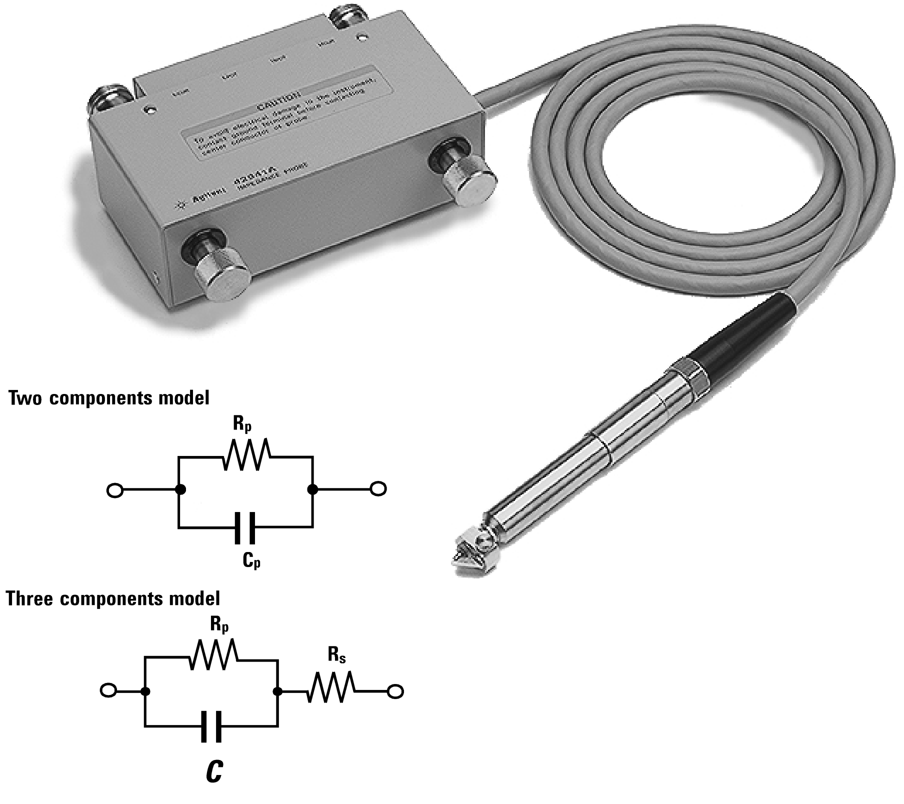
Agilent
Evaluation of MOS Capacitor Oxide C-V Characteristics Using the Agilent 4294A

Application Note 4294-3



Agilent Technologies

1 Introduction

As a result of extremely high integration of logic LSIs, MOS FETs with gate lengths of 0.1 µm or less have been produced recently. A consequence of this miniaturization has been the need for very thin gate oxide layers. In the past, C-V measurements using the Agilent 4284A precision LCR meter have been performed up to 1 MHz, however for gate oxide thicknesses of less than 2 nm, traditional C-V measurements cannot be used due to large leakage currents.

The Agilent 4294A is a state-of-the-art precision impedance analyzer, providing the broadest impedance coverage and expanding the measurement frequency range up to 110 MHz. Furthermore, combining the 4294A with the Cascade Microtech probe station has made it possible to achieve highly accurate and repeatable measurements, even for MOS FETs with very thin gate oxide layers.

In this product note, the breakthrough technologies of the Agilent Technologies 4294A are discussed. Integration of a practical measurement system, suitable for ultra-thin gate oxide evaluation, also is explained. Several problems that may occur during actual device evaluations then are outlined. Finally, detailed solutions for these problems are discussed.

2 The differences between the 4284A and the 4294A

This section describes the functionality of the 4294A and provides comparisons to the 4284A. Table 1 summarizes the functionality differences between the 4284A and the 4294A.

Function	4284A	4294A
Frequency range	20 Hz to 1 MHz	40 Hz to 110 MHz
Sweep function	No: Point measurement only	Yes: Frequency (linear sweep/log sweep) DC bias (voltage/current) AC signal level (voltage/current)
Constant voltage and current DC bias function	No	Yes (auto level control function)
List sweep function	Yes: Point measurement only	Yes: Sweep measurement
Display function	Numeric display	Graphic display
Internal programming function	No: External PC is required	Yes: Internal IBASIC programming function (standard)
Extension cable	1 m/2 m/4 m	1 m/2 m (with phase compensation function)
Data transfer interfaces	GPIB	GPIB, LAN
Grounded device measurement	No	Yes: 42941A (impedance probe)
Other		Touchstone format support (firmware rev. 1.1 or later)

As shown in this table, the 4294A covers not only a wider measurement frequency range than the 4284A, but also is equipped with various analysis functions for the evaluation of ultra-thin gate oxides.

Table 1. Comparison of 4284A and 4294A

3 Breakthrough technology: Impedance probe use

The 4294A achieves the broadest impedance coverage at high frequencies, using the Four-Terminal Pair configuration (4TP) with the Auto-Balancing-Bridge (ABB) method. Furthermore, grounded device measurement is realized with the 4TP and ABB measurement method and is kept by using the 4294A together with the 42941A impedance probe. The 42941A provides not only easy connection to a probe station, but also stable measurement results at high frequencies. In this section, the measurement principle of the 42941A impedance probe and the connection with a probe station is explained.

3.1 Measurement principle of the 42941A impedance probe

The measurement technology of the 42941A is different from the 41941A (previous I-V method). The 42941A achieves an expansion of both the frequency range and the impedance measurement range.

There are two main technical differences in the design of this advanced probe due to the distinctions between the previous I-V method and the new I-V method.

1. With the new method, a nearly ideal current meter is used, without the need for a transformer. This enables accurate measurement of small currents, which enhances the ability to measure high-impedance.
2. Since the transformer is not employed in the advanced I-V method, the operational frequency range of the 42941A probe is not dependent on the frequency response of the transformer. This is of particular importance in the lower frequency range, where the 41941A was limited to a minimum of 10 kHz. Using the advanced method the 42941A can be used from 40 Hz.

Both the impedance measurement and the measurement ranges of the 42941A compared to the 41941A have been drastically improved due to above-mentioned technologies. The 42941A's advanced I-V probing methodology makes ultra-thin gate oxide evaluation possible.

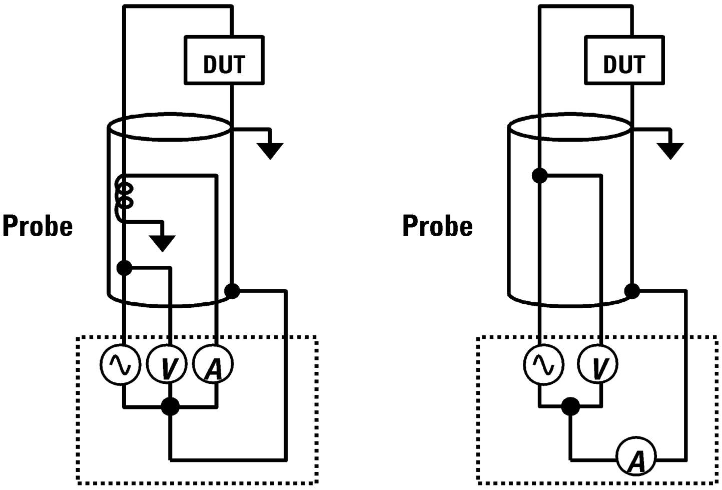
Figure 1. 42941A impedance probe

4. Breakthrough technology: ABB method with 4TP

In this section, the measurement basics of the ABB method with the 4TP are explained. The breakthrough technologies that enable the frequency range expansion of the 4294A also are discussed. By understanding these advanced measurement technologies in the 4294A, knowledge of the actual probe system installation will make sense.

