

Superconductor-insulator transition in a capacitively coupled dissipative environment

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We present results on disordered amorphous films that are expected to undergo a field-tuned superconductor-insulator transition. The addition of a parallel ground plane in proximity to the film changes the character of the transition. Although the screening effects expected from “dirty-boson” theories are not evident, there is evidence that the ground plane couples a certain type of dissipation into the system, causing a dissipation-driven phase transition. The dissipation that drives this phase transition couples similarly into quantum phase transition systems, such as superconductor-insulator transitions and the Josephson junction arrays.

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Although quantum phase transitions (QPT's) have attracted much attention in recent years, there are still discrepancies between theoretical expectations and experimental results. QPT's occur at zero temperature, where quantum fluctuations are relevant and the system's dynamics and thermodynamics are intertwined. A continuous transition occurs as one parameter in the Hamiltonian of the quantum system is varied; then, quantum critical phenomena are expected to give rise to interesting, universal physics.¹ Of particular interest is the field-tuned superconductor-insulator transition (SIT), where effects of Coulomb repulsion, disorder, and dissipation are all expected to affect the QPT.² While this transition was long thought to be a paradigm of the “dirty-bosons” theory, recent experiments demonstrating a low-temperature metallic state intervening in the SIT and a coupling of the system to dissipation have cast doubt on this model.^{3,4} Similar results on other QPT systems—especially those expected to be in the same universality class, such as the quantum Hall liquid to insulator transition—have suggested that the common one-parameter scaling analysis of QPT's, and concurrent neglect of dissipation, is no longer sufficient.⁵ A better understanding of the role of dissipation is needed, and can be achieved if dissipation can be changed in a controlled way.

In this Communication, we present results on the effects of capacitively coupling a ground plane to an SIT system. Resistance and magnetoresistance measurements taken on thin films of $\text{Mo}_{43}\text{Ge}_{57}$ insulated by ~ 160 Å from a thick gold film manifest two main results: (1) there is no observed change in physics due to increased screening, and (2) there is evidence of a dissipation-driven quantum phase transition. The first of these results contradicts expected theories of the SIT, and is consistent with what would be expected in a system where intrinsic dissipation already exists. The second result demonstrates the extent to which dissipation can couple in to the system. Similar results have been found in the Josephson junction arrays that also undergo dissipative phase transitions.⁶ A strong parallel can thus be made between thin films and arrays.

The samples used in this study are 30-Å and 40-Å films of $\text{Mo}_{43}\text{Ge}_{57}$, grown by magnetron sputtering on SiN substrates, with a Ge buffer layer and cap. The 30-Å and 40-Å films have sheet resistances at 4.2 K of $R_N \sim 1500$ Ω/□ and $R_N \sim 800$ Ω/□, respectively; T_c 's of 0.5 K and 1 K; and

H_{C2} 's of 1.4 T and 1.9 T. Previous studies have determined that the films are amorphous and homogeneous on all relevant length scales.⁷ The “ground-plane” samples consist of MoGe films patterned into four-probe structures, with the area between voltage taps covered with an insulating layer (40-Å Ge, 80-Å AlO_x , 40-Å Ge), then topped with a conducting ground plane (20-Å Ti, 400-Å Au). In order to directly compare samples with and without a ground plane, each MoGe film contained three patterns: one bare sample ($R_N = 1.55$ kΩ), one sample with an insulating layer ($R_N = 1.5$ kΩ), and one sample with an insulating layer covered by a metallic film ($R_N = 1.49$ kΩ). In this way, we were able to determine that the Ge/ AlO_x insulating layer did not affect the behavior of the film, and that any changes we saw were only due to the gold ground plane. Also, measurements of the ground plane and bare sample were normalized to account for the slight differences in R_N at 4 K (due to imprecision in patterning). The films were measured in a dilution refrigerator using standard low-frequency ($f_{AC} = 27.5$ Hz) lock-in techniques with an applied bias of 1 nA (well within the ohmic regime).

