MEASUREMENT OF DIELECTRIC PROPERTY DISTRIBUTION IN THIN FILMS ON A METALLIC BASE

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The possibility of using a frequency-phase method to record the dielectric permittivity distribution of thin films to a resolution of at least 1 mm is considered.

Dielectric permittivity, one of the most characteristic macroscopic parameters of dielectric materials, provides information on the character of thermal field distribution at the surface when protective dielectric films are products by anodization [1]. The apparatus used for this purpose requires increased resolving power over coordinate while maintaining, or if possible, increasing, sensitivity.

Present-day methods for performing dielectric measurements [measurements of the complex dielectric permittivity $\varepsilon + \varepsilon' + i\varepsilon''$ and related quantities, for example the dielectric loss angle tangent ($\tan\delta = \varepsilon''/\varepsilon'$)] are in the majority of cases based on capacitive methods [2]. The various physicochemical characteristics of the object under study which affect the parameters of the capacitive transducer can be divided into three groups: those which it is desired to measure, those for which compensation may be made (disturbances producing the greatest interference to measurements), and those which may be neglected (the effects of which are not considered). In order to separate the desired signal from interference the dimensions of the transducer electrodes should be chosen so that change in geometry of the electric-field force line distribution of the transducer does not depend significantly upon change in thickness of the dielectric film being monitored.

In the case of multiparameter control applications, the frequency, phase, and amplitude of the capacitive transducer output signal, or some combination thereof, are often used. However, in a number of cases limitations develop upon the use of capacitive transducers. For example, the amplitude—phase method is not usable for monitoring details where a gap must be eliminated between the transducer and the surface being monitored, since the complex capacitance hodograph does not then have a segment parallel to one of the coordinate axes. In our case, for a characteristic gap the main limitations on decreasing plate area are reduction in sensitivity with decrease in the ratio $\Delta C/C$ and the effect of change in field force line geometry at $\ell/d < 5$ [2]. Analysis of data on the electric field intensity distribution of a two-electrode symmetrical capacitive transducer and geometric parameters of monitored dielectric layers shows that limitations exist on the dimensions of capacitive transducers.

We will consider the possibility of using such a transducer to measure dielectric permittivity. The transducer is connected as a capacitor into the simplest possible RC phase-shift circuit (Fig. 1). A high stability sine wave signal is applied to the input. As the capacitor (transducer) capacitance C changes in time the phase difference between the input and output signals will also change. The value of the frequency shift involved is then uniquely related to the rate of change of the capacitance, and the change in phase shift is related to the magnitude of the capacitance change. The frequency shift Δf and the phase shift $\Delta\varphi$ are related by the expression [3]

$$\Delta\varphi(\tau) = 2\pi \int_0^{\tau_0} (f(\tau) - f_0)\, d\tau. \quad (1)$$

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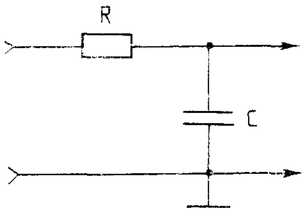

Fig. 1

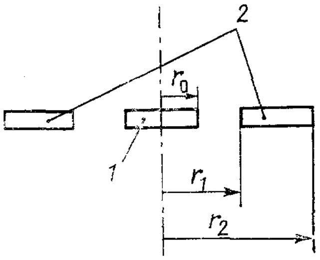

Fig. 2

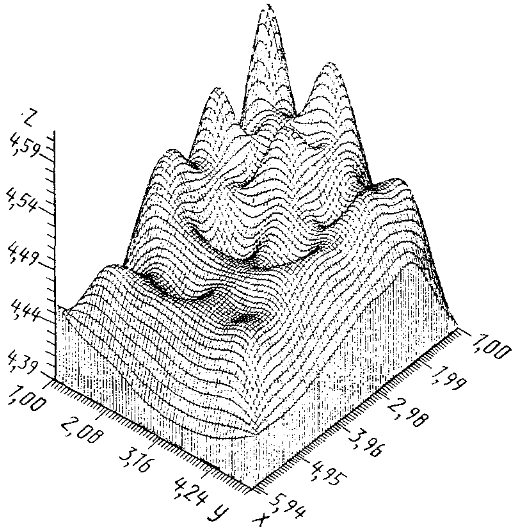

Fig. 3

Fig. 1. RC phase shift circuit (C, capacitive transducer).

