Solutions for Measuring Permittivity and Permeability with LCR meters and Impedance Analyzers

Application Note 380-3

1. Introduction

Recently, the technology of electronic equipment has been evolving dramatically to a point where the electronic component's material characteristics have become the key determinant factor of a circuit's behavior. For example, in the manufacture of high capacitance MLCCs (multi-layer ceramic capacitors),which are gaining use in digital (media) appliances, the employment of high κ material is highly required. In addition, various electrical performance evaluations such as frequency and temperature response must be performed before the adoption of the material.

In the field outside of electronic equipment, electrical characteristic evaluations of materials have become increasingly populous. This is because composition and chemical variations of materials such as solids and liquids can adopt electrical characteristic responses as substituting performance parameters.

For material evaluation, precise measurement instruments, test fixtures (to hold the material under test), software (to calculate and display the basic material parameters such as permittivity and permeability) are necessary for a total measurement system.

This application note will focus on the measurement methods and systems for permittivity and permeability. Various measurement methods have been proposed (See Table 1). However, here the focus will primarily be on the methods that employ the impedance measurement technology, which has advantages as shown below:

- Wide frequency range from 20Hz to 1GHz
- High measurement accuracy
- Simple preparations (fabrication of material, measurement setup) for measurement

Table 1. Measurement Technology and Methods for Permittivity and Permeability

Measurement Parameter	Measurement Technology	Measurement Method
Permittivity	Impedance	Parallel Plate
	Network Analysis	Reflection Wave
	|	S Parameters
	|	Cavity
	|	Coxial Probe
	V	Free Space
Permeability	Impedance	Inductance
	Network Analysis	Differential Coil
	|	Reflection Wave
	|	S Parameters
	V	Cavity

Permittivity Evaluation

2.1. Definition of Permittivity

Permittivity describes the interaction of a material with an electric field. The principal equations are shown in Fig.1. Dielectric constant (κ) is equivalent to complex relative permittivity (ε_r*)、or the complex permittivity (ε*) relative to permittivity of free space (ε_0) . The real part of complex relative permittivity (ε_r') is a measure of how much energy from an external field is stored in a material. $\varepsilon_r' > 1$ for most solids and liquids. The imaginary part of complex relative permittivity (ε_r'') is called the loss factor and is a measure of how dissipative or lossy a material is to an external field. ε_r'' is always > 0 and is usually much smaller than ε_r'. The loss factor includes the effects of both dielectric loss and conductivity.

When complex permittivity is drawn as a simple vector diagram as shown in Fig.1, the real and imaginary components are 90° out of phase. The vector sum forms an angle δ with the real axis (ε_r') . The tangent of this angle, tan δ or loss tangent , is usually used to express the relative "lossiness" of a material. The term "dielectric constant" is often called "permittivity" in various technical literatures. In this application note, the term permittivity will be used to refer to dielectric constant and complex relative permittivity.

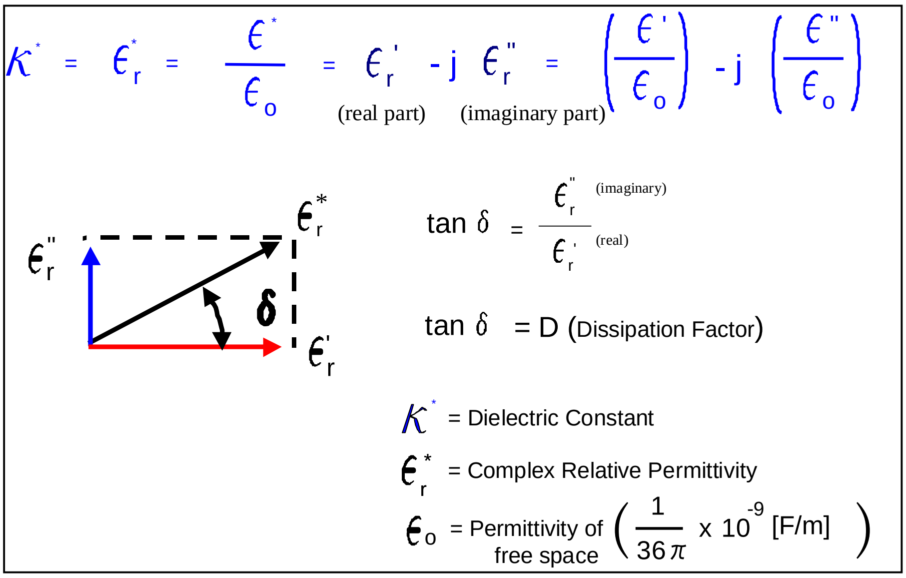


Fig.1 Definition of Relative Complex Permittivity (εr*)

2.2. Method of Measuring Permittivity

When using a impedance measuring instrument to measure permittivity, the parallel plate method is usually employed. The overview of the parallel plate method is shown in Fig. 2.

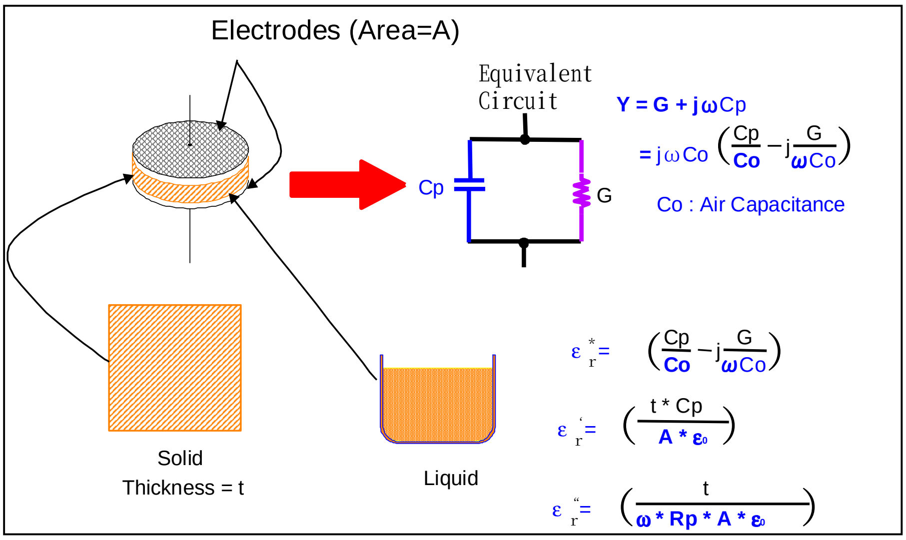


Fig.2 Parallel Plate Method

The parallel plate method (or the three terminal method as described in ASTM D150) involves sandwiching a thin sheet of material or liquid (will use MUT – Material Under Test from here onwards) between two electrodes to form a capacitor. The measured capacitance is then used to calculate permittivity. Hence, in an actual test setup, two electrodes are configured with a test fixture to sandwich the dielectric material. The impedance measuring instrument would measure vector components of capacitance (C) and dissipation (D) and a software calculates permittivity and loss tangent.

The flow of the electrical field in an actual measurement is shown in Fig.3. When simply measuring the dielectric material between two electrodes, stray capacitance (also known as edge capacitance) is formed on the edges of the electrodes and consequently the measured capacitance is larger than it actually is. The edge capacitance causes a measurement error, since the current flows through the dielectric material and edge capacitance.

A practical solution to the measurement error caused by the edge capacitance is to use the guard electrode. The guard electrode absorbs the electric field at the edge and the capacitance that is measured between the electrodes is composed of the current that flows only through the dielectric material. Therefore, accurate measurements are possible. (When the main electrode is used with a guard electrode, the main electrode is called guarded electrode.)

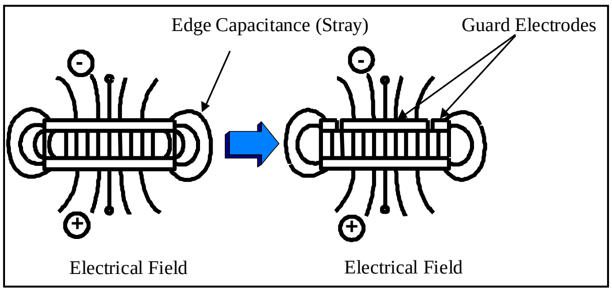


Fig.3 Effect of Guard Electrode

Contacting Electrode Method ：

This method derives permittivity by measuring the capacitance of the electrodes contacting the MUT directly (Fig.4). Permittivity and loss tangent is calculated using the equations below:

Cp: Equivalent parallel capacitance of MUT [F]

D: Dissipation factor (measured value)

ta: Average thickness of MUT [m]

A: Guarded electrode' surface area [m^2]

D: Guarded electrode's diameter [m]

ε_0: permittivity of free space = 8.854x10-12 [F/m]

Equation ：

$$\varepsilon r = \frac{(ta * Cp)}{(A * \varepsilon_0)} = \frac{(ta * Cp)}{(\pi (\frac{d}{2})^2 * \varepsilon_0)}$$

$$Dt = D$$

This method requires no material preparations and the operation involved when measuring is rather simple. Therefore, it is the most widely used method. However, due to the reasons mentioned below, a significant measurement error is involved when using this method.

