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Post-deposition resistance changes in cermet and discontinuous thin films

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The resistance of both discontinuous thin gold films and Au–SiO cermet films increases immediately after deposition in vacuo. *This increase corresponds to a decay of film temperature to a final value from the high temperature caused by radiation heating by the source.*

Introduction

Both discontinuous and high resistivity cermet films consist of discrete metal islands separated by an insulating medium. Conduction processes in these films have been the subject of much investigation but the experimental result[1–7]

$$R(T)=R_\infty \exp(\delta E/kT) \quad (1)$$

is all that is required here, where

T=absolute film temperature

$R(T)$=film resistance

R_∞=constant

δE=activation energy of conduction

k=Boltzmann's constant.

Film resistance varies after deposition; in most of the films considered here it increases but occasionally a decrease or complex effect is noted. This paper discusses only the increases and relates them to known thermal effects. Present theories have not been able to explain the effect[8,9].

Experimental

Discontinuous Au and Au–SiO cermet films were deposited at pressures around 10^{-6} torr, in an oil diffusion vacuum system. The cermets were co-evaporated on Corning 7059 substrates which, along with soda-lime glass and Kapton-H polyimide, were also used for the Au films. Substrate heating, when used, was by a wire wound contact heater.

Deposition rates were less than 100 Å/min for Au and less than 500 Å/min for SiO.

Radiation heating by source

Radiation heating of the substrate surface by the deposition source has been observed by others[10,11] and has been recently considered theoretically[12]. A number of experiments were performed to evaluate the effect for the present study.

(a) Deposition of Au directly on Ni–Au thin film thermocouples on the substrate face caused a maximum temperature rise of approximately 5°C at 40 Å/min deposition rate.

(b) For SiO, the higher evaporation temperature is expected to produce more heating. The substrate was replaced by a strip of 0.005 in. stainless steel foil. The foil temperature rise at a deposition rate of 5 Å/sec is shown in Figure 1.

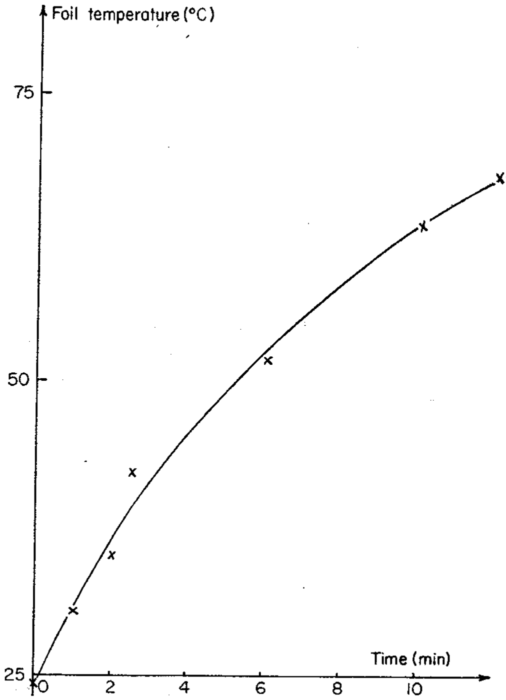

Figure 1. Substrate temperature variation for deposition of SiO.

(c) With the source power reduced till no evaporation takes place, the foil temperature reaches equilibrium at 75°C. This shows that radiation dominates any direct energy transfer from the vapour stream as the source of heat.

(d) During cermet deposition the linear plot of conductance vs time intersects the time axis at approximately 10 sec which is the time taken for the substrate face to reach thermal equilibrium (cf Figure 1).

Theory

The film temperature $T(t)$ is assumed to decay exponentially with time, t, from its initial value, $T_0+\Delta T$, to the final value, T_0, ie.

$$T(t)=T_0+\Delta T_0 \exp-(t/\tau) \quad (2)$$

where τ is the time constant. Equation (1) is now rewritten as

$$R(t)=R_\infty \exp\left[(\delta E/kT_0)(1+(\Delta T/T_0)\exp-(t/\tau))^{-1}\right] \quad (3)$$

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which becomes

$$\log_{10}[(\delta E/2.3kT_0)(\log_{10}(R(t)/R_\infty))^{-1}-1]=\log_{10}(\Delta T/T_0)-t/2.3\tau \qquad (4)$$

after taking logs twice and writing $\log_e 10 \approx 2.3$.

Equation (4) can be used to demonstrate the validity of the theory, provided δE, R_∞ and T_0 are known, and to evaluate ΔT and τ for a given deposition. If these quantities are unknown it must be assumed that

$$(\Delta T/T_0)\exp-(t/\tau) << 1 \qquad (5)$$

and the form

$$\log_{10}\log_{10}[R_0/R(t)]=\log_{10}(\delta E.\Delta T/2.3kT_0^2)-t/2.3\tau \qquad (6)$$

can be used provided approximation (5) is valid. R_0 is the final resistance at T_0.

Results

1. Au–SiO cermet films. Immediately after deposition the resistance measured is much less than that given by equation (1) with R_∞ and δE determined by later measurement in either air or *vacuo*, and with the assumption that T is the original substrate temperature. (There is no change in film properties with admission of air.) ΔT can be determined from the resistance after deposition, δE and R_∞ measured later and equation (1) used. These values are listed in Table 1.

