Electrostatic Tuning of the Superconductor-Insulator Transition in Two Dimensions

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Superconductivity has been induced in insulating ultrathin films of amorphous bismuth using the electric field effect. The screening of the electron-electron interaction was found to increase with electron concentration in a manner correlated with the tendency towards superconductivity. This does not preclude an increase in the density of states being important in the development of superconductivity. The superconductor-insulator transition appears to belong to the universality class of the three dimensional XY model.

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Superconductor-insulator (SI) transitions in ultrathin films [1] are believed to be examples of quantum phase transitions (QPTs) [2]. Such transitions occur at zero temperature in response to the tuning of an external parameter of a system that alters its ground state. Although many systems exhibit QPTs, including ^{4}He adsorbed on random substrates, two-dimensional electron gases, and numerous complex strongly correlated electron materials including high temperature superconductors, the SI transition is one of the most fundamental because of its apparent connection with the phase-number uncertainty relation of quantum mechanics [3]. The standard approaches to tuning SI transitions involve increasing film thickness and applying perpendicular magnetic fields. Both of these can introduce complications. Increasing film thickness changes carrier density but may also alter the disorder landscape. Applying perpendicular magnetic fields introduces vortices and the complexity of vortex physics.

Here we report the electrostatic tuning of the SI transition in ultrathin amorphous bismuth (a-Bi) films using the electric field effect. This tuning changes the carrier density without altering the disorder landscape. Modulation of superconductivity using the field effect is an old idea [4], which has been revived by recent work on high temperature (cuprate) superconductors [5,6]. However, these studies have not revealed significant features of the transitions between the various ground states. The difficulties of preparing high quality cuprate films with thicknesses on the order of the electrostatic screening length and chemically doped so that they are near a phase boundary has limited the usefulness of these studies. These constraints are either irrelevant or easily satisfied in work on homogeneously disordered ultrathin films.

A single-crystal of (100) $SrTiO_3$ (STO) served as both the substrate and the gate insulator. Its unpolished surface was mechanically thinned [7], leaving parallel surfaces approximately 50 μm apart. Platinum was predeposited at 300 K forming a 1000 Å thick gate electrode on the thinned back surface and 100 Å thick measurement electrodes on the epipolished front surface. The substrate was then placed in a dilution refrigerator/UHV deposition apparatus [8]. A 10 Å thick underlayer of amorphous antimony (a-Sb) followed by subsequent layers of a-Bi were deposited *in situ* under UHV conditions ($\sim 10^{-9}$ torr) through shadow masks. The substrates were held at liquid-helium temperatures during deposition. Films grown in this manner are believed to be homogeneously disordered [9].

Resistances were measured by employing standard four-probe dc methods using a 1 nA current, a value well within the linear regime of the $I - V$ characteristics. A voltage source provided the gate-film bias. All electrical leads were filtered at 300 K with RC filters to attenuate 60 Hz noise and π-section filters to attenuate rf noise, and at the mixing chamber of the refrigerator with 2 m long Thermocoax cables [10] to attenuate GHz noise. The measurement and deposition processes were alternated, with the film always kept below 14 K in a UHV environment, permitting the study of the evolution of electrical transport properties with thickness.

In the sequence of films in which electrostatic gating was studied, the film thickness was varied from 9.60 to 10.22 Å in four steps. All films were insulating, with $R(T)$ exhibiting a temperature dependence consistent with Mott variable range hopping. All curves exhibited resistance flattening for $T \lesssim 60$ mK. We will argue later that this behavior is not evidence of an intermediate metallic regime. It is believed to be a consequence of the electrons in the film failing to cool despite significant efforts to shield them from external noise and thermal radiation.

The 10.22 Å thick film was the first in the sequence in which an electrostatically tuned SI transition (Fig. 1) could be induced. Resistance decreased with increasing positive gate voltage (V_G) at all temperatures, consistent with previous observations that the carriers in metallic a-Bi are electrons [11]. A logarithmic dependence on temperature became a better fit at about 7 V and continued to do so for all larger gate voltages at high temperatures despite the presence of superconducting behavior at low temperatures.

