PHYSICAL REVIEW B, VOLUME 64, 060504(R)

True superconductivity in a two-dimensional superconducting-insulating system

Nadya Mason and Aharon Kapitulnik

Departments of Applied Physics and Physics, Stanford University, Stanford, California 94305

(Received 7 June 2000; published 23 July 2001)

We present results on disordered amorphous films which are expected to undergo a field-tuned superconductor-insulator transition. Based on resistance and *I-V* characteristics, we find evidence of a low field metal-to-superconductor transition. This transition is characterized by a rapid drop in resistance and discontinuities in the *I-V* curves. The metallic phase just above the transition seems to be an unusual, non-Fermi metal and the superconducting phase seems to be a true zero resistance state.

DOI: 10.1103/PhysRevB.64.060504 PACS number(s): 74.20.Mn, 73.43.−f, 74.76.−w

The theory of a metallic phase in two dimensions (2D) at zero temperature is currently a matter of intense debate.[1,2] Indeed, such a phase was thought for many years not to be possible.[3,4] Recently, however, compelling experimental evidence has accumulated suggesting the existence of such "metallic" phases, that is, phases with finite dissipation in the zero temperature limit. While there is as yet no microscopic understanding of these observations, it seems that metallic phases are common whenever interaction effects are strong.[2] In particular, metallic phases seem to intervene near quantum phase transitions in systems which exhibit quantum percolation behavior near a critical magnetic field[5–7]—for example, in the quantum-Hall liquid to insulator transition, the quantum-Hall plateau transition, and superconductor-insulator transition. These observations cast doubt on the existence of a superfluid phase in the zero temperature limit. Thus, finding a "true" superfluid phase in these field-tuned quantum phase transition systems has been the missing link necessary to give us a coherent picture of their phase diagram.

In this paper we concentrate on the superconductor-insulator transition (SIT),[8] presenting results on the transition between a metallic state and a superconducting phase in 2D MoGe films. Observations of a dramatic drop in magnetoresistance at a critical magnetic field H_{SM}, along with instabilities in *I-V* curves, point to the existence of a low-field quantum phase transition to a superconducting state. Unlike the metallic state at higher fields, where the film's resistance saturates at low temperatures and seems to remain finite as $T \rightarrow 0$, the superconducting state has zero resistance to within the limits of our measurements and shows no signs of an approach to a finite resistance. The superconducting state can be characterized by vortices (far separated due to the low field) which are pinned on impurities to provide the true zero resistance state.

Typical theoretical treatment of the SIT is to map it onto the so-called "dirty-boson" model, which considers bosons (i.e., Cooper pairs) interacting in the presence of disorder.[9] This model predicts that for a field tuned transition with an arbitrary amount of disorder a true superconducting state exists at $T=0$, when vortices are localized into a vortex-glass phase and Cooper pairs are delocalized.[10] Above a critical field H_{SI}, vortices are delocalized and Cooper pairs localize into an insulating Bose-glass phase. A Bose metal, with universal sheet resistance, should exist at the critical resistance.[11] Early experiments seemed to confirm this scenario, although there was some concern that the apparent critical exponents resembled those of classical percolation[12] and that the critical resistance at the transition was not the expected quantum of resistance for Cooper pairs, $h/4e^2$.[13–15] However, recent experiments[16–18] have challenged the general existence of a pure SIT, demonstrating that the apparent transition is merely a crossover to a new metallic state at low temperatures. Similar results have been obtained on quantum Hall liquid-to-insulator transitions[19] and on arrays of Josephson junctions.[20]

