Dissipation Effects on the Superconductor-Insulator Transition in 2D Superconductors

N. Mason and A. Kapitulnik
Department of Applied Physics, Stanford University, Stanford, California 94305
and Department of Physics, Stanford University, Stanford, California 94305
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Results on the superconductor to insulator transition in two-dimensional films are analyzed in terms of a coupling of the system to a dissipative bath. Upon lowering the temperature the parameter that controls this coupling becomes relevant and a wide range of metallic phase is recovered. [S0031-9007(99)09549-6]

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Quantum phase transitions (QPT) continue to attract intense theoretical and experimental interest. These transitions—where changing an external parameter in the Hamiltonian of the system induces a transition from one quantum ground state to another, fundamentally different one—have been invoked to explain data from various experiments, including quantum-Hall liquid to insulator, metal to insulator, and superconductor to insulator (SI) measurements. Many experiments have focused on the SI transition, which can be tuned by both disorder and magnetic field [1–3]. Usually, theoretical understanding of this transition is obtained by mapping the problem onto the so-called "dirty-boson" model, where it is described in terms of interacting bosons (Cooper pairs or vortices) moving in the presence of disorder [4]. At zero temperature, quantum fluctuations and disorder activate vortex-antivortex pairs, thereby tuning the SI transition. The transition is also tuned by a magnetic field, which induces vortices of one vorticity; with no disorder an Abrikosov lattice of these vortices realizes the superconducting phase. However, an arbitrary amount of disorder disrupts the lattice and a true superconducting phase is assumed to be recovered only at $T = 0$. In the superconducting phase, vortices are localized into a so-called vortex-glass phase [5] and the Cooper pairs are delocalized. Above a critical field H_c, vortices delocalize and Cooper pairs localize into a Bose-glass phase. Further increase of the magnetic field gradually dissociates the Cooper pairs, and fermion degrees of freedom then determine the properties of the system. A finite conductivity is expected at the SI transition, where both vortices and Cooper pairs are delocalized in a "Bose-metal" phase. The above scenario was the basis for a scaling theory proposed by Fisher [5] in which a field-tuned transition was considered as a continuous transition with an associated diverging length $\xi \sim (H_c - H)^{-\nu}$, as well as a finite, universal conductivity at the transition [6].

In previous field-tuned experiments on amorphous MoGe [3], we showed good scaling for a range of disorder in agreement with the aforementioned scaling theory of the SI transition [5]. However, we did not find a universal critical resistance. Subsequently, a more detailed study of the superconducting phase (i.e., the vortex-glass phase) revealed that at low fields and lower temperatures the resistance changes from being activated to being temperature independent [7]. This unexpected behavior in the vortex glass phase has been seen in other systems [8,9] and was interpreted as quantum tunneling of vortices or dislocations [7]. With the assumption of continuity as a function of increasing magnetic field, we concluded that there was no true superconducting phase all the way to the critical field. Since the above results are incompatible with the presently acceptable theory that describes the SI transition [5], a better understanding of the experimental evidence for the QPT is in order.

The present paper is therefore aimed at resolving the above puzzle by a detailed investigation of scaling close to the critical point. This is done by measuring at lower temperatures and with higher resolution than before, such that we are able to distinguish statistical from systematic scatter in the data. Our present results suggest that while the quantum critical point is indeed apparent at low temperatures and the agreement with scaling is excellent, lowering the temperature further results in a rapid disruption of scaling. We interpret these results as evidence of a coupling of our system to a dissipative environment, presumably a background of delocalized fermions whose existence was first conjectured by Yazdani and Kapitulnik [3]. Such coupling to dissipation could lead to a new phase diagram for the system, shown pictorially in Fig. 1 where to the standard H-T disorder phase diagram [5], we add a new axis, α, representing the strength of the coupling to a dissipative bath (so the figure is a slice at fixed disorder). Upon cooling the system the coupling to the bath becomes more relevant and the system flows away from the unstable critical point (the pure dirty bosons point) into a wide range of "metallic" behavior. In fact, depending on the system, the opening of the metallic region could leave a diminishingly small region where true superconductivity can be found. In the case of MoGe with $R_\square$ of order 1.5 kΩ we showed [7] that already at 20% of H_c, superconductivity is lost. The proposed phase diagram for the QPT in the SI case should be viewed as very general. The implications of our analysis go much beyond the SI problem, and in fact

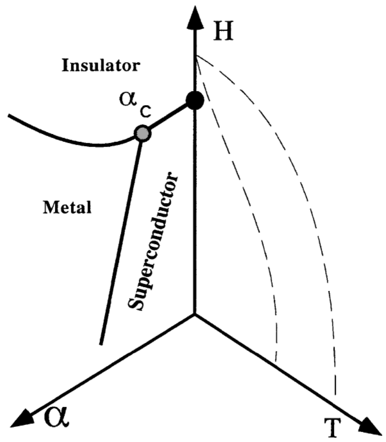

FIG. 1. Phase diagram for the field-tuned SI transition: H-T dissipation strength diagram at finite disorder. α_c marks the point at which a finite range of metallic phase opens up.

