

Applicability of discontinuous palladium films as strain gauges

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Discontinuous palladium films were prepared by evaporation and sublimation. The variation of the direct current resistance of the as-deposited films with time was investigated in air at room temperature. Films prepared by sublimation exhibited better stability as compared with that of films prepared by evaporation. The piezoresistance of the discontinuous palladium films was measured at different strains and the gauge factor, ν , was deduced. It was found that ν of films prepared by sublimation was higher than that of films prepared by evaporation. Palladium films prepared by sublimation are thus good candidates as sensors for measuring extremely small strain.

1. Introduction

Discontinuous metal films (DMF) consist of discrete microparticles (islands) randomly distributed onto insulating substrate. The islands [1] are of different sizes (1–10 nm) and the spacings among them are of the same order. The inherent structure of such films lends them distinguished electrical properties, and they are therefore good candidates for thin film sensors, such as high sensitivity miniature strain gauges [2], displacement transducers and temperature sensors [3]. As far as the published literature is concerned, and to the best of our knowledge, these sensors are not yet available, presumably because there is an outstanding problem, i.e. the drift in the electrical resistance of DMF with time [4]. A thorough survey of the literature revealed that no attempt has been made to study the stability and the piezoresistance of DMF prepared by sublimation rather than evaporation. The present paper tries to fill this gap. Palladium was selected because it is one of the limited number of metals which have appreciable vapour pressures before they melt. Four films were prepared (2, 5, 7 and 9 nm) by evaporation and sublimation and the ageing (variation of the direct current (d.c.) resistance with time) of the as-deposited films was studied in air at room temperature. The piezoresistance of these films was measured at different strains and the gauge factor, ν , defined as the relative change in resistance per unit strain, $\nu = (\Delta R/R)/\epsilon$, was deduced for each film.

2. Experimental procedure

Corning 7059 glass slides of dimensions $76 \times 25 \times 0.8$ mm were used as substrates. This type of glass was selected because it is alkali-free and hence considered an appropriate substrate [5] for thin films, especially when measuring their electrical properties.

The substrates were cleaned by following the recommended method [6]. Two planar thick aluminium films (electrodes), separated by a gap of 2 mm, were vacuum deposited onto the centre of each glass slide. Two fine connecting leads were attached [7] to the electrodes by using quick-drying silver paste. Palladium of purity 99.99% (Kochlight, UK) was evaporated from tungsten helix. On the other hand, the sublimation of Pd took place by passing electric current directly [8] through Pd wire filaments. The evaporation and sublimation processes were conducted in vacuum at a pressure of 1.333×10^{-4} Pa. Since the evaporation and sublimation rates affect the properties of the deposited films [9, 10], it is therefore necessary to keep the evaporation rate constant and also the sublimation rate for all the Pd films investigated in the present work. The constancy of the two rates was achieved by (i) fixing the source area and (ii) keeping the source temperature constant. The constancy of the latter was maintained by controlling the power input to the source [11, 12]. The source temperature was kept at 1580 °C and 1170 °C during evaporation and sublimation, respectively. The source temperature was measured with an optical pyrometer [5]. A mechanical shutter was used to halt the deposition of Pd films, across the gap between the electrodes, at the prescribed mass thickness d_m [13, 14]. The mass thickness is defined as the deposited mass per unit area divided by the bulk density of the metal and in the present work, d_m was directly measured in Ångströms by a quartz crystal thickness monitor [15].

Each glass slide, loaded with Pd film, was transferred to an electrically shielded metal box to monitor the change in resistance with time in air at room temperature because these will be the most probable working conditions for the hopeful use of discontinuous Pd films as strain gauges. The d.c. resistance was

measured by using an electrometer [16] (Keithley 617). The lid of the box was provided with a micrometer head [16] to develop tensional strain in the glass slide and hence in the Pd film. The value of the strain was calculated from the relation [17]

$$\varepsilon = 4td/L^2 \quad (1)$$

where t is the thickness of glass slide, D is the depression of the centre of the slide and directly measured from the micrometer head and L is the distance between the two supporting pillars of the slide within the box.

