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Semiconductor Capacitance Measurement: An Overview

Agilent Technologies

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Review of Semiconductor Capacitor Basics

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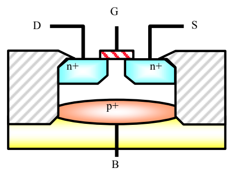
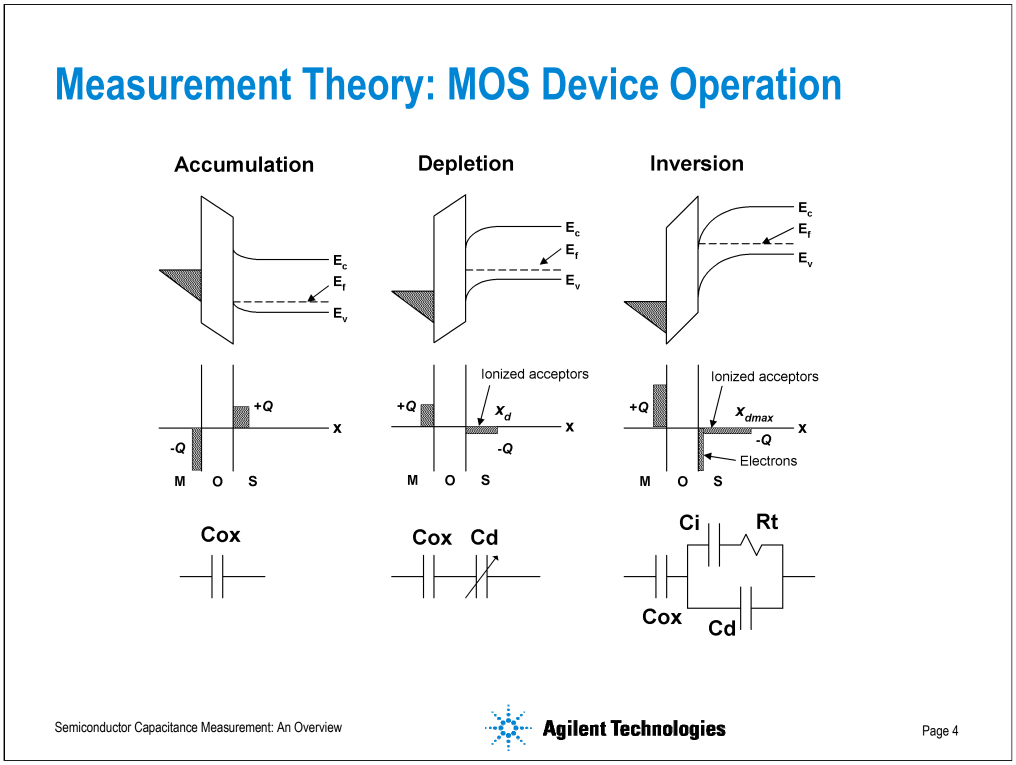
Everyone Needs to Measure Capacitance



- **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 *tox*. Since it is a pure gate oxide capacitance, we denote its value as *Cox*.

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 Cox and the capacitance across the surface depletion region, *Cd*. Note that Cd 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_{dmax}, 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, *Ci* and the depletion resistance, *Rt*

Step Voltage CV Measurement Technique

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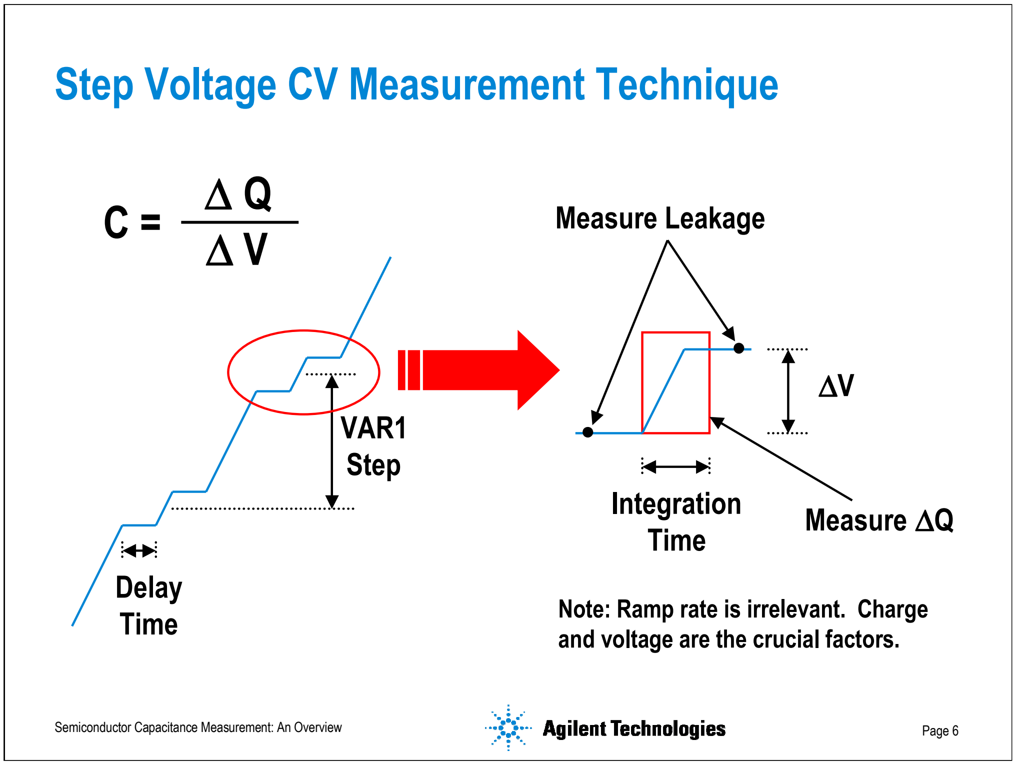
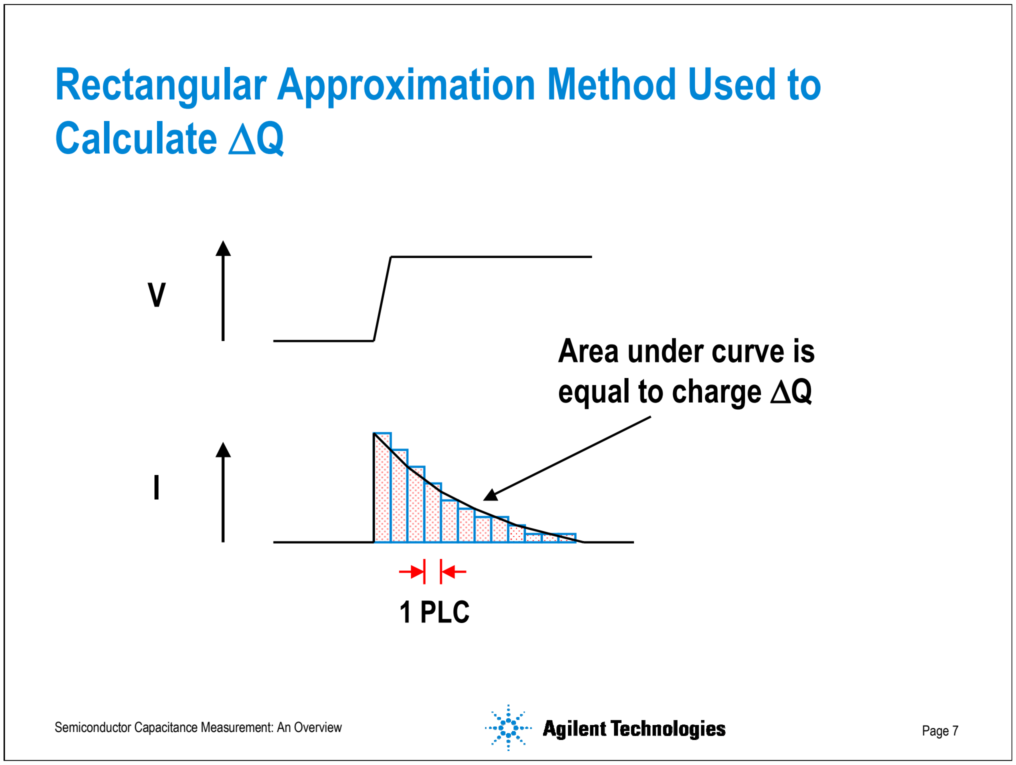


The step voltage technique is somewhat similar to a standard sweep voltage measurement. You specify a start, stop, and step voltage. However, there are many additional parameters that you must specify as well. One important one is the voltage step (cvoltage). The cvoltage is the amount that the capacitor voltage will be "bumped" by during each voltage step. Obviously, step voltage >= cvoltage.

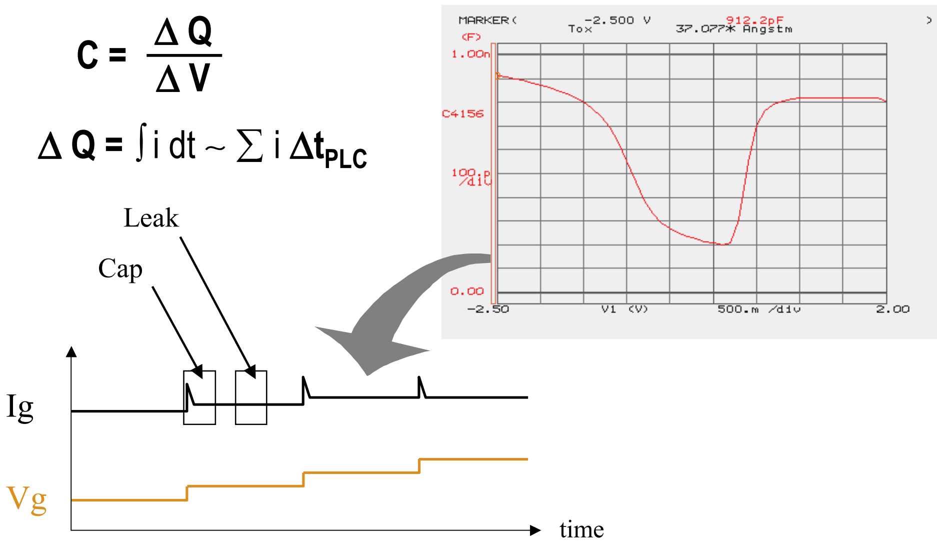


The 4155C/4156C use a rectangular approximation method to determine the area under the current spike each time you apply the cvoltage.

How Capacitance is Measured

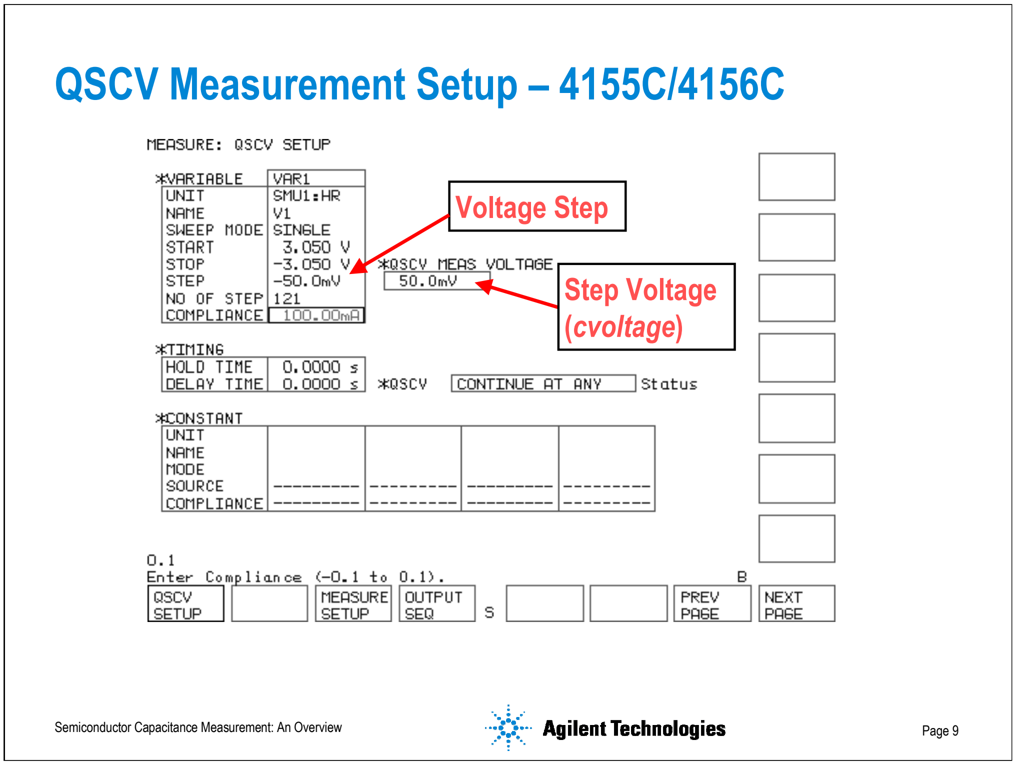
$$C = \frac{\Delta Q}{\Delta V}$$

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



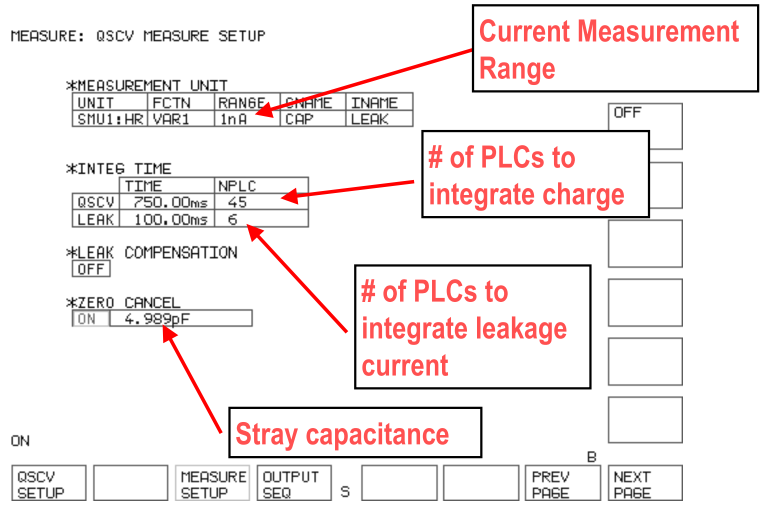
Semiconductor Capacitance Measurement: An Overview   Agilent Technologies   Page 8

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.

QSCV Measurement Setup – 4155C/4156C



Semiconductor Capacitance Measurement: An Overview

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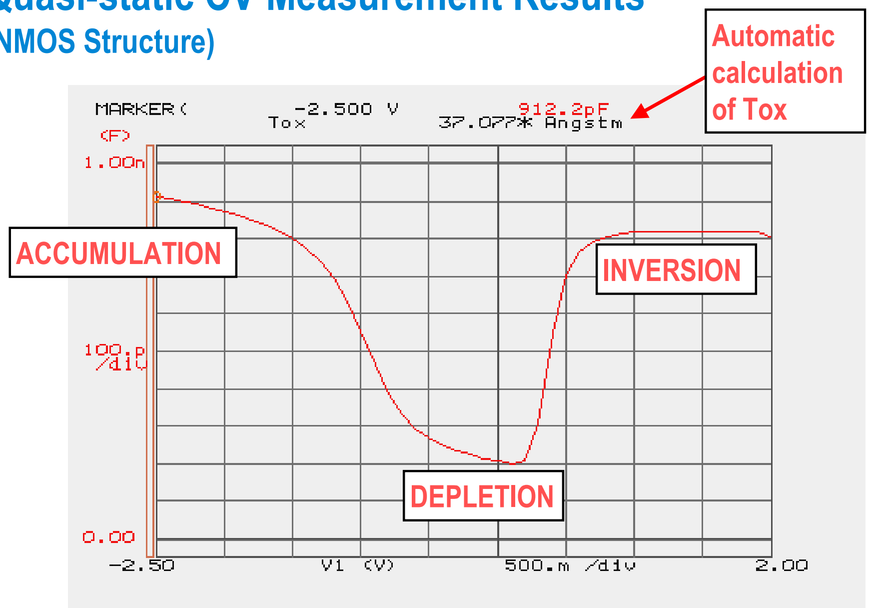
Page 10

This page is completely new on the 4155C/4156C. It contains all of the important measurement fields to define a QSCV measurement.

