Superconducting-Insulating Transition in Two-Dimensional a-MoGe Thin Films

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A zero-temperature magnetic-field-tuned superconducting-insulating transition is observed in two-dimensional a-MoGe films. The low temperature transport properties of these films show scaling behavior consistent with a transition driven by long-range Coulomb interactions and quantum phase fluctuations in a two-dimensional superconductor. However, contrary to the theoretical predictions we find the critical resistance to be sample dependent. We suggest that the apparent lack of universality in the critical resistance is due to the finite contribution of fermionic excitations to the resistance.

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The interplay near the metal-insulator transition between randomness, Coulomb repulsion, and the pairing mechanism that creates superconductivity is a topic of intense research. In two dimensions, this interplay becomes particularly interesting, since the lower critical dimension for both localization and superconductivity is 2. A number of previous studies of ultrathin film superconductors have established that increasing the disorder by increasing the sheet resistance results in the suppression of superconductivity in two dimensions [1]. More recent results for the high disorder regime suggest that increasing the disorder to a critical amount results in a continuous zero-temperature superconducting-insulating transition driven by quantum fluctuations [2,3].

The existence of superconductivity in the high disorder limit becomes even more intriguing when one considers that the application of a magnetic field drastically alters the nature of superconductivity in two dimensions by inducing vortices, which remain mobile at any finite temperature due to the presence of disorder [4]. Superconductivity in the sense of zero resistance requires that the vortices not be mobile and is hence expected to exist only at $T = 0$, where vortices freeze into a vortex glass phase [5]. Considering the importance of quantum fluctuations in this vortex glass phase, Fisher [6] has proposed that there will be a $T = 0$ superconducting-insulating (SI) transition, tunable with a magnetic field, which is caused by the competition between quantum fluctuations of the phase of the order parameter and the long-range Coulomb repulsion. Relying on the duality between charges and vortices in a model which ignores fluctuations in the superconducting amplitude, Fisher argued that at the critical field for this SI transition, a Bose metal exists with a universal sheet resistance, independent of all material parameters, and close to the quantum of resistance for Cooper pairs, $R_Q = h/4e^2 \sim 6.4\ \mathrm{k}\Omega$. This SI transition is predicted to be continuous, with a correlation length ξ that diverges as B approaches B_c as $\xi = \xi_0[B - B_c]^{-\nu}$, with $\nu > 1$. Near the transition, the energy relaxation in this system is determined by a dynamical exponent z such that the characteristic energy $\Omega \sim \xi^{-z}$. For the case of long-range Coulomb repulsion between the pairs in two dimensions, $z = 1$.

To date, there have been a number of reports of experimental evidence for the proposed transition in amorphous thin films [7], high-T_c superconductors [8], and Josephson junction arrays [9]; however, there are still a number of important issues regarding the nature of this transition which have not been addressed. One such issue is the fact that the scaling theory has been constructed as a boson-only model with coreless vortices, while in real materials there is always a parallel channel of fermionic excitations. At this time, the importance of such excitations and their effects on the proposed transition remains unclear. On the experimental side, the values of the critical exponents for this transition have not been determined independently and the universality of the critical sheet resistance R_c is still an open question.

In this Letter, we report the experimental observation of a magnetic-field-tuned superconducting-insulating transition in a-MoGe films. From the scaling of the transport properties near the critical field B_c at low temperatures, we are able for the first time to independently extract the critical exponents ν and z for samples covering a wide range of disorder. However, our measurements of the critical value of the sheet resistance, R_c, show a wide variation, in contradiction to the prediction of a universal $R_c \simeq R_Q$. Motivated by these results, we have considered the possibility that the presence of normal unpaired electrons induced by the finite magnetic field could affect the universal behavior predicted for this transition.

The samples used in this study are a-MoGe films of two different compositions grown by multitarget magnetron sputtering on Si substrates with a Ge buffer layer. As shown in Table I, the samples studied here are at various stages of disorder, with $R_\square$ ranging from 600 Ω to 2000 Ω. It is important to note that the normal state resistivities of these ultrathin films are not much higher (factor of about 1.5) than the normal state resistivities of bulk samples with the same compositions [10]. We therefore expect these samples to be highly amorphous, with a characteristic length scale for the disorder potential of the order of a

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TABLE I. The samples and their derived parameters.