Table 1. Comparison of calculated temperature rises with SiO deposition rates

Film	Approx temp rise (°C)	Approx SiO rate (Å/min)
C2	230	170
C3	230	not constant
C4	170	220
C5	180	200
C6	360	120
C7	450	170
C8	1350	140
C9	420	90
C10	800	190
C11	660	160
C12	660	100
C13	420	130
CB	220	340
CC	40	small
CE	140	180

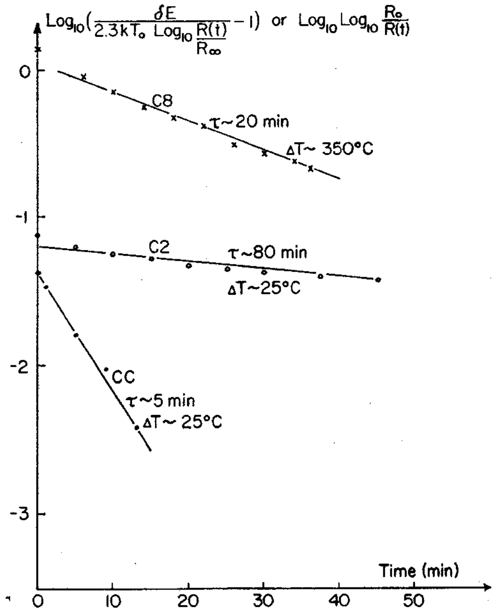

Figure 2. Verification of theory for cermet films.

There is little correlation between ΔT and deposition rate and in control of cermet film properties it is essential to control SiO source radiation levels rather than deposition rates.

Figure 2 shows the plot of equation (4) for films C2 and C8 and of equation (6) for film CC. Post-deposition coalescence is not usually a factor as is demonstrated by the stability of the resistance if Au deposition is stopped and SiO deposition continues to maintain thermal equilibrium. Film C2 (and two others) did, however, show a small decrease in resistance before the usual increase.

2. Discontinuous Au films. Film resistance generally decreases for these films (film 6 in Figure 3) but often a composite effect (film 7) is noted and occasionally the increase alone (film 18)[13]. Equation (6) is used to analyze six resistance increases in Figure 4. The results are given in Table 2. δE is typically around

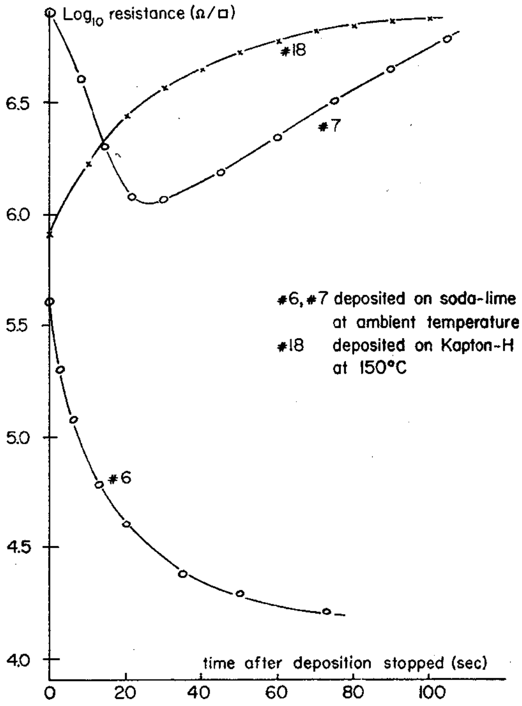

Figure 3. Variation of discontinuous film resistances with time after deposition.

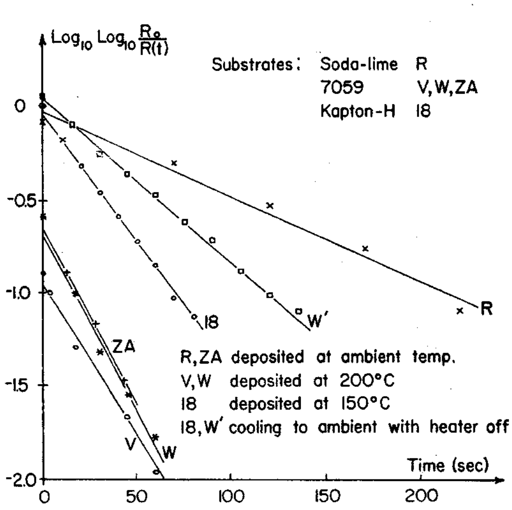

Figure 4. Verification of theory for discontinuous films.

0.5 eV for films deposited under similar conditions. ΔT is therefore much less than for the cermet films, as expected. τ is also less since radiation loss is expected to be more efficient.

Table 2. τ and $\delta E \cdot \Delta T$ for discontinuous films from Figure 4.

Film	τ (sec)	$\delta E \cdot \Delta T$ (eV °C)
18	30	33
ZA	25	4
V	30	5
R	100	17
W	25	9
W′	50	20

Discussion

The cooling characteristics of both cermet and discontinuous films conform to the theory. Post deposition resistance increases are entirely attributable to substrate temperature decreases. Derived values of ΔT and τ are not unreasonable. Thermal increases in cermets are due to radiation from the SiO source which must be directly controlled for uniformity of electrical properties.

Acknowledgements

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