Quasi-static CV Measurement Results

(NMOS Structure)



Semiconductor Capacitance Measurement: An Overview

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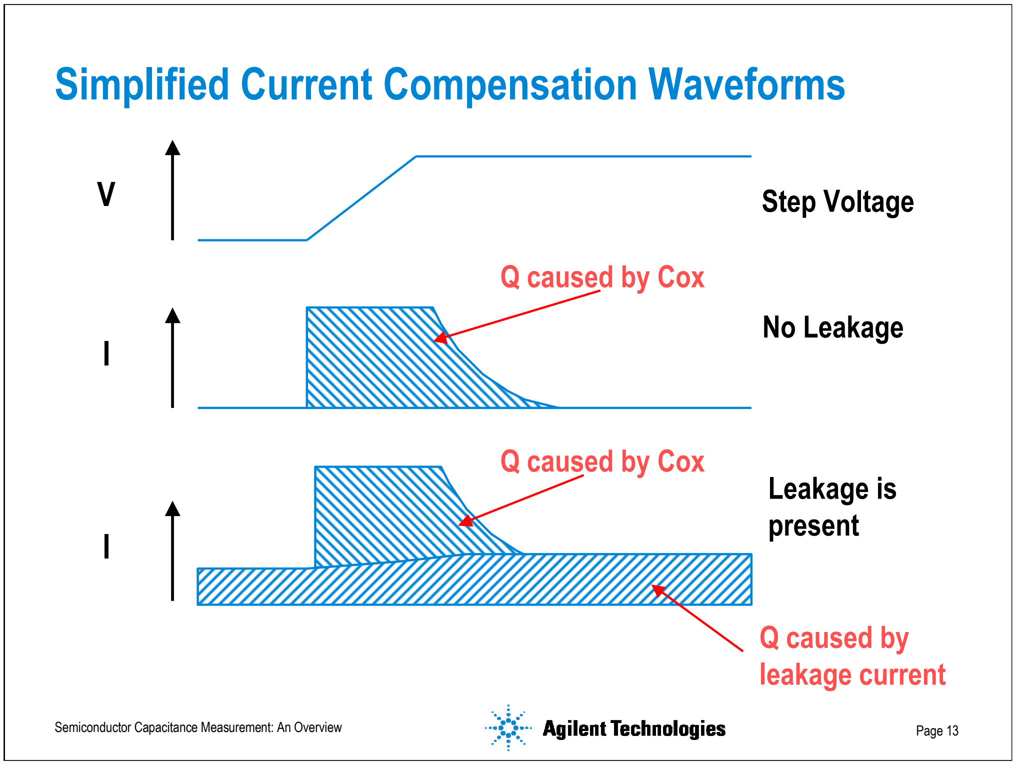
Page 11

Here is a classic QSCV measurement done on a relatively thick oxide device (37 Angstroms).

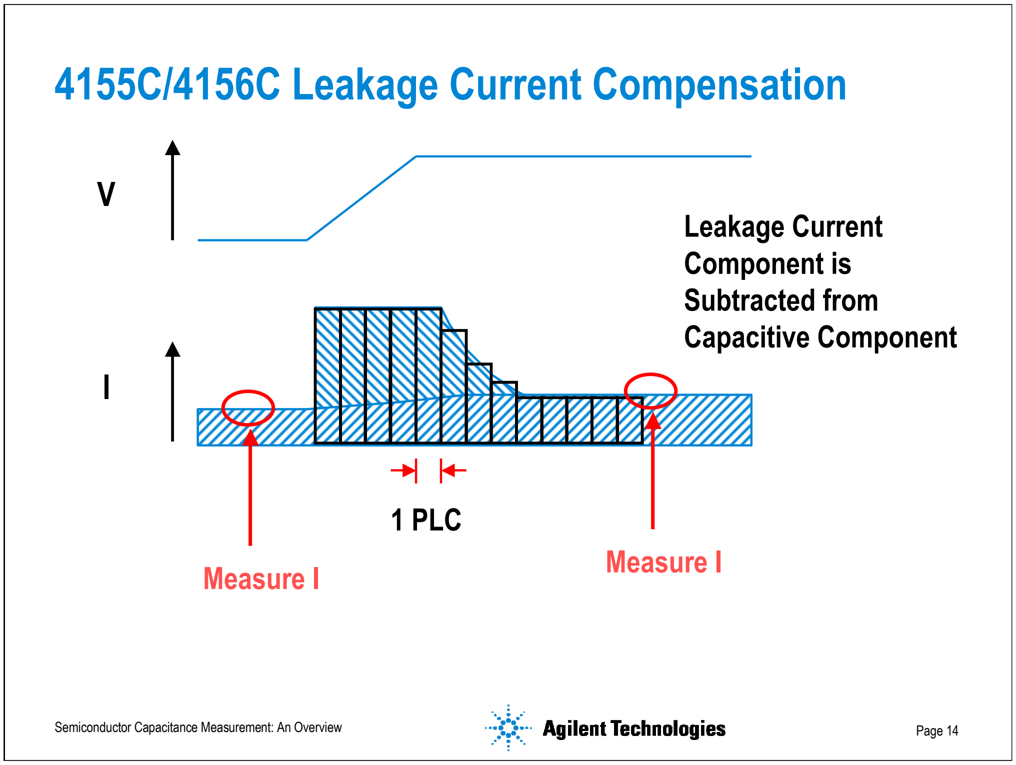
Thin Oxides (<40 A) Present New Measurement Challenges

- **At <40 A, 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.

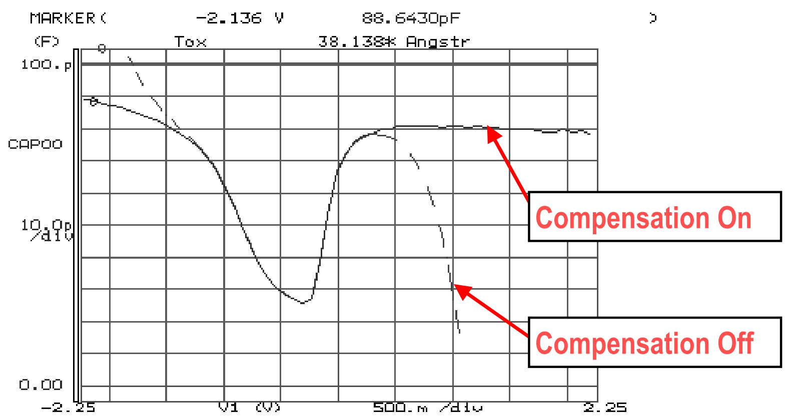


These simplified current waveforms show the two cases where there is no gate leakage current, and where there is appreciable gate leakage current.



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.

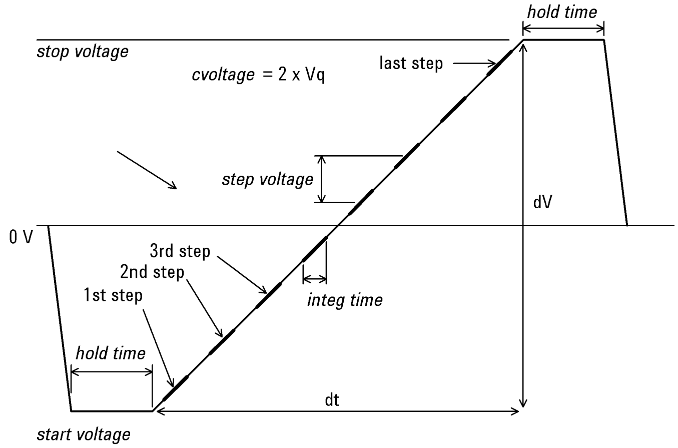
Thin Gate Oxide QSCV Measurement Showing Benefit of Leakage Current Compensation



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:

$$C = I/(dV/dt)$$

to calculate capacitance.

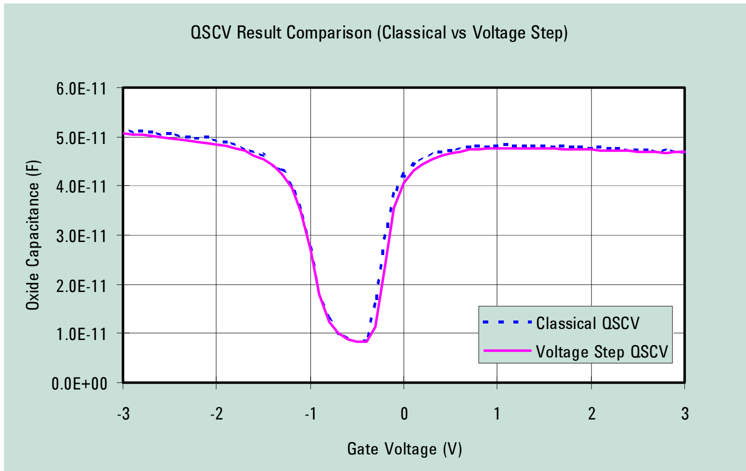
4140B Measurement Parameter Determination

- 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

$$\text{delay time} = \frac{\text{step voltage - cvoltage}}{dV/dt}$$

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



Semiconductor Capacitance Measurement: An Overview

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Page 18

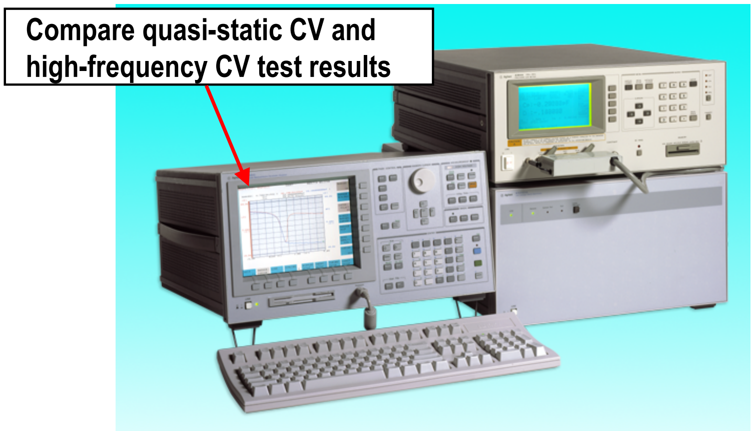
This Excel plot shows the correlation between a 4156C QSCV measurement and a 4140B QSCV measurement. The agreement is quite good.

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.

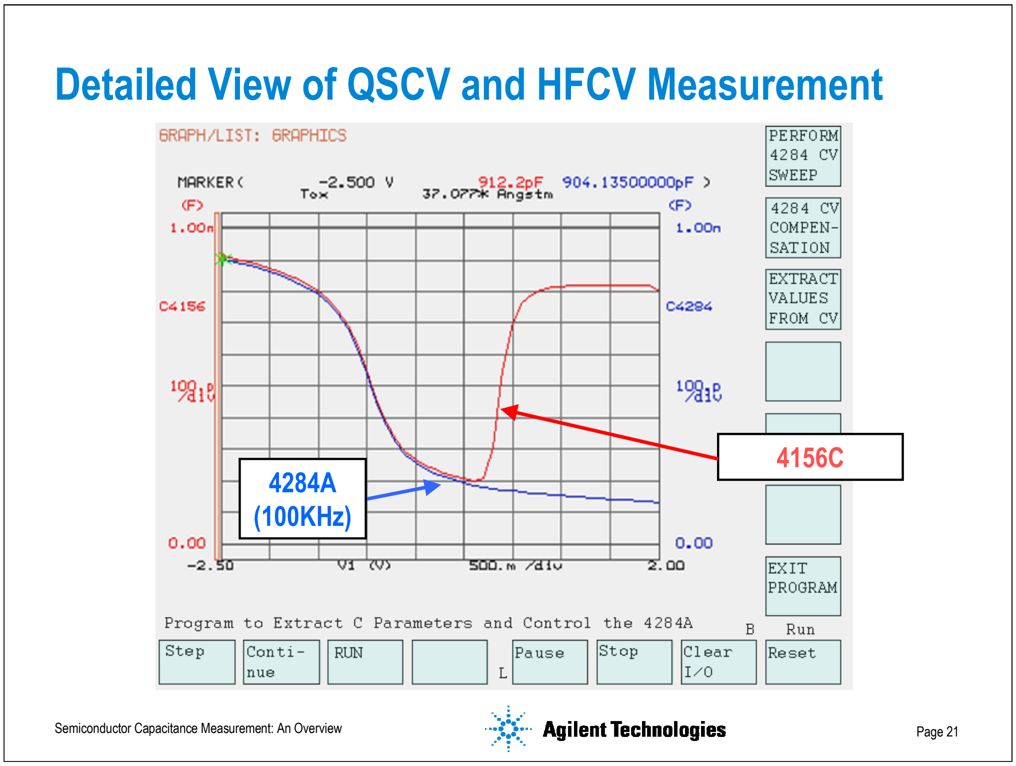
Build a Cost-Effective CV-IV Test Solution



Semiconductor Capacitance Measurement: An Overview — Agilent Technologies — Page 20

A complete CV-IV “system” can now consist of simply a 4155C/4156C, E5250A, and 4284A.

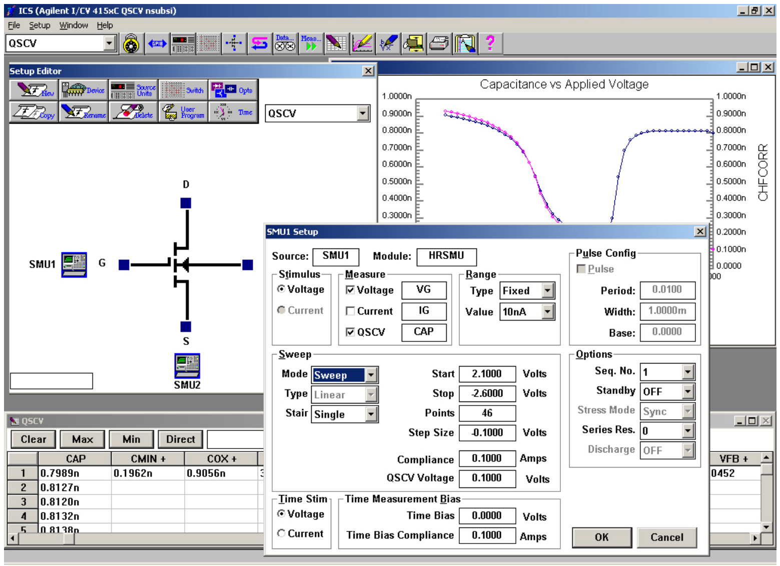
Agilent has a CV application disk available that contains an IBASIC program to control the 4284A and display sweep results on the front panel of the instrument. The disk also includes documentation on how to use the software.



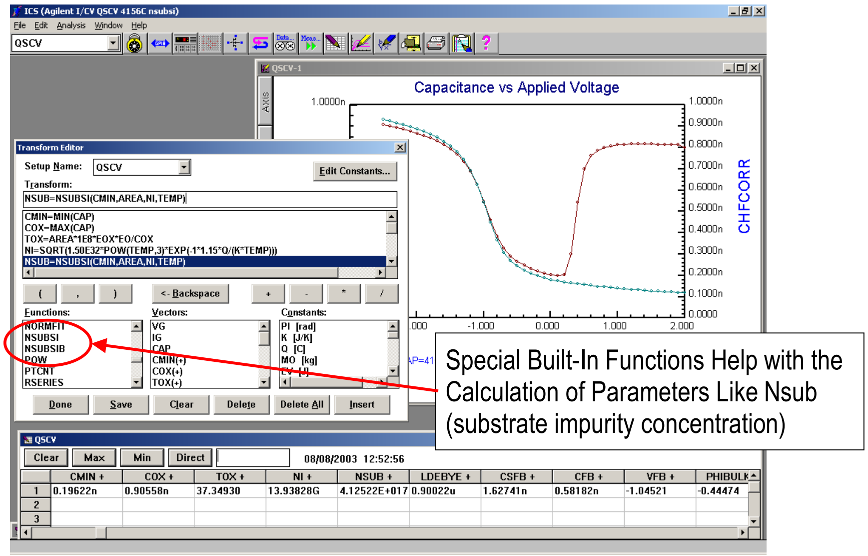
The ability to display both QSCV and HFCV curves on the same plot is very important. This allows the calculation of Nss (trap density), which is an important measure of oxide quality.