4.1 Basic measurement theory

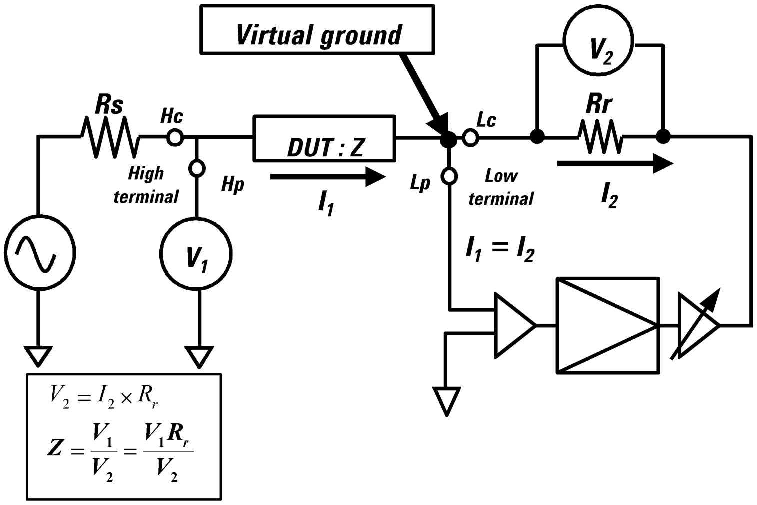
The 4294A provides the best measurement accuracy and the broadest impedance coverage using the 4TP configuration with the ABB method. (Refer to Figure 4.) Figure 3 shows the circuit diagram of the ABB method. In this circuit, the voltage at the virtual ground point is maintained close to the zero voltage; and the current (I_1), which flows through the DUT, goes to the range resistor (Rr). The DUT impedance (Z) is calculated using a voltage measurement (V_1) at the high terminal and a current measurement (I_2), which is given as the voltage measurement (V_2) at the range resistor.



I-V method
4194A + 41941A

Advanced-I-V method
4294A + 42941A

Figure 2. Circuit diagram of the 42941A and the 41941A



$$V_2 = I_2 \times R_r$$

$$Z = \frac{V_1}{V_2} = \frac{V_1 R_r}{V_2}$$

Figure 3. Auto-Balancing-Bridge method

In order to improve measurement accuracy, the 4TP configuration is employed by the 4294A. The 4TP configuration can reduce the effects of lead impedance because the signal path and the voltage sensing cables are independent. In addition to this, the configuration also solves the mutual coupling problem because it uses coaxial cables to isolate the voltage sensing cables from the signal current path.

As shown in Figure 4, at the Hc and Lc terminals, the currents of the inner and outer (shield) conductors are at the same level and flowing in the opposite direction. Therefore, the magnetic flux generated by the inner and outer conductor (shield) cancel each other. At the Hp and Lp terminals, only the difference of voltage between the inner and outer conductor (shield) is detected. The generated electromotive force due to the external magnetic flux at the inner conductor and outer conductor therefore can be eliminated. Consequently, it is possible to measure a wide impedance range without the effect of measurement path length because the magnetic flux generated from the measurement cables and sensitivity to the external magnetic flux are drastically reduced by using the 4TP configuration.

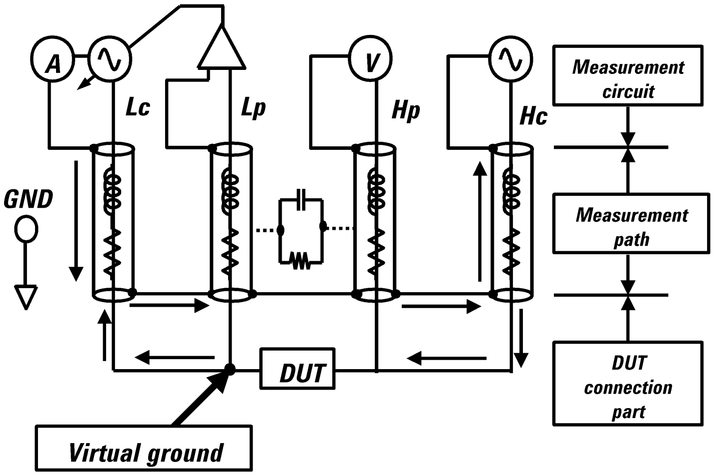


Figure 4. Four-Terminal Pair cable configuration

To ensure this measurement performance, the outer conductor of the measurement cable (shield) should not be connected to ground. In other words, the whole system should be floating from the actual ground level. If the virtual ground of the ABB were connected to the actual ground, the ABB circuit would not operate correctly. This is a key point of the cabling of the 4294A to the probe station, which will be discussed later in this product note.

For more details about the measurement theory, refer to *Impedance Measurement Handbook, 2nd Edition* (Publication number 5950-3000).

4.2 Frequency extension of the 4294A

The 4294A measurement frequency range has been extended to 110 MHz. In order to achieve the frequency extension, the 4294A uses several breakthrough technologies described below.

1. The 4294A uses an innovative technology called the Cable-terminated Auto-Balancing-Bridge method. As shown in Figure 5, the measurement path is terminated by the characteristic impedance of the cable (R_0 = 50 ohm) at high frequencies. This termination solves the standing wave problem at high frequencies so that the measurement signal can be precisely conveyed, independent of the frequency or the measurement path length. Hence, this technology provides highly accurate impedance measurements for higher frequencies, and is utilized above 15 MHz without cable extension. It is also valid above 5 MHz when a 1 m or 2 m extension cable is used. When a 42941A (impedance probe) is used with the 4294A, the cable terminated ABB method also is effective.

2. The bridge circuit is stabilized by using phase compensation technology. In order to improve the bridge balance stability at high frequencies, the 4294A has a special circuit circuit designed to compensate sate for the null-loop characteristics, which can vary with frequency and cable length. The null-loop circuit is located at the low terminal, as shown in Figure 3, and adjusts the feedback loop to maintain a zero voltage at the virtual ground.

In the null-loop circuit, shown in Figure 6, the signal source (Eϕ) is located in front of the vector generator, and the vector voltmeter (Vϕ) is located after the integrated circuit. When connecting both low terminals, Lp and Lc, together, the output signal from the signal source (Eϕ) can flow clockwise through the null-loop circuit, and is measured at the vector voltmeter (Vϕ) in order to characterize the whole null-loop circuit. By performing this phase compensation, the ABB circuit acquires the capability to balance both at high frequencies, and when long extension cables are used.

