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Single-atom point contacts in the superconducting state

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Recently it has become possible to fabricate long-term stable point contacts with a constriction as small as a single atom. Here we present experimental investigations on one-atom point contacts in the superconducting state. An applied pressure or tensile force on this atom results in large effects in the superconducting properties. Furthermore, we show that one-atom point contacts can be broken and reestablished in a perfectly reproducible manner.

INTRODUCTION

Inherently stable one-atom point contacts can be realized experimentally fairly simple. Various properties of these smallest possible contacts between two electrodes were studied experimentally and it was found that the conductance carried by one atom is of the order of $2e^2/h$. However, a number of fundamental issues related to these microscopic contacts are still unknown in part because of a lack of theories describing these systems. A related difficulty is the nonuniversality, the "sample to sample" fluctuations. For example, two one-atom point contacts of the same material may show a difference in conductance reflecting a difference in a nonadiabaticity of the potential distribution in the contact region. This in term may result from a defect or a difference in electrode geometry coupled to the bridging atom. On the other hand it has been shown for a material like copper that various one atom contacts show a conduction close to $2e^2/h$ (see Ref. 1), indicating that up to some extent there exists a universality with a statistical mean which can be calculated. Indeed the theoretical simulations from Todorov and Sutton[2] have a nice resemblance to the experiment in this particular case.

In this work we present experiments performed on single-atom point contacts in the superconducting state. We focus on effects at the single-atom level which are reproducible, we do not attempt to obtain a statistical mean over many different single-atom point contacts.

EXPERIMENTS

We used the mechanically controllable break (MCB) technique to obtain atomic size contacts.[3] A schematic drawing of the MCB sample mounting is shown in the upper inset of Fig. 1. The basic principle of this technique is that a length change of the piezo results in a reduced change of the separation between the two electrode halves. The reduction factor in our samples, imposed by the sample geometry, is estimated to be of the order of 10^2 to 10^3. Due to this large factor it is possible to change contact sizes over subatomic dimensions, enabling us to study, e.g., contact formation or to fabricate inherently stable contacts with a constriction as small as a single atom. This technique utilizes the roughness on an atomic scale of two freshly broken electrodes. The experiments are performed at 1.3 K, magnetic shielding (μ metal) yields a field at the sample location less than 1 μT. All measurements leads entering the cryostat are filtered using feedthrough π filters. In addition, before entering the copper and lead shielded sample area the leads are filtered by low-temperature copper powder filters. The experimental setup is the same as described in Ref. 3. All experiments are performed by current biasing the sample in a standard four-probe configuration.

In Fig. 1 a current-voltage (I-V) curve is shown of a contact which consists of one atom. The I-V curve shows a clear linear part for voltages larger than the superconducting gap voltage $2\Delta/e$. The slope of this linear part is used to determine the normal resistance, R_N, of the contact. Sharp kinks in the voltage range $\pm 2\Delta/e$ at voltages $\pm 2\Delta/ne$ with $n=1,2,3,\ldots$ are present. This subgap structure is observable over a wide range of R_N values. Subgap structure is known to be present in I-V curves of point contacts, however also tunnel junctions show this kind of structure.[4] Near zero voltage a clear

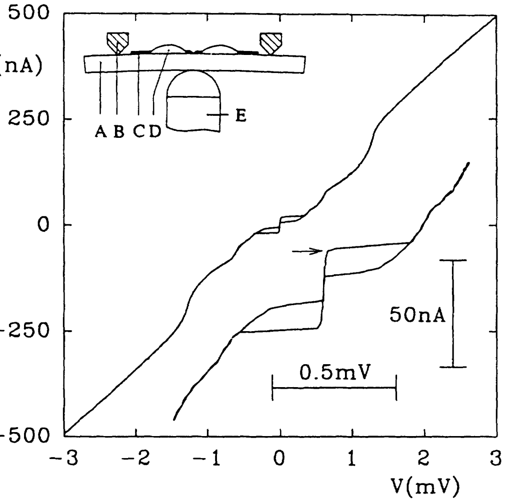

FIG. 1. The I-V curve of a single-atom contact (Sn electrodes) shows the threshold current region, subgap structure, and a linear branch. The lower inset is an enlargement of the central section, the arrow indicates the threshold current I_t. The upper inset shows a schematic drawing of the sample mounting, with A: bending beam, B: counter support, C: notched metal filament, D: epoxy adhesive and E: piezo element.

