manually switch measurement instruments and devices.



Figure 1. Agilent 4156C, 4284A, and E5250A with wafer prober



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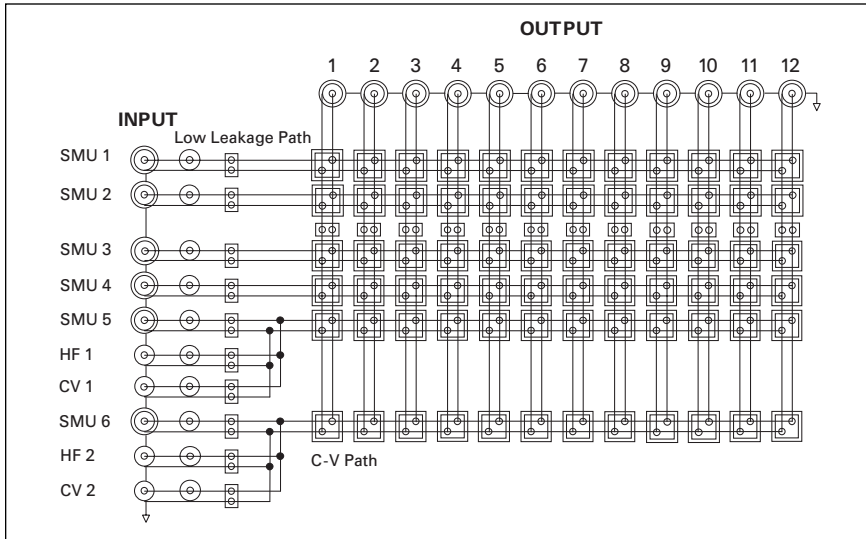


Figure 2. E5250A Matrix Switch block diagram

Solution Using the Agilent E5250A Low Leakage Switch Mainframe

The Agilent E5250A Low Leakage Switch Mainframe provides the solutions to those problems. There are two types of plug-in modules: Option 001 10 × 12 Matrix Switch Module and Option 501 24-channel Multiplexer Module.

The 10 × 12 Matrix Switch Module can be used for precise parametric test. It improves measurement efficiency by eliminating the need to manually change the probing positions on a manual probe station. Figure 2 shows the block diagram of Matrix Switch Module. The Agilent E5250A has four slots, so you can configure a 10-input and 48-output matrix switch by using

four modules. There are six SMU input terminals. The SMU1 and SMU2 inputs are specially designed for low current measurements. Using with the Agilent 4156C, you can measure sub pA level current accurately. The CV1 and CV2 inputs are designed to be used with capacitance measurement instruments such as Agilent 4284A Precision LCR Meter.

The Agilent E5250A Matrix Switch Module has special capacitance compensation routine for accurate measurements, which can be used with the Agilent 4284A. It is available as an Agilent IBASIC subroutine or with Agilent E5230B Interactive Characterization Software (Agilent ICS). By using the Agilent E5250A with

Agilent ICS, you can easily automate switching measurement instruments and test devices.

Instrument Connection

Figure 3 shows an example connection of Agilent 4284A, E5250A, 16495A/B Connector Plate, and a probing station. The Agilent 4284A is connected to the input terminals CV1 and CV2 of E5250A by using the Agilent 16048D/E 4-terminal pair test lead. The high potential and high current terminals are connected together using a T-connector. The low potential and low current terminals are also connected together. This means 4-terminal pair connection is terminated at the input of E5250A and 2-terminal pair connection is used after the matrix switch. Though 2-terminal pair connection has a slightly narrower coverage of measurement impedance range than 4-terminal pair, it makes the device probing easier.

For the output of the matrix switch, the Agilent 16494A Triaxial Cables are used to connect to the Agilent 16495A/B connector plate. The connector plate should be fixed to the wall of shield box that surrounds probing station. From the connector plate to the probe card or probe needles, Agilent P/N 8120-4461 low noise coaxial cable is used. Note that the triaxial and coaxial cables should have same length for high and low terminal for capacitance compensation. In general, using shorter cables improves measurement accuracy.

