Review of Semiconductor Capacitor Basics
Everyone Needs to Measure Capacitance

• High-frequency CV (HFCV) allows you to determine tox, Vfb, Nss, etc.
• Quasi-static CV (QSCV) enables you to see
  – Depletion to Inversion transition
  – Poly depletion effects

Capacitance versus voltage (CV) is an important measurement in parametric test. Only CV measurements can reveal several crucial process parameters.
If the silicon is held at ground and a negative voltage is applied to the gate, the MOS capacitor will begin to store positive charge at the silicon surface. The surface has a greater density of holes than $N_a$ (the acceptor density), and this condition is known as surface accumulation. In this condition the mobile charge on both sides of the oxide can respond rapidly to changes in applied voltage, and the device looks just like a parallel plate capacitor of thickness $t_{ox}$. Since it is a pure gate oxide capacitance, we denote its value as $C_{ox}$.

If a positive gate voltage is applied to the gate relative to the silicon, the built-in positive voltage between the gate and silicon is increased. The silicon surface becomes further depleted of carriers as more acceptors become exposed at the surface, resulting in the condition known as surface depletion. In this condition electrostatic analysis shows that the total MOS capacitance consists of the series combination of $C_{ox}$ and the capacitance across the surface depletion region, $C_d$. Note that $C_d$ depends upon the applied voltage.

If the positive gate voltage is further sufficiently increased, then the energy bands bend away considerably from their levels in the bulk of the silicon. The depletion region reaches a maximum width, $x_{d_{max}}$, and all of the electron acceptors within this region are fully ionized. In the surface region generation of carriers exceeds recombination, and the generated electrons are swept by the electric field into the oxide-silicon interface where they remain due to the energy barrier between the conduction bands of the silicon and the oxide. Thus, the total charge in the silicon consists of the sum of these two charges. Electrostatic analysis again shows that the total MOS capacitance can be modeled as the oxide capacitance in series with the parallel combination of the depletion capacitance and the series combination of surface charge capacitance, $C_i$ and the depletion resistance, $R_t$. 
Step Voltage CV Measurement Technique
The step voltage technique is somewhat similar to a standard sweep voltage measurement. You specify a start, stop, and step voltage. However, there are many additional parameters that you must specify as well. One important one is the voltage step (cvoltage). The cvoltage is the amount that the capacitor voltage will be "bumped" by during each voltage step. Obviously, step voltage >= cvoltage.
The 4155C/4156C use a rectangular approximation method to determine the area under the current spike each time you apply the cvoltage.
How Capacitance is Measured

\[ C = \frac{\Delta Q}{\Delta V} \]

\[ \Delta Q = \int i \, dt \sim \sum i \Delta t_{PLC} \]

This slide shows the appearance of gate voltage and current during a CV sweep.
This page is similar to a simple voltage sweep. However, there are several differences. The most obvious one is that there is a field where you can enter the value of the step voltage (cvoltage). Also, there is a “MEASURE SETUP” softkey at the bottom of the page. This takes you into the “MEASURE: QSCV MEASURE SETUP” page.
This page is completely new on the 4155C/4156C. It contains all of the important measurement fields to define a QSCV measurement.
Here is a classic QSCV measurement done on a relatively thick oxide device (37 Angstroms).
Thin Oxides (<40 Å) Present New Measurement Challenges

- At <40 Å, electron tunneling current becomes more pronounced
- The tunneling current starts to become comparable to the capacitive current that you are trying to measure
- Traditional quasi-static methods no longer work

Measuring capacitance on leaky gate oxides is a major challenge facing the industry today. Traditional QSCV measurement techniques no longer work.
These simplified current waveforms show the two cases where there is no gate leakage current, and where there is appreciable gate leakage current.
To use the leakage current compensation, you must turn this feature “ON,” and you must enter an appropriate leakage current integration time into the leakage current field. The 4155C/4156C uses a complicated trapezoidal approximation to calculate the leakage current component and subtract it from the capacitive component.
This slide shows the benefit of having the leakage current compensation feature.
Do 4155C/4156C QSCV Measurements Agree with “Classical” Measurement Techniques?

Classical QSCV Measurement using the Agilent 4140B:

This slide shows the classical QSCV measurement technique using the Agilent 4140B. This technique uses a constant ramp rate (dV/dt) and the basic equation:

\[ C = \frac{l}{dV/dt} \]

to calculate capacitance.
**4140B Measurement Parameter Determination**

- Same start, stop, and step voltages used
- 4155C/4156C voltage step calculated by multiplying 4140B ramp rate by 4140B integration time
- 4155C/4156C integration time (cinteg) is set to be the same as the 4140B integration time
- 4155C/4156C leakage compensation feature disabled
- 4155C/4156C delay time calculated from
  \[
  \text{delay time} = \frac{\text{step voltage} - \text{cvoltage}}{dV/dt}
  \]

This slide outlines the procedure to correlate 4155C/4156C QSCV measurements with QSCV measurements made using the 4140B. Note that only relatively thick gate oxide devices can be correlated, since the 4140B fails when the leakage current gets to be too large.
Correlation Between 4155C/4156C and 4140B QSCV Measurement

This Excel plot shows the correlation between a 4156C QSCV measurement and a 4140B QSCV measurement. The agreement is quite good.
Possible Causes if Correlation Cannot Be Obtained:

