

SOME DIELECTRIC AND CONDUCTION PROPERTIES OF THE R. F. REACTIVELY SPUTTERED Al_2O_3 THIN FILM

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Abstract—Dielectric films of Al_2O_3 were prepared by r. f. reactive sputtering. Investigation was then made on their dielectric dispersion and leakage characteristics.

I. INTRODUCTION

Aluminum oxide films are receiving increasing attention with respect to their use in MOS(metal-oxide-semiconductor) devices. In addition to studies of the semiconductor surface, the fundamental properties of the film itself under d. c. and a. c. conditions are also receiving much investigation¹⁻⁵. Due to the amorphous structure of these thin dielectric films, however, they may exhibit properties which differ significantly according to the method of preparation. In the present work, some of the dielectric and conduction properties of Al_2O_3 thin film prepared by r. f. reactive sputtering are reported.

II. EXPERIMENTAL TECHNIQUES

Dielectric films of Al_2O_3 of about 3000Å in thickness were prepared by r. f. reactive sputtering. The deposition was performed in a diode type sputtering system. The substrate, a low resistivity (0.0014–0.0026 ohm-cm) polished silicon wafer, was coated with a 3000Å thick layer of evaporated aluminum. It was then set on a grounded plate about $1\frac{1}{2}$ inches from an aluminum target which is 5 inches in diameter. The deposition glow discharge was operated at 13.560 MHz, at a 6 millitorr oxygen pressure, with a 1200 volt peak-to peak r. f. voltage (150 watts input power) and with deposition rates in the order of 30Å/min. Finally, the counter electrode, a circular aluminum dot $3.44 \times 10^{-3} \text{ cm}^2$ in area (26 mil diameter) was made by evaporation and photomasking.

Electrical measurements were made on the above described parallel plate capacitor, with a conventional electrometer and a. c. capacitance bridge.

III. RESULTS

The measured characteristics of the dielectric film indicated a dielectric constant of 7.85 at 1 MHz and at room temperature. The temperature coefficient of capacitance is in the order of 350 ppm/°C at 100°C and 1000 ppm/°C at 350°C, both at a frequency of 1 MHz. The dielectric strength ranged from $1 \sim 2 \times 10^6$ v/cm. The loss

tangent and capacitance versus frequency with ambient temperature as parameters obtained from small a. c. signals are shown in Figs. 1(a) and 1(b), respectively. It can be seen that as the temperature is increased, the loss peak shifts to higher frequencies and remains at about the same height. The corresponding capacitance is roughly inversely proportional to the frequency. If the logarithm of the frequency corresponding to the dielectric loss peak is plotted against reciprocal temperature, a straight line results as in Fig. 2, implying that there is an exponential distribution of relaxation times with temperature $\tau = \tau_0 \exp(E/kT)$. The activation energy E of the dispersion process is found to be 0.855 eV. In a Cole-Cole diagram⁶ shown in Fig. 3, the data points fall on an arc and thus indicates the dispersion of relaxation

