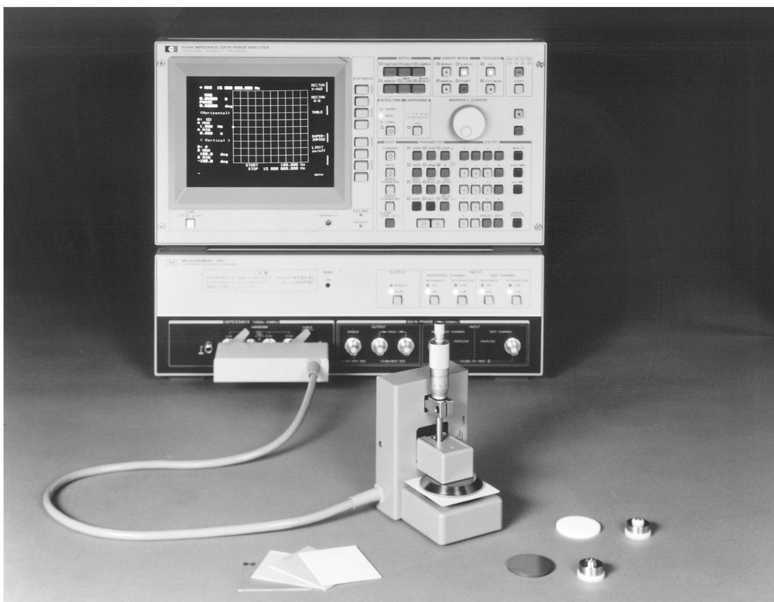
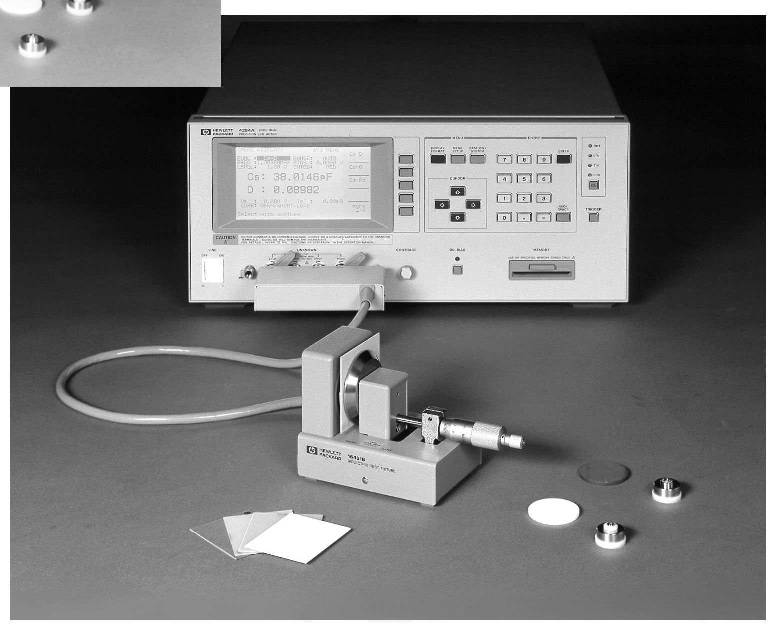
HEWLETT PACKARD
Expanding Possibilities

Dielectric Constant Measurement of Solid Materials

Application Note 380-1

Using HP 16451B Dielectric test fixture





Introduction

To improve the quality of the dielectric solid materials such as polymer, electric insulator, PC board, ceramic substrate etc., it is very important to evaluate their electrical and physical characteristics, such as molecular structure and density. The dielectric constant measurement is a very popular evaluation method. Using the HP 16451B Dielectric Test Fixture with an HP LCR meter/Impedance Analyzer, accurate and easy dielectric constant and dissipation factor (tan (δ))[1] measurements are possible. This application note explains the features and benefits of the HP 16451B and measurement methods, and shows an example of measuring a plate type dielectric materials.

Dielectric Constant Measurement Problems

The dielectric constant is calculated from the C-D (Capacitance and Dissipation factor) measurement results using an HP LCR meter/Impedance analyzer. However, there were many problems in the realization of precise C-D measurement and easy connections between the measurement instrument and the test fixture. Thus dielectric constant measurement was difficult.

HP 16451B Main Features and Benefits

(1) The HP 16451B can be connected directly to 4-Terminal Pair measurement instruments.