Although, as mentioned previously, the dirty-bosons model is not adequate to fully account for our results, it is still useful to use this model and its scaling expectations⁸ as a guideline for data analysis. The dirty-bosons model predicts a field-tuned, zero-temperature SIT, caused by competition between quantum fluctuations of the phase of the order parameter and long-range Coulomb repulsion. A true superconducting state is expected to exist at $T = 0$, when vortices are localized into a vortex-glass phase and Cooper pairs are delocalized; above a critical field, vortices delocalize while Cooper pairs localize into an insulating Bose-glass phase. This SIT is predicted to be continuous, with a correlation length that diverges as H approaches H_c as $\xi = \xi_0[(H - H_c)/H_c]^{-\nu}$ with $\xi_0 \sim \xi_{GL}$, the Ginzburg-Landau correlation length, and $\nu \geq 1$. The characteristic frequency Ω of quantum fluctuations should vanish near the transition as $\Omega \sim \xi^{-z}$. However, at finite temperatures, thermal energy cuts off this frequency scale, leading to a temperature-dependent crossover length $L_T \sim 1/T^{1/2}$. The dynamical exponent z thus determines the energy relaxation of the system, and is expected to have the value $z = 1$ in two-dimensional systems with long-range $1/r$ Coulomb interactions, and $z = d$ (where d is the dimension) in systems with neutral or screened

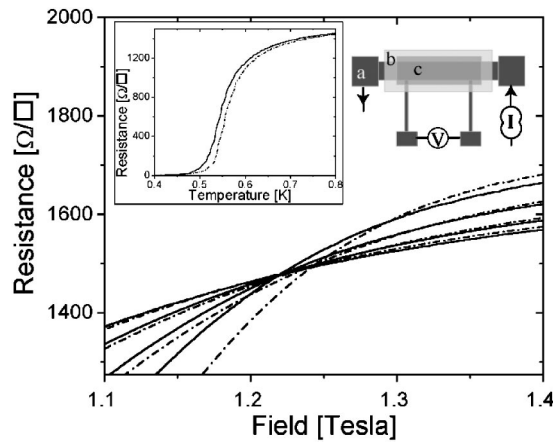


FIG. 1. Temperature-independent “crossing point” for bare and ground-plane samples, at $T=50, 100, 150,$ and 200 mK. Inset shows $H=0$ transition for the bare sample (solid line) and the ground-plane sample (dashed line). Top right part shows the experimental configuration: (a) MoGe sample, (b) insulating oxide layer, and (c) gold ground plane.

bosons.^{9,10} Values of ν and z can be extracted from expected scaling forms of the resistance with temperature, $R \sim \mathcal{F}_T([H-H_c]/T^{1/z\nu})$, and of the dynamical resistance with electric field, $\delta V/\delta I \sim \mathcal{F}_E([H-H_c]/E^{1/(z+1)\nu})$. Previous measurements of ν and z for thin films have consistently found that $\nu \sim 4/3$ and $z \sim 1$.^{11,12} The value of $\nu=4/3$ is consistent with that expected from classical percolation and thus adds credence to other indications that the SIT is a percolative transition.¹³ The value of $z=1$ corresponds to what is expected from theory for a system of charged bosons. However, recent experiments showing that the expected SIT is likely only a crossover to an unusual metallic state have cast doubt on the dirty-bosons theory, as well as on some of its assumptions regarding the critical exponents.^{4,5,14} For example, it remained unclear whether a system already coupled to a bath of fermions could have Coulomb interactions screened in such a way that the dynamical exponent could change from $z=1$ to $z=2$. The relationship between screening and dissipation was unknown, as were the ways in which the sample was coupled to dissipation. These questions could be better answered by studying the effect of a ground plane on SIT systems.

Figure 1 shows the effect of a ground plane on the 30-Å film near the critical regions. Although there is some difference between the ground-plane and bare samples, measurements of T_{c0} , R_c , and H_c show that this difference is slight. As can be seen in the inset of Fig. 1, T_{c0} of the ground-plane sample is increased by ~ 12 mK, or $\sim 2.5\%$. H_c and R_c , evident in Fig. 1 at the temperature-independent “crossing point” expected from theory, have similar values with and without the ground plane (1.24 T, 1495 $\Omega/\square$ and 1.22 T, 1480 $\Omega/\square$, respectively). Although the difference in values near the critical region is consistent with increased screening, if the differences are small. In particular, neither the universal (e.g., critical exponents) nor the nonuniversal (e.g., R_c and H_c) properties seem to change with the proximity of a ground plane. Figure 2 shows the scaling curves (resistance

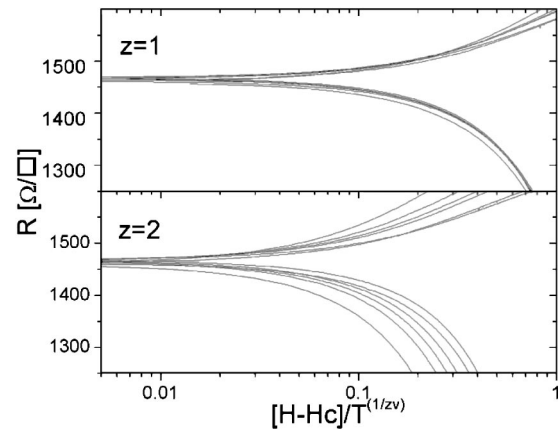


FIG. 2. Scaling curves for $T=30, 50, 75, 100, 150, 200$ mK. Upper graph shows fit for $z\nu=4/3$, lower graph shows fit for $z\nu=8/3$.