One can qualitatively distinguish between insulating and superconducting ground states by examining the sign of dR/dT at low temperatures. At low V_G, $dR/dT < 0$, suggesting an insulating state. With increasing V_G, dR/dT

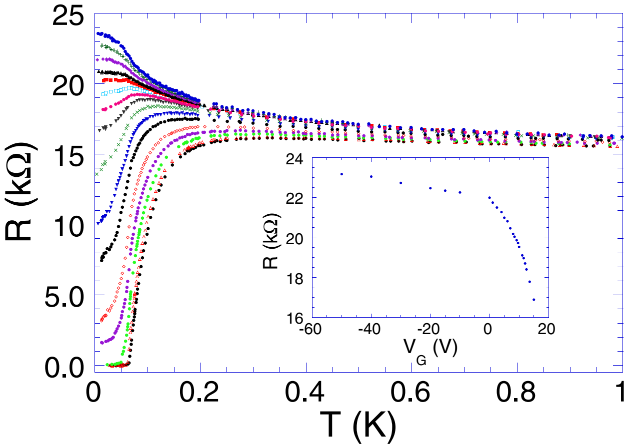

FIG. 1 (color online). $R(T)$ as a function of V_G for the 10.22 Å film. From top to bottom, gate voltages are 0, 2.5, 5, 7, 8, 9.6, 11, 12.5, 14.5, 17, 19.5, 24, 28, 33, 38, and 42.5 V. Approximately 40 data curves have been omitted for clarity. Inset: Resistance versus gate voltage for the 10.22 Å film at 65 mK.

eventually changed sign, suggesting a superconducting state. Zero resistance, within the limits of the scatter of the data, was observed for $V_G > 38$ V. The highest temperature at which zero resistance was observed increased monotonically with V_G, from 52 mK at 38 V to 59 mK at 42.5 V. At 42.5 V, all effects due to gating saturated, so $R(T)$ for $V_G > 42.5$ V was identical to $R(T)$ at 42.5 V.

The response of the resistance to V_G was stronger at low temperatures than at high temperatures, implying that the high temperature conductance was affected much less by electrostatic charging than the superconducting pairing mechanism. The major changes in $R(T)$ in response to V_G appeared only as low temperature deviations from the weakly insulating $V_G = 0$ curve. Qualitatively similar behavior has been found in the perpendicular magnetic field-tuned SI transition of $\mathrm{In_2O_3}$ films [12], as well as in studies of the metal-insulator transition [13].

The inset of Fig. 1 shows the field effect for both signs of gate voltage at 65 mK for the 10.22 Å thick film. Negative V_G produces a small change in film resistance, while positive V_G causes a large decrease. At higher temperatures, all $R(T)$ curves for negative V_G largely coincide with the $V_G = 0$ curve. Thus hopping transport is only changed a small amount. Similarly, for a 10.69 Å thick film (not shown) with a 446 mK transition temperature, the asymmetry in the response for the two signs of gate voltage was evident in that for $V_G = 50$ V, T_c increased to 502 mK, while for $V_G = -50$ V, it decreased only to 436 mK. This film was prepared in an earlier sequence of depositions in which the superconductor-insulator transition was overshot.

Measurements at low temperatures using thinned STO as a gate dielectric have demonstrated that electron transfer is approximately linear with gate voltage from zero at $V_G = 0$ to approximately 3×10^{13} cm^{-2} at $V_G = 50$ V [7] and it does not saturate above that value. Thus, the observed saturation of film behavior cannot result from properties of the gate dielectric. The film's intrinsic electron concentration is unknown, as the geometry in this particular set of studies was limited to parallel magnetic fields, precluding Hall effect measurements.

The simplicity of electrostatic charging as a tuning parameter provides an opportunity to analyze data in ways not possible for either the thickness or magnetic field-tuned SI transitions. The behavior of $R(T)$ at high temperatures, as a function of gate voltage, can reveal features of the disordered 2D electron system relevant to its superconductivity. In 2D metals, in zero magnetic field, the conductance is the sum of the classical Boltzmann conductance (G_B) and corrections due to coherent backscattering/weak localization (G_{WL}) [14] and electron-electron interactions ($G_{e\text{-}e}$) [15]. Both produce a decrease in conductance that goes as the logarithm of temperature. This is based on a perturbative analysis valid when $k_F l \gg 1$, where k_F is the 2D Fermi wave vector and l is the electronic mean free path. However, it is possible that this analysis may work even when $k_F l \gtrsim 1$. (The value of $k_F l$ for these films, estimated from their high temperature conductivity is approximately 1.6.) Thus,

$$G_{\mathrm{WL}}(T) + G_{e\text{-}e}(T) = \left[\alpha p + \left(1 - \frac{3}{4}F^*\right)\right]\frac{e^2}{2\pi^2\hbar}\ln(T).$$

The weak localization correction is determined by the temperature exponent of the inelastic scattering time, p, and the localization parameter, α. The interaction term is controlled by a screening parameter, F^*, which increases from 0 to 0.866 as the electron-electron interaction changes from being unscreened to completely screened. The inset in Fig. 2 shows a plot of G vs $\ln(T)$ for the $V_G = 12.5$ V curve of the 10.22 Å thick film. This curve is nonlinear at low T because the system in tending towards superconduc-