The 4-Terminal Pair measurement method adopted in recent impedance measurement instruments offers accurate measurement over a wide measurement range. However, there was no test fixture for solid materials which could be connected directly to 4-Terminal Pair measurement instruments. The HP 16451B can be connected directly to these instruments to obtain accurate measurements.

(2) Additional Measurement Errors can be Corrected.

Stray admittance and residual impedance of the test fixture are the error sources in a dielectric constant measurement. The HP 16451B can eliminate these additional error factors with the OPEN/SHORT error correction function of the measurement instrument by using the furnished OPEN/SHORT attachment. Edge capacitance is another error source (Figure 1). The HP 16451B can also eliminate the edge capacitance error by using a guarded electrode (3-Terminal method).

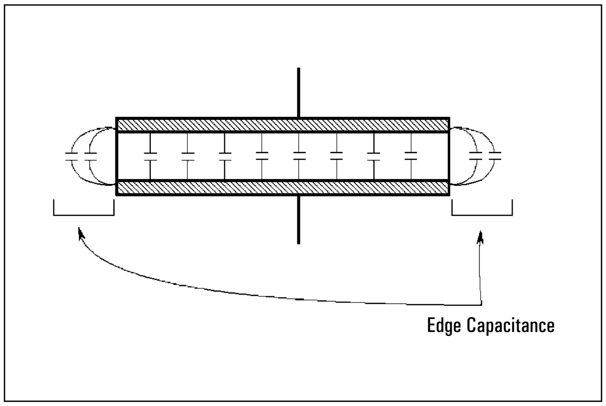


Figure 1. Additional Error Due to Edge Capacitance

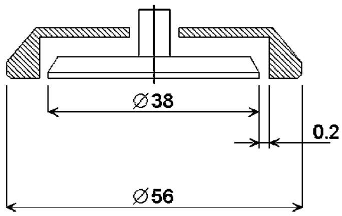
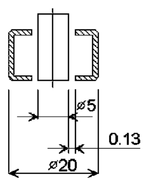
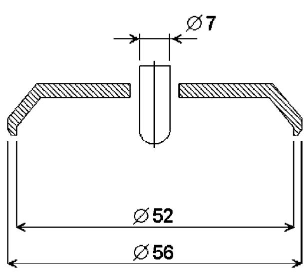
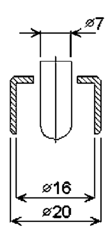
(3) Interchangeable Electrodes

If a test fixture has only one type of electrode, it is necessary to adjust the size of the Material Under Test (MUT) or to form thin film electrodes on the surface of the MUT.

Four types of electrodes are furnished with the HP 16451B so that the best electrode for the MUT can be selected. This eliminates the extra work and makes it possible to evaluate the MUT while meeting ASTM[2] size requirements.

A description for each of the furnished electrodes and their applicable measurement methods are given in Table 1.

Table 1. Electrode Selection Guide

Type of Electrode	**Electrode Dimensions**	**MUT Dimensions**	
Electrode-A (38 mm Guarded/ Guard Electrode)		Diameter: 40 mm ～ 56mm Applicable measurement method: Contacting Electrode method (Rigid Metal Electrode) Non-contacting Electrode method (Air Gap Method)	Thickness: ≤ 10 mm
Electrode-B (5 mm Guarded/ Guard Electrode)		Diameter: 10 mm ～ 56mm Applicable measurement method: Contacting Electrode method (Rigid Metal Electrode) Non-contacting Electrode method (Air Gap Method)	Thickness: ≤ 10 mm
Electrode-C (Guarded/Guard Electrode for Large Thin Film Electrodes)		Diameter: 56mm Diameter of guarded thin film electrodes: 5 mm ～ 50mm Inside diameter of guard thin film electrodes: ≤ 52 mm (greater than a diameter of guarded thin film electrode) Applicable measurement method: Contacting Electrode method (Thin Film Electrode)	Thickness: ≤ 10 mm (including the thickness of thin film electrodes)
Electrode-D (Guarded/Guard Electrode for Small Thin Film Electrodes)		Diameter: 20 mm ～ 56mm Diameter of guarded thin film electrodes: 5 mm ～ 14 mm Inside diameter of guard thin film electrodes: ≤ 16 mm (greater than a diameter of guarded thin film electrode) Applicagle measurement method: Contacting Electrode method (Thin Film Electrode)	Thickness: ≤ 10 mm (including the thickness of thin film electrodes)

Applicable Measurement Methods

The HP 16451B offers three measurement methods. Each feature of these measurement methods is described below.

