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LETTER TO THE EDITOR

2D to 3D percolation crossover in the resistivity of co-evaporated Al–Ge mixture films

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Abstract. We demonstrate, experimentally, the percolation dimensionality crossover as it is reflected in the resistivity measurements of co-evaporated Al–Ge random mixture films. The resistivity exponents as well as the correlation length exponent and its amplitude are found to be in good agreement with the theory.

Random binary systems of metal and insulator can undergo a percolation transition if the metal grains are large enough to be viewed as 'classical'. A system having a metal concentration X will conduct in a metallic fashion only if $X > X_c$, X_c being the percolation threshold (Kirkpatrick 1978, Abeles 1976, Deutscher *et al* 1978).

The case of metal–insulator thin mixture films is rather more complicated (Abeles 1976, Deutscher *et al* 1978, Kapitulnik *et al* 1981). Here we assume that the system with a small dimension (the film thickness), l, will behave like a three-dimensional (3D) system when l is much larger than the concentration dependence correlation length, $\xi(X)$, and will exhibit 2D behaviour when $l \ll \xi(X)$. By matching the critical behaviour in the two cases at $l = \xi(X)$ and assuming simple power-law dependence for the coefficients on l, interdimensional scaling laws have been obtained (Fisher and Barber 1972, Imry *et al* 1973, Clerk *et al* 1980, Rappaport and Entin-Wohlman 1982).

In this paper we report on a complementary investigation to a preliminary work of Kapitulnik *et al* (1981). A 2D to 3D crossover is observed in the resistivity of Al–Ge thin mixture films. We show for the first time in real films that this crossover can occur at a given thickness by varying the metal concentration. We relate the observed crossover in the resistivity to the predicted concentration dependence of $\xi(X)$. The measured thickness dependence of X_c is also shown to correlate with $\xi(X)$.

Random continuous percolation theory predicts (Kirkpatrick 1978) $X_c = 15\%$ and $X_c = 50\%$ for the 3D and 2D cases, respectively. In the case of short-range correlations, one expects the critical behaviour to remain the same, though the threshold concentration need not be (Kapitulnik and Deutscher 1982).

In the granular Al–Ge form (Al crystalline grains embedded in an amorphous Ge matrix), obtained by evaporation onto room temperature substrates, $X_c \simeq 60\%$ (Deutscher *et al* 1978). In the random form, obtained by evaporation onto a hot substrate ($T \simeq 180\,^\circ\mathrm{C}$), with Al and Ge crystallite size $d \simeq 250$ Å (Kapitulnik *et al* 1981), X_c approaches the theoretical value of 15% in the thick film limit. These films are therefore appropriate for a study of the 2D to 3D crossover.

The Al and Ge were co-evaporated onto glass substrates from two electron beam guns through a mask with slits to combined thicknesses between 600 Å and 4000 Å.

On each substrate up to eighteen samples were obtained, with different metal concentrations due to different distances of the slits from the sources. The combined evaporation rate on all substrates was ~ 40 Å s^{-1} and the pressure during evaporation was $\sim 5 \times 10^{-6}$ Torr.

Electrical measurements were made using the four terminal method. The log–log plot of the resistivity, ρ, against the distance from the threshold concentration, $X - X_c$, shown in figure 1, is typical of intermediate thickness films. It shows a break in slope between two linear regions that can each be fitted to

$$\rho = \rho_0 (X - X_c)^{-t} \tag{1}$$

with $t = 0.9 \pm 0.25$ close to $X_c(l)$ and $t = 2.1 \pm 0.5$ far from $X_c(l)$ using $X_c = 15\%$.

