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Nanoscale high-temperature superconductivity

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Abstract

We discuss the exciting prospects of studying high-temperature superconductivity in the nanometer scale from the perspective of experiments, theory and simulation. In addition to enabling studies of novel quantum phases in an unexplored regime of system dimensions and parameters, nanoscale high-temperature superconducting structures will allow exploration of fundamental mechanisms with unprecedented insight. The prospects include, spin-charge separation, detection of electron fractionalization via novel excitations such as vison, stripe states and their dynamics, preformed cooper pairs or bose-condensation in the underdoped regime, and other quantum-ordered states. Towards this initiative, we present the successful development of a novel nanofabrication technique for the epitaxial growth of nanoscale cuprates. Combining the techniques of e-beam lithography and nanomachining, we have been able to fabricate the first generation of high-temperature superconducting nanoscale devices, including Y-junctions, four-probe wires and rings. Their initial transport characterization and scanning tunneling microscopy reveal the integrity of the crystal structure, grown on nanometer scale lateral dimensions. Here, we present atomic force micrographs and electrical characterization of a few nanoscale $YBa_2Cu_3O_7$ (YBCO) samples.

Keywords: Unconventional superconducivity; High-temperature superconductivity; Nanoscale superconductivity

1. Introduction

The problem of high-temperature superconductivity has reached an interesting crossroad. After almost two decades of rich phenomenology, and equally intriguing theoretical ideas, it is on the verge of a convergence, of theories, experiments and simulations, towards a critical direction. A relatively new, and yet a feasible, approach to the understanding of the microscopic mechanism is to explore high-T_c superconductors microscopically, with controlled experiments on structures only a few unit cells wide and a few monolayers thick. This bottoms-up approach to a mechanism, which works for much larger, millimeter-size structures, is motivated by a number of recent advances, both in experiments and theoretical ideas. First, let us consider the characteristic length scales of the problem, depicted in Fig. 1. Even with the best possible growth techniques, largest single-crystal domains in high-T_c superconducting (HTS) cuprate structures are only a few nanometers in size [1]. Scanning tunneling microscopy on a typical HTS surface gives microscopic length scales of unit cells and domains, typically in the range of 0.2 and 20 nm respectively [2]. Two other fundamental length scales in the HTS materials are the coherence length—on the order of angstroms, and the penetration depth—typically on the order of microns. In this spectrum of length scales crowded in the sub-micron regime, there is yet another important scale—that is, of stripes. The idea of stripe states, which are now well known, and experimentally proven to exist in a certain regime of the HTS phase diagram [3], forms the basis of certain theories of the fundamental mechanism. The characteristic length scale associated with the stripe state is the width of the stripe, known to be on the order of a few lattice spacings,

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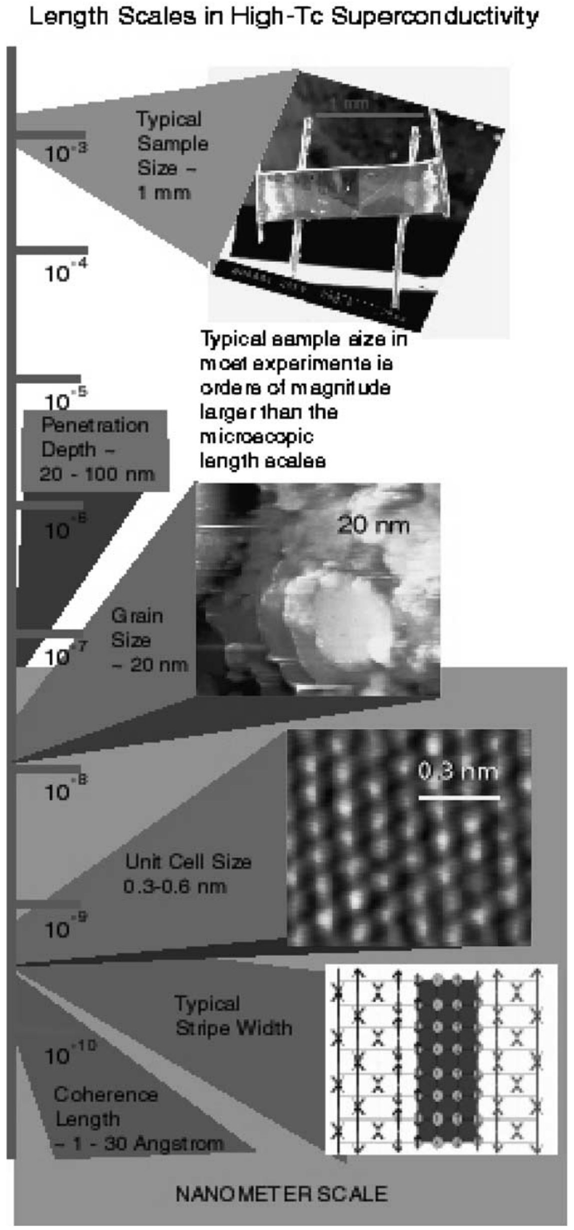


Fig. 1. Most characteristic length scales in high-temperature superconductivity lie in the sub-micron range.

amounting to a couple of nanometers [4]. It is apparent that most of the fundamental length scales in high-T_c superconductivity are on the nanometer scale. Therefore, experimental investigation of structures on this scale can be vital to the understanding of the microscopic mechanism. Not only will it help discern various states in the HTS phase diagram by virtue of the system size, it will enable direct and controlled studies of the exotic phases microscopically [5].

