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Electrostatic modification of the conductive properties of amorphous Bi ultrathin films

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Abstract

The application of the field-effect transistor principle to novel materials to achieve electrostatic doping is a relatively new research area with roots that go back to the turn of the 20th century. The technique in principle provides the opportunity to modify the electronic and magnetic properties of materials through controlled and reversible changes in carrier concentration, without altering the degree of disorder or the chemical composition. Electrostatic doping can also serve as a tool for studying quantum critical behavior, by allowing the ground state of a system to be tuned in a controlled fashion. This is precisely what has been done in tuning the transition between insulating and superconducting ground states of ultrathin films of amorphous bismuth.

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1. Introduction

Disorder, which may be relevant to superconductivity can be morphological or chemical. Early on, Philip Anderson [1] showed that nonmagnetic impurities have no significant effect on the superconducting transition by pointing out that Cooper pairs are formed from time-reversed eigenstates, which have disorder included. However this idea applies only to weakly disordered systems with their extended electronic states. Disorder can be increased to a level at which the electronic wavefunctions become localized [2]. The study of superconductivity in that regime provides a unique opportunity for studying the competition between the attractive interaction responsible for superconducting pairing and the pair-breaking effects of disorder-enhanced localization and Coulomb repulsion [3–5]. As a consequence, one might expect that superconductivity should disappear as disorder increases and states become localized.

Of particular interest are very thin films, where both superconductivity and metallic behavior are marginal. In two dimensions, the superconducting transition is a topological Kosterlitz–Thouless–Berezinskii (KTB) transition [6]. Also weakly interacting systems in two dimensions are always localized even for very weak disorder. The modification of a film's superconducting properties by disorder depends upon the strength of the disorder and its geometrical scale relative to intrinsic scales such as the interatomic spacing, the inverse Fermi moment, the electronic mean free path, the London penetration depth, and the coherence length. Ultra-thin films can be fabricated with disorder on different length scales.

One approach to studying the evolution from insulating to superconducting behavior is to use a process of repeated cycles of *in situ* deposition at liquid helium temperatures and measurement. If such studies are carried out on substrates pre-coated with thin layers of either amorphous Ge or Sb, one obtains films that are disordered on atomic

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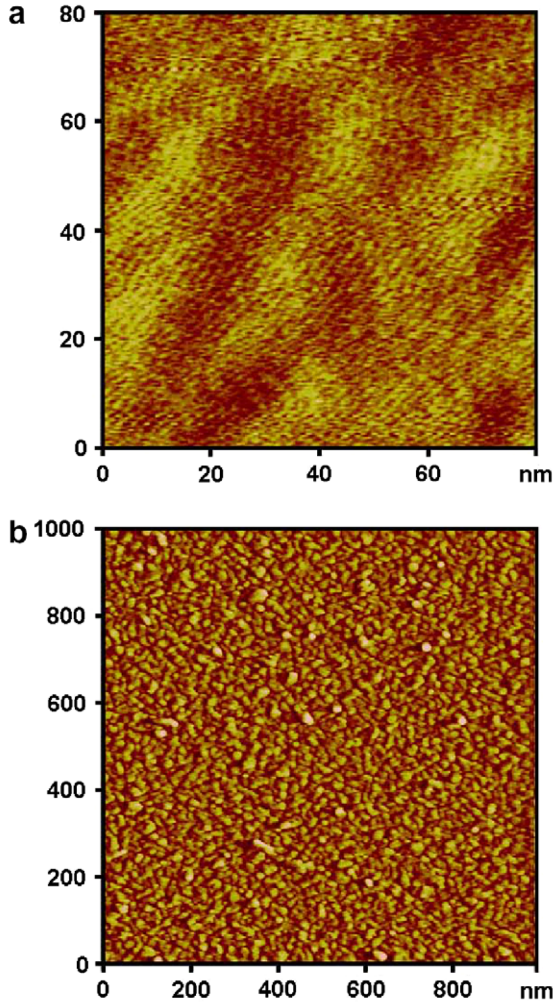

Fig. 1. Atomic force microscope images of amorphous and granular Bi films. (a) Deposited onto an *a*-Sb film (b) grown directly on a substrate. The variations in height in (a) are 0.3 nm and those in (b) are the order of the grain size.

scales [7]. Fig. 1 shows AFM traces of films prepared with and without the above-mentioned underlayers. The film with the underlayer (Fig. 1a) is seen to be feature free, whereas that without (Fig. 1b) is granular.

On the other hand there is no guarantee that using this approach that the repeated depositions do not change the morphology in some unknown fashion, as it is impossible to monitor the structure after each deposition. This drawback has led us to explore the insulator superconductor transition at fixed disorder, in a single film using the technique of electrostatic doping [8]. Although there is a long history of investigation of the control of superconductivity using electric fields, beginning with Glover and Sherill [9], there has been no significant tuning of superconductivity in metallic systems. The actual nature of the normal state when superconductivity is achieved in disordered systems is an open question that has been raised previously in the context of the behavior of granular films and high temperature superconductors [10].

2. Experimental techniques

The present studies were carried out using a geometry in which a $SrTiO_3$ (STO) crystals served as both substrates and a gate insulators in a field-effect transistor configuration [11]. To fabricate the desired structure, a small section of the unpolished back surface of a 500 μm thick single crystal of (1 0 0) STO substrate 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. Pt films, 10 nm thick were also deposited onto the substrates front surface to form a four-probe measurement geometry. The substrate was then placed in a Kelvinox-400 dilution refrigerator/UHV deposition apparatus [12]. A 1 nm thick layer of amorphous Sb and successive layers of amorphous Bi (*a*-Bi) were thermally deposited in situ under UHV conditions through shadow masks onto the front surface. The substrates were held at about 7 K during the deposition process. Films grown in this manner are thought to be disordered on an atomic scale.

In effect 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 10 K ($\kappa \sim 20{,}000$), and since the substrate is reduced in thickness, large electric fields that can produce substantial charge transfers are possible. For example with positive gate voltage, V_G transferred electron densities were found to be between 0 (at $V_G = 0$) and $3.35 \times 10^{13}/\mathrm{cm}^2$ (at $V_G = 42.5$ V) [11]. A calibration of the charge transfer vs. gate voltage was obtained as the former is the natural control variable given the variation of the dielectric constant of STO with electric field.

The electrical measurement lines were heavily filtered so as to minimize the level of electromagnetic noise in the sample chamber. The approach was to use RC filters at room temperature to attenuate 60 Hz noise, π-section filters at room temperature to attenuate radio frequency noise, and 2 m long Thermocoax cables at the mixing chamber to attenuate GHz noise from warmer parts of the refrigerator [13]. The measurements used DC rather than AC techniques to avoid complications arising from the filter configuration.

The films fail to cool much below 60 mK even though the refrigerator cools to 7 mK. This results from a combination of the residual noise environment and limitations on the thermal grounding of the electrical leads. There are also issues with the measuring currents, even at very low levels providing significant thermal load. Careful attention was given to ensuring that measurements were made only while the film was in thermal equilibrium. Ramping V_G even at slow rates cause heating, because of the real current flowing in the film in response to the displacement currents, induced by changing V_G. Although we do not discuss mag-