- The 4140B ramp rate (dV/dt) is too steep
- The delay time or cinteg time is too short
- The leakage current compensation feature is turned ON
- You have specified the leakage current to be displayed, which causes the leakage current to be calculated even if the compensation is turned OFF

This slide outlines the reasons why you may not obtain good correlation between the 4155C/4156C and the 4140B. If you cannot obtain correlation, then please check if any of these conditions apply.
Build a Cost-Effective CV-IV Test Solution

Compare quasi-static CV and high-frequency CV test results

A complete CV-IV “system” can now consist of simply a 4155C/4156C, E5250A, and 4284A. Agilent has a CV application disk available that contains an IBASIC program to control the 4284A and display sweep results on the front panel of the instrument. The disk also includes documentation on how to use the software.
The ability to display both QSCV and HFCV curves on the same plot is very important. This allows the calculation of $N_{ss}$ (trap density), which is an important measure of oxide quality.

The aforementioned CV application disk can help you perform this comparison.
I/CV Also Supports the 4155C/4156C QSCV Feature
The I/CV Transform Editor Has Special Functions to Help with the Calculation of CV Parameters

I/CV has several built-in functions to help with the calculation of device parameters from CV measurements.
Quasi-static CV Measurement Summary:

- The 4155C/4156C step voltage technique can accurately measure QSCV
- Thin oxide devices not measurable with the linear ramp technique can be measured using the step voltage technique
- The measurements correlate well with the classical QSCV technique

The 4155C/4156C step voltage technique shows great promise for helping to solve many thin gate oxide CV measurement problems. Moreover, it is very economical to be able to do both CV and IV measurements on the same instrument.
The Fundamentals of Ultra-Thin Gate Dielectric Measurements

With thanks to:
Bill Verzi
Instrument Support Specialist
Austin, TX
Agenda

- Introduction
- Requirements for thin film measurements
- Satisfying these requirements
- Effective Test Structure Design
- A Complete Solution
- Our Proposal
EOT has already become lower than the 2 nm now and leakage current of oxide become over 100 A/cm$^2$.

For high performance device like MPU or ASIC, gate leakage increase tremendously. This increase of leakage of thinner gate dielectrics causes the serious problems.

Glossary
EOT: Effective Oxide Thickness
Thickness of gate dielectrics converted to the silicon dioxide. The dielectric constant of SiO$_2$ is about 3.9.
Top Three Requirements for the C-V Measurement of Leaky Gate Dielectrics:

- High frequency measurement over 1 MHz
- Measurement model suitable for the leaky gate dielectrics
- Measuring the actual device

On-wafer C-V measurement of leaky gate dielectrics is one of the most advanced application of capacitance measurement!

On-wafer C-V measurement of leaky gate dielectrics is one of the most advanced/complicated application of capacitance measurement.

So to understand it, understanding of the fundamentals of capacitance measurement is absolutely necessary.
Increased Measurement Frequency

First Requirement for C-V Measurements of Leaky Gate Dielectrics
In principle, a capacitance meter measures the impedance of the DUT by applying a voltage/current and measuring a current/voltage.

\[ Z = \frac{V}{I} \]

The only difference from DC measurements is that the capacitance meter uses an AC signal to measure the impedance of the DUT.

The components of the equivalent circuit are calculated based on the equations shown above.

For thinner gate dielectrics, an increase of leakage current implies a smaller equivalent parallel resistance.

This reduces the relative current flow through the capacitor, making it difficult to measure accurately.

Looking at the impedance plane, a smaller \( R_p \) means a larger \( D \) (Dispersion). This implies that the accuracy of the capacitance measurement is degraded and also that the influence from external noise is increased.

To increase the current flow through the capacitance (decrease the \( D \)), a higher measurement frequency is required to reduce the impedance of capacitance \((1/j\omega C)\).

For this reason, ultra-thin gate oxide measurements require higher measurement frequencies.
**1 MHz with 4284A is Not Enough**

10 MHz or more is needed

\[ D = \frac{1}{\omega C p R p} = \frac{R e}{X c} \]

**Example:**
Tox: 2 nm
10A/cm² @ 1V --> 100A/cm² @ 2V
Rp(dc) = \(2.0 \times 10^{-2}\ \Omega\) cm² @ 2V
Rp(ac) < \(1.1 \times 10^{-2}\ \Omega\) cm²

\(\theta\) @ 1MHz: -6.8°
D @ 1MHz: -8.4°

Difficult to execute accurate and repeatable measurement!

\(\theta\) @ 10MHz: -50°
D @10MHz: -0.84

No degradation of Accuracy
Stable against noise

Accurate & Repeatable!

This slide shows a measurement example.

Key points:
- Rp is NOT a DC resistance. It is the differential resistance for the AC measurement.
- Differential
- From our experience, at least 10 degree of phase are required for accurate measurement.
A More Accurate Device Model

Second Requirement for C-V Measurements of Leaky Gate Dielectrics
This graph shows the C-V curve for an ultra-thin gate oxide made with a conventional C-V meter like 4284 or 4294A.

Cp is calculated by the parallel model (Cp-Rp) described here.

Many users have reported that the measured curve at higher bias becomes lower than the physically expected value.