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



Semiconductor Capacitance Measurement: An Overview

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Page 23

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

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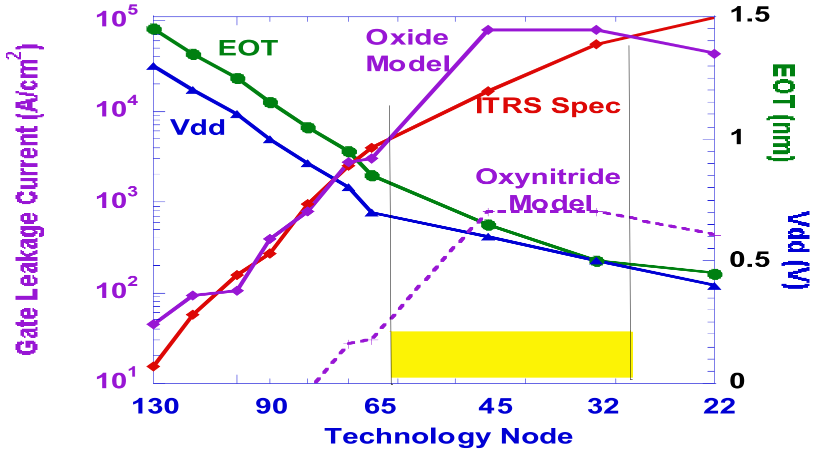
Agenda

- Introduction
- Requirements for thin film measurements
- Satisfying these requirements
- Effective Test Structure Design
- A Complete Solution
- Our Proposal

ITRS Roadmap of Gate Dielectrics

For MPU & ASIC



From: ITRS 2002

Semiconductor Capacitance Measurement: An Overview   Agilent Technologies   Page 27

EOT has already become lower than the 2 nm now and leakage current of oxide become over 100 A/cm^2.

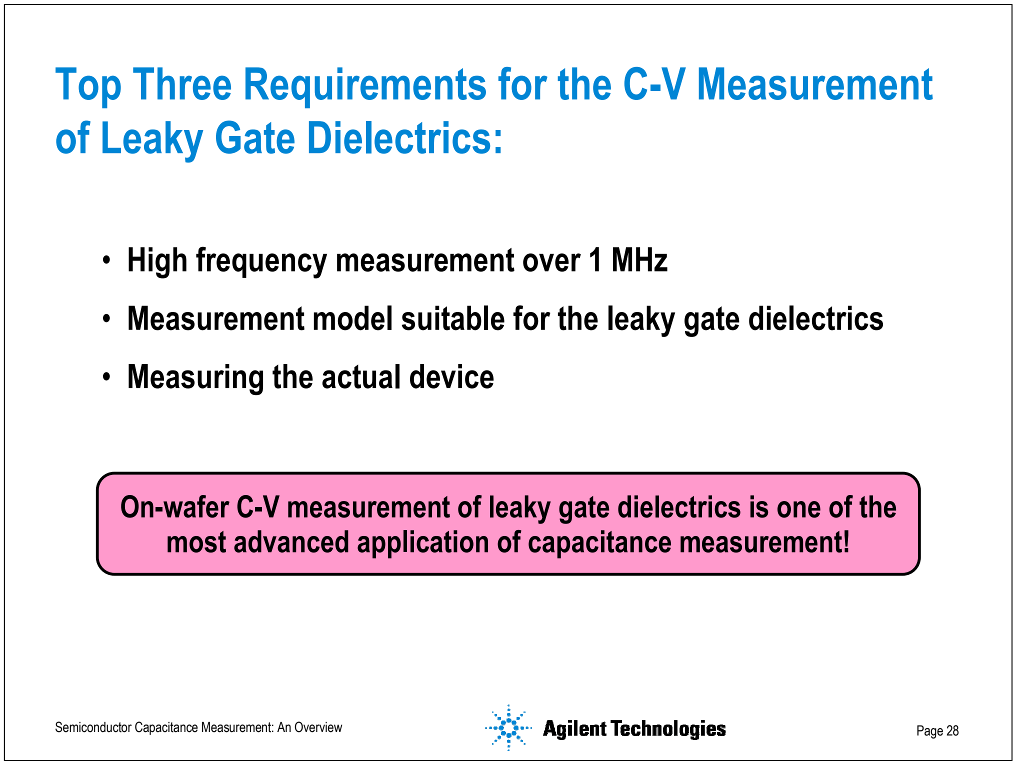
For high performance device like MPU or ASIC, gate leakage increase tremendously.

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.



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

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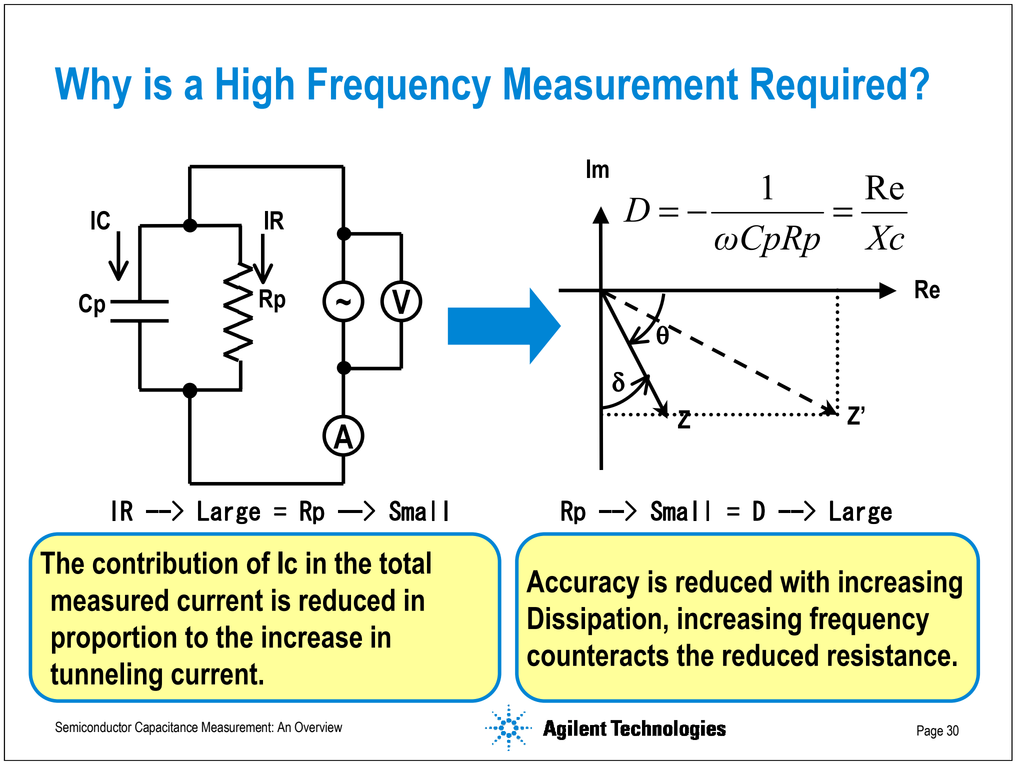


In principle, a capacitance meter measures the impedance of the DUT by applying a voltage/current and measuring a current/voltage.

Z = 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.

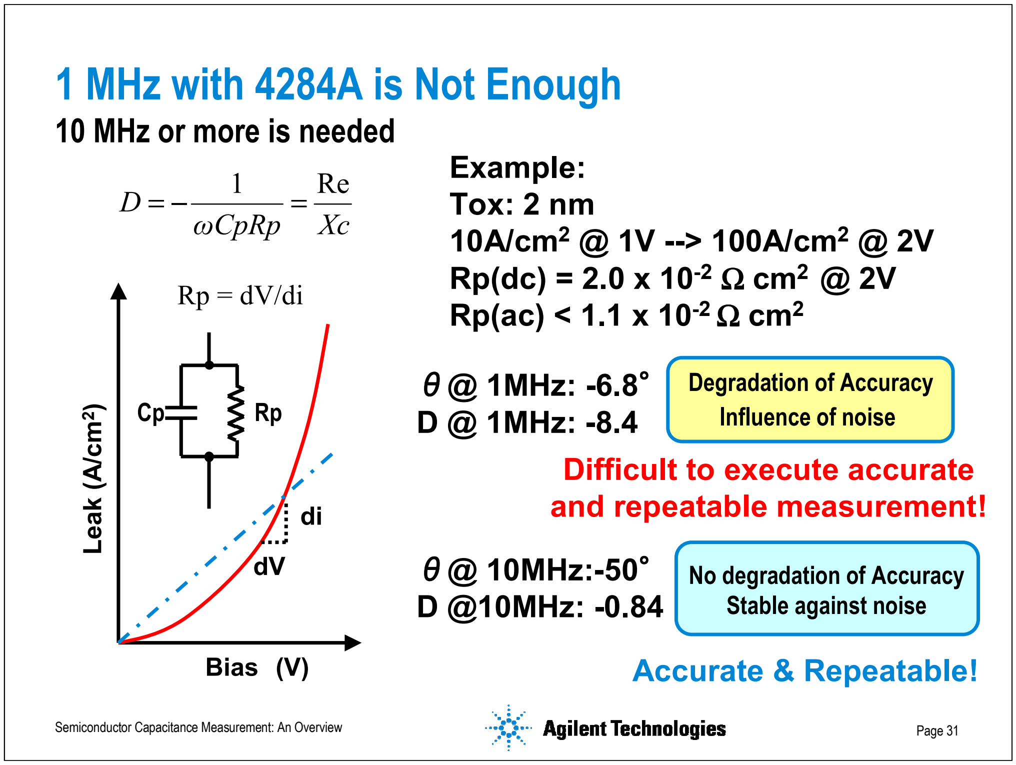
For thinner gate dielectrics, an increase of leakage current implies a smaller equivalent parallel resistance.

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

Looking at the impedance plane, a smaller Rp 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 throw the capacitance (decrease the D), a higher measurement frequency is required to reduce the impedance of capacitance(1/jwC)

For this reason, ultra-thin gate oxide measurements require higher measurement frequencies.



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

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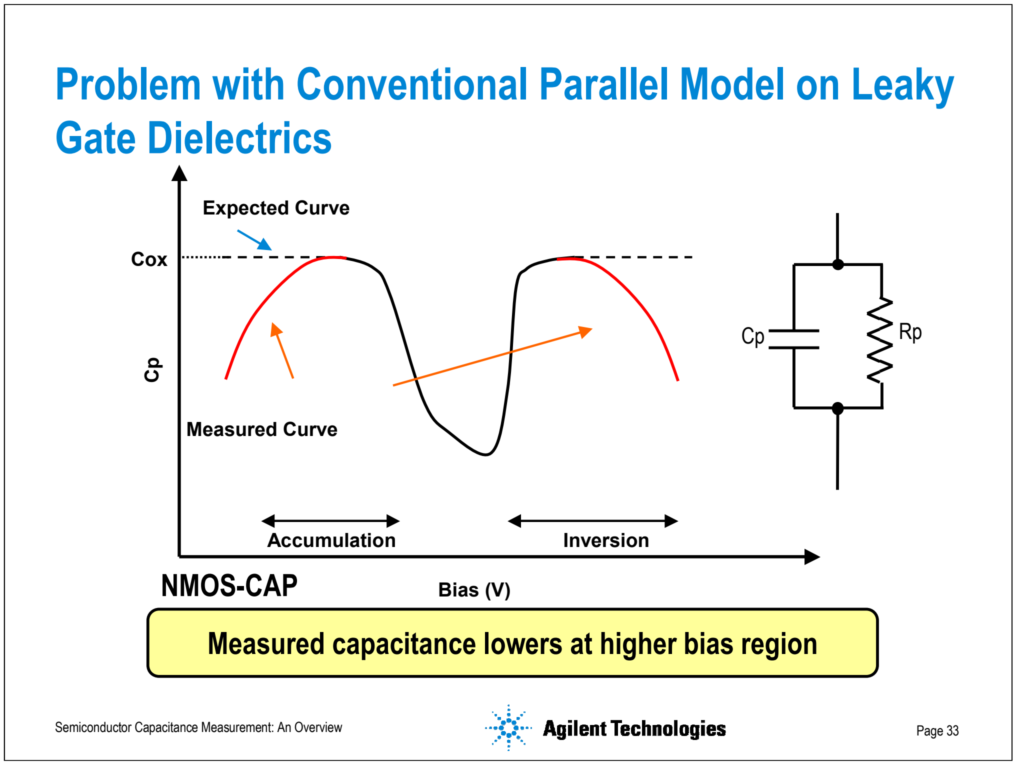


This graph shows the C-V curve for an ultra-thin gate oxide made with a conventional C-V meter like 4284 or 4294A.

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

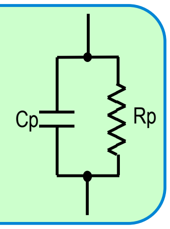
Many users have reported that the measured curve at higher bias becomes lower than the physically expected value.

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

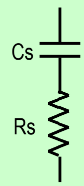
Parallel Model (Rs negligible):

- ✓ Z (1/(Xc+Rp)) >> Rs @ Frequency
- ✓ Rp >> Rs & 1/jwCp >> Rs

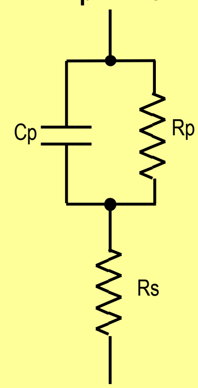


Series Model (Rp negligible)

- ✓ Xc (1/jwCp) << Rp @ Frequency
- ✓ Rs ~ Xc



For Thinner Oxides
Rp << Rs



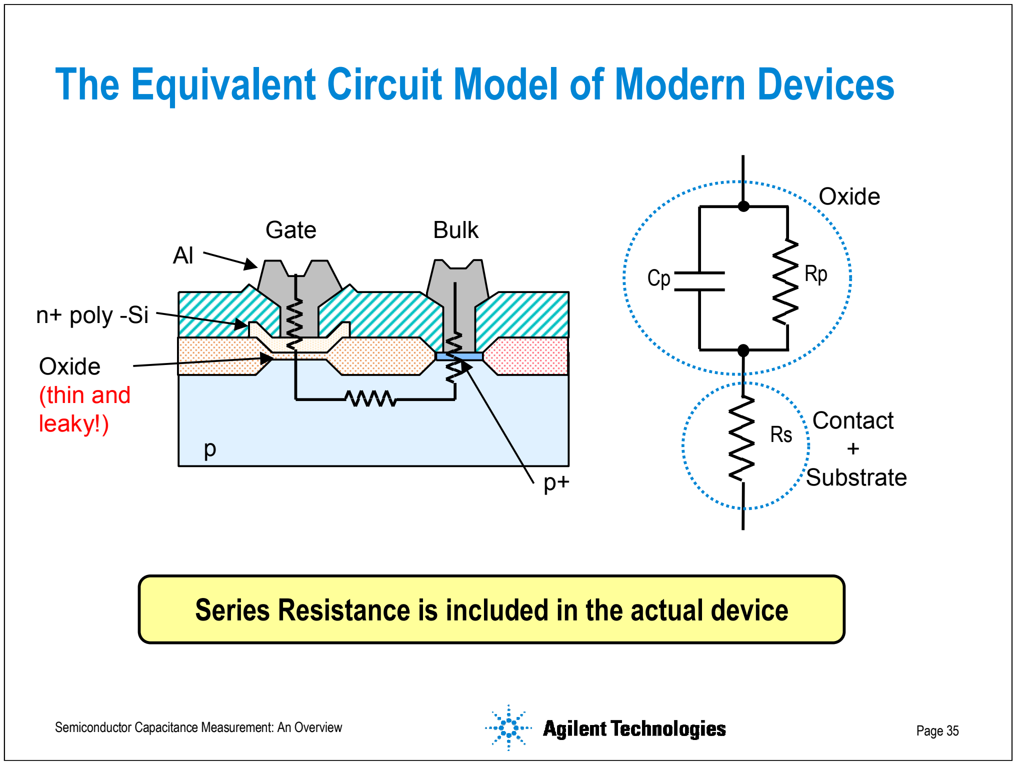
For the conventional thick gate dielectrics, the equivalent parallel resistance Rp is much larger than the series resistance Rs. This means that Rs can be ignored when making relatively low-frequency measurements under 1MHz. For this reason the parallel model has been valid until now.

Conversely, for higher frequencies the impedance of the capacitor Cp becomes small compared with the parallel resistance Rp. In this case Rp can be ignored and a series model with Cs and Rs only can be used.