(1) Contacting Electrode Method (Rigid Metal Electrode)

This method derives the dielectric constant using the C-D measurement results (electrodes contacted directly to the MUT). This method requires only one measurement to derive the dielectric constant and does not need to use thin films applied to the surface of the MUT. However, the surface must be flat and have low compressibility to prevent an air gap between the MUT and the electrodes which will cause measurement error. Electrode-A or Electrode-B must be used. (Figure 2)

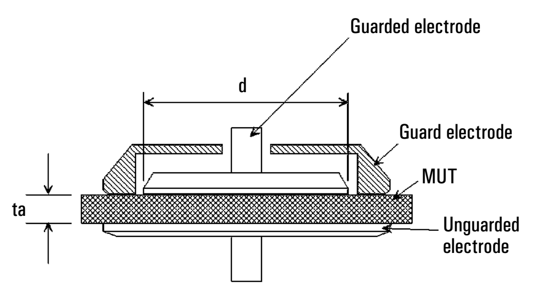


Figure 2. Contacting Electrode Method (Rigid Metal Electrode)

(2) Contacting Electrode Method (Thin Film Electrode)

This method derives the dielectric constant from the C-D measurement results (electrodes contact a thin film applied to the surface of the MUT). This measurement method also required only one measurement to derive the dielectric constant. The thin film electrode must be applied before the measurement, but this method can be used for MUTs whose surface is not flat or have low compressibility.

The measurement error caused due to the air gap between the MUT and the electrodes can be minimized. Electrode-C or Electrode-D must be used. (Figure 3).

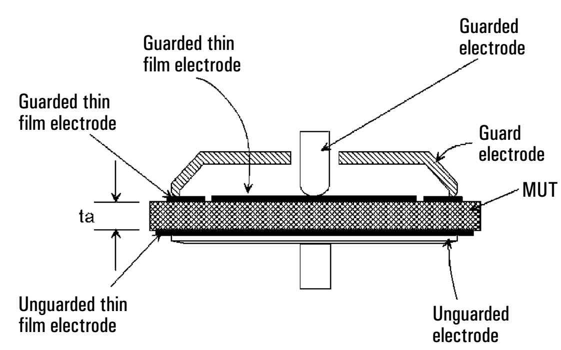


Figure 3. Contacting Electrode Method (Thin Film Electrode)

The following equation is used to derive the dielectric constant[3] and dissipation factor is applicable to the above methods.

Parameters Needed:

C_p	:	Equivalent parallel capacitance of MUT [F]
D	:	Dissipation factor of MUT (measured value)
t_a	:	Average thickness of MUT [m]
A	:	Area of Guarded electrode [m^2]
d	:	Diameter of Guarded electrode [m]
ϵ_o	:	Dielectric constant of free space = 8.854 x 10^{-12} [F/m]

Equations:

$$\epsilon_r = \frac{t_a \times C_p}{A \times \epsilon_o} = \frac{t_a \times C_p}{\pi \times \left(\frac{d}{2}\right)^2 \times \epsilon_o}$$

$$D_t = D$$

Where,

ϵ_r	:	Dielectric constant of MUT
D_t	:	Dissipation factor of MUT

(3) Non-contacting Electrode Method (Air Gap Method) (This method is not applicable to the MUT with thin film electrodes).

This method is used to derive the dielectric constant by using the results of two C-D measurements obtained with the MUT inserted between the electrodes without it inserted between the electrodes. This method requires two measurements. However, accurate C-D measurements and dielectric constant calculation are possible, because the air gap and the compressibility of the MUT do not after the measurement result. Electrode-A or Electrode-B must be used. (Figure 4).

The following equation is used to derive the dielectric constant and dissipation factor applicable to this method.