This deviation from the expected value means that the conventional two-element model needs modification.
The Reason Why the 2 Element Model was Valid for Conventional Devices of the Past

For the conventional thick gate dielectrics, the equivalent parallel resistance $R_p$ is much larger than the series resistance $R_s$. This means that $R_s$ can be ignored when making relatively low-frequency measurements under 1MHz. For this reason the parallel model has been valid until now.

Conversely, for higher frequencies the impedance of the capacitor $C_p$ becomes small compared with the parallel resistance $R_p$. In this case $R_p$ can be ignored and a series model with $C_s$ and $R_s$ only can be used.

Note: The key point is the relative values of $R_p$ and $R_s$. For the thicker oxides, $R_p$ is always much larger than $R_s$.

$R_s \sim 100 \text{ ohm}$

$R_p > 10^6 \text{ ohm}$
For actual devices, the most simplified equivalent circuit of the MOS-CAP includes the series resistance in addition to the parallel resistance. This series resistance comes from the resistance of the substrate and electrode.
For Leaky Gate Dielectrics

For ultra-thin gate oxides under 2 nm in thickness, the magnitude of $R_p$ is comparable with that of $R_s$.

This means that $R_s$ cannot be ignored at low frequencies and that $R_p$ cannot be ignored at higher frequencies.

Ultra-thin gate oxides must be modeled as a 3 elements device including $C_p$, $R_p$ and $R_s$.

This graph shows the simulated results when 3 elements device is measured as conventional parallel model calculated from the equation here.
Measuring the Right Device

Third Requirement for C-V Measurements of Leaky Gate Dielectrics
Many users have reported that they observe a negative capacitance in the higher bias region.

This negative capacitance effect cannot be explained by the 3 element model.

Negative capacitance results when the imaginary part of the measured impedance has a positive value. An impedance with a positive imaginary implies an “inductance”. This has directed some users to try to explain the negative capacitance effect as an inductance caused by the generation and recombination of holes and electrons. However, these approaches have not proven successful.
Agilent has found that the negative capacitance effect occurs when a 4 terminal pair measurement is used for on-wafer measurement. It is not innately coming from the device.

The above circuit diagram shows the whole measurement system including the wafer chuck. The key point is the capacitive coupling that is occurring between the wafer chuck and the return path of the signal (outer shield of the BNC cable or Earth).

In this case, when using the 4 terminal pair, part of the signal flow through the DUT leaks through the capacitive coupling of wafer chuck. The measured impedance is actually described by the equation shown above. From this equation, if the product of \( C_p \) and \( R_p \) is smaller than the product of \( C_r \) and \( R_s \), then the imaginary part of measured impedance becomes positive.

Because \( R_p \) comes from the direct tunneling of gate dielectrics, the effective \( R_p \) rapidly decreases as gate bias is increased. Therefore, a negative capacitance is observed when the gate bias lowers the value of \( R_p \) to the point where \( C_p R_p < C_r R_s \).

This method precisely explains the phenomenon that many users have observed when performing the C-V measurements on ultra-thin gate oxides.
The wafer chuck must become part of the test circuit to remove the negative capacitance. The I-V method is used to eliminate the inductance.

When using the I-V method, it is still possible to observe negative capacitance at higher bias regions of the C-V curve.

However, in the case of the I-V method, this is caused by the actual residual inductance of the current leaking through the wafer chuck.

This means that the negative capacitance observed using the I-V method will be smaller than that observed using the conventional 4 terminal pair measurement.

Note: When floating the wafer chuck and using relatively low frequencies, the negative capacitance effect should be small enough to neglect.
Conclusion

- To Perform the C-V measurement of leaky gate dielectrics
- Use high frequency enough to keep the accuracy
- Use the appropriate device model to extract the parameters (3 element model)
- Select appropriate device to measure
- Use the appropriate configuration of measurement instrument (I-V method with 4294A + 42941A)
The 4294A 110MHz Impedance Analyzer

The Agilent Technologies’ HF-CV solution
Novel Method to Evaluate Thin Gate Oxides

- Agilent has proposed a new method that is more appropriate than the 4 terminal pair configuration.
  - Higher frequency measurement on wafer.
  - Less anomalous negative capacitance effect.

Proven with the many of our customers, and published in the literature!

SSDM 2002, International Conference of Solid State Device and Materials
ICMTS 2003 Microelectronic Test Structures: Okawa, et. al.

Now Agilent developed Agilent 4070 HF-CV solution to resolve those problems that customer faced.

At first, Agilent proposed new method to evaluate the thickness of thinner gate oxide.

This method is developed with the one of most advanced customer in Japan, Toshiba, and customer has made a presentation at SSDM 2002 to show how new method is useful to evaluate thinner gate dielectrics.

Agilent is listed as a coauthor of this paper.

To use I-V method, Agilent 4294A precision impedance analyzer is the best instrument because of its

- Wide Frequency Range (up to 110MHz)
- Precision Measurement
- Support both 4TP and I-V Method.

The Agilent 4294A is the impedance meter using the auto balancing bridge like 4284A and 4285A. But measurement circuit is modified to support the I-V method when using the 42941A impedance probe.

The Agilent 42941A only supports 4294A, not valid with 4284A or 4285A.

The main reason is the connection of the circuit common.

In the 4284A and 4294A, the low side of the signal source (Hp) is connected to the circuit common. But in 4294A, the signal source is floating and the low side of the Lp is connected to the circuit common.