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

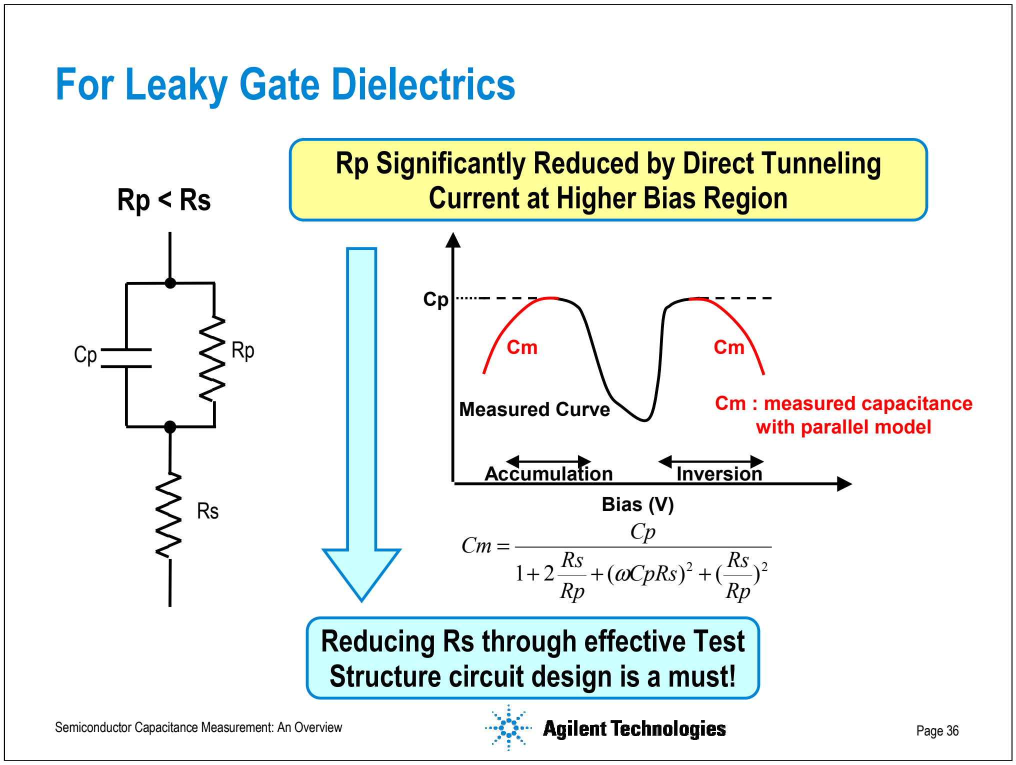
Rs ~ 100 ohm

Rp > 10^6 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 ultra-thin gate oxides under 2 nm in thickness, the magnitude of Rp is comparable with that of Rs.

This means that Rs cannot be ignored at low frequencies and that Rp cannot be ignored at higher frequencies.

Ultra-thin gate oxides must be modeled as a 3 elements device including Cp, Rp and Rs.

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

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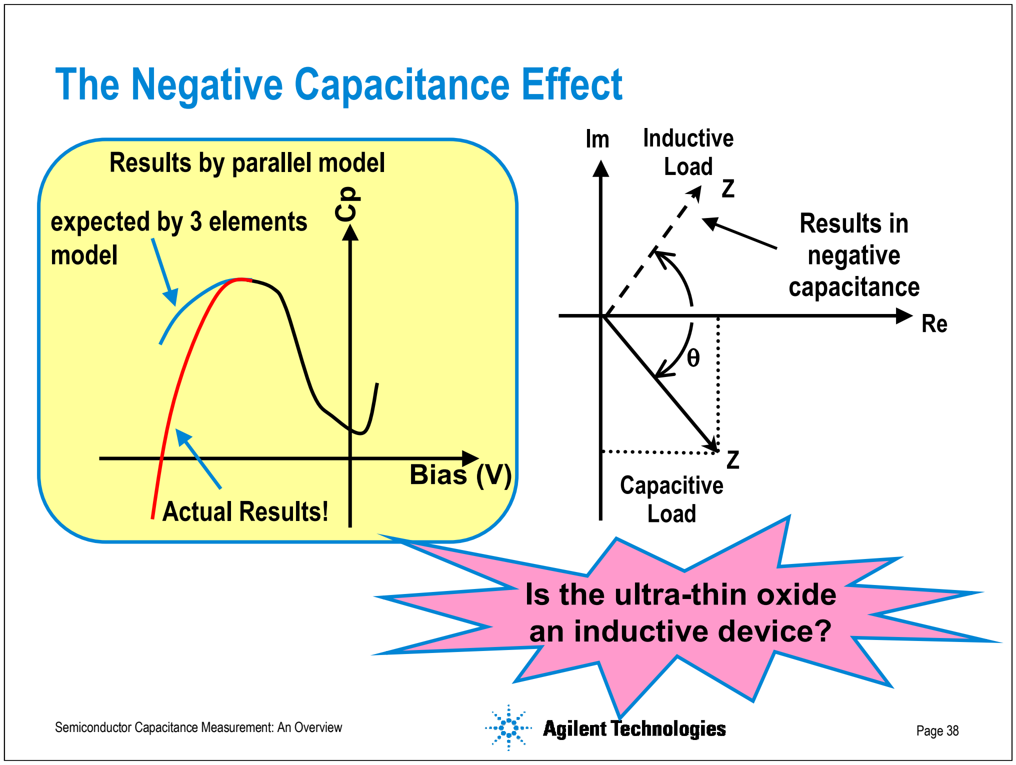


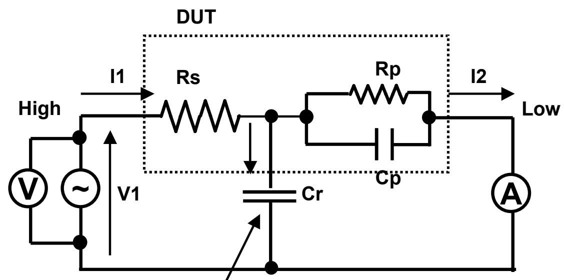
Many users have reported that they observe a negative capacitance in the higher bias region.

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.

Influence of Wafer Chuck causes the Negative Capacitance Effect

The case of the 4 terminal pair measurement



Chuck to Ground (or Guard of LCR meter) Capacitance

$$Zmeas = \frac{V1}{I2} = \frac{Rp + Rs + \omega^2 Cp^2 Rp^2 Rs + \omega^2 Cp\ CrRp^2 Rs - j\omega Rp(CpRp - CrRs)}{1 + \omega^2 Cp^2 Rp^2}$$

Imaginary part of Z becomes positive at $CpRp < CrRs$

Negative Capacitance at Higher Bias!!

Semiconductor Capacitance Measurement: An Overview — Agilent Technologies — Page 39

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).

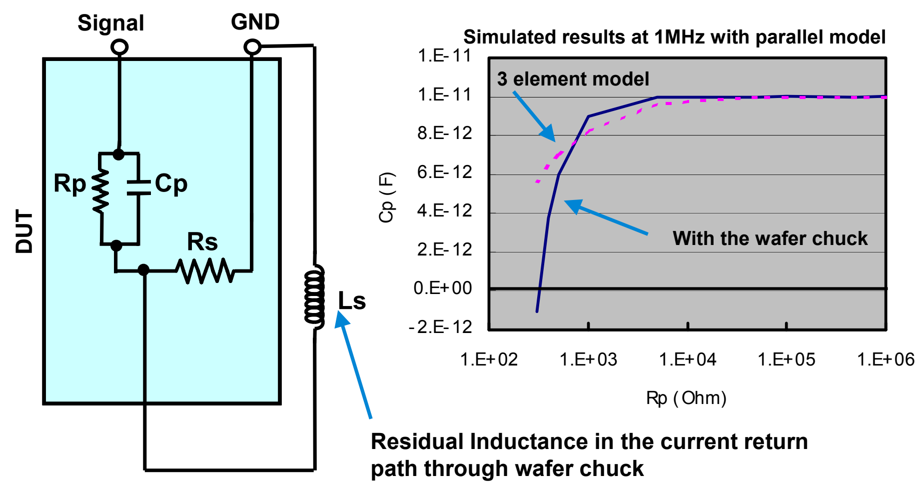
In this case, when using the 4 terminal pair, part of the signal flow through the DUT leaks through the capacitive coupling of wafer chuck. The measured impedance is actually described by the equation shown above. From this equation, if the product of Cp and Rp is smaller than the product of Cr and Rs, then the imaginary part of measured impedance becomes positive.

Because Rp comes from the direct tunneling of gate dielectrics, the effective Rp rapidly decreases as gate bias is increased. Therefore, a negative capacitance is observed when the gate bias lowers the value of Rp to the point where CpRp < CrRs.

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



Semiconductor Capacitance Measurement: An Overview   Agilent Technologies   Page 40

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

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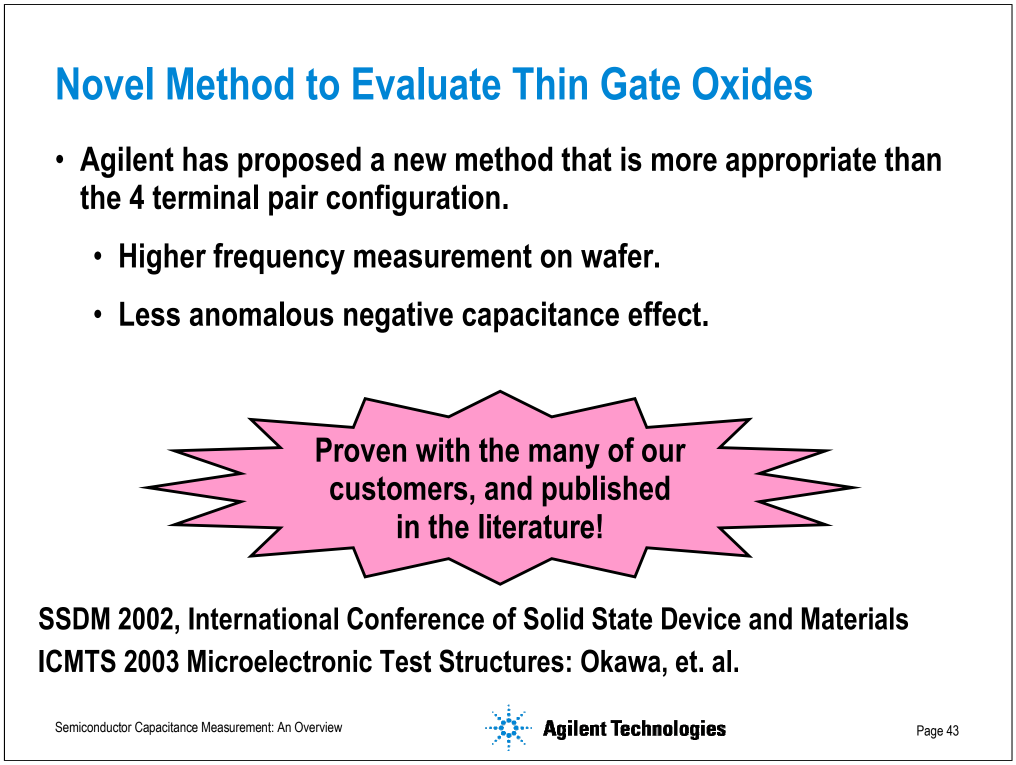


Now Agilent developed Agilent 4070 HF-CV solution to resolve those problems that customer faced.

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.

"Methodology for Accurate C-V Measurement of Gate Insulators below 1.5nm EOT", Extended Abstracts of the 2002 International Conference on Solid State Device and Materials, Nagoya, 200, pp.748-749.

Best Instrument for HF-CV Measurement

4294A Impedance Analyzer

- ✓ Based on proven Auto Balancing Bridge (4 terminal pair)
- ✓ 40Hz to 110MHz Frequency Range
- ✓ 3mΩ to 500MΩ Impedance Range
- ✓ 0.08% Basic Accuracy
- ✓ Various Sweep Function(Bias, Signal, Frequency)
- ✓ Powerful Analysis Function
- ✓ Flexible Cable length Calibration

42941A Impedance Probe

- ✓ Convert 4294A 4 terminal to I-V method (Advanced I-V method)
- ✓ SMA 3.5mm compatible
- ✓ Flexible probe tips are available

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

Semiconductor Capacitance Measurement: An Overview   Agilent Technologies   Page 44

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.

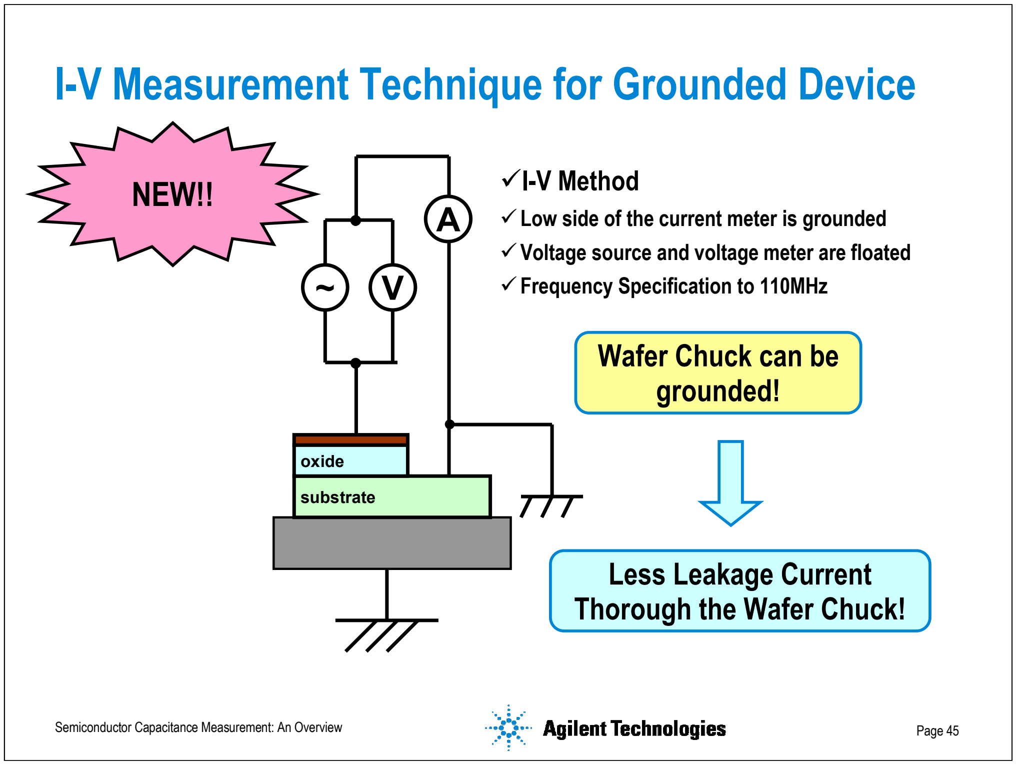
The Agilent 4294A is the impedance meter using the auto balancing bridge like 4284A and 4285A. But measurement circuit is modified to support the I-V method when using the 42941A impedance probe.

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.

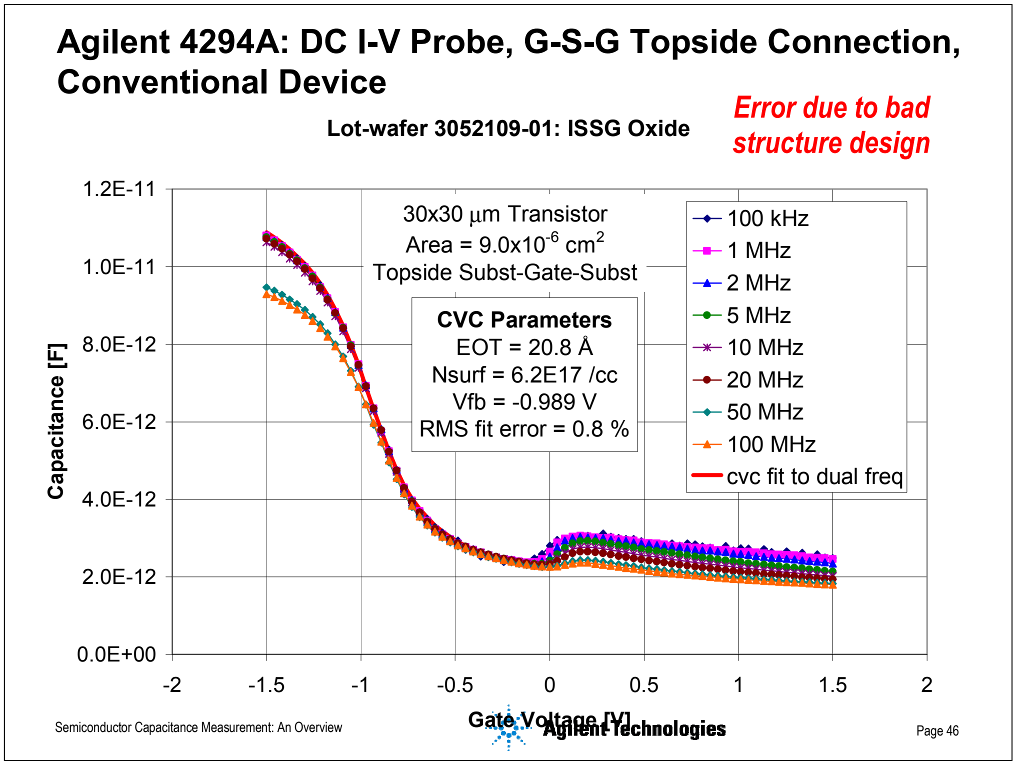
This configuration results that 4294A supports both conventional 4 terminal pair configuration and I-V method by using 42941A.