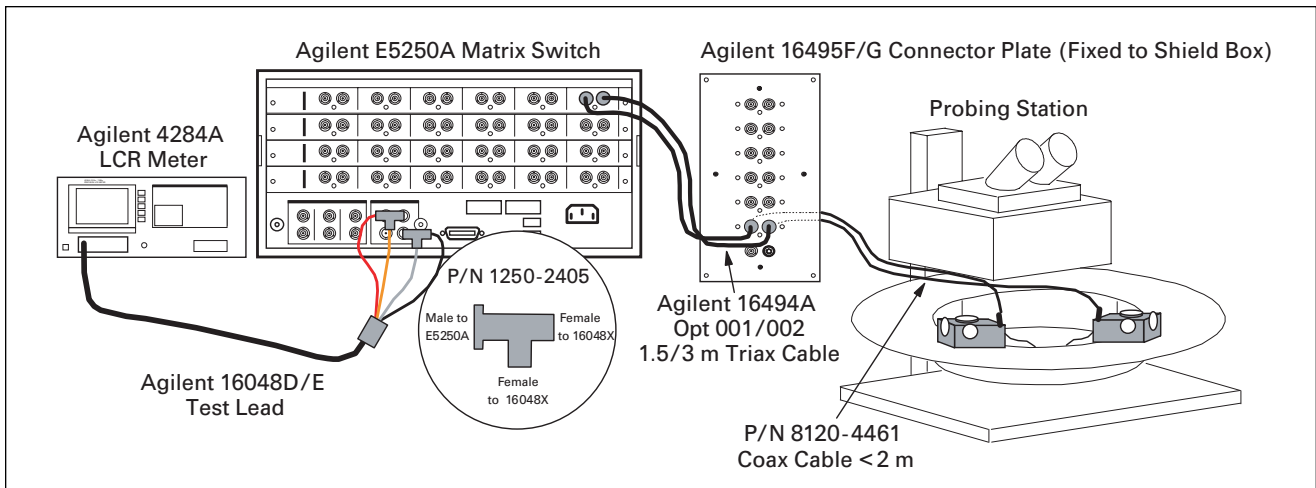


Figure 3. Instruments connection for capacitance measurement

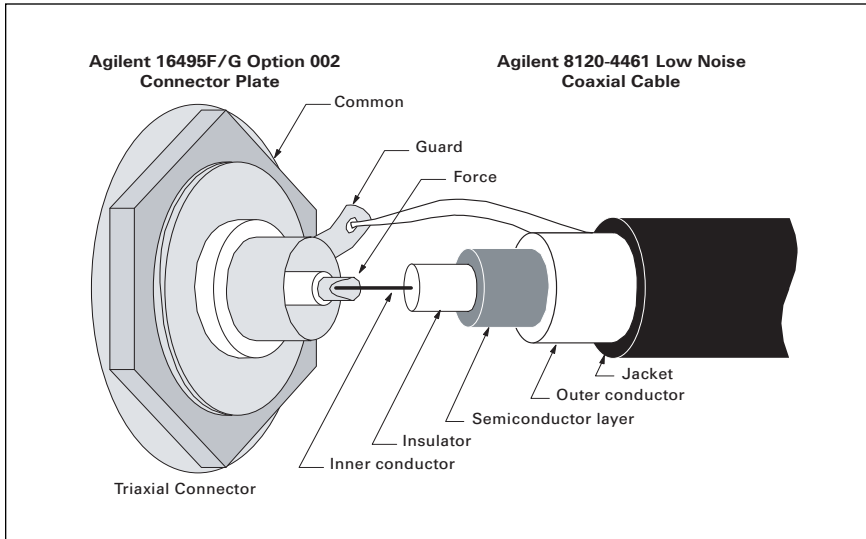


Figure 4. Soldering coax cable to the Agilent 1645A/B connector plate

Maximum lengths for triaxial and coaxial cables are 3 m and 2 m, respectively.

The Agilent P/N 8120-4461 coaxial cable has a semiconductor layer to minimize the triboelectricity generated by frictional motion at boundary between the conductor and insulator. This special design enables you to perform accurate dc measurements through this cable as well as capacitance measurement.

To connect this cable to the connector plate, it is necessary to isolate the inner conductor from the semiconductor layer. To do this, cut the semiconductor layer and insulator as shown in Figure 4. Then solder inner conductor to force terminal of a triaxial connector and outer conductor to guard terminal.

Note that dangerous voltage may appear at the force and guard terminals. To prevent electric shock, cover the triaxial connectors with metal cover. Install an interlock circuit to stop dangerous voltages when door of shield box is open.

Capacitance compensation is performed based on F matrix calculation for matrix and cables. Predetermined values of residual impedance and stray admittance per cable length are used. Therefore, if you use other than recommended cables, compensation cannot be performed correctly.

