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Absence of a zero-temperature vortex solid phase in strongly disordered superconducting Bi films

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We present low-temperature measurements of the resistance in magnetic field of superconducting ultrathin amorphous Bi films with normal-state sheet resistances, R_N, near the resistance quantum, $R_Q=\hbar/e^2$. For $R_N<R_Q$, the tails of the resistive transitions show the thermally activated flux flow signature characteristic of defect motion in a vortex solid with a finite correlation length. When R_N exceeds R_Q, the tails become nonactivated. We conclude that in films where $R_N>R_Q$ there is no vortex solid and, hence, no zero resistance state in magnetic field. We describe how disorder induced quantum and/or mesoscopic fluctuations can eliminate the vortex solid and also discuss implications for the magnetic-field-tuned superconductor-insulator transition.

The question of whether a superconducting film can superconduct in the presence of disorder and a perpendicular magnetic field continues to receive a great deal of theoretical and experimental attention.[1–7] As a general question, it reflects on investigations of how disorder influences both thermal and quantum phase transitions.[8,9] More specifically, the answer impacts our understanding of the possible electronic phases of strongly correlated electronic systems.[10,11] A type-II superconductor in the mixed state exhibits zero dc resistance if the magnetic-field induced flux lines remain fixed in the presence of an applied current. This requires that the flux lines form a solid phase and that disorder in the superconductor is sufficiently strong to pin the solid. The pinning effects of disorder, however, can also interfere with the formation of an ordered flux-line solid.[12] Moreover, very strong disorder is expected to create mesoscopic and quantum fluctuation effects that also oppose ordering.[3,13]

Experiments suggest that flux-line solids with finite correlation lengths do form in low sheet resistance, $R_N \ll R_Q = \hbar/e^2 = 4.12\,\mathrm{k}\Omega$ (i.e., weakly disordered) quasi-two-dimensional superconductors. Signatures of melting[14] and thermally activated flux flow (TAFF) resistance with an activation energy consistent with the activation of mobile defects in a solid phase have been observed.[15–17] While these films are not expected to superconduct at nonzero temperatures because the energy to activate defects (e.g., edge dislocation pairs) is finite in two dimensions, it is possible that they superconduct at zero temperature.

Recently, a great deal of work has focused on the strongly disordered regime where $R_N \to R_Q$, and the superfluid density is low.[18–20] There have been opposing opinions over the extent of a vortex solid phase. Magnetotransport measurements on numerous systems have been interpreted and analyzed in terms of a superconductor-to-insulator quantum phase transition.[21] This picture requires the existence of a vortex solid phase that persists up to a critical field H_c that in some experiments is a substantial fraction of the superconducting upper critical field, H_{c2}.[22] In contrast, other experiments suggest that quantum fluctuations associated with the small superfluid density destroy the superconducting state at fields below H_c. In previous work, we proposed that quantum fluctuations cause the vortex solid to melt below H_c to form a quantum vortex liquid.[17] Other studies on single-layer[23] and multilayer systems[24] substantiate the claim that two-dimensional (2D) vortices are susceptible to disorder induced quantum fluctuations. In this work, we present strong evidence of a regime, $R_N \geq R_Q$, in which films which are zero-field superconductors do not superconduct in any finite magnetic field. We propose that strong mesoscopic and quantum fluctuation effects prevent the formation of the vortex solid phase.

The Bi/Sb films used in these experiments were deposited on a fire-polished glass substrate held near 4 K on the cold stage of a dilution refrigerator.[25,26] The film resistance was measured in a 2 mm×3.66 mm region with the standard four terminal technique using a lock-in amplifier at low frequency. The voltage in the sample was measured in the regime which was linear with excitation in the film and, for small sample voltage, checked against the slope of dc current-voltage characteristics at zero bias. A neighboring region of film was checked for uniformity of T_{c0} and R_N in each sample. The reported values for applied fields include a correction for flux trapping in the superconducting solenoid.