3. Results

The variation of the d.c. surface resistivity, R_{\square} (Ω/\square), of discontinuous Pd films with time is presented in Figs 1 and 2. The results are representative of a long series of measurements all showing the same behaviour. It is obvious, from Figs 1 and 2, that the surface resistivity exhibits fast variation followed by a relatively slow one. At the end of the ageing period (100 h) the surface resistivity would be denoted by $R_{\square 100}$, which increases as the film thickness decreases. The values of $R_{\square 100}$, for Pd films prepared by evaporation and of thicknesses 2, 5, 7 and 9 nm, were 3.2×10^{10} , 10^9 , 1.8×10^7 and 10^6 , respectively. For Pd films prepared by sublimation and of thicknesses 2, 5, 7 and 9 nm, the values of $R_{\square 100}$ were 1.6×10^{11} , 4.5×10^9 , 10^8 and 3.2×10^8 , respectively. To reveal the precise manner which describes the variation of R_{\square} with time, the normalized surface resistivity $R_{\square}/R_{\square 100}$ was plotted versus the time on a linear scale as shown in Figs 3 and 4. It is clear that the tendency of Pd films to attain stability increases as the film thickness increases. Also

Pd films prepared by sublimation show remarkably better stability as compared with those prepared by evaporation.

The variation of the relative change in the film resistance $\Delta R/R$ with the strain is illustrated in Figs 5 and 6, where R is the unstrained resistance which is related to $R_{\square 100}$ by the equation $R = SR_{\square 100}$; S is the aspect ratio of the film (in our case $S = 0.08$). ΔR is the change in the film resistance, from its initial value R , resulting from the application of external strain. It should be mentioned that the time interval required for measuring the piezo-resistance (a few minutes) was too short to allow for appreciable ageing effect. This is important, especially for Pd films prepared by evaporation (Fig. 3) and for the Pd films of thicknesses 2 and 5 nm which were prepared by sublimation (Fig. 4). The calculated gauge factor ν linearly decreases as the film thickness increases. The value of ν for films prepared by sublimation is higher than that for films prepared by evaporation for the same d_m as shown in Fig. 7.

4. Discussion

Many investigators [18–20] have tackled the subject of ageing of DMF. Their studies involved monitoring the variation of the d.c. resistance of the films with time in vacuum and in air. The main outcome of their studies is the increase in resistance with time. Different reasons [21–33] were suggested to account for such an increase. The results presented in Figs 1 and 2 comply with the reported [24] behaviour of DMF. The dependence of ν on film thickness as shown in Fig. 7 could be explained by assuming the electrical conduction in discontinuous Pd films to take place through the thermally activated tunnelling mech-

