Nanosized superconducting constrictions

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Nanowires of lead between macroscopic electrodes are produced by means of a scanning tunneling microscope. Magnetic fields may destroy the superconductivity in the electrodes, while the wire remains in the superconducting state. The properties of the resulting microscopic Josephson junctions are investigated. [S0163-1829(98)03941-1]

It is well known that the magnetic field suppresses superconductivity in type-I materials only if the dimensions of the sample are sufficently large compared to the coherence length.[1,2] Superconductivity survives in small systems. A number of experiments showed the enhancement of the critical field in thin films.[3] Advances in nanotechnology have made it possible to study this effect in small metallic particles.[4–6] A different realization can be achieved by applying a magnetic field above the bulk critical value to microscopic constrictions.[7,8] Then, it can happen that the constriction itself remains superconducting, while the electrodes become normal[9,10]. This device allows us to probe superconductivity at small scales through transport measurements. Properties such as the critical current, and its dependence on field and thickness, can be studied in detail.

When the shape of the constriction is highly irregular, the critical current will be limited by its narrowest section, and/or the internal barriers which may exist within it. The system will behave as a Josephson junction of microscopic dimensions.

Narrow constrictions are generated by pressing a scanning tunneling microscope (STM) tip made of a metal which remains normal at low temperatures (Pt-Ir or Au) into a Pb substrate. The substrate has an area of approximately 1 cm^2 and a thickness of 0.5 mm. When the tip is first pressed into the substrate, it gets covered by lead atoms. Upon succesive raising and lowering of the tip, a lead bridge is formed between the tip and the substrate. The aspect ratio of this bridge can be varied by changing the position of the tip in a controlled way and its size can be estimated from the evolution of the conductance during this process as detailed in Ref. 11. The advantage of working with normal tips is that the magnetic field needs only to be applied to the substrate and the constriction. A magnetic field of 2.6 kG (approximately five times the zero temperature critical field of lead) at the surface of the sample was produced by a small permanent magnet placed under the sample.

I-V characteristics for different constrictions are shown in Fig. 1, along with a sketch of the typical dimensions of the device. The curves show clear signatures of the Josephson effect, with and without the magnetic field.

The conductance at high voltages is determined by the shape of the constriction. It is given, approximately, by $2e^2/h$ times the number of channels which can be acommodated within the narrowest part. The number of channels, in turn, goes as the cross section over an area of atomic dimensions. Hence, the high voltage conductance gives a measurement of the cross section of the constriction.

At zero voltage, the Josephson effect shunts the constriction, leading to the observed peak in the conductivity. The residual resistivity is due to scattering in the normal parts, outside the constriction. We also observe resonance processes at finite voltages, but below the expected value of the gap of the superconducting region. We interpret these features as arising from Andreev reflections at the weak link. It should be noted that the system contains, at least, two normal metal-superconductor interfaces. Additional reflections there are also to be expected.

Figure 2 shows the critical current versus normal state conductance with and without a magnetic field. In the absence of an applied field, both quantities are proportional. This can be understood because the critical current of a constriction measures the number of conducting channels within it.

A magnetic field above the bulk critical value reduces the critical current. The effect is more pronounced in the wide

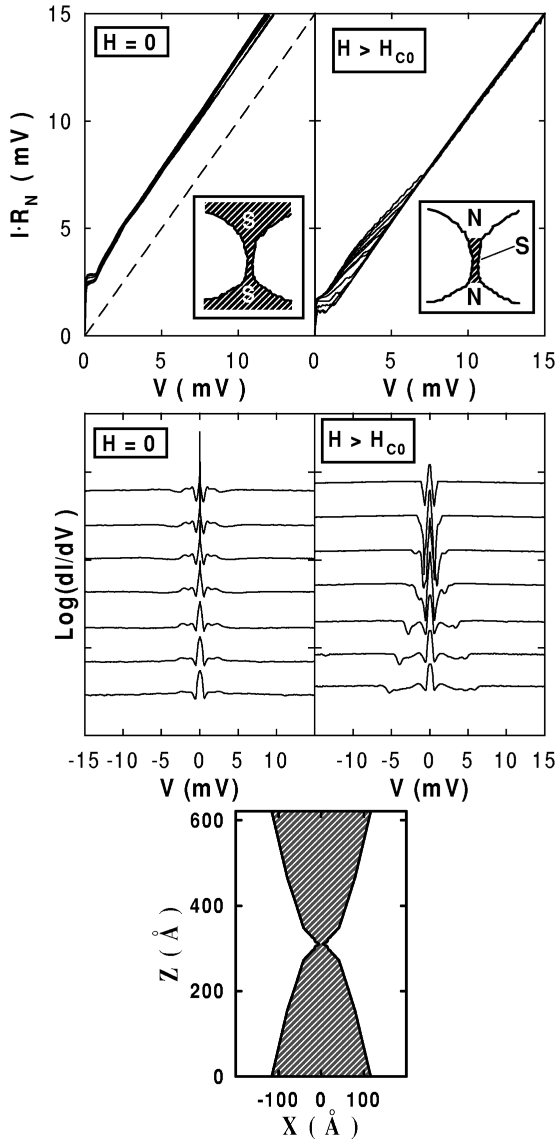

FIG. 1. Top panel: *I-V* characteristics of Pb constrictions with and without an applied field. The inset shows a sketch of the expected situation at the constriction. The applied field is five times the bulk critical field of lead. Middle panel: conductances for the same constrictions as in the top part. Bottom panel: estimated dimensions of a typical constriction following the procedure of Ref. 11.