An example of the TAFF signature exhibited by many two-dimensional systems is shown in Fig. 1(a). The tails of the resistive transitions of this Bi/Sb film ($R_N/R_Q=0.86$, $T_{c0}=0.81\,\mathrm{K}$) follow $R=R_0\exp(-T_0/T)$ (where R_0 is a roughly field independent prefactor[17]) over the range $0.05<H/H_{c2}<0.5$ and $0.06<T/T_{c0}<0.5$. Experiments on a range of films show that the activation energy, T_0 depends on magnetic field, T_{c0}, and film thickness, t, as

$$T_0 \propto T_{c0} t \ln \frac{H_0}{H}, \qquad (1)$$

where the characteristic field H_0 corresponds to the field at which the activation energy extrapolates to zero. This dependence is demonstrated in the inset of Fig. 1(a). Scaling the measured activation energies by $T_{c0}t$ and adjusting the field scale H_0 for each film in a series of films in the range $0.6\,\mathrm{K}<T_{c0}<3$ K lead to the collapse of the activation ener-

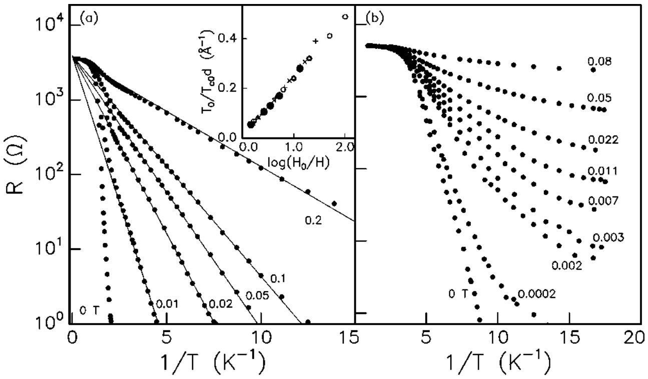

FIG. 1. (a) Thermally activated dissipation in a Bi/Sb film with $R_N = 3.53\,\mathrm{k}\Omega$ and $T_{c0} = 0.81$ K in applied fields of 0 T, 0.01 T, 0.02 T, 0.05 T, 0.1 T, and 0.2 T. The solid lines are fits to the activated portions. Similar behavior is observed in Bi/Sb films with $0.6 < T_{c0} < 3$ K. The inset shows the activation barriers as a function of magnetic field for a series of Bi/Sb films. The activation energies and the field scale for each film have been scaled by T_{c0} and t, and H_0, respectively. H_0 was chosen to achieve the best collapse of the data sets. The points extracted from the fit lines in Fig. 1(a) are shown as the larger black circles overlaid on previously published Bi/Sb data. (b) Nonthermally activated dissipation in a Bi/Sb film with $R_N = 4.84\,\mathrm{k}\Omega$ and $T_{c0} = 0.255$ K in applied fields: 0 T, 0.0002 T, 0.002 T, 0.003 T, 0.007 T, 0.011 T, 0.022 T, 0.05 T, and 0.08 T.

