What are the effects of granularity and percolation on the I-S transition?

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Abstract

We have studied the insulator-superconductor transition (IST) by tuning the thickness in quench-condensed Bi films. The resistive transitions of the superconducting films are smooth and can be considered to represent homogeneous films. The observation of an IST very close to the quantum resistance for pairs $h/4e^2$ on several substrates supports this idea. The relevant length scales here are the localization length, and the coherence length. However, at the transition, the localization length is much higher than the superconducting coherence length, contrary to expectation for a homogeneous transition. This suggests the invalidity of a purely fermionic model for the transition. Furthermore, the current-voltage characteristics of the superconducting films are hysteretic, and show the films to be granular. The relevant energy scales here are the Josephson coupling energy and the charging energy. However, Josephson coupling energies (E_{J}) and the charging energies (E_{c}) at the IST, they are found to obey the relation $E_{\mathrm{J}}, E_{\mathrm{c}}$. This is again contrary to expectation, for the IST in a granular or inhomogeneous system. Hence, a purely bosonic picture of the transition is also inconsistent with our observations. We conclude that the IST observed in our experiments may be either an intermediate case between the fermioinc and bosonic mechanisms, or in a regime of charge and vortex dynamics for which a quantitative analysis has not yet been done.

Key words: Bi thin films; Quench condensation; Transport properties

1. Introduction

The interplay between disorder and superconductivity in two dimensions has been an active field of study during the last decade. Weak localization in two dimensions1 is a phenomenon where electronic states are localized by any arbitrary amount of disorder in the absence of interaction, resulting in nonmetallic behavior. Superconductivity is an effect in the opposite extreme, in which phase coherence is established due to electron-electron interaction, across the entire length of the sample. The interplay between these two opposing phenomena has led to various interesting results. [1–5]

2. Experimental Results

Our observations suggest that the film can be considered as a random array of Josephson junctions, which are shunted by a resistance. Consequently the resistively and capacitively shunted junction RCSJ model [6] can be used to describe the hysteretic behavior of the I-V curves, with the capacitance being the intrinsic capacitance of the junction. From the ratio of $I_{\min}/I_{mathrmc}$, the value of the admittance ratio β can be calculated. Here $\beta = \omega_{\mathrm{c}} C/G$, where $\omega_{\mathrm{c}} = (2e/\hbar) I_{\mathrm{c}} R_{\mathrm{s}}$. C is the intergranular capacitance and G the normal state conductance of the array. The values are calculated using single values of C and G, which correspond to capacitance and conductance of the array. C and G will have a range of values, the distribution of these values and the moments of the

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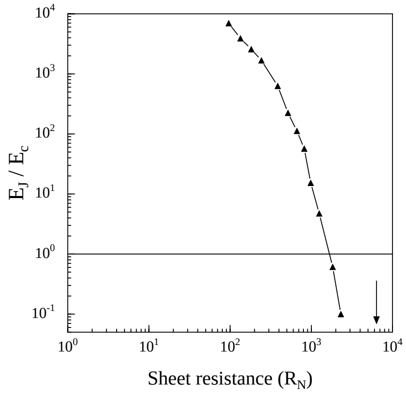

Fig. 1. Variation of $E_\mathrm{J}/E_\mathrm{c}$ with thickness.

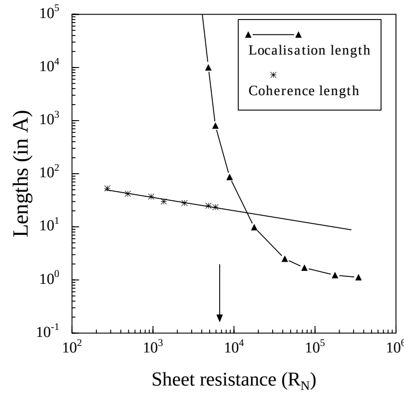

Fig. 2. Variation of ξ and ξ_{loc} with thickness.

distribution will of course depend on film thickness. We measure the critical current I_c for different films at T=2.0 K, lower than T_c for all the thicknesses studied, and calculate the relevant energy parameters such as the charging energy (E_c), Josephson coupling energy (E_J), etc.

Figure 1 shows the ratio of the Josephson coupling energy to the charging energy vs the sheet resistance for the films quench condensed on Ge underlayer at the temperature where the I-Vs were acquired, T=2.25 K. We find that even though the IST occurs near (R_c) , the relevant energy scales become equal at a much higher thickness. This suggests that the purely bosonic mechanism may be an incorrect picture for understanding the destruction of superconductivity in these films. We next investigate the validity of the fermionic mechanism.

To check whether the fermionic mechanism is a good representation of the physical mechanism, we estimate the electron localization length from the high-temperature resistance data, neglecting interactions. In previous work, which involved studies of quench condensed films on different substrates whose dielectric constants varied from 1.5 for solid Xe underlayers to 15 for Ge underlayers, we have demonstrated that the IST is robust and unaffected by the dielectric constant of the substrate. [7] This is our justification for neglect of interactions. We use the theory of Wølfle and Vollhardt [9] which describes the transition from weak to strong localization, neglecting interaction.

We determine the superconducting coherence length from upper critical field data (which has been presented in a separate publication [8]) using the Ginzburg-Landau definition. Fig. 2 shows the variation of the superconducting coherence length and the localization length with sheet resistance of the films. From the behavior of ξ at lower sheet resistances, this approximation is clearly justified. As is evident from Fig. 2, the IST occurs at a point where the localization length is much larger than the coherence length ξ_{oc} is 800 Å , whereas ξ is only 25 Å . The ratio ξ_{loc}/ξ is 32 in our study of quench condensed Bi films. This is to be contrasted with the results of Kagawa *et al.* [10] who found a ratio of two for Pb films. Whether this difference is due to the different materials studied, or the differing deposition geometry, is unclear to us at the present time.

Acknowledgements

The work is supported by DST and UGC, Government of India. KDG thanks CSIR for the research fellowship.

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