Metal-insulator transition in thin nickel films

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We report on measurements of the electrical resistance of thin nickel films deposited at room temperature (22 °C) under a pressure of less than 2×10^{-7} Torr with a deposition rate of 0.1 nm/s. The mechanisms responsible for the conduction in the film have been identified. In the thickness region $5.7 \le d \le 10.4$ nm the resistance of the film is well described by $(d-d_c)^{-t}$, where $t=1.27\pm0.10$ and $d_c=3.8\pm0.2$ nm. This agrees well with the theoretical calculations of t for conduction in two-dimensional systems and with our previous work on chromium films.

Thin metallic films have been of great interest recently for the determination of the critical exponent t associated with percolation conductivity. Octavio *et al.*[1] have done experiments on thin silver films evaporated and ion-milled at liquid-nitrogen temperature and found $t=1.33\pm0.04$ and 1.33 ± 0.05, respectively. Very thin chromium films were used by Lourens *et al.*[2] who determined a value of $t=1.34\pm0.11$ in the metal-insulator region in the presence of conduction mechanisms other than percolation. These experiments provide evidence for the universality of the critical exponent t, and agree remarkably well with the theoretical calculations[3] and with experiments involving model percolation systems by Dubson and Garland[4] who found $t=1.29\pm0.03$ for site percolation on a square lattice and $t=1.34\pm0.07$ for random void continuum percolation.

During the early stages of film evaporation, small isolated islands form and highly activated conduction mechanisms are present.[5] As the average thickness d of the film increases, the small islands merge giving rise to larger islands which join together leading to the formation of continuous paths, and the film undergoes a metal-insulator transition. The resistance of the film in the transition region is proportional to $(p-p_c)^{-t}$, where p is the occupation probability of a conducting square on the insulating substrate. With the assumption that $(p-p_c)\propto(d-d_c)$ near p_c, the resistance should scale as $(d-d_c)^{-t}$. As the void fraction diminishes, the conductivity of the film is controlled by surface, grain boundary, and roughness scattering.

The resistance of thin nickel films as a function of average thickness was measured in our four probe system.[6] A starting vacuum of 2×10^{-7} Torr was produced using two Vacsorb pumps, a titanium pump, and a Vacion pump. The substrate (Corning glass #7059) was maintained at room temperature after being annealed at 400 °C for a few hours. Nickel was then deposited at a rate of 0.1 nm/s by evaporation from a tungsten boat. The thickness of the film was determined by a crystal oscillator with an estimated error of 0.2 nm. The final film thickness was 14.5 nm and its dimensions were 4.0×1.8 cm^2. As shown in Fig. 1, the resistance of the film drops sharply from the onset of conduction, at $d=2$ nm to

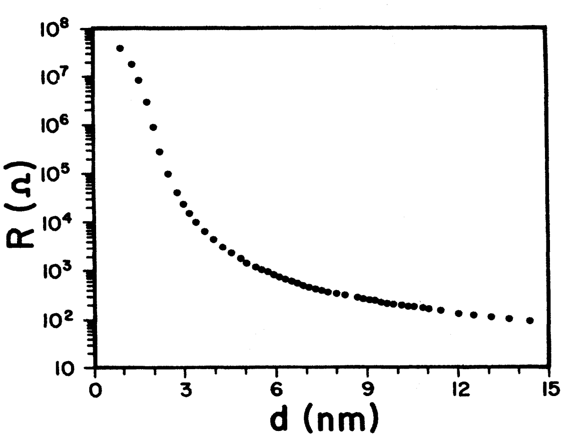

FIG. 1. The log of the resistance R vs thickness d for a Ni thin film.