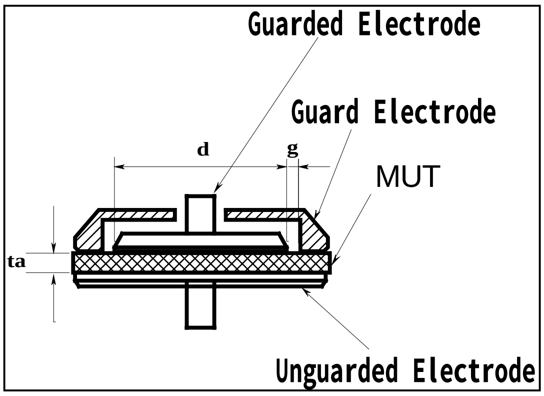
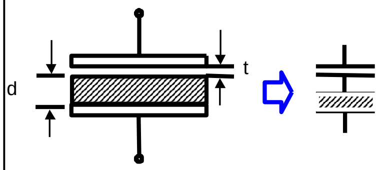


Fig.4 Contacting Electrode Method

When contacting the MUT directly with the electrodes, an airgap is formed between the MUT and the electrodes. No matter how flat and parallel both sides of the MUT is fabricated, an airgap will still form. This airgap is the cause for measurement error because the measured capacitance will be the sum of the capacitance of the dielectric material and the airgap. The relationship between the airgap's thickness and measurement error is determined by the equation shown in Fig. 5. Measurement error is a function of the relative permittivity ($\varepsilon r'$) of the MUT, thickness of the MUT (d), and the airgap's thickness (t). Sample results of measurement error have been calculated in Table 2. Notice that the effect is greater with thin materials and high κ materials.



$$C_0 = \varepsilon_0 \frac{s}{t}$$ Capacitance of airgap

$$C_x = \varepsilon_x \varepsilon_0 \frac{s}{d}$$

Measured capacitance: $$C_{err} = \frac{1}{\frac{1}{C_0} + \frac{1}{C_x}} = \varepsilon_{err} \varepsilon_0 \frac{s}{d+t}$$

Measurement error due to airgap $$1 - \frac{\varepsilon_{err}}{\varepsilon_x} = \frac{\varepsilon_x - 1}{\varepsilon_x + \frac{d}{t}}$$

Fig. 5 Airgap Effects

Table 2. Measurement Error Caused by Airgap

εr' / t / d	2	5	10	20	50	100
0.001	0.1%	0.4%	1%	2%	5%	9%
0.005	0.5%	2%	4%	9%	20%	33%
0.01	1%	4%	8%	16%	33%	50%
0.05	5%	16%	30%	48%	70%	83%
0.1	8%	27%	45%	63%	82%	90%

This airgap effect can be eliminated, by applying a thin film electrode to the surfaces of the dielectric material. An extra step is required for material preparation (fabricating a thin film electrode), but the most accurate measurements can be performed.

Non-Contacting Electrode Method :

This method was conceptualized to incorporate the advantages and exclude the disadvantages of the contacting electrode method. It does not require a thin film electrode and it still solves the airgap effect. Permittivity is derived by using the results of two capacitance measurements obtained with the MUT and without it (Fig. 6).

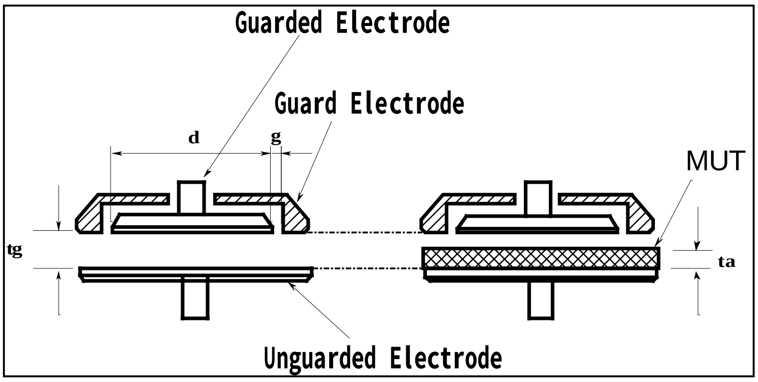


Fig.6 Non-Contacting Electrode Method

Theoretically, the electrode gap (tg) should be a little bit larger than the thickness of the MUT (ta). In other words, the airgap (tg – ta) should be extremely small when compared to the thickness of the MUT (ta). These requirements are necessary for the measurement to be performed appropriately. Two capacitance measurements are necessary, and the results are used to calculate permittivity. The equation is shown down below:

Cs1: Capacitance without MUT inserted [F]
Cs2: Capacitance with MUT inserted [F]
D1: Dissipation factor without MUT inserted
D2: Dissipation factor with MUT inserted
tg: Gap between Guarded/Guard electrode and Unguarded electrode [m]
ta: Average thickness of MUT [m]

Equation：

$$\varepsilon r = \frac{1}{\left(1-\left(1-\frac{C_{S1}}{C_{S2}}\right)*\frac{tg}{ta}\right)}$$

$$Dt = D_2 + \varepsilon r * (D_2 - D_1) * \left(\frac{tg}{ta} - 1\right) \quad (Dt \ll 1)$$

Table 3 summarizes the advantages of the three methods

Table 3. Comparison of Measurement Methods

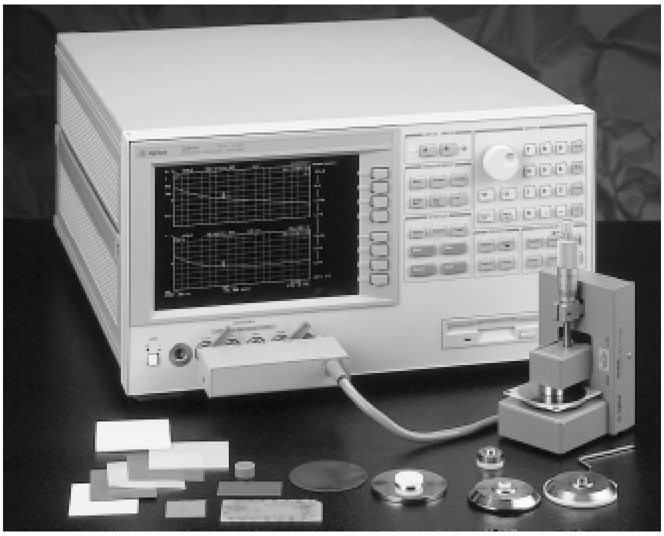
Method	Contacting Electrode (without thin film electrode)	Non-Contacting Electrode	Contacting Electrode (with thin film electrode)
Accuracy	LOW	MEDIUM	HIGH
Applicable MUT	Solid material with a flat and smooth	Solid material with a flat and smooth	Thin film electrode must be applied onto
Operation	1 measurement	2 measurements	1 measurement

2.3. Permittivity Measurement System

Two measurement systems that employ the parallel plate method will be elaborated upon from here. The first is the 16451B Dielectric Test Fixture, which has capabilities to measure solid materials up to 30MHz. The latter is the 16453A Dielectric Material Test Fixture, which has capabilities to measure solid materials up to 1GHz. The details of each measurement system will be described using the following headings.

1) Main Advantages
2) Applicable MUT
3) Structure
4) Principal Specifications
5) Operation Method
6) Cautioning Factors
7) Sample Measurements

2.4. Measurement System Using the 16451B Dielectric Test Fixture



Applicable Measurement Instruments

4263A/B, 4268A, 4278A, 4279A, 4284A, 4285A, 4294A

2.4.1. Main Advantages

- Precise measurements are possible in the frequency range up to 30MHz
- Four electrodes are provided to accommodate the contacting and non-contacting electrode methods and various sizes of MUT.
- Guard electrode to eliminate the effect of the edge capacitance
- Attachment simplifies OPEN and SHORT compensation
- Can be used with any Impedance measuring instrument that has a 4-terminal pair configuration.

2.4.2. Applicable MUT

The applicable dielectric material is a solid sheet that is smooth and has equal thickness from one end to the other. The applicable dielectric material's size is determined by the measurement method and type of electrode to be used.

Electrodes A and B are used for the contacting electrode method without the fabrication of thin film electrodes. Electrodes C and D are used for the contacting electrode method with the fabrication of thin film electrodes.

When employing the non-contacting electrode method, electrodes A and B are used. In this method, it is recommended to process the dielectric material to have a thickness of a few millimeters.

The difference between electrodes A and B is that the diameter is different (same difference for electrodes C and D). Electrodes A and C are adapted for large sizes of MUT, and electrodes B and D are adapted for small sizes of MUT. The applicable MUT sizes for each electrode are shown in tables 4 and 5. The dimensions of each electrode are shown in Fig.7 through Fig.10.

Table 4. Applicable MUT Sizes for Electrodes A and B

Electrode Type	Material Diamete	Material Thicknes	Electrode Diameter
A	40mm ～56mm	t ≦ 10mm	38mm
B	10mm ～ 56mm	t ≦ 10mm	5mm

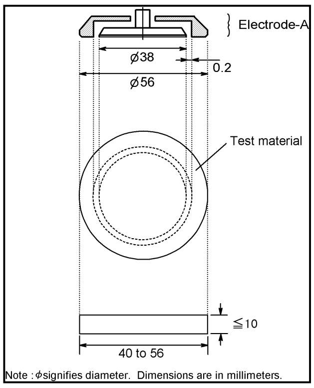


Fig.7 Electrode A Dimensions

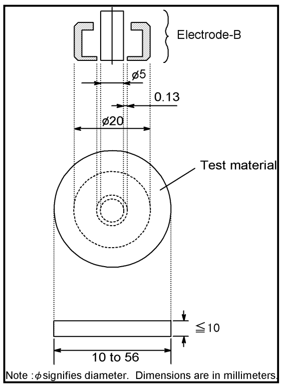


Fig. 8 Electrode B Dimensions

Table 5. Applicable MUT Sizes for Electrodes C and D

Electrode Type	Material Diamete	Material Thicknes	Electrode Diameter*
C	56mm	t ≦ 10mm	5～50mm
D	20mm ～56mm	t ≦ 10mm	5～14mm

*Diameter of applied thin film electrode on surfaces of dielectric material.

