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Enhanced Superconductivity in Nanosized Tips of Scanning Tunnelling Microscope

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Nanosized Pb junctions exhibit superconducting correlations at magnetic fields more than an order of magnitude higher than the zero-temperature critical field of the bulk Pb. The strongly enhanced critical field is a spectacular demonstration of nanosize effect where the Meissner screening currents become ineffective for junction's tip smaller than the London penetration depth (32 nm for Pb). From the enhanced critical field we characterize the geometry of a particular junction using the variable radius pair breaking theoretical model of Suderow et al.

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1. Introduction

The scanning tunneling microscope (STM) [1] is a versatile tool that allows studying the topography and electronic properties of a conductive surface with atomic resolution. However, to achieve the ultimate resolution, the use of an atomically sharp tip is of utmost importance; so that only the foremost atom of the tip will "see" the surface. In the following, we demonstrate a procedure that enables the fabrication of an atomically sharp Pb tip. Moreover, the examination of the critical magnetic field of the tip which can be by orders higher than in a bulk material enables a direct *in situ* estimate of the tip apex dimensions.

2. Experimental

All experiments were performed by means of a home-made scanning tunneling microscopy (STM) head [2] with a Pb tip over a Pb sample, inserted in a commercial Janis SSV ^{3}He refrigerator operated at 0.45 K (unless specified otherwise) with Nanotec's Dulcinea SPM controller.

3. Results

Apart from the classical use of the STM tip for imaging, it could also be used to modify the sample or the tip itself on a nanometer scale by formation of a metallic contact of atomic dimensions [3]. The STM tip repeatedly crashing on the spot of the sample from the same material can be cold welded with the sample. When the tip is retracted (in the z-direction) and contact is broken fresh surfaces are exposed. This cleaning procedure works particularly well at low temperatures where the surfaces can stay clean for long periods of time since all reactive gases are frozen.

Figure 1 shows an STM current vs. distance curve at a fixed bias voltage for a clean Pb contact at 5 K. The current/conductance decreases in a stepwise manner indicating quantization as the tip is retracted from the surface and the size of the contact decreases, consequentially. Nevertheless, the distance z of the tip from the surface in STM experiments is not directly related to the size of the contact: as the contact is submitted to strain, its atomic configuration changes in a stepwise manner. The conductance of the last plateau (before breaking the contact) is quite well defined with a value of approximately single quantum conductance ($2\mathrm{e}^2/h$) corresponding to a single-atom contact. By this procedure, it is possible to obtain atomically sharp tips [4].

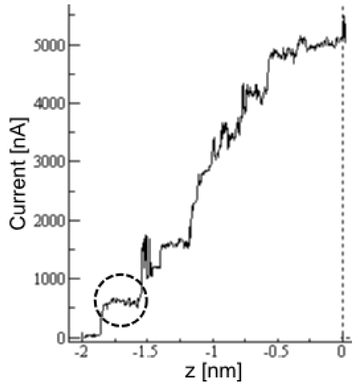

Fig. 1. Current vs. distance measured at a fixed bias voltage $V = 10$ mV at 5 K. The last plateau (in the dashed circle) is at *ca.* 650 nA; this corresponds to a conductance of 65 μS. For a single-atom contact the quantum conductance of approximately $2e^2/h \approx 77$ μS is expected. The exact value varies slightly due to the influence of the local atomic geometry.

In the subsequent experiment, one half of the broken contact, i.e. a nanotip, was positioned above a flatter region on the Pb surface [5] in order to avoid the interaction with the protrusion formed by the cleaning procedure. Figure 2 shows the differential conductance versus voltage STM spectra measured in such a tunneling junction at different magnetic fields applied at 0.45 K. The STM spectrum is generally proportional to the convolution of the density of states of both electrodes forming the junction. The superconducting density of states (SDOS) of the BCS superconductor as Pb reads as $N(E) = \mathrm{Re}[E/(E^2 - \Delta^2)^{1/2}]$, where E is the quasiparticle energy and Δ the superconducting energy gap. At magnetic fields below the critical field of the bulk Pb ($H_c^{\mathrm{bulk}}(0\ \mathrm{K}) \approx 0.1$ T) SDOS of the tip and the bulk are identical. Then, tunneling conductance reveals a sharp peak symmetrically at positive and negative voltage $2\Delta_{\mathrm{Pb}}/e$ above the zero conductance region (where $\Delta_{\mathrm{Pb}} \approx 1.4$ meV near 0 K and e is the electron's charge).