No.	Comp.	d [Å]	R_n [Ω]	R_c [Ω]	T_{c0} [K]	B_c [kG]	B_{c2} [kG]	ν	z	R_b [kΩ]
1	$Mo_{21}Ge$	70	1980	2026	0.100	2.82	...[a]	1.28 ± 0.09	1.0 ± 0.1	...[a]
2	$Mo_{21}Ge$	80	1710	1750	0.150	4.19	...[a]	1.36 ± 0.05	1.0 ± 0.1	...[a]
3	$Mo_{43}Ge$	30	1400	1372	0.50	12.4	14 ± 0.1	1.30 ± 0.10	1.0 ± 0.1	6.0 ± 0.5
4	$Mo_{43}Ge$	40	951	924	1.01	17.7	19 ± 0.1	1.30 ± 0.10	1.0 ± 0.1	6.0 ± 0.5
5	$Mo_{43}Ge$	60	658	651	1.02	25.6	27 ± 0.1	1.30 ± 0.07	1.0 ± 0.1	6.0 ± 0.5

[a]Unable to estimate from the data.

few atomic spacing. For the purpose of the transport measurements, the samples were patterned and mounted close to the mixing chamber of a dilution refrigerator operating inside a shielded room.

Figure 1 shows the temperature dependence of the zero bias sheet resistance $R_\square$ for sample 2 measured at different values of the magnetic field. At low magnetic fields, as the temperature is reduced, $R_\square$ shows a rapid drop from its normal state value R_n and continues to drop as $R_\square = R_0 e^{-U/T}$, due to the thermally activated motion of vortices at finite temperatures. Raising the magnetic field increases the low temperature limit of $R_\square$ and eventually, at large fields, $R_\square$ rises with decreasing temperature, signaling the onset of insulating behavior in the zero temperature limit. In this regime, the resistance follows the form $R_\square(T) = -R_0 \ln T$, characteristic of weak localization. The inset of Fig. 1 shows the behavior of the same sample, replotted as a function of the magnetic field for different fixed temperatures. The inset shows clearly the existence of a critical value of the magnetic field, $B_c = 4.19$ kG, at which $R_c = R_\square(B_c) = 1750\ \Omega$ is independent of temperature. The value R_c for this sample appears to be close to—but different from—the normal state resistance R_n, which is determined in zero field. For these samples with $R_c < R_n$, at fields $B_c \leq B \leq B_{c2}$, the mean field upper critical field, there is a minimum in the resistance as a function of temperature, indicative of the presence of a nonzero superconducting amplitude for fields $B > B_c$. For these films it is possible to estimate $B_{c2}(0)$ as the field at which the resistance minimum disappears and instead the resistance rises monotonically with decreasing temperature. The results of these estimates of critical fields are tabulated in Table I along with the measured values of R_c for each sample. The wide variation of the critical resistance among our samples clearly challenges the prediction of a universal $R_c \simeq 6.4$ kΩ.

The dynamical resistance ($\delta V/\delta I$) measured at low frequencies as a function of dc voltage also reflects the presence of a SI transition. Figure 2 shows the dynamical resistance measured for sample 2 at 70 mK in the presence of magnetic fields close to the critical field $B_c = 4.19$ kG. For fields $B < B_c$, the behavior of the dynamical resistance is consistent with the dissipative motion of vortices in a two-dimensional superconductor at finite temperature. The nonlinearity in the resistance in this regime is caused by the depinning of the vortices by the applied currents. However, at B_c where $\delta V/\delta I$ equals R_c, $\delta V/\delta I$ is also approximately independent of the bias voltage. The Ohmic response at B_c indicates metallic behavior, which is usually not present in disordered two-dimensional electron systems. For $B \geq B_c$, $\delta V/\delta I$ drops with the applied voltage, $R(E) \simeq -R_0 \ln(E)$ which, together with the low temperature behavior of the zero bias resistance, indicates the presence of an insulating phase at zero temperature.