Samples for which we present data in this paper are 30, 40, and 60 Å $Mo_{43}Ge_{57}$ thin films, sandwiched between insulating layers of amorphous Ge on SiN substrates. The 30, 40, and 60 Å samples have sheet resistances at 4.2 K of $R_N \sim 1300\ \Omega/\square$, $R_N \sim 800\ \Omega/\square$, and $R_N \sim 600\ \Omega/\square$, respectively; T_C's of 0.5, 1, and 1.1 K; H_{C2}'s of 1.4, 1.9, and 2.7 T. The films were magnetron sputtered in a system which has previously been shown to produce high-quality films with constant equivalent bulk properties down to 10 Å.[21] The amorphous and homogeneous properties of films similar to ours have been ascertained in various studies, and microstructural inhomogeneities have been shown to be smaller than 2–3 atomic length scales ($4-8$ Å).[22] We patterned the films into 4-probe structures, and measured them in a dilution refrigerator using standard low-frequency lock-in techniques. Data was taken at a measurement frequency of $f_{AC} = 27.5$ Hz with an applied bias of 1 nA (well within the Ohmic regime). Spurious noise and temperature effects were minimized as discussed elsewhere.[13,16,17] Current-voltage characteristics were measured as dV/dI curves, using battery-operated electronics to add a slow dc ramp voltage to a lockin ac output.

Figure 1 shows magnetoresistance isotherms and scaling for a 40 Å sample, for temperatures 80–200 mK. The temperature-independent "crossing point" is expected from scaling theories,[10] and is of the same magnitude and quality as that obtained previously on similar samples.[13,16,17] The scaling curve, shown in the inset, shows an excellent fit to the expected scaling form of the resistance, $R = R_q F[(H - H_c)/T^{(1/z\nu)}]$. All of the measured samples scale similarly, with $z\nu \sim 4/3$ and H_c of the same order as H_{c2}. The quality of the crossing point and scaling at high temperatures suggest that our system corresponds to the usual SIT and quantum phase transition theory for homogeneous films; that is,

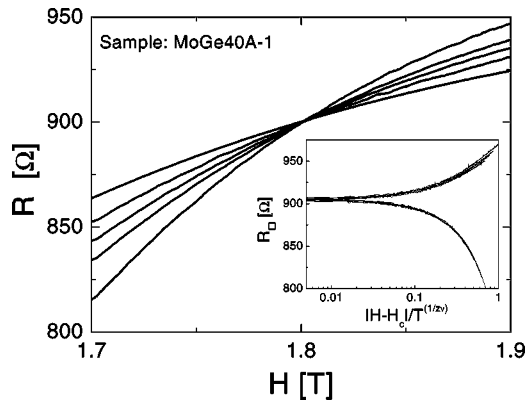

FIG. 1. Magnetoresistance of a 40 Å sample, 80–200 mK. Inset shows resistance plotted as a function of the scaling parameter.

the physics is dominated by the long length scale physics of an approach to a quantum critical point. However, at low temperatures close to the quantum critical point, the resistance saturates, scaling is disrupted, and the system enters an unexpected metallic regime.[17]

Below the crossing point, the temperature curves enter an ''activated'' regime, where $R\sim e^{-U(H)/T}$ and the derived activation energy, $U(H)$, is consistent with $U(H) = U_0\ln(H_0/H)$, a form expected in the collective creep regime of vortices[23] (here U_0 is of order of dislocation energy and H_0 is approximately H_{c2}). At lower fields, the different temperature curves collapse onto each other, with the lower temperatures collapsing at higher fields: this collapse marks where the system enters a temperature-independent regime previously associated with quantum tunneling.[16] Experimentally, we find that the temperature-independent resistance, R, is related to field as $R\sim e^{H/H_0}$. The knee in the magnetoresistance curve, evident in Fig. 2, shows when this regime begins for the lowest temperatures. While it was previously unclear whether this ''metallic'' region (of finite, temperature-independent resistance) persisted to zero temperature, it is now evident that the system enters a new phase at very low fields. For the 40 Å sample, for example, near

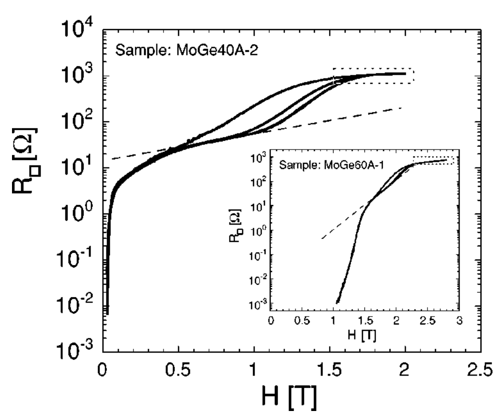

FIG. 2. Magnetoresistance of a 40 Å sample, 20–200 mK. Dashed line represents the region for which $R\sim e^{H}$. Inset shows similar data for a 60 Å sample, 20–100 mK. Dotted-line boxes mark the regions of crossing (see Fig. 1).