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.

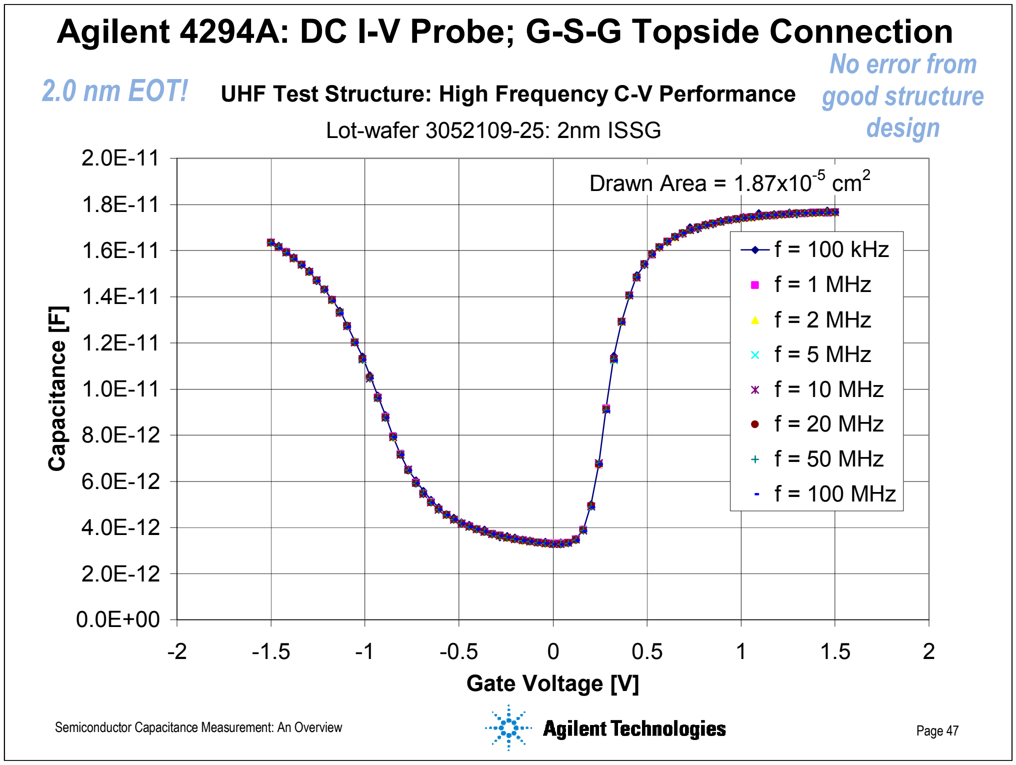
Because wafer chuck is not driven by the signal source directly, there will be less AC leakage that might cause the resonance like influence at the higher measurement frequency.



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!



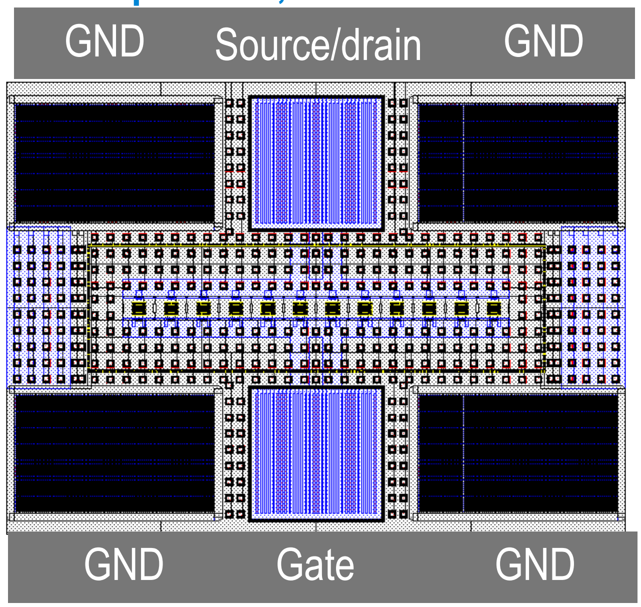
A well-designed capacitance measurement structure can often produce good measurement results in spite of poor measurement technique.

However, a poorly designed capacitance measurement structure will probably never produce good measurement results no matter how well you perform the measurement.

From J. Schmitz of Philips/IMEC; ICMTS 2003

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.

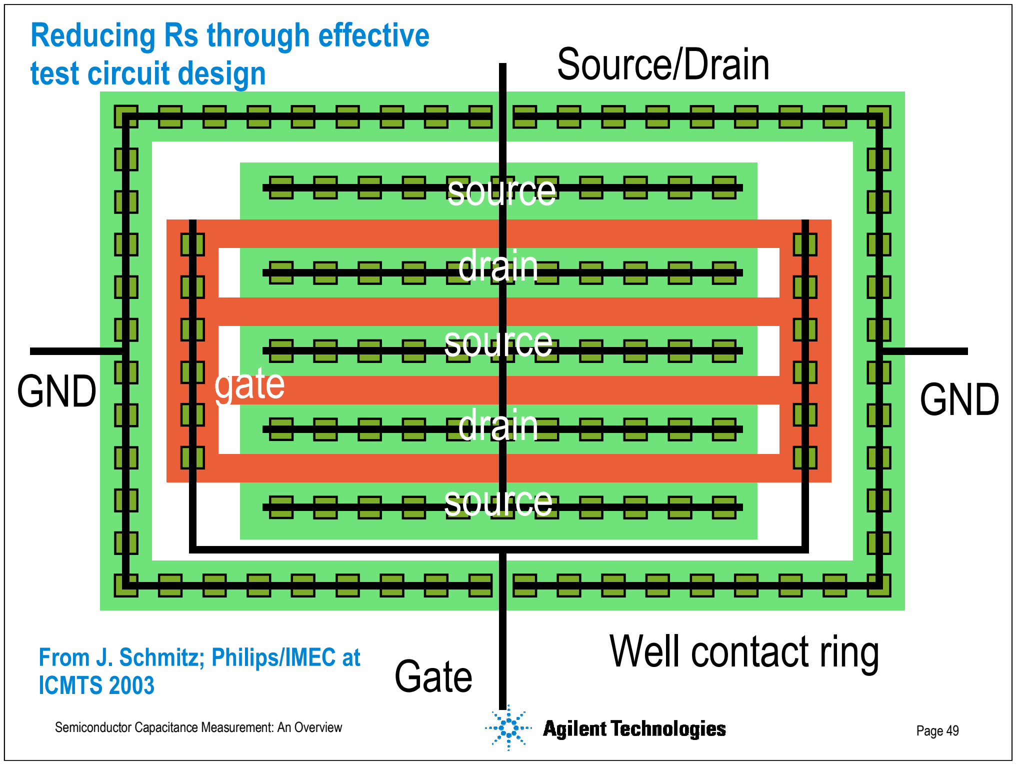


Semiconductor Capacitance Measurement: An Overview

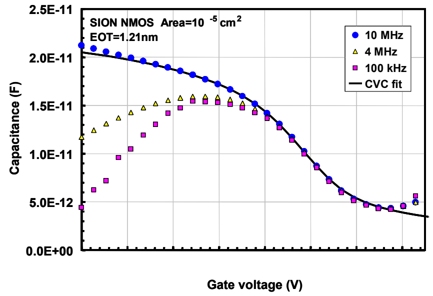
Agilent Technologies

Page 48

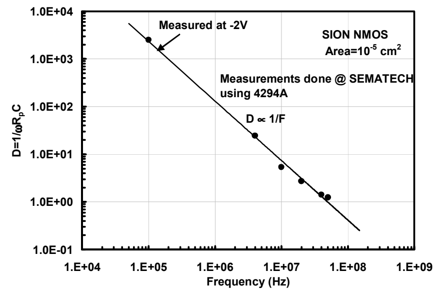
Here is one example of good measurement design technique.


Reducing Rs through effective test circuit design
Source/Drain
source
drain
source
gate
drain
source
GND
GND
From J. Schmitz; Philips/IMEC at ICMTS 2003
Gate
Well contact ring
Semiconductor Capacitance Measurement: An Overview
Agilent Technologies
Page 49

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 ($1/2\pi f R_p C$) which results in the distortion of CV data. For values of D> 3, CV data becomes invalid.

Solution to this problem involves:

- o Performing CV measurements in MHz frequency range so dissipation < 3.
- o Use of special structures to minimize series impedance.

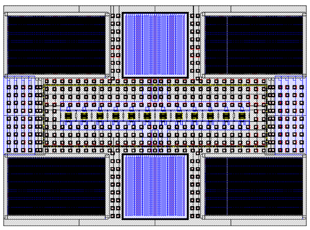
"Customer Conclusion: Results from the demonstration of the 4294A indicate an immediate need for this impedance analyzer which would help us extract EOT from CV data obtained on devices made with scaled SION or high-k films."

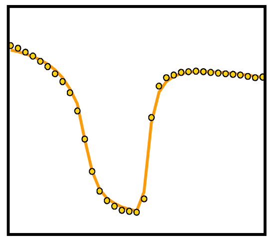
Semiconductor Capacitance Measurement: An Overview   Agilent Technologies   Page 50

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.



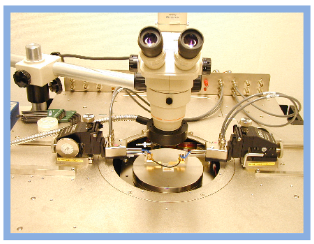


High-Frequency (> 5 MHz) CV Measurement: Tips & Tricks

Agilent Technologies

Agenda

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



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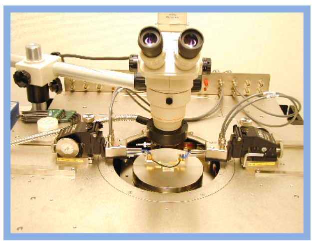
Achieving High Accuracy Measurements

- System Outline
- Advanced I-V Method
- Auto Balancing Bridge Method
- Extension to LF band
- Cautions for cabling
- Compensation



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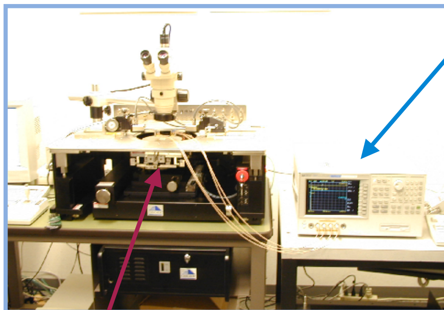
Achieving High Accuracy Measurement
- System Outline (Summit Probe Station with 4294A) -



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.

Semiconductor Capacitance Measurement: An Overview

Agilent Technologies

Page 55

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:

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)

This table compares the 4284A with the 4294A.

Achieving High Accuracy Measurement

- Recommended Measurement System -

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

Note that measurement frequency range changes due to an environment such as cable, probe station, etc.

Recommended Measurement System

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

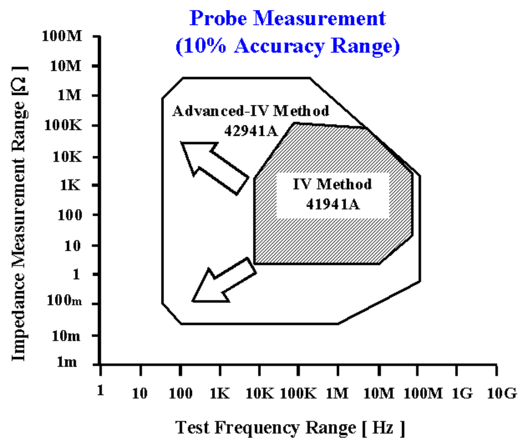
Probing directly above the wafer is simpler than probing through the chuck and it makes it possible to extend the measurement frequency easily. Especially, the 42941A is the best solution which can be introduced at present. On the other hand, the measurement frequency is limited 10 MHz* or less when 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**



Semiconductor Capacitance Measurement: An Overview

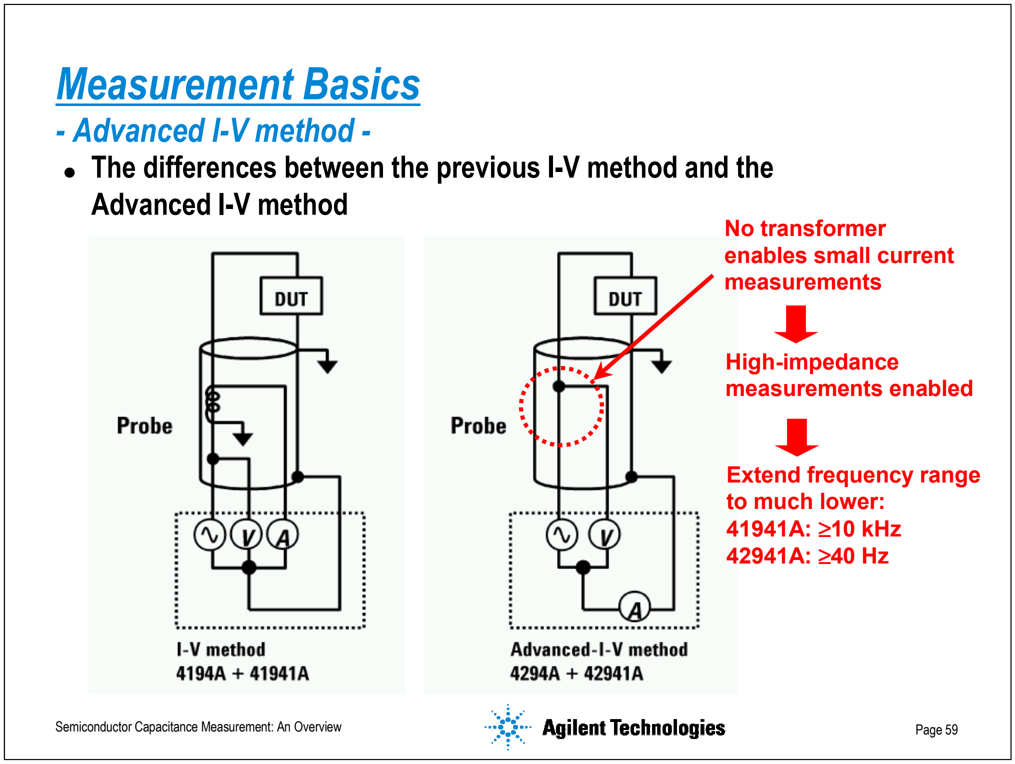
Agilent Technologies

Page 58

Advanced I-V Method

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

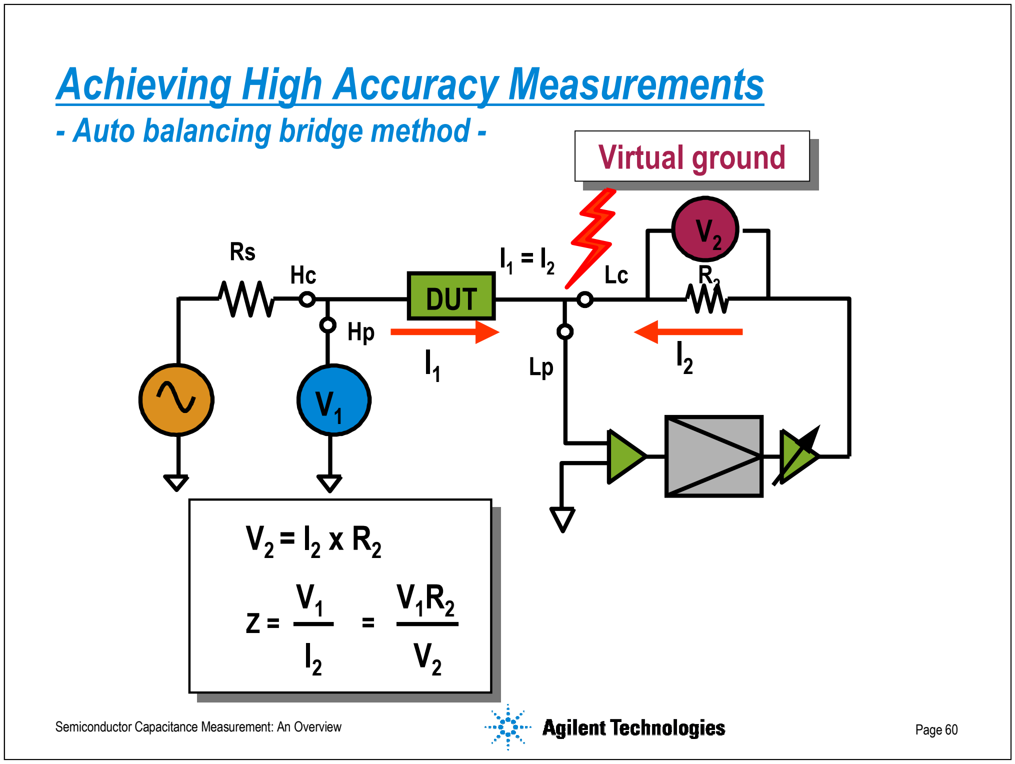
This slide shows the typical 10% measurement accuracy range of the 42941A compared to the 41941A. This clearly shows that the 42941A has a much wider impedance and frequency range than the 41941A. The 42941A's advanced I-V probing methodology made possible an ultra-thin gate oxide evaluation.



