Electrostatic Tuning of a Quantum Phase Transition

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Abstract. Quantum phase transitions are transitions between the ground states of physical systems traversed by varying a parameter of the Hamiltonian. We have been examining the properties of ultrathin quench-condensed films of amorphous Bi, which exhibit a number of quantum phase transitions tuned by disorder, perpendicular and parallel magnetic fields and charge density. We have developed a procedure in which the substrate for film growth serves as the gate insulator in a field effect transistor configuration. This permits electrostatic tuning of a transition between insulating and superconducting behaviour. Finite size scaling of the conductivity has been carried out yielding critical exponents that suggest that the insulator-superconductor transition belongs to the universality class of the 3D XY model. This electric field-induced superconductivity can in turn be destroyed by magnetic fields and the data can also be scaled in with essentially the same results. These findings are quite different from those obtained in the study of substantially thicker films of indium oxide and titanium nitride.

1. Introduction

Disordered films have been used to study the interplay between localization and superconductivity, a problem originally treated by Anderson and Abrikosov and Gor’kov [1], who considered a low-disorder limit. For strong disorder, approaches include fermionic mean field theories [2] and theories that focus on universal critical properties near the superconductor-insulator (SI) transition in which case the transition belongs to the dirty boson universality class [3]. The latter and its many extensions were motivated by experiments in which the SI transition was traversed in films using various tuning parameters, including film thickness, perpendicular and parallel magnetic fields, and most recently charge density [4].

Here we discuss a series of investigations of the transition in ultrathin films between an insulator and a superconductor using the technique of electrostatic doping, which has been discussed extensively by Ahn et al. [5]. Although this subject has a long history, beginning with Glover and Sherrill [6], it is only recently that significant effects have been realized. In the following we will describe the simple experimental techniques and two experiments, one involving tuning of amorphous Bi films across the transition electrostatically, and a second, quenching superconductivity that has been induced electrostatically with a parallel magnetic field. In both instances it has been possible to carry out finite size scaling analyses that yield exponent products consistent with a 3D XY model. This result is consistent with results obtained for the SI transition of a-Bi films by a perpendicular field, but differs from the findings for the thickness tuned transition, and the results of experiments on Mo$_3$Ge, and In$_3$O$_7$ films in perpendicular fields [7].
2. Experimental Procedures
The approach was to employ a geometry in which SrTiO$_3$ (STO) single crystals served as both substrates and gate insulators in a field effect transistor configuration. To fabricate the desired structure, a small section of the unpolished back surface of a 500 μm thick single crystal of a (100) STO was thinned mechanically, producing a membrane between the epi-polished front surface and the back surface, which was 45±5 μm thick. A 0.5 mm by 0.5 mm, 100 nm thick Pt layer was deposited onto the thinned section of the back surface opposite the eventual location of the measured square of film. This layer served as a gate electrode. Platinum films, 10 nm thick were also deposited onto the front surface to form four-probe measurement geometry.

The substrate was wired up and then placed in a Kelvinox-400 dilution refrigerator/UHV deposition apparatus [8]. A 1 nm thick layer of amorphous Sb ($\alpha$-Sb) and successive layers of $\alpha$-Bi were thermally deposited in situ under UHV conditions through shadow masks on the front surface. The substrates were held at about 7 K throughout the deposition process. Films grown in this manner are disordered on an atomic scale and are not granular. This approach permits cycles of deposition and measurement all in situ at low temperatures, so that the properties of a film can be tracked as a function of thickness.

The film and the gate electrode form a parallel plate capacitor with the thinned layer of STO serving as the dielectric spacer. Since STO crystals have large dielectric constants at temperatures below 10K ($\kappa \sim 20000$) and since the substrate has been reduced in thickness, large electric fields that can produce significant charge transfers are possible. As an example, with positive gate voltage, $V_G$ transferred electron densities were found to be between 0, with $V_G = 0$, and $3.35 \times 10^{13}$/cm$^2$ with $V_G = 42.5$ V. It was necessary to measure the actual charge transfer as a function of gate voltage given the dependence of the dielectric constant of STO on electric field.

There are two additional experimental issues. The electrical measurements lines need to be filtered so as to minimize the level of electromagnetic noise in the sample chamber. The procedure was to use REC filters at room temperature to attenuate 60 Hz noise, $\pi$-section filters at room temperature to attenuate radio frequency noise, and 2 m long Thermocox cables at the mixing chamber to attenuate GHz Johnson noise from warmer parts of the apparatus [9]. Measurements employed DC rather than AC techniques to avoid complications that might arise from the filter configuration.

A second issue relates to the failure to cool films much below 50 mK despite the fact that the refrigerator reaches temperatures of order 5 mK. This results from a combination of the residual noise environment and limitations on the thermal grounding of electrical leads. There can be issues with measuring currents, even at low levels of excitation. Ramping $V_G$ even at slow rates can cause heating because of real currents flowing in the film in response to displacement currents induced by changing $V_G$. Similarly, ramping the magnetic field will produce Eddy currents. In very high magnetic fields thermal time constants were also dramatically long.

