Magnetic-Field-Tuned Superconductor-Insulator Transition in Two-Dimensional Films

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A magnetic field is used to tune through a new superconducting-insulating transition of amorphous-composite indium oxide films at various stages of disorder. The results are in accord with scaling theory which identifies a universal sheet resistance separating a superconducting phase of localized vortices and Bose-condensed electron pairs from an insulating phase of Bose-condensed vortices and localized electron pairs. A unity dynamical exponent is confirmed and scaling behavior of the resistance over a wide range of temperatures and magnetic fields is found.

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Superconductivity in two dimensions (2D) provides a unique arena in which a wide variety of novel and fundamental physical phenomena occur. There is now, for example, almost unanimous agreement that the seminal ideas of Berezinskii[1] and Kosterlitz and Thouless[2] are applicable both to the melting of the Abrikosov vortex lattice and to the zero-magnetic-field vortex-antivortex phase transition. In addition, the systematic introduction and control of disorder provides an opportunity to explore the validity of predictions[3,4] and the suggestions of experiment[5] that a superconducting-insulating transition should have universal properties, including a universal metallic sheet resistance near $h/4e^2=6450\ \Omega/\square$ at the transition.

In experimental systems, the presence of disorder can introduce complications related to specific materials properties such as microstructure, contamination, chemical composition, and defect concentration. If the microscopic disorder is sufficiently homogeneous in the sense that the length scale characterizing the uniformity of disorder is longer than the length scale used by the theory to model the superconducting behavior, then there is an opportunity for a realistic comparison of experimental behavior and theoretical prediction. In this Letter, we present such a comparison using scaling theory of the magnetic-field-tuned superconductor to insulating transition, discussed in a companion paper,[6] to model the temperature- and field-dependent behavior of the resistance of amorphous-composite indium oxide (α-InO_x) films fabricated at different stages of disorder.

In this theory, disorder is measured by a variable Δ which is assumed to have continuous behavior through the transition. The superconducting coherence length ξ, introduced in the theory, diverges as $|\Delta_c-\Delta|^{-\nu}$ when disorder approaches criticality, $\Delta\rightarrow\Delta_c$. The exponent ν, not measured in our experiments, is predicted to have a lower bound of unity in 2D. The identification of the Kosterlitz-Thouless transition temperature T_c with a characteristic frequency (energy) which scales as ξ^{-z} *together with* the expectation that the critical field B_c will vanish as ξ^{-2} implies the relation $B_c\sim T_c^{2/z}$, where z is the dynamical exponent. Our experimental determination of T_c and B_c for films with varying amounts of disorder confirms the predicted value $z=1$. Furthermore, we verify the scaling dependence of the sheet resistance R on both T and B near this heretofore unstudied and new superconducting-insulating phase boundary using a procedure in which all free parameters have been determined experimentally. Finally, we find a value for the critical longitudinal sheet resistance R^* of the vortex-glass phase boundary to be near 5000 Ω but are unable to ascertain how constant this value is over a wide range of disorder.

In considering film properties and the appropriateness of α-InO_x for these studies, it is important to consider the roles of uniformity and disorder as they apply to this material. We note that metallic grains of In do not exist in these films[7] and thus one need not consider tunneling transport between grains, a process which can lead to large variations in the local resistance because of the sensitivity of tunneling to grain size, separation, and distribution. The measured variation in R between adjacent 100×100-$\mu\mathrm{m}^2$ squares is typically on the order of a few parts in a thousand, a stringent standard by most accounts. The amount of atomic or microscopic disorder is proportional to the film resistivity which in turn is related to the amount of oxygen present during film growth. Uniformity of atomic disorder on macroscopic length scales is also manifested in the transport properties: namely, a 3D scaling dependence of the conductivity on temperature[8] and a dependence of the mean-field transition temperature on resistivity down to thicknesses of 100 Å.[9] With respect to vortices, the good homogeneity of the films is manifested in measurements of the vortex unbinding temperature T_c.[10] The overall consistency of these measurements with theory implies that the longest length scales, set by available temperature, current, and magnetic field, are not limited by inhomogeneity. This evidence for unusually good homogeneity in atomically disordered α-InO_x films is also supported by the work of others.[11,12] Accordingly, we anticipate and will show below that α-InO_x films are suitable candidates for testing new scaling predictions in the quantum regime[6] at long length scales. These length scales are set by the magnetic field and turn out to be, for the lowest field, on the order of 3000 Å.