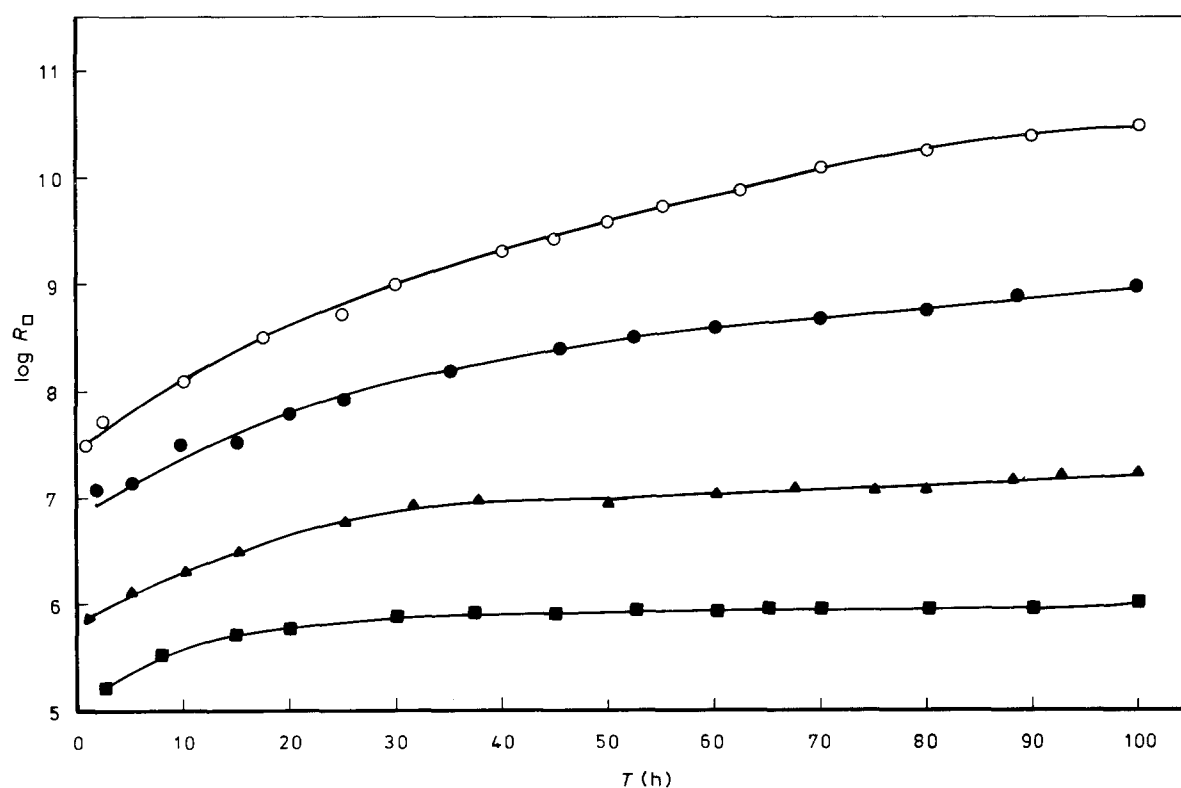


Figure 1 Ageing of discontinuous Pd films prepared by evaporation. (○) 2 nm, (●) 5 nm, (▲) 7 nm, (■) 9 nm.