Figure 5 shows measurement circuit diagram of Agilent 4284A including matrix switch and cables. The connector plate is used as a part of return path for the measurement signal current. The compensation calculation is performed assuming the outer shield of triaxial cables are connected to each other at connector plate as shown in Figure 5. If you use a connector plate other than Agilent 16495A/B, such as a connector plate that has an insulator between the outer shields of the triaxial connectors, the compensation may be incorrect.

As for the necessary instruments and accessories, refer to Table 1. Ordering Example, on page 8.

Device Connection

When connecting LCR meter to measurement capacitors on semiconductor wafers, you need to take the device structure and LCR meter’s measurement circuit into account.

Because the ammeter is in the low side of the circuit, as shown in Figure 5, LCR meter’s low terminal is more sensitive to noise than the high terminal. Therefore, for example, connect the high terminal to the wafer chuck of prober or to the substrate terminal on wafer, which generally has wider antenna area to gather noise than small gate area in case of oxide capacitance measurements. For more tips, please refer to *Tips for More Accurate Capacitance Measurements*.

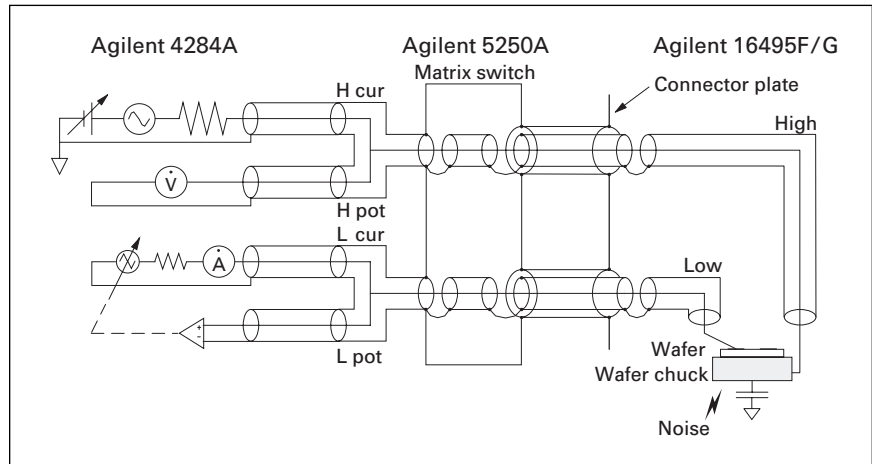


Figure 5. Connection of high and low terminals

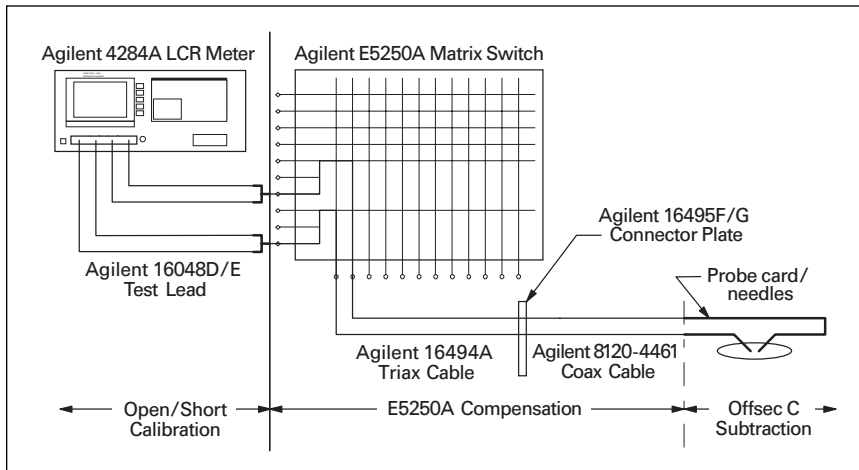


Figure 6. Compensation theory

The outer conductor of coaxial cables works as a shield to minimize stray capacitance between center conductors and circuit common. The outer conductors should be extended as close as possible to measurement device without contacting anything (*i.e.*, should be floating). Note that they work as guard terminals in case of dc measurements, that are to minimize leakage current.

Cable Calibration and Compensation

For accurate capacitance measurements, perform the following three steps shown in Figure 6.

- **Open/Short Calibration of Agilent 16048D/E Test Lead**

Perform open/short calibration at the end of the Agilent 16048D/E Test Lead on the Agilent 4284A's front panel. To perform short calibration, use the Agilent 42091A Short Termination adapter to connect high and low terminals together as shown in Figure 7. For open calibration, attach the test leads to the CV1 and CV2 input terminals of E5250A. All matrix switch relays should be open.

