Indirect Magnetic-Field-Tuned Superconductor-Insulator Transitions and Weak Localization of Bosons of Quasi-Two Dimensional Metal Films

Yen-Hsiang Lin and A. M. Goldman

School of Physics and Astronomy, University of Minnesota,
116 Church St. SE, Minneapolis, MN 55455, USA
(Dated: 10/04/09)

Abstract

Magnetic field and electrostatically tuned superconductor-insulator (SI) transitions of ultrathin metal films with levels of disorder that place them near the disorder-tuned SI transition appear to be direct, continuous quantum phase transitions. When films with lower levels of disorder are subjected to a perpendicular magnetic field, instead of a direct transition, a mixed superconductor-nonsuperconductor regime emerges at the lowest temperatures. The zero temperature limit of the resistance is either insulating or superconducting, depending upon the value of the field, suggesting that the behavior in this limit is governed by percolation physics. At high fields and low temperatures, in the nominally insulating regime, the resistance rather than the conductance is found to be a logarithmic function of temperature corresponding to predictions for the weak localization of bosons.

Highly-disordered, homogeneous, quench-condensed, ultrathin films of metals can be tuned between superconducting and insulating behavior by magnetic field, thickness or carrier density [11]. These transitions are of interest because they are among the simplest of quantum phase transitions, and the field and carrier density tuned transitions appear to belong to the (2+1)D XY universality class. Recently there has been increased interest in highly-disordered, amorphous compounds such as In$_2$O$_3$ and polycrystalline TiN, ranging in thickness from tens to hundreds of Angstroms. In addition to undergoing superconductor-insulator (SI) transitions tuned by perpendicular field, these systems exhibit magnetoresistance, $R(B)$, peaks in the insulating regime[3–7]. Although this effect was first observed and interpreted as evidence of a Bose insulating regime by Paalanen, Hebard, and Ruel [8] almost two decades ago, recent experiments have displayed enhancements of resistance by many more orders of magnitude[9, 10]. Furthermore, for less disordered films, an intermediate metallic phase has been reported to occur between the superconducting and insulating regimes[11]. What is surprising is that in work on the much thinner, atomically disordered (amorphous), quench-condensed films, peaks in $R(B)$ in the insulating regime of have only been observed in films patterned with a nanohoneycomb array of holes[12], and there appears to not be an intrinsic intermediate metallic regime. In most of the measurements, normal resistances were close to the critical values associated with thickness-tuned SI transition. The present study, which was motivated by a search for magnetoresistance peaks in quench-condensed films, extends the regime of parameter space to normal resistances below criticality, yet not so far below that the field-tuned transition is to a metallic state.

There have been two striking findings. The first is the behavior in the high-field limit, where the resistance, $R(T)$, rather than the conductance, $G(T)$, was found to vary as $lnT$. This is suggestive of the weak boson localization phenomenon predicted by Das and Doniach [13], and reported for under-doped cuprates whose superconductivity was completely quenched by magnetic fields [14]. In addition there was no peak in $R(B)$ in fields up to 10 T. A second finding is that at high temperatures (around 2K ~ 4K) the data could be collapsed using a finite size scaling analysis. With decreasing temperature scaling broke down because curves of $R(T)$ became nonmonotonic functions of temperature in the manner suggestive of thickness tuned SI transitions of granular films [15]. This change in the physics with decreasing temperature is reminiscent of the approach to a quantum critical point of some strongly correlated electron systems in a magnetic field, in which new physics turns on before the quantum critical point is reached [16]. Mixed phases in the case of the field-driven SI transition have been discussed in the theoretical literature [17] [18].