constrictions. In order to analyze this effect, we calculate the free energy of a cylindrical superconductor in the presence of a field, which also supports a current. Let us assume that the field is constant within the cylinder. This situation describes cylinders much narrower than the penetration depth $r \ll \lambda(T)$ well. The current carried by the condensate is proportional to the gradient of the phase of the order parameter, which we write as $|\psi|e^{i\phi}$. Then, the free energy, per unit length is

$$g=\pi r^2\left[\left(\alpha+\frac{\hbar^2}{2m}|\nabla\phi|^2\right)|\psi|^2+\frac{\beta}{2}|\psi|^4+\frac{e^2r^2}{8mc^2}H^2|\psi|^2\right], \tag{1}$$

where $\alpha,\beta,$ and m follow the standard notation.[1]

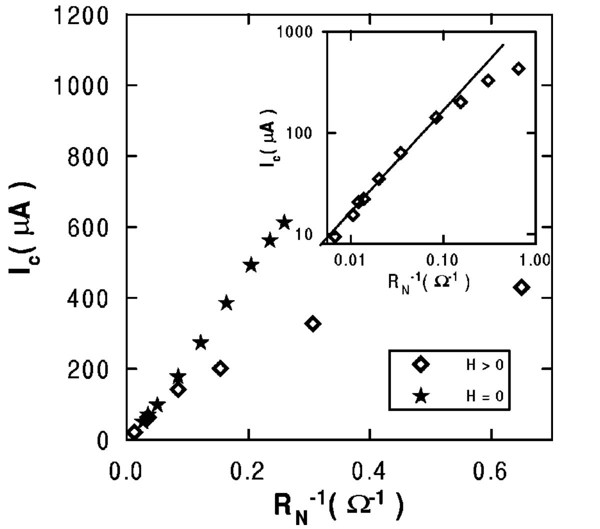

FIG. 2. Values of the critical current, versus the high voltage conductance, for different constrictions. The applied magnetic field is five times the critical magnetic field of Pb. The inset shows in a logarithmic plot, the linear dependence of I_c on R_N at low conductance.

Minimizing with respect to $|\psi^2|$, we obtain

$$|\psi|^2=|\psi_0|^2\left(1-\frac{(\hbar^2/2m)|\nabla\phi|^2+(r^2e^2/8mc^2)H^2}{|\alpha|}\right), \tag{2}$$

where $\psi_0^2=\alpha/\beta$. In addition, $\alpha=(2e^2/mc^2)H_c^2(T)\lambda^2(T)$. Hence,

$$|\psi|^2=|\psi_0|^2\left(1-\frac{\hbar^2|\nabla\phi|^2}{2m|\alpha|}-\frac{\epsilon^2h^2}{16}\right), \tag{3}$$

where $\epsilon=r/\lambda(T)$ and $h=H/H_c(T)$. Finally, we relate $\nabla\phi$ to the current flowing along the cylinder. The critical current, in the absence of a field, of a cylinder of radius r is[2] $I_c(T)=H_c(T)r^2c/3\sqrt{6}\lambda(T)$. In terms of $f=\psi/\psi_0$, we can write

$$f^2=1-\frac{h^2\epsilon^2}{16}-\frac{4}{27}\frac{i^2}{f^4}, \tag{4}$$

where $i=I/I_c$.

Equation (4) allows us to determine the critical field of a cylinder with no current flowing: $H_{\text{cyl}}(T)=4H_c(T)[\lambda(T)/r]$. This formula is valid for $r<\lambda(T)$. For sufficiently large values of r, solutions with vortices threading the cylinder are also possible.[12,13]

In the presence of a current, we obtain the critical field by first extracting $h(f,i)$ from Eq. (4) and then calculating the value of f which maximizes h. In this way, we find $H_{\text{cyl}}(I,T)=H_{\text{cyl}}(T)\sqrt{1-[I/I_c(T)]^{2/3}}$. Analogously,

$$I_c(H,T)=I_c(T)\left[1-\left(\frac{H}{H_{\text{cyl}}(T)}\right)^2\right]^{3/2}. \tag{5}$$

The transition to the normal state is discontinuous, as in a thin film.[1] When the current reaches its critical value, the superconducting order parameter in the constriction jumps to zero.