Close to the SI transition, i.e., $B \simeq B_c$ and $T \simeq 0$, the linear response and the nonlinear response of the system are governed by the divergence of the correlation length

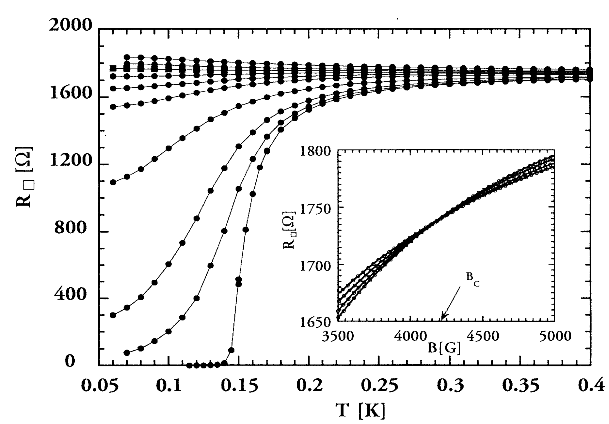

FIG. 1. Zero bias resistance of sample 2 plotted versus temperature at $B = 0$, 0.5, 1.0, 2.0, 3.0, 4.0, 4.4, 4.5, 5.5, 6 kG. In the inset, $R_\square(B, T, E = 0)$ for the same sample measured versus field, at $T = 80$, 90, 100, 110 mK.

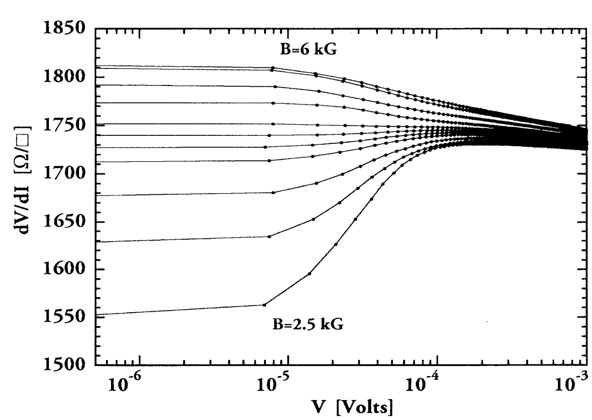

FIG. 2. Dynamical sheet resistance measured for sample 2 as a function of the bias voltage at 70 mK for $B = 2.5$, 3.0, 3.4, 3.8, 4.0, 4.2, 4.4, 4.8, 5.4, 5.9, 6 kG.

ξ and the characteristic energy Ω. At low but finite temperature, in the critical regime, the divergence of ξ is cut off by a length scale L_T, which is determined by the temperature: $L_T \sim T^{-1/z}$. Similarly, at finite voltages, the experiment probes the system on a length scale set by the applied electric field, $L_E \sim E^{-1/1+z}$. Using these characteristic lengths, we can derive a scaling relation for $R_\square$ with temperature, electric field, and magnetic field near B_c [6]:

$$R_\square(B,T,E) = R_c \mathcal{F}\left(\frac{c_a|B - B_c|}{T^{1/z\nu}}, \frac{c_b|B - B_c|}{E^{1/(z+1)\nu}}\right), \qquad (1)$$

where c_a and c_b are nonuniversal constants and $\mathcal{F}(B,T,E)$ is the scaling function. This scaling function can be reduced to a single-variable function if we fix the value of either the electric field E or the temperature T. Two independent measurements determine z and ν independently: Scaling of the zero bias resistance with T and B determines the product $z\nu$ while the scaling of the dynamical resistance with E and B determines $(z + 1)\nu$.

For each sample, the $R_\square(B,T,E = 0)$ data were used to test the scaling prediction by varying B in small increments at fixed temperatures. As shown for sample 2 in the inset of Fig. 1, these measurements can determine B_c accurately (within 2%). Using the B_c determined from this method, we then plot the measured $R_\square(B,T,E = 0)$ against the scaling variable $|B - B_c|/T^{1/z\nu}$, and adjust the power $z\nu$ to obtain the best visual collapse of the data [11]. Figure 3 shows the collapse of $R_\square(B,T,E = 0)$ onto two branches, for two different samples (2 and 5), using $z\nu = 1.36$. Figure 3 also demonstrates that the scaling prediction with the above value for $z\nu$ is equally well obeyed for samples with very different critical resistances. However, despite the sample dependences of R_c, normalizing $R_\square(T,B)$ by R_c for samples 2 and 5 as shown in the inset of the lower panel of Fig. 3 yields one curve which is independent of sample and, perhaps, *universal*. This collapse suggests that there is a universal scaling function for the resistance as predicted by the scaling analysis above.