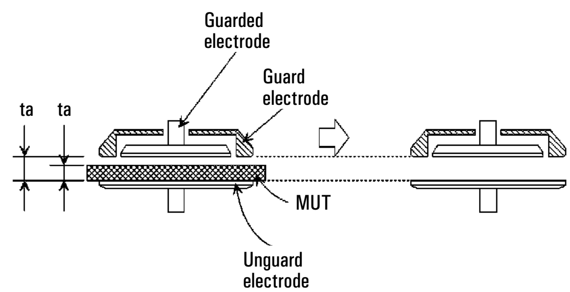


Figure 4. Non-contacting Electrode Method (Air Gap Method)

Esquations:

$$\epsilon_r = \frac{1}{1 - \left(1 - \frac{C_{s1}}{C_{s2}}\right) \times \frac{t_g}{t_a}}$$

$$D_t = D_2 + \epsilon_r \times (D_2 - D_1) \times \left(\frac{t_g}{t_a} - 1\right)$$

Where, $D_t^2 \ll 1$

ϵ_r : Dielectric constant of MUT

D_t : Dissipation factor of MUT

Parameters Needed:

C_{s1} : Capacitance wothout MUT inserted [F]

D_1 : Dissipation factor wothout MUT inserted

t_g : Gap between Guarded/Guard electrode and Unguarded electrode [m]

C_{s2} : Capacitance with MUT inserted [F]

D_2 : Dissipation factor with MUT inserted

t_a : Average thickness of MUT [m]

Typical Measurement Example Using the HP 16451B with the HP 4194A

The electrical and physical characteristics of materials are subject to change dependent on the measurement conditions and a materials frequency dependent characteristics is popularly used for material characterization. Frequency is one of the popularly used factors to determine the characteristics. So, it is very important to evaluate the dielectric constant and dissipation factor of the materials at the actual operating frequency.

Here is an example of evaluating the frequency characteristics of the dielectric constant of a glass-epoxy laminate, one of the materials used for Printed Circuit Boards (PCB), using the HP 16451B and the HP 4194A Impedance/Gain-phase Analyzer. In this example. the dielectric constant and dissipation factor (Figure 6) and the complex dielectric constant4 (Figure 7) are automatically calculated from the C-D measurement results and displayed. This C-D measurement is made using the Non-contacting method, and sweeping the frequency from 1kHz to 15MHz with the HP 4194A's internal programming function, ASP (Auto Sequence Program). The ASP program listing used for this evaluation is shown in Figure 5.

```
10 !DIELECTRIC CONSTANT MEASUREMENT
20 !          USING HP 16451B
30 ! *********************************
40 R0=8.854E-12    ! E0
50 R1=5E-3 ! GAP BETWEEN ELECTRODES   (DEFAULT)
60 R2=1E-3 ! AVERAGE THICKNESS OF DUT (DEFAULT)
70 ! *********************************
80 RST
90 CMT""
100 IMP14;SWT2;START=1K;STOP=15M
110 NOP=101;ITM2;NOA=2;CMPN2;Z=0
120 DISP "COMPEN? Y=1 / N=CONT"
130 BEEP
140 PAUSE
150 IF Z=1 THEN GOSUB 580
160 OPN1;SHT1
170 DISP "TA(m)? DFT",R2 ! THICKNESS OF DUT
180 BEEP
190 PAUSE
200 IF Z=0 THEN GOTO 230
210 R2=Z
220 Z=0
230 CMT" SET GAP TO TG! "
240 DISP "TG(m)? DFT",R1 ! GAP BETWEEN ELECTRODES
250 BEEP
260 PAUSE
270 CMT""
280 IF Z=0 THEN GOTO 310
290 R1=Z
300 Z=0
310 ! *********************************
320 SWTRG
330 RA=A;RB=B;AUTO
340 DISP "PUT DUT!"
350 BEEP
360 PAUSE
370 SWTRG
380 ! *********************************
390 CMT"DIELECTRIC CONSTANT"
400 RC=A;RD=B
410 RE=1/(1-((1-RA/RC)*R1/R2))
420 RF=RD+RE*(RD-RB)*(R1/R2-1)
430 UNIT0;MKR=1M;A=RE;B=RF;AUTO
440 DISP "A=D.CONST. / B=TAN.DELTA"
450 BEEP
460 PAUSE
470 ! *********************************
480 CMT"COMPLEX DIELECTRIC CONSTANT"
490 A=RE*COS(ATAN(RF));B=RE*SIN(ATAN(RF))
500 AUTO;DISP "A=REAL / B=IMAGINALY"
510 BEEP
520 PAUSE
530 ! *********************************
540 CMT"COLE-COLE PLOT"
550 DSP2;AUTO
560 BEEP
570 END
580 ! *********************************
590 ! OPEN/SHORT COMPENSATION
600 ITM2
610 BEEP
620 DISP "OPEN COMPEN (AT 16451B)"
630 PAUSE
640 ZOPEN
650 BEEP
660 DISP "SHORT COMPEN (AT 16451B)"
670 PAUSE
680 ZSHRT
690 OPN1;SHT1;ITM2
700 Z=0
710 RETURN
```