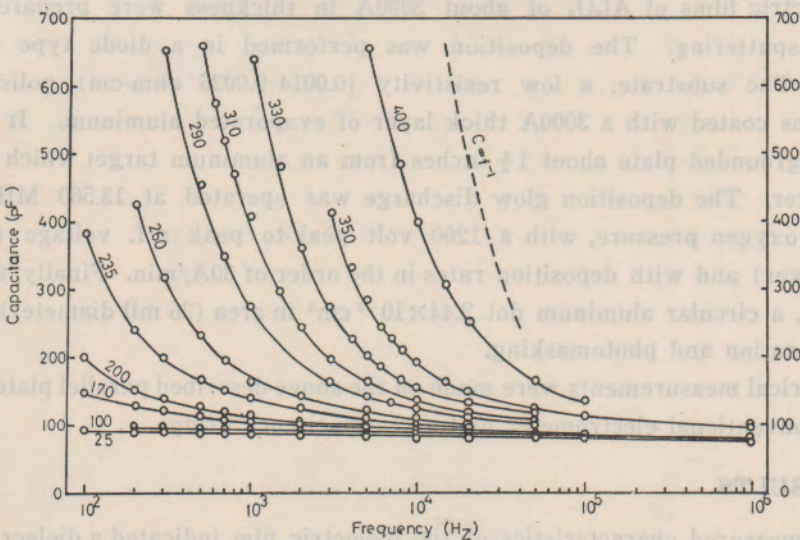
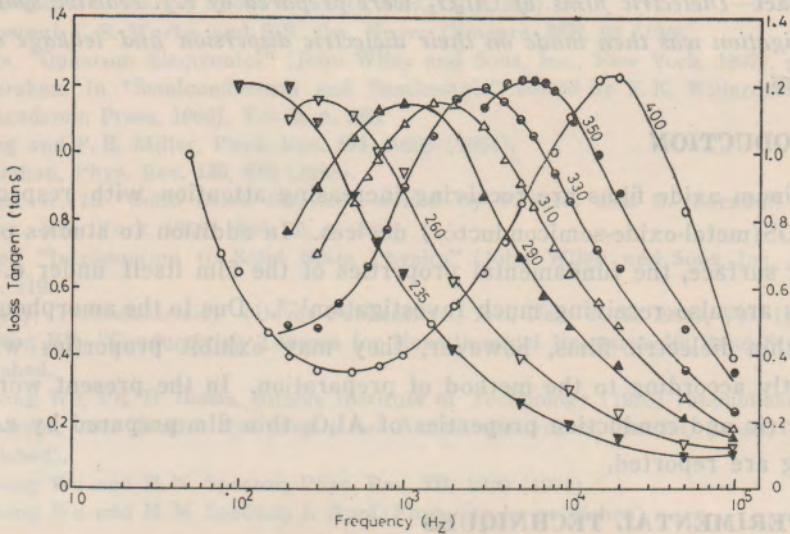


Fig. 1. Loss tangent (a) and capacity (b) behavior as a function of frequency at different temperatures. The number on each curve shows the temperature (in °C) at which each measurement was made.

type. However, two features of the diagram are to be noted. First, the data points obtained at lower frequencies (right part of the diagram) tend to deviate from the arc. This representation, together with the rising trend of loss tangent at lower frequencies as is evident from Fig. 1(a), points to the existence of another well separated dispersion region which is beyond the available frequency range. Second, the arc of the Cole-Cole diagram is displaced downward. A poly-dispersion with several closely distributed relaxation times⁷ would explain the phenomena. It is widely accepted that the dielectric constant can be expressed, in this case, as

$$\epsilon(w) - \epsilon_{\infty} = \frac{\epsilon_0 - \epsilon_{\infty}}{1 + (i\omega\tau)^{\beta}}$$

where β represents a measure of deviation from the monodisperse system and its meaning is shown in Fig. 3,

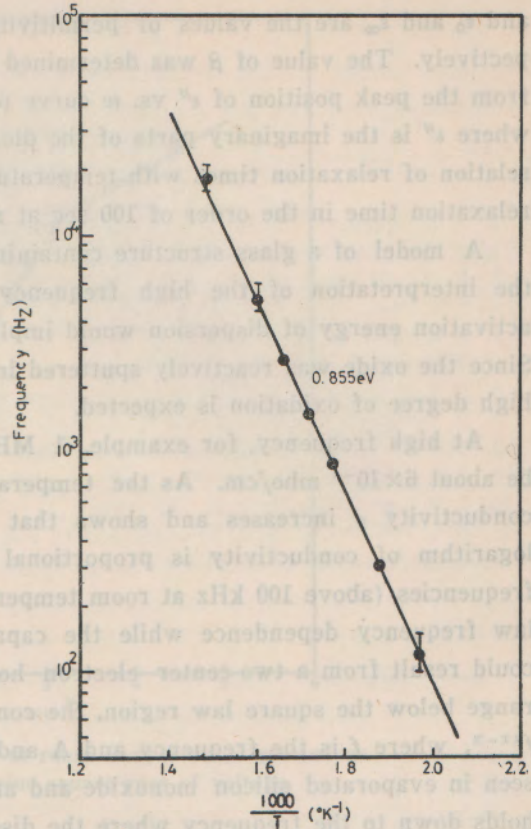


Fig. 2. Loss peak frequency as a function of reciprocal temperature (Arrhenius plot).