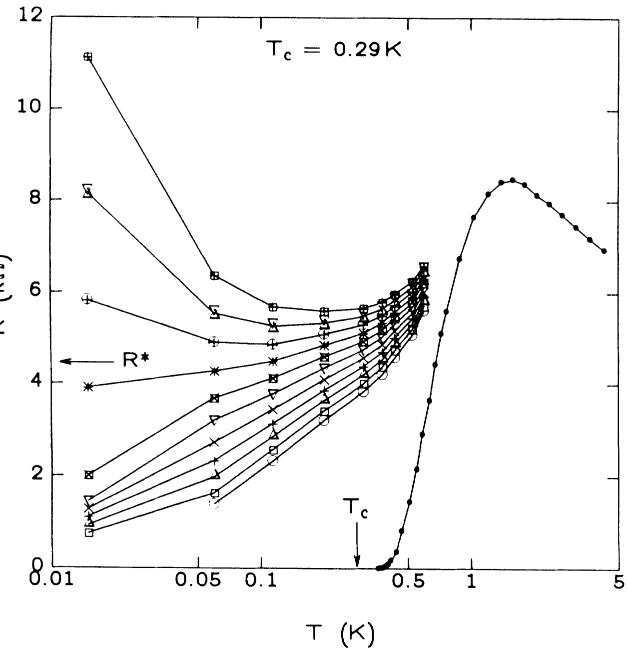

FIG. 1. Logarithmic plots of the resistance transitions in zero field (●) and nonzero field (open symbols) for a film with $T_c=0.29$ K. The isomagnetic lines range from $B=4$ kG (○) to $B=6$ kG (□) in 0.2-kG steps. The horizontal and vertical arrows identify R^* and T_c, respectively.

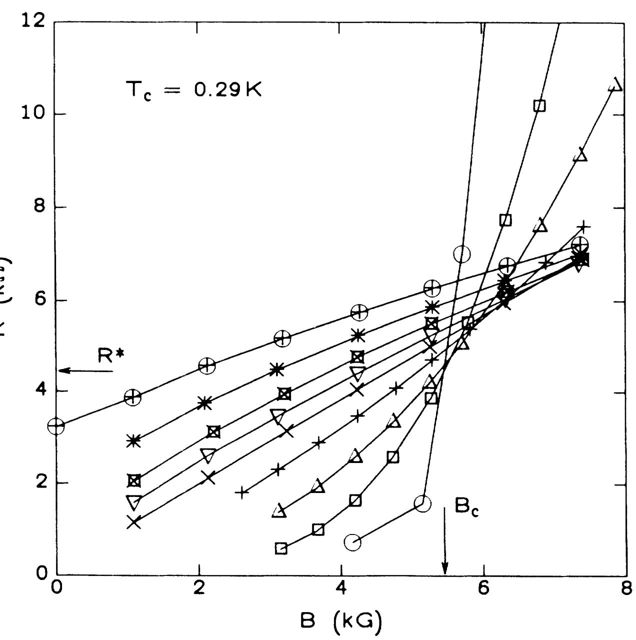

FIG. 2. Magnetic-field dependence of the resistance isotherms for the same film shown in Fig. 1. The temperatures and corresponding symbols are 0.015 K (○), 0.060 K (□), 0.114 K (△), 0.200 K (+), 0.308 K (×), 0.379 K (▽), 0.434 K (□), 0.528 K (*), and 0.599 K (⊕). The horizontal and vertical arrows identify R^* and B_c, respectively.