This configuration results that 4294A supports both conventional 4 terminal pair configuration and I-V method by using 42941A.
Now Agilent proposes the new method to get the clear frequency characteristics over 100 MHz.

Agilent supplies the impedance measurement instrument by using I-V method. By using this, wafer chuck can be grounded. It means that the High port can be connected to the gate and low port (GND) can be connected to the wafer chuck.

Because wafer chuck is not driven by the signal source directly, there will be less AC leakage that might cause the resonance like influence at the higher measurement frequency.
The three most important factors in making good CV measurements (to borrow a cliché from the real estate trade) are:

1. Structure Design
2. Structure Design
3. Structure Design

Essentially, the most important aspect of making a good capacitance measurement does not even involve measurement equipment!
A well-designed capacitance measurement structure can often produce good measurement results in spite of poor measurement technique.

However, a poorly designed capacitance measurement structure will probably never produce good measurement results no matter how well you perform the measurement.
Effective Test Structure design extends usefulness of the IV measurement technique beyond 65nm.

Design structure to minimize Rs, and to minimize Gate Leakage to product specifications, tracking technology requirements.

Here is one example of good measurement design technique.
Reducing Rs through effective test circuit design

From J. Schmitz; Philips/IMEC at ICMTS 2003

Reducing Rs through effective test circuit design

Source/Drain

GND

Gate

Well contact ring

Source

Drain

Source

Drain

Gate

Source

Drain

Source

Gate

From J. Schmitz; Philips/IMEC at ICMTS 2003
1.21 nm EOT measurements with the 4294A

At 100kHz test frequency from the 4284 the data is dominated by gate leakage. EOT cannot be obtained accurately. Measurement at 10MHz show significant improvement.

Increasing gate leakage increases dissipation $D = \frac{1}{2\pi f Rc}$ which results in the distortion of CV data. For values of $D > 3$, CV data becomes invalid.

Solution to this problem involves:
- Performing CV measurements in MHz frequency range so dissipation < 3.
- Use of special structures to minimize series impedance.

"Customer Conclusion: Results from the demonstration of the 4294A indicate an immediate need for this impedance analyzer which would help us extract EOT from CV data obtained on devices made with scaled SION or high-k films."

A practical customer measurement example.
Conclusions

- Gate leakage drives us to new C-V measurements
- Normal C-V curves can be obtained with 4294 DC-IV methods
- Test structure design is critical, external resistances must be well controlled
- Solution can be made manufacturable because of easy calibration, temperature stability, and excellent accuracy vs impedance characteristics.
High-Frequency (> 5 MHz) CV Measurement: Tips & Tricks
Agenda

- Achieving high accuracy measurements
- Connection with Probe Station
- Measurement Tips
- RF C-V Measurement Solution
Achieving High Accuracy Measurements

- System Outline
- Advanced I-V Method
- Auto Balancing Bridge Method
- Extension to LF band
- Cautions for cabling
- Compensation
**Achieving High Accuracy Measurement**
- System Outline (Summit Probe Station with 4294A) -

**Agilent 4294A**
- Precision Impedance Analyzer
- Frequency range: 40Hz to 110MHz
- Basic impedance measurement accuracy: ±0.08%
- Various sweep parameters (DC Bias, AC signals)
- Internal IBASIC program function
- Data transmission through LAN

**Summit Probe Station**
by Cascade Microtech Inc.

---

**System Outline**

In this solution, the Agilent products are the 4294A precision impedance analyzer and the 16048G or H test leads. Agilent standard cables are used to extend the measurement port. The Probe station, probe heads and calibration standard are supplied by Cascade Microtech. This system covers the frequency from 40 Hz to 110 MHz, and it can provide 0.08 % basic accuracy.
The 4284A versus the 4294A:

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

This table compares the 4284A with the 4294A.
Recommended Measurement System

As shown in this table, several measurement methods are available and each method has some features.

Probing directly above the wafer is simpler than probing through the chuck and it makes it possible to extend the measurement frequency easily. Especially, the 42941A is the best solution which can be introduced at present. On the other hand, 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.

*Note that the measurement frequency range can vary due to measurement environmental factors such as cabling, probe station, and so on.
**Achieving High Accuracy Measurements**

- **Advanced I-V method** -
  - 42941A has a much wider impedance and frequency range than the 41941A

---

**Advanced I-V Method**

The 42941A provides not only easy connection to a probe station but also stable measurement results at high frequencies.

This slide shows the typical 10% measurement accuracy range of the 42941A compared to the 41941A. This clearly shows that the 42941A has a much wider impedance and frequency range than the 41941A. The 42941A’s advanced I-V probing methodology made possible an ultra-thin gate oxide evaluation.
**Measurement Basics**

- **Advanced I-V method** -
  - The differences between the previous I-V method and the Advanced I-V method

  ![Diagram showing differences between I-V method and Advanced I-V method]

  **No transformer enables small current measurements**
  **High-impedance measurements enabled**
  **Extend frequency range to much lower:**
  - 41941A: ≥10 kHz
  - 42941A: ≥40 Hz

---

**Advanced I-V Method**

The differences between the previous I-V method and the Advanced I-V method are as follows:

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 thereby enhances the ability to measure high-impedance. Since a transformer is not employed in the "Advanced I-V method", the operational frequency range of this 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, whereas the 42941A can be used down to 40 Hz.
**Achieving High Accuracy Measurements**