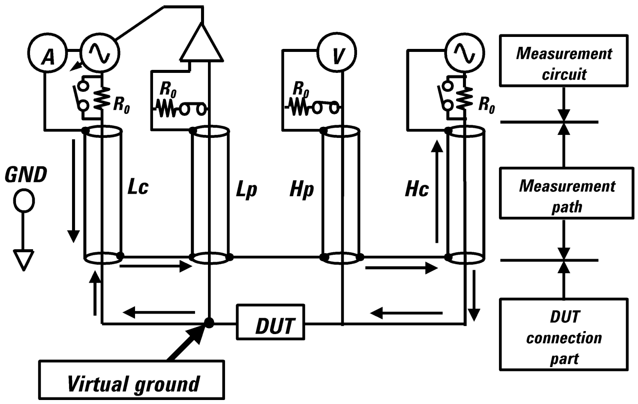


Figure 5. Cable terminated Auto-Balancing-Bridge method

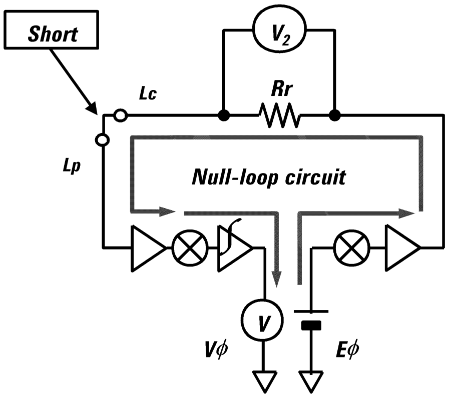


Figure 6. Bridge circuit stability improvement by phase compensation

5. Measurement system installation (Probing directly above the wafer)

As shown in Table 2, several measurement methods are available.

This section initially introduces the required products for the probe system, which are needed to evaluate ultra-thin gate oxides by probing directly above the wafer. Next, measurement issues such as system configuration and calibration are discussed. Finally, special considerations and the resolutions devised to deal with these issues will be explained.

Probing directly above the wafer is simpler than probing through the chuck, and it makes it possible to extend the measurement frequency easily. While the 42941A is, at present, the best solution for obtaining such measurements, the measurement frequency is limited 10 MHz* or less when probing the wafer through the chuck. Therefore, probing directly above the wafer is strongly recommended.

Contact method		Instruments	Measurement method	Features
Probing directly above the wafer	Best	4294A+42941A (Refer to the section 5.1.1)	Advanced I-V method	• Setup is easy • Stable measurement is achieved at high frequencies
	Good	4294A (Refer to the section 5.2.1)	4TP method	• Measurement frequency is higher than probing through the chuck configuration • Setup is complicated
Probing through the chuck	Not Recommended	4294A (Refer to the section 6.1)	3T method	• Setup is comparatively easy • Measurement frequency is limited about 10 MHz

Table 2. Measurement system

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* Note: The measurement frequency range changes due to elements in the measurement environment such as cable, a probe station, or other items.

5.1 System configuration using the 42941A

5.1.1 Required products for 42941A system

The following items are necessary to set up the probe system using the 42941A.

1. Agilent 4294A precision impedance analyzer with 42941A impedance probe (Table 3).

   The cable, which connects the 42941A to the ACP probe, is not a manufactured product so it needs to be constructed by the user. The length of this cable should be as short as possible, because it can be an error source for the entire system.

2. Cascade Microtech probe station, ACP probe head, and impedance standard substrate (Table 4).

5.1.2 Special considerations when connecting the 42941A to a probe station

Figure 7 illustrates a cable connection when probing directly above the wafer.

A cable (SMA (m) to SMA (m)) is used to connect the 42941A and the ACP probe. This cable should be as short as possible since residual inductance of the cable may cause measurement error at high frequencies.

Item	Description	Remarks
4294A	Precision impedance analyzer	
42941A	Impedance probe	
	SMA (m) to SMA (m) cable (1 each)	Semi-rigid cable is recommended

Table 3. Agilent products required for 42941A system

Items	Description	Remarks
Probe station	Summit 11000 or 12000 series S300 series	
Probe	ACP series	Frequency range: DC to 40 GHz

Table 4. Cascade Microtech products required for 4294A system

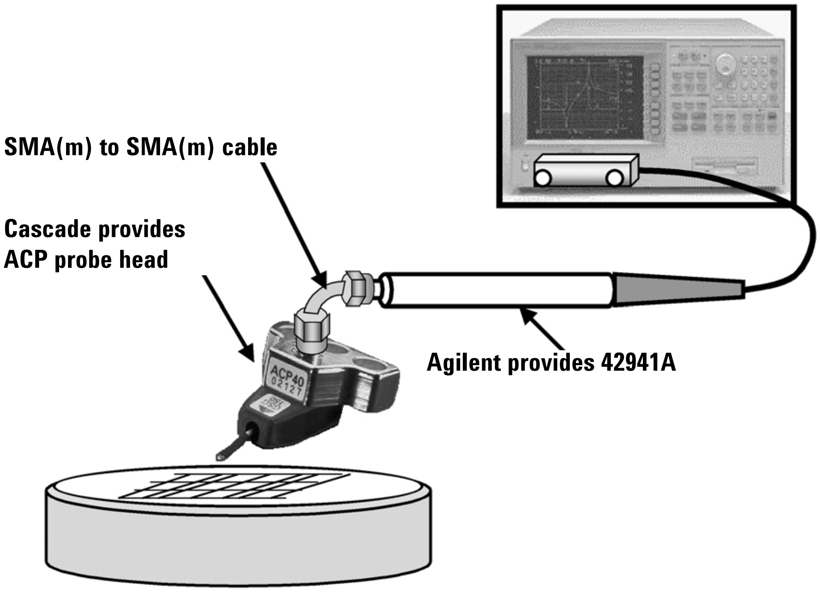

Figure 7. Cabling for the probing directly above wafer

Note: Cascade Microtech products listed in Table 4 need to be purchased from Cascade Microtech.

5.1.3 Compensation procedures for the 42941A

For accurate measurements, it is very important to perform compensation properly.

1. **Phase compensation**
   As shown in Figure 6, the phase compensation function is available on the 4294A.
   - Push the **[Cal]** button and choose **[PROBE]** in the **[Adapter]** menu.
   - Choose **[PHASE COMP]** in the **[SETUP]** menu and then perform the phase compensation. The phase compensation should be performed with nothing connected to the 3.5-mm port. When the phase compensation data measurement is completed, the softkey label changes to **PHASE COMP[DONE]**.
   - After the phase compensation sequence, push the **[DONE]** button. In the 4294A's operation manual, the open, short, and load measurement is also mentioned. However, this is not necessary since open/short/load compensation will be performed at the tip of the ACP probe.
2. **Open/short/load compensation**
   Figure 8 shows the effect of open/short/load compensation data, which compares the measurement data with and without open/short/load compensation. The open/short/load compensation can drastically improve the measurement accuracy and stability at high frequencies. It also is possible to improve measurement accuracy when non-standard-length test leads or external circuits are used.

In the case of probing above the wafer, the open/short/load compensation can be performed by using the Impedance Standard Substrate (ISS).