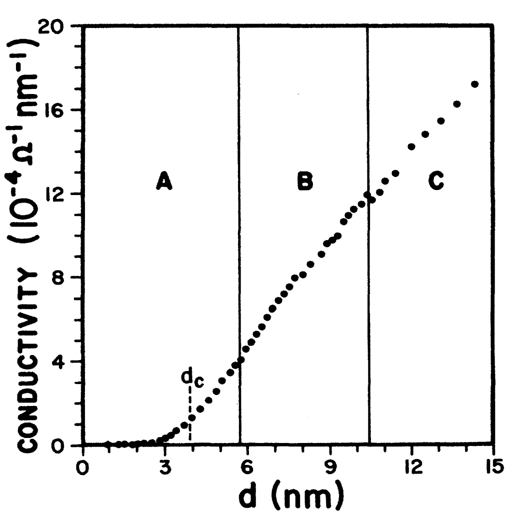

FIG. 2. Ni film conductivity vs thickness d. The critical thickness d_c is indicated by a dashed vertical line (not all data points are shown).

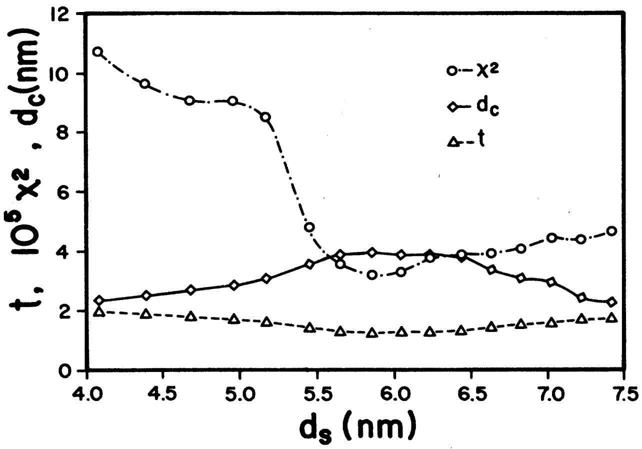

FIG. 3. The critical exponent t, the critical thickness d_c, and χ^2 vs the starting thickness d_s.

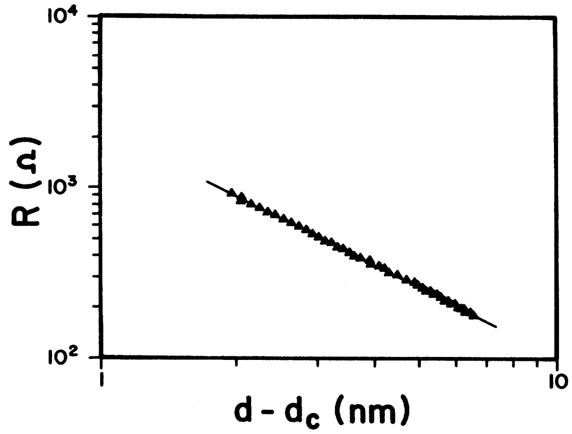

FIG. 5. The film resistance R vs $(d-d_c)$ in the metal-insulator region. The slope of the straight line is 1.33 and the critical thickness is 3.84 nm.

about $d=5$ nm, due to the presence of highly activated conduction mechanism. Figure 2 shows the conductivity of the film versus average film thickness. Three regions corresponding to different types of mechanisms affecting the conduction in the film are indicated. Highly activated mechanism occurs in region A. Region B is the metal-insulator region, and region C is the region where the conductivity of the film can be described by the relation[7] $Rd=A_0+A_1/d+A_3/d^3$. Here the second and third terms characterize grain boundary and roughness scattering, respectively.