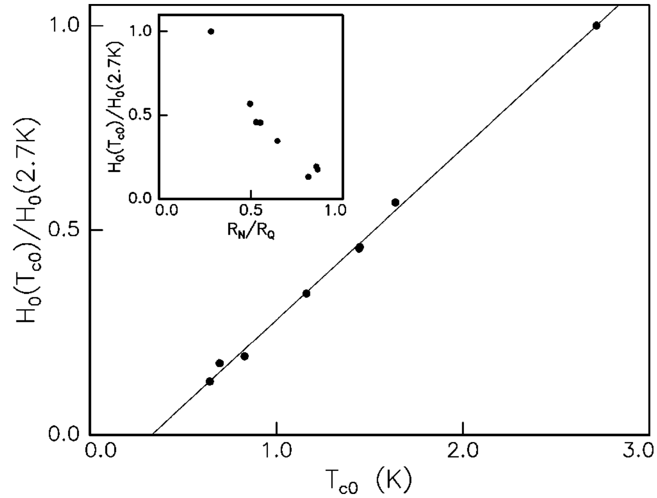

FIG. 2. The characteristic field scale, H_0, measured relative to its value for a $T_{c0} = 2.7$ K film as a function of T_{c0} for Bi/Sb films over the range of disorder where the vortex solid is exhibited [i.e., the scaling implied by Eq. (1) is observed]. The field H_0, determined from the data collapse in the inset of Fig. 1(a) decreases linearly with T_{c0}. The solid line shows a fit to the data which extrapolates to and implies that H_0 is zero for Bi/Sb films with $T_{c0} \approx 0.35$ K. The inset shows the dependence of $H_0/H_0(2.7\,\mathrm{K})$ with film R_N normalized by $R_Q = 4.12\,\mathrm{k}\Omega$.

gies shown. The logarithmic dependence works over at least a decade in field. The H_0 values obtained by creating the best collapse of the data agree well (to within 10%) of those obtained as the intercept of the fit of each data set to the logarithmic dependence.

The scaling of TAFF behavior shown in [Eq. (1a)] agrees with models that ascribe the dissipation to the thermally activated motion of defects in a collectively pinned, glassy vortex solid. Those models predict that a film superconducts in the low-temperature limit, as long as $H < H_0$, i.e., there is a finite barrier to dissipative processes. In earlier work, we pointed out that $H_0 < H_{c2}$ in Bi/Sb films,[27] implying the existence of a regime, $H_0 < H < H_{c2}$, which neither superconducts nor insulates. We referred to it as a quantum vortex liquid regime (QVL). Here, we present evidence that in more strongly disordered films, $H_0 \to 0$ implying that the QVL persists to arbitrarily low magnetic field.

Figure 2 exhibits how H_0 depends on T_{c0} and hence, disorder for a series of Bi/Sb films. The fields have been normalized to the characteristic field of the $T_{c0} = 2.7$ K film to emphasize that the collapse of the data achieved in the inset of Fig. 1(a) is sensitive to the relative magnitudes of the H_0's. We estimate that the error in these ratios is less than 10%. The solid line is a least-squares linear fit to the data with an x-axis intercept of $T_{c0}^* = 0.35 \pm 0.05$ K.[27] The fit gives a slope of 1.22 ± 0.03 T/K for $H_0(T_{c0})$. This finite intercept is significant as it implies that the average barrier to the thermal activation of dissipative processes is zero in films with $T_{c0} < T_{c0}^*$. Thus, TAFF behavior should cease when $T_{c0} < T_{c0}^*$ or, according to the inset of Fig. 2, $R_N/R_Q \approx 1$. Indeed, as shown in Fig. 1(b), the low-field transport of Bi/Sb films with $T_{c0} < T_{c0}^*$ deviates from TAFF behavior. These data come from a Bi/Sb film with $R_N/R_Q = 1.17$ and a $T_{c0} = 0.255$ K that was deposited in the same experiment as the film in Fig. 1(a). The tails of its transitions continuously curve away from a simple activated form and tend to level off, with the slope of each curve asymptotically approaching zero with decreasing temperature (i.e., approaching metallic behavior). We were unable to obtain good fits to these data using any simple power-law relationship [i.e., $\ln(R) \propto T^a \ln(H)]^b$ where a and b are constants) that have been suggested for vortex solids with nonlogarithmic interactions.[28] Nonthermally activated resistive transitions have been observed for all applied fields in two Bi/Sb films with R_N and T_{c0} of 4.85 kΩ and 0.255 K and 4.5 kΩ and 0.336 K, respectively.[29]

The lack of TAFF at any field implies the absence of a zero resistance, vortex solid phase even at $T = 0$. Furthermore, the systematic evolution of H_0 with T_{c0} and the coincidence of $T_{c0}{}^*$ with the disappearance of TAFF strongly suggests that a QVL replaces the vortex solid for $T_{c0} < T_{c0}{}^*$. This coincidence makes unlikely the alternative explanation that with increasing disorder the melting temperature of the solid phase becomes lower than accessible temperatures. The replacement of the vortex solid by the QVL that we propose, however, may not be complete. Patches of liquid and solid with a range of melting temperatures could coexist in this regime and render the same behavior. These patches may arise naturally (see discussion below) in a uniformly disordered system. The possibility that macroscopic inhomogeneities have occurred in the low T_{c0} films is ruled out by the recovery of TAFF with a submonolayer deposition of Bi on top of the film [See Fig. 1(a)].