Five 100-Å-thick α-InO_x films[13] have been used for this study. Shown in Fig. 1 is the temperature dependence of the resistance of a film with $T_c=0.29$ K. The voltage scales linearly with current for all resistance measurements reported here. The solid circles represent the $B=0$ transition and the large open symbols represent isomagnetic curves for B ranging from 4 to 6 kG in 0.2-kG steps. We interpret the quasireentrant behavior near T_c as evidence for the partial formation of a superconducting condensate (above T_c and below the local maximum) which at lower temperatures evolves into the vortex phase that ultimately dominates the boson physics of the $T=0$ superconducting-insulating transition. The transition temperature T_c has been determined from the criterion that $R(T_c)\propto B$ for low field. This criterion was originally justified by concomitant observation of a cubic power-law dependence of voltage on current at the same temperature.[13] Recent arguments based on the Kosterlitz-Thouless renormalization equations[14] and on scaling theory[15] provide additional support for such a procedure. The rapidly changing slopes of the isomagnetic curves at low temperature in Fig. 1 are consistent with the presence of a $T=0$ field-tuned superconducting-to-insulating phase transition. The critical resistance at this transition, $R^*=4450$ Ω, is calculated by plotting $(dR/dT)|_B$ vs R at the lowest temperature and interpolating to the resistance (horizontal arrow) where the slope is zero. We expect accuracy to be best at the lowest temperatures where quadratic corrections[6] in T/T_c are minimized.

Identification of B_c is obtained by a similar procedure, this time by plotting $(dR/dT)|_B$ vs B at the lowest temperature and interpolating to the field where the slope is zero. For the film shown in Fig. 1, this zero-slope isomagnetic curve occurring at $B_c=5460\pm20$ G lies between the 5400- and 5600-G curves shown straddling the horizontal arrow at $R=R^*$. The isotherms of the R vs B plots of Fig. 2 reveal more clearly the significance of B_c (vertical arrow). As the temperature is lowered the crossover from low resistance (superconducting) to high resistance (insulating) becomes significantly more pronounced. The crossover sharpens up at $B=B_c$ and as $T\rightarrow0$ is expected to become a sharp transition in which an *infinitesimal change of field* can, in principle, drive the film from the superconducting state, through the critical resistance R^*, to the insulating state.

From the logarithmic plot of Fig. 3, the dependence of B_c on T_c for the five films is seen to be power law with an exponent $2/z=2.04\pm0.09$. This direct and unambiguous measurement of the dynamical exponent at the $B=0$, $T=0$ transition, i.e., $z=0.98\pm0.04$, is in excellent agreement with the theoretical prediction of unity. The independent determinations of T_c and B_c to accuracies on the order of a few percent over a range in which T_c varies by more than a factor of 10 and B_c varies by more than a factor of 100 attest to the insensitivity of the

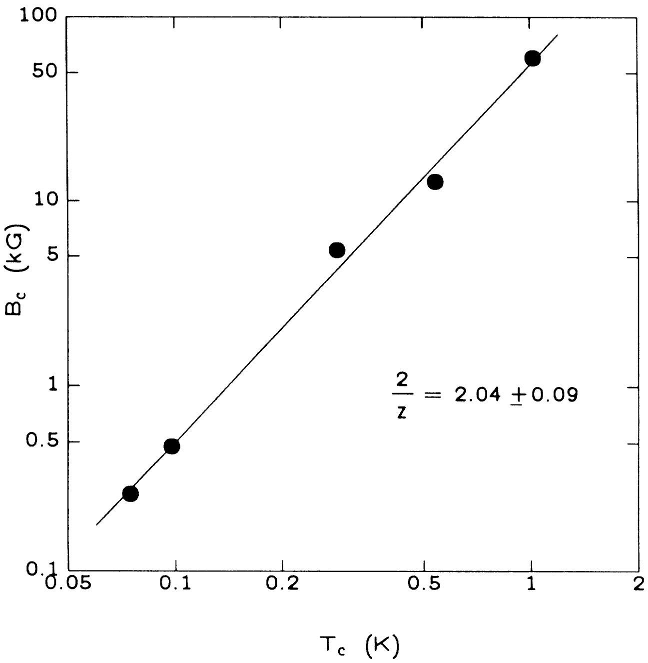

FIG. 3. Logarithmic plot of the critical field B_c vs the vortex unbinding transition temperature T_c for the five films studied. The slope $2/z$ is a direct measure of the dynamical exponent z.