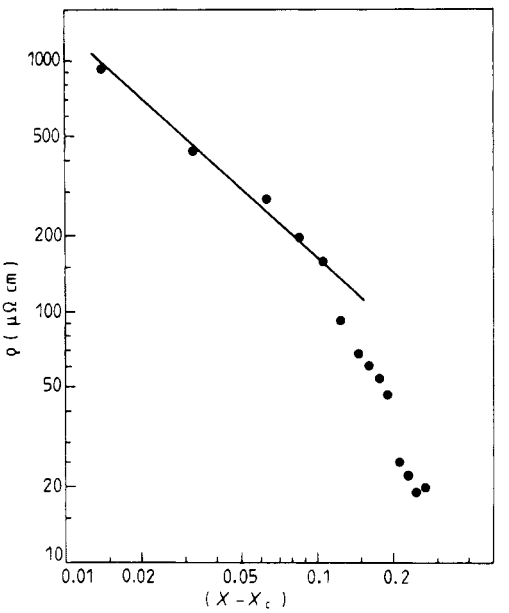

Figure 1. Log–log plot of the resistivity against the distance from the threshold concentration for one of the samples ($l \simeq 1200$ Å). The two straight lines are the best fit for the near and far values of X.

These exponents agree with recent theoretical values for the 2D ($\xi(X) > l$) and 3D ($\xi(X) < l$) regimes, respectively. (For a recent comparison of indices, see Bergman (1983).) The crossover is expected to occur when the 3D correlation length $\xi_{3D}(X) \cong l$. From the measured values of l, $(X - X_c)$ at the crossover and the equation

$$\xi_{3D} = \xi_0 (X - X_c)^{-\nu_3} \tag{2}$$

where $\nu_3 \cong 0.9$ (see e.g. Kirkpatrick 1978, Hoshen *et al* 1978, Rappaport and Entin-Wohlman 1982) we obtain $\xi_0 = (130 \pm 80)$ Å. This value is in agreement with the expectation that ξ should be equal to the crystallite size d, times a multiplicative constant b of order unity ($b \simeq 0.5$ in fair agreement with Hoshen *et al* (1978)).

The second graph (figure 2) is a log–log plot of the threshold concentration against the film thickness. For films of small to intermediate thickness, X_c was determined as the value giving the best fit to the power law (equation (1)). At large thicknesses,

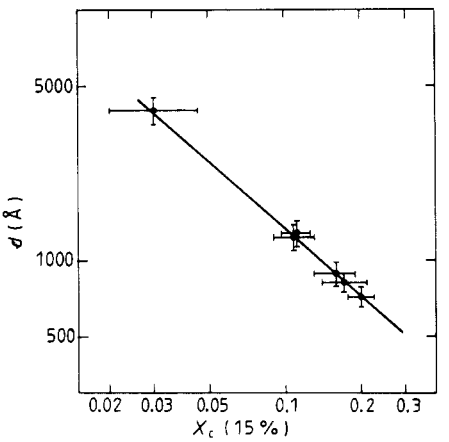

Figure 2. Log–log plot of the thickness against the critical concentrations.

no good fit could be obtained and X_c was selected as the value at which $\rho \simeq 1 \times 10^{-3} \Omega$ cm, but in practice the metal–insulator transition is very sharp in this material with ρ going up by orders of magnitude in the transition region so that somewhat different values criteria result in only slightly different values for X_c. Certainly the error bars are nevertheless larger for these samples.

The data are consistent with the predicted (Imry *et al* 1973) power-law behaviour:

$$X_c(l) - 0.15 = (l_0/l)^{1/\nu_3}. \tag{3}$$

The slope of figure 2 gives $\nu_3 = 0.9 \pm 0.2$ in good agreement with theory. The length l_0 ($l_0 = b^{\nu_3} d$) is found from the data to be equal to (170 ± 90) Å, i.e. $l_0 \approx \xi_0$ as expected.

In conclusion, we have found the thickness dependence of X_c to be consistent with the 2D to 3D crossover behaviour of the resistivity. These constitute two independent verifications of the scaling hypothesis as applied to percolation. In random metal–insulator mixture films the values obtained for t in the 2D and 3D regimes as well as the value for ν_3 and the amplitude of the correlation length are consistent with theoretical predictions.

Discussions with M L Rappaport are warmly acknowledged.

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