- *Auto balancing bridge method*

![Diagram of auto balancing bridge](image)

\[ V_2 = I_2 \times R_2 \]

\[ Z = \frac{V_1}{I_2} = \frac{V_1 R_2}{V_2} \]

**Auto Balancing Bridge Method**

4294A employs a measurement technique called the “Auto-Balancing-Bridge”. This auto balancing bridge can be conceptualized as an Op Amp circuit. Ohm's law applies: \( V = I \times R \). The device is stimulated by an AC signal, with the actual voltage applied to the device being monitored at the H (high) terminal. The L (low) terminal is driven to 0 volt by the virtual ground of the Op Amp. The current, \( I_2 \), through the range resistor is equal to the current through the DUT. Therefore, the output voltage is proportional to the current through the device. Voltage and current are automatically balanced, thus giving rise to its name. To cover a wide frequency range, a null-detector and a modulator are used instead of an amplifier in practical circuits.
**Achieving High Accuracy Measurements**  
*Auto balancing bridge method*

- 4-terminal pair (4TP) measurement method  
  (4284A/4294A etc.)

**Auto Balancing Bridge Method**

In order to maximize the performance of auto-balancing-bridge technique, this circuit is used with the cabling technique called “4-terminal-pair” cabling method.

In general, if you extend the measurement port using cables, these cables may generate some measurement errors. There are 3 factors we need to talk about. 1) Cables themselves have residual impedance, 2) stray capacitances exist between cables or ground, 3) currents that flow in 2 cables generates mutual inductance. If these things happen, the impedance measurement range gets narrower.

But, by using 4-terminal-pair cabling method like shown in this figure, we can avoid concerns above, and we can get very wide impedance coverage for the cabling.

For example, 1) we can avoid the influence of cable’s residual impedance by using 4 cabling method or so-called Kelvin connection. 2) stray capacitance problem can be avoided by having shields of cables, 3) mutual inductance problem can be avoided by making currents flow through inner and outer conductors in opposite directions.

In result, this is the cabling technique we are using for our probe system and we need to work out for this cabling when we install the system.
Achieving High Accuracy Measurements
- Extension to LF band -

- Extension of measurement frequency at terminal

50-ohm termination minimizes standing wave at high frequency

Cable terminated Auto-Balancing-Bridge method
The 4294A uses an innovative technique called the “Cable terminated Auto-Balancing-Bridge method”. As shown in this slide, the measurement path is terminated by the characteristic impedance of the cable \( R_0 = 50 \Omega \) 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 can be utilized above 15 MHz without cable extensions. It is also valid above 5 MHz when a 1 m or 2 m extension cable is used. When 42941A (impedance probe) is used with the 4294A, the Cable terminated Auto-Balancing-Bridge method is also effective.
Achieving High Accuracy Measurements
- Extension to LF band -

- Null loop phase compensation
  - Perform phase compensation with balanced bridge when connecting with extension cable.
  - Short low terminals and perform compensation using internal source

Regardless of measurement conditions, repeatability and phase accuracy at high frequency can be improved.

Phase Compensation

There is one more thing we need to remember about 4294A.

With 4294A, we succeeded to extend the frequency range and usable cable length. It is realized by doing this operation.

That is ..... Before we use an extension cable, we need to compensate the whole measurement circuit including internal circuit and extension cable. We connect Lc and Lp together at the end of extension and measure the characteristics of null loop circuit. This data is used to compensate the whole circuit when you measure DUT.

This process is called “Cable Correction” or “Phase Compensation” in 4294A.
Cautions for cabling
When we combine the 4-terminal-pair cabling technique with auto-balancing-bridge method, there is an important thing we need to remember:

The low terminal of the auto-balancing-bridge is called a virtual ground, and it must be floating with respect to the earth ground. If this point touches the earth ground, the bridge circuit can not operate properly. The outer conductor (or we can call it a shield) of each cable also has same voltage level as the virtual ground and it should be floated too. Please do not connect these points to earth ground.
Achieving High Accuracy Measurements
- Compensation-

Locate measurement reference plane to the DUT contacts
**Achieving High Accuracy Measurements**

**Compensation**
This slide shows the effect of Open/Short/Load compensation data, which compares the measurement data with and without Open/Short/Load compensation. As you can see in this slide, the Open/Short/Load compensation can drastically improve the measurement accuracy and stability at high frequencies. It is also possible to improve measurement accuracy when non-standard-length test leads or external circuits are used.
Achieving High Accuracy Measurements
- Compensation-

OPEN / SHORT / LOAD Compensation is Recommended

- Test fixture of your own
- Non-Agilent extension cable
- Circuit such as scanner

\[
Z_{dut} = \frac{Z_{std} (Z_{o} - Z_{sm}) (Z_{xm} - Z_{s})}{(Z_{sm} - Z_{s}) (Z_{o} - Z_{xm})}
\]

- \(Z_{o}\) : Measured value of OPEN
- \(Z_{s}\) : Measured value of SHORT
- \(Z_{sm}\) : Measured value of standard DUT
- \(Z_{std}\) : True value of the standard DUT
- \(Z_{xm}\) : Measured value of the DUT
- \(Z_{dut}\) : Corrected value of the DUT

Compensation
The model of the Open/Short/Load compensation is shown in this slide.
Connection with Probe Station