Advanced I-V Method

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

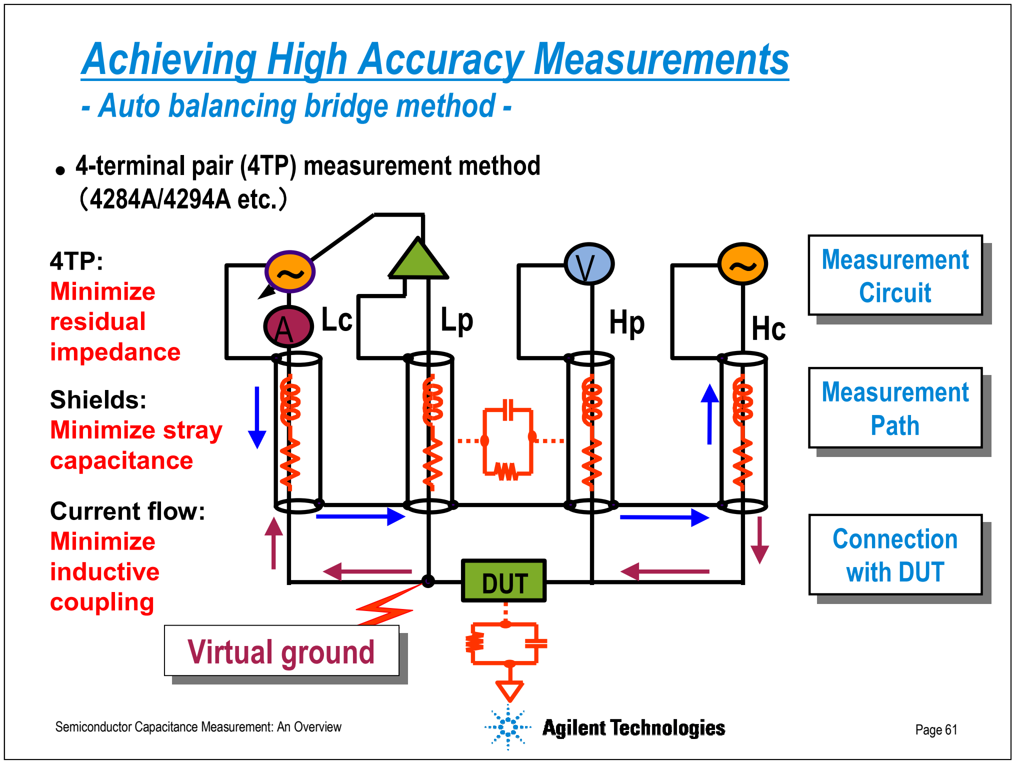
With the new method, a nearly ideal current meter is used, without the need for a transformer. This enables accurate measurement of small currents which thereby enhances the ability to measure high-impedance. Since a transformer is not employed in the “Advanced I-V method”, the operational frequency 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.



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•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, I2, 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.



Auto Balancing Bridge Method

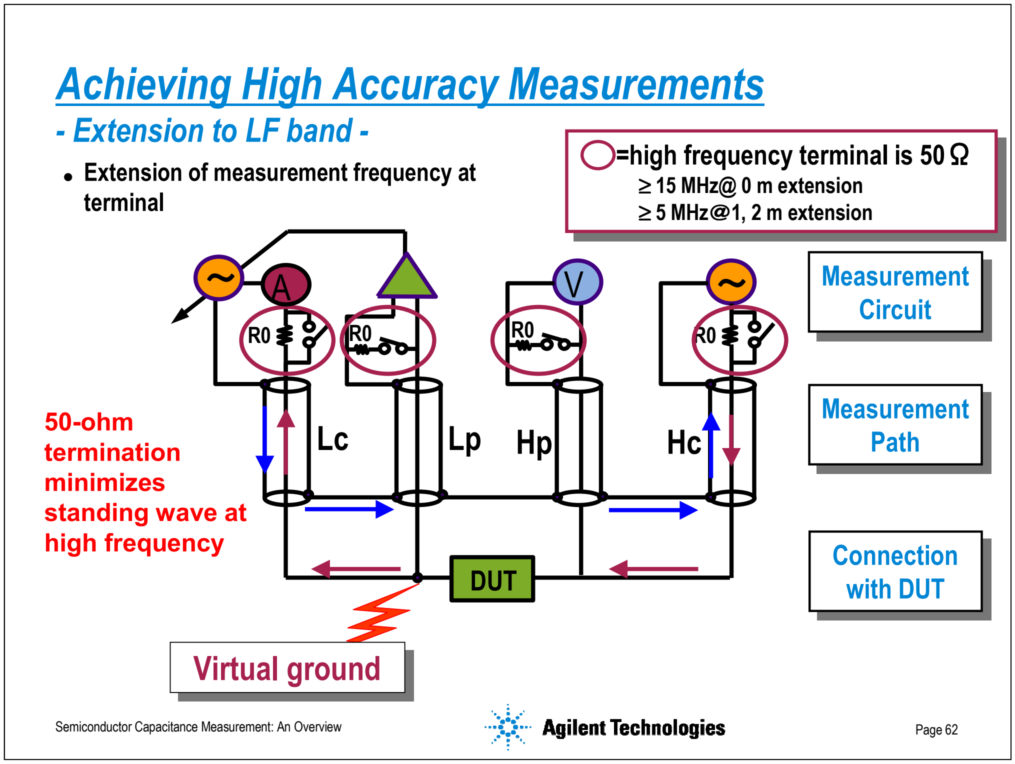
In order to maximize the performance of auto-balancing-bridge technique, this circuit is used with the cabling technique called “4-terminal-pair” cabling method.

In general, if you extend the measurement port using cables, these cable 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.



Cable terminated Auto-Balancing-Bridge method

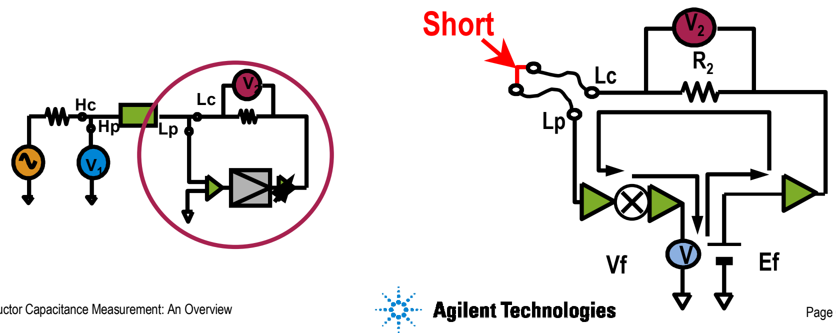
The 4294A uses an innovative technique called the "Cable terminated Auto-Balancing-Bridge method". As shown in this slide, the measurement path is terminated by the characteristic impedance of the cable (R_0 = 50 Ω) at high frequencies. This termination solves the standing wave problem at high frequencies 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.



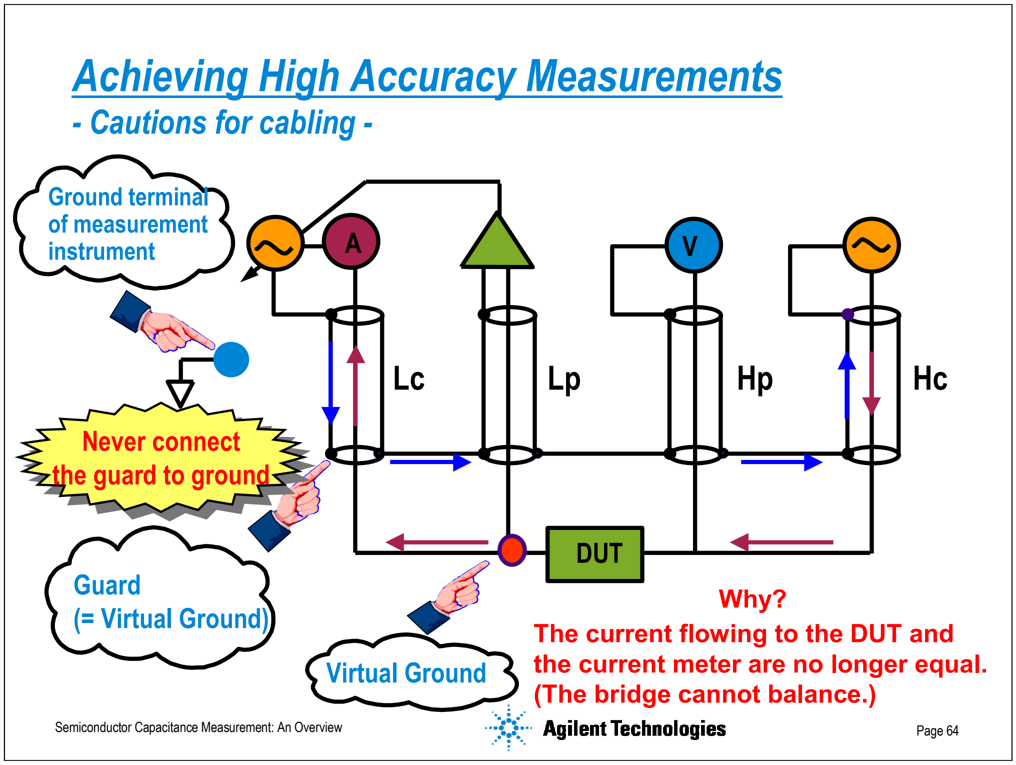
Phase Compensation

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

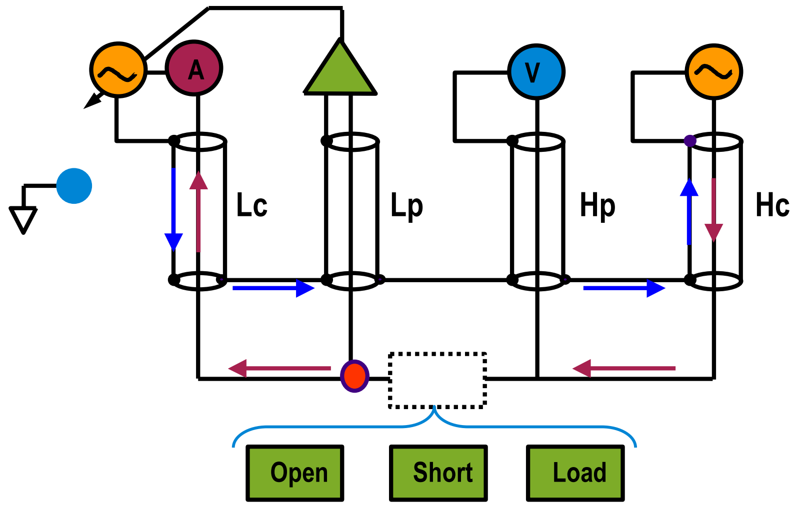
When we combine the 4-terminal-pair cabling technique with auto-balancing-bridge method, there is an important thing we need to remember:

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-

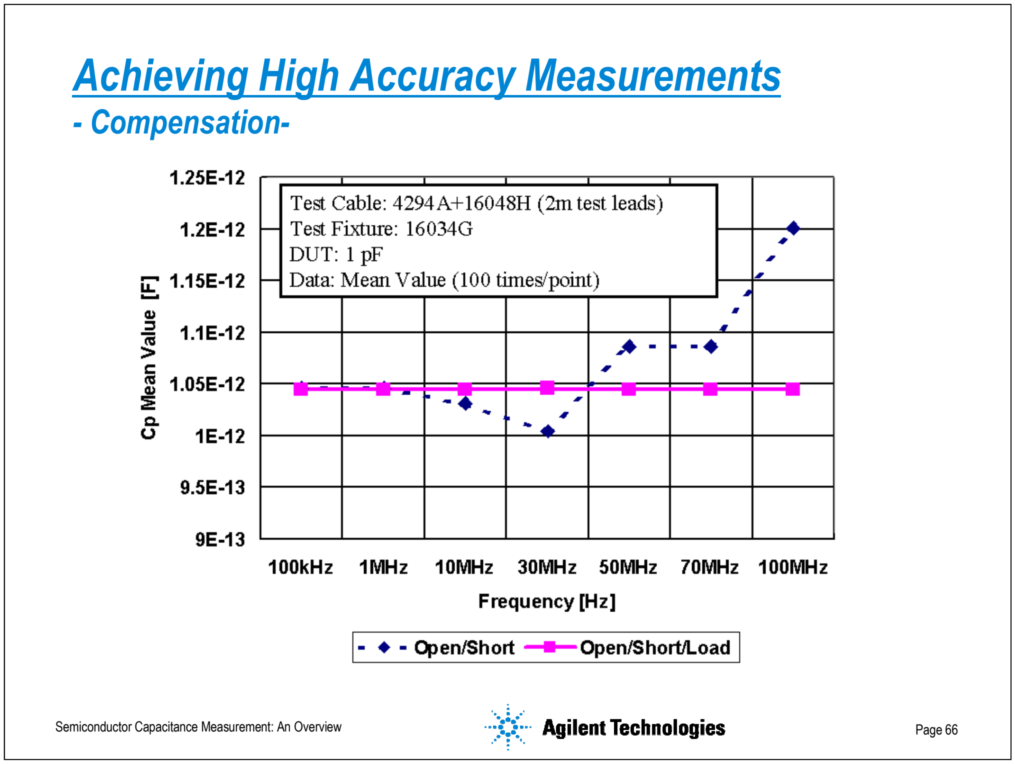
Locate measurement reference plane to the DUT contacts



Semiconductor Capacitance Measurement: An Overview

Agilent Technologies

Page 65



Compensation

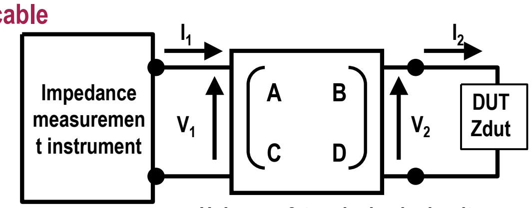
This slide shows the effect of Open/Short/Load compensation data, which compares the measurement data with and without Open/Short/Load compensation. As you can see in this slide, the Open/Short/Load compensation can drastically improve the measurement accuracy and stability at high frequencies. It is 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



Unknown 2-terminal pair circuit

$$Zdut = \frac{Zstd\,(Zo - Zsm)\,(Zxm - Zs)}{(Zsm - Zs)\,(Zo - Zxm)}$$

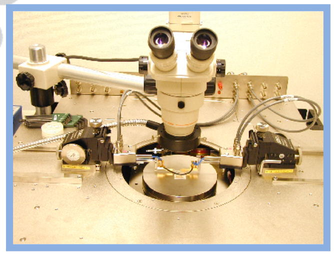
Z_0 : Measured value of OPEN
Zsm : Measured value of standard DUT
Zxm : Measured value of the DUT
Zs : Measured value of SHORT
Zstd : True value of the standard DUT
Zdut : Corrected value of the DUT

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



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Connection with Probe Station

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

Semiconductor Capacitance Measurement: An Overview

Agilent Technologies

Page 69

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

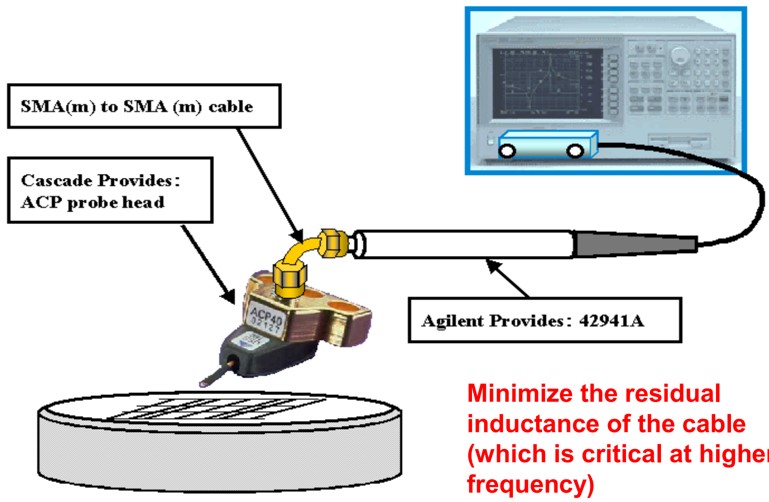
- But,
  - Probe pitch is pre-defined
  - System configuration is NOT flexible
  - Price is higher than DCP probe system

Impedance Probe Configuration

Connection with Probe Station

- Advanced IV (Impedance Probe) Configuration -

- **SMA to SMA cable should be short as much as possible**



Minimize the residual inductance of the cable (which is critical at higher frequency)

Semiconductor Capacitance Measurement: An Overview   Agilent Technologies   Page 71

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

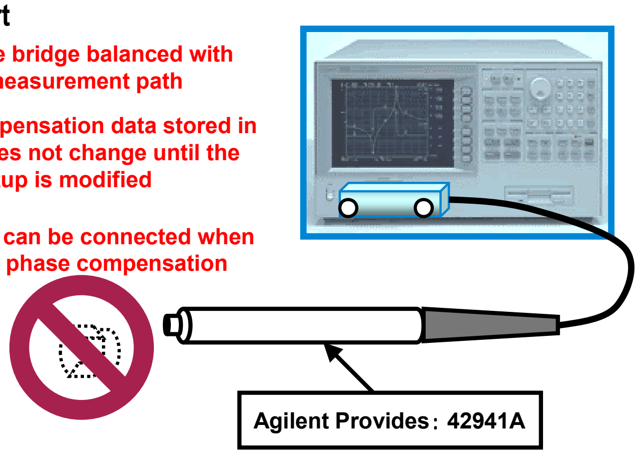
- Advanced IV: Phase Compensation -

- **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.