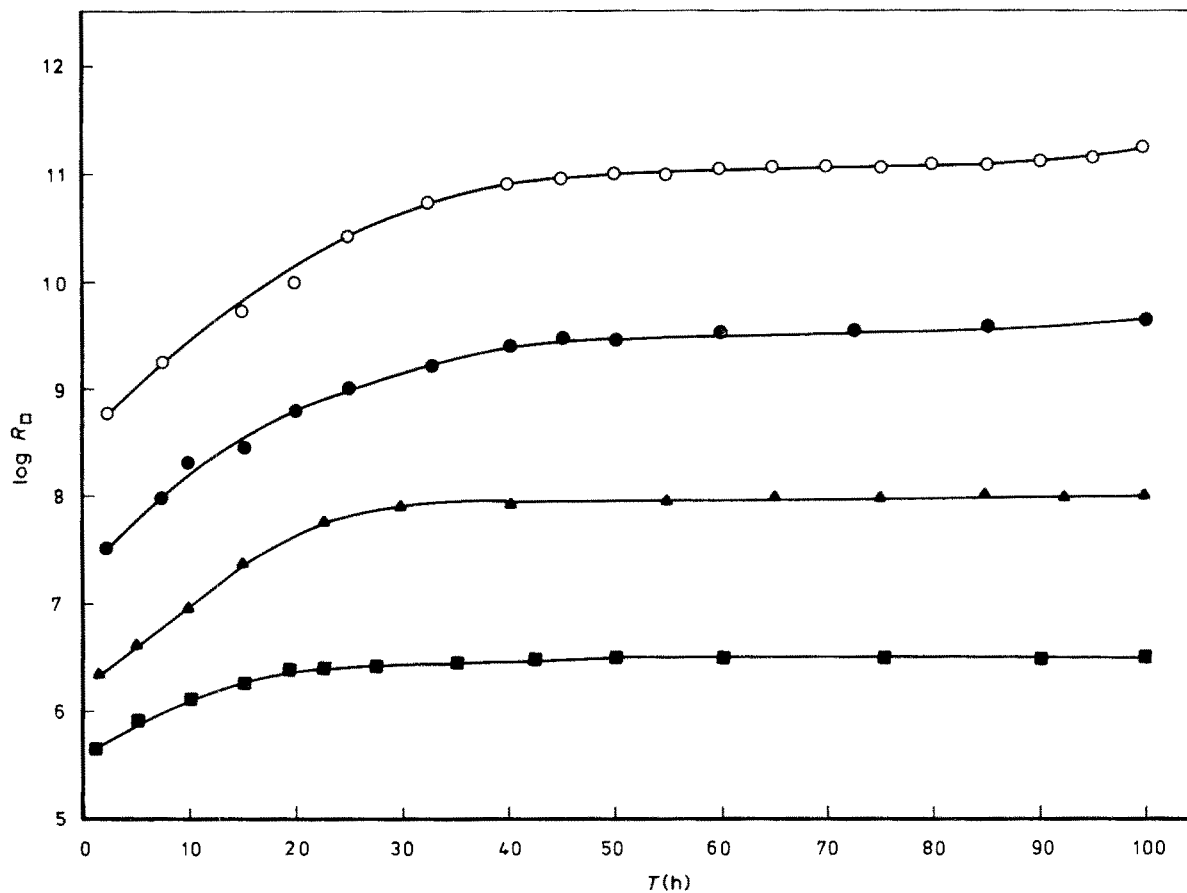


Figure 2 Ageing of discontinuous Pd films prepared by sublimation. (○) 2 nm, (●) 5 nm, (▲) 7 nm, (■) 9 nm.

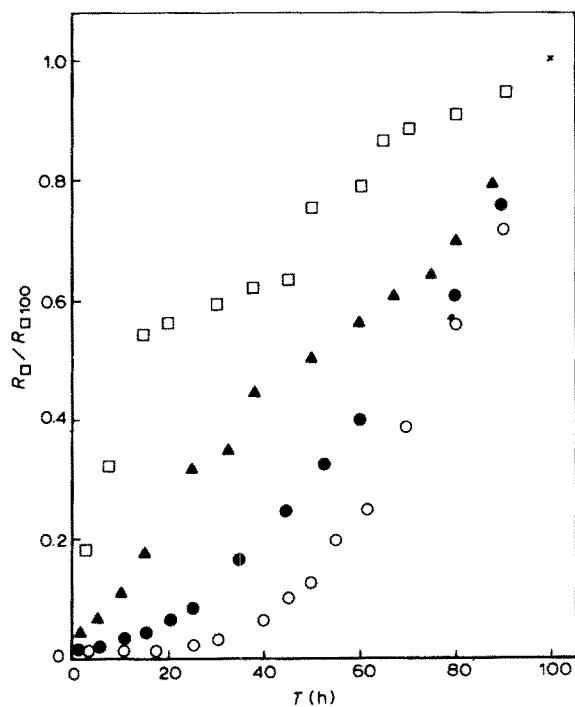


Figure 3 Dependence of the normalized surface resistivity on time for Pd films prepared by evaporation. (○) 2 nm, (●) 5 nm, (▲) 7 nm, (□) 9 nm, (x) ≡ (○, ●, ▲, □).