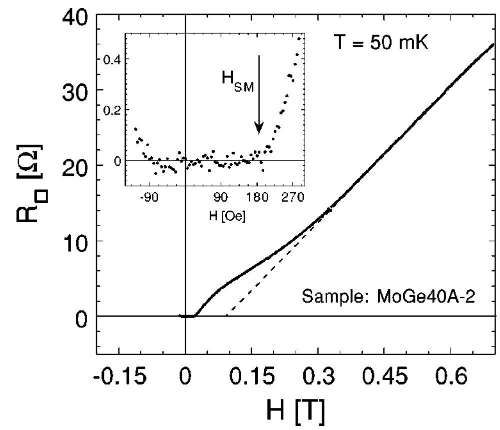

FIG. 3. Low field portion of the magnetoresistance shown in Fig. 1. Dashed line represents a linear fit with an intersection field of 850 Oe. The inset shows the actual critical field of the sample of 185 Oe.

0.1 T, the resistance suddenly drops by more than three orders of magnitude, approaching zero resistance to within the limits of our measurement. As is evident in Fig. 3, this drop can be best fit by $R\sim 60(H-0.085)^{\mu}$ with $\mu\sim 1$. A kink in the magnetoresistance interrupts the power law and a true zero resistance state seems to occur below $\sim$185 Oe.

To better examine the low field superconducting behavior, we took more sensitive resistance measurements for a small field range around zero for all measured samples. Figure 3 is an example of such data, which is independent of temperature below 100 mK, and is not affected by changes in bias current to within two orders of magnitude. Some samples showed hysteresis near the critical field, thus exhibiting activated vortex motion as expected in a true superconducting phase. The value of the critical field, for the 40 Å sample corresponds to a vortex separation of $\sim 5\xi_0 - 7\xi_0$, where ξ_0 is the vortex core size. The critical field varies with resistance, with less resistive (less disordered) samples showing higher critical fields.

Further evidence of a low field phase transition to a superconducting state is evinced by the dV/dI curves. Figure 4 shows typical dV/dI curves for a 30 Å film at 20 mK and

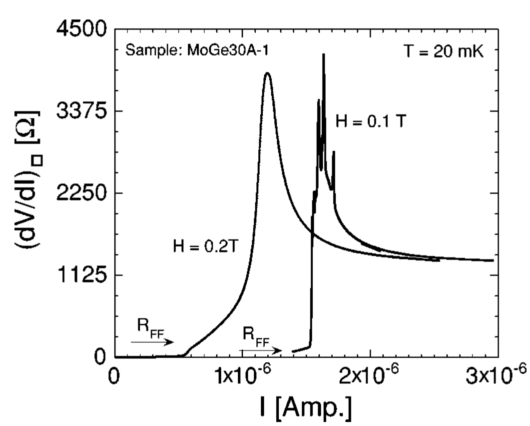

FIG. 4. Dynamic resistance of a 30 Å sample at 200 Oe and 100 Oe. R_{FF} denotes the flux-flow resistance for the two fields.

fields of 0.2 and 0.1 T. The 0.2 T curve is at the end of the temperature-independent region of the magnetoresistance curve. The peak, evident at ~ 1.2 μA with a value almost four times the normal state resistance, is typical for both vortices in the flux-flow regime (see, e.g., Ref. 24) and Josephson junctions.