1. Cable Connection and compensation
   - Advanced IV (Impedance Probe) Configuration
   - 4TP Configuration
   - 3TP Configuration

2. Measurement Performance
## Connection with Probe Station

<table>
<thead>
<tr>
<th>Contact method</th>
<th>Instruments</th>
<th>Measurement method</th>
<th>Features</th>
</tr>
</thead>
</table>
| Probing directly above  | 4294A+4294A | Advanced IV method | • Setup is easy  
| above the wafer         |             |                    | • Stable measurement is achieved at high frequencies |
| Good                    | 4294A       | 4TP method         | • Measurement frequency is higher than probing through the chuck configuration  
| Not Recommended         | 4294A       | 3T method          | • Setup is comparatively easy  
| Probing through the chuck|             |                    | • Measurement frequency is limited about 10 MHz  |

### Recommended Measurement System

As shown in this table, several measurement methods are available and each method has unique features.

Probing directly above the wafer is simpler than probing through the chuck and it makes it possible to extend the measurement frequency easily. Especially, the 42941A is the best solution which can be introduced at present. On the other hand, 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.

*Note that measurement frequency range changes due to a measurement environment such as cable, probe station, and so on.
**Connection with Probe Station**

- *Advanced IV (Impedance Probe) Configuration -*

  - 42941A Impedance probe with ACP (or Infiniti) probe head solution provides stable measurement up to 110 MHz

  - Compare to the 4TP solution,
    - System configuration is much simpler
    - Frequency is easily extended

  - But,
    - Probe pitch is pre-defined
    - System configuration is NOT flexible
    - Price is higher than DCP probe system

---

**Impedance Probe Configuration**
**Impedance Probe Configuration**

This slide illustrates a cable connection when probing directly above the wafer. The following points are indicated as special considerations for the actual probe system configuration.

- **Cabling**

A cable (SMA (m) to SMA (m)) is used for the connection between the 42941A and the ACP probe as shown in this slide. This cable should be as short as possible since residual inductance of the cable may cause measurement error at high frequencies.
Connection with Probe Station

- Advanced IV: Phase Compensation -

• Phase compensation should be performed with nothing connected to the 3.5-mm port

To keep the bridge balanced with specified measurement path

Phase compensation data stored in EPROM does not change until the adapter setup is modified

ACP probe can be connected when performing phase compensation

Note that Open/Short/Load compensation is not necessary in this step, because this will be performed at the tip of the probe in the fixture compensation step.

Compensation

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.
**Connection with Probe System**

- **Advanced IV: Fixture Compensation** -
  - Calibration kit should be defined in advance.
  - ACP probe head has own open capacitance (C-Open), Short inductance (L-Short) and Load inductance (L-Term)
  - Each value is written at the lid of ACP probe head case. (ex. Probe pitch 150 um)
  - You can easily enter each value at the Cal Kit Menu
  - Use “USER” compensation point mode

<table>
<thead>
<tr>
<th>Pitch</th>
<th>C-Open</th>
<th>L-Short</th>
<th>L-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-11.0</td>
<td>33.5</td>
<td>36.5</td>
</tr>
<tr>
<td>125</td>
<td>-11.0</td>
<td>41.7</td>
<td>47.2</td>
</tr>
<tr>
<td>150</td>
<td>-11.0</td>
<td>49.8</td>
<td>57.8</td>
</tr>
<tr>
<td>200</td>
<td>-11.0</td>
<td>66.2</td>
<td>79.2</td>
</tr>
<tr>
<td>250</td>
<td>-11.0</td>
<td>82.5</td>
<td>100.5</td>
</tr>
</tbody>
</table>

**FIXED compensation mode:**
Measure at fixed frequency points, then interpolate to get compensation data
**USER compensation mode:**
Measure at user specified frequency points, which provides more accurate compensation data

**Compensation**
Perform the Open/Short/Load compensation at the tip of the ACP probe by using the Impedance Standard Substrate (ISS). Before performing compensation, calibration kit values need to be entered in the 4294A. This enables you to perform a 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.
**Connection with Probe System**

* Advanced IV: Fixture Compensation *

- Open, Short and Load Compensation should be performed by using the ISS from Cascade Microtech.

**Compensation**

For calibration, you use Cascade’s impedance standard substrate. It has open/short/load on it and makes possible to do calibration at the probe tip.

When you purchase a probe head and ISS, you need to be careful about the combination of them. Frequency and pitch need to match each other for your application.

Here is the fixture compensation procedure.

- 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.
### Connection with Probe Station

<table>
<thead>
<tr>
<th>Contact method</th>
<th>Instruments</th>
<th>Measurement method</th>
<th>Features</th>
</tr>
</thead>
</table>
| Probing directly above the wafer | Best       | Advanced IV method | • Setup is easy  
• Stable measurement is achieved at high frequencies |
|                        | 4294A       | 4TP method        | • Measurement frequency is higher than probing through the chuck configuration  
• Setup is complicated |
| Probing through the chuck | Not Recommended | 3T method | • Setup is comparatively easy  
• Measurement frequency is limited about 10 MHz |

#### Recommended Measurement System

As shown in this table, several measurement methods are available and each method has some features.

Probing directly above the wafer is simpler than probing through the chuck and it makes it possible to extend the measurement frequency easily. Especially, the 42941A is the best solution which can be introduced at present. On the other hand, 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.