Recent theories predict that nonthermal quantum and/or mesoscopic fluctuation effects can be sufficient to melt or partially melt the vortex solid when $R_N \approx R_Q$ in support of this interpretation. Blatter and Ivlev proposed that quantum fluctuations make vortices ''fuzzy'' or their cores effectively larger.[3] This effect causes the vortex solid to melt at lower fields than strictly thermal models would predict.[15] Melting at zero temperature[14,17] occurs at a field given by

$$\frac{H_m}{H_{c2}} = 1 - 1.2 \exp \frac{\pi^3 c_L^2 R_Q}{R_N}. \tag{2}$$

For a reasonable Lindemann parameter $c_L \sim 0.2$, Eq. (2) predicts that quantum fluctuations suppress H_m to near zero for $R_N \approx R_Q$. Within this framework, the onset of nonactivated transport below T_{c0}* occurs when quantum fluctuations make the average effective size of the vortex cores so large that H_m becomes zero.

Mesoscopic fluctuations in the number of electronic states near the Fermi energy may also contribute to or be the primary cause of the rise of the QVL. As noted previously, the number of electronic states in a superconducting coherence volume that are within Δ, the superconducting energy gap, of the Fermi energy approaches two in the limit $R_N \approx R_Q$.[19,20] Fluctuations in this number will be of the same order and will manifest themselves as spatial fluctuations in the order-parameter amplitude, or H_{c2} (Ref. 13) or T_{c0}.[4,9] Recently, we observed structure in zero magnetic field dc-IV curves of Bi/Sb films with $T_{c0} < T_{c0}$* that was consistent with the presence of fluctuations in the order parameter amplitude.[20] Spivak and Zhou showed that in finite magnetic field mesoscopic fluctuations lead to a distribution of H_{c2}'s with a width given by $\langle (\delta H_{c2})^2 \rangle / (H_{c2}^0)^2 = \gamma (R_N/R_Q)^2$ in a single sample ($\gamma \sim 1$).[13] To account for our observations we propose that areas with lower than average H_{c2} and larger than average vortices grow and create more of the measured dissipation with increasing R_N. The measured activation energy must then be an average over a distribution of energies. On mesoscopic scales, the energy to activate defects in the vortex solid or to unpin vortices in these low H_{c2} regions can be much smaller than the measured activation barrier. The deviations from activated behavior occur when regions with $H_{c2} \approx 0$ percolate across the film.

Our data provide evidence, in accord with the above theories, that the effective size of the vortex cores grows anomalously fast as $R_N \rightarrow R_Q$. The evidence comes from interpreting the field scale H_0. Within the TAFF models, H_0 [cf. Eq. (2)] should be proportional to H_{c2}. The latter sets the characteristic length scale, $\xi = \sqrt{\Phi_0 / 2\pi H_{c2}}$, the vortex core radius, in the logarithmic vortex-vortex interaction potential, where Φ_0 is the superconducting flux quantum. In accord with this expectation, the linear dependence of H_0 on T_{c0} shown in Fig. 2 quantitatively agrees with the mean-field, dirty limit, dependence of H_{c2} on T_{c0} (i.e., $H_{c2} = \Phi_0 k_B T_{c0}/0.18 hD$, where D is the electronic diffusivity). However, the finite x-axis intercept in Fig. 2 implies that $H_0 < H_{c2}$ and correspondingly, the effective size of the vortices in the Bi/Sb films, $\xi_q = \sqrt{\Phi_0 / 2\pi H_0}$ exceeds the superconducting coherence length as $T_{c0} \rightarrow T_{c0}$*. This discussion leads to the picture that the effective vortex core size relevant to vortex-vortex interactions grows faster with decreasing T_{c0} than expected for a mean-field dirty limit superconductor.