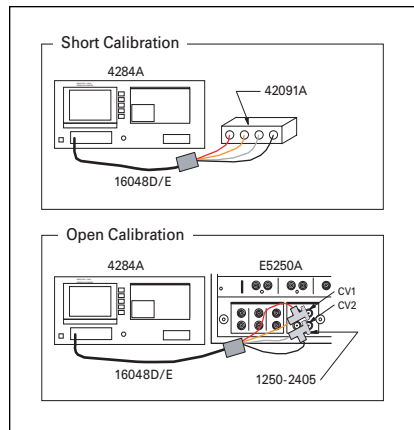


Figure 7. Open/short calibration

Open/short calibration can be done to the end of the 4-wire connection (16048D/E). If a matrix switch and cables are used, they

are not calibrated by open/short calibration. In general, load calibration should be additionally performed in such a case. But, for wafer measurements, it is very difficult to have stable and accurate load, so you should perform compensation as described next instead of load calibration.

- **E5250A/Output Cables Compensation**
Specify cable length of the Agilent 16494A Triaxial Cable and Agilent P/N 8120-4461 Coaxial Cable in the capacitance compensation routine. Its usage is described later.

Instead of load calibration, the routine compensates the measurement error generated by residuals in the matrix switch modules and output cables. As long as you use recommended cable, you can easily compensate the error by specifying the cable length.

- **Probe Card/Needles Offset Capacitance Subtraction**

Perform a measurement of offset capacitance caused by probe card or probe needles. This cannot be compensated by E5250A's compensation calculation, so it should be actually measured and subtracted from device capacitance value. Don't connect measurement device during offset capacitance measurement.

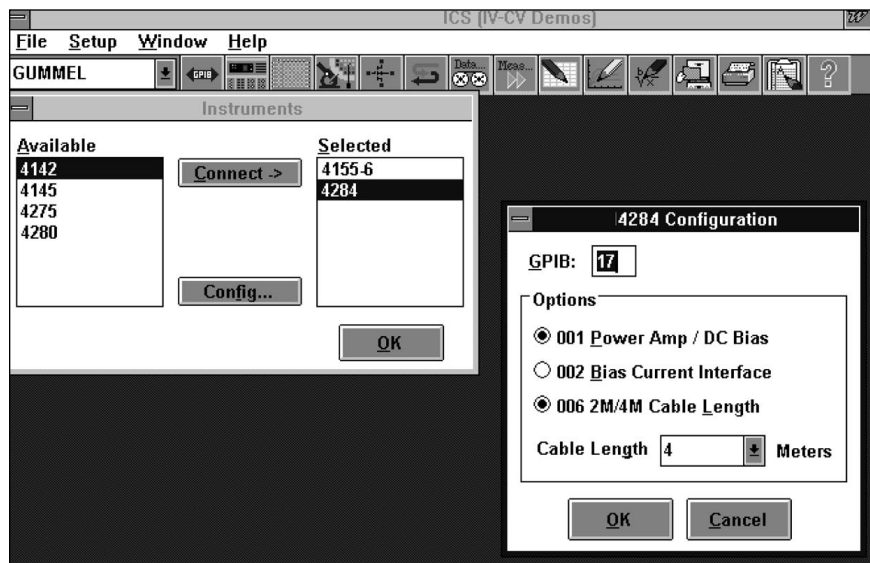


Figure 8. Agilent 4284A configuration setup

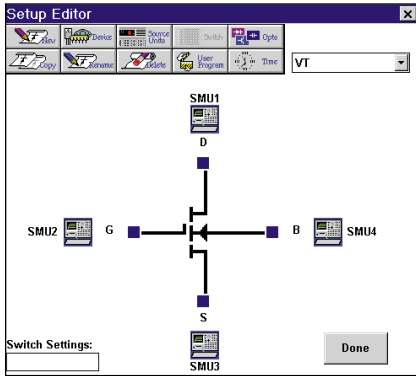


Figure 9. Setup editor

Capacitance Measurement Using Agilent ICS

To measure capacitance using Agilent ICS, perform the following steps. The C-V driver (Agilent E5232B) and Matrix Switch driver (Agilent E5233B) must be installed with Agilent ICS.

- **Agilent 4284A Configuration Setup**

Set the Agilent 4284A configuration as shown in Figure 8. Specify appropriate GPIB address, and select Option 001 for dc bias and Option 006 for 2 m/4 m cable length in the Agilent 4284A Configuration dialog box. If using the 16048D, specify 2 m in Cable Length field. In case of 16048E, specify 4 m.