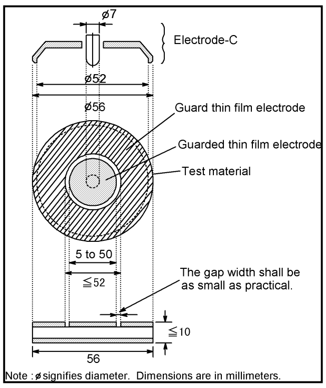


Fig.9 Electrode C Dimensions

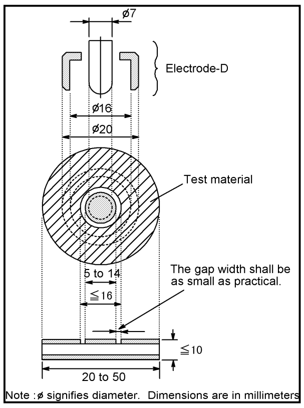


Fig.10 Electrode D Dimensions

2.4.3. Structure

In order to eliminate the measurement error caused by the edge capacitance, a three-terminal configuration (including a guard terminal) is employed. The structure of 16451B is shown in Fig. 11.

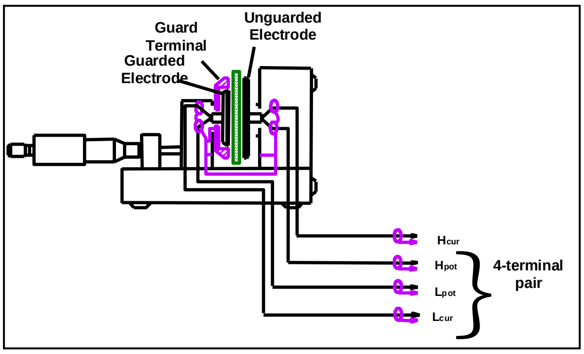


Fig.11 Structure of 16451B

The electrodes in 16451B are made up of the following:

1. Unguarded electrode, which is connected to the measurement instrument's HIGH terminal.
2. Guarded electrode, which is connected to the measurement's instrument's LOW terminal.
3. Guard electrode, which is connected to the measurement instrument's guard terminal (the outer conductor of the BNC connectors).

The guard electrode encompasses the guarded (or main) electrode and absorbs the electric field at the edge of the electrodes. Thus, accurate permittivity measurements are possible.

2.4.4. Principal Specifications

Table 6. Principal Specifications of 16451B

Frequency	30MHz (depends on permittivity of
Max. Voltage	42V
Operating Temperature	0 to 55 degrees C
Terminal Configuration	4-terminal pair, BNC
Cable Length	1m
Compensation	OPEN/SHORT*

*When using the 4285A or 4294A above 5MHz, it is necessary to perform LOAD compensation in addition to OPEN and SHORT compensation. For more details, please refer to 2.4.5 Operation Method

The principal specifications are shown in Table 6 and Fig. 12 and 13 show the measurement accuracy when 4294A is used. Further details about the measurement accuracy can be obtained from the 16451B Profile (PN 5950-2368)

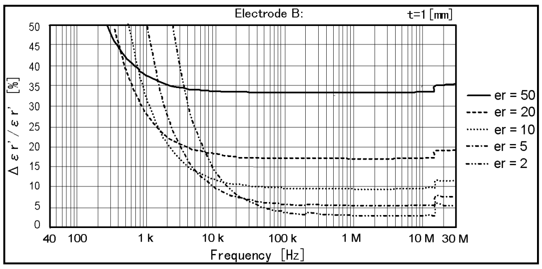


Fig.12 Permittivity Measurement Accuracy (Supplemental Data)

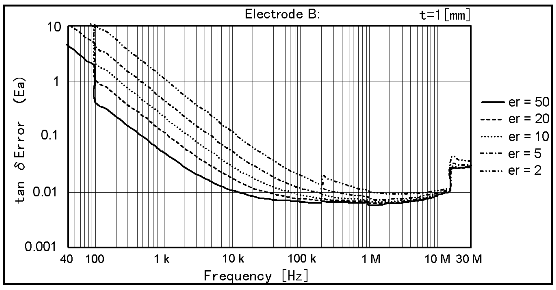


Fig.13 Loss Tangent Measurement Accuracy (Supplemental Data)

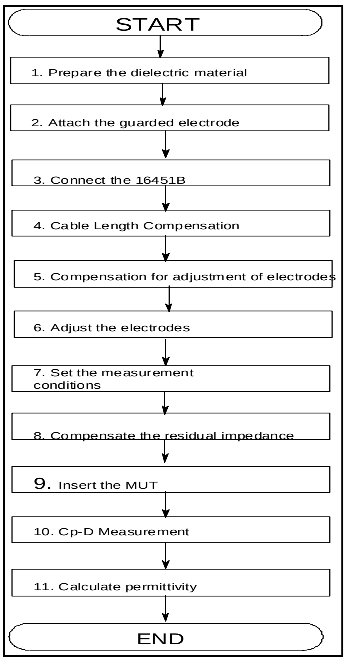


Fig.14 Measurement Procedure Flowchart for the 16451B

2.4.5. Operation Method

Fig.14 displays the flowchart when using the 16451B for permittivity measurements. Below are the descriptions of each step in the flowchart.

Step 1. Prepare the dielectric material: Fabricate the MUT to the appropriate size. Use Fig.7 through 10 as a reference. If the contacting electrode method with thin film electrodes is employed, apply thin film electrodes to the surfaces of the MUT.

Step 2. Attach the guarded electrode: Select the appropriate electrode and fit it into the 16451B.

Step 3. Connect the 16451B: Connect the 16451B to the UNKNOWN terminals of the measurement instrument.

Step 4. Cable Length Compensation: Set the measurement instrument's cable length compensation function to 1m. Refer to the measurement instrument's operation manual for the setting procedure.

Step 5. Compensate the residual impedance of the 16451B: Use the furnished attachment to perform OPEN and SHORT compensation to perform the adjustment of electrodes at a specified frequency.

Step 6. Adjust the electrodes: To enhance the measurement performance, a mechanism is provided to adjust the guarded and unguarded electrodes to be parallel to each other. By performing this adjustment, the occurrence of the airgap when using the contacting electrode method is minimized and an airgap with uniform thickness is created when using the non-contacting electrode method. The adjustment procedure is discussed in the operation manual of the 16451B.

Step 7. Set the measurement conditions: Measurement conditions such as frequency and test voltage level are set on the measurement instrument. Refer to the measurement instrument's operation manual for the setting procedure.

Step 8. Compensate the residual impedance of the 16451B: Use the furnished attachment to perform OPEN and SHORT compensation.

When using the 4285A or 4294A above 5MHz, it is necessary to perform LOAD compensation. When measuring at high frequencies, it is difficult to disregard the residual impedance that cannot be removed by OPEN and SHORT compensation.

In order to compensate the frequency response of the 16451B, a measured value at 100kHz is used as a standard value and LOAD compensation is performed at high frequencies. The air capacitance formed by creating an airgap between the electrodes (with nothing inserted) is adopted as the LOAD device for the 16451B. Table 7 lists the recommended capacitance values that are obtained by adjusting the height of the airgap between the electrodes. It is assumed that the air capacitance has no frequency dependency, no loss and has a flat response. The capacitance value (Cp) at 100kHz (G is assumed to be zero) is used for LOAD compensation.

Table 7. LOAD Values

Electrode	Recommended Capacitance*
A	50pF (0.5pF tolerance)
B	5pF (0.05pF tolerance)
C、D	1.5pF (0.05pF tolerance)

* Measured Cp value at 100kHz

Step 9. Insert MUT: Insert the MUT between the electrodes.

Step 10. Cp-D Measurement: The capacitance (Cp) and dissipation factor (D) is measured. When employing the non-contacting electrode method, 2 Cp-D measurements are performed, with and without the MUT.

Step 11. Calculate permittivity: As discussed in section 2.2, use the appropriate equation to calculate permittivity.

When using the 4294A as the measurement instrument, a sample IBASIC program, which follows the steps described above, is available. The sample program is furnished with the operation manual of 4294A.

2.4.6 Cautioning Factors

As mentioned before, to reduce the effect of the airgap, which occurs between the MUT and the electrodes, it is practical to employ the contacting electrode method with thin film electrodes (Refer to section 2.2). Electrodes C and D are provided with the 16451B to carry out this method.

Furthermore, MUT, which transform under applied pressure cannot keep a fixed thickness. This type of MUT is not suitable for the contacting electrode method. Instead, the non-contacting method should be employed.

The micrometer on the 16451B is designed to make a precise gap when using the non-contacting electrode method. Accurate measurements of the thickness of MUT cannot be realized, when employing the contacting electrode method. This is because the micrometer scale is very dependent upon how parallel the guard and the unguarded electrodes are. Hence, it is recommended to use a separate micrometer for thickness measurements.