Fig. 2. Electrode arrangement in plated symmetrical capacitor (r_0, r_1, r_2, electrode dimensions): 1) central electrode; 2) outer electrode.

Fig. 3. Film dielectric permittivity distribution (z-axis).

The argument of the complex transfer function of the phase shift network is

$$\varphi = -\arctan(1/\omega_0 R_0 C). \tag{2}$$

Change in the capacitance by an amount ΔC produces a change in phase shift

$$\Delta\varphi = -\frac{\omega_0 R_0}{1+(\omega_0 R_0 C)^2}\Delta C. \tag{3}$$

The quantity $\Delta\varphi/\Delta C$ found from Eq. (3) has an extremum at $R_0 = 1/\omega_0 C$, which corresponds to the maximum slope of the circuit phase characteristic, and thus, maximum transducer sensitivity. If C_0 is the initial capacitance and $R_0 = 1/\omega_0 C_0$, then

$$\Delta\varphi = -\frac{C_0}{C_0^2 + C^2}\Delta C. \tag{4}$$

One variant of the capacitive transducer is the plated symmetrical capacitor (Fig. 2). The capacitance of such a device is given by

$$C = \frac{2K(K_0)}{K(K_0')}\varepsilon_0(\varepsilon_1+\varepsilon_2), \tag{5}$$

where $K(K_0)$, $K(K_0')$ are full elliptic integrals of the first sort with moduli K_0 and K_0', respectively, which can be obtained from the expressions:

$$K_0 = \frac{r_0}{r_1}\sqrt{\frac{r_2^2 - r_1^2}{r_1^2 - r_0^2}}, \quad K_0' = \sqrt{1 - K_0^2}. \tag{6}$$

The quantities r_0, r_1, r_2 are the electrode dimensions, as shown in Fig. 2, while the value of the geometric coefficient $A = 2K(K_0)/K(K_0')$ can be found from the tables presented in [2]. On the other hand, we are concerned with determining the dielectric permittivity of the medium being studied ε_2. Taking $\varepsilon_1 = 1$ (air), we obtain

$$\varepsilon_2 = \frac{C}{A\varepsilon_0} - 1. \tag{7}$$

At the present time determination of local change in the dielectric permittivity of films 10-100 μm thick on a metal substrate is a problem of practical interest. In connection with this, we propose the following expression for the dielectric permittivity of the medium being monitored: for the condition $d \ll r_0$ and $r_1 > 5r_0$

$$\varepsilon_2 = \frac{(C - C_0)\, d\, (r_0^2 + r_2^2 - r_1^2)}{\pi\varepsilon_0 r_0^2 (r_2^2 - r_1^2)}. \tag{8}$$

A device was constructed to determine dielectric permittivity by measuring the phase shift $\Delta\varphi$ with a resolution of no less than $4\pi \cdot 10^{-4}$ at a frequency of 1 MHz. The quantity ΔC was determined from Eq. (4), while Eq. (8) gives the specimen dielectric permittivity ε_2. Figure 3 shows the dielectric permittivity of a film 30-μm thick, obtained by anodizing an aluminum substrate (z-axis).

The proposed method permits a resolution of 1 mm in the plane (a quite high specification for traditional capacitive measurements), and an accuracy of 10^{-2} for permittivity, a good specifiction for local measurements.

NOTATION

d, dielectric film thickness; $\omega_0 = 2\pi f_0$; R_0, constant resistance; ℓ, characteristic dimension of inner plate of capacitive transducer; $\Delta f(\tau) = f(\tau) - f_0$; $f(\tau)$ and f_0, signal frequency at output and input of phase shift circuit; τ_0, measurement time; ΔC, change in capacitance; C, measured capacitance.

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