anism. Accordingly, v could be expressed in the form [24, 25]

$$v = (4\pi/h)(2m^*\phi)^{1/2}l \quad (2)$$

where h is Planck's constant, m^* is the effective mass of

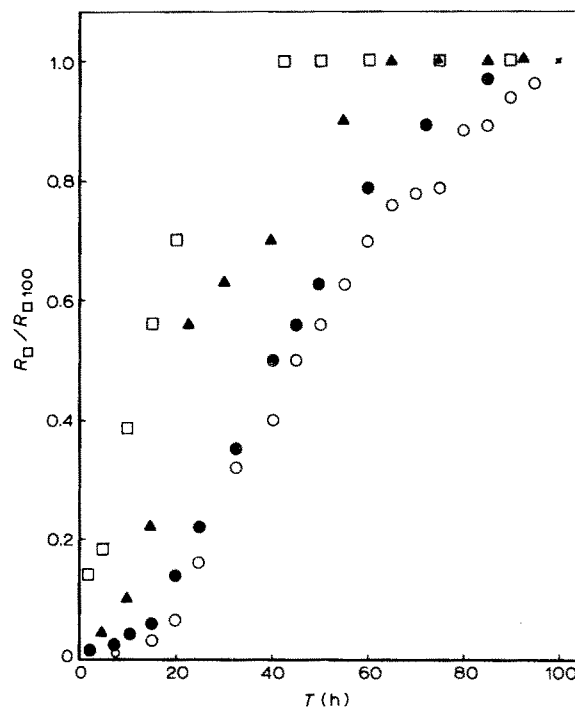


Figure 4 Dependence of the normalized surface resistivity on time for Pd films prepared by sublimation. (○) 2 nm, (●) 5 nm, (▲) 7 nm, (□) 9 nm, (x) ≡ (○, ●, ▲, □).

the electron, ϕ is the effective barrier height between the islands and l is the inter-island spacing. Equation 2 accounts, qualitatively, for the decrease of v as the film thickness increases, i.e. as l decreases. The better stability and the higher values of v for Pd films

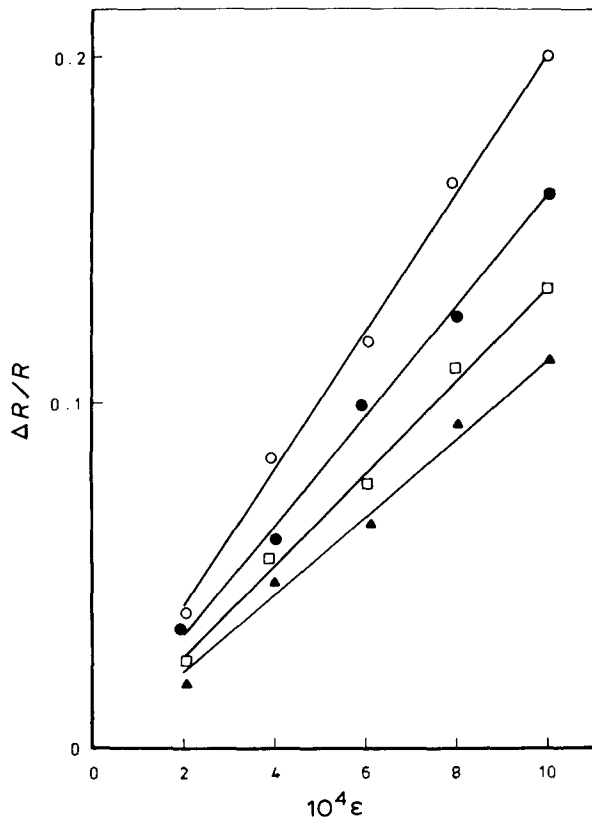


Figure 5 Variation of the relative change in resistance with strain for Pd films prepared by evaporation. (○) 2 nm, $\nu = 200$, (●) 5 nm, $\nu = 160$, (□) 7 nm, $\nu = 135$, (▲) 9 nm, $\nu = 113$.

