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A.C. PROPERTIES OF DISCONTINUOUS METAL THIN FILMS*

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INTRODUCTION

Electron micrographs of discontinuous metal films clearly show that the island and gap dimensions vary throughout the film. Yet most Arrhenius conductance plots yield single values of the activation energy which is presumed to depend upon these parameters. D.C. measurements over a small temperature range probably provide information about only a single meandering conduction path of necessarily lower than typical resistance[1]. For highly distributed film structures, the information gained may relate to only a few of the gaps along this single atypical path. This paper demonstrates that additional information can be gained about alternative current paths by the use of low frequency a.c. measurements and transient responses. It will also be shown that either hopping conductivity takes place between the islands or gap capacitances are much larger than expected.

EXPERIMENT

Results are presented for five films (Fig. 1). Only films 1 and 2 were discontinuous as deposited; both structures consist of small discrete islands (~10 nm in diameter) with little aggregation or filament formation. Films 3 and 4 were originally continuous and discontinuous properties were induced by burning out the continuous paths by Joule heating[1]. Film 5 was "semi-continuous", *i.e.* long meandering filaments were observed. This last film possessed switching characteristics but "partially" stabilized in the high resistance or discontinuous state after thermal annealing. Corning 7059 substrates were used for films 1 and 3; films 2, 4 and 5 were deposited onto soda-lime glass.

All a.c. admittances were measured with a 10 V peak-to-peak sine wave through the 0.01 Hz to 10 MHz frequency range. The low voltage and "high" minimum frequency avoid the ion drift effects previously observed with large applied fields of long duration[2]. Nevertheless, field enhancement due to the filamentary nature of film 5 still led to significant non-ohmic effects, observed as crossover distortion in the current waveform. This observation was made at low frequencies only (see later) and was accompanied by directional asymmetry and switching instability.

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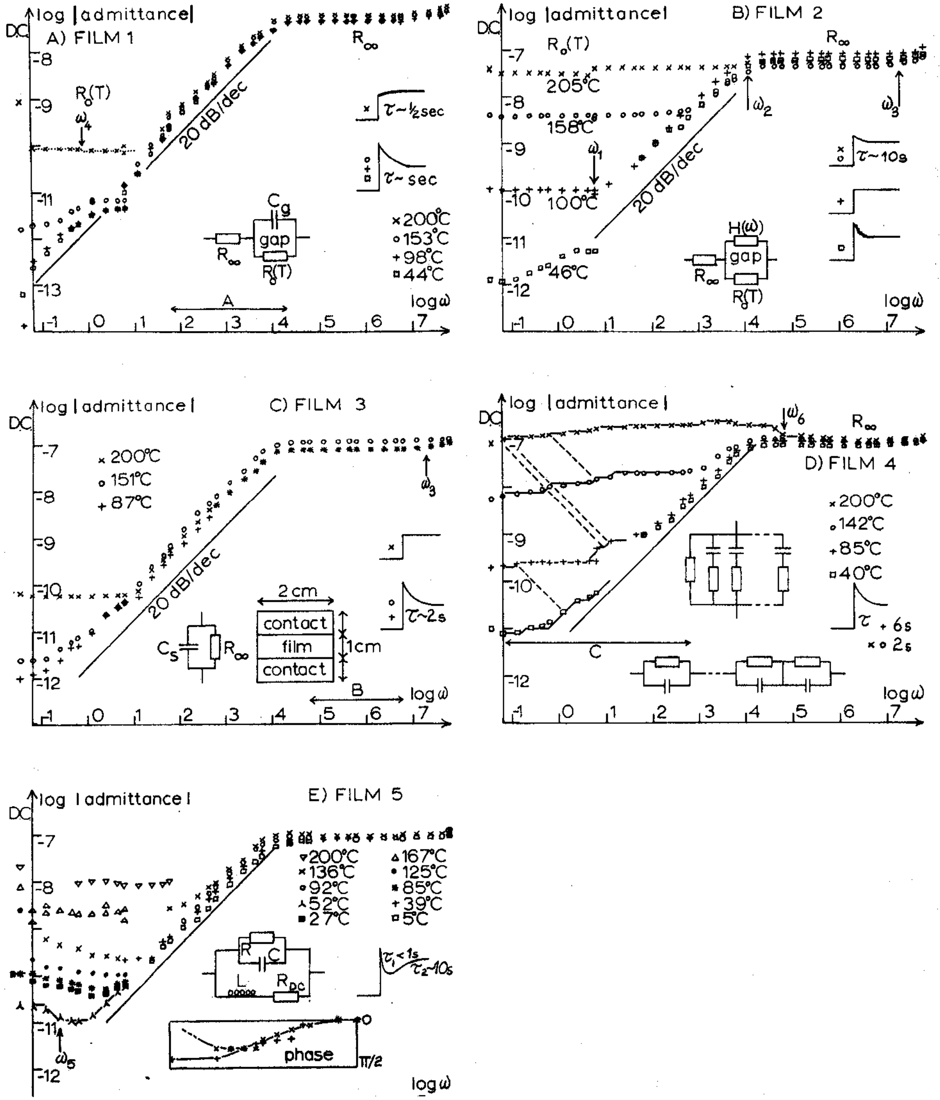
MID-FREQUENCY RANGE