According to Eq. (1), $\delta V/\delta I$ should also show scaling behavior near the transition at B_c with respect to the scaling variable $[B - B_c]/E^{1/(z+1)\nu}$. However, this prediction holds only at the lowest temperatures in the intermediate voltage regime when $L_T \ll L_E \sim \xi$. As shown in Fig. 4 for sample 2, $\delta V/\delta I$ data which are measured at fixed voltages while varying B can be accurately scaled using $\nu(z + 1) = 2.73$. Since the best scaling of the linear resistance data for this sample was obtained using $z\nu = 1.36$, we determine the exponents $\nu = 1.36 \pm 0.05$ and $z = 1.0 \pm 0.1$. A similar scaling analysis of both the zero bias and dynamical resistance in other samples yields similar values for the critical exponents, tabulated in Table I. Moreover, the sample-independent values of the critical exponents measured here are clearly different than those describing the mean-field transition at B_{c2} and they

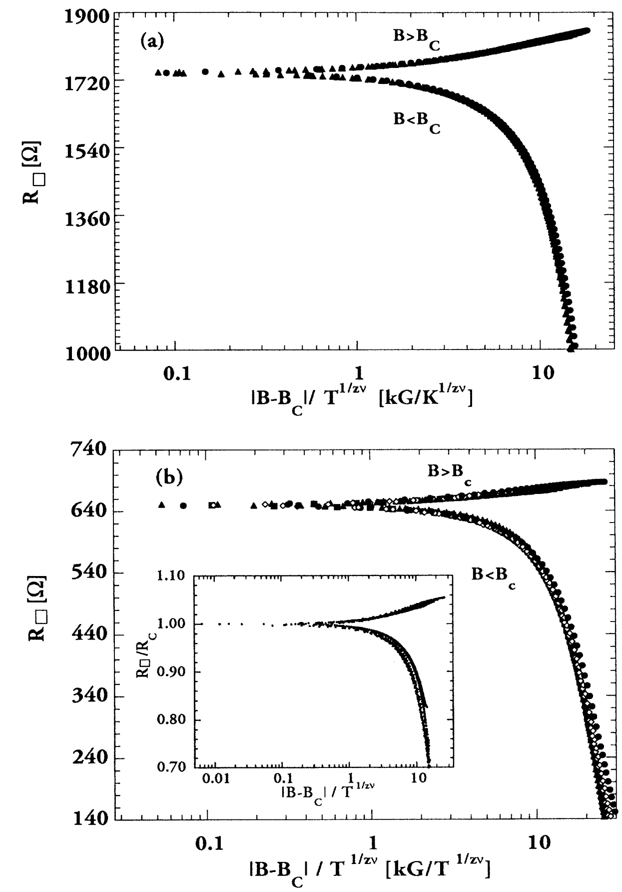

FIG. 3. Top: Scaling of $R_\square(B,T,E = 0)$ for sample 2 measured at $T = 80$, 90, 100, 110 mK ($B_c = 4.19$ kG, $\nu z = 1.36$). Bottom: Scaling for sample 5 of the data measured at $T = 100$, 200, 300, 400 mK ($B_c = 25.6$ kG, $\nu z = 1.36$). Bottom inset: $R_\square/R_c$ versus the scaling variable for samples 2 and 5 together.

in are good agreement with the theoretical estimates by Fisher [6] for the SI transition.

While the scaling analysis described above shows clear evidence for the proposed SI transition, due to the proximity of B_c to B_{c2} and R_c to R_n, we must consider the possible effects of the unpaired normal electrons on the transport properties near the SI transition. A simple approach is to consider a two-fluid model for the conduction near the SI transition: $\sigma = \sigma_f + \sigma_b$, where σ_f represents a conduction channel due to the fermionic excitations, i.e., the unpaired electrons, and σ_b is the contribution to the conduction by the Cooper pairs (bosons). While at zero temperature the total conduction is either zero or infinite depending on the magnetic field; at any finite temperature the conduction is finite and is due to both the paired and the unpaired electrons. Following this approach, in the critical regime for the field-tuned transition at $B = B_c$, the measured critical conductance $\sigma_c = 1/R_c$ is the sum of the critical conductance for the bosons (Cooper pairs),