2.4.7. Sample Measurements

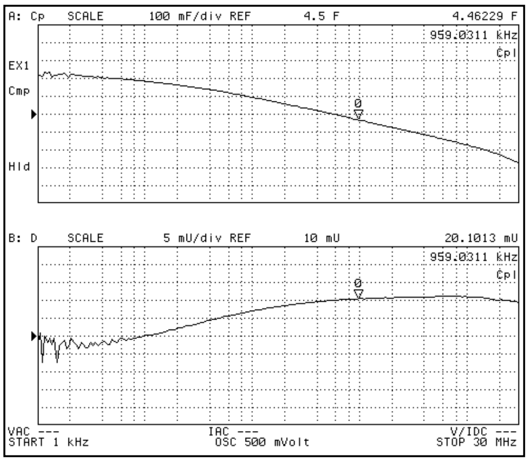


Fig.15 Frequency Response of Printed Circuit Board

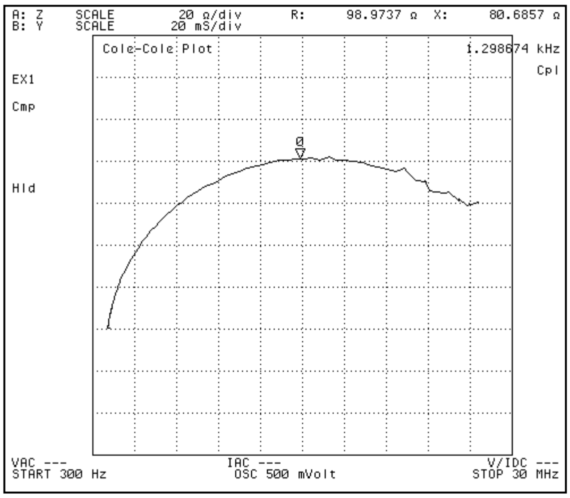


Fig.16 Cole-Cole Plot of a Ceramic Material

2.5. Measurement System Using the 16453A Dielectric Material Test Fixture

Applicable Measurement Instrument

4291B（Option 002）＊

*In addition option 013 high temperature high impedance test head is required for temperature-response evaluation. A heat resistant cable, which maintains high accuracy, and an IBASIC program for chamber control and data analysis is included with option 013.

2.5.1. Main Advantages

- Wide frequency range from 1MHz – 1GHz
- 4291B's (Option 002 material measurement software) internal firmware solves edge capacitance effect
- Temperature characteristics measurements are possible from –55°C to +200°C
- Open, short and load compensation
- Direct readouts of complex permittivity are possible with the 4291B's (Option 002 material measurement software) internal firmware.

2.5.2. Applicable MUT

The applicable dielectric material is a solid sheet that is smooth and has equal thickness from one end to the other. The applicable MUT size is shown in Fig. 17.

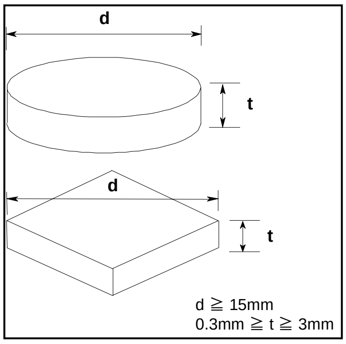


Fig.17 Applicable MUT Size

2.5.3. Structure

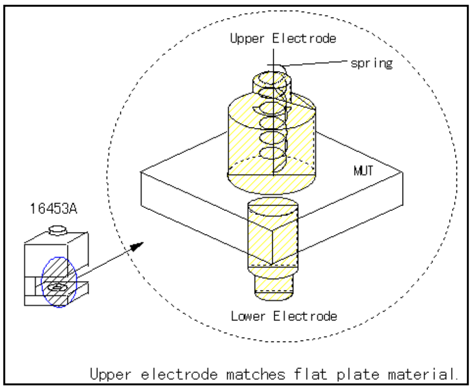


Fig.18 Structure of 16453A

The structure of 16453A can be viewed in Fig.18. The upper electrode has an internal spring, which allows the MUT to be fastened between the electrodes. The applied pressure can be adjusted as well.

The 16453A is not equipped with a guard electrode like the 16451B. This is because a guard electrode at high frequency only yields in greater residual impedance and poor frequency characteristics. To constructively lessen the effect of edge capacitance, a correction function based on simulation results is used in the 4291B option 002 firmware.

Also, residual impedance which is a major cause for measurement error, cannot be entirely removed by OPEN and SHORT compensation. This is why TEFLON is provided as a LOAD compensation device.

2.5.4. *Principal Specifications*

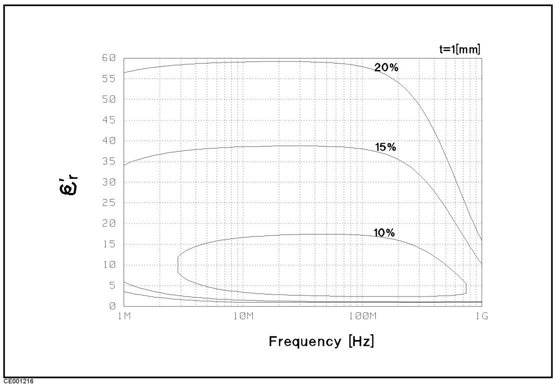
Table 8. Principal Specifications of 16453A

Frequency	1MHz to 1GHz
Max. Voltage	42V
Operating Temperature	-55 to +200 degrees C *
Terminal Configuration	7mm
Compensation	Open,short and load

*When using option 013

The principal specifications are shown in Table 8 and Fig. 19 and 20 show the measurement accuracy when 4291B is used. Further details about the measurement accuracy can be obtained from the operation manual of 4291B.

Fig.19 Permittivity Measurement Accuracy (Supplemental Data)



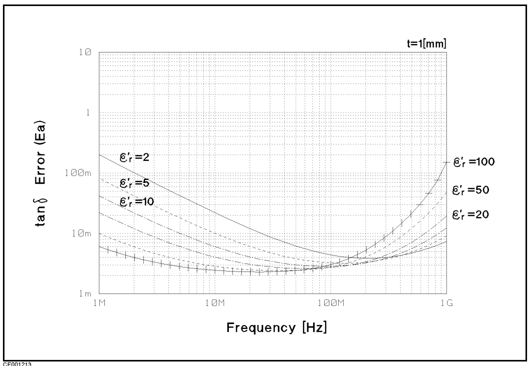


Fig.20 Loss Tangent Measurement Accuracy (Supplemental Data)

2.5.5. *Operation Method*

Fig.21 displays the flowchart when using the 16453A for permittivity measurements. Below are the descriptions of each step in the flowchart. For further detail, please refer to the Quick Start Guide of 4291B.

Step 1. Calibrate the 4291B: Calibrate at the 7mm terminal of the 4291B.

Step 2. Connect the 16453A: Connect the 16453A to the 7mm terminal of the 4291B and select 16453A as the fixture on the MEAS menu.

Step 3. Input the thickness of LOAD device: Before compensation, enter the furnished LOAD device's thickness into the 4291B.

Step 4. Compensate the residual impedance of the 16453A: Perform open, short and load compensation.

Step 5. Input the thickness of MUT: Enter the thickness of the MUT into the 4291B. Use a micrometer to measure the thickness.

Step 6. Insert MUT: Insert the MUT between the electrodes.

Step 7. Set the measurement conditions of the 4291B: Measurement conditions such as frequency, test voltage level, measurement parameter are set on the measurement instrument.

Step 8. Measure the MUT: The measurement result will appear on the display of 4291B. The data can be analyzed using the marker functions.

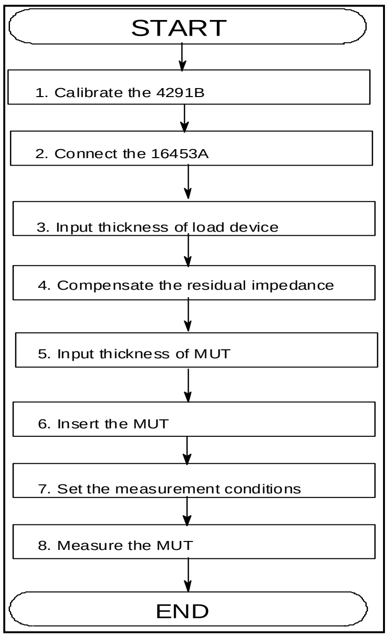


Fig.21 Measurement Procedure Flowchart for the 16453A

2.5.6 Cautioning Factors

As with the previous measurement system, an airgap, which is formed between the MUT and the electrodes, is a primary cause for measurement error. Thin materials and high κ materials are most prone to this effect. In addition, rough-surfaced materials (Fig.22) are also affected by the airgap similarly as thin materials are.

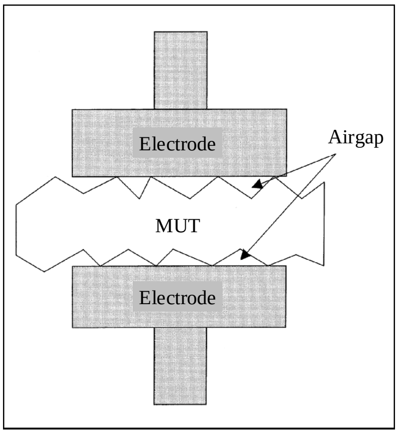


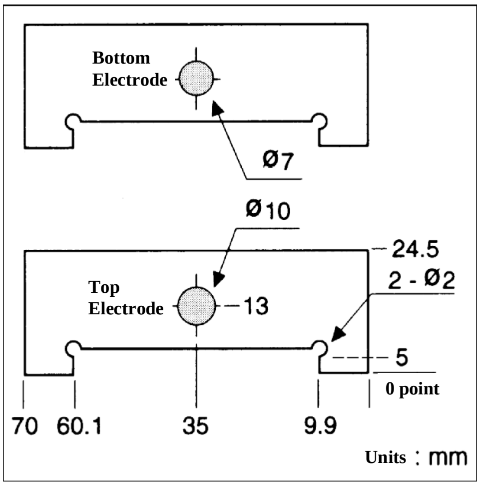
Fig.22 Rough-Surfaced Dielectric Material

In order to eliminate the airgap that occurs between the MUT and the electrodes, there is a technique to apply a thin film electrode onto the surfaces of the dielectric material. This technique is shown in Fig.23. The exact shape and sized electrode of the 16453A is fabricated onto the dielectric material. In this case, it is vital to appropriately position the fabricated thin film electrode onto the MUT and the MUT must be shaped to match the structure of the 16453A. By carrying out this process, a higher quality measurement is possible.