versus the scaling parameter, $[H-H_c]/T^{1/z\nu}$) for the ground-plane sample for values of $z=1$ and $z=2$ (with $\nu=4/3$). As is evident from the figure, the curves scale for $z=1$ much better than they do for $z=2$. The slight deviations that are evident in the “ $z=1$ ” case appear at the lowest temperatures, indicating the previously observed disruption of scaling at low temperatures.⁴ To confirm the best value of z , we developed a computer program to independently fit the scaling curves, using crossing point $z\nu$, and data range as independent parameters; from this, we determined a best fit for $z\nu=1.25$. This is consistent with data on dozens of films with different thicknesses, with or without ground planes, which show that $z\nu$ has a value between 1.25 and 1.35. While in-plane screening exists at all length scales, out-of-plane screening affects the transition only at length scales below the correlation length; hence, a ground plane closer to the sample than a correlation length is expected to change the universality class (i.e., $z=1$ changes into $z=2$). Since $\xi_0 \sim \xi_{GL} \sim 250$ Å, our ground-plane distance of 160 Å should have been sufficient to see this screening effect for a wide range around the critical field. It is possible that we do not observe changes in physics due to screening because there are already dissipation-causing free fermions in the sample; then, the addition of a nearby plane of fermions would not cause further screening. In this case the value of the critical exponent z would be independent of screening effects. It is also possible that the mechanism of dissipation (dissipative quantum tunneling, for example) cuts off the correlation length at short length scales. In this case, the Coulomb interactions could only be screened at a very short distance d , where $d \ll \xi$.

Although the ground plane does not seem to affect the film near the critical region of the SIT, it does have a dramatic effect on the behavior of the system at low temperatures. The main panel of Fig. 3—data from a 30-Å film with a ground plane 160-Å away—shows that samples with a ground plane have lower resistances at low fields and higher resistances at high fields than samples without a ground plane. The inset is a magnification of the transition region. The 40-Å thick samples with a ground plane 250 Å away

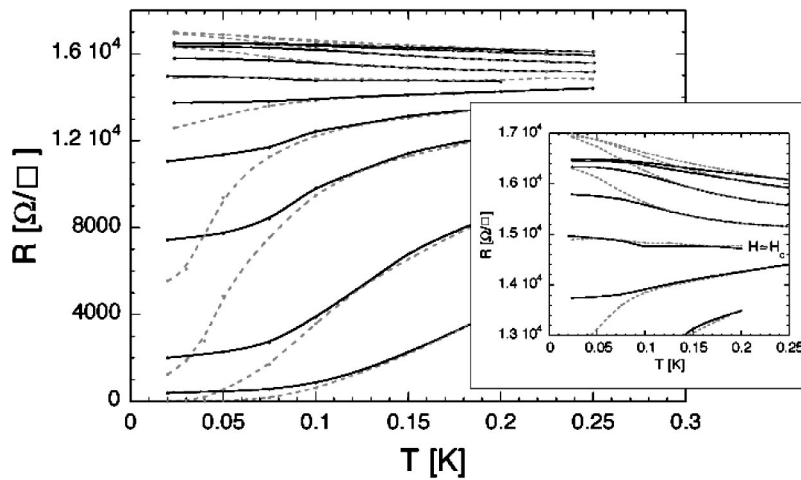


FIG. 3. Resistance versus temperature curves for bare (solid line) and ground-plane (dashed line) samples. Main figure shows 30-Å sample at $H=0.6, 0.8, 1.0, 1.1, 1.18, 1.25$, and 1.5 T. Inset shows the vicinity of the SIT.

from the sample show similar behavior. It was previously found that bare samples exhibit a metallic phase at low temperatures, with a levelling of resistance evident as $T \rightarrow 0$.⁴ This metallic phase has unique characteristics, including Josephson-junction-like I - V curves and a resistance exponentially related to magnetic field, and can be clearly distinguished from the superconducting and insulating phases that also exist in the samples.^{4,14} The addition of a ground plane seems to inhibit resistance levelling, or to prevent the system from entering the metallic phase.

