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SELF-HEATING EFFECTS IN DISCONTINUOUS METAL FILMS

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The effects of localized Joule self-heating in a discontinuous metal film are briefly described with an elementary model. Switching in nearly continuous films is predicted for sufficiently high local field strengths and/or channelled current densities. The simple model does not adequately explain the observation of anomalously large activation energies.

The measured electrical conductance σ of a discontinuous metal film generally obeys a law of the form[1, 2]

$$\sigma = \sigma_0 \exp(-\delta E/kT) \tag{1}$$

where σ_0 and δE are constants for a given film, k is Boltzmann's constant and T is the absolute measurement temperature. Such films typically consist of discrete metal islands (with typical diameters of the order of a nanometre) separated by gaps (<10 nm wide) where charge transport between islands takes place by substrate tunnelling[2]. The activation energy δE is believed to result from the associated electrostatic charging of the islands[1, 2]. While good numerical agreement between theory and experiment has been achieved for the ideal discontinuous structures described above[2], observed values of δE typically exceed prediction by a factor of 2 to 3 for nearly continuous films[3, 4]. In the latter films, the small islands are interspersed[5, 6] between large agglomerated metal islands (or filaments) of diameter (length) up to 10^5 nm. An earlier note[3] proposed a mechanical explanation of the δE anomaly based on thermal variation of the effective gap width. The original purpose of the study reported here was to determine whether Joule self-heating of the film could cause significant temperature rises within the film and consequently yield an excessive value for measured δE.

Significant self-heating has been demonstrated for highly agglomerated discontinuous gold films by the use of a liquid crystal temperature sensor[7]. In films of this type there is considerable local field enhancement across the gaps owing to the filaments or agglomerates[5]. The films tested showed switching characteristics which were clearly related to Joule heating effects. Furthermore, the temperature increases (in excess of about 25 °C) were clearly localized[7].

An even more dramatic demonstration of the existence of Joule heating was seen during the testing[8] of a gold film on Kapton-H. Despite possessing "useful properties" to beyond 440 °C, the substrate momentarily ignited and charred a small hole. This occurred with an average power dissipation of only 5×10^{-5} W cm^{-2} at a field of 100 V cm^{-1} in an ambient temperature of 200 °C. Both results[7, 8] (and others[8, 9]) imply that current flow across the film is restricted to relatively few conducting channels.

As a first model, consider a film 1 cm square with uniform island and gap sizes and conductance

$$\sigma = \sigma_0 \exp(-\delta E/kT_s) \tag{2}$$

where now T_s, the actual film temperature, exceeds T_0, the ambient temperature. The relationship between T_s and T_0 is given to a first approximation (with the rear of the substrate at T_0) by

$$T_s = T_0 + (t/a\eta)\, VI \tag{3}$$

where η is the thermal conductivity of the substrate of thickness t, a is the film area, V is the applied voltage and $I=\sigma V$ is the film current. Note that thermal radiation has been ignored (since it provides a negligible heat loss for small $\Delta T = T_s - T_0$) and it is assumed that convection is either zero (experiment under vacuum) or is not forced (so $\Delta T \propto VI$ and can be included in an effective value of t/η). For a glass substrate 1 mm thick, $t/a\eta \approx 15$ K J^{-1}. The next step is to modify eqn. (3) by introducing field enhancement and channelled flow factors (k_1, k_2) for the agglomerated films. Equation (3) may then be modified to

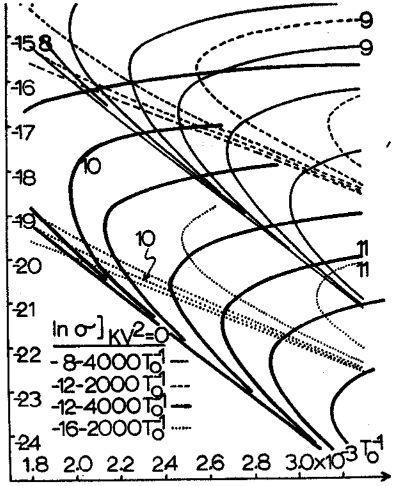
$$T_s = T_0 + KV^2\sigma \tag{4}$$

where $K = (t/\eta)\,(k_1k_2/a)$. Note that we still assume that heat is only lost from the gaps by perpendicular flow through the substrate and that we neglect surface heat flow. The film structure is now regarded as a finite number of conducting channels (all others are open circuit) consisting of zero resistance filaments with a finite number of identical island-gap resistive elements. Equation (2) then becomes

$$\sigma = \sigma_0 \exp\left(-\frac{\delta E/k}{T_0 + KV^2\sigma}\right) \tag{5}$$

