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Superconductivity of very thin films: The superconductor–insulator transition

Yen-Hsiang Lin [1], J. Nelson, A.M. Goldman *

School of Physics and Astronomy, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455, USA

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ABSTRACT

The study of thin superconducting films has been an important component of the science of superconductivity for more than six decades. It played a major role in the development of currently accepted views of the macroscopic and microscopic nature of the superconducting state. In recent years the focus of research in the field has shifted to the study of ultrathin films and surface and interface layers. This has permitted the exploration of one of the important topics of condensed matter physics, the superconductor–insulator transition. This review will discuss this phenomenon as realized in the study of metallic films, cuprates, and metallic interfaces. These are in effect model systems for behaviors that may be found in more complex systems of contemporary interest.

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Contents

1. Introduction

The subject of thin film superconductivity is quite broad, and if treated in detail would encompass several monograph volumes. In this review we will limit the discussion to the superconductor–insulator transition. Superconductor–insulator transitions (SITs) in two dimensions, especially those implemented in thin films and interfaces, can provide the simplest examples of the continuous quantum phase transition paradigm [1]. Quantum phase transitions differ from thermal phase transitions in that they occur at zero temperature and involve a change of the ground state in response to the variation of an external parameter of the Hamiltonian. In the example of the superconductor–insulator transition, this control parameter could be a parallel or perpendicular magnetic field, disorder, or charge density. Quantum phase transitions are studied through measurements at nonzero temperature of physical behaviors influenced by the quantum fluctuations associated with the zero-temperature transition that persist at nonzero temperatures. Here we focus on aspects of superconductor–insulator transitions in films that are effectively two-dimensional insofar

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* Corresponding author.
E-mail address: goldman@physics.umn.edu (A.M. Goldman).

[1] Current address: Department of Physics, University of Maryland, College Park, MD 20742-4111, USA.

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as their superconducting properties are concerned. In addition to work on disordered thin films, recent developments such as the superconductor–insulator transitions observed in the metallic layer found at interfaces between certain different insulators, and those associated with the electrostatic tuning of high temperature superconductors will be included. We will not discuss transitions in either three-dimensional systems [2] or Josephson junction arrays [3].

Quantum phase transitions are studied through measurements at nonzero temperature of physical behaviors influenced by quantum fluctuations. Among other systems exhibiting quantum phase transitions are ^{4}He adsorbed on random substrates, two-dimensional electron gases, and numerous complex, strongly correlated electron materials. The concept is also relevant to the physics of cold atoms, which in some instances can serve as model systems for many condensed matter phenomena[4]. Superconductor–insulator transitions are of particular importance because of their connection with the fundamental phase-number uncertainty relation, which makes them the simplest of such transitions. Although the subject of SITs might be considered to be mature, there remain many open issues resulting from the study of new materials, the application of new experimental techniques, and the continued extension of measurements to lower temperatures and higher magnetic fields. Although there are common observations in diverse experiments involving rather different types of materials, there are dramatically contrasting results in others involving similar materials and similar measurements. In some studies there is a direct transition between the insulating and superconducting regimes as a function of the control parameter, whereas in others, there is evidence of the spontaneous appearance of inhomogeneity near the transition, which may be manifested as an intermediate metallic regime or a breakdown of scaling as zero temperature is approached. The nature of the insulating state (or localizing quantum-corrected metallic state) is a subject of ongoing research. Not all of the magnetic field tuned SITs exhibit a giant magnetoresistance peak above the critical field for the SIT and although there has been progress, there is of yet no consensus as to its explanation in those circumstances in which it is found. The grouping of the various transitions into two distinct groups, bosonic and fermionic, also appears to be in need of refinement.