Set measurement conditions. (Line 100 - 110)

Enter the thickness of the MUT. (Line 170 - 190)

Set the gap between the electrodes and enter its reading on the micrometer. (Line 230 - 260)

Measure before inserting the MUT. (Line 320 - 330)

Measure after inserting the MUT. (Line 340 - 370)

Calculate and display a dielectric constant, dissipation factor and complex dielectric constant. (Line 390 - 520)

Display Cole-Cole plot. (Line 540 - 570) (The result is not shown in this application note.)

Perform Open/Short correction with Open/Short attachment. (Line 590 - 710)

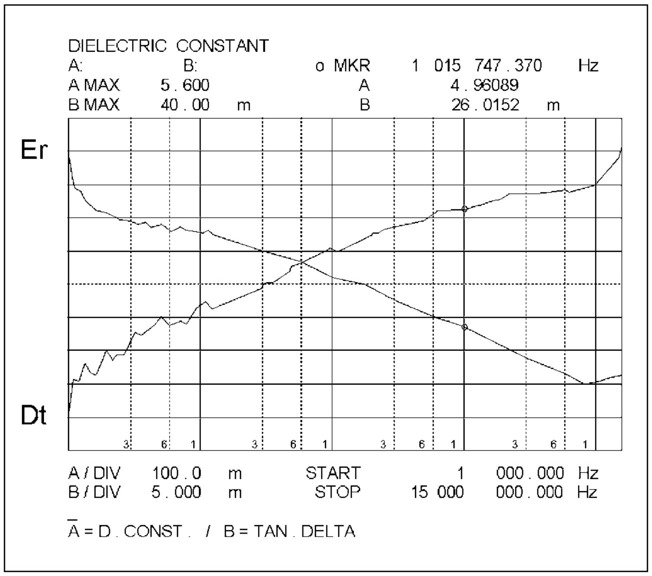


Figure 6. Dielectric Constant and Dissipation Factor of Glass-Epoxy Laminate

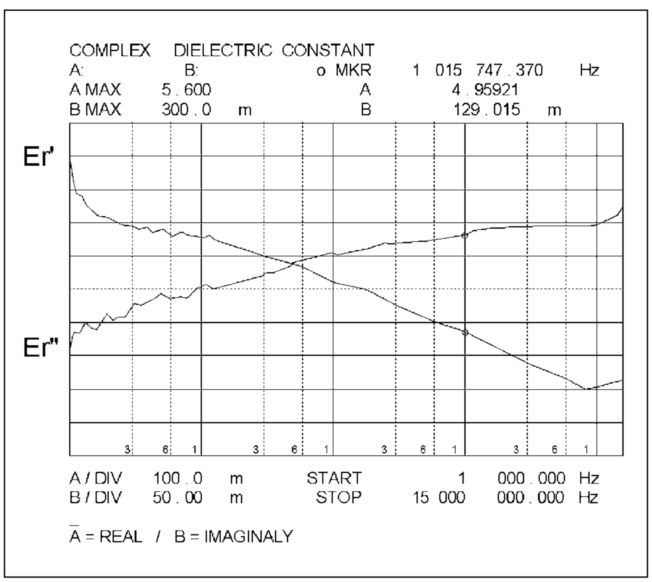


Figure 7. Complex Dielectric Constant of Glass-Epoxy Laminate

Conclusion

The HP 16451B is the best test fixture to use with an HP LCR meter/Impedance analyzer to simply and accurately evaluate the dielectric constant characteristics of solid materials.

Applicable measurement instruments:

HP 4192A, HP 4194A, HP 4274A, HP 4278A, HP 4284A

[1] Dissipation factor = Dt = $\tan(\delta)$ = Er"/Er'

[2] ASTM - American Society for Testing and Materials

[3] In this application note, it means the *Relative Dielectric Constant* (Er).

[4] The dielectric constant modeled in the complex form as follows considering the "Dielectric after effect" phenomenon

Er* = Er' - jEr"

Er' = Er*cos (δ) = Er*cos [$\tan^{-1}$ (Dt)]

Er" = Er*sin (δ) = Er*sin [$\tan^{-1}$ (Dt)]

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