*Note that measurement frequency range changes due to a measurement environment such as cable, probe station, and so on.
Cautions for cabling

Now, let’s move on to the actual cabling and calibration theory. To make 4294A system, you need to consider many things.

1) Try to use Agilent standard cable to extend the cable. Agilent evaluated these cables and we know they are stable. In addition, we can get the guaranteed specification by using them.

2) When you extend the port using extra cables, please do not connect cables’ outer conductors to earth ground.

3) Extra cables should be short and stable.

4) Maintain 4-terminal-pair configuration up to the probe head.

5) Just before the probe head, 4 outer conductors need to be connected. This makes the current possible to go back to the measurement circuit. Sometimes, we forget to connect low and high terminals together. Be careful about it. Use a short cable and connect them.

6) Perform the cable correction for the total cable length. Open/short/load compensation also need to be performed at the end of probe head.

Even if you make your system by yourself, you can make a reliable system by following these instructions.
Connection with Probe System
- 4TP Configuration -

- A cable (BNC-SSMC Cable:105-540) that can directly connect with Cascade DCP probe is available

4TP Configuration

The BNC-SSMC cable (P/N: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.
Connection with Probe System

- 4TP Configuration -

- Connection when conversion to BNC-Tri-axial cable is needed in combination with Cascade Summit 12000 series

Cautions for cabling

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 tip of these cables. When these cables are used with the probe station, BNC to tri-axial BNC adapters (P/N: 1250-2650) are required. As shown in this slide, 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.
**Connection with Probe Station**

- **4TP: Actual Cable connection** -

- When probing from directly above DUT

  - 1250-2650; Tri-axial-BNC adapter
  - 16048G or H: Extension cable
  - Cascade Tri-axial cable or Cascade Direct connection by BNC-SSMC cable
  - Cascade Cable (for Guard)

**Actual Cable Connection**

As shown in this slide, the guards of the low and the high terminal should be connected together using the guard cable (P/N: 123-625) provided by Cascade Microtech. It is desirable that the 4TP configuration is maintained very close to the tip 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.
**Connection with Probe Station**

- **4TP: Actual Cable connection** -
  - Use the tri-axial BNC cables (or equivalent) to connect probe head.
  - Cascade provides Tri-axial BNC cables and BNC to tri-axial BNC exchange connectors

---

**Actual Cable Connection**

This is a connection part of Agilent cables and extra triaxial cables.
Connection with Probe Station

- **4TP: Actual Cable connection** -
  
  - When parallel resonance occurs during measurement, short guard cable is effective
    
    Note that the parallel resonance may occur even if the BNC-SSMC cable is used.

  - Lg: Guard Cable inductance
  - Cg: Stray Capacitance between Chuck and guard
  - Cc: Stray Capacitance between Chuck and actual ground
  - Connect both probes using the shortest cable
  - Top Deck
  - Connect both probes using the shortest cable

**Actual Cable Connection**

It is important to note that wafer evaluation may be incorrect at certain measurement frequencies and environmental conditions even though the guard cable (P/N: 123-625) is used. In such a case, connect both guards with a shorter cable. Since 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. Consequently, the length of the guard cable should be carefully considered.
**Connection with Probe System**

- **4TP: Compensation** -
  
  • Phase compensation
    
    • Short Low terminal and perform phase compensation.
      
      - Non-Kelvin probe: the probe in the air
      - Kelvin probe: the probe on short standard

  • Open/Short/Load compensation
    
    • Open/Short/Load compensation using Cascade ISS (Impedance Standard Substrate)

---

**Compensation**

The phase compensation function is available on the 4294A. After setup is complete, phase compensation should be performed.

In the case of probing above the wafer, the Open/Short/Load compensation can be performed by using the ISS.
**Connection with Probe Station**

<table>
<thead>
<tr>
<th>Contact method</th>
<th>Instruments</th>
<th>Measurement method</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probing directly above the wafer</td>
<td>Best</td>
<td>Advanced IV method</td>
<td>• Setup is easy</td>
</tr>
<tr>
<td></td>
<td>4294A+42941A</td>
<td></td>
<td>• Stable measurement is achieved at high frequencies</td>
</tr>
<tr>
<td>Good</td>
<td>4294A</td>
<td>4TP method</td>
<td>• Measurement frequency is higher than probing through the chuck configuration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Setup is complicated</td>
</tr>
<tr>
<td>Probing through the chuck</td>
<td>Not Recommended</td>
<td>3T method</td>
<td>• Setup is comparatively easy</td>
</tr>
<tr>
<td></td>
<td>4294A</td>
<td></td>
<td>• Measurement frequency is limited about 10 MHz</td>
</tr>
</tbody>
</table>

*Note that measurement frequency range changes due to a measurement environment such as cable, probe station, and so on.*

**Recommended Measurement System**

As shown in this table, several measurement methods are available and each method has some features/benefits.

Probing directly above the wafer is simpler than probing through the chuck and it makes it possible to extend the measurement frequency easily. Especially, the 42941A is the best solution which can be introduced at present. On the other hand, 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.

*Note that measurement frequency range changes due to a measurement environment such as cable, probe station, and so on.*
**Connection with Probe System**

- **3TP Configuration** -

  - To bridge space between High and Low terminals, use 3 terminal connection

  1. Combine from 4 to 2 terminals in as short a distance as possible (10cm or less)

  2. Connect the guards and start phase compensation

  3. 3 terminal connection effects on low impedance measurement due to residual impedance in cable.