The absence of a vortex solid phase precludes the existence of a magnetic field tuned superconductor-to-insulator quantum phase transition (SIT). It implies the existence of an intermediate metallic regime such as the QVL. In accord with this assertion, the $R(T,H)$ of Bi films in higher magnetic fields do not follow the scaling behavior that has been taken as the primary evidence of a direct SIT.[10,22] Figures 3(a) and (b), which show the $R(T,H)$ of two films, one with $T_{c0} > T_{c0}$* and one with $T_{c0} < T_{c0}$* demonstrate this point. It is not possible to identify, in either data set, a single, critical magnetic field for which $dR/dT = 0$ in the low-temperature limit as is necessary for scaling the data. Instances for which scaling ''works'' are either at higher temperatures or in lower R_N films whose normal states have a weaker temperature dependence than shown in Fig. 3 (with notable exceptions[21]). To fix problems with scaling such as those in Fig. 3(a), Gantmakher suggested that the critical field corresponds to where the second derivative of the resistance with respect to temperature is zero rather than the first derivative.[31] Until theory justifies this modification it seems more reasonable to assume that no critical field exists. Within the quantum vortex liquid interpretation, the transition to the normal insulating state at high magnetic fields would be expected to be a crossover rather than a phase transition. The crossover would be similar to that which occurs near H_{c2} at nonzero temperatures in high-T_c superconductors.[30] The smooth evolution of the data in Figs. 3(a) and (b) seem more consistent with such a crossover.

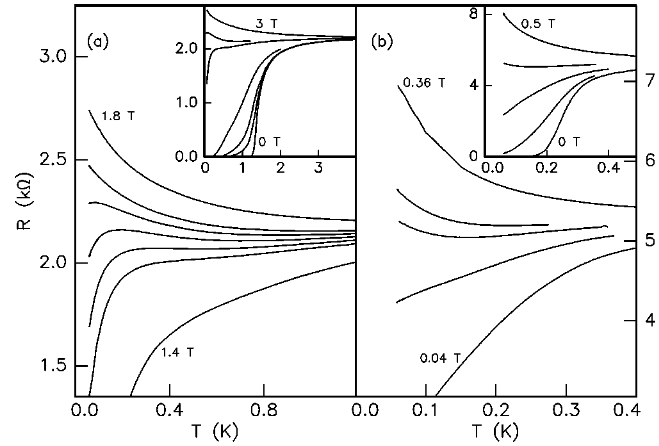

FIG. 3. Transport in Bi/Sb films with R_N above and below R_Q in fields ranging from zero Tesla to near H_{c2}. Neither data set features a ''critical field'' H_c at which the resistive transition exhibits $dR(H_c)/dT = 0$ over a reasonable range of temperature. (a) Bi/Sb with $T_{c0} = 1.44$ K in fields 1.4 T, 1.45 T, 1.5 T, 1.55 T, 1.6 T, and 1.8 T. Inset: Resistive transitions of the same film in applied fields 0 T, 0.1 T, 0.2 T, 0.5 T, 1.4 T, 1.55 T, and 3 T. (b) Transport in a Bi/Sb film with $T_{c0} = 0.255$ K in fields 0.04 T, 0.1 T, 0.15 T, 0.2 T, and 0.36 T. Inset: Resistive transitions of the same film in applied fields 0 T, 0.02 T, 0.1 T, 0.2 T, and 0.5 T.

In summary, thermally activated flux flow observed in superconducting Bi/Sb films in applied magnetic fields disappears when film disorder approaches a normal-state sheet resistance $R_N = R_Q = 4.12\ \mathrm{k}\Omega$. The disappearance in homogeneously disordered Bi/Sb coincides with the point at which the activation barrier observed in the less disordered films extrapolates to zero. This behavior implies that a superconducting vortex solid phase does not exist in these ultrathin, strongly disordered superconducting films. Theories suggest that mesoscopic and/or quantum fluctuation effects become strong enough in films where $R_N=R_Q$ that they melt the vortex solid phase at any applied field giving rise to a regime with metallic transport.

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