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finite critical current is present. In Ref. 5 it was shown that in the tunnel regime and in the high Ohmic contact regime, as shown here, this critical current obtained a small slope. This is more clearly visible in the lower inset, which is an enlargement of the central section. The critical current exhibits a small slope, which is not an artifact of the four probe measurement. Because the I-V curve does not show a zero-voltage critical current the maximum current, indicated by the arrow in Fig. 1, was called a threshold current I_t. It was speculated that the threshold current originates from Cooper pairs which gain enough energy from the environment to overcome a Coulomb barrier. In correspondence with Ref. 5 we will also use the I_t notation here for the "sloped supercurrent". When increasing the current in the I-V curve of Fig. 1 there is a sudden jump to a large voltage (300 μV) whenever the current reaches I_t. This is characteristic for all our I-V curves of superconductors. Here this jump is used to define I_t experimentally by using a setpoint voltage of typically 100 μV. The equipment ramps the current; when the setpoint voltage is reached the current switches back to zero. The current value at the setpoint is held at an output terminal and is updated with a frequency of 20 Hz. This procedure is used in the following experiments to continuously monitor I_t when changing the contact configuration over subatomic distances. The normal resistance is determined with a lock-in technique at a current level with corresponding voltages much larger than $2\Delta/e$.

In the following experiments the transitions from contact to tunneling and tunneling to contact are studied for the two superconductors Sn and Ta. Only the data in the contact regime will be displayed. The first stage of the ex experiment, a one-atom contact, is manually adjusted with the use of a voltage on the piezo. Once this is achieved a small slowly varying piezo voltage ramp (V_p) is superimposed on the voltage. This triangularly shaped ramp is shown in the top panel of Fig. 2. The next panel shows the continuous I_t measurement of a Sn junction during the V_p variation. At $t=0$ the junction is in the tunnel regime. By reducing the piezo voltage the two electrodes will come closer together. Because the electrodes are broken prior to operation they are rough on an atomic scale and a single-atom contact will be formed where two atoms on opposite electrodes are nearest. At a certain point a jump to contact is observed, which results in a relatively large I_t value of 25 nA. Reducing V_p even further results in a changing pressure at the contact location and an increase of I_t. When increasing V_p (pulling the electrodes apart), I_t decreases even beyond the 25-nA value. Then a step in I_t occurs to approximately its double value. We attribute this jump to a sudden rearrangement of the atom, which bridges the electrodes. When the electrodes are pulled further apart I_t decreases again, followed by a jump to the tunnel regime where tunneling takes over. In this regime the equipment is not capable of measuring I_t continuously. However, from I-V curves taken in this regime we know that I_t is typically smaller than 1 nA. Repeating the V_p sweep leads to a *perfectly reproducible measurement* showing that it is not only possible to make a single-atom contact, but also that applied changes of pressure on this single atom result in reproducible effects.

This reproducibility allows us to perform a continuous R_N measurement after the I_t sequence is recorded. Thus, although the I_t and R_N measurements are not performed at the same time, they can be attributed to exactly the same contact configuration. The R_N measurement is shown in the third panel of Fig. 2. The maximum in the piezo voltage served as a zero time reference, so at a time t the I_t and R_N panel show the corresponding values for a specific contact configuration. Coming from the tunnel