For compensation, the 4294A has two modes. One is the COMP POINT: FIXED mode, which measures compensation data at pre-specified frequency points and determines the compensation's affect at other frequency points by using interpolation. The other mode is the COMP POINT: USER, which measures compensation data at the frequency points that are actually set up. In this case, you can make accurate measurements, but compensation needs to be performed again when the measurement frequency is changed. In other words, if measurement parameters are changed frequently, COMP POINT: FIXED mode is recommended and if highly accurate measurements are required, COMP POINT: USER mode is recommended.

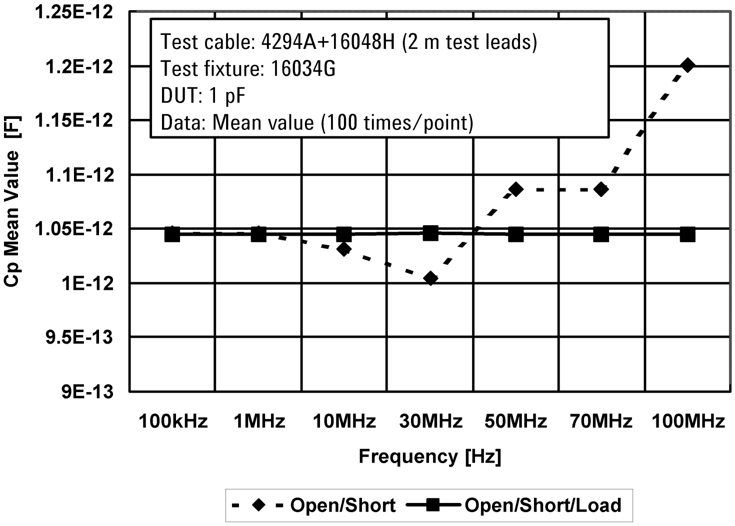

Figure 8. The effect of the open/short/load compensation

Perform the open/short/load compensation by using the ISS at the tip of ACP probe. Before performing compensation, calibration kit values need to be entered in the 4294A. This enables you to make more accurate compensation.

- Push the **[Cal]** button and choose the **[FIXED]** or **[USER]** mode from the **[COMPOINT]** menu.
- Push the **[Cal]** button again and choose the **[DEFINE VALUE]** from the **[FIXTURE COMPEN]** menu.
- In the case of ACP probe, the value of calibration kit is indicated in the box of probe head. The value of **[OPEN CAP(C)]**, **[SHORT INDUCT(L)]**, and **[LOAD INDUCT(L)]** values corresponding to the ACP probe need to be entered.
- Go to the **[FIXTURE COMPEN]** menu and begin performing the **[OPEN]**, **[SHORT]**, and **[LOAD]** compensation using the ISS.
- When performing the open compensation, ACP probe needs to be floating from the chuck.
- Perform short compensation by connecting both probes to the short on the ISS.
- Perform load compensation by connecting both probes to the load on the ISS.

5.2 System configuration using the 4294A

5.2.1 Required products for 4294A system

The following items are necessary to set up the 4TP configuration system when probing directly above the wafer.

1. Agilent 4294A precision impedance analyzer with 16048G or H test leads (Table 5).

2. Cascade Microtech probe station, probe head, and impedance standard substrate (Table 6).

Item	Description	Remarks
4294A	Precision impedance analyzer	
16048G or H	Test leads, BNC (1 m or 2 m)	These items are not required when Cascade Microtech's BNC-SSMC cable (Part number 105-540) is used
	BNC (m) to BNC (m) adapters (4 each) Part number 1250-0216 Tri-axial BNC(m) to BNC(f) adapters (4 each) Part number 1250-2650	

Table 5. Agilent products required for 4294A system

Items	Description	Remarks
Probe station	Summit 11000 or 12000 series S300 series	
Probe	DCP-100 series or DCP-HTR series	Frequency range: DC to 100 MHz Probe type: Kelvin/non-Kelvin
Cable	Tri-axial cables (4 each) Part number104-330-LC	These items are not required when BNC-SSMC cable (P/N: 105-540) is used
	BNC-SSMC cables Part number 105-540	Connect to the DCP probe directly
	Guard cable Part number 123-625	
Standard for calibration	Impedance standard substrate (ISS)	Choose the appropriate ISS for the probe used

Table 6. Cascade Microtech products required for 4294A system

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Note: Cascade Microtech products listed in Table 6 need to be purchased from Cascade Microtech.

5.2.2 Special considerations when connecting the 4294A to a probe station

Figure 9 illustrates the cable connection when probing directly above the wafer.

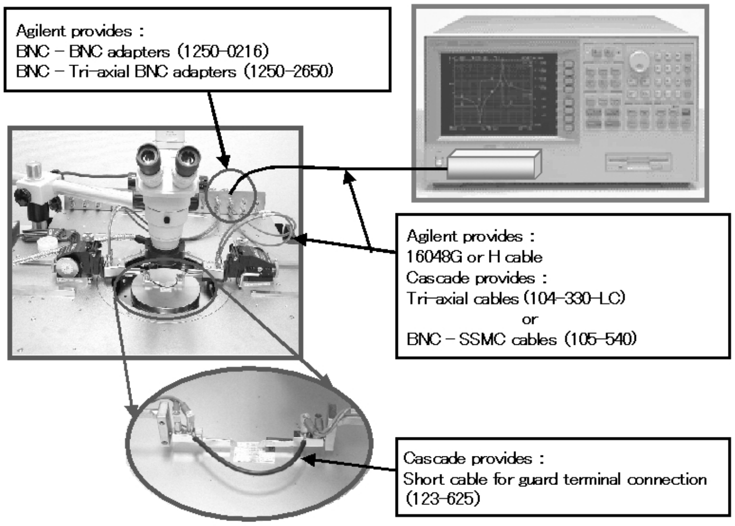


Figure 9. Configuration for probing directly above the wafer

The following points are indicated as special considerations for the actual probe system configuration.

1. **Test leads and adapters**
   The BNC-SSMC cable (Part number 105-504), which is provided by Cascade Microtech, is recommended for connecting to the probe station. With this cable, the 4294A and DCP series probe can be connected directly.

   Furthermore, the 4TP configuration is terminated when using a probe positioner for C-V measurement, because the outer (shield) and the inner conductor are connected together in the probe positioner. As a result, residual impedance, which exists in the cable between the probe positioner and the probe itself, has a negative effect on measurement results. Therefore, in order to keep the 4TP configuration very close to the tip of probes, it is recommended to use the BNC-SSMC cable.

   When connecting through the connecting plate of the probe station, the Agilent 16048G or H (1 m or 2 m) cable is recommended. The characteristics of these cables are carefully evaluated by Agilent Technologies and measurement accuracy is defined at the tips of these cables. When these cables are used with the probe station, BNC to tri-axial BNC adapters (Part number 1250-2650) are required. As shown in Figure 9, the outer shield and the inner shield (guard) of these adapters are not connected together, so the 4TP configuration is maintained to the probe positioner. Using this configuration, however, measurement frequency is limited to 60 MHz* due to the frequency response of these adapters.