2. Disordered materials and tuning parameters for the SIT

Experiments on various materials with different tuning parameters do not clearly distinguish between competing theoretical pictures. Indeed there may be several types of SI transitions. First, the mechanism may depend upon the tuning parameter, which can be disorder, electrostatic charge, perpendicular or parallel magnetic field, surface magnetic impurities, or dissipation. Second, the mechanism and phase diagram may depend upon the type of system being investigated, *i. e.*, whether it is an ultrathin quench condensed amorphous or granular film, an amorphous film of InO_x, MoGe, $Nb_{0.15}Si_{0.85}$, or Ta, a polycrystalline film of TiN, a monolayer or ultrathin film of a high temperature superconductor, or a conducting interface separating two band insulators. Third, in the case of films, the character of the substrate may matter. The nature of the transition could be altered in the presence of a high dielectric constant substrate such as $SrTiO_3$, or may depend upon the nature of an underlayer. The roughness of the substrate may serve as a template for the roughness of the film, which in turn may control the character of the transition. Finally another issue is the role of spin–orbit scattering. Experiments on high-Z elements (*a*-Bi or *a*-Pb) may produce different results from those carried out on low-Z elements (*a*-Be or Al), where there is minimal spin–orbit scattering.

Among some of the phenomena that have sparked continuing interest in the field are the giant magnetoresistance peaks found in some nearly critical SIT systems, leading in some instances to what has been called "superinsulating" behavior at sufficiently low temperatures [5,6]. In some systems there appears to be a "quantum metal" in the limit of very high magnetic fields [7,8]. A deep analogy may exist between the insulating regime of some of these systems and the pseudogap regime of the high temperature superconductors [9,10]. Other issues include the possibility of an intermediate metallic phase between the superconductor and insulator in some perpendicular magnetic field tuned transitions [11].

The nature of the insulating regime, apart from the magnetoresistance peak, is a critical issue. There is experimental evidence from a variety of sources that for some, but not all systems, superconducting coherence may persist over finite length scales in the insulating regime [12–15]. The Nernst effect has emerged as a means of exploring the insulating regime of magnetic field-tuned SITs [16–18].

The possibility of electrostatically inducing superconductivity has been demonstrated, allowing the exploration of behavior that does not depend on possible changes in morphology associated with different doping or film thickness [19,20]. Using electrostatic charging it is possible to import into the study of the SIT some of the approaches used in 2D electron gas physics. Very recent additions to this direction of research have been the use of electric double layer transistors (ELDTs) employing ionic liquids to electrostatically gate the SIT of monolayers [21] and ultrathin films [22,23] of high temperature superconductors and the gating of superconductivity at the interface between insulators [24,25].

3. Theoretical scenarios for the SIT of disordered materials

Interest in SI transitions arose in the context of study of the interplay between superconductivity and disorder. Anderson [26] and Abrikosov and Gor'kov [27] showed that nonmagnetic impurities do not affect the superconducting transition temperature because Cooper pairs form from extended time-reversed eigenstates, which have disorder included. On the other hand with sufficient disorder Anderson localization occurs, and superconductivity will not develop, even in the presence of an attractive electron–electron attraction [28]. This leads to the question of how superconductivity disappears with increasing disorder [29–34]. At nonzero temperatures, the superconducting phase transition is a continuous phase transition, so that there are fluctuations. For a transition suppressed to zero temperature, the fluctuations become quantum in character and the transition becomes a quantum phase transition.

In two-dimensions (2D) there is added complication as the superconducting transition at nonzero temperatures is a topological, or Berezinskii–Kosterlitz–Thouless (BKT) transition [35]. Furthermore all 2D electronic systems were initially believed to be localized, even for arbitrarily weak disorder. This changed with the observation of apparent metal–insulator transitions in strongly-interacting, high-mobility low-carrier-density MOSFETs [36], although the "metallic" state in MOSFETs is still under debate. Superconductor–insulator transitions in 2D are additional examples in which interactions play a critical role.

There have been four general approaches to explaining the demise of superconductivity in the 2D limit as a function of disorder or magnetic field. The first is based on a perturbative microscopic description of homogeneous systems and considers the interplay between the attractive and repulsive electron–electron interactions in the presence of disorder. In this microscopic description, suppression of the critical temperature follows from the renormalization of the electron–electron interaction in the

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