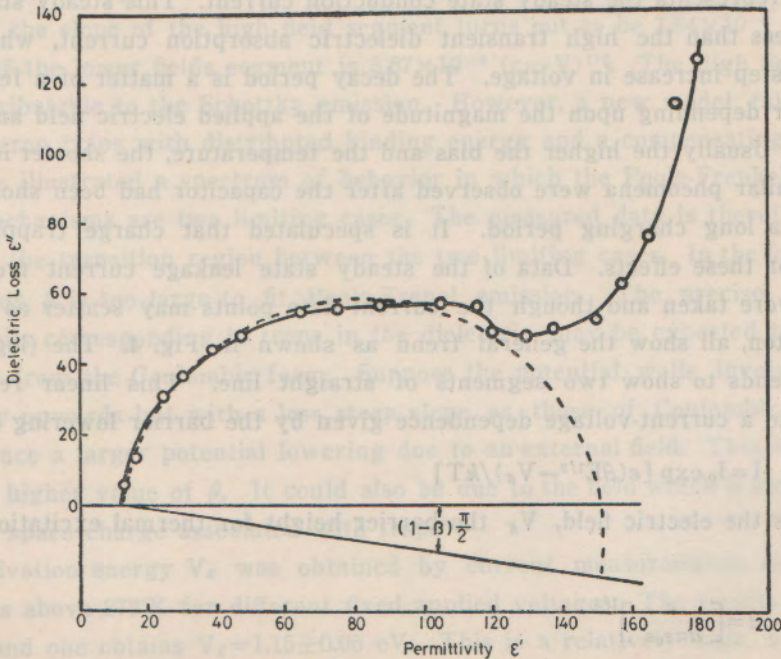


Fig. 3. Cole-Cole diagram for aluminum oxide with aluminum electrode at 400°C.

and ϵ_0 and ϵ_∞ are the values of permittivity at zero and infinite frequencies respectively. The value of β was determined to be 0.9. The value of τ was estimated from the peak position of ϵ'' vs. ω curve to be in the order of 100 μsec at 330°C, where ϵ'' is the imaginary parts of the dielectric constant. From the exponential relation of relaxation times with temperature, this type of dispersion possesses a relaxation time in the order of 100 sec at room temperature.

A model of a glass structure containing impurity ions has been proposed³ for the interpretation of the high frequency dispersion results. The relative high activation energy of dispersion would imply a rigid structure of the dielectric film. Since the oxide was reactively sputtered in pure oxygen at a relatively low rate, a high degree of oxidation is expected.

At high frequency, for example, 1 MHz, the a.c. conductivity σ was found to be about 6×10^{-8} mho/cm. As the temperature is increased, this fixed frequency conductivity σ increases and shows that at high temperatures above 400°K the logarithm of conductivity is proportional to the absolute temperature. At high frequencies (above 100 kHz at room temperature), the conductivity shows a square law frequency dependence while the capacitance remains nearly constant. This could result from a two-center electron hopping process³. In a lower frequency range below the square law region, the conductivity follows the relationship $\sigma_{ac} = f^{A-T-B}$, where f is the frequency and A and B are constants, and is similar to that seen in evaporated silicon monoxide and anodized aluminum oxide³. This relation holds down to the frequency where the dissipation peak occurs [see Fig. 1(a)] and is therefore true in limited frequency and temperature ranges.