The present investigations were carried out using films grown on (100) SrTiO$_3$ (STO) single-crystal substrates. Platinum electrodes, 100Å thick, were deposited ex situ onto the substrate’s epi-polished front surfaces to form a configuration suitable for both resistance and Hall resistance measurements. The substrate was then placed in a Kelvinox-400 dilution refrigerator/UHV deposition apparatus [19]. A 10Å thick under-layer of a-Sb and successive layers of a-Bi were thermally deposited in situ under ultra-high vacuum conditions through shadow masks onto the substrate’s front surface. The substrate was held at about 7 K during the depositions. Films grown in this manner are believed to be homogeneously disordered on a microscopic, rather than on a mesoscopic scale [20]. The sample measurement lines were heavily filtered so as to minimize the electromagnetic noise environment of the film. To avoid complications arising from this filtering, measurements were made using AC, rather than DC, methods. The ion and turbo pumps connected to the growth chamber were electrically isolated from the cryostat using vacuum nipples with ceramic spacers.
Figure 1: a-Bi (with a 10Å thick a-Sb underlayer) film in different perpendicular magnetic fields. The values of field from top to bottom are 10, 5, 2.5, 2, 1.8, 1.6, 1.4, 1.3, 1.2, 1, 0.8, 0.6, 0 Tesla. Inset: Sheet resistance vs. temperature for the thickness-tuned superconductor-insulator transition of granular (without an underlayer) Bi films adopted from Ref. 15. The thicknesses are 21.11 (top), 21.41, 21.75, 21.83, 21.94, 22.04, 22.10, 22.14, 22.17, 22.23, 22.38, 22.63, 22.95, 23.37, 23.66, 24.52, 25.40, 26.07, and 27.56 Å(bottom). Notice that these two plots involve films with different morphologies and different tuning methods.

Figure 2: (a) Conductance $G(T)$ in zero magnetic field. (b) Scaling analysis for the perpendicular magnetic field tuned transition between $2K < T < 4K$ and $0.6T < B < 5T$. Resistance, normalized to the critical resistance (3384$\Omega$), is plotted as a function of $|B - B_c|/T^{1/\nu}$ with $\nu z=0.4$ and $B_c=1.58T$.

Figure 1 shows a series of curves of $R(T)$ as a function of magnetic field charting the transition from superconductor to insulator. The significant feature is the non-monotonic behavior of $R(T)$ at values of magnetic field that are close to those separating superconducting and nonsuperconducting behavior. This strongly suggests that there is a range of magnetic field over which the system breaks into a mixture of superconducting and nonsuperconducting regions at nonzero temperatures despite the homogeneity of the film. Behavior of this sort is usually found for granular films. To make the point, the inset of Fig. 1 shows the evolution from insulator to superconductor as a function of thickness for a granular film, which also shows a non-monotonic variation of $R(T)$ [15], but with much larger scale in both resistance and temperature.

This 11.2Å thick film is homogeneous even though it exhibits non-monotonic behavior at nonzero temperature within a range of fields over which it is undergoing a transition from superconducting to insulating behavior in the low temperature limit. Hall effect measurements support this. They reveal the areal carrier concentration to $1.5 \times 10^{16} \text{ cm}^{-2}$, which is close the value expected for a metal. From the carrier concentration, one can obtain the Fermi wavevector $k_F = 2.5 \times 10^{-3} \text{ cm}^{-1}$. Combining this with result for the sheet resistance, which gives $k_F \ell \sim 6$, we find the electronic mean free path $\ell$ to be around 2.4Å. This indicates that the disorder is on an atomic rather than a mesoscopic scale. The carrier concentration would not be expected to be as high in a granular film.

We now turn to the details of the transport. The conductance $G$ can be fit by $\ln T$ in the normal state in zero field and in low magnetic fields. The coefficient of $\ln T$ is $5.23 \times 10^{-6} \Omega^{-1}\square$ which agrees with the theory of weak localization including electron-electron interactions, for the case of strong spin-orbit coupling [21]. The coefficient of the logarithm also agrees with that found in previous work [2]. A sample fit, with the range of applicability clearly delineated is shown in Fig. 2a.

In the vicinity of the crossover magnetic field, the resistance at relatively high temperatures could be loosely fit with the form $R \sim R_{\text{exp}}(T_0/T)$, with a negative value of $T_0$ for films that smoothly become superconducting and a positive value for those which ultimately become insulators. This suggested that $R(T, B)$ might be col-
lapsed using the finite-size scaling relation suggested by Fisher [22]. Figure 2b shows the result of this analysis for $2K < T < 4K$ and $0.6T < B < 5T$ employing the form $R/R_0 \sim F(|B-B_0|/T^{1/\nu_z})$ with the critical exponent product $\nu_z = 0.4$. The scaling fails when applied to data outside of these ranges.