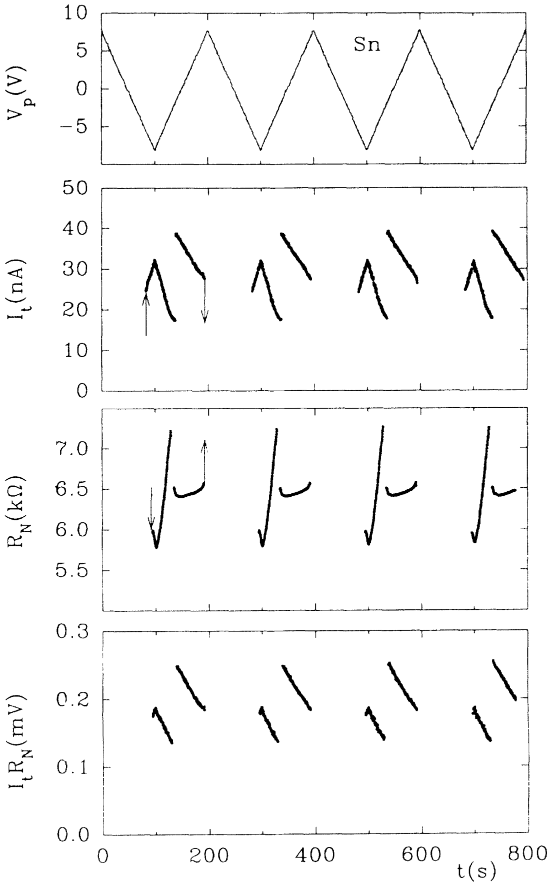

FIG. 2. The nature of the experiment is to break and reestablish a one-atom contact; this is achieved with Sn by applying a slowly varying triangular voltage on the piezo element (upper panel). The rest of the panels display data in the contact regime only. Starting in the tunnel regime ($t=0$) the reduction of V_p (electrodes move towards each other) results in a one-atom contact. A subsequent increase in V_p (electrodes move apart) results in a rearrangement of the atom followed by a jump back into the tunnel regime. Both the I_t and R_N measurement represent the same contact at a specific time t. Furthermore, the jump to contact, the rearrangement of the atom and the jump into the tunnel regime line up perfectly in the I_t and R_N panel. The arrows indicate the subsequent increase or decrease of I_t and R_N after a jump. The reproducibility shows that during contact formation and breaking the bridging atom favors one specific site. The I_tR_N panel is obtained by multiplying the I_t with the R_N panel.

regime (R_N typically larger than 40 kΩ) a jump to a 6-kΩ contact value is measured simultaneously with the discontinuous I_t increase. Initially R_N decreases with increasing pressure and R_N increases when the tips are pulled apart. The jump to another point-contact configuration lines up perfectly with the jump observed in I_t. However, the relative size of the jump is about 25% for R_N whereas I_t shows an increase of about 100%. After this rearrangement R_N decreases and slightly increases. A clear turnup is visible just before a jump to the tunnel regime occurs. During this trajectory I_t shows a monotonic decrease. The I_tR_N result, obtained by multiplying the I_t panel with the R_N panel, is shown in the bottom panel of Fig. 2. This panel mainly reflects the dependence of I_t on V_p due to the much larger variations in I_t than in R_N.

A similar measurement is performed on a Ta break junction, which is shown in Fig. 3. The I_t panel shows a variation of approximately a factor of 2 in I_t with changing V_p. As in the Sn measurement there is a jump to tunneling for increasing V_p followed by a jump to contact when V_p is reduced. In this measurement, however, we do not observe a jump in the contact regime, which means that the constriction atom does not rearrange with respect to both electrodes. The measurement is again perfectly reproducible. The R_N panel shows a R_N variation of only 7% in the contact regime. For decreasing V_p (increasing contact pressure) a reduction of R_N coincides with a reduction in I_t. For increasing V_p (pulling the electrodes apart) a monotonic increase of R_N coincides with an increase followed by a decrease of I_t until the jump to tunneling occurs. Similar as in Fig. 2 the I_tR_N panel is reflecting mainly the I_t variations (of almost a factor of 2).

