Correspondence

Measurement of the Permittivity of Insulating Films at Microwave Frequencies

Advances in the state of the art of both integrated circuit technology and solid-state devices have led to the integration of microwave circuits. Dielectric films may be used in a variety of applications for the integrated circuits, and a knowledge of the properties of the films at microwave frequencies is essential for circuit design and material evaluation. The transmission method [1] and the standard cavity perturbation technique [2] are difficult to use when measuring dielectric films. The film is usually grown or deposited on a substrate that may introduce a frequency or phase shift which masks the effect due to the film. This difficulty may be overcome by first introducing the substrate without any film and then repeating the measurement with a film on the substrate. The second difficulty consists in accurately measuring the very small frequency or phase shift which most films produce.

The method discussed in this paper overcomes both of these problems. The first is eliminated by using the cavity end plate or center post as a substrate. The second is reduced by using the average of a large number of frequency readings which tends to cancel randomly distributed errors.

A curve of the resonant frequency of a cylindrical re-entrant cavity shown schematically in Fig. 1(a) is determined as a function of gap spacing by moving the center post. Either the center post or the end plate of the cavity is removed, and the dielectric film is grown or deposited on the removed part. The part is replaced and a new curve of resonant frequency as a function of gap space is determined. The permittivity of the film can be determined from the average displacement of the curves. The Q of the film can be determined from the change in Q of the cavity when the film is present.

When the height h of the cavity is much less than the cavity outer diameter r_0, an E mode rather than a coaxial mode will be excited. Both the section of the cavity beneath the center post and the section of the cavity outside the post area may be treated as radial transmission lines. It may be shown that in the lowest-order mode of the narrow gap cavity, the shorted transmission line outside the post presents an inductance that resonates the total gap capacitance. For a small-diameter post, this capacitance is approximately

$$\frac{B(r_1)}{\omega} \approx \frac{\epsilon_1 \pi r_1^2}{d_1} + 4\epsilon_2 r_1 \ln \frac{eh}{4d_1} = C_{g1} + C_{D1} \qquad (1)$$

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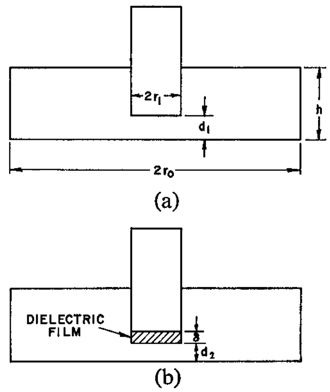

Fig. 1. Cylindrical re-entrant cavity. (a) Unperturbed cavity. (b) Cavity perturbed with dielectric film.

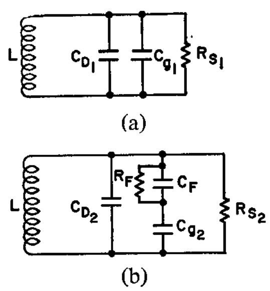

Fig. 2. Analysis of cavity. (a) Equivalent lumped circuit of unperturbed cavity. (b) Equivalent lumped circuit of cavity perturbed with film with losses.

where ϵ_1 and ϵ_2 are the permittivities of the sections under and exterior to the plunger, and C_{g1} and C_{D1} represent the first and second terms of the RHS of (1). The lumped-element equivalent of the unperturbed cavity is shown in Fig. 2(a).

The perturbed cavity is shown schematically in Fig. 1(b) and in an equivalent circuit form in Fig. 2(b). The capacitances are given by

$$C_{g2} = \frac{\pi \epsilon_0 r_1^2}{d_2}$$
$$C_F = \frac{\pi \epsilon_0 K_F r_1^2}{\delta} \qquad (2)$$
$$C_{D2} \cong 4\epsilon_0 r_1 \ln \frac{eh}{4d_2}$$

where K_F is the relative dielectric constant of the film.