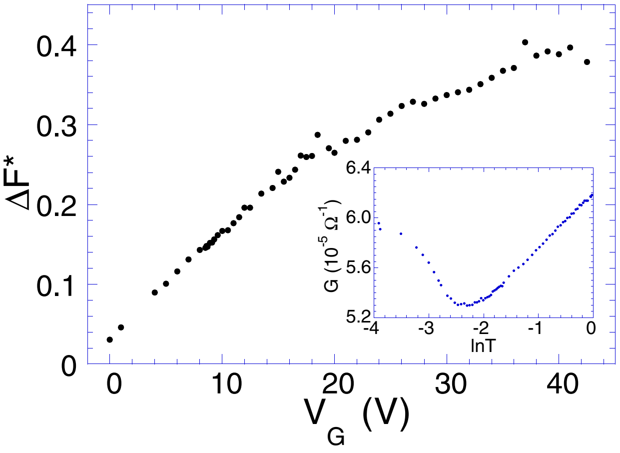

FIG. 2 (color online). Change in the screening parameter ΔF^* versus V_G. Inset: Conductance versus $\ln(T)$ for the $V_G = 12.5$ V curve.

tivity. For $T > 175$ mK, the curve is linear in $\ln(T)$, and the coefficient of the logarithm depends on the values of αp and F^*. Assuming the weak localization contribution, αp, to be constant for all V_G, by subtracting slopes of $G[\ln(T)]$ at nonzero V_G from the slope of $G[\ln(T)]$ at $V_G = 0$, one can determine the value of $\Delta F^* = F^*(V_G) - F^*(V_G = 0)$. This function, which is then the increase in screening constant induced by the gate voltage, relative to the screening constant intrinsic to the ungated film, is shown in Fig. 2. F^* increases monotonically by approximately 0.35 from $V_G = 0$ to $V_G = 42.5$ V. F^* will increase with this functional form, no matter the precise value of αp or $F^*(V_G = 0)$. (Note that in this analysis, we force a logarithmic fit to the exponential insulating curves. This is fairly accurate at temperatures higher than roughly 150 mK.) A positive magnetoresistance, logarithmic in B, that would allow determination of αp and of $F^*(V_G = 0)$ is expected in fields $B \gg k_B T/g\mu_B$. We observed positive magnetoresistance for all B at 300 mK at $V_G = 10$ V, but no specific field dependence could be determined.

The increase in F^* with V_G is correlated with the enhancement of the tendency towards superconductivity. In conventional metals the latter is controlled by the competition between the Coulomb repulsion and the phonon-mediated attractive interaction. Increased screening leads to the suppression of Coulomb repulsion, ultimately permitting superconductivity to develop. Once superconductivity is achieved, increased screening should move T_c to higher temperatures. Saturation of both T_c and F^* with V_G might not be unexpected in the limit of strong metallicity, as the density of states for a 2D metal is a constant independent of carrier concentration. The electron density determines the value of conductivity at high temperatures. Since a major change in the low temperature behavior occurs without a substantial change in the resistance at higher temperatures, screening, which changes significantly, and not the areal charge density, might be controlling the transition to superconductivity. However, in the BCS model, the product of the density of states and the interaction potential determines the transition temperature. Therefore, an increase in the density of states may also contribute to the inducing of superconductivity.

The asymmetry of the response to the sign of V_G would suggest that the Fermi energy of the ungated film is close to the mobility edge. Increasing the electron concentration with positive V_G would then increase the screening and the density of states significantly, whereas decreasing the electron concentration with negative V_G would result in small changes in the hopping transport, screening, and the density of states.

It is expected that conductivity data associated with continuous QPTs can be collapsed using a finite-size scaling analysis [2]. As data has been acquired at increasingly lower temperatures, such analyses have been observed to fail because of flattening of the curves of $R(T)$. Scaling also appears to fail when curves of $R(T)$ that exhibit the onset of superconducting behavior fan down from weakly insulating curves. In the present work, finite-size scaling of $R(T)$ data with V_G as the tuning parameter was successful because we confined the temperature range and used fine increments of values of the control parameter. All data for $T \leq 60$ mK was excluded, assuming that the observed flattening of $R(T)$ was due to a failure to cool the electrons. In the inset of Fig. 3, $R(V_G)$ is plotted at fixed temperature for 15 isotherms between 65 and 100 mK. This yields a well-defined crossing point at $V_G = 11$ V, which is taken to be the critical value of the tuning parameter, V_{GC}. The critical resistance (R_C) of 19 100 Ω is large in comparison with values found for the SI transition with other tuning parameters. Plotting R/R_C versus $|V_G - V_{GC}|T^{-1/\nu z}$ for 54 values of V_G between 0 and 42.5 V, the product $\nu z = 2/3$ is found to yield the best collapse of data onto two separate branches, one for superconducting films and the other for insulating films. This is shown in Fig. 3. Assuming the value of z to be 1, the value $\nu = 2/3$ is consistent with the universality classes of either the three dimensional (3D) XY or inverse XY models. The latter is believed to describe the transition to superconductivity in 3D [16] and might be expected for a QPT in a system governed by the 2D XY model at nonzero temperature with $z = 1$ [2]. This value of the exponent product is different from those found using thickness as a tuning parameter for a-Bi films [1] and magnetic field as a tuning parameter for InO$_x$ [17] and MoGe [18] films, but is consistent with a study of the magnetic field-tuned transition in a-Bi films [19].