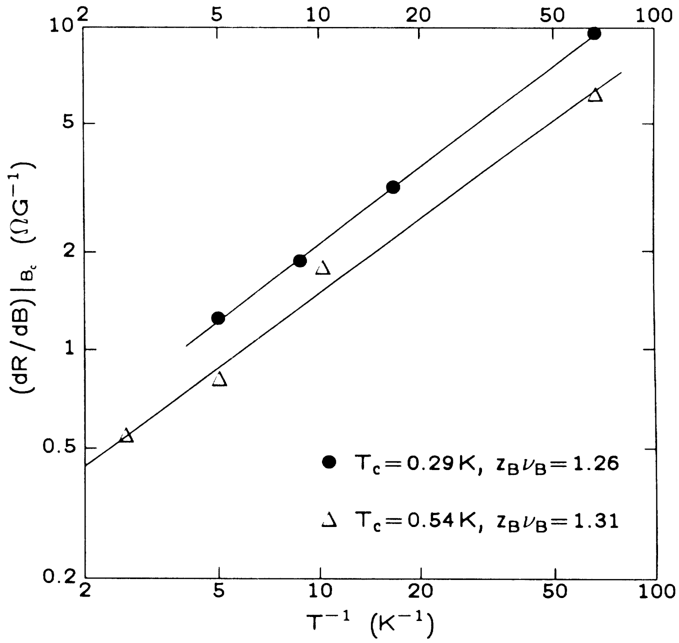

FIG. 4. Logarithmic plot of $(dR/dB)|_{B_c}$ vs $1/T$ for the film with $T_c = 0.29$ K (●) and the film with $T_c = 0.54$ K (Δ). The product of exponents, $z_B \nu_B$, is equal to the reciprocal of the slopes.

value of z to experimental uncertainties. Using the relation $\xi^2 \sim \Phi_0/B_c$, these data imply $\xi \sim 180$ Å for the highest field ($B_c = 60.7$ kG) and $\xi \sim 2800$ Å for the lowest field ($B_c = 0.26$ kG). This suggests that disorder in the films is uniform out to length scales on the order of at least 3000 Å.

The coherence length ξ and the exponents z and ν characterize the scaling behavior of the $B = T = 0$ transition. The dependence of B_c on ξ, a length which diverges with increasing disorder Δ, is analogous to the well-known dependence [i.e., $2\pi H_{c2}(T)\xi_{\rm GL}^2(T) = \Phi_0$] of the upper critical field H_{c2} on the Ginzburg-Landau length $\xi_{\rm GL}$, a length which diverges with increasing temperature and is also defined at $B = 0$. A different set of exponents, z_B and ν_B, and a different scaling function, $\tilde{R}[c_0(B - B_c)/T^{1/z_B\nu_B}]$, characterize the behavior of the resistance near the field-tuned superconducting vortex-glass ($T = 0$, $B \neq 0$) to insulator phase boundary.[6] The constant c_0 is nonuniversal. Fortunately, an experimental determination of the product $z_B\nu_B$ can be made by evaluating $(dR/dB)|_{B_c}$ at fixed T, i.e.,

$$(dR/dB)|_{B_c} = (h/4e^2)c_0 T^{-1/z_B\nu_B}\tilde{R}'(0)\,, \qquad (1)$$

and then plotting $(dR/dB)|_{B_c}$ vs T^{-1} using logarithmic scales. We note that $\tilde{R}'(0)$ is finite. The resulting dependences, shown for two different films with respective T_c's indicated in the legend, are shown in Fig. 4. Only data for $T < T_c$ has been used. The power-law slopes (solid lines) for the two films are consistent with Eq. (1) and agree to within 4%. By evaluating the reciprocals we find $z_B\nu_B = 1.26$ for the $T_c = 0.29$ K film and $z_B\nu_B = 1.31$ for the $T_c = 0.54$ K film. These values are consistent with the predicted theoretical constraints $z_B = 1$ and $\nu_B \geq 1$.