To determine the actual size of the metal-insulator region and its lower and upper boundaries, sliding least-squares fits were done on 4.0-nm segments of data. For each segment, specified by a starting thickness d_s, values of t and d_c corresponding to the best χ^2 were obtained. A summary of the results is displayed in Fig. 3 which shows a clearly defined region of starting thicknesses $5.7 \leq d_s \leq 6.4$ nm, in which χ^2 is minimum, and both t and d_c have almost constant values of 1.32 ± 0.05 and 3.8 ± 0.2 nm, respectively. The same procedure was repeated for segments of data of widths 3, 4.5, and 5.5 nm giving similar results. The overall values of the critical exponent t and the critical thickness d_c were found to be equal to 1.27 ± 0.10 and 3.8 ± 0.2 nm, respectively. We should point out that the error of 0.10 in t is mainly due to the overlapping of the different conduction mechanisms at both ends of the percolation region. The implication is that the onset of percolation occurs at a film thickness of about 3.8 nm, where it is competing with an activation mechanism. At a thickness of about 5.7 nm, percolation starts to dominate the conduction process. The upper limit of the percolation region was found by the least-squares fitting of the film conductivity to the relation $Rd=A_0+A_1/d+A_3/d^3$. This function describes the data well for thicknesses greater than 10.4 nm with the parameter values of $A_0=628$ Ω nm, $A_1=6.77\times10^3$ Ω nm^2, and $A_3=7.005\times10^5$ Ω nm^4 as

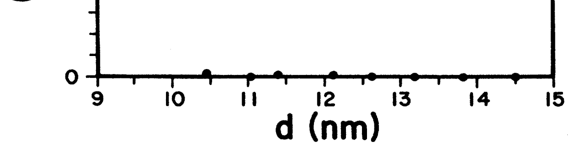

FIG. 4. $(\Delta R)^2=(R-R_{\rm fit})^2$ vs film thickness d.

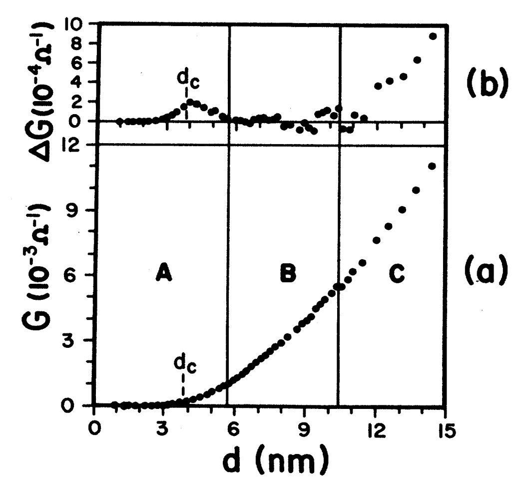

FIG. 6. (a) The conductance G of the film vs film thickness d. (b) $\Delta G=(G-G_{\rm fit})$ vs film thickness d.

shown in Fig. 4. Figure 4 also shows how rapidly this function fails for thicknesses less than 10.4 nm, $(\Delta R)^2=(R-R_{\rm fit})^2$ reaching a value of 64 Ω^2 at a thickness of about 9 nm. These results are consistent with those obtained using the sliding least-squares fits in the metal-insulator region. A log-log plot of the film resistance R versus $(d-d_c)$ in the metal-insulator region is given in Fig. 5. The conductance G of the film is plotted as a function of film thickness in Fig. 6(a). The fit of the conductance G in the percolation region, $G\propto(d-d_c)^t$, was subtracted from the data. The result, $\Delta G=(G-G_{\rm fit})$, is shown in Fig. 6(b). The conductance due to the activated mechanism is a Gaussian with a maximum around the critical thickness d_c as shown in region A of Fig. 6(b). This agrees with the fact that, as the first percolation path forms, the void fraction diminishes leading to a decrease of the effects of the activated mechanism on the conduction in the film. Region B of Fig. 6(b) shows the deviation of the conductance data from its fit in the percolation region. The largest relative deviation is 2.5%. The scattering mechanisms dominate in region C.

In conclusion, we have located a percolating region in thin nickel films in the presence of other conduction mechanisms. In this region, the resistance of the films behaves as $(d-d_c)^{-t}$ with $t=1.27\pm0.10$ and $d_c=3.8\pm0.2$ nm. The conductivity of the films is well described by $Rd=A_0+A_1/d+A_3/d^3$ in the thickness range $10.4\leq d\leq 14.5$ nm. Moreover, the activation conductance was evaluated and found to be a Gaussian with a maximum around the critical thickness d_c.

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