- **Measurement Algorithm**

Figure 9 is an example Setup Editor setting for C-V measurement of MOSFET gate oxide capacitor. Connect CMH (High terminal) and CML (Low terminal) to substrate and gate, respectively. This connection minimizes the noise effect at wafer chuck.

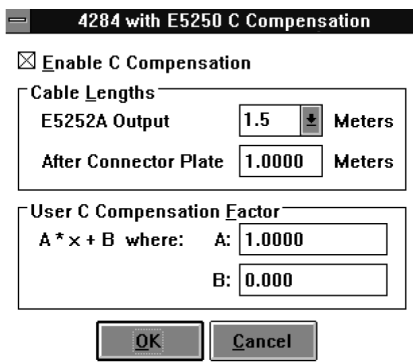


Figure 11. Agilent E5250A Capacitance Compensation dialog

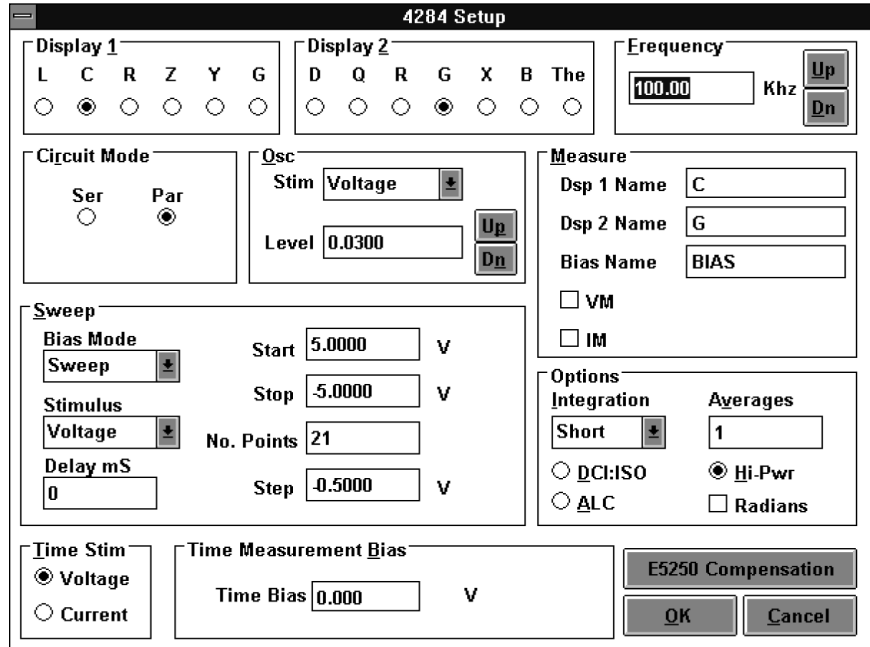


Figure 10. Agilent 4284A Setup dialog box

Click CMH icon to open the Agilent 4284A Setup dialog box, which is shown in Figure 10. In this example, substrate voltage is swept from +5 V to -5 V with step -0.5 V. Note that we apply reverse bias to the substrate. In this dialog box, you can specify oscillation level, measurement frequency and integration time too. These are very important settings for accurate measurement, which is discussed on page 7. Note that if you enable capacitance compensation (next step), parallel circuit mode is used, so capacitance

and conductance are measured in parallel mode.

- **Capacitance Compensation**

Click Agilent E5250A Compensation button. A dialog opens as shown in Figure 11. Enable capacitance compensation. Then specify the triaxial cable length (Agilent E5252 Output) and coaxial cable length (After Connector Plate) in meters. In this example, they are 1.5 m and 1.0 m, respectively. You need to measure your cables and use the correct lengths.

Active Switch Settings for E5250A card 1.

Output	1	2	3	4	5	6	7	8	9	10	11	12
Input	Drain	Gate	Sour	Sub	D2	G2	S2	B2	D3	G3	S3	B3
1	smu1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2	smu2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	smu3	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4	smu4	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7	Vm1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8	Vm2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9	CMH	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10	CML	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Slot 1, E5252A 10x12 Switch Card, Bias Port 1, Disabled

Figure 12. Matrix Switch setup

- **Setup Matrix Switch**

Figure 12 is the matrix switch setup dialog box, which allows you to easily control the matrix switches. Click cross point boxes of switchings to close. This example setup is for the gate-substrate capacitance of a MOSFET. CMH is connected to the substrate terminal and CML is connected to gate.