2. **Guard connection**
   As shown in Figure 9, the guards of the low and the high terminal should be connected together using the guard cable (Part number 123-625) provided by Cascade Microtech. It is desirable that the 4TP configuration be maintained very close to the tips of the probes in order to obtain high accuracy. If a guard is improperly connected, the current path between the inner and the outer (shield) conductor is not formed and it may cause not only an unbalanced bridge, but also inaccurate measurement results. It is also important to note that wafer evaluation may be incorrect at certain measurement frequencies and environmental conditions even though the guard cable (Part number 123-625) is used. In such a case, connect both guards with a shorter cable to reduce the residual impedance and extend the system's operation frequency, as shown in Figure 10. This figure shows a measurement result of a short on the ISS without the open/short/load compensation. It compares the guard cable (Part number 123-625) with the shorter guard cable (about 2 cm).

From this measurement result, it can be inferred that the residual inductance of the guard cable can't be ignored at high frequencies. Usually, such a residual inductance can be removed to a certain extent by performing compensation. However, when residual inductance is large, as shown in Figure 10, compensation does not work well due to the variations in the residual inductance value. As a result of this, not only does the measurement accuracy degrade. but the measurement also becomes very unstable. In addition, a resonance caused by the inductance of the guard cable and the stray capacitance between the chuck and the actual ground, or the top deck and the chuck, can degrade measurement accuracy as well (Figure 11). Consequently, the length of the guard cable should be carefully considered.

3. **Exchange from 4TP configuration**
   When using a probe from a company other than Cascade Microtech, the length between the 4TP termination point and the tip of the probe should be less than 10 cm. If the length is longer, the bridge may be unbalanced. Please note that cable extension using a non-4TP configuration has a negative effect on measurement results due to the obvious symptoms of residual impedance and mutual inductance.

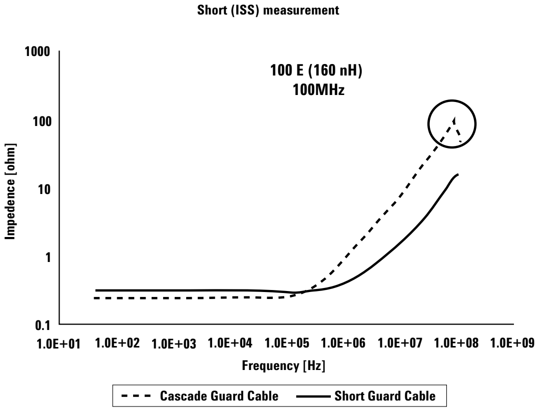


Figure 10. The guard cable's effect on the measurement

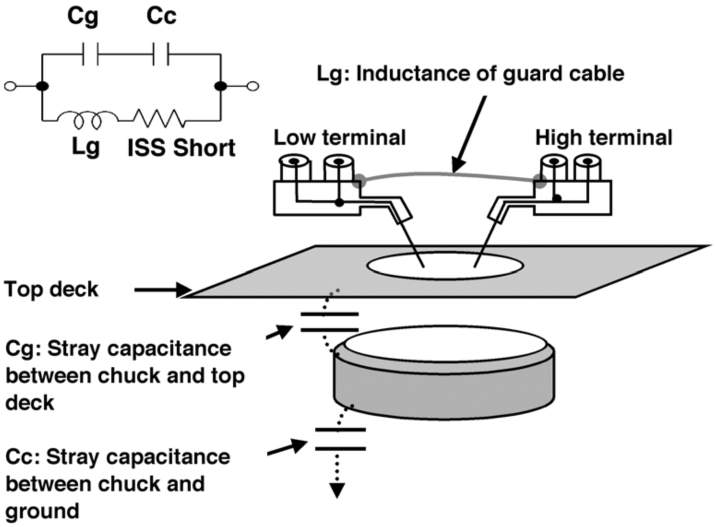


Figure 11. The variety of factors that influence measurements results

5.2.3 Compensation Procedures for the 4294A

For accurate measurements, it is very important to perform compensation properly. This is especially true when the 4294A uses extension cables and adapters for connecting to the probe station.

1. **Phase compensation**
   As shown in Figure 6, the phase compensation function is available on the 4294A. After setup is complete, phase compensation should be performed.

   - Push the **[Cal]** button and in the **[Adapter]** menu choose the extension cable length **[4TP 1M]** or **[4TP 2M]**, whichever is closest to the total cable length.

   - Connect the two low terminals, Lp and Lc, together as shown in Figure 6. When using the DCP probe (non-Kelvin type) from Cascade Microtech, the probe should be floating from the chuck because both terminals already have been connected together in the probe. When using the Kelvin probe, Lp and Lc terminals should be connected together by using the short on the ISS, which is provided from Cascade Microtech.

   - Choose **[PHASE COMP]** in the **[SETUP]** menu. After the phase compensation sequence, push the **[DONE]** button. In the 4294A's operations manual, the load measurement is mentioned, however its use is not necessary since load compensation will be performed later.

2. **Open/short/load compensation**
   In the case of probing above the wafer, the open/short/load compensation can be performed by using the ISS.

   - Push the **[Cal]** button and choose the **[FIXED]** or **[USER]** mode from the **[COMPOINT]** menu.

   - Go to the **[FIXTURE COMPEN]** menu and begin performing the **[OPEN]**, **[SHORT]**, and **[LOAD]** compensation using the ISS. When performing the open compensation, each probe should be kept at the same distance of the DUT's electrode pitch. This technique is particularly effective when measuring small capacitances.

   - When performing the open compensation, probes need to be floating from the chuck. If using the Kelvin probes, both probes should contact the short standard on the ISS.

   - Perform short compensation by connecting both probes to the short on the ISS.

   - Perform load compensation by connecting both probes to the load on the ISS.

   - Standard DUT values, which are used in compensation, can be set in the **[DEFINE VALUE]** menu.

6. Measurement system installation (probing through the chuck)

In this section, the required products for the probe system and the details about the system configuration are explained. Compensation techniques of the instrument and special considerations also will be discussed.

6.1 System configuration

The following items are necessary to set up the probe system when probing the wafer through the chuck.

1. Agilent 4294A precision impedance analyzer with BNC cables (Table 7)

2. Cascade Microtech probe station, probe head, and ISS (Table 8)

6.2 Special considerations when connecting the 4294A to the probe station

Figure 12 illustrates the concept of cable connection when probing through the chuck.

1. **Test leads**
   When probing through the chuck, the 16048G or H test lead cannot be used with the probe station because the high and the low terminals are apart from each other, so general-purpose BNC cables are required.

2. **Guard connection**
   As for the connection cables and the adapters, the same products can be used for probing directly above the wafer. To perform the measurement, a three-terminal configuration is recommended for probing a wafer through the chuck. (Refer to Figure 12.)

3. **Connection to the chuck**
   The stray capacitance, which is generated by leakage current between the chuck and the actual ground, has a negative effect on measurement results. As shown in Figure 13, to reduce the measurement errors due to leakage current, the high terminal should be connected to the chuck. This configuration eliminates measurement error because only the current flowing through the DUT is measured by the 4294A.