Examination of the high current regime suggests that the system's behavior is more similar to that of Josephson junctions than to flux flow vortices, since the leveling resistance at high bias current is approximately the normal state resistance (i.e., more than 10 times the calculated flux flow resistance). At low fields and high currents the sample seems to enter a new regime: the structure evident in the 0.1 T curve —peaks in dV/dI, or discontinuities in I-V—manifests sample behavior near H_{SM}. This curve is both reproducible and hysteretic. Discontinuities in I-V characteristics are likely due to vortex jumps and local heating. This can be caused by local inhomogeneities in the sample, possibly phase separation into regions with different critical currents. These discontinuities in IV curves are apparent in various samples; in 60 Å films, for example, the transition from smooth to discontinuous IV curves occurs at $H=0.35$ T with a peak centered around $I_{bias}=13$ μA. Similar discontinuous behavior has been seen in other SIT (Ref. 18) and quantum-Hall[25] quantum phase transitions. It is important to emphasize that, from the point of view of the SIT, the relevant electronic length scales near the transition (for example, the superconducting coherence length $\xi\sim 50$ Å, or the fundamental length associated with scaling) are much larger than the largest possible length scale of microstructural inhomogeneities, 4–8 Å. Thus, the observed metallic and Josephson junction–like phenomena are clearly due to long-length scale physics near the quantum phase transition.

The above results point to a different physical situation of the superconducting film at low temperatures and magnetic fields below the upper critical field. The metallic state, which exists for a wide range of fields at $T=0$, can now be contrasted with the superconducting state, which appears at very low fields.

The metallic phase stabilizes at low temperatures, and is not a simple extrapolation of the normal state ''Fermi-metal'' that we observe just above the bulk transition temperature. This metal is characterized by very low resistance which depends exponentially on magnetic field. As can be seen from Fig. 1, at 0.2 T this resistance is more than two orders of magnitude below the normal state resistance; at that field the resistance is temperature independent below ~ 150 mK.[17] Furthermore, the transport is different from a conventional metal in that the I-V are nonlinear at relatively low currents. The overall shape of the I-V characteristics resembles that of a resistively shunted Josephson junction. The superconducting state, in contrast, is characterized by a low critical field, a rapid drop to zero resistance, and discontinuities in the IV curves near the transition.

The possibility of a metallic phase intervening between the insulating and superconducting phases has been a subject of many recent theoretical papers.[17,26–29] In particular Mason and Kapitulnik[17] suggested an amended phase diagram for the SI system in which a superconductor-metal transition exists and depends on the parameter, α, which describes a coupling to dissipation.[17] This paper also showed that at higher temperatures the system almost undergoes a superconductor-insulator transition with a correlation length exponent very close to that of classical percolation. This observation further strengthened the proposals[26,30] that the system breaks into superconducting and insulating ''puddles'' that almost connect via a classical percolation process before settling into a metallic phase that is dominated by vortex dissipation. The Josephson-junction–like I-V characteristics are perhaps the most striking evidence that indeed the system breaks down into domains which are connected via Josephson tunneling. In addition, discontinuites in IV curves are consistent with a picture of puddles fluctuating near a critical field and thereby creating different percolation paths. The ''puddle'' picture agrees with a unified framework for treatment of two-dimensional superconducting films, whether homogeneous or inhomogeneous. For example, Feigel'man and Larkin[28] proposed a model of small superconducting islands embedded in a dirty thin metal film to discuss the general problem of quantum superconductor-metal transition in 2D. They found a transition from a superconducting to a normal conducting state as a function of the distance between grains. Further analysis of a puddle-like model consisting of strongly fluctuating superconducting grains embedded in a metallic matrix led Spivak *et al.*[29] to predict a metal-to-superconductor transition with a metallic phase just above the transition which is dominated by Andreev reflections from the almost superconducting grains. The resistance of such a phase has to be much lower than the ''normal'' resistance of the system, an occurrence that has consistently been observed in our samples.

In summary, we presented in this paper evidence of a zero temperature quantum phase transition between a different metallic state and a superconducting state in 2D films. While a simple phenomenology based on a ''puddle'' model of superconducting and metallic regions can qualitatively explain the main features of our experiment, more work is needed to fully understand the nature of this unusual metallic state and the superconducting transition.

We thank David Ephron whose thesis work motivated parts of this study. We thank Steve Kivelson and Boris Spivak for many useful discussions. We especially thank Steve Kivelson for a critical reading of the manuscript. This work was supported by NSF/DMR. N.M. thanks Lucent CRFP for support. Samples were prepared at Stanford's Center for Materials Research.