The effect shown in Fig. 3 is strongest below H_c , where the proximity of a ground plane clearly promotes superconductivity. The lower resistance of the ground-plane sample at low temperatures is too large to be accounted for by the same effects that caused T_c to change, or by the slight difference in H_c and R_c . The effect is also not likely due to temperature differences, as the ground-plane and bare samples are on the same chip, with identical thermal anchoring. Rather, the promotion of superconductivity can be explained by assuming that the capacitive coupling of the ground plane causes the suppression of the quantum fluctuations that drive the SIT and destroy superconductivity. A plausible model involves dissipative coupling.¹⁵ In this case the coupling strength α is assumed to fit a Caldeira-Leggett model of a dissipative quantum-mechanical environment, where $\alpha \sim R_q/R$ and R_q

$= h/4e^2$.¹⁶ It has been proposed that a capacitively coupled ground plane adds ohmic dissipation to the system within a fluctuation frequency range determined by the capacitance of the ground plane and the capacitance of the sample.¹⁷ Alternatively, the added capacitance could couple to the inertial term of the phase fluctuations, adding to its mass.¹⁸ In either case, this type of coupling is expected to damp quantum fluctuations and help restore phase order.

A similar promotion of superconductivity due to a coupling to dissipation was recently observed in arrays of Josephson junctions. Josephson junctions are expected to undergo an SIT as a function of the ratio of the Josephson energy to the charging energy. A dissipation-induced phase transition (DPT) was seen both when the shunt resistance of junctions were explicitly changed¹⁹ and when the resistance of a capacitively coupled plane was varied.⁶ The observation of similar DPT's in both thin films and Josephson-junction arrays demonstrates that dissipation enters into the two systems in a similar way. The analogy between the two systems can help identify the origin of the intervening metallic phase found in SIT systems.⁴ Because pure capacitive coupling tends to pin a superconducting phase,^{15,20} we conclude that particle exchange with the heat bath plays a key role in the physics of the metallic phase. With the suppression of quantum fluctuations, the motion of the excitations responding to

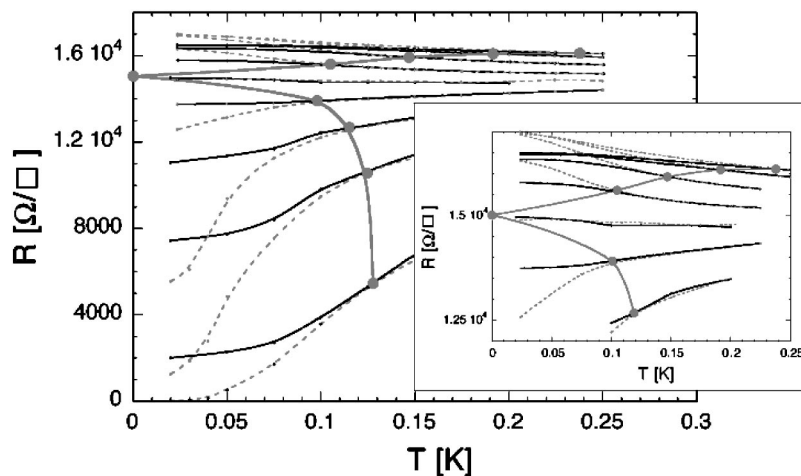


FIG. 4. Location of the points at which the ground-plane transitions diverge from the bare-sample transitions for the 30-Å sample. Inset shows the vicinity of the SIT.

the external field is diffusive and classical, with characteristics inherited from the heat bath [which for the thin films is the background residual fermions, and for arrays the shunts in a resistively shunted Josephson-junction (RSJ) system]. A combined system of shunt and capacitive coupling therefore demonstrates the competition between the tendency to pin the superconducting phase and the tendency to produce a metallic phase at low temperatures. This conclusion is also backed by a recent theoretical analysis of a model system of strongly fluctuating superconducting grains embedded in a metallic background, recently proposed by Feigelman and Larkin²¹ and by Spivak *et al.*²² In their model, for weak enough intergrain coupling, a low-temperature superconducting state is destroyed by quantum fluctuations, yielding a metallic phase.

Our results on the “insulating side” of the transition differ from those on arrays in that our ground plane also seems to promote the insulating state. As can be seen in Fig. 3, the ground plane sample has a higher resistance than the bare sample at low temperatures, for $H > H_c$. The effect is weaker than in the superconducting state, and more difficult to analyze because of the weakness of the insulator, and the proximity of H_c to H_{c2} . However, the effect may point to a restoration of the weakly localized state in the presence of strong enough capacitive coupling.