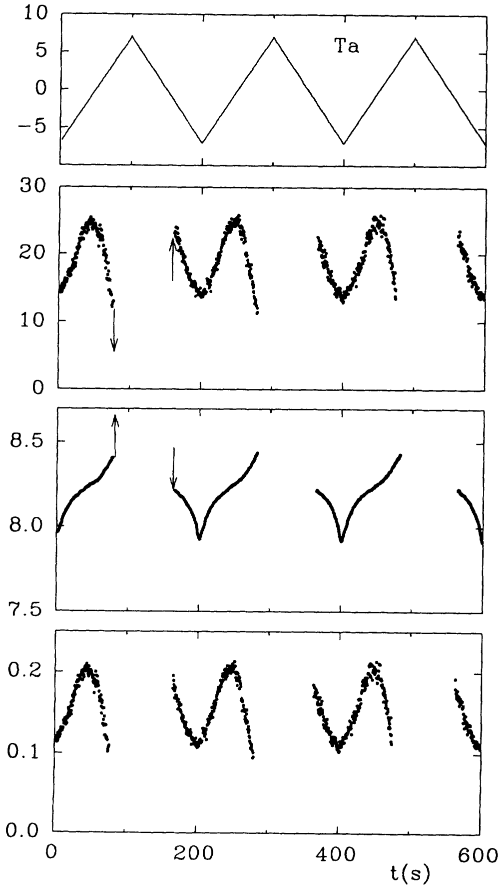

FIG. 3. A similar measurement as presented in Fig. 2 performed on superconducting Ta. Note the factor of 2 change in I_t during the continuous increase of R_N.

DISCUSSION

Both measurements show a hysteresis in contact formation and the breaking of the contact. The jump to contact takes place at a smaller V_p than the jump to the tunnel regime. This hysteresis reflects the elasticity in the electrode ends and the bonding forces of the front most atoms once a contact is formed. When a one-atom contact is formed a higher V_p is needed to break the contact due to some elasticity in the electrode ends. The value of the resistance when a contact is formed or is broken is difficult to predict. The Sharvin resistance,[6] which relates resistance to constriction diameter, is not valid for contacts of the order of the Fermi wavelength. The Landauer formalism provides a conductance of $2e^2/h$ per conductance channel. When we attribute one conductance channel to one atom, we expect a resistance of $h/2e^2 \simeq 13$ kΩ for a single-atom contact. From 20 measurements similar as shown in Figs. 2 and 3, performed with superconducting electrode material consisting of Sn, Ta, Nb, In, and Pb, we conclude that the jump to tunneling for these materials occurred at a conductance value between $2e^2/h$ and $4e^2/h$.

It is difficult to predict how thermal fluctuations will effect the I_t value. At 1.3 K, using the Josephson coupling energy, $k_BT=\hbar I_T/2e$ results in a thermal current, I_T, of 55 nA which is comparable to the measured threshold current. In our case zero-point fluctuations in the parabolic part of the washboard potential may play an even more important role than thermal fluctuations. Assuming a capacitance between 10^{-14} and 10^{-15} F for the single-atom contact, the zero-point energy $\frac{1}{2}\hbar\omega_p$ is larger then k_BT and is comparable to the Josephson coupling energy, which equals the amplitude of the washboard potential. However, at this stage we are not able to describe the interplay between the thermal fluctuations, the zero-point fluctuations and the Coulomb barrier associated with the small capacitance. It is shown experimentally that the I_t variation can be as large as a factor of 2, whereas the normal resistance undergoes a relatively small variation. This leads to a large variation of the I_tR_N product. In contrast to this finding, in tunnel junctions the I_tR_N product was found to be approximately constant.[5] The explanation for this result may find its origin in the scattering on a single defect in the contact region[7] and the change in scattering probabilities when a pressure or a tensile force is applied on the atom which spans the electrodes.

In conclusion we have examined the superconducting characteristics of one-atom point contacts. It is shown that although the constriction was built from one atom, the threshold current could change by a factor of 2, depending on the applied pressure or tensile force on this atom.

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