3. Experimental Results
A number of sequences of $\alpha$-Bi films grown on substrates pre-coated with $\alpha$-Sb were studied [4, 10]. In every case there was a stronger response of curves of R(T) with positive gate voltage than with negative. Positive gate voltage added electrons to the films, and negative removed them. The sign of the Hall coefficient found in studies by Buckel [11] of relatively thick (~ 50 nm) $\alpha$-Bi films were interpreted as evidence that electrons were the majority carriers. The present results are consistent with that finding, although there may be other processes at work that enhance the asymmetry in the response to $V_G$. In particular there may be asymmetries in the potential barriers at the $\alpha$-Bi/Pt interfaces, which allow easier flow of carriers in one direction and not the other. This might explain the much smaller response to negative values of $V_G$ found in the measurements.

Some details of the transition from an insulator to a superconductor that was tuned with charge transfer are shown in Fig. 1 for a 1.022 nm thick film. Various values of the charge transfer are shown in the caption. For all films with charge transfers less than $0.85 \times 10^{13}$/cm$^2$, the temperature...
dependence over the range from 0.065 K to 12K could be described by two-dimensional (2D) Mott variable range hopping. For larger charge transfers, the conductance could be described by a logarithm and was given by

$$G(T) = G_0 + k \ln\left[ T/T_0 \right]$$  \hspace{1cm} (1)$$

which resembles what one might expect for the regime of quantum corrections to the conductance of a 2D metal. An important caveat is that the high temperature sheet resistance is of order 8 k\$\Omega$, which implies that $k_F\ell$, where $k_F$ is the Fermi wave vector and $\ell$ is the carrier mean-free-path. Also unusual is the observation that the coefficient $k$ of the temperature dependent term is a linear function of the charge transfer. We have no simple physical explanation based on standard quantum corrections that would explain this.

**Figure 1.** Resistance vs. temperature, $R(T)$, as a function of increasing charge transfer. From top to bottom, the values of $n$ are 0 (top), 0.5, 1.1, 1.27, 1.52, 1.75, 1.92, 2.09, 2.38, 2.64, 2.86, and $3.35 \times 10^{13}/cm^2$ (bottom). For clarity only a small fraction of the data is presented.

**Figure 2.** Finite size scaling of the charge tuned SI transition results in a critical exponent product $\nu z = 0.7 \pm 0.2$. The analysis includes values of $R(T)$ from 65 mK up to 1K. The critical value of the charge transfer was $\Delta n_c = 0.85 \times 10^{13}/cm^2$, with a critical resistance of 8.88k\$\Omega$.

We are able to collapse the data of $R(T)$ at various charge transfers using the finite size scaling form appropriate to a 2D quantum phase transition [12]. In this case

$$R/R_c = F \left[ (|\Delta n - \Delta n_c|/T)^{1/\nu z} \right]$$  \hspace{1cm} (2)$$

where $F(x)$ is some unknown function, $\nu$ is the correlation length exponent, and $z$ is the dynamical critical exponent. The data collapse has been carried out using this form after removing the contributions to $R(T)$ responsible for the lnT dependent conductance channel.

The effect of parallel magnetic fields on a-Bi films, both for those which were superconducting by virtue of thickness and for those whose superconductivity was induced electrostatically was investigated. The scaling analysis in each case resulted in a nearly identical exponent product. Attempts to perform an analysis of the nonlinear conductance-voltage characteristics of films as a function of a control parameter, and to collapse data using electric field scaling did not yield anything useful. The nonlinearities found could all be explained by hot electron effects [10]. It was possible to relate the power dissipated in a film to the effective electron temperature and essentially map the electric field scaling onto temperature scaling.
4. Discussion

Most previous scaling studies of various SI transitions tuned by thickness, perpendicular and parallel magnetic fields have yielded a range of exponent products. The most common result is $z \sim 1.3$ [7, 13] and if $z = 1$, this result is consistent with the scaling theory [14], the (2 +1) dimensional XY model with disorder [15] and with various numerical studies [16]. This value has also been suggested as being consistent with percolation theory in 2D, raising the issue as to whether these transitions are percolation transitions [17]. The exceptions to this are measurements of electrostatic, and parallel and perpendicular field tuning of the transition of $a$-Bi, where the exponent product is found to be 0.7 and with $z=1$, with the 3D XY model. This result disagrees with the theorem that predicts $\nu > 1$ in the presence of disorder [18]. The possible irrelevance of his theorem has been discussed by Chamon and Nayak [19]. In summary, in studies of $a$-Bi films all of the tuning parameters, parallel and perpendicular field and charge yield an exponent product of 0.7, which assuming dynamical critical exponent of unity, imply that the universality class of the transition is that of the (2+1)D or 3D XY model [15, 20] or the Bose Hubbard model without disorder. These results are very different from the recent work of Steiner, Breznay and Kapitulnik [21] in which a perpendicular field tuned transition in In$_x$O$_y$ films exhibits an exponent product close to 7/3, as might be expected for quantum percolation.

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