The fact that the ground plane promotes both the superconducting and insulating states, preventing a levelling of

resistance, suggests that the presence of the ground plane works *against* the tendency to create a metallic state, strengthening the influence of the zero-temperature quantum critical SIT point to much lower temperatures (i.e., we expect the metallic state to reassert itself at much lower temperatures in systems with a ground plane). In Fig. 4 we have marked where the ground-plane and bare-sample resistances begin to diverge. Since this divergence is strongest away from the apparent SIT quantum critical point (at H_c), and nonexistent at H_c , this set of points tracks the region of influence of the quantum critical point. It is possible that these points indicate a transition between two distinct metallic states in the bare sample (one in the insulating and the other in the superconducting regime). To verify this observation a stronger insulator will be needed. It is likely that the higher-field flattening is a direct consequence of the sample being only weakly localized, and the true high-field phase is an insulator.

In conclusion, we have presented results demonstrating that a ground plane capacitively coupled to an SIT system that has inherent dissipation couples to the system in a way that damps phase fluctuations and promotes a pure SIT. This implies that the inherent dissipation comes from particle exchange with the heat bath, which is composed of residual fermions in the film, or of shunts in an RSJ system.

¹For a review see, e.g., S.L. Sondhi, S.M. Girvin, J.P. Carini, and D. Shahar, *Rev. Mod. Phys.* **69**, 315 (1997).

²For a review see, e.g., A. Goldman and N. Markovic, *Phys. Today* **51** (11), 39 (1998).

³D. Ephron, A. Yazdani, A. Kapitulnik, and M.R. Beasley, *Phys. Rev. Lett.* **76**, 1529 (1996).

⁴N. Mason and A. Kapitulnik, *Phys. Rev. Lett.* **82**, 5341 (1999).

⁵A. Kapitulnik, N. Mason, S.A. Kivelson, and S. Chakravarty, *Phys. Rev. B* **63**, 125322 (2001).

⁶A.J. Rimberg, T.R. Ho, C. Kurdak, J. Clarke, K.L. Chapman, and A.C. Gossard, *Phys. Rev. Lett.* **78**, 2632 (1997).

⁷J.M. Graybeal and M.R. Beasley, *Phys. Rev. B* **29**, 4167 (1984); J.B. Kortright and A. Bienenstock, *ibid.* **37**, 2979 (1988).

⁸M.P.A. Fisher, *Phys. Rev. Lett.* **65**, 923 (1990).

⁹D.S. Fisher, and M.P.A. Fisher, *Phys. Rev. Lett.* **61**, 1847 (1988).

¹⁰M.P.A. Fisher, G. Grinstein, and S.M. Girvin, *Phys. Rev. Lett.* **64**, 587 (1990).

¹¹A. Yazdani and A. Kapitulnik, *Phys. Rev. Lett.* **74**, 3037 (1995).

¹²A.F. Hebard and M.A. Paalanen, *Phys. Rev. Lett.* **65**, 927 (1990).

¹³E. Shimshoni, A. Auerbach, and A. Kapitulnik, *Phys. Rev. Lett.* **80**, 3352 (1998).

¹⁴N. Mason and A. Kapitulnik, *Phys. Rev. B* **64**, 060504 (2001).

¹⁵S. Chakravarty, G.L. Ingold, S. Kivelson, and A. Luther, *Phys. Rev. Lett.* **56**, 2303 (1986); S. Chakravarty, G.L. Ingold, S. Kivelson, and G. Zimanyi, *Phys. Rev. B* **37**, 3283 (1988).

¹⁶A.O. Caldeira and A.J. Leggett, *Ann. Phys. (N.Y.)* **149**, 374 (1983).

¹⁷K. Wageneblast, A. van Otterlo, G. Schon, and G. Zimanyi, *Phys. Rev. Lett.* **79**, 2730 (1997).

¹⁸S. Doniach (private communication); see also D. Das and S. Doniach, *Phys. Rev. B* **64**, 134511 (2001).

¹⁹Y. Takahide, R. Yagi, A. Kanda, Y. Ootuka, and S.I. Kobayashi, *Phys. Rev. Lett.* **85**, 1974 (2000).

²⁰A. Schmid, *Phys. Rev. Lett.* **51**, 1506 (1983).

²¹M.V. Feigelman and A.I. Larkin, *Chem. Phys.* **235**, 107 (1998).

²²B. Spivak, A. Zyuzin, and M. Hruska, *Phys. Rev. B* **64**, 132502 (2001).