In addition, if the MUT is very thin (on the order of a 100μm), it is possible to simply stack 3 to 4 other MUT and measure. This way the airgap will be reduced and precise measurements are possible. The MUT must however be smooth and not transform to applied pressure.

Fig.23 Fabricated Thin Film Electrode's Size

Another cautioning point is to carefully consider the adjusting mechanism of the upper electrode's spring pressure. It is recommended to make the spring pressure the greatest, in order to minimize the occurrence of the airgap between the MUT



and the electrodes. However, MUT, which transform under extreme pressure, cannot be measured correctly, since the thickness is affected also. To achieve stable measurement, it is advisable to lower the spring pressure to a level where the MUT does not transform.

2.5.7. *Sample Measurements*

Measurement results of frequency and temperature characteristics of BT Resin are shown down below in Fig.24 and 25. The 4291B and the 16453A were used to obtain these results.

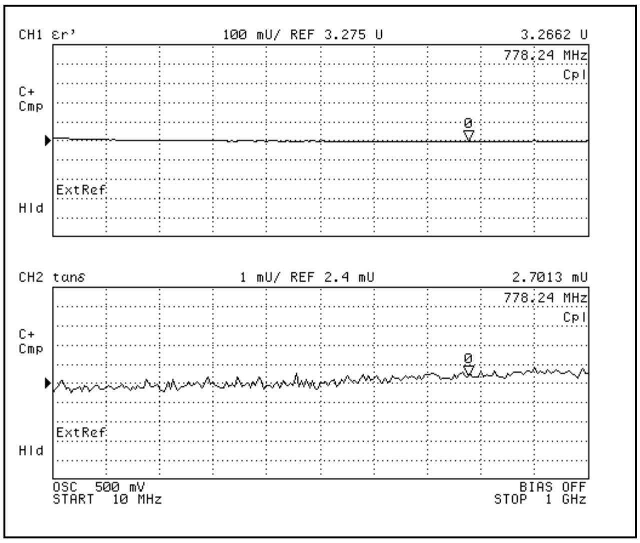


Fig.24 Frequency Response of BT Resin

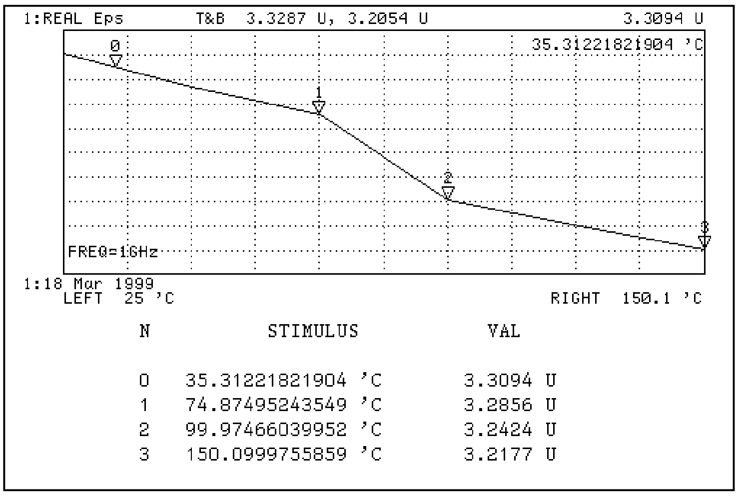


Fig.25 Temperature Response of BT Resin

2. Permeability Evaluation

3.1. Definition of Permeability

Permeability describes the interaction of a material with a magnetic field. It is the ratio of induction, B, to the applied magnetizing field, H. Complex relative permeability (μ_r*) consists of a real part (μ_r') that represents the energy storage term and imaginary part (μ_r") that represents the power dissipation term. It is also the complex permeability (μ*) relative to the permeability of free space (μ_0) as shown in Fig.26.

The inefficiency of magnetic material is expressed using the loss tangent, tan σ. The tanδ is the ratio of (μ_r") to (μ_r'). The term "complex relative permeability" is simply called "permeability" in various technical literatures. In this application note, the term permeability will be used to refer to complex relative permittivity.

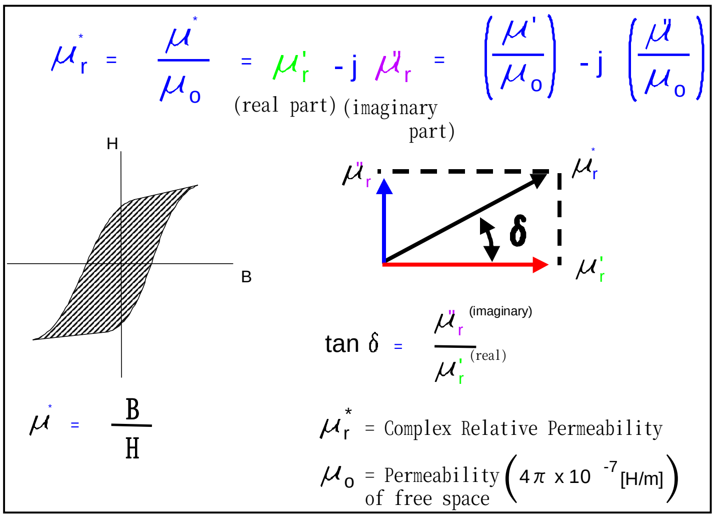


Fig.26 Definition of Complex Permeability (μ*)

3.2. Method of Measuring Permeability

Relative permeability derived from the self-inductance of a magnetic material that has a closed loop (such as the toroid) is often called effective permeability. The conventional method to measure effective permeability is to wind some wire around the core and evaluate the inductance with respect to the ends of the wire. This type of measurement is usually performed with a impedance measuring instrument. Effective permeability is derived from the inductance measurement result using the following equations:

$$\mu e' = \frac{L*l}{\mu_0 * N^2 * A}$$

$$\mu e'' = \frac{l*(Reff - Rw)}{\mu_0 * N^2 * \omega * A}$$

Reff: Resistance of toroid including wire

Rw: Resistance of wire only

N: Turns

l: Average magnetic path length of toroid [m]

A: Cross-sectional area of toroid [m^2]

ω: 2*π*f (frequency)

μ_0: 4πx10^-7[H/m]

Depending on the applied magnetic field and the location where the measurement is situated on the hysteresis curve, permeability can be classified under numerous degrees, such as initial or maximum. Initial permeability is the most often used parameter among manufacturers because most industrial applications involving magnetic material are employed at low power levels

In this application note, the focus will be on effective permeability and initial permeability, derived from the inductance measurement method.

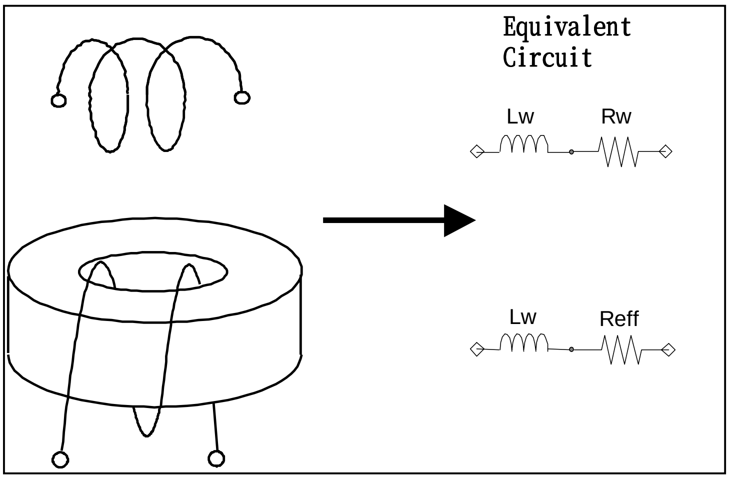
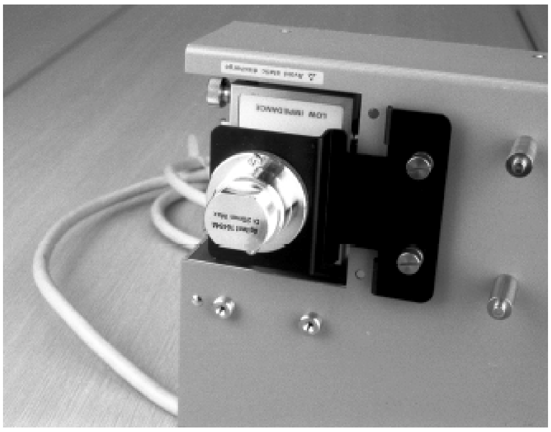


Fig.27 Method of Measuring Effective Permeability

3.3. Permeability Measurement System

The 16454A Magnetic Material Test Fixture will be introduced as a permeability measurement system and discussed from here.

3.4. Measurement System Using the 16454A Magnetic Material Test Fixture



Applicable Instruments

4291B (Option 002) *、 4294A +42942A

*In addition option 014 high temperature low impedance test head is required for temperature-response evaluation. A heat resistant cable, which maintains high accuracy, and an IBASIC program for chamber control and data analysis is included with option 014.

3.4.1. Main Advantages

- Wide frequency range from 1kHz～1GHz
- Simple measurements without the need to wind a wire around the toroid.
- Two fixture assemblies are provided to hold various sizes of MUT
- Compatible with the 4291B(Option 002 material measurement software) and the 4294A. Direct readouts of complex permeability are possible with the internal firmware or an IBASIC program.
- Temperature characteristics measurements are possible from –55°C to +200°C (must be accompanied by the 4291B)

3.4.2. Applicable MUT

The applicable magnetic material can only be a toroid. The applicable MUT size is shown in Fig. 28.