The perturbed and unperturbed cavities will resonate at the same frequencies when the total capacitances for both cases are identical. Thus,

$$C_{D1} + C_{g1} = C_{D2} + \frac{C_{g2} C_F}{C_F + C_{g2}}. \qquad (3)$$

The resonance of each case is varied by adjusting the gaps d_1 and d_2, respectively. When (1) and (2) are substituted into (3), the unknown dielectric constant can be found in terms of the difference in gap spacings to achieve the same resonance frequency:

$$K_F = \frac{\delta}{d_1 - d_2} \cdot \frac{1 - \frac{4d_1}{\pi r_1} \ln \frac{d_1}{d_2}}{1 + \frac{4d_1}{\pi r_1} \frac{d_2}{d_1 - d_2} \ln \frac{d_1}{d_2}}. \qquad (4)$$

An average K_F may be found by using an ensemble of d_1 and d_2 values. This tends to cancel random measurement errors. For films that are relatively thin and for $d_1 \ll r_1$, (4) reduces to

$$d_1 - d_2 \approx \delta / K_F. \qquad (5)$$

Thus the curves of resonant frequency as a function of gap spacing for the perturbed and unperturbed cases will be nearly parallel. The permittivity can be computed from the average displacement of the curves.

The imaginary component of the permittivity can be determined from the perturbation of the cavity Q when the film is present. In Fig. 2 R_s represents the cavity losses and is determined from a measurement of the unperturbed cavity:

$$R_{s1} = \frac{Q_{01}}{\omega_1 (C_{D1} + C_{g1})} \qquad (6)$$

where Q_{01} is the unloaded Q of the unperturbed cavity, and ω_1 is the resonant frequency.

The resistance R_F of Fig. 2(b) represents all loss mechanisms present in the insulating film at the measurement frequency. The unloaded Q for the perturbed cavity is

$$Q_{02} = \omega_2 \frac{C_{D2} + \frac{C_F C_{g2}}{C_F + C_{g2}}}{\frac{1}{R} + \frac{1}{R_{s2}}} \qquad (7)$$

where

$$R = R_F \left(\frac{C_F + C_{g2}}{C_{g2}} \right)^2.$$

The R_s values of (6) and (7) are very nearly the same if $\omega_1 \approx \omega_2$. An effective Q for the film may be determined by combining (6) and (7) and inserting the expressions given earlier for the capacitances. Thus,

$$Q_F = \frac{K_F}{\delta} \left(\frac{\delta}{\delta + K_F d_2} \right)^2 \cdot \frac{1}{\frac{1}{Q_{02}} \left[\frac{4}{\pi r_1} \ln \frac{eh}{4d_2} + \frac{K_F}{\delta + K_F d_2} \right] - \frac{1}{Q_{01}} \frac{\omega_1}{\omega_2} \left[\frac{4}{\pi r_1} \ln \frac{eh}{4d_1} + \frac{1}{d_1} \right]}. \qquad (8)$$

The imaginary component of permittivity is related to Q_F by

$$K_F' = \frac{K_F}{Q_F} = K_F \tan \delta' \qquad (9)$$

where $\tan \delta'$ is the dissipation factor.

In order to test the technique, a Mylar sheet 1 mil thick was measured at 2.8 GHz. A K_F of 2.21 and $\tan \delta'$ of 0.0035 were found experimentally; these values show excellent agreement with the corresponding published values [3] of 2.20 and 0.003, respectively.

The technique described above was used to measure the properties of a silicon monoxide (SiO) film at S-band. The cavity for these measurements is shown in Fig. 3. It is convenient to measure the real part of the permittivity with the dielectric film deposited on the end plate A of the cavity and the imaginary part with the film deposited on the post B.

Plate A should be baked at a temperature exceeding the maximum temperature encountered during formation of the film. The cavity with the baked but uncoated end plate is calibrated by obtaining a curve of resonant frequency as a function of gap space. The gap space is controlled by placing washers of known thickness under surface C and a weight on surface D. Airholes E are used to permit smooth and repeatable motion of the center post. There is an initial gap (with no washers present) to prevent damage to the films. The calibration curve is found with the various washers inserted. Each point on the curve is the average of ten frequency readings. The spread at each point is less than 2.3 MHz.

After the calibration is completed, plate A is removed and coated. The film geometry and location are controlled by either mechanical masking or photoresist techniques. Plate A is replaced and a new curve of frequency as a function of gap spacing is determined, once again averaging over a large number of frequency readings for each washer.

It is desirable to use a high unloaded Q cavity for measurement of the imaginary component of permittivity. This cannot be achieved with a removable lower plate since the high-current path at the plate edges will be interrupted by the space between the plate and the cavity body. Therefore, for the Q measurement, a cavity similar to that discussed above is used. The end plate of this cavity is brazed into place and the film is deposited on the end of the center post. While it is inconvenient to use two cavities, better accuracy can be obtained for each of the measurements. The two cavities used in the tests reported below showed nearly identical performance.