- **Invert Bias Polarity**

Transform Editor enables you to define functions to calculate data vectors or parameters. We apply reverse staircase voltages to substrate in C-V measurement. So it is necessary to calculate the difference of potential between gate and substrate by defining a function as shown in Figure 13. In this example, gate voltage is defined as VGATE vector. You can define any other functions to analyze measured data too in this dialog box.

- **Subtract Offset Capacitance**

Measure offset capacitance of probe card and/or probe needles. Move probe needles off wafer so needles are not connected to anything. After sweeping substrate voltages, open data window spreadsheet and determine average offset capacitance value as shown in Figure 14. C_COMP shows the compensated offset capacitance vector data.

	C	G	BIAS	C_COMP
1	2.6242p	24.542n	5.0000	2.3373p
2	2.6224p	30.400n	4.5000	2.3355p
3	2.6232p	18.135n	4.0000	2.3363p
4	2.6230p	20.554n	3.5000	2.3360p
5	2.6224p	20.607n	3.0000	2.3355p
6	2.6233p	23.790n	2.5000	2.3364p
7	2.6230p	21.717n	2.0000	2.3370p
8	2.6245p	26.533n	1.5000	2.3376p
9	2.6225p	21.173n	1.0000	2.3356p
10	2.6232p	13.980n	500.00m	2.3363p
11	2.6238p	22.190n	0.0000	2.3368p
12	2.6238p	17.225n	-500.00m	2.3368p
13	2.6231p	25.470n	-1.0000	2.3362p
14	2.6229p	19.394n	-1.5000	2.3360p
15	2.6231p	9.7630n	-2.0000	2.3362p
16	2.6245p	18.127n	-2.5000	2.3376p
17	2.6238p	19.744n	-3.0000	2.3369p
18	2.6233p	17.894n	-3.5000	2.3364p

Figure 14. Data window

Then enter the negative average value of offset capacitance in the B field in E5250A C Compensation dialog as shown in Figure 15. In this example, average offset capacitance was 2.337 pF.

- **C-V Measurement**

Perform C-V measurement of Gate-Substrate capacitor. Contact the probe needles on the wafer, then measure. A graph of compensated capacitance value versus gate voltage will be drawn in a plot window. An example measurement result is shown in Figure 16. The Agilent E5250A Matrix Switch only adds an additional 1% error so you can perform accurate capacitance

Figure 15. Register offset cap

measurements even when using the matrix.

Automated Test Using Agilent ICS

Agilent ICS enables you to automate your tests. You can have multiple measurement setups in one project of ICS. By using the Auto Sequence function, you can sequentially perform selected measurements. Figure 17 shows the Auto Sequence dialog box to define sequence of tests. In this example, the project has five measurement setups and four setups are selected to be executed. Using this function with E5250A matrix switch, you can automate tests including IV and C-V measurements.