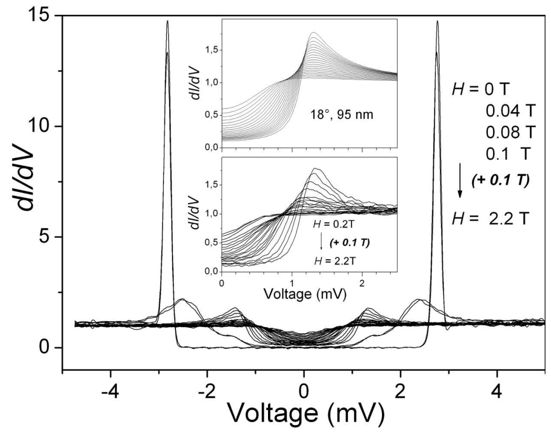

Fig. 2. STM spectra measured over bulk Pb with a Pb nanotip at 0.45 K at different magnetic fields (values on the right). Insets: bottom — measured spectra at $H > H_c^{\mathrm{bulk}}$; top — calculated spectra curves with corresponding parameters (see text).

At fields H near H_c^{bulk}, the spectrum shows two smaller peaks at *ca.* 1.4 mV and 2.3 mV. This can be attributed to the fact that at these fields the bulk will be in the intermediate state mixing the normal and superconducting regions with its SDOS strongly smeared and gapless (with finite conductance at zero bias and broadened "gap-like" peaks at suppressed Δ_{sup}). The tip with much higher critical field than H_c^{bulk} (see below) retains its SDOS as it was. Then, the convolution of two such different SDOS will result in the spectra observed between 0.04 and 0.1 T, where the first peak corresponds to the undisturbed gap Δ_{Pb} of the tip and the second peak corresponds to a sum $\Delta_{\mathrm{Pb}} + \Delta_{\mathrm{sup}}$.

At fields higher than 0.1 T (the spectra shown also in the lower inset of Fig. 2) the bulk sample is in the true normal state, while the tip remains superconducting. This is evident from the spectra, as the peak corresponding to $2\Delta_{\mathrm{Pb}}$ disappears, while a smaller peak corresponding to Δ_{Pb} is observed up to magnetic fields significantly higher than the bulk critical field.

Strong enhancement of the tips critical field is explained by the fact that the size of the tip is smaller than the London penetration depth (the zero-temperature limit of the penetration depth for Pb is $\lambda_0 = 32$ nm). The reduced dimensionality blocks the creation of the Meissner screening currents, and the kinetic energy associated with them does not contribute to the total free energy of the superconducting state. The critical magnetic field of the tip as well as the shape of the corresponding spectrum changes dramatically with the geometry of the tip. In different junctions the critical magnetic field of the tip (H_c^{tip}) varied from 0.2 T to 2.5 T. In Fig. 2 H_c^{tip} is above 2.2 T. This variation can be exploited to estimate the geometry of each individual tip in the following manner. The measured spectra can be simulated by the variable radius pair breaking theoretical model of Suderow et al. [6] using Usadel's formalism. The model yields the temperature and magnetic field evolution of the SDOS of a cone-like tip depending on the parameters of its apex, namely the length of the tip L and the opening apex angle α. The measured spectra shown in the lower inset of Fig. 2 could be simulated by the above mentioned model with the length of the tip $L = 95$ nm and the opening apex angle $\alpha = 18°$. The simulated curves are shown in the upper inset of Fig. 2. In other junctions L spread between 95 nm and 200 nm and α between 18° and 77° was found.

4. Conclusions

We demonstrated a procedure that allows producing atomically sharp STM tips. The resulting nanosized tips have shown strongly enhanced critical magnetic fields where the enhancement depends on the tip length and the opening apex angle. Those parameters are possible to evaluate from the evolution of the spectra in magnetic fields using the variable radius pair breaking theoretical model The estimated length scattered between 95 nm and 200 nm and the apex angle between 18° and 77°.

Acknowledgments

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References

[1] R. Wiesendanger, *Scanning Probe Microscopy and Spectroscopy*, Cambridge University Press, Cambridge 1994.

[2] S.H. Pan, E.W. Hudson, J.C. Davis, *Rev. Sci. Instrum.* **70**, 1459 (1999).

[3] N. Agraït, A.L. Yeyati, J.M. van Ruitenbeek, *Phys. Rep.* **377**, 81 (2003).

[4] J.K. Gimzewski, R. Möller, *Phys. Rev. B* **36**, 1284 (1987).

[5] J.G. Rodrigo, H. Suderow, S. Vieira, *Eur. Phys. J. B* **40,** 483 (2004).

[6] H. Suderow, E. Bascones, W. Belzig, F. Guinea, S. Vieira, *Europhys. Lett.* **50**, 749 (2000).