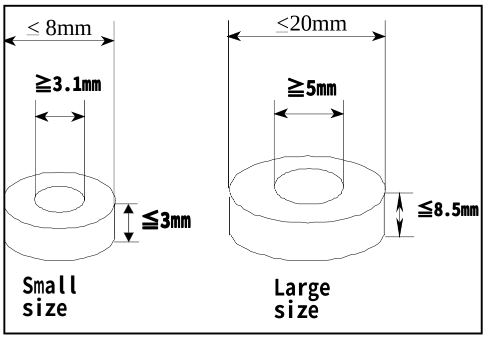


Fig.28 Applicable MUT Size

3.4.3. Structure

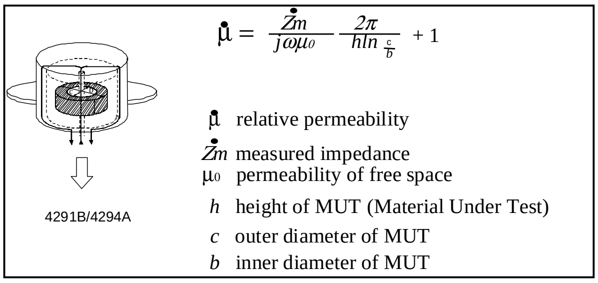


Fig.29 Structure of 16454A and Measurement Concept

The structure of 16454A and the measurement concept is shown in Fig.29. When a toroid is inserted into the 16454A, an ideal single turn inductor, with no flux leakage, is formed. Permeability is derived from the inductance of the toroid with the fixture.

3.4.4. Principal Specifications

Table 9. Principal Specifications of 16454A

Frequency	1kHz to 1GHz
Max. DC BIAS Current	+/-500mA
Operating Temperature	-55 to +200 degrees C*
Terminal Configuration	7mm
Compensation	SHORT

*When using4291B(option 014)

The principal specifications are shown in Table 9 and Fig. 30 and 31 show the measurement accuracy when either the 4291B or the 4294A is used.

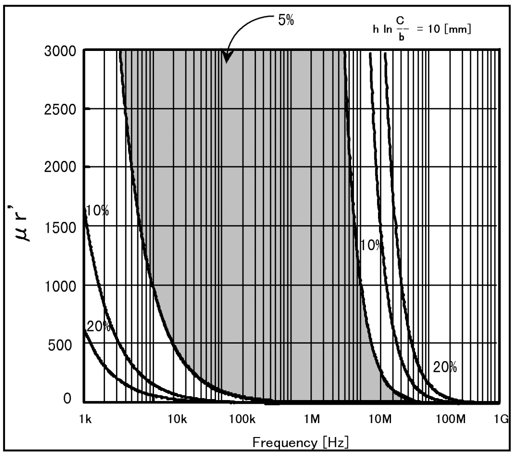


Fig.30 Permeability Measurement Accuracy (Supplemental Data)

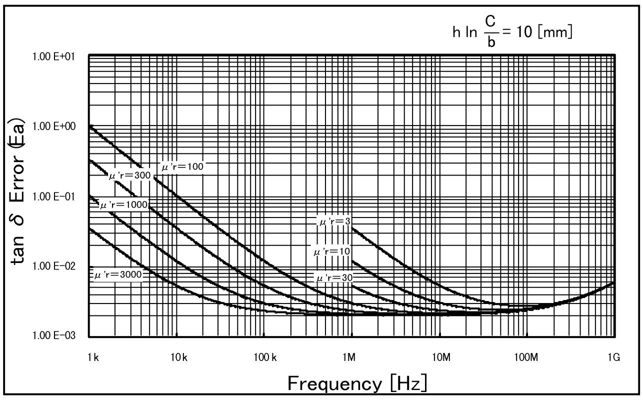


Fig.31 Loss Tangent Measurement Accuracy (Supplemental Data)

3.4.5. Operation Method

Fig.32 displays the flowchart when using the 16454A for permeability measurements. Below are the descriptions of each step in the flowchart.

Step 1. Calibrate the measurement instrument: When using the 4291B, calibrate at the 7mm terminal. When using the 4294A, perform SETUP on the 7mm terminal of the 42942A.

Step 2. Connect the 16454A: Connect the 16454A to the instrument's 7mm terminal. When using the 4291B, select 16454A as the fixture on the MEAS menu.

Step 3. Compensate the residual impedance of the 16454A: Insert only the MUT holder and perform SHORT compensation.

Step 4. Input size of MUT: Enter the size of the MUT into the measurement instrument's menu. Use a micrometer to measure the size.

Step 5. Insert MUT: Insert the MUT with the holder into the 16454A.

Step 6. Set the measurement conditions: Measurement conditions such as frequency, test signal level, measurement parameter are set on the measurement instrument.

Step 7. Measure the MUT: The measurement result will appear on the display of 4291B. The data can be analyzed using the marker functions.

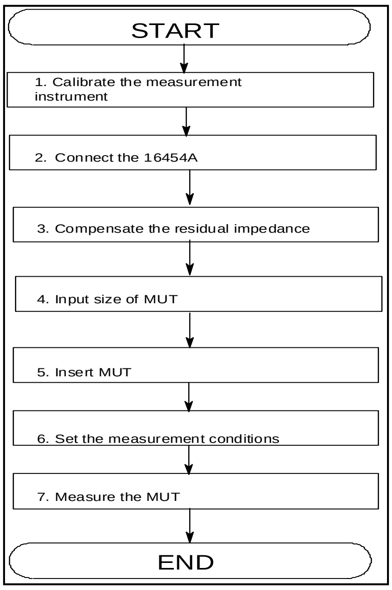


Fig.32 Measurement Procedure Flowchart for the 16454A

When using the 4294A with the 16454A, a sample IBASIC program, which follows the steps described above, is available. The sample program is furnished with the operation manual of 4294A. On the other hand, when using the 4291B (Option 002), the internal firmware comes furnished with a material measurement function. For more details, refer to the operation manual of 4291B.

3.4.6. Cautioning Factors

When measuring a magnetic material with a high permittivity (about 10 and above), precise measurements cannot be performed near 1GHz. Permeability is derived from the inductance value of the combined impedance of the MUT and the fixture. Under the circumstances of the measurement theory, the impedance must be composed purely of inductance only. When the magnetic material's permittivity is high, current flows through the space between the MUT and the fixture. This is equivalent to a capacitor connected in parallel to the inductor and resistor (of the MUT). This parallel LCR circuit causes a impedance-resonance at a destined frequency. The higher the permittivity is the lower the resonant frequency will be and consequently precise measurements will be impossible.

3.4.7. Sample Measurements

Measurement results of frequency and temperature characteristics of the MnZn ferrite core are shown down below in Fig.33 and 34. The 4291B and the 16454A were used to obtain these results.

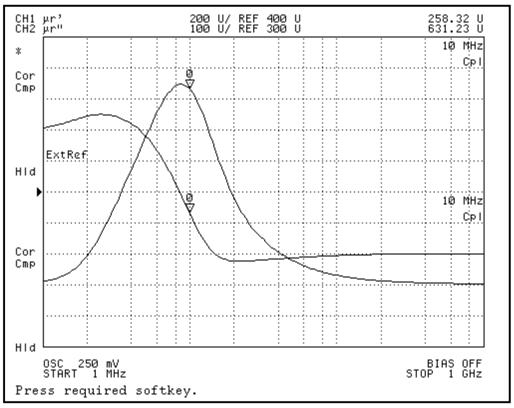


Fig.33 Frequency Response of MnZn Ferrite Core

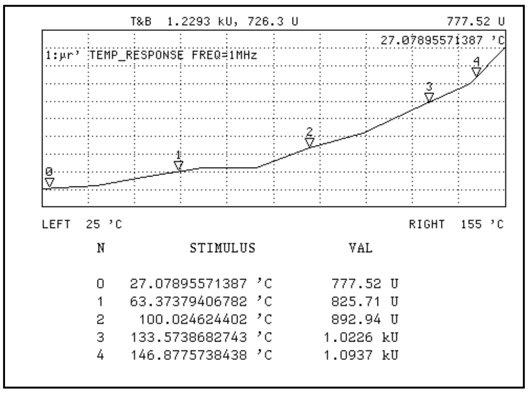


Fig.34 Temperature Response of MnZn Ferrite Core

The low frequency response of MnZn ferrite core was measured using the 4294A and the 16454A (Fig.35).

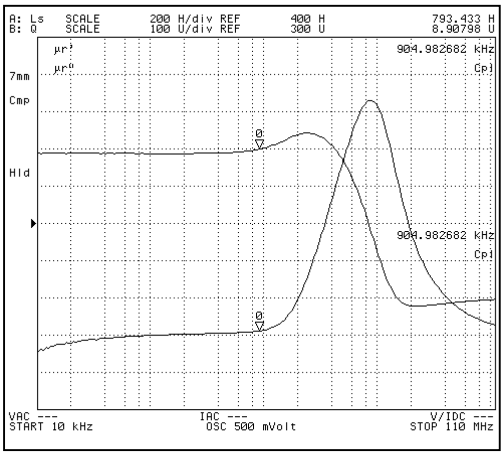


Fig.35 Frequency Response of MnZn Ferrite Core

4. Conclusion

In this application note, permittivity and permeability measurement methods that employ the impedance measurement technology was discussed.

The discussion has covered on the test fixture's structure, applicable MUT sizes, operation methods and cautioning factors. By utilizing this application note as a reference, a solution to meet measurement needs and conditions can be selected.