Well into the insulating regime, where one might expect a return to $G \sim \ln T$, but one finds instead, that $R$ rather than $G$ is better described by $\ln T$. A comparison of these two forms for data obtained at a field of 10T is presented in Fig 3. This relationship was also found at lower values of magnetic field. We compared the values of chi square $\chi^2 = \sum [(R_i - R_{fit}(T))/\sigma_i]$ for the two functional forms ($R \sim \ln T$ and $G \sim \ln T$), where the $R_i$ are the data points, $R_{fit}(T_i)$ is the fitted function, and the $\sigma_i$ are the errors of the data points. We include data over the range from 100 mK to 1 K, and in magnetic fields of 2.5, 3, 4 and 5 T. For $R \sim \ln T$ the values were 6104, 7063, 2932, and 1291 respectively, whereas for $G \sim \ln T$ they were 37276, 40298, 19957, and 8216, respectively. This makes the case for $R \sim \ln T$ being the better description of the data.

Futhermore, if one forces the data to be fit by the functional form $G \sim \ln T$, as shown in Fig 3(b), the coefficient of $\ln T$ is nearly three times larger than that found in the high-temperature low-field regime. For example, in zero field in the temperature range of $5K \sim 10K$, the coefficient is $5.23 \times 10^{-6} \Omega^{-1} \cdot$ whereas it is $1.63 \times 10^{-5} \Omega^{-1} \cdot$ at $10K$ over the temperature range from $0.1K \sim 1K$ when forced. This indicates that the resistance of the film in the high field, low temperature regime increases more rapidly than that of a quantum corrected metal.

In the high-field regime the behavior is clearly insulating although there is no magnetoresistance peak which has been taken as evidence that the insulator is a Cooper pair insulator. The latter behavior has only been observed in compound amorphous films or in quench condensed films patterned with nanohoneycomb hole arrays. The high magnetic field regimes of the films of the present work are not a quantum corrected 2D metals, because as demonstrated above, $R(T)$ rather than $G(T)$ is better fit by $\ln T$ over an extended range of temperature. The temperature dependence is the same as that predicted in the work of Das and Doniach [13], which describes a Bose-Heisenberg weak localization model. Although the coefficient of the $\ln T$ term is an order of magnitude smaller than that which they predict, the model may be relevant. Similar behavior has been observed in underdoped cuprate superconductors when superconductivity is quenched by a magnetic field [14]. Moreover, the coefficient of $\ln T$ in the present work is close to that found in that work. If one converts the sheet resistance into resistivity, the coefficient of $\ln T$ in a field of 2T is $-6.9 \times 10^{-5} \Omega \cdot \text{cm}$, while for the case of $\chi = 0.13$ of La$_{2-x}$Sr$_x$CuO$_4$, it was found to be $-7.2 \times 10^{-5} \Omega \cdot \text{cm}$ when current is in the ab plane.

The fact that at higher temperatures the data can be scaled, suggests the existence of a quantum critical point. However, a direct quantum phase transition never occurs, because the two-phase regime develops as one lowers the temperature. In the limit of zero temperature the film is either insulating or superconducting so that it is likely that percolation physics plays a role in the SI transition. The value of the critical exponent product $\nu z = 0.4$ found in the regime in which the data scales is not as-
associated with any particular model relevant to ultrathin films. However this value has been found in a Monte Carlo simulation of (2+1)D XY Josephson junction arrays without disorder and with frustration $f = 1/4$ [23]. Furthermore, this simulation exhibits a first order phase transition when the frustration drops to $f = 1/5$. A two-phase regime such as inferred from our data could also imply a first order quantum phase transition. Modeling a disordered film with a junction array would appear to require a Monte Carlo simulation including disorder, which is not included in the simulation of Lee and Cha. On the other hand, Kim and Stroud performed a simulation including disorder but without magnetic field [24]. A simulation with disorder and frustration would be needed to model films such as those reported in this work.

