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Fabrication and characterization of scanning tunneling microscopy superconducting Nb tips having highly enhanced critical fields

A. Kohen [a,*], Y. Noat [a], T. Proslier [a], E. Lacaze [a], M. Aprili [b], W. Sacks [a], D. Roditchev [a]

[a] *Groupe de Physique des Solides, UMR7588 au CNRS, Univ. Paris 6 and Paris 7, 140 rue de Lourmel, 75015 Paris, France*
[b] *Laboratoire de Spectroscopie en Lumière Polarisée—CNRS ESPCI 10, rue Vauquelin 75005 Paris, France*

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Abstract

We report a simple method for the fabrication of Niobium superconducting (SC) tips for scanning tunneling microscopy which allow atomic resolution. The tips, formed in situ by the mechanical breaking of a niobium wire, reveal a clear SC gap of 1.5 meV and a critical temperature $T_c = 9.2 \pm 0.3$ K, as deduced from Superconductor Insulator Normal metal (SIN) and Superconductor Insulator Superconductor (SIS) spectra. These match the values of bulk Nb samples. We systematically find an enhanced value of the critical magnetic field in which superconductivity in the tip is destroyed (around 1 T for some tips) up to five times larger than the critical field of bulk Nb (0.21 T). Such enhancement is attributed to a size effect at the tip apex.

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1. Introduction

Among the variety of surface techniques, Scanning tunneling microscopy and spectroscopy (STM, STS) has a special role in the investigation of surface topography and local electronic properties on the atomic scale [1]. The device is based on the precise measurement of the vacuum tunneling current between an atomically sharp tip and a sample as a function of the applied voltage. The magnitude of the current depends on the tip sample distance and on the density of electronic states

* Corresponding author. Tel.: +33 01 44274676; fax: +33 01 43542878.
E-mail address: kohen@gps.jussieu.fr (A. Kohen).

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of both the tip and the sample. Usually the STM tip is made of a normal metal in which the density of electronic states (DOS) near the Fermi level can be considered, in a first approximation, constant. Thus the measured current as a function of tip position reflects changes in either the sample DOS or the topography.

Meservey [2] had suggested the use of an SC material for the fabrication of the STM tip. One advantage of an SC tip is the enhanced spectroscopic resolution due to the singularity in the SC DOS at the gap edge. This reduces significantly the thermal smearing, due to the Fermi–Dirac distribution, in comparison to the case of a normal metal tip. Of major interest, an SC tip with an SC sample allows, in principle, direct cooper pair tunneling (Josephson current [3]), which is well known in point contact and planar SIS junctions [4]. In the investigation of local electronic properties of superconductors, the STM is almost exclusively used with a normal tip, thus exploiting single electron processes, resulting in the well known BCS tunneling DOS. The gap function is inferred from the spectrum but does not indicate directly the existence of a condensate. With an SC tip on the other hand the appearance of a Josephson current is a definite signature of a coherent state.

In general a proper STM tip has to be sharp enough to allow for good spatial resolution (in the best case atomic resolution). From a theoretical point of view it was questioned whether an atomically sharp tip would still show SC properties. One certainly expects that the geometry and dimensions of the tip could have an effect on it's properties as, for example, in the case of an applied magnetic field. Additionally, one must avoid the oxidation of the surface layer of the tip, which for normal metals is easily achieved, for example, by mechanically cutting a PtIr wire in air. For an SC tip this is not so trivial: SC elements from which tips can be formed like Al, Nb and Pb oxidize rapidly. Other materials, such as high temperature superconductors, suffer from surface degradation and the difficulty in controlling the geometry, due to their complex structure and composition.

Pan and Hudson [5] have shown that atomic resolution and superconductivity can be obtained at the same time. They have used a mechanically cut Nb wire to obtain a sharp tip and further apply a voltage pulse between the tip and an Au target inside the STM vacuum chamber. This removes the oxide and further sharpens the tip. The tips were indeed superconducting and allowed for atomic resolution; however, the measured gap values varied from one tip to the other, ranging from a few tenths of a meV and up to 1.5 meV. The authors suggest that the superconductivity measured at the end of the tip is in fact due to a proximity effect induced by the bulk. In such a scenario, the amplitude of the measured gap can vary due to changes in tip apex geometry and composition. The latter are claimed to be a result of the voltage pulse application.

Naaman et al. [6] have used a two layer deposition method in which a 5000 Å layer of Pb is deposited on a mechanically cut PtIr tip and then covered by a 30 Å layer of Ag. In this method, the Ag layer serves as a protection against the oxidation of the lead. The superconductivity of the tip is based on the proximity effect and a gap is induced in the Ag layer. Finally Suderow et al. [7] have used a method in which the STM tip is successively driven into and pulled out of a Pb layer and results in the formation of a Pb tip. As the process is done inside a vacuum chamber and at a temperature of $\sim$4.2 K, the resulting tip is mechanically stable and does not oxidize.

The last two methods are inferior to the first one, as they use Pb which has a lower critical temperature and gap value ($T_c = 7.2$ K; $\Delta(T=0) = 1.3$ meV) in comparison to Nb, being the element with the highest critical temperature ($T_c = 9.2$ K; $\Delta(T=0) = 1.5$ meV). This limits the temperature range in which the tip can be used and enlarges the effect of thermal fluctuations on the measured Josephson current [15]. Giubileo et al. [8] have used a MgB_2 grain glued to a PtIr tip as a STM tip, this technique allowed obtaining atomic resolution and has the advantage of a high critical temperature (39 K) and a relatively large SC gap (2–7 meV). However spatial resolution is not easily reproduced in tips of this kind and the non trivial two band effects in MgB_2 [8] hinder the interpretation of the measured conductance spectra.