Some typical calibration and perturbation curves for an SiO film are shown in Fig. 4. The resonant frequency is plotted as a function of washer thickness.

A 10μ thick film was vacuum-deposited through a mechanical mask at a rate of 2500 Å/min from a source at 1250°C onto an aluminum substrate at an average temperature of 95°C. Figure 5 shows a plot of K_F as a function of d_2. The departure from a linear d_1-d_2 relationship is reflected in the large change in K_F. This occurs when a spacing is reached where the capacitance calculation is no longer valid. The dielectric constant of the SiO film used in Fig. 5 is found to be 4.2

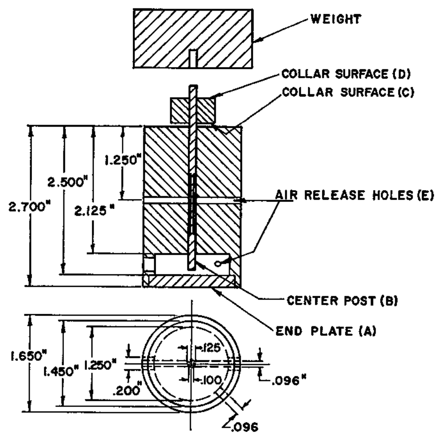

Fig. 3. Cavity used in tests.

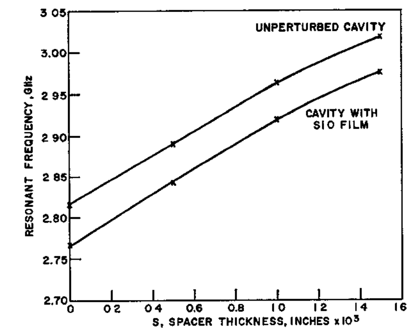

Fig. 4. Resonant frequency as a function of washer thickness for perturbed and unperturbed cavities.

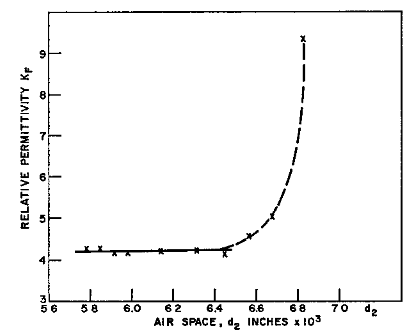

Fig. 5. K_F of SiO as a function of d_2, at S-band.

at S-band. Tests on other films showed values between 4 and 5. The low-frequency dielectric constant at 1 MHz of these films was between 5 and 5.5. This is consistent with published [4] values at 1 MHz.

The Q_F of the SiO film at S-band (2894 MHz) was found to be 34.3 corresponding to $\tan \delta' = 0.0292$. The $\tan \delta'$ of the film at 1 MHz was 0.018 compared with the published value of 0.015.

The accuracy obtainable with the method described above is determined by the ability to control in known steps the gap spacing; such accuracy also requires a precise value of film thickness. The calculation of K_F involves taking a difference between two similar numbers, and can result in large errors unless the spacings are precisely known. Equation (5) shows that to keep a constant accuracy, thicker films are required for higher dielectric constants.

As an example of the degree of accuracy that careful work can result in, the thickness of a 1μ film with a dielectric constant of nearly 20 was measured by the cavity technique with an accuracy of better than ten percent. In general, however, it is suggested that films of at least 10μ thickness be used.

In summary, a perturbation method for measuring the complex permittivity of dielectric films at microwave frequencies has been demonstrated. Results can be obtained from straightforward measurements and calculations.

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H. Sobol
J. J. Hughes
RCA Laboratories
Princeton, N. J.

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Experimental 4-Port E-Plane Junction Circulators

Introduction

This correspondence reports on the experimental investigation of broadbanding 4-port E-plane cross-junction circulators. The circulator experiments were carried out in X-band (WG 16). From previous work on 3-port E-plane circulators[1] it was decided to adopt a ferrite configuration using two flat disks positioned against the narrow walls at the intersection of the crossed waveguides as shown in Fig. 1. The ferrite disks are magnetized by a dc magnetic field parallel to the ferrite axis.

The investigation was empirical as a theoretical treatment is complicated by the variation of RF magnetic field in the direction of the dc polarizing field. There were three stages in the development of this device: the search for a circulating mode which allows broadbanding techniques to be applied, adjustments of the operating frequency, and high-power tests on the optimized configuration.

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