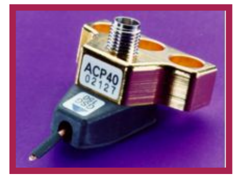
• Choose **[PHASE COMP]** in the **[SETUP]** menu and then perform the phase compensation. The phase compensation should be performed with nothing connected to the 3.5-mm port. When the phase compensation data measurement is completed, the softkey label changes to **PHASE COMP[DONE]**.

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



Pitch	C-Open fF	L-Short pH	L-Term pH
100	-11.0	33.5	36.5
125	-11.0	41.7	47.2
150	-11.0	49.8	57.8
200	-11.0	66.2	79.2
250	-11.0	82.5	100.5

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

Semiconductor Capacitance Measurement: An Overview Agilent Technologies Page 73

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.

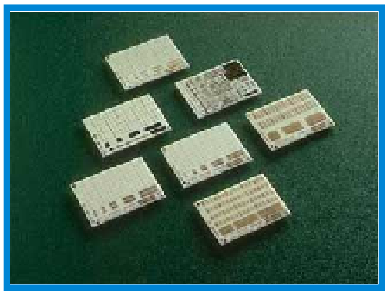
• Push the **[Cal]** button again and choose the **[DEFINE VALUE]** from the **[FIXTURE COMPEN]** menu.

• 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.

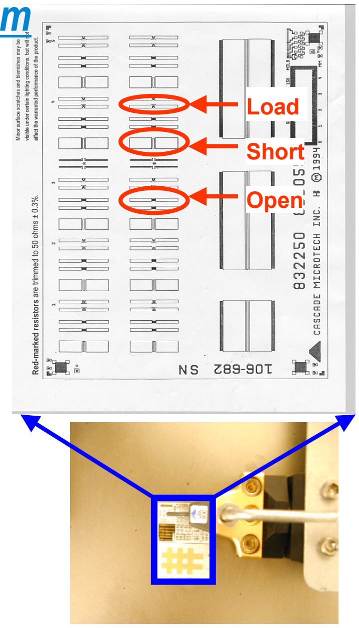
Connection with Probe System

- Advanced IV: Fixture Compensation -

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



ISS (Impedance Standard Substrate)



Semiconductor Capacitance Measurement: An Overview

Agilent Technologies

Page 74

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

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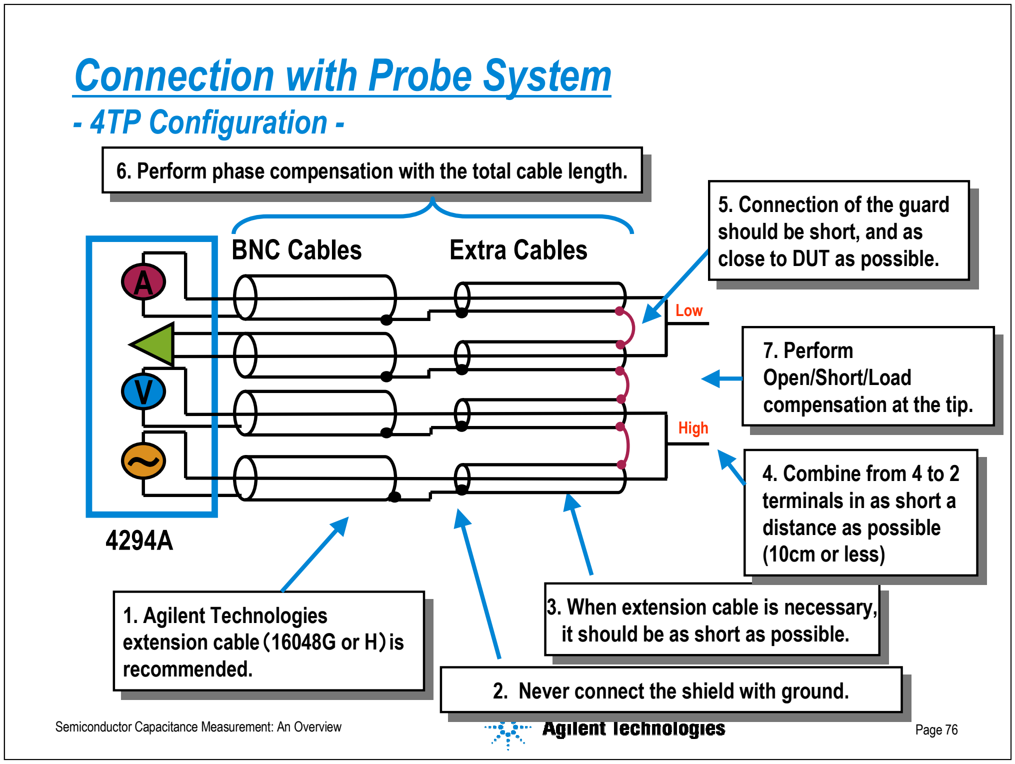
*Note that measurement frequency range changes due to a measurement environment such as cable, probe station, and so on.



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.

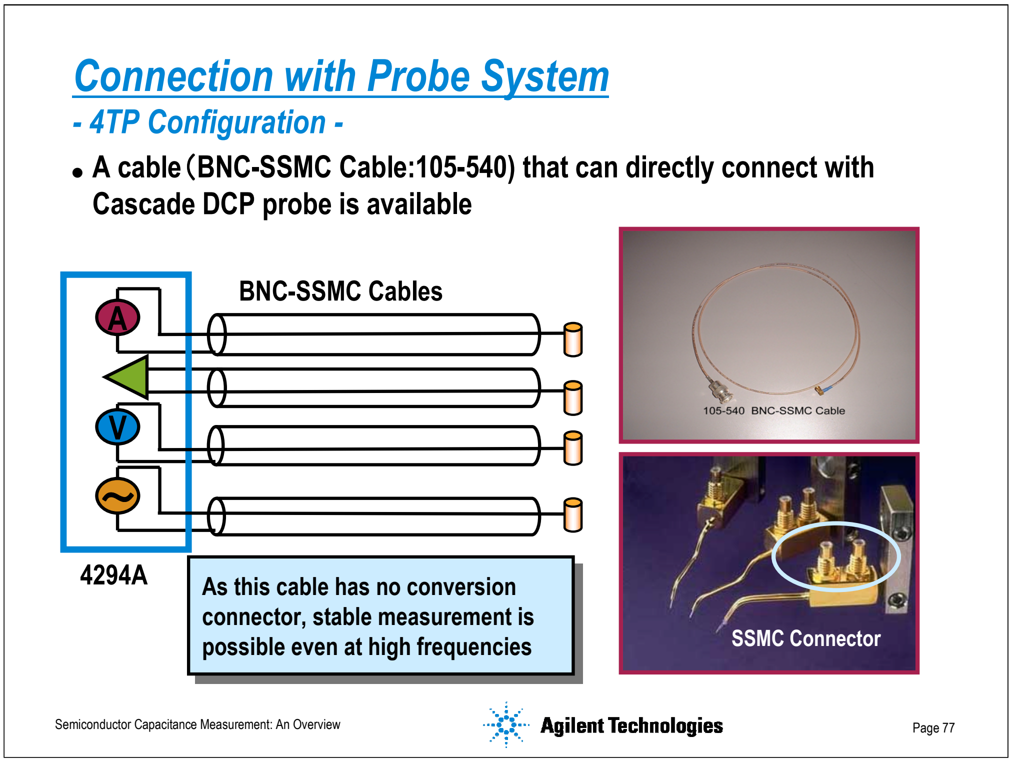
3) Extra cables should be short and stable.

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.



4TP Configuration

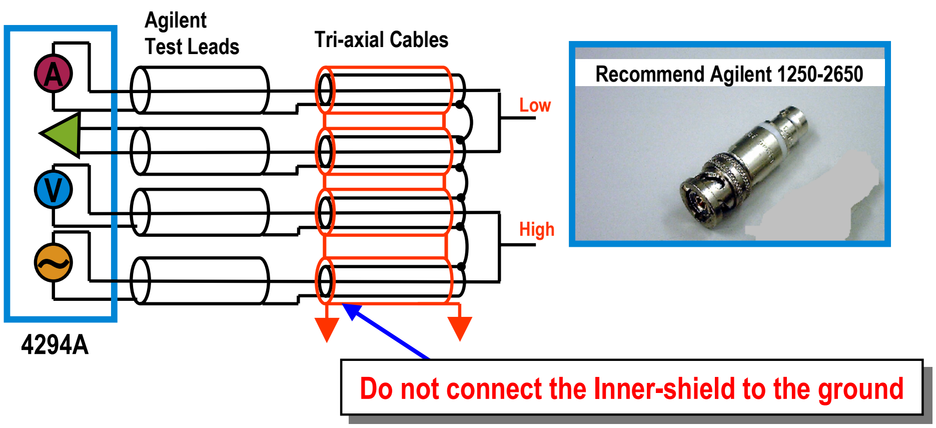
The BNC-SSMC cable (P/N:105-504), which is provided by Cascade Microtech, is recommended for connecting to the probe station. With this cable, the 4294A and DCP series probe can be connected directly.

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

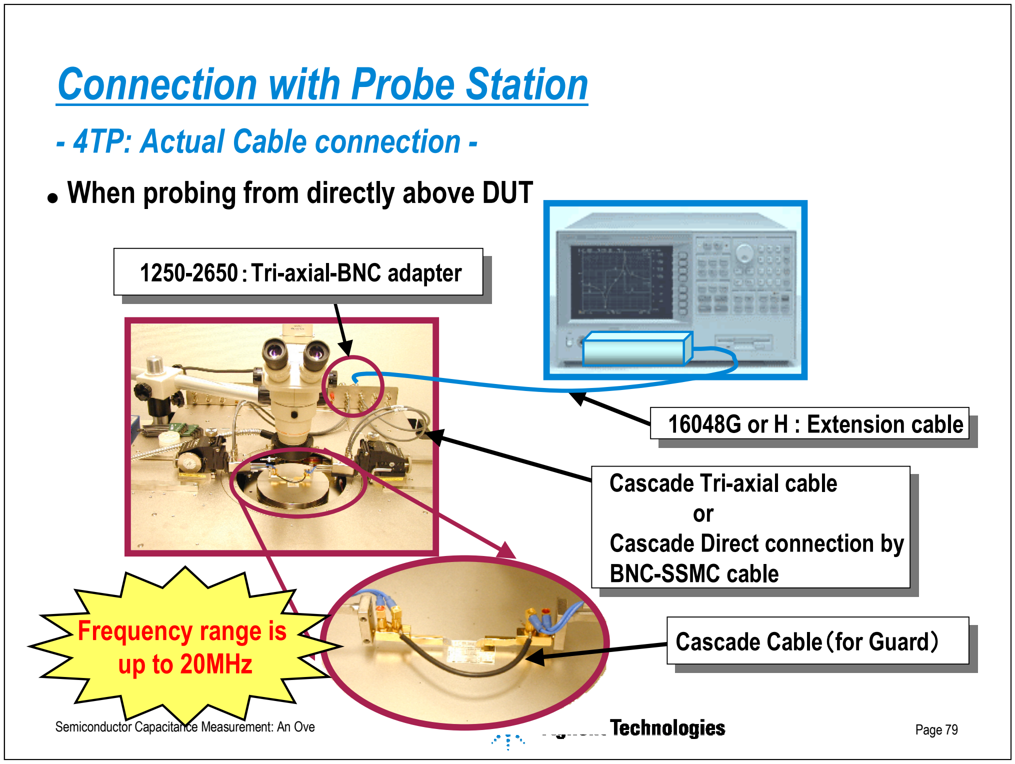
- 4TP Configuration -

- **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.



Actual Cable Connection

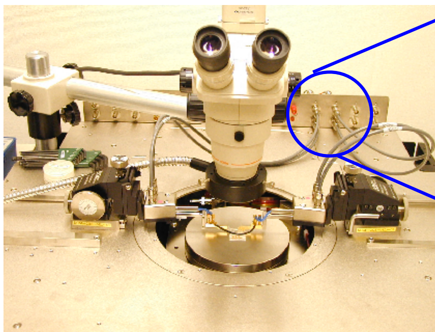
As shown in this slide, the guards of the low and the high terminal should be connected together using the guard cable (P/N: 123-625) provided by Cascade Microtech. It is desirable that the 4TP configuration is maintained very close to the tip of the probes in order to obtain high accuracy. If a guard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

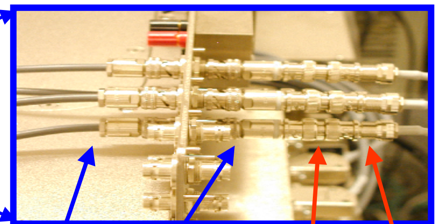
Connection with Probe Station

- 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**

Red: Agilent Product
Blue : Cascade Product

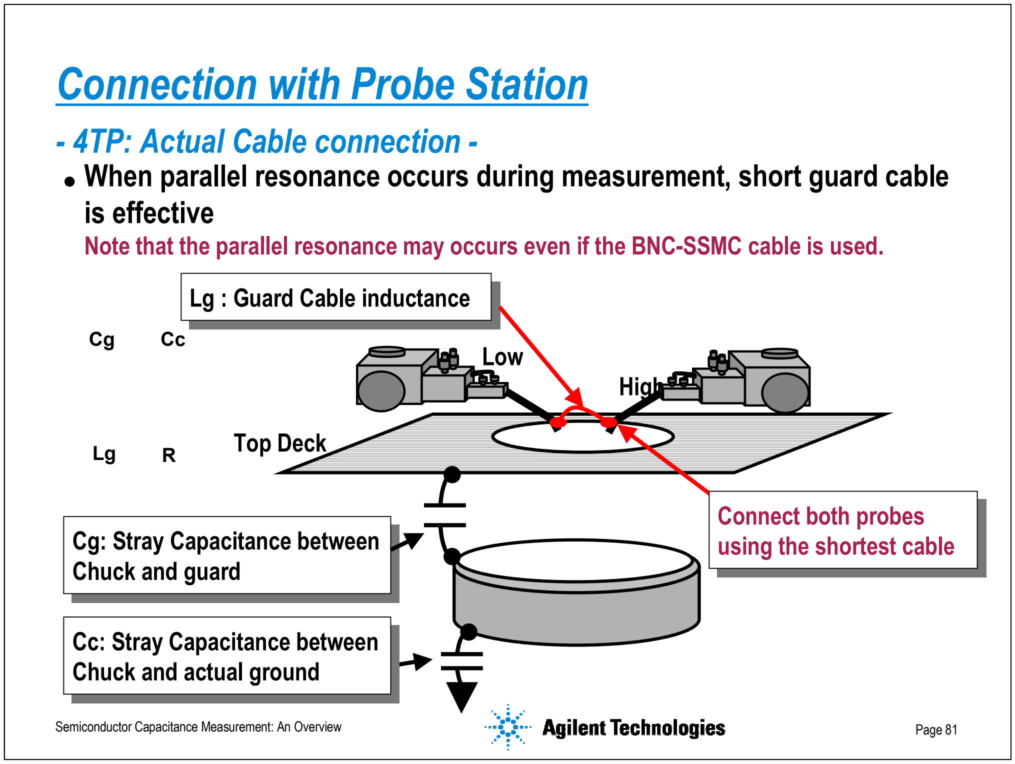




Semiconductor Capacitance Measurement: An Overview Agilent Technologies Page 80

Actual Cable Connection

This is a connection part of Agilent cables and extra triaxial cables.