[1] E. Abrahams, S. V. Kravchenko, and M. P. Sarachik, Rev. Mod. Phys. **73**, 251 (2001).
[2] A. Kapitulnik, N. Mason, S. Kivelson, and S. Chakravarty, Phys. Rev. B **63**, 125322 (2001).
[3] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979).
[4] B. L. Altshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980).
[5] S. Kivelson, D.H. Lee, and S.-C. Zhang, Phys. Rev. B **46**, 2223 (1992).
[6] J. T. Chalker and P. D. Coddington, J. Phys. C **21**, 2665 (1988).
[7] D. H. Lee, Z. Wang, and S. Kivelson, Phys. Rev. Lett. **70**, 4130 (1993).
[8] For a review, see, e.g., A. Goldman and N. Markovic, Phys. Today **51** (11), 39 (1998).
[9] For a review, see S.L. Sondhi, S.M. Girvin, J.P. Carini, and D. Shahar, Rev. Mod. Phys. **69**, 315 (1997).
[10] M.P.A. Fisher, Phys. Rev. Lett. **65**, 923 (1990).
[11] M.P.A. Fisher, G. Grinstein, and S.M. Girvin, Phys. Rev. Lett. **64**, 587 (1990); K. Kim and P.B. Weichman, Phys. Rev. B **43**, 13 583 (1991).
[12] D. Stauffer and A.Aharony, *Introduction to Percolation Theory*, 2nd ed. (Taylor and Francis, London, 1994).
[13] A. Yazdani and A. Kapitulnik, Phys. Rev. Lett. **74**, 3037 (1995).
[14] A.F. Hebard and M.A. Paalanen, Phys. Rev. Lett. **65**, 927 (1990).
[15] N. Markovic, A.M. Mack, G. Martinez-Arizala, C. Christiansen, and A.M. Goldman, Phys. Rev. Lett. **81**, 701 (1998).
[16] D. Ephron, A. Yazdani, A. Kapitulnik, and M.R. Beasley, Phys. Rev. Lett. **76**, 1529 (1996).
[17] N. Mason and A. Kapitulnik, Phys. Rev. Lett. **82**, 5341 (1999).
[18] J.A. Chervenak and J.M. Valles, Jr., Phys. Rev. B **59**, 11 209 (1999).
[19] D. Shahar, M. Hilke, C.C. Li, D.C. Tsui, S.L. Sondhi, J.E. Cunningham, and M. Razeghi, Solid State Commun. **107**, 19 (1998).
[20] H.S.J. van der Zant, W.J. Elion, L.J. Geerligs, and J.E. Mooij, Phys. Rev. B **54**, 10 081 (1996); C.D. Chen, P. Delsing, D.B. Haviland, Y. Harada, and T. Claeson, *ibid.* **51**, 15 645 (1995).
[21] J. Graybeal, Ph.D. thesis, Stanford University, 1985.
[22] For extensive studies of the microstructure of Mo_xGe_{1-x} films, see, e.g., J.B. Kortright and A. Bienenstock, Phys. Rev. B **37**, 2979 (1988); J.M. Graybeal and M.R. Beasley, *ibid.* **29**, 4167 (1984); J.S. Urbach *et al.*, Phys. Rev. Lett. **69**, 2407 (1992).
[23] M.V. Feigel'man, V.B. Geshkenbein, and A.I. Larkin, Physica C **167**, 177 (1990).
[24] M.C. Hellerqvist, D. Ephron, W.R. White, M.R. Beasley, and A. Kapitulnik, Phys. Rev. Lett. **76**, 4022 (1996).
[25] K.B. Cooper, M.P. Lilly, J.P. Eisenstein, L.N. Pfeiffer, and K.W. West, Phys. Rev. B **60**, 11 285 (1999).
[26] E. Shimshoni, A. Auerbach, and A. Kapitulnik, Phys. Rev. Lett. **80**, 3352 (1998).
[27] Denis Dalidovich and Philip Phillips, Phys. Rev. Lett. **84**, 737 (2000); D. Das and S. Doniach, Phys. Rev. B **60**, 1261 (1999).
[28] M. Feigel'man and A. Larkin, Chem. Phys. **235**, 107 (1998).
[29] B. Spivak, A. Zyuzin, and M. Hruska, cond-mat/0004058 (unpublished).
[30] B. Spivak and F. Zhou, Phys. Rev. Lett. **74**, 2800 (1995).