Solutions to eqn. (5) are plotted in Figs. 1 and 2 for two values of δE and two values of σ at 500 K. The implications of these results are discussed below. For the extremes of (i) single-channel conduction (say 10 nm wide), (ii) maximum observed field enhancement[5] (say 10^5) and (iii) applied fields of 100 V cm^{-1}, KV^2 may reach about 10^{13} for a 1 cm^2 film.

If we consider Fig. 1 first, it is apparent that the slopes of the Arrhenius plots may be significantly increased for sufficiently high values of KV^2, as can be predicted analytically from $\partial(\ln\sigma)/\partial(1/T_0)$. The anomalously large values



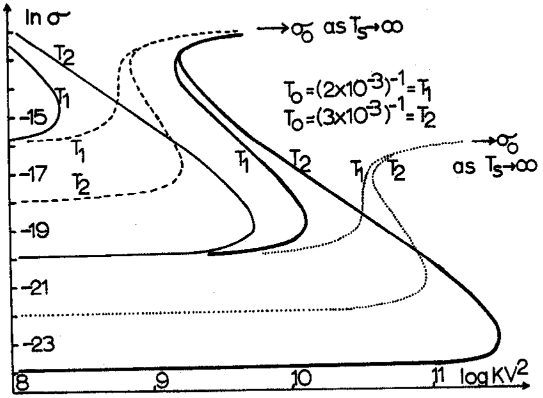


Fig. 1. The variation of ln σ with reciprocal temperature for the four combinations of $\delta E/k = 2000$ K, 4000 K and ln σ at 500 K $= -16, -20$. The third parameter is $KV^2 = 10^n$, 2×10^n, 5×10^n etc. where n is indicated on the curve for 10^n.

Fig. 2. The current-controlled negative differential resistance effect for the four films of Fig. 1 at $T_0 = 333.3$ K and 500 K. The asymptotic limits on σ correspond to $T_s = T_0$ and $T_s \rightarrow \infty$. Note $\delta E = 4kT_0$ (no negative resistance) for two curves.

curvature this theory predicts. Unless K is dominated by channelling at the expense of field enhancement, there should also be a large self-heating non-ohmic effect at appropriate levels of KV^2. This effect does not conform to observed non-ohmic relationships[1, 2, 5, 8–11] between σ and V. It is noted that the usual field reduction[1, 2, 5, 8–11] of δE has not been included in the model for three reasons: (i) for simplification, (ii) because of a recent suggestion[12] that the usual non-ohmic model is not valid and (iii) (as a result of (ii)) to determine whether self-heating might produce the observed non-ohmic behaviour (it does not). The parallel prediction[12] that ln σ should vary linearly with $T_0^{-1/2}$ rather than T_0^{-1} produces even more severe curvature in the Arrhenius plots with self-heating. Both the activation energy and non-ohmic behaviour problems for nearly continuous films are to be pursued further with the self-heating model applied to distributed film geometries[13].

In both figures it is evident that there may be two solutions of eqn. (5) under appropriate conditions. Differentiation of $KV^2 = f(\ln \sigma)$ shows that there is a negative resistance region provided $\delta E > 4\,kT_0$, *i.e.* the ambient temperature is not too high. The existence of current-controlled negative differential resistance is to be expected in such films and has been treated generally for other systems[14]. Instabilities encountered with discontinuous film testing at high fields and/or high temperatures[8, 10] and "voltage annealling"[8, 9] are clearly thermal in origin. Obviously constant current sourcing is necessary to plot the V–I characteristic, and conducting channels may well burn out under voltage cycling[7] unless current is limited by finite filament resistance. It must be noted that other switching modes have been observed in discontinuous films[7, 15, 16] which are inconsistent with the self-heating model.

In summary, a simple theoretical model suggests that Joule self-heating will be significant in sufficiently agglomerated discontinuous films and that it leads to a switching effect. Anomalous activation energy measurements cannot be explained by the idealized model.

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