The present results deepen the mystery associated with the superconductor-insulator transition. Although various models may account for the behavior of specific systems, there is no model that explains their different behaviors. For example, it is not clear as to why some transitions are direct, and with small changes in the level of disorder an intermediate two-phase regime emerges. Also the reasons for the differences between the high field regimes of different materials are not known.

This work was supported in part by the National Science Foundation under grants NSF/DMR-0455121 and NSF/DMR-0854752.

[1] N. Markovic, C. Christiansen, A. M. Mack, W. H. Huber, and A. M. Goldman, Phys. Rev. B 60, 4320 (1999).
[2] Kevin A. Parnedo, K. H. Sarwa b. Tan, and A. M. Goldman, Phys. Rev. B 73, 174527 (2006).
[3] M. A. Steiner, G. Boebinger, and A. Kapitulnik, Phys. Rev. Lett 94, 107008 (2005).
[4] V. F. Gantmakher, M. V. Golubov, V. T. Dolgopolov, G.E. Tsdyrzhapov, and A. A. Shushkin, Physica B 284-288, 649 (2000).
[5] G. Sambandamurthy, L. W. Engel, A. Johansson and D. Shahar, Phys. Rev. Lett. 92, 107005 (2004).
[6] Myles Steiner and Aharon Kapitulnik, Physica C 422, 16 (2005).
[7] T. I. Baturina, A. Yu. Mironov, V. M. Vinokur, M. R. Baklanov, and C. Strunk, Phys. Rev. Lett. 99, 257003 (2007).
[8] M. A. Palanen, A. F. Hebard, and R. R. Ruel, Phys. Rev. Lett 69, 1604 (1992).
[9] G. Sambandamurthy, L. W. Engel, A. Johansson, E. Peled, and D. Shahar, Phys. Rev. Lett. 94, 017003 (2005).
[10] Valerii M. Vinokur, Tatyana I Baturina, Mikhail V. Fistul, Aleksey Yu. Mironov, Mikhail Baklanov, and Christoph Strunk, Nature 452, 613 (2008).
[11] Myles A. Steiner, Nicholas P. Breznay, and Aharon Kapitulnik, Phys. Rev. B 77, 212501 (2008).
[12] H. Q. Nguyen, S. M. Hollen, M. D. Stewart, Jr., J. Shainline, Aijun Yin, J. M. Xu, and J. M. Valles, Jr., Phys. Rev. Lett 103, 157001 (2009).
[13] D. Das and S Doniach, Phys. Rev. B 57, 14440 (1998).
[14] Yoichi Ando, G. S. Boebinger, A. Passner, Tsuyoshi Kimura and Kohji Kishio, Phys. Rev. Lett. 75, 4662 (1995).
[15] Kevin A. Parendo, K. H. Sarwa B. Tan, and A. M. Goldman, Phys. Rev. B 76 100508 (2007).
[16] N. D. Mathur, F. M. Grosche, S. R. Julian, I. R. Walker, D. M. Freye, R. K. W. Haselwimmer and G. G. Lonzarich, Nature 394, 39 (1998).
[17] B. Spivak, P. Oreto and S. A. Kivelson, Physical Review B 77, 214523 (2008).
[18] Yonatan Dubi, Yigal Meir, and Yshai Avishai, Nature 449, 876 (2007).
[19] L. M. Hernandez and A. M. Goldman, Rev. Sci Instrum. 73, 162 (2002).
[20] M. Strongin, R. S. Thompson, O. F. Kammerer, and J. E. Crow, Phys. Rev. B 1, 1078 (1970).
[21] E. Abrahams, P. W. Anderson, D. C. Licciardello and T. V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979); B. L. Altschuler and A. G. Aronov, Solid State Commun. 46, 429 (1983).
[22] M. P. A. Fisher, Phys. Rev. Lett. 65, 923 (1990).
[23] Hunpyo Lee and Min-Chul Cha, Phys. Rev. B 65, 172505 (2002).
[24] Kwangmoo Kim and David Stroud, Phys. Rev. B 78, 174517 (2008).