The breakdown of scaling when data above 0.1 K is included suggests that the critical regime only extends from zero to some low temperature on the order of 0.1 K. Except for the limited temperature range, the quality of the curve is as good as or better than that of earlier scaling analyses, from the highest value of R/R_c down to 0.6 and

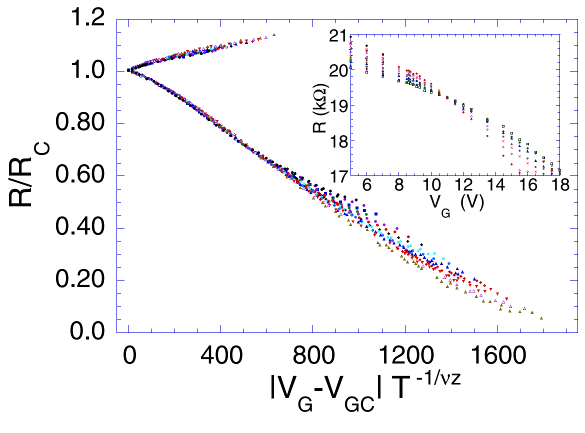

FIG. 3 (color online). Scaling analysis of $R(T)$ with V_G as tuning parameter. The critical exponent product $\nu z = 2/3$. Inset: $R(V_G)$ for isotherms from 65 to 100 mK, yielding a distinct crossing point at the critical gate voltage of 11 V.

for a range of $|V_G - V_{GC}|T^{-1/\nu z}$ extending from 0 to over 700. The analysis is shown down to $R/R_C = 0$ to demonstrate how isotherms deviate from the superconducting scaling branch. The bottom curve is for the lowest temperature and appears to adhere to the scaling function. Curves generated from data taken at increased temperatures deviate at higher values of R/R_C. This implies that scaling works best at the lowest temperatures. In this work, all $R(T)$ curves tend toward becoming temperature independent below approximately 60 mK. Curves for which $11\ \mathrm{V} < V_G < 38\ \mathrm{V}$ have nonzero resistance at the lowest measured temperature, while curves for which $V_G \geq 38\ \mathrm{V}$ show zero resistance. The fact that all $R(T)$ curves from both groups satisfy the same scaling function for the same νz suggests that these two regimes are not different. This is the main reason for our earlier assertion that *in this instance* the observed flattening of resistance is not intrinsic. In other experimental situations, the flattening could be a real metallic phase.

Any scaling analysis has a lower temperature bound. Thus, data that appear on the insulating branch may actually belong on the superconducting one, as $R(T)$ curves that appear to be insulating might actually be observed to be superconducting if lower temperatures became accessible. The continuous nature of the scaling function at the zero of $|V_G - V_{GC}|$ would allow for a higher critical resistance than that identified here without change of the critical exponent product.

The electrostrictive response of STO can be ruled out as an explanation of the observed effects because $R(V_G)$ is asymmetric in V_G while the electrostrictive response of STO is symmetric [7].

The thinness (10 Å) of the *a*-Sb layer rules out the possibility that screening may be caused by an accumulation of a mobile charge at the interface between the STO substrate and the *a*-Sb layer, similar to the field-effect modulation found between STO and Al_2O_3 [20]. The fact that negative gate voltage causes little if any change in the film is different from what was found in previous work on *a*-Bi grown on *a*-Ge [21].

In summary, the electric field effect has been used to tune the 2D SI transition. The evolution of superconductivity is correlated with an increase in screening. The size of the critical regime appears to be quite small. The exponent product $\nu z \sim 2/3$ is found, so the universality class of the transition appears to be that of the 3D XY model. This product is different from the value $\nu z \sim 4/3$ that has been found in numerous previous experiments, which has been suggested to be a signature of classical percolation in 2D [22]. It is possible that the underlying mechanism for this electrostatically tuned transition is different from those in studies that are tuned by changing film thickness or applying magnetic fields.

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