Conductance and Supercurrent Discontinuities in Atomic-Scale Metallic Constrictions of Variable Width

C. J. Muller, J. M. van Ruitenbeek, and L. J. de Jongh

Kamerlingh Onnes Laboratory, Leiden University, P.O. Box 9506, 2300 RA Leiden, The Netherlands

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A mechanically controllable break junction is used to study quantum size effects on conduction in metallic constrictions. When changing the constriction radius, we observe reproducible jumps in the conductance which are of the order of $2e^2/h$. For contacts adjusted at a jump the conductance switches in time between two values, which we interpret as "two-level fluctuations" in the site of a single atom in the constriction. For superconducting point contacts we observe concomitant jumps in the supercurrent of order $e\Delta/\hbar$, which is consistent with a recent prediction.

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In 1987 it was discovered [1] that the conductance of a small constriction in a two-dimensional electron gas (2DEG) is quantized in units of $2e^2/h$ if the constriction diameter is varied. Four years later it was shown [2] that the transmitted power of light through a slit of variable width is similarly quantized. As can be understood from the Landauer formula (for a review see Ref. [3]), the quantization of the transmission of electrons through a narrow channel is the consequence of the integer number of modes (conductance channels) that contribute to the conductance, the number being determined by the ratio of the channel width to the wavelength of the electrons. The formalism is not restricted to a 2DEG and is also expected to describe the conduction in a small metallic point contact. Here, we investigate whether it is possible to observe conductance quantization in metallic point contacts with extremely small constriction diameters. A novel quantization effect is expected if the metal is in the superconducting state. For a short