The current-voltage characteristics at room temperature are shown in Fig. 4. The data represents the steady state conduction current. This steady state current is much less than the high transient dielectric absorption current, which results from the step increase in voltage. The decay period is a matter of a few minutes to an hour depending upon the magnitude of the applied electric field and the temperature. Usually the higher the bias and the temperature, the shorter is the decay time. Similar phenomena were observed after the capacitor had been short circuited following a long charging period. It is speculated that charge trapping⁸ would account for these effects. Data of the steady state leakage current from several samples were taken and though the current data points may scatter as much as a factor of ten, all show the general trend as shown in Fig. 4. The $(\log I)$ versus $V^{1/2}$ plot tends to show two segments of straight line. This linear relation corresponds to a current-voltage dependence given by the barrier lowering equation

$$I = I_0 \exp [e(\beta E^{1/2} - V_g) / kT]$$

where E is the electric field, V_g the barrier height for thermal excitation and β is given by

$$\beta = \left[\frac{e}{a\pi\epsilon_0\epsilon} \right]^{1/2}$$

where ϵ is the high frequency value of the dielectric constant and $a=4$ for Schottky

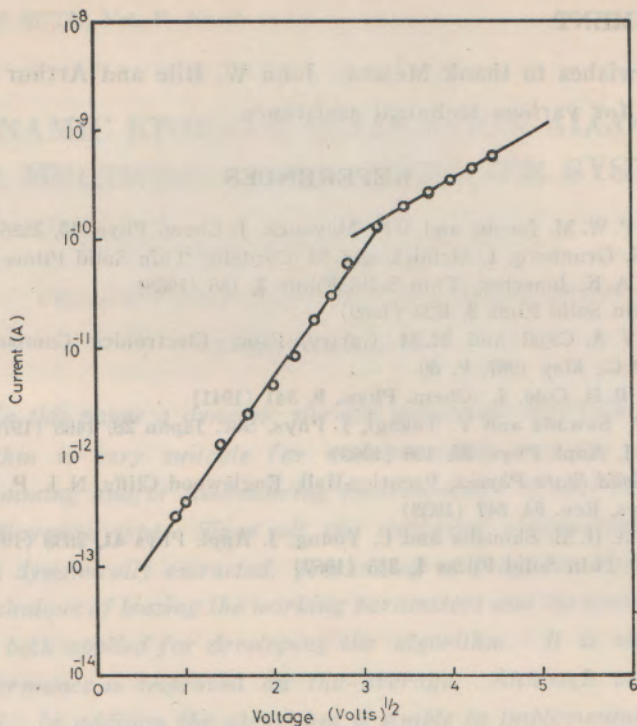


Fig. 4. Current voltage behavior at room temperature plotted as logarithm of current versus square root of voltage.

emission⁹ over a contact barrier and $a=1$ for Poole-Frenkel emission¹⁰ from localized centers in the bulk. Using the value of $\epsilon=7.85$, β should be 1.36×10^{-4} and 2.72×10^{-4} (cm-V)^{1/2} for Schottky and Poole-Frenkel emission respectively. Experimentally, from Fig. 4, the slope of the high field segment turns out to be 1.64×10^{-4} (cm-V)^{1/2} while that of the lower fields segment is 3.87×10^{-4} (cm-V)^{1/2}. The high field range is likely attributable to the Schottky emission. However, a new model taking into account electron traps with distributed binding energy and a compensating positive charge¹¹, has illustrated a spectrum of behavior in which the Poole-Frenkel and the Schottky mechanisms are two limiting cases. The measured data is therefore more precisely in the transition region between the two limiting cases. In the lower field part, however, β is too large to fit Poole-Frenkel emission. The precise shape of potential wells corresponding to traps in the dielectric may be expected to deviate significantly from the Coulombic form. Suppose the potential wells involved open up gradually upwards but with a less steep slope as those of Coulombic, then it will experience a larger potential lowering due to an external field. This, therefore, results in a higher value of β . It could also be due to the field which is appreciably modified by space charge associated with traps¹¹.

The activation energy V_g was obtained by current measurements at various temperatures above 273°K for different fixed applied voltages. The results are quite consistent, and one obtains $V_g=1.15 \pm 0.05$ eV. This is a relatively high value and would be associated with ionic transport.¹²

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