Appendix

A. Resistivity Evaluation

A.1. Method of Measuring Resistivity

Surface and volume resistivity are evaluation parameters for insulating materials. Frequently, resistivity is derived from resistance measurements following a 1-minute charge and discharge of a test voltage. An equation is used to calculate the resistivity from the measured result. The difference in measuring surface resistivity and volume resistivity will be explained using Fig. 36 and 37.

In Fig.36, the voltage is applied to the upper electrode and the current, which flows through the material and to the main electrode, is detected (Ring electrode acts as the guard electrode). The measured result yields volume resistance. Volume resistivity is calculated from volume resistance, effective area of the main electrode, and the thickness of the insulating material.

In Fig.37, the voltage is applied to the ring electrode and the current, which flows along the surface of the material and to the main electrode, is detected (Upper electrode acts as the guard electrode). The measured result yields surface resistance. Surface resistivity is calculated from surface resistance, effective perimeter of the main and ring electrodes and the gap between the main and the ring electrodes.

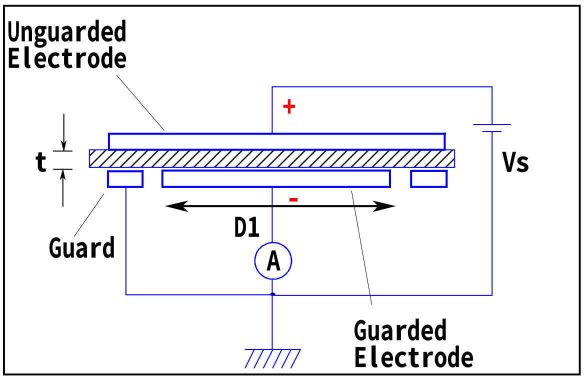


Fig.36 Volume Resistivity

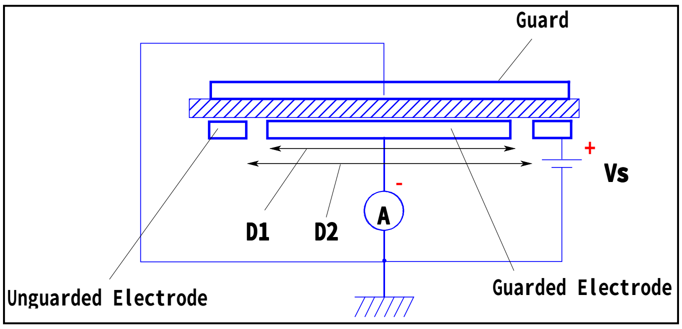


Fig.37 Surface Resistivity

The following are the equations for calculating surface and volume resistivity.

Volume Resistivity

$$\rho_v = \frac{\pi \times \left(D_1 + \frac{B(D_2 - D_1)}{2}\right)^2}{4t} \times R_v$$

Surface Resistivity

$$\rho_s = \frac{\pi(D_1 + D_2)}{D_2 - D_1} Rs$$

D1 ：Diameter of main electrode (mm)

D2 ：Diameter of ring electrode (m)

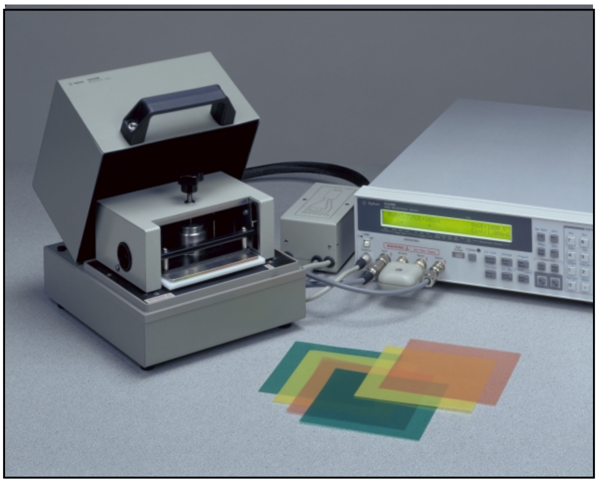
t ：Thickness of insulating material (m)

Rv ：Volume resistance

Rs ：Surface resistance

B ：Effective area constant (equal to 1 for ASTM D257 and 0 for JIS K6911).

A.2. Resistivity Measurement System Using the 4339B and the 16008B



The 4339B High Resistance Meter and the 16008B Resistivity Cell will be introduced as a resistivity measurement system and discussed from here.

A.2.1. Main Advantages

- Automatic calculation of resistivity by entering electrode size and thickness of insulating material.
- Three kinds of electrodes (diameter: 26mm/50mm/76mm), provided for the 16008B, can satisfy various insulation measurement standards such as ASTM D-257.
- Triaxial input terminal configuration minimizes the influences due to external noise and as a result, high resistance up to 1.6 x $10^{16}\Omega$ can be measured accurately.

- Automating charge/measure/discharge is possible using the test sequence program.
- OPEN compensation function minimizes the influences due to leakage current.

A.2.2. Applicable MUT

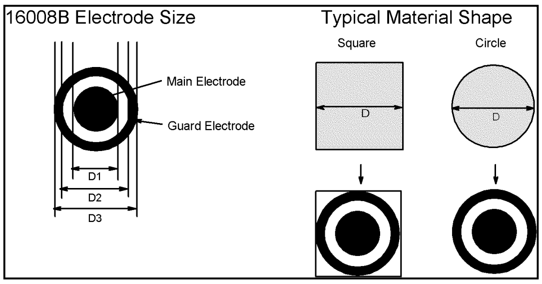


Fig.38 Applicable MUT sizes

The applicable insulating material is a solid sheet that has a thickness between 10µm and 10mm. Three types of electrodes are provided with the 16008B, so that various sizes of insulating materials can be accommodated. Further details are shown in Table 10. It is important to select electrodes so that the diameter of the guard electrode fits within the insulating material's diameter.

A.2.3. Structure

The 16008B Resistivity Cell has a triaxial input configuration to minimize the influence of external noise; a cover for high-voltage safety; an electrode to make stable contacts; and a switch to toggle between surface and volume resistivity configurations. The contact pressure applied onto the MUT can be set appropriately to match the characteristics of the insulating material (Maximum applied contact pressure is 10kgf).

Table 10. Applicable MUT Sizes

D1	D2	D3	Ordering Information	D
Main Electrode	**Guard Electrode (Inner Diameter)**	**Guard Electrode (Outer Diameter)**	——	**Insulating Material Size**
26mm	38mm	48mm	Supplied with Opt.001 or 002	50mm* to 125mm
50mm	70mm	80mm	Standard - equipped	82mm* to 125mm
76mm	88mm	98mm	Supplied with Opt.001 or 003	100mm*to125mm

*Outer Diameter of Guard Electrode + 2 mm

A.2.4. Principal Specifications

Table 11 and 12 exhibit the principal specifications of the resistivity measurement system using the 4339B and the 16008B.

Table 11. Principal Specifications of the 4339B+16008B Measurement System

Frequency	DC
Max. Voltage	1000V
Max. Current	10mA
Operating Temperature	-30 to +100 degrees C (excluding connectors)
Terminal Configuration	Triaxial Input (special screw type)、High Voltage BNC (special type)
Cable Length	1.2m
Compensation	OPEN

Table 12. Resistivity Measurement Range (Supplemental Data)

	Measurement Range
Volume Resistivity	4.0x10^18Ωcm (max.)
Surface Resistivity	4.0x10^17Ω (max.)

A.2.5. Operation Method

Fig.39 displays the flowchart when using the 4339B and the 16008B for resistivity measurements. Below are the descriptions of each step in the flowchart. For further detail, please refer to the User's Guide of 4339B.

Step 1. Select the electrodes: Select the main electrode and guard electrode according to the diameter of the MUT. Open the cover of 16008B and set the main and guard electrodes.

Step 2. Connect the 16008B: Connect the 16008B to the UNKNOWN terminals of 4339B.

Step 3. Select the measurement parameter (Rv/Rs): The measurement mode can be switched between volume and surface resistivity by toggling the selector switch on the 16008B.

Step 4. Input source voltage: Input the value of the source voltage, which will be applied to the MUT, into the 4339B.

Step 5. Calibrate the 4339B: Perform the calibration of 4339B.

Step 6. Perform OPEN compensation: Apply the source voltage and perform OPEN compensation. After compensation, turn the source voltage to OFF.

Step 7. Insert MUT: Insert the MUT between the electrodes of 16008B.

Step 8. Input parameters and electrode's size: Input the measurement parameters, MUT thickness, and electrode's size into the 4339B.

Step 9. Configure the test sequence program: Select the parameter, charge time, and measurement sequence mode.

Step 10. Measure the MUT: Measurement will begin once, the prescribed charge time is over.

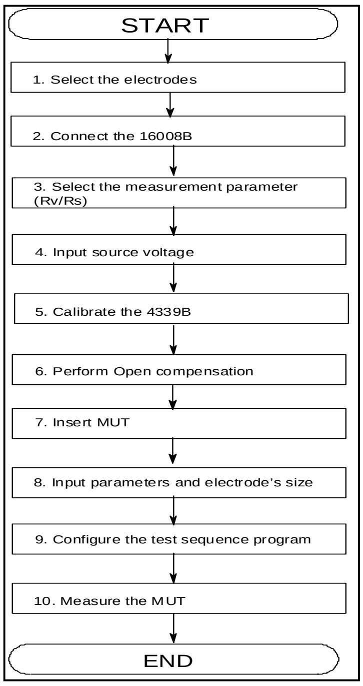


Fig.39 Measurement Procedure Flowchart for the 4339B and the 16008B

A.2.6. Cautioning Factors

Measurements of insulating materials are known to be very sensitive to noise and have a tendency to be extremely unstable. In this measurement system, the measurement instrument and test fixture has been designed to minimize the effects of external noise. However, there are a number of factors that should be cautioned when conducting precise measurements:

- Do not allow vibration to reach the 16008B.
- Do not perform any measurements near a noise emitting equipment
- Electrodes should be kept clean

A.2.7. Sample Measurements

Results of surface and volume resistivity measurements of polyimide are shown in Fig.40.