As a function of the radius of the constriction, Eq. (5) predicts that the critical current shows a maximum at $r^2/\lambda^2(T)=32H/5H_c(T)$. For $H\approx 5H_c$, we have $r\gtrsim\lambda$. The present calculations need to be modified because the field will not be homogeneous within the constriction. Note, however, that the maximum field compatible with superconductivity is not much larger than $\sim H_c$ for a constriction with $r\sim\lambda$. Hence, the maximum in $I_c(r)$ cannot be reached, if the applied field is much larger than H_c. It is interesting to note that in a cylinder of variable width, regions threaded by vortices and regions with no vortices can coexist. As the symmetry of the order parameter is different in each region, a phase boundary should be generated, and the critical current will be suppressed.

The general trend of I_c as a function of r is consistent with the results shown in Fig. 2. In the presence of a field, we find that $I_c\propto r^2$ for narrow constrictions $r\ll\lambda(T)$. For wider constrictions, I_c is strongly supressed by a field.

Finally, we have studied the dependence of I_c on temperature. The theory presented here predicts that the critical temperature, in the presence of an applied field above the bulk critical value, should depend on the radius of the constriction. In Fig. 3(a) we have represented, for two different constrictions, the temperature dependence of $(dI/dV)_{V=0}R_n-1$, which must go to zero as we approach the critical temperature. We are aware that in some circumstances the effect of thermal fluctuations on the properties of the superconducting region can limit the significance of the critical temperatutre deduced from Fig. 3(a). However, it is clear from Fig. 3(b) that the value of the critical current shows a marked dependence on temperature consistent with the existence of superconductivity in the region of the constriction. The full dependence of I_c on T and r is

$$I_c=\frac{H_c(0)r^2c}{3\sqrt{6}\lambda(0)}\sqrt{\frac{1-(T/T_c)^2}{1+(T/T_c)^2}}\times\left[1-\frac{H^2r^2}{16H_c^2(0)\lambda^2(0)}\,\frac{1+(T/T_c)^2}{1-(T/T_c)^2}\right]^{3/2}. \qquad (6)$$

This expression predicts that I_c has a linear dependence on r^2 at low temperatures, and curves downward as the temperature is increased, in agreement with Fig. 3(b).

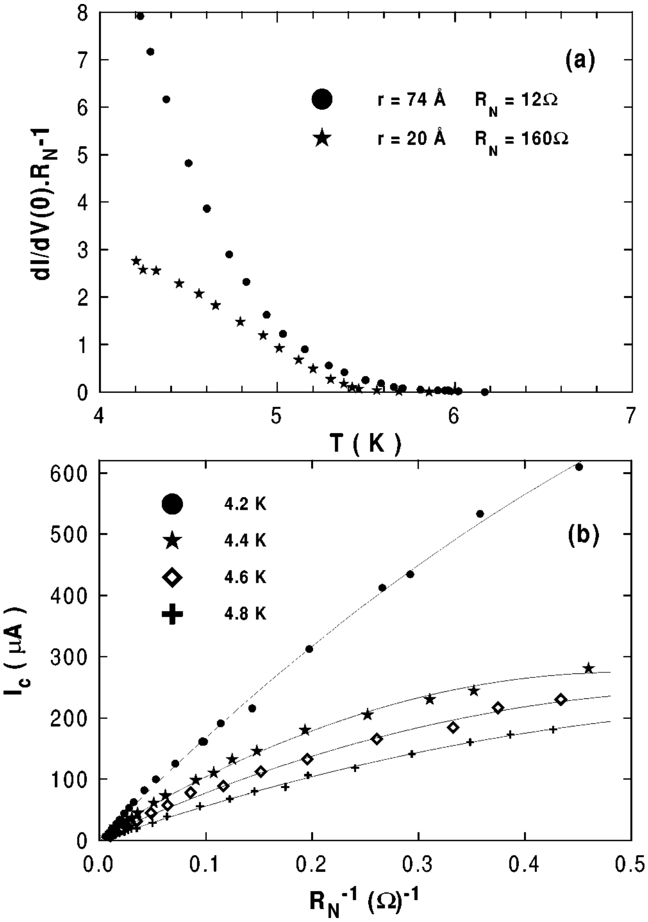

FIG. 3. (a) Plot of $(dI/dV)_{V=0}R_N-1$ vs T for two different constrictions with estimated radius of 74 Å (circles) and 20 Å (stars). (b) Critical current vs constriction high voltage conductance at different temperatures. The lines have been drawn to guide the eye.

In conclusion, we presented devices in which to study superconductivity at small scales. In contrast to previous work, our superconducting regions are strongly coupled to its environment, which greatly facilitates the measurement of transport properties. The results presented here are in agreement with the expected behavior for a narrow superconducting cylinder in an applied field, in particular, the dependence of critical currents on width.

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