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

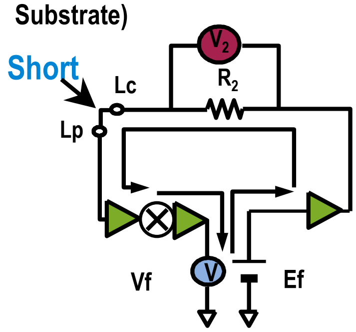
- 4TP: Compensation -

• Phase compensation

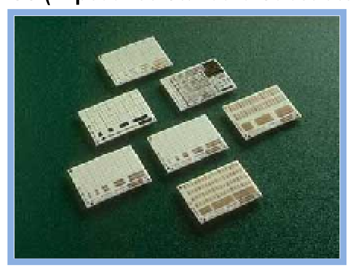
- **•Short Low terminal and perform phase compensation.**
  - **Non-Kelvin probe: the probe in the air**
  - **Kelvin probe: the probe on short standard**

•Open/Short/Load compensation

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



ISS (Impedance Standard Substrate)



Semiconductor Capacitance Measurement: An Overview

Agilent Technologies

Page 82

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

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

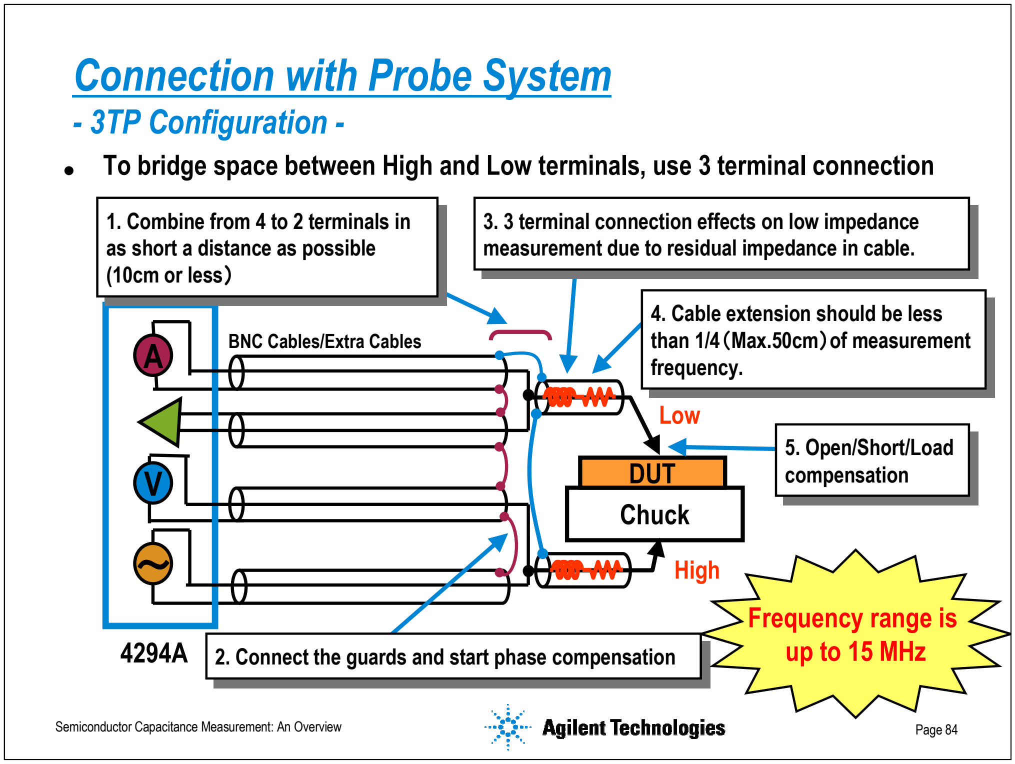
Semiconductor Capacitance Measurement: An Overview — Agilent Technologies — Page 83

Recommended Measurement System

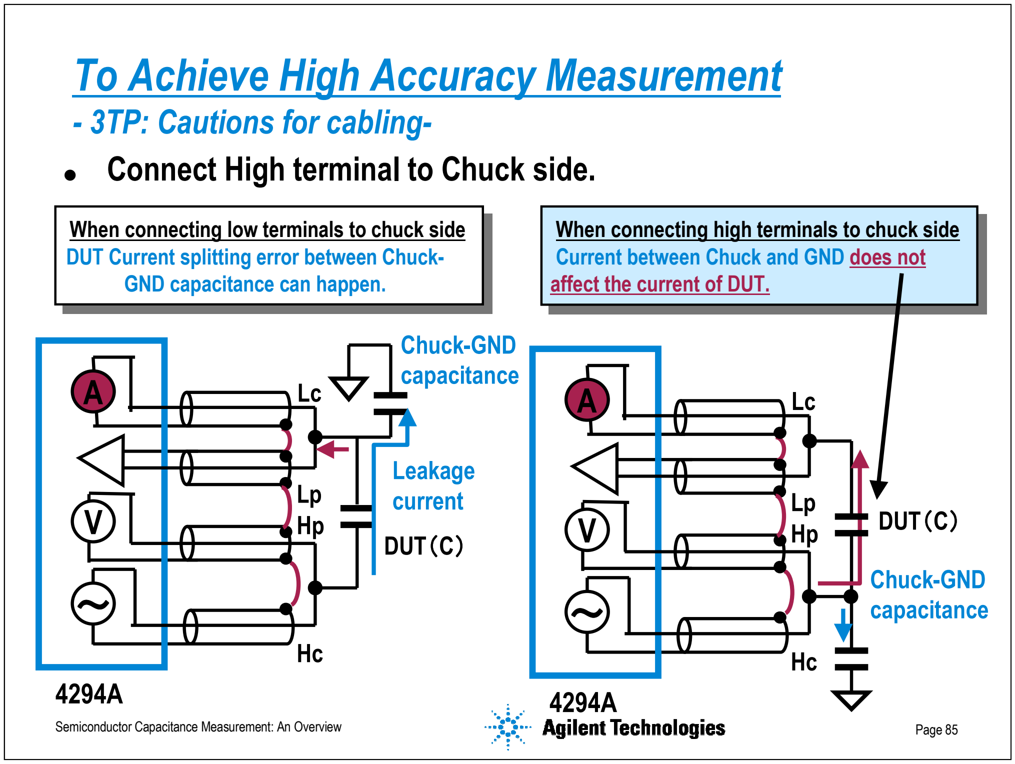
As shown in this table, several measurement methods are available and each method has some features/benefits.

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.



3TP Configuration



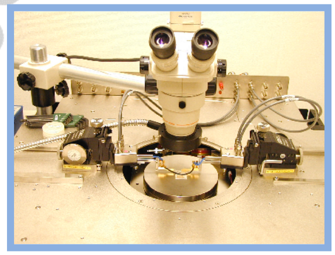
3TP Configuration

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



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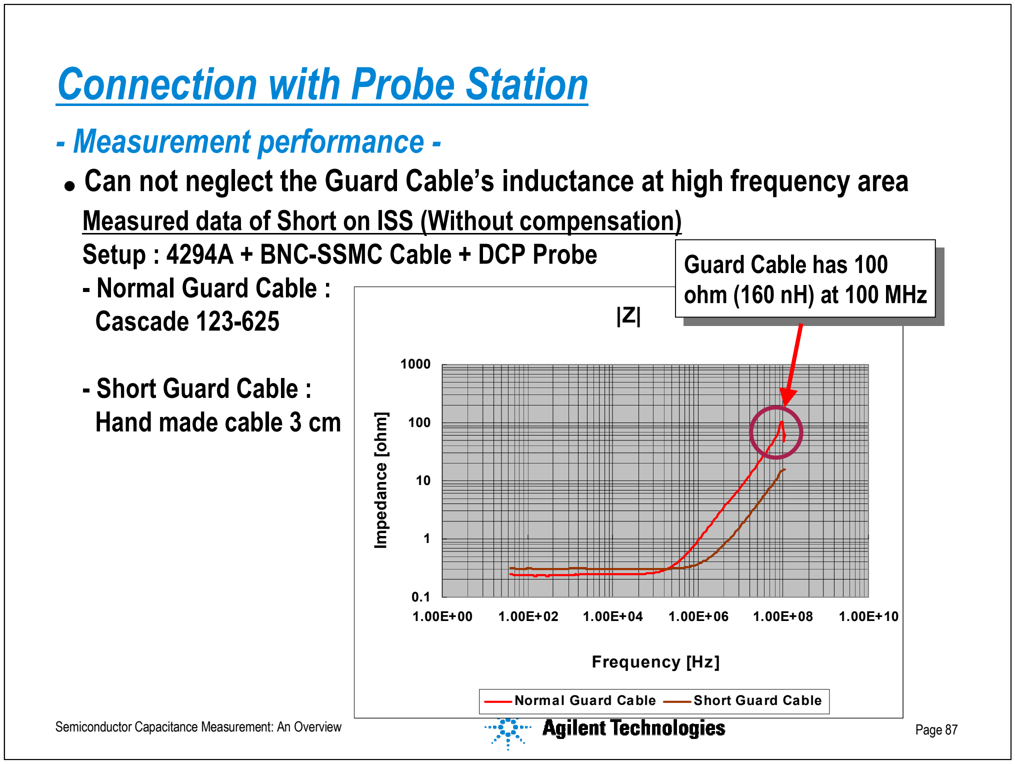
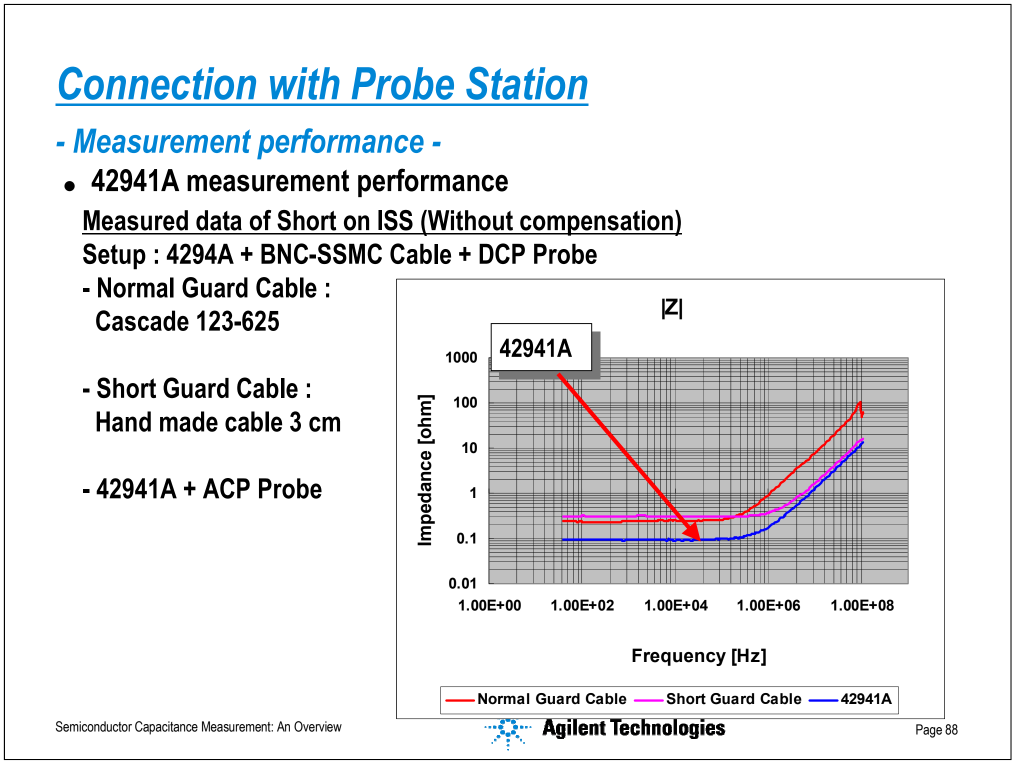


Measurement Performance

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.

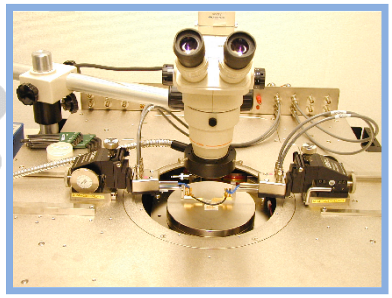


Measurement Performance

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



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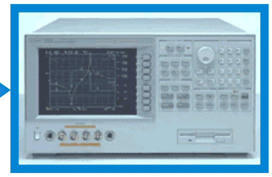
Measurement Tips
-Problems with 4284A -

4284A

- External PC is required when calculating 3-element model
- Analysis with point sweep up to 1MHz
- DC bias point sweep measurement
- Use of predefined cable

4294A



- Auto-calculation of each parameter in 3-element model by internal IBASIC
- Analysis up to 110MHz by Frequency sweep
- DC bias sweep measurement with constant voltage mode
- Equipped with phase compensation function
- Support the Touchstone format (Rev.1.1)

Semiconductor Capacitance Measurement: An Overview

Agilent Technologies

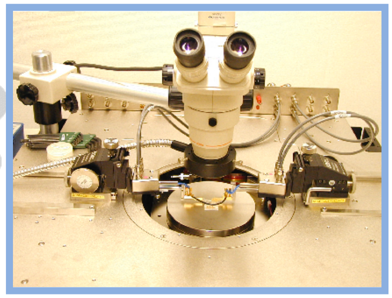
Page 90

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



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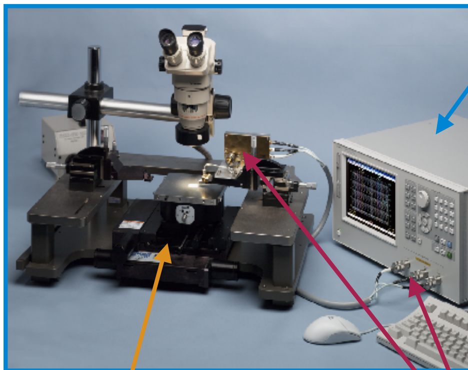
RF Solution

- System Outline (Summit Probe Station with E4991A) -

New



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 CITI file
- Data transfer by LAN

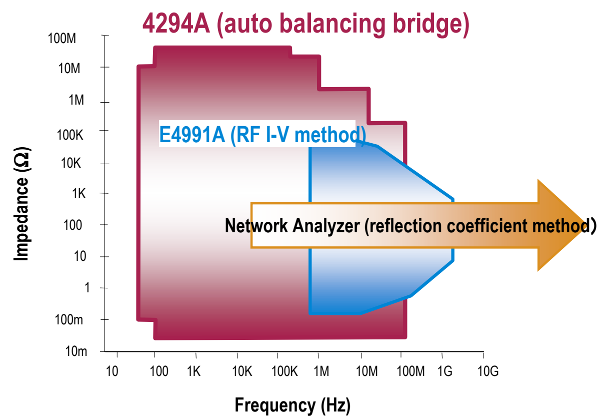
Summit Series Probe Station by Cascade Microtech

E4991A Option 010
Probe Station connection Kit

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



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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 Technologies, Impedance Measurement Handbook, 2nd Edition" (P/N 5950-3000)
- 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)

Semiconductor Capacitance Measurement: An Overview
Agilent Technologies
Page 94

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/**