The most striking observation, common to all five films, is the linear increase in film admittance with frequency through the middle range (region A of Fig. 1(a)). This is consist with the equivalent electrical model of the film shown in Fig. 1(a), with the observed



phase relation between voltage and current (Fig. 1(e)) and responses to square wave excitation.

The problem arises when the equivalent gap capacitance C_g is evaluated from the corner frequencies (*e.g.* ω_1 and ω_2 in Fig. 1(b)) giving $C_g \sim 10$ pF for all films. A reasonable explanation can be developed for such a large gap capacitance between the massive aggregates or very long filaments of films 3, 4 and 5 but it cannot possibly apply to the fine island structures of films 1 and 2. The possibility that the effect may be due to parasitics of the measurement apparatus can be eliminated.

Tick and Fehlner[3] have noted a similar frequency relationship for discontinuous films and have interpreted it as hopping conductivity. In their case variation was linear with $\omega^{0.9}$ rather than ω as seems the best fit here. Nevertheless, hopping conductivity through a substrate surface impurity layer between the islands seems an attractive explanation of the results and leads to the model shown in Fig. 1(b). The observed phase variation means, however, that there must be a significant imaginary component to the hopping element $H(\omega)$.

HIGH FREQUENCY REGION

In all cases the film resistance falls to a minimum value R_∞ at high frequencies (region B in Fig. 1(c)). The further decrease at around 10 MHz (ω_3 in Fig. 1(c)) for all films is assumed to be caused by a self-capacitance[4] C_s of about 0.005 pF (see film geometry and model, Fig. 1(c)). R_∞ itself varies slightly with temperature but there is no consistent trend amongst the films. R_∞ is assumed to be the resistance of the metallic grains themselves.

LOW FREQUENCY REGION

In the low frequency region, the conductance $R_0(T)$ is of the thermally activated type typical of discontinuous metal films and cermets. Film 4 (Fig. 1(d)) provides the most detailed demonstration of the low frequency behaviour (region C) with its sectioned series of roll-offs. The general form of the behaviour may be explained by either the series or the parallel model (Fig. 1(d)). The step response has also been recorded in this low frequency region and the general shapes and time constants are indicated in the diagrams. For the most part they follow the form expected from the frequency domain results. A more detailed analysis of the response on a logarithmic scale should yield complementary information about the fine detail of the frequency response (*e.g.* ω_4, Fig. 1(a)). It must be remembered that the roll-off time constant of a given gap is a function of $R_0(T)$ and hence of T. Corresponding corner frequencies at different temperatures should therefore be along a −20 dB/decade line (Fig. 1(d)) and this fact can be useful in interpreting the data.

Once again, however, evaluation of gap capacitances from the corner frequencies lead to unexpectedly high values, in the range of 1 to 10^4 pF. At this stage it is noted that the proposal of hopping conductivity in the middle frequency range resulted from a similar calculation of an unexpectedly high junction capacitance. The same arguments would apply here, leading to the proposition of hopping conductivity components to replace the capacitances in the models of Fig. 1(d).

A final note must be made of the observation of an admittance decrease with frequency (ω_5, transient response, equivalent circuit of Fig. 1(e), ω_6 in Fig. 1(d)). Again, calculations of equivalent inductive elements from corner frequencies produce impossibly large values even for the long filaments of film 5. This is the region of non-ohmic and asymmetric effects described earlier. The apparent link between these properties and switching instability would be worth further pursuit.

ACKNOWLEDGMENT

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