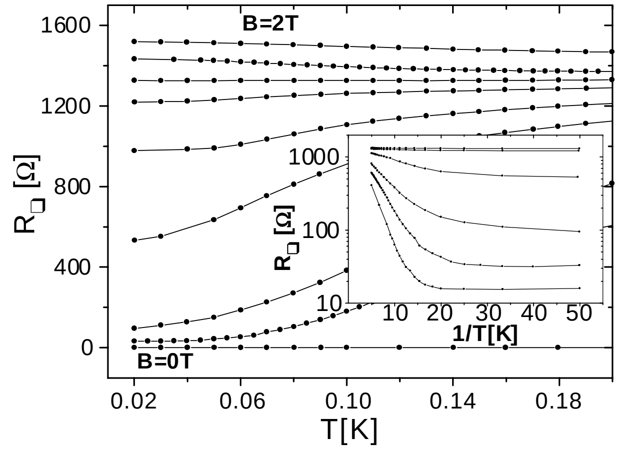

FIG. 2. Set of resistance vs temperature curves for $B = 2$, 1.3, 1.23, 1.18, 1.1, 1.0, 0.75, 0.70, and 0 T. Inset: $\log R_\square$ vs $1/T$ for $B = 0$, 0.6, 0.7, 0.75, 1, 1.18, and 1.21 T.

bear on all QPT in two dimensions, as will be explained below.

Continuing to use amorphous-MoGe films as our model system, we have conducted further measurements to better examine the low temperature temperature-independent behavior and dissipative coupling. These experiments were performed on thin films grown by multitarget magnetron sputtering on a SiN substrate with a Ge buffer layer. The films were grown in the same sputtering runs as those used in [3] and [7]; details of growth and characterization are described elsewhere [10]. Most of the data reported in this paper were taken on films with $x = 0.43$, thickness of 30 Å, and $T_c \sim 0.5$ K. Previous studies have determined the films to be highly amorphous and homogeneous over all relevant length scales. The films were patterned into 4-probe structures, and measured in a dilution refrigerator using standard low-frequency lock-in techniques. Care was taken to eliminate spurious noise and heating effects. Measurement conditions were similar to those in [3,7]; however, for the current experiments, an improved dilution refrigerator allowed us access to lower temperatures and greater stability. A typical set of resistance vs temperature for increasing magnetic field data is given in Fig. 2. Similar results were obtained for all films including those reported in [3,7]. A main feature of these results is that upon lowering the temperature the activated behavior of the resistance changes to a temperature independent resistance as the temperature approaches zero, as can be seen in the log $R_\square$ vs $1/T$ inset of Fig. 2. In [7] the low temperature saturation value of the resistance obeys the empirical form

$$R(H) = R_0 e^{c(\hbar/e^2 R_\square)H/H_{c2}}, \qquad (1)$$

with $R_\square$ being the resistance per square of the sample and $c \simeq 2$ is a constant. This unusual behavior was explained by Shimshoni *et al.* [11] using dissipative quantum tunneling of vortices from one "insulating" puddle to its neighbor. The source of dissipation was assumed to be the electrons in the core of the vortex, suggesting the use of Bardeen-Stephen [12] expression for the viscosity in the Euclidian action governing the tunneling. If the vortex tunneling is mediated by coupling to a dissipative bath, then finite diffusion appears which explains the flattening of the resistance as T approaches zero. This model produces an excellent fit to the experimental data (e.g., the theoretical model, using Bardeen-Stephen dissipation gives $c \simeq 1.6$ for the prefactor). Since the superconducting phase is obtained in this model by percolation of couplings of superconducting puddles, this model also explains the exponent $\nu \simeq 1.35$ found in all field-tuned transitions by many groups, since the correlation-length exponent in 2D classical percolation is $4/3$.