  4. Cable extension should be less than 1/4 (Max. 50cm) of measurement frequency.

  5. Open/Short/Load compensation

  4294A

  Frequency range is up to 15 MHz

**3TP Configuration**
To Achieve High Accuracy Measurement

- 3TP: Cautions for cabling-
  - Connect High terminal to Chuck side.

When connecting low terminals to chuck side
DUT Current splitting error between Chuck-GND capacitance can happen.

When connecting high terminals to chuck side
Current between Chuck and GND does not affect the current of DUT.

3TP Configuration

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 this slide, 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.
Connection with Probe Station

1. Cable Connection and compensation
   - Advanced IV (Impedance Probe) Configuration
   - 4TP Configuration
   - 3TP Configuration

2. Measurement Performance
**Measurement Performance**

Connect both guards with a shorter cable. This way the residual impedance is reduced and the system’s operation frequency can be extended as shown in this slide. This slide shows a measurement result of a short on the ISS without the Open/Short/Load compensation. It compares the guard cable (P/N: 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 this slide, 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 also the measurement becomes very unstable.
Measurement Performance

This slide shows a measurement result of a short on the ISS without the Open/Short/Load compensation. It compares the guard cable (P/N: 123-625), the shorter guard cable (about 2 cm), and the Impedance probe (42941A+ACP probe). From this measurement result, the 42941A is strongly recommended for C-V measurement.
**Measurement Tips**

1. Problems with 4284A
2. Calculation of Equivalent Circuit Parameters
3. Utilization of EDA tool
**Measurement Tips**

*Problems with 4284A -

<table>
<thead>
<tr>
<th>4284A</th>
<th>4294A</th>
</tr>
</thead>
<tbody>
<tr>
<td>• External PC is required when calculating 3-element model</td>
<td>• Auto-calculation of each parameter in 3-element model by internal IBASIC</td>
</tr>
<tr>
<td>• Analysis with point sweep up to 1MHz</td>
<td>• Analysis up to 110MHz by Frequency sweep</td>
</tr>
<tr>
<td>• DC bias point sweep measurement</td>
<td>• DC bias sweep measurement with constant voltage mode</td>
</tr>
<tr>
<td>• Use of predefined cable</td>
<td>• Equipped with phase compensation function</td>
</tr>
<tr>
<td></td>
<td>• Support the Touchstone format (Rev.1.1)</td>
</tr>
</tbody>
</table>

**Problems with 4284A**

This table summarizes the difference of functionality between the 4284A and the 4294A. As shown in this Table, the 4294A covers not only a wider measurement frequency range than the 4284A, but is also equipped with various analysis functions for the evaluation of ultra-thin gate oxides.
RF C-V Measurement Solution

1. System Outline
2. Measurement Range
**RF Solution**

- **System Outline (Summit Probe Station with E4991A)** -

  - Summit Series Probe Station by Cascade Microtech

  - Agilent E4991A RF impedance/material analyzer
    - Frequency range: 1MHz to 3GHz
    - Basic impedance measurement accuracy: ±0.8%
    - Various sweep parameters (DC Bias, AC signals)
    - Windows style GUI
    - Internal VBA program function
    - Link to EDS tool
      - Support of CIT file
      - Data transfer by LAN

  - E4991A Option 010 Probe Station connection Kit

  - New
**C-V Measurement Solution**
- Measurement Range (4294A, E4991A, Network Analyzer) -

- **Agilent 4294A**
  - up to 110 MHz

- **Agilent E4991A**
  - up to 3GHz

- **Network Analyzer**
  - 3GHz or more

![Graph showing frequency vs. impedance range for 4294A, E4991A, and Network Analyzer](image-url)
Information Sources

- Agilent 4294A
  - Product Note 4294A-3 “Evaluation of MOS Capacitor Oxide C-V Characteristics Using the Agilent 4294A” (P/N 5988-5102EN)
  - Agilent 4294A Product Overview (P/N 5968-3808E)
  - Agilent 4294A Technical Specification (P/N 5968-3809E)
  - Product Note 4294-2, “New Technologies for Accurate Impedance Measurement up to 110MHz” (P/N 5968-4506E)

- Probe Measurement Application
  - Application Note 1369-3, “Accurate Impedance Measurement using Cascade Microtech Probe Station” (P/N 5988-3279EN)

- Impedance Measurement Theory

- Agilent E4991A
  - Agilent E4991A Product Overview (P/N 5980-1234E)
  - Agilent E4991A Technical Specification (P/N 5980-1233E)
  - Application Note 1369-2, “Advanced measurement capability of the RF I-V method compared to network analysis” (P/N 5988-0728EN)

This lists all related documents and information resources.
The first document, the product note 4294A-3, describes all details about this solution. Please look at it at first.
The others are supportive documents of application note. If you need more information about instruments or technologies, please look at these documents.
For Cascade products, please look at Cascade Microtech web site.
Information Sources

- Agilent URL http://www.agilent.com/find/impedance
- Kobe URL http://kobemktg.jpn.agilent.com/field_eng/
- Kobe C-V measurement URL http://kobemktg.jpn.agilent.com/field_eng/product/4294a/c_v/index.htm
- Cascade Microtech URL http://www.cascademicrotech.com/