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Percolation critical currents in lead thin films

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We study the superconductor-insulator percolation threshold in a two-dimensional system and provide experimental evidence for the non-universality of the critical exponents for the critical current in two different cases: evaporated thin lead films and ion milled thin lead films. For evaporated films, the exponent measured was $v = 1.88 \pm 0.09$ and for ion milled films $v = 1.84 \pm 0.05$. In both cases, we found critical exponents greater than the exponents predicted for a discrete two-dimensional lattice ($v = 1.333$) and that are consistent with continuum percolation models and the microstructure of our films.

In two dimensional disordered superconductor systems, effects such as localization and scales of disorder, affect in a determinant way the superconducting properties of the material.

In granular films with a mesoscale disorder, localization effects are negligible and in this case, the superconductor-insulator threshold may be explained using percolation models.

Transport properties in disordered continuum systems near the percolation threshold can not be understood, in general by classical discrete percolative models. This problem can be resolved using continuum models in which there is a continuum distribution of occupied links in the lattice. We will consider, to explain our results, two types of continuum percolation models: to understand the evaporated films we use the Inverse Swiss Cheese model, in which islands of superconductors are located randomly in a insulating base. The ion milled films are explained using the Swiss Cheese model, which consist of holes randomly located in a superconductor uniform medium.

Critical exponents in this superconducting-insulating systems near the percolation threshold have been predicted to be non-universal. We present experimental evidence for the non-universality of the critical exponents for the critical current in two different systems: evaporated and ion milled films. We find in both cases critical exponents greater than the exponent for a classical discrete lattice.

The electrical characterization of the films was made through its voltage-current curve, at a constant temperature of 4 K and different thicknesses of the sample.

Samples were characterized at a temperature of 4 K in a dewar with liquid helium surrounded by a cylinder filled by liquid nitrogen. The lead films were formed by thermal evaporation and have a dimension of about 1×7 mm. The evaporated films have a measured thickness between 20 and 60 Å. The ion milled films were made from a previously deposited film of 500 Å formed at liquid nitrogen temperature. An ion gun allowed us to erode the films and if we suppose that the ion milling is uniform, the ion milling time can be related directly to the thickness of the film.

I-V characteristics were measured, during thermal evaporation, when the sample started to conduct and at intervals of 3 Å to 5 Å (at a thickness between 20 Å and 60 Å). We can see that in this regime the critical current increases strongly with the sample thickness (for the ion milled samples, the I-V curves for different ion milling times have the same shape that in evaporated films).

From these curves, we can plot the dependence of critical current with thickness for the two cases studied. We can assume that in this regime percolation theory is applicable and that the critical currents scales with thickness like $I_c \propto (d - d_c)^\gamma$,when d is the sample thickness and d_c is the critical thickness at which a critical current first appears (for ion milled films $I_c \propto (t_c - t)^\gamma$, where t_c is the ion milling time at which critical current disappears). With this, we can determine experimentally the critical exponent γ and try to related it with theoretical results. If we plot the critical current vs. $d - d_c$ (for evaporated films) or vs. $t_c - t$ for ion milled samples; and adjust d_c and t_c to obtain a power law, we can determine the

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exponent γ for both cases. Figure 1 presents these plots: (a) I_c vs. $d-d_c$ and (b) I_c vs. t_c-t. From these we found that $v = 1.88 \pm 0.09$ for evaporated films and $v = 1.84 \pm 0.05$ for ion milled films.

To understand these, consider the critical current density of a two dimensional percolative superconductor system which has the form[1]: $J_c \propto I_c \xi_p^{-1}$, when ξ_p, the percolation correlation length, varies near the percolation threshold like $(p-p_c)^{\nu}$. The term I_c, near the percolation threshold scales like $(p-p_c)^m$ and the critical current density in a two dimensional superconductor system near the percolation threshold has the form: $J_c \propto (p-p_c)^v$ when $v = m + \nu$. The exponent m depends on the micro structure and characteristic scales of the system[2] and gives the non universal behavior of the critical exponents in this systems.

From theory and in agreement with simulations made assuming a distribution of critical currents, the values of v are those shown in Table I:

Table I

Discrete Lattice	Swiss Cheese Josephson	Swiss Cheese Depairing	Inverse Swiss Cheese Josephson	Inverse Swiss Cheese Depairing
1.333	1.821	2.318	1.333	1.821

Which has to be compared to the exponent v determined experimentally (with an average over three samples for each case) of: $v = 1.88 \pm 0.09$ for evaporated films and $v = 1.84 \pm 0.05$ for ion milled films. In both cases the exponents measured are greater than the exponent expected for a discrete two dimensional lattice and the exponents measured in similar systems (for evaporated lead films on a germanium substrate)[3].

If we compare our results with those expect with theory, we find that our experiments will only be consistent if the typical island size for evaporated films, near the superconductor-insulator percolation threshold, is bigger than the coherence length for lead a 4 K, which in our case is 950 Å. This result have been verified by micrographs of transmission electron microscopy of samples evaporated at liquid helium near the percolation threshold. In agreement with theory, this result indicates that the system is in the regime where the smallest neck behaves like an one-dimensional wire (depairing case).

For ion milled fims, the exponent found suggest, near the percolation superconductor insulator threshold, a holes size less than 950 Å,

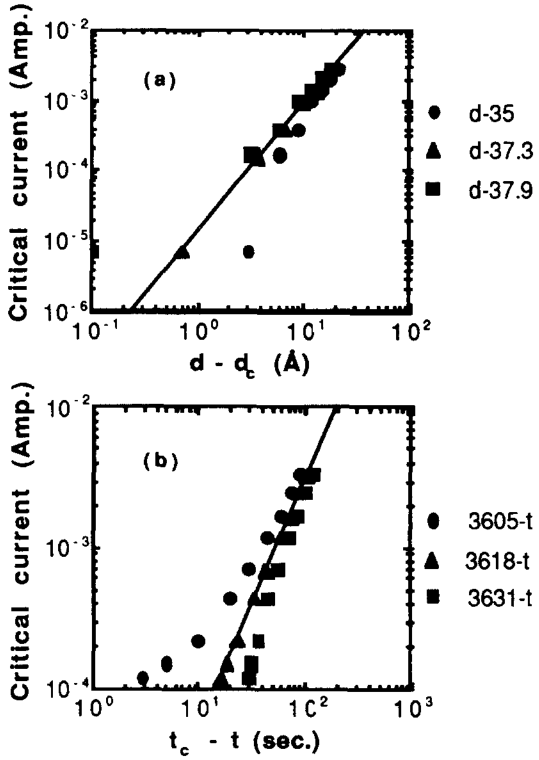

Figure 1

Figure 1. (a) Critical current vs. d - d_C for evaporated films at different thickness.

(b) Critical current vs. t_C - t for ion milled films at different ion milled time (thickness).

which is reasonable if we realize that erosion is due to collision of argon ions. In this case, the smallest neck behaves like a Josephson junction.

In conclusion, we have determined experimentally, for the first time, the non-universality of the critical exponents for the critical current in a two-dimensional superconductor system for two different cases, evaporated and ion milled films.

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