Figure 13. Transform editor

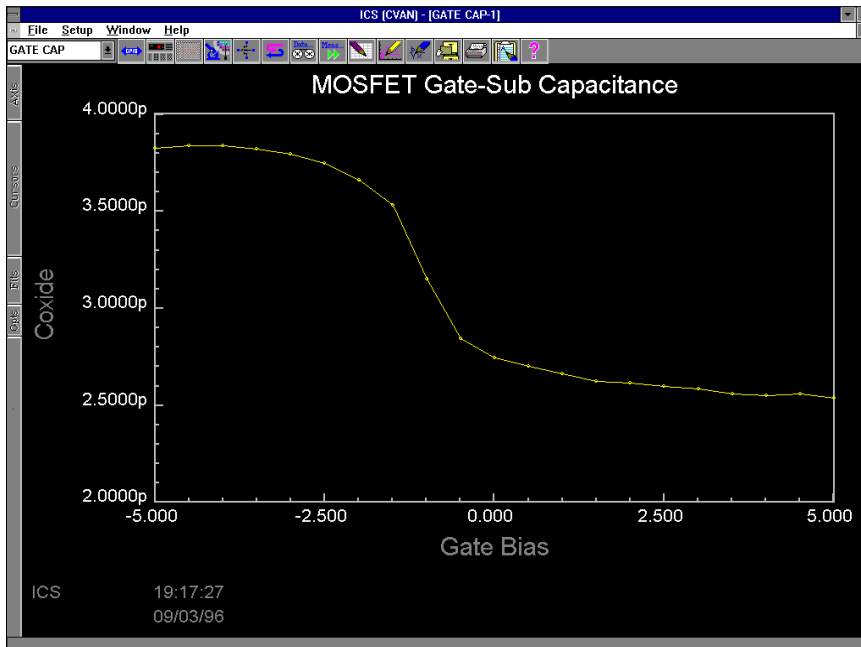


Figure 16. C-V measurement example

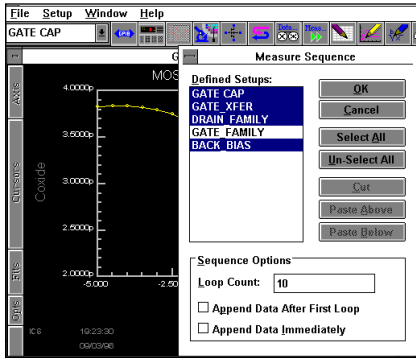


Figure 17. Sequence setup

Compensation Using Agilent IBASIC Program

Capacitance compensation routine is available as a sample program on a diskette furnished with Agilent E5250A Switch Mainframe.

You can use the routine as a subprogram of Agilent BASIC or Agilent Instrument BASIC. By specifying cable lengths, measurement frequency, and raw capacitance and conductance data as parameters to the subprogram, you can obtain compensated data.

An advantage of using this routine is that you can modify the cable parameters used in compensation calculation so that you can use cables other than Agilent 16494A or P/N 8120-4461. Measure your cable parameters and modify the parameter values in compensation routine.

Tips for More Accurate Capacitance Measurements

• Wafer Chuck Capacitance

In general, wafer chuck should be isolated from circuit common and ground. This means it should have higher impedance at the measurement frequency. A common problem is measurement error due to large capacitance between wafer chuck and circuit common. Thermal chuck (or so called hot chuck) has larger capacitance. As the wafer size became larger, the wafer chuck sizes increased, so the chuck capacitance became larger too. This error cannot be compensated by open/short calibration or E5250A compensation. The error is in proportion to $w^2 L_{cable} C_{chuck}$,

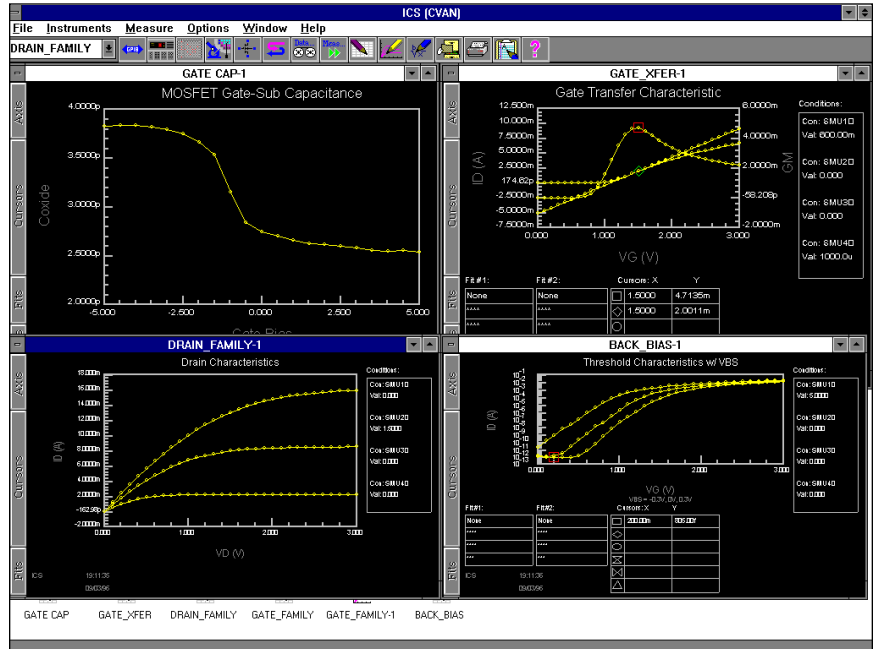


Figure 18. Automated test example

where:

w is defined as $2\pi f$,
 f is measurement frequency,
 L_{cable} is inductance in cables between matrix switch and device,
and C_{chuck} is capacitance between wafer chuck and circuit common.

To minimize the error, use well isolated wafer chuck and make the measurement cables shorter. Using lower frequency is most effective. If you use ICS, set the frequency value in 4284 Setup dialog box shown in Figure 10.

