Critical fields and flux-flow resistances in strongly disordered ultra-thin superconducting films

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Abstract

Strongly disordered ultra-thin films of *Bi* and *Sn*, (< 100Å) produced by quench-condensation, are well known systems that show insulator to superconductor transition. Some aspects of the transition and the nature of the superconducting state are weakly dependent on the material and substrate, but we find that the critical field (B_{c2}) of *Bi* and *Sn* films of comparable resistance show different temperature dependences. For *Sn* the mean field B_{c2} is seen to vary with tempearature as $B_{c2}(T) = B_{c2}(0)(1-(\frac{T}{T_c})^2)$, whereas for *Bi* it is found to be $B_{c2}(T) = B_{c2}(0)(1-\frac{T}{T_c})^\alpha$ with $\alpha \approx 1.14$. In films with low sheet resistance we find a dissipationless vortex solid regime. The flux-flow resistance calculated from the *I*-*V* traces taken in several magnetic fields show a much faster field dependence than existing theories predict.

Key words: flux-flow, critical field, vortex-solid, disorder, quench-condensed

1. Introduction

Superconducting thin films placed in a transverse magnetic field cannot expel the field from its body unlike bulk superconductors in the Meissner phase. In a homogeneous thin film the normal and the superconducting regions arange themselves in an alternating striped pattern[1]. In case of a strongly disordered ultrathin film, the structure of this phase is likely to be more complicated. In this paper we present the $B_c - T$ phase diagram of these films obtained from *in-situ* measurements of resistivity of quench-condensed Bi and Sn films. We estimate the $T = 0$ coherence length of the Cooper pairs from the slope of the experimentally obtained $B_c - T$ line. The power laws that fit our observations as well as the rise of the flux flow resistance, much faster than the Bardeen-Stephen prediction,[2] has not been reported in these systems before. Certain properties of these systems which exhibit an insulator to superconductor transition are believed to be weakly dependent on the material and substrate, but clearly there are properties which differ significantly from material to material.

2. Experimental set-up

The experiments are done in a UHV cryostat, equipped with a 7 Tesla superconducting magnet, custom designed[3] for *in-situ* transport studies on quench-condensed films. The metal is evaporated from a Knudsen cell about 50 cm away from the a-quartz or crystalline sapphire substrate. The substrate is held at 14K during deposition and the deposition rate is $\sim$ 5Å/min. Hydrocarbon free vacuum of 5×10^{-8} Torr is maintained throughout the cooldown, deposition and measurement stages. At a time two identical Hall bar shaped samples are deposited and measured on the same substrate. One of them has a pre-deposited Ge underlayer.

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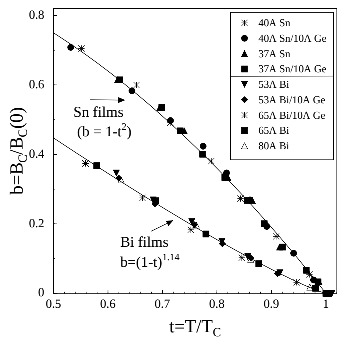

Fig. 1. Data from several films have been scaled, by T_c and $B_c(0)$ to obtain a data collapse. The data points from Sn and Bi films fall on two different curves on the B-T plane.

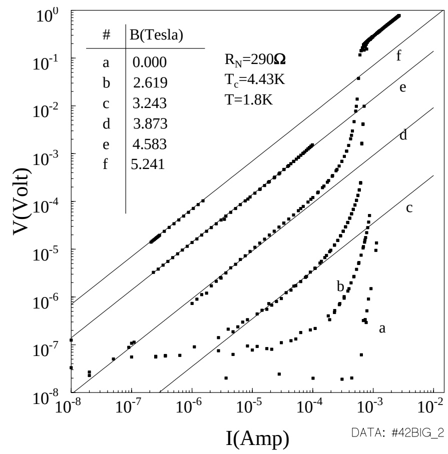

Fig. 2. I-V characteristics of a Bi film taken in magnetic fields. In this case curves a, b and c do not show a disipative region at low currents. Curves d, e and f have a linear and hence dissipative region, suggesting a vortex liquid phase.

For determining the B-T phase diagram, resistance vs temperature data is taken under several magnetic fields (data not shown). The temperature at which the resistance of the film drops to half of its normal state value is taken to be the T_c at that particular field. The flux flow resistance is determined from the I-V curves taken at temperatures below T_c under successively increasing magnetic fields.

3. Results

We show the B-T phase diagram for several films of Sn and Bi in a reduced plot 1 shown in fig 1. The data collapse on to two separate curves clearly brings out the difference between the films. The empirical fits to the curves are

$B_c(T)/B_c(0) = (1 - \mathrm{T/T_c})^{1.14}$ for Bi films and

$B_c(T)/B_c(0) = (1 - (\mathrm{T/T_c})^2$ for Sn films.

$B_c(0)$ is the extrapolated value of the upper critical field at $T = 0$. From the slope of the B_c-T_c line near T_c one can estimate the zero temperature coherence lengths $\xi(0)$ using the fact that near T_c,

$\xi(T) \approx 0.74\xi(0)/(1 - \mathrm{T/T_c})^{0.5}$.

Writing $B_c(T) = \frac{dB_c(T)}{dT_c}(T - T_c)$, we obtain $\xi(0)^2 \approx \Phi_0/(0.7\pi\frac{dB_c}{dT_c})$. From the phase diagram we see that the curve for Sn films approach T_c with a higher slope and hence $\xi(0)$ for Sn may be expected to be smaller than that for Bi. It is also of some interest to note that the behaviour of the Sn films follow that of a bulk type-I superconductor, the behaviour of a disordered (dirty) thin film is unlikely to be type-I. Whether this is an accidental coincidence needs further investigation.

The I-V curves taken in the superconducting regime also indicates that there is a dissipationless vortex solid phase at low temperatures and fields (curves a, b, c in fig 2). This gives way to a vortex liquid phase in which there is a clear linear, dissipative region (d, e, f in fig 2). The flux flow resistance at a particular field can then be calculated from each I-V characteristic with a linear region. Plots of $R_{\rm ff}$ vs B (not shown) indicate that $R_{\rm ff}$ rises much faster than the linear rise predicted by the Bardeen-Stephen model[2].

Acknowledgements

The authors acknowledge G. Sambandamurthy for help with several measurements. This work was supported by DST, Government of India. KDG thanks CSIR, Govt. of India for a research fellowship.

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