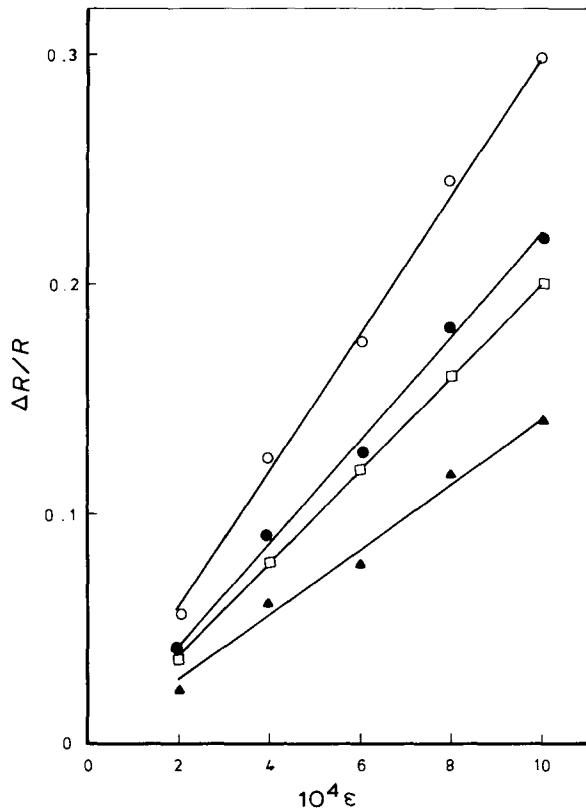


Figure 6 Variation of the relative change in resistance with strain for Pd films prepared by sublimation. (○) 2 nm, $\nu = 300$, (●) 5 nm, $\nu = 220$, (□) 7 nm, $\nu = 200$, (▲) 9 nm, $\nu = 140$.

prepared by sublimation could be interpreted in view of the fact that the kinetic energy of the sublimed Pd atoms is higher [26] than that of evaporated ones.

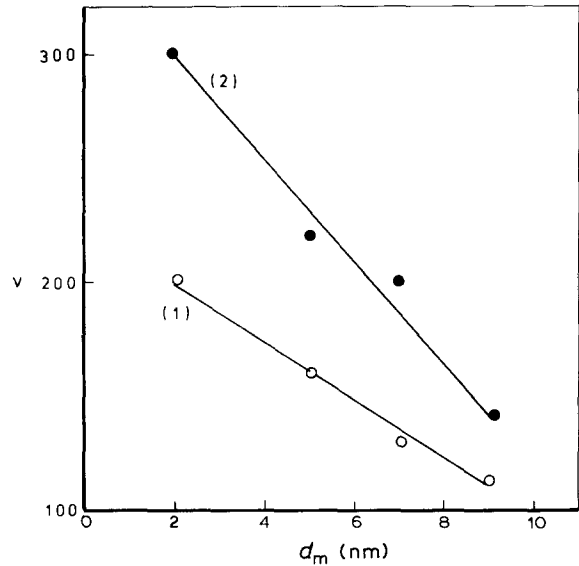


Figure 7 Gauge factor as a function of mass thickness. (1) and (2) for Pd films prepared by evaporation and sublimation, respectively.

Therefore, films prepared by sublimation should have larger [27] island size and higher magnitudes of l with two implications: (i) higher values of ν according to the Equation 2; (ii) reduction in the agglomeration among islands which causes better stability. The values of ν for Pd films prepared by evaporation agree with the only available results concerned with Pd films reported by Parker and Krinsky [28]. The higher values of ν and the better stability of discontinuous Pd films prepared by sublimation make them candidates for strain gauges for the measurement of small strains, [29] such as those found in creep processes, phase transformations and geological deformation processes.

5. Conclusions

1. Discontinuous Pd films prepared by sublimation have better stability as compared with films obtained by evaporation.
2. The gauge factor of Pd films prepared by sublimation is higher than that of films obtained by evaporation.
3. The gauge factor increases as the film thickness decreases whatever the method of preparation.

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