To check the scaling and flattening of the resistance in the MoGe films, we extended the temperature range by measuring down to 20 mK from low field through the presumed SI transition. A blowup of the transition region is shown in Fig. 3. Here we observe that as we go to low temperatures, all curves, whether initially decreasing or increasing, flatten. This affects scaling in a dramatic way. Following [5] we fit isotherms for $T \geq 100$ mK to $R = R_c \mathcal{F}[(H - H_c)/T^{1/z\nu}]$. The scaling function $\mathcal{F}(x)$ displays two branches, for positive ("insulating") and negative ("superconducting") arguments. A best fit to the scaling function for high temperature isotherms gives $z\nu = 1.33 \pm 0.05$, as shown in the upper part of Fig. 4. The dotted and dashed lines in the figure show the deviation of the 20 and 50 mK lines from the other scaled curves. This deviation, which evinces the breakdown of scaling with respect to the critical point, is amplified in the lower part of Fig. 4. We believe that this low temperature deviation from scaling and flattening of resistance manifests that the isolated metallic point at H_c "opens up" to a region of metallic behavior as a function of some parameter that becomes relevant at low temperatures. Adding the hypothesis of vortex tunneling in a dissipative medium, we

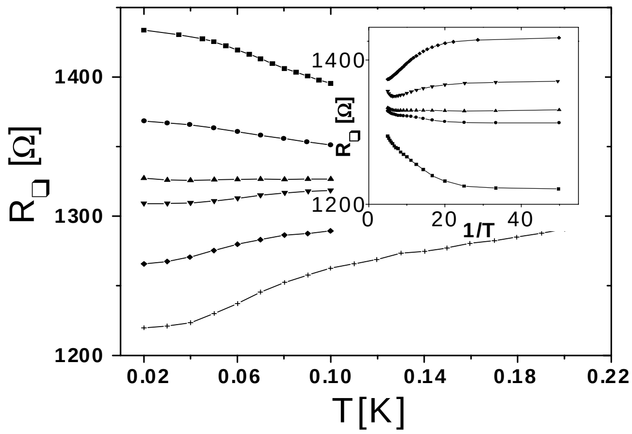

FIG. 3. Set of resistance vs temperature curves for $B = 1.3$, 1.26, 1.23, 1.21, 1.2, and 1.18 T. Flattening of the resistance at low temperatures coincides with breakdown of scaling. Inset: $\log R_\square$ vs $1/T$ for the same data set.

conclude that the natural parameter that "pulls" the system away from the SI transition critical point is the strength of the coupling to the dissipative bath. Starting with a system with fixed disorder we naturally arrive at the phase diagram presented in Fig. 1. Note that the phase diagram allows for a finite range of α in which the SI transition is preserved, a feature that we discuss next.

Dissipation in connection with the SI transition was first studied by Chakravarty *et al.* [13,14] with a quantum statistical mechanics model of an array of resistively shunted Josephson junctions. This model predicted a superconducting to normal-state transition as a function of dissipation. More recently, Wagenblast *et al.* [15] attempted to explain nonuniversal results observed in experiments on homogeneous [3] and inhomogeneous thin films [1] by introducing a model with local dissipation in which the dissipative term couples only to the phase of a single island. Their model led to a new universality class at the SI transition. In particular, they found that the conductivity at criticality is nonuniversal and is characterized by a damping-dependent dynamical critical exponent. Both models [14,15] preserve the SI transition but do not allow for a range of a metallic phase. Along with the fact that neither model includes disorder (in [13] randomness was discussed and argued not to change the nature of the phase diagram), we believe that the absence of dual excitations (i.e., vortices) in the treatment of the transition excludes a finite range of metallic phase. In the absence of vortices, a metallic phase is excluded automatically, according to our proposed scenario as outlined below [16]. However, in the absence of dissipation and for strong enough disorder a pure SI transition is expected according to [5], and thus we allow for a range, $\alpha < \alpha_c$, for which a metallic phase exists only at the transition point itself. For weak disorder this range may be very small, as is presumably the case for the MoGe films discussed here.