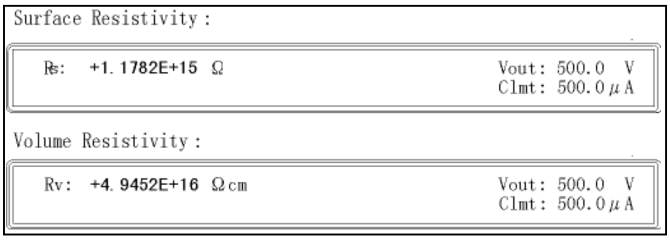


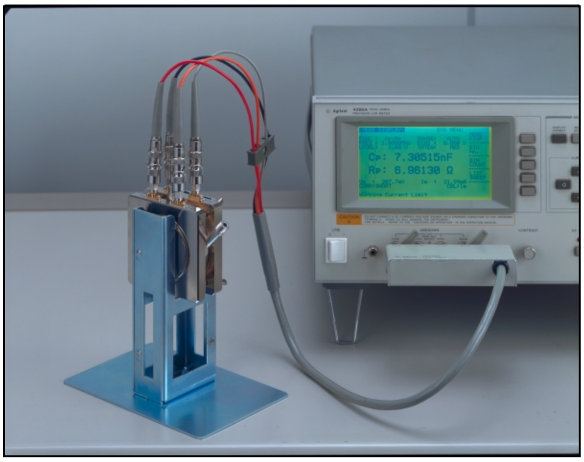
Fig.40 Surface and Volume Resistivity of Polyimide

B. Permittivity Evaluation of Liquids

Permittivity measurements are often used for evaluation of liquids' characteristics. Permittivity measurements do not change the liquid physically and can be conducted rather simply and quickly in a short period of time. As a result, it is utilized in a wide array of research areas. Here the 16452A Liquid Test Fixture, which employs the parallel plate method, will be introduced as a permittivity measurement system for liquids.

B.1. Measurement System Using the 16452A Liquid Test Fixture

Applicable Instruments



4194A, 4284A, 4285A , 4294

B.1.1. Main Advantages

- Wide frequency range from 20Hz to 30MHz
- Plastic resins, Oil-based chemical products etc. can be measured
- Measurement is possible with a small test liquid volume, and thus MUT does not go to waste.
- Temperature characteristics measurements are possible from -20 to +125 degrees C
- Compatibility with 4-terminal pair impedance measuring instrument.

B.1.2. Applicable MUT

The sample liquid capacity is dependent upon the spacer that is used. The spacer adjusts the gap between the electrodes and hence the air capacitance is altered as well. Table 13 lists the available spacers and the corresponding sample liquid capacities.

Table 13. Relationship between Spacers and Liquid Capacity

Sample Liquid Capacity	3.4ml	3.8ml	4.8ml	6.8ml
Air Capacitance (no liquid present)	34.9pF +/-25%	21.2pF +/-15%	10.9pF +/-10%	5.5pF +/-10%
Spacer thickness	1.3mm	1.5mm	2mm	3mm

B.1.3. Structure

The structure of 16452A is shown in Fig.41. Three liquid inlets simplify pouring and draining and the fixture can be easily disassembled so that the electrodes can be washed. Nickel is used for the electrodes, spacers, liquid inlet and outlet and fluoro-rubber is used for the O-rings.

A 1m cable is required for connection to the measurement instrument. Appropriate cables are listed in Table 14.

Table 14. 1m Cables for 16452A

Temperature	P/N
0 to 55 degrees C	16048A
-20 to 125 degrees	16452-61601
-20 to 150 degrees	16048G (4294A only)

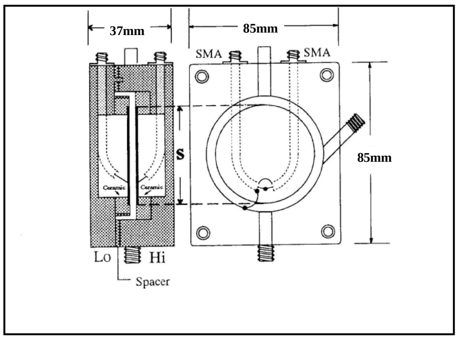


Fig.41 Structure of 16452A

B.1.4. Principal Specifications

Table 15. Principal Specifications of 16452A

Frequency	20Hz to 30MHz
Max. Voltage	42V
Operating Temperature	-20℃～+125℃
Terminal Configuration	4-terminal pair, SMA
Compensation	SHORT

The principal specifications of 16452A are shown in Table 15 and the measurement error is calculated using the following equation.

Measurement Accuracy = A + B + C [%]

Error A：See Table 16

Error B： when $\varepsilon r=1$ See Fig.42

Error C：Error of Measurement Instrument

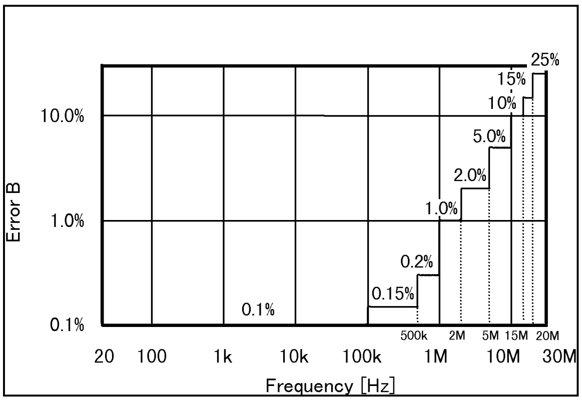


Fig.42 Relative Measurement Accuracy (Supplemental Data)

Table 16. Error A

Spacer Thickness(mm)	B (%)
1.3	0.005 x MRP
1.5	0.006 x MRP
2.0	0.008 x MRP
3.0	0.020 x MRP

M.R.P is Measurement Relative Permittivity

B.1.5. Operation Method

Fig.43 displays the flowchart when using the 16452A for permittivity measurements of liquids. Below are the descriptions of each step in the flowchart.

Step 1. Assemble 16452A and insert the short plate: While attaching the high and low electrodes, insert the short plate in between them. Next, prepare the 16452A for measurement by connecting the SMA-BNC adapters to the terminals of the fixture and putting the lid on the liquid outlet.

Step 2. Connect the 16452A to the measurement instrument: Select the appropriate 1m cable depending on the operating temperature and the measurement instrument. Connect the 16452A to the UNKNOWN terminals of the measurement instrument.

Step 3. Compensate the cable length: Set the measurement instrument's cable length compensation function to 1m. Refer to the measurement instrument's operation manual for the setting procedure.

Step 4. Check the SHORT residual of the 16452A: To verify whether the 16452A was assembled properly, measure the SHORT plate at 1MHz and check if the value falls into the prescribed range. Perform this verification before short compensation. For further details, refer to the operation manual of 16452A.

Step 5. Set the measurement conditions: Measurement conditions such as frequency and test voltage level are set on the measurement instrument. The measurement parameter should be set to Cp-Rp. Refer to the measurement instrument's operation manual for the setting procedure.

Step 6. Perform SHORT compensation: Perform SHORT compensation with the SHORT plate inserted between the electrodes.

Step 7. Measure the air capacitance: Remove the short plate, and insert the appropriate spacer that is required for the sample liquid volume. The air capacitance that exists between the electrodes is measured with the parameter Cp-Rp.

Step 8. Pour liquid in: Pour the liquid into the inlet of the fixture.

Step 9. Measure liquid: Perform a Cp-Rp measurement with the liquid in the fixture.

Step 10. Calculate permittivity: Permittivity and loss factor is calculated using the following equations:

$$\varepsilon r = \frac{Cp}{Co} - \left(\frac{1}{2\pi f} \times Co \times Rp\right)$$

Cp: Equivalent parallel capacitance of MUT [F]

Co: Equivalent parallel capacitance of air [F]

Rp: Equivalent parallel resistance of MUT [Ohm]

f: Frequency [Hz]

Step 11. Drain liquid out: Drain the liquid out from the outlet of the fixture.

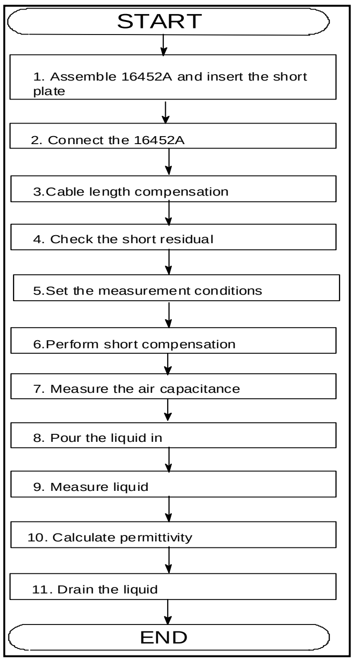


Fig.43 Measurement Procedure Flowchart for the 16452A

B.1.6. Cautioning Factors

There is a high possibility that liquids with bulk conductivity such as salt (Na+ Cl-) or ionic solutions cannot be measured. This is due to the electrode polarization phenomenon, which causes incorrect capacitance measurements to occur for such liquids.