Item	Description	Remarks
4294A	Precision impedance analyzer	
	BNC (m) to BNC (m) cables (4 each) Part number 8120-1839 or 8120-1840 (61 cm/122 cm)	Cable connection for the chuck

Table 7. Agilent products required for 4294A system

Item	Description	Remarks
Probe station	Summit 11000 or 12000 series	
Probe	DCP-100 series or DCP-HTR series	Frequency range: DC to 100 MHz Probe type: Kelvin/non-Kelvin
Cable	Tri-axial cables (2 each) Part number 104-330-LC	Cable connection for the probes
Standard for calibration	Impedance standard substrate (ISS)	Choose the appropriate ISS for the probe used
Adapter	Tri-axial BNC (m) to BNC (f) adapters (4 each) Part number 1250-2650	

Table 8. Cascade Microtech products required for 4294A system

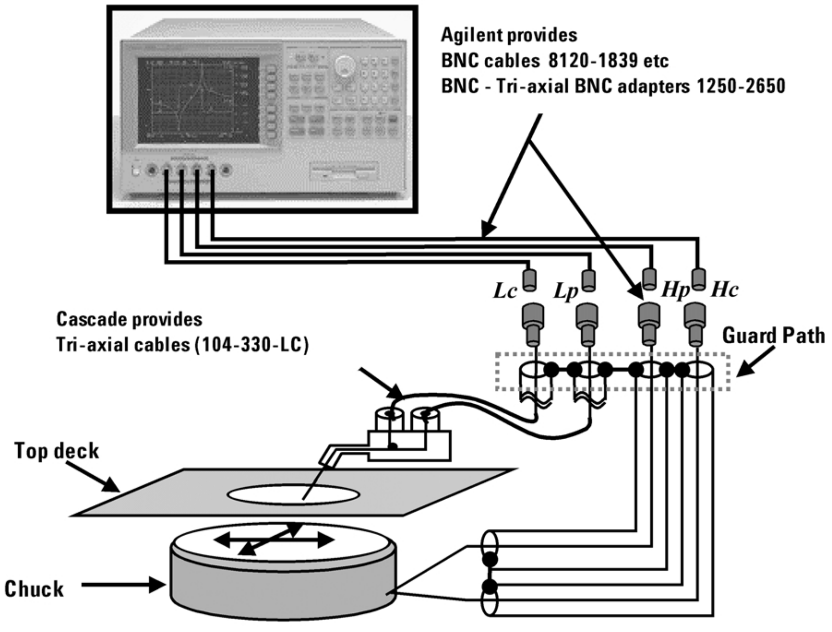


Figure 12. Cabling when probing through the chuck

Note: Cascade Microtech products listed in Table 8 need to be purchased from Cascade Microtech.

6.3 Compensation procedures for the 4294A

Although performing open/short/load compensation properly is crucial to the measurement, compensation when probing through the chuck gets extremely difficult. A useful compensation method is described below.

1. **Phase compensation**
   Phase compensation should be performed in the same manner as probing above the wafer. If a non-Kelvin probe is used, the probe should be floating from the chuck, since both low terminals (Lp and Lc) are already connected together in the Cascade Microtech probe. If a Kelvin probe is used, both low (Lp and Lc) terminals should be shorted by using the short standard on the ISS.

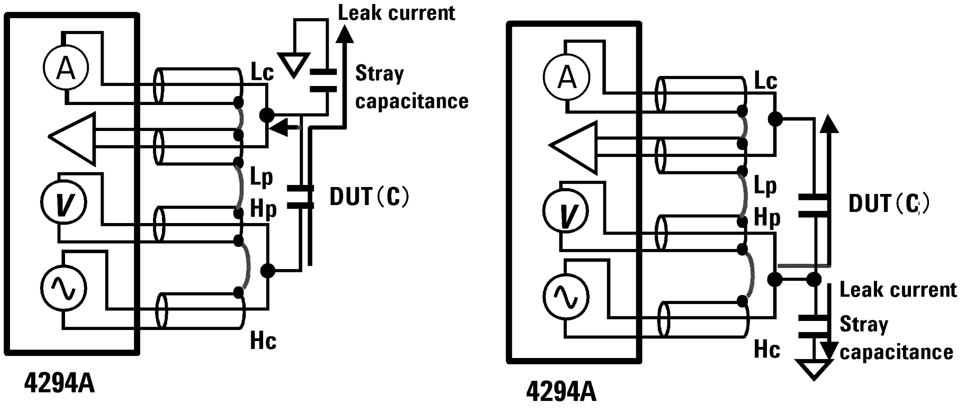
2. **Open/short/load compensation**
   The ISS cannot be used for the compensation of the wafer measurement through the chuck. Therefore, it is very difficult to perform an accurate compensation when compared to the probing above the wafer configuration. The following procedure is one example of the open/short/load compensation through the chuck.

   - Open compensation should be performed by floating the probe from the chuck.

   - Short compensation should be performed by connecting the probe directly to the chuck.

   - One of the ideas of performing load compensation is to use a 50 W Surface Mount Device (SMD) resistor as the standard DUT to substitute for the load on the ISS. In this case, an insulator should be inserted under the one of the electrodes of the SMD in order to isolate the electrode from the chuck. Standard DUT values, which are used in compensation, can be set at the **[DEFINE VALUE]** menu.

If further operation information is required, please refer to the previous section.


When connecting low terminals to chuck side

Flowing current of DUT branches off to the stray capacitance and it will cause a measurement error

When connecting to high terminals to chuck side

Leak current due to the stray capacitance does NOT effect the measurement current of DUT

Figure 13. Cable connection to the chuck

7. Actual measurements

In this section, the evaluation of actual ultra-thin gate oxides and some cautioning factors relating to the measurement are discussed.

7.1 Two-frequency technique

An equivalent circuit of the current two-parameter model, such as a parallel capacitance (C_p) and a parallel resistance (R_p), as shown in Figure 14, is not enough to express the actual ultra-thin gate oxide behavior when leakage current increases. It has already been noted that the three-parameter equivalent circuit model, as shown in Figure 14, is used as the model for ultra-thin gate oxides.

The two-frequency technique is convenient for extracting the parameters from the three-parameter model. This technique is used to calculate the capacitance values of three-parameter mode using the following equation. In this equation, Cp and D values are obtained at two different frequencies.

$$C = \frac{f_1^2 C_{p1}(1+D_1^2) - f_2^2 C_{p2}(1+D_2^2)}{f_1^2 - f_2^2}$$

f_1, f_2: Frequency at two different points

D_1, D_2: Dissipation at two different frequencies

C_{p1}, C_{p2}: Capacitance at two different frequencies

As long as the difference of the impedance values at the two different points is large, accurate capacitance values can be obtained. However, if the difference is not wide enough, the obtained parameters may be inaccurate. Therefore, it is important to choose two appropriate frequency points.*

7.2 Minimum phase detection method

The minimum phase detection method is a new technique to obtain the parameters of the three-parameter model from the frequency characteristics of the |Z|-q measurement. As shown in Figure 15, the capacitance values (C) can be calculated by frequency (f_0), phase (q_0), and impedance ($|Z_0|$) values at the minimum phase point. A constant DC bias voltage should be applied during the |Z|-q measurement. In order to obtain a precise capacitance value, it is desirable to measure capacitance at the frequency where the dissipation factor (D) is the smallest. In other words, the loss of device becomes smallest at the minimum phase point. Eventually, the C-V characteristics plot can be obtained from several fixed DC bias |Z|-q frequency sweeps.