• Device Structure

Figure 19 shows typical device structures for oxide capacitance measurements. In general, most accurate capacitance measurement can be done on structure A because measurement device is isolated from wafer chuck by NP junction. Structure B is better than C because structure B has higher impedance ($R_{contact}$ and C_{chuck}) at wafer chuck. Measurement data of structure A also includes error due to series resistance. If possible, change device structure so that wafer chuck does not affect the device measurement.

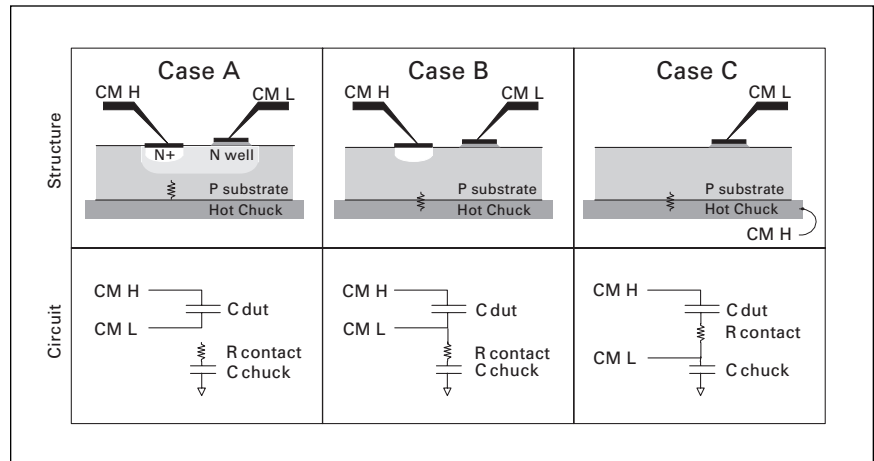


Figure 19. Device connection

Table 1. Ordering Example

E5250A	(*)	Low Leakage Switch Mainframe	1
	001	10 x 12 Matrix Switch Card (E5252A)	4+
	301	Relay Function Test Adapter	1
16494A		Triaxial Cable	52+
	001	Triaxial Cable (1.5 m)	48+
	003	Triaxial Cable (80 cm)	4
4284A	(*)	Precision LCR Meter	1
	001	Power Amplifier/ DC Bias	1
	006	Compensation for 2 m/4 m Cable	1
4156A	(*)	Precision Semi. Para. Analyzer	1
	010	Delete Kelvin Triaxial Cable Set	1
16495B		Connector Plate	2+
	002	Connector to contacts to soldering	2+
8120-4461		Low noise coaxial cable	2m x 48+
16048E		BNC Test Cable for 4284A (4 m)	1
1250-2405		BNC T-Connector for 16048E Cable	2
42091A		Standalone Short Termination	1
10833A		GPIB Cable (1 m)	2
10833B		GPIB Cable (2 m)	1
E5230B		Interactive Characterization Software	1
E5231B		IV Driver Library	1
E5232B		CV Driver Library	1
E5233B		Switch Driver Library	1

* Select appropriate power line and localization options.
 + Decide appropriate numbers upon usage
 A PC with supported GPIB interface is needed for ICS operation.

Measurement Circuit Mode

If your device has large resistance in series, it may be necessary to convert measured parallel capacitance (Cp) and conductance (G) values obtained by E5250A capacitance compensation to the capacitance (Cs) and resistance (Rs) values of a series equivalent circuit. Calculate as follows:

$$Cs = (1 + D^2) Cp$$

$$Rs = \frac{D_2}{1 + D_2} \times \frac{1}{G}$$

where $D = \frac{G}{\omega Cp}$, $\omega = 2\pi f$, and f is measurement frequency.

Noise Reduction

If your test room is electrically noisy, do the following:

–Surround your wafer prober with complete shield to prevent outside electrical noise from going in, and use shorter measurement cables.

–Use longer integration time to average measurement errors. Using higher test signal (oscillation) level is also effective because signal-noise ratio will be higher. Set them appropriately in 4284A Setup dialog box (Figure 10) in ICS.

Conclusion

By using Agilent E5250A's Matrix Switch Modules with capacitance compensation for the Agilent 4284A LCR Meter, you can perform accurate capacitance measurements. Combining with Agilent 4155C/4156C Parameter Analyzer and Agilent ICS enables you to integrate a low cost automatic parametric test system for efficient and accurate characterization and evaluation of multiple devices.

Note: The information contained in this application note is also applicable to the Agilent 4155A/4156A and Agilent 4155B/4156B.

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