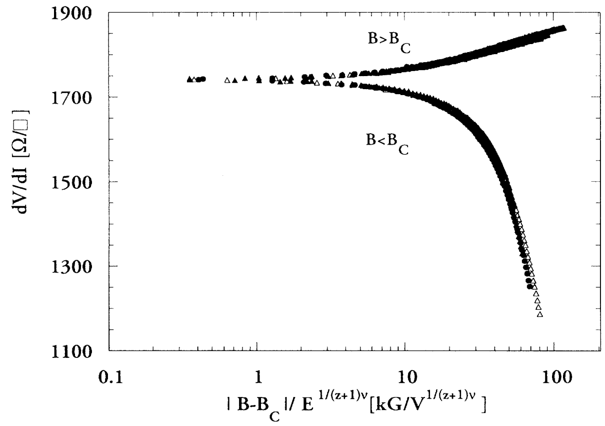

FIG. 4. Scaling of the $\delta V/\delta I$ for sample 2 measured at $T =$ 70 mK [$B_c = 4.19$ kG, $\nu(z+1) = 2.73$].

$\sigma_b = 1/R_b$, and a background conduction due to unpaired electrons, $\sigma_f = 1/R_f$, which is, in principal, related to the normal state resistance, giving $R_c = R_b/[1 + (R_b/R_f)]$. From this relation, we expect that when $R_f \gg R_b$, i.e., when unpaired electrons are strongly localized, the critical resistance at the transition is determined solely by the Cooper pairs and $R_c = R_b(B_c)$ which is expected to be close to R_Q. Indeed, the previously reported value of $R_c \sim 5$ kΩ in InO_x films [7] with $R_n \sim 10$ kΩ appears to be in this highly disordered limit. In the opposite limit (the samples reported here), the unpaired electrons are only weakly localized and they contribute significantly to the conduction at finite temperatures; hence, R_c is close to $R_f \sim R_n$ and no longer universal. However, in our experiment the fact that R_f depends weakly on temperature makes possible the observation of the critical behavior associated with the Cooper pairs near the SI transition. It is also interesting to note that, while finite temperatures naturally lead to fermionic excitations in a superconductor, such excitations may also occur due to the gapless nature of the BCS excitations in high magnetic fields near B_{c2} [12].

In the above discussion we have used our two-fluid model to account for the wide range of values of R_c observed in our films, while assuming that $R_b(B_c) \simeq R_Q$. However, we can check equivalently the universality of $R_b(B_c)$ by using the above model and the measured values for R_c, R_n, B_c, and B_{c2}. Inverting the relation above, we have $R_b = R_c/[1 - (R_c/R_f)]$. In making this estimate of $R_b(B_c)$, we can approximate the contribution of the unpaired electrons $R_f \sim R_n n_e(B)/n_e$, where $n_e(B)/n_e$ is the normal electron fraction, which can be estimated using the Ginzburg-Landau result $n_e(B)/n_e \sim (B/B_{c2})^2$. As shown in Table I, the consistent value of about 6 kΩ for R_b derived for three different samples is very suggestive. It is important to note that the uncertainty in the above estimate of R_b is due to our inaccurate determination of B_{c2} and resistance R_f at this field. However, the experimental problem of determining B_{c2} is fundamentally related to the ill-defined nature of the mean-field transition in two-dimensional samples.

In conclusion, the low temperature transport properties of a-MoGe films show scaling behavior consistent with a continuous SI transition driven by field-induced localization of Cooper pairs, phase fluctuations, and long-range Coulomb repulsion. We find the values of the critical exponents to be sample independent and in agreement with the theoretical estimates. In contrast, the values of the critical resistance show wide variation among the samples, contrary to the predicted universal value close to $h/4e^2$. We have suggested that the apparent lack of universality may be due to the conduction of the unpaired electrons which are present in finite magnetic fields and at finite temperatures in any superconductor. However, despite the importance of the normal electrons, we have used a two-fluid model of conduction and have estimated the Cooper pair contribution to the resistance at the SI transition to be of the order of $h/4e^2$ within our experimental error. This interpretation suggests that the universal properties predicted for Cooper pairs at SI transition remain unchanged despite the presence of fermions in the system.

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