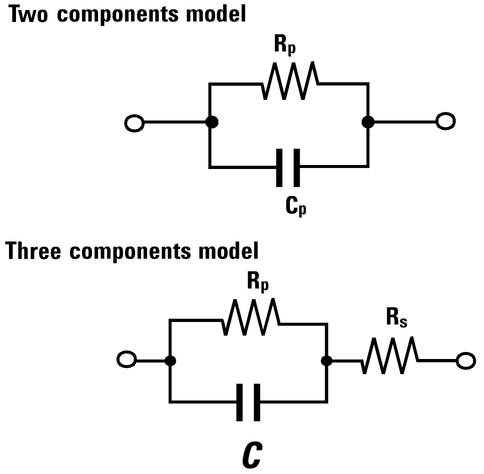
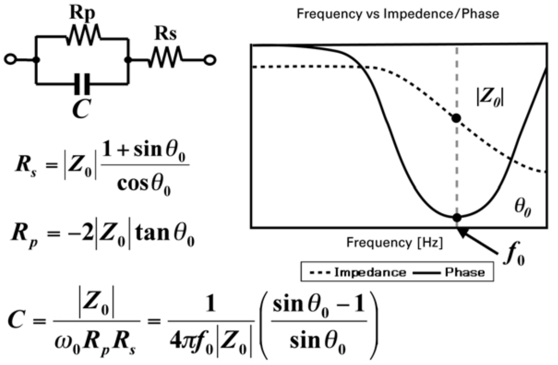


Figure 14. Two-frequency technique



$$R_s = |Z_0|\frac{1+\sin\theta_0}{\cos\theta_0}$$

$$R_p = -2|Z_0|\tan\theta_0$$

$$C = \frac{|Z_0|}{\omega_0 R_p R_s} = \frac{1}{4\pi f_0 |Z_0|}\left(\frac{\sin\theta_0 - 1}{\sin\theta_0}\right)$$

Figure 15. Minimum phase detection method

---

*For information on choosing frequency points, refer to reference paper 8.

The equation for the minimum phase detection method is as follows.

$$C = \frac{1}{4\pi f_0 |Z_0|}\left(\frac{\sin\theta_0 - 1}{\sin\theta_0}\right)$$

f_0 : Frequency at minimum phase point

$|Z_0|$: Impedance value at minimum phase point

θ_0 : Phase value at minimum phase point

The 4294A is equipped with the Instrument BASIC (IBASIC) programming function and so the calculation of the minimum phase detection method can be accomplished within the instrument itself. Hence, an external PC is not required for calculation, although it is need when using the 4284A. Figure 16 shows the calculation results of each parameter, which were calculated with IBASIC using the minimum phase detection method, and displayed on the 4294A.

Figure 17 shows the measured and corrected capacitance for an ultra-thin gate oxide using the minimum phase detection approach presented above. As shown in this figure, the minimum phase detection method is valid to obtain accurate C-V measurement results.

7.3 Another two-frequency technique

When a minimum phase point does not appear due to measurement frequency limitations, the capacitance values cannot be obtained by the minimum phase detection method. In this case, the two-frequency technique presented above, or the use of a two-frequency technique using the |Z|-q measurement results, is convenient. However, the later method may not be able to get the precise capacitance value when dissipation factors (D) are large at both frequency points.

$$C = \frac{A_1 f_2 - A_2 f_1}{2\pi A_1 A_2 (f_1^2 - f_2^2)} \_ A_1 = |Z_1|\sin\theta_1 \_ A_2 = |Z_2|\sin\theta_2$$

$$R_P = \frac{A_1 A_2 (f_2^2 - f_1^2)}{\sqrt{f_1 f_2 (A_1 f_1 - A_2 f_2)(A_2 f_1 - A_1 f_2)}}$$

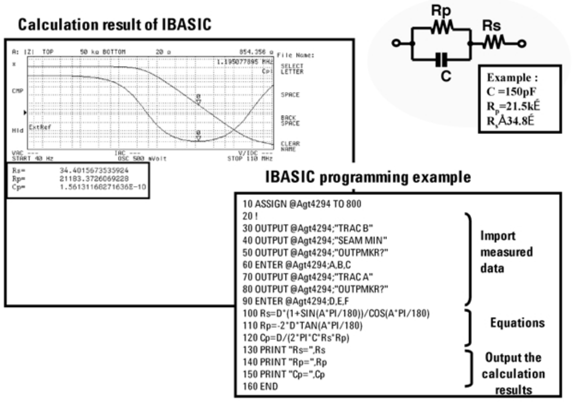
$$R_S = \frac{A_1 A_2 (B_2 f_2 - B_1 f_1)}{A_1 f_2 - A_2 f_1} \_ B_1 = \frac{1}{\tan\theta_1} \_ B_2 = \frac{1}{\tan\theta_2}$$

Where

f_1, f_2 : Frequency at each frequency point

$|Z_1|, |Z_2|$: Impedance value at each frequency point

θ_1, θ_2 : Phase value at each frequency point



```
Rs=         34.4015673535924
Rp=         21183.3726069228
Cp=         1.56131168271636E-10
```

Example :
C =150pF
R_p=21.5kÉ
R_sÅ34.8É

```
10 ASSIGN @Agt4294 TO 800
20 !
30 OUTPUT @Agt4294;"TRAC B"
40 OUTPUT @Agt4294;"SEAM MIN"
50 OUTPUT @Agt4294;"OUTPMKR?"
60 ENTER @Agt4294;A,B,C
70 OUTPUT @Agt4294;"TRAC A"
80 OUTPUT @Agt4294;"OUTPMKR?"
90 ENTER @Agt4294;D,E,F
100 Rs=D*(1+SIN(A*PI/180))/COS(A*PI/180)
110 Rp=-2*D*TAN(A*PI/180)
120 Cp=D/(2*PI*C*Rs*Rp)
130 PRINT "Rs=",Rs
140 PRINT "Rp=",Rp
150 PRINT "Cp=",Cp
160 END
```

Figure 16. Calculation results using IBASIC

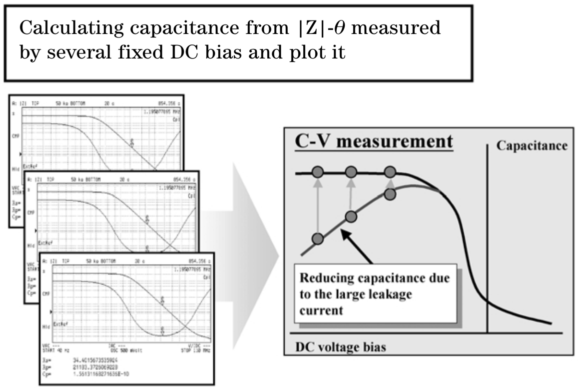


Figure 17. C-V characteristics for ultra-thin gate oxide

7.4 Cautions for actual measurements

1. When a DC bias voltage is applied to the DUT, leakage current from the DUT should be carefully considered since it will cause the DC bias voltage to drop. In the case of the 4284A, DC bias source impedance is 100 W so if 1 mA current leaks, the DC bias voltage level drops 100 mV and hence the actual applied DC voltage will be different from the initial conditions. On the other hand, the 4294A is equipped with the DC Bias Auto Level Control (ALC) function, which is based on the feedback loop technique and accurately maintains the applied DC voltage bias. Therefore, a constant DC voltage bias can be applied to the DUT regardless of the leakage current.

2. It is recommended that the DC current measurement range (1 mA/10 mA/100 mA) be set properly in order to prevent the 4294A from a DC current overload condition due to the leakage current.

3. It is very convenient to use the list sweep function when measuring the |Z|-q characteristics under various DC voltage bias conditions. The list sweep function enables different measurement setups in a single sweep by dividing the sweep range in to segments. The measurement setup, including frequency range, number of points, bandwidth, DC bias and so on can be set differently for each segment. This will drastically reduce measurement time because a single sweep covers several DC voltage bias measurements.

7.5 Beyond the 110 MHz measurement

It may not be possible to measure the phase minimum point beyond the measurement frequency of 110 MHz, because the minimum phase point is shifted to higher frequencies when the gate oxide thickness becomes thin and leakage currents increase.

The equation, which becomes a phase minimum, can be expressed with an equivalent three-parameter circuit model in the following form.

$$\omega_0 = \frac{\sqrt{R_p + R_s}}{C\, R_p \sqrt{R_s}}$$

Since leakage currents increase exponentially against the gate oxide thickness, the parallel resistance (Rp) decreases by one order of magnitude when the gate oxide thickness decreases by one-half. When leakage currents become very large and Rp becomes smaller than Rs (Rp << Rs), the above equation can be expressed as follows.

$$\omega_0 \cong \frac{1}{C\, R_p}$$

In this case, the Rp value becomes the dominant factor. The capacitance value (C) of the gate oxide has minimal influence because it will only double even if the thickness becomes one-half. As a result, the value of ω_0 increases and the minimum phase point shifts to the higher frequencies. In this case, the use of the Agilent E4991A RF impedance/material analyzer with Cascade Microtech's ACP probe is recommended. This configuration can measure impedance characteristics up to 3 GHz. (For more details, refer to Agilent E4991A Application Note 1369-3, *Accurate Impedance Measurement with Cascade Microtech Probe System*, (Publication number 5988-3279EN).)

However, some of devices that do not have a minimum phase point within 100 MHz cannot be measured by simply increasing the measurement frequency range. If the value of Rp becomes equal or less to the value of Rs, the phase becomes constant over an entire frequency range. In other words, it is difficult to measure capacitance value precisely because it becomes the condition of measuring a device which has a high dissipation factor. The only way to solve this problem is to redesign the interconnect and contact pad structures. By redesigning these structures at the device design phase, it becomes possible to reduce the value of Rs.

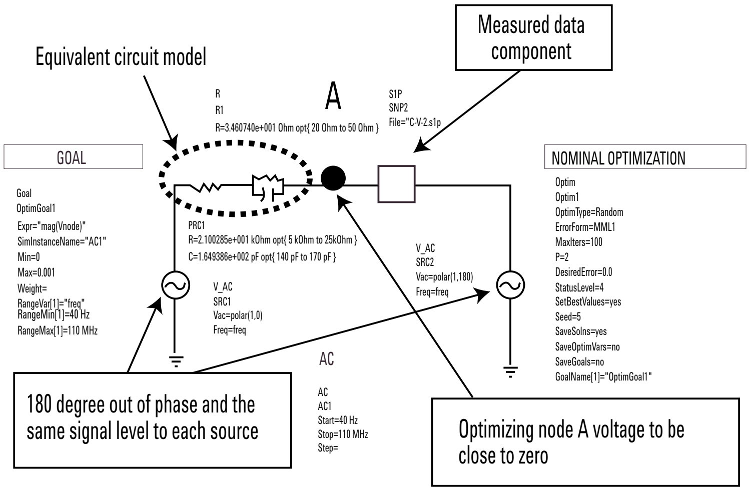


Figure 18. Balancing circuit

8. Equivalent circuit modeling using ADS

In this section, the modeling method for a more complex device using the Agilent EEsof Advanced Design System (ADS) is introduced.

1. Save the measured data in touchstone format and import it into the ADS using the data item component, which allows measurement data to be used in the simulation.
2. The balancing circuit shown in Figure 18 balances the voltage applied to the equivalent circuit model and the data item component. This is accomplished by applying two signals that are the same frequency and signal level but 180 degrees out of phase to each other, and then optimizing the node voltage between the equivalent circuit model and the data item component to be close to zero. In order for this goal to be accomplished, before running the optimization, each of the elements in the equivalent circuit must be defined as variables that can be optimized.

3. Verify that the optimized node voltage is close to zero. If the optimized node voltage is greater than 0.1 V, try changing the equivalent circuit model or the parameter range that was set prior to the optimization. If the extracted parameters are still inaccurate, use the tuning function in ADS to tune the equivalent circuit's frequency response to better match the measure impedance data.

4. The simulation of the three-parameter model is performed in Figure 18, and a model of further complexity is also possible. By taking advantage of simulation tools such as ADS, a complex equivalent circuit model can be easily extracted in a short period of time.

9 Conclusion

In this product note, we discussed how to evaluate the capacitance of ultra-thin gate oxides using an impedance analyzer with a probe station. Proper cabling and calibration enables you to evaluate a device accurately, even it has a large leakage current. We hope this product note makes it easier for you to build an ultra-thin gate oxide evaluation system using the Agilent 4294A and Cascade Microtech Probe Stations.

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Related Literature

Impedance Measurement Handbook, 2nd Edition,
part number 5950-3000.

Accurate Impedance Measurement with Cascade Microtech Probe System, Agilent E4991A Application Note 1369-3, literature number 5988-3279EN.

Glossary

4TP	Four-Terminal Pair configuration
ABB	Auto-balancing-bridge
ACP	Air coplanar probe
ADS	Advanced design system
ALC	Auto level control
BNC	Bayonet Navy connector
BNC-SSMC	Bayonet Navy connector – small subminiature C
C-V	Capacitance vs. voltage
DCP	DC probe
DCP-HTR	Cascade Microtech product
DUT	Device under test
FET	Field-effect transistor
GPIB	General-purpose interface bus
IBASIC	Instrument BASIC
ISS	Impedance standard substrate
I-V	Current-voltage measurement
LAN	Local area network
LSI	Large-scale integration
MOS	Metal-oxide semiconductor
SMA	Subminiature A
SMD	Surface mount device

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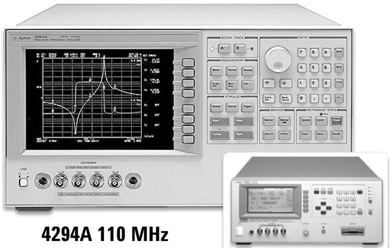

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