With a knowledge of B_c and $z_B\nu_B$, the scaling form of $\tilde{R}$ can now be directly tested *without the use of fitting parameters*. This is done, as shown in Fig. 5 for the two samples of Fig. 4, by plotting $R(T,B)$ against the absolute value of the scaling variable $(B - B_c)/T^{1/z_B\nu_B}$. Each plotting symbol, identified in the caption, represents $R(T,B)$ at fixed B for different T. The branches $B > B_c$ and $B < B_c$ are identified in the figure. Good scaling occurs when all of the data fall on the same curve. The cusplike curves shown in Fig. 5 reveal such scaling for a factor-of-10 variation in R and a factor-of-100 variation in the scaling variable. The quality of scaling is insensitive to the value of $z_B\nu_B$ but extremely sensitive to B_c. For example, only a 5% increase or decrease in B_c produces a noticeable excursion of these data from the scaling curve. We conclude that scaling is well obeyed.

The horizontal arrows in Fig. 5 are drawn at the values of the critical resistance R^* determined by the procedure described earlier. These values, $R^* = 4450$ Ω for the $T_c = 0.29$ K film and $R^* = 4800$ Ω for the $T_c = 0.54$ K film, are in close proximity to the cusps of the scaling curves. Although these two values of R^* differ by less than 10%, we are currently not comfortable in making a definitive statement about the universality of R^*. If universality does indeed hold, then the scaling functions for samples having a large variation in disorder

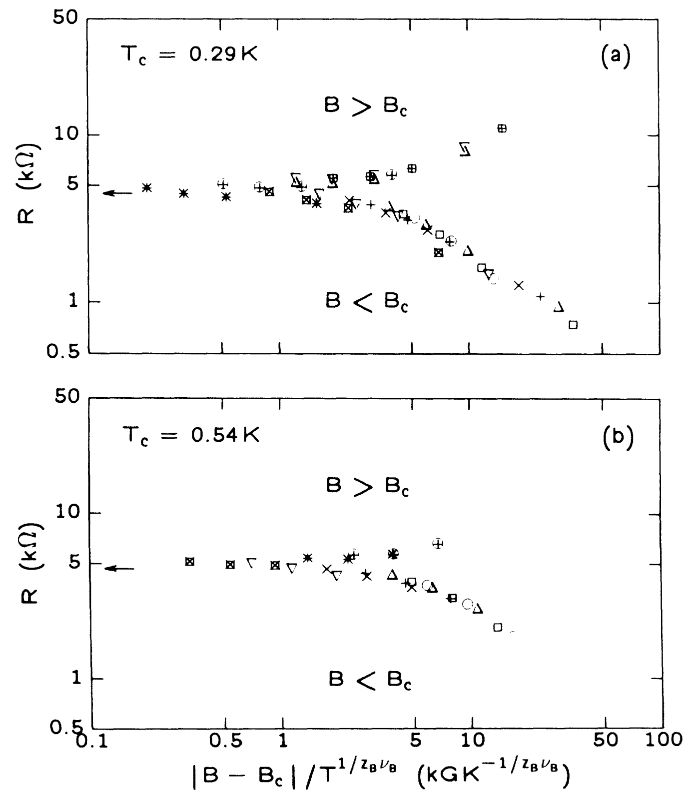

FIG. 5. Scaling dependence of the resistance for (a) the film with $T_c = 0.29$ K and (b) the film with $T_c = 0.54$ K. The two branches, $B > B_c$ and $B < B_c$, take into account the change in sign of the scaling variable $|B - B_c|/T^{1/z_B\nu_B}$. The symbols in (a) follow the same field sequence as in Fig. 1 although the temperatures corresponding to each symbol are restricted to $T < T_c$. Similar labeling applies to panel (b). The horizontal arrow in each panel locates the zero-slope determination of R^* for each film.

should all coincide and converge to the same value of R^* in the cusp region. This would occur only after taking into account the differences in c_0, a sample-dependent constant which affects the horizontal placement of the curves shown in Fig. 5. For the two most disordered samples reported here with T_c's below 0.1 K, the reduced temperature T/T_c was not sufficiently low to obtain an accurate measure of the zero-slope isomagnetic line (cf. Fig. 1), thus leading to less precision in the determination of B_c. In addition, as disorder increases and $T_c \to 0$, the domain of the scaling region for the vortex-glass transition becomes considerably diminished and the determination of R^* more problematical.

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