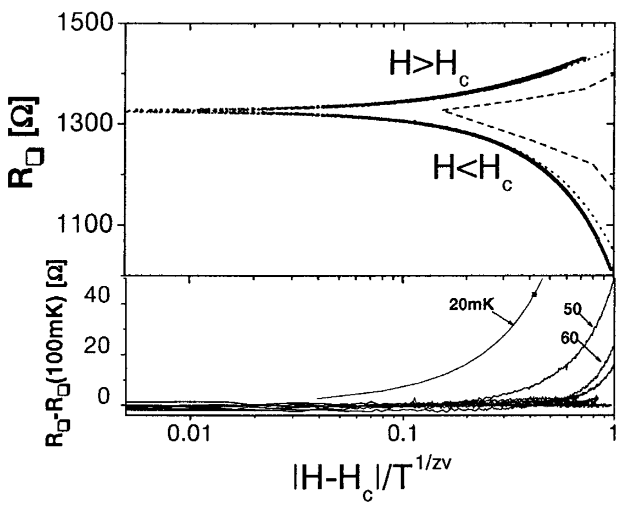

FIG. 4. Upper: Scaling for $T \geq 100$ mK, yielding $z\nu = 1.33 \pm 0.05$. 20 mK (dashed line) and 50 mK (dotted line) curves strongly deviate from others. Lower: Deviation of scaled curves from "standard" (100 mK) curve. Note that only the low temperature curves show significant deviation.

Leveling of the resistance—and therefore a probable coupling to dissipation—in field tuned transitions has been observed in other experiments on thin superconducting films [8] and in Josephson Junctions arrays [9]. Even more intriguing is the fact that the analogous problem of the quantum Hall effect to insulator transition (QHIT) exhibits similar effects. In this problem a sharp change in the behavior of the resistivity at low temperature as a function of the magnetic field has been interpreted as a quantum phase transition between localized bosons and localized vortices [17]. While scaling has been observed with high accuracy for this problem [4], recent experiments reveal that occasionally samples fail to exhibit scaling, and the resistance on the quantum Hall liquid side levels to a constant, suggesting quantum tunneling [18].

Quantum tunneling of vortices in the SI transition problem, or of edge states in the QHIT problem, are a natural consequence of the Shimshoni *et al.* model [11]. This model predicts continuous transitions for the SI transition or QHIT cases which are percolationlike. Its importance is that it allows for a destruction of the superfluid phase due to incoherent tunneling of vortices (in the SI transition) or of edge states (in the QHIT). The missing ingredient of the model is the existence of a dissipative bath to which the system may couple with some strength α. This deficiency, which is corrected in the present paper, leads to the generalized phase diagram presented in Fig. 1. Combining the percolation model of [11], the argument of [13] that in the random array model the transition is governed by the properties of the typical junction, and the argument of Schmid [19] that depending on the parameters of the junction its behavior will change from coherent to diffusive, it seems that a metallic phase must exist in the SI problem. A similar argument should hold for the QHIT problem. However, for samples in which the dissipation is weak the QHIT may still be preserved, as has been observed by many authors [20]. In these cases it is no surprise that the resistance at the critical field is the quantum resistance, h/e^2, and that the exponent is $\nu \sim 7/3$, a value consistent with quantum percolation. The failure to observe scaling in samples that show flattening of the resistance [18] is interpreted as an indication that a stronger α exists in these samples. We therefore suggest that for these samples scaling should be attempted with the high temperatures data only. This should lead to a result similar to the one presented here for the SI transition with $\nu \sim 4/3$. In fact, following our prediction we examined Fig. 3(a) of [18], which presented the asymptotical behavior of the activation energy in the QH state. This activation energy is proportional to $T^{1/z\nu}$ and gives $1/z\nu \simeq 3/4$, very different from other QHIT results of $3/7$ or $3/14$. While scaling is observed in this high temperature limit, the critical resistance is different from the universal resistance, similar, again, to the SI results. Dephasing in the QHIT problem on the insulating side was discussed by Pryadko and Auerbach [21] resulting in a finite Hall resistivity at $T = 0$. However, the source of dissipation is still unknown in this problem.

Finally, we comment that our discussion above is very general and should apply to any two-dimensional quantum critical point where dissipation can be relevant. A possible candidate is the newly discovered metal-insulator transition in Si MOSFETs. Here the insulator is believed to be a Wigner crystal. In the presence of disorder this problem resembles that of a vortex glass in the SI transition problem [22].

In conclusion, in this paper we presented a new phase diagram for the superconductor-insulator transition problem in the presence of coupling to a dissipative bath. We argued that as the critical point is approached by, e.g., lowering the temperature, this coupling may become a relevant variable in the problem and thus pull the system to a new phase which is metallic in nature. We further proposed that this scenario is very general and may explain the recent results on flattening of the resistance observed in quantum Hall to insulator transitions.

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