A second—and, fundamentally, important—point concerns the state of the art in the current computational studies. A prominent example is the density-matrix renormalization group calculation [6] of the ground state and the first few low-lying excitations of a strongly correlated electron gas, a model for the copper oxide layer. This powerful technique shows stripes of charge ordering in 2D clusters of sizes on the order of 10×10 lattice spacings. Interestingly, such stripe states with a width of a few lattice spacings have been detected in a number of experiments. Further motivation for the study of stripes comes from a dominant theoretical basis for a fundamental mechanism of high-temperature superconductivity. Under these circumstances, what is exciting is that cuprate structures can be physically engineered and fabricated, down to a scale comparable to the cluster size studied in simulation. Additionally, structures on this scale could contain as few as one or two stripes. Their experimental investigation is expected to show a number of exotic edge states of stripes.

From computational determination to theoretical proposals, transport studies of nanoscale devices can be instrumental in discerning the nature of the ground state in various mechanisms. For example, the resonance valence bond (RVB) states proposed by Anderson [7] demonstrate spin-charge separation. In one version [8], the electron fragments into a spin excitation state (spinon) and a charge excitation state (chargon), and superconductivity arises due to the condensation of the chargons that are bosonic in nature due to their separation from the spins. This mechanism of electron fractionalization is expected to manifest in the dynamics of vortex-like excitations [9], called visons, which can be probed by trapping them in a micron-sized ring with transverse dimensions in the nanometer scale. Both the detection of vison escape in hysteresis measurements and h/e flux contributions in the underdoped regime can be made with high sensitivity by Aharonov–Bohm quantum interference measurements in mesoscopic ring structures. In other proposals, preformed pairing [10] or bose-condensation [11] is expected in the normal state of the underdoped regime. Aharonov–Bohm experiments in this regime can provide confirmation by the direct measurement of the charge. Nanoscale cuprate devices offer a novel approach to the study of these theoretical proposals.

2. Nanofabrication of high-T_c superconducting devices

Challenges in the fabrication of nanoscale high-T_c superconducting materials with single-crystal integrity arise due to two essential problems. (a) Conventional mask definition techniques such as e-beam lithography on e-beam resists are not useful for insulating substrates like lanthanum aluminium oxide, or strontium titanate

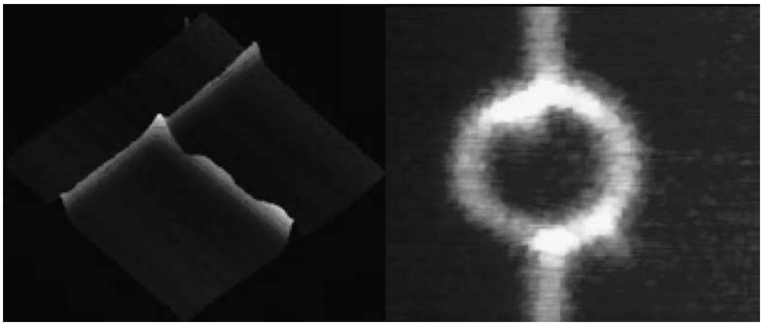


Fig. 2. (Left) An AFM picture of a Y-junction of optimally-doped YBCO (width: 60 nm, thickness: 20 nm). (Right) An Aharonov–Bohm ring of underdoped cuprate by the novel fabrication technique of nanomachining. The diameter of the ring (1.6 μm) corresponds to a flux periodicity (h/e) of roughly 20 Gauss. Because of its size, the structure is capable of sensitive detection of single vortex-like (vison) motion. In a similar structure grown below the underdoped regime, the charge of the carriers can be accurately determined by interference measurement as e, $2e$ or any fraction thereof.

due to charging problems. Furthermore, these devices are treated at high-temperatures for epitaxial crystal growth conditions, incompatible with the conventional e-beam resists. (b) Chemical contamination of the material by the residual e-beam resist or the selective wet etching for liftoff can severely compromise the film integrity. Therefore it is essential that (i) the film deposition is the last step in the nanofabrication process, and (ii) no further chemical or physical (plasma cleaning or ion milling) treatments are done after the film deposition (growth).

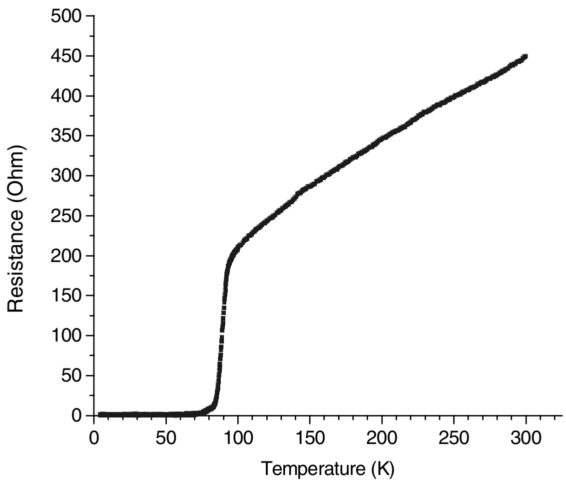
Combining electron-beam lithography and nanomachining techniques, we have developed a nanofabrication process in which the material is deposited in the last step. The nanoscale definition of the structure is made by masking the structure area and machining down the substrate to a depth of a micron, followed by a process of cleaning the mask. This creates a bridge along the defined pattern over which the cuprate material is grown by pulsed laser deposition. Because of the height of the bridge, materials deposited on the subsurface are physically and electrically disconnected from the structure over the bridge. With this technique, we have fabricated a number of structures (see Fig. 2), designed for transport measurements, discussed in the previous section.

3. Electrical characterization

Characterization of the structures is essential to ensure film quality. Although scanning probe microscopy techniques provide surface topography of the structure, resistitivity measurement can be sufficient, at least, for optimally-doped structures. Our preliminary characterization of a number of optimally-doped nanowires with lateral width down to 60 nm and thickness of 20 nm shows that the structures have very high critical temperatures ($\sim$87–89 K) with sharp transitions (<3 K) (Fig. 3). Furthermore, it is determined that the degree of disorder is rather low in these structures. It is essential to characterize the degree of disorder, presence of magnetic and nonmagnetic impurities and extrinsic two-level fluctuators for the entire range of measurements: stripe dynamics by switching events in real time or vison escape or Aharonov–Bohm oscillation for the determination of charge. Over the last two decades, transport measurements have been performed extensively on mesoscopic structures of metals and semiconductors; these studies have emphasized the importance of mesoscopic aspect of the structures through a number of subtle, and not-so-subtle effects, which dominate in the mesoscopic range. These include, nonlocal effects, negative magnetoresistance due to ballistic scattering and probe configurations. Even more important is the proper isolation from external noise sources, which are detrimental for most mesoscopic devices. In our approach to a complete transport characterization of nanowires, rings and Y-junctions, fabricated from cuprates with a range of doping, we are performing controlled studies of the above mesoscopic effects. Towards that end, our preliminary studies in the mesoscopic or nanoscale high-T_c superconducting structures are highly encouraging.

4. Outlook

The studies of high-temperature superconductivity in the nanometer scale hold potential for fundamental discovery, in theory, experiment and simulation. Because of this natural convergence, mesoscopic transport will be an essential tool. For example, the evolution and dynamics of stripe states in high-T_c nanowires are already underway in a number of laboratories [12], including ours. In spite of obvious analogies in mesoscopic physics of metals and semiconductors, theoretical



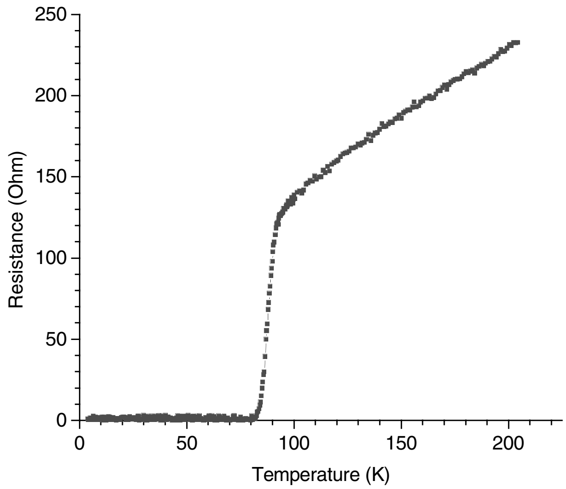


Fig. 3. Electrical characterization of two (optimally-doped $YBa_2Cu_3O_7$) nanowires shows high-temperature superconductivity at critical temperatures of 89 and 87 K, both with sharp ($\sim$3 K) transitions. This authenticates the cleanliness of our nanofabrication process.

framework for transport properties in the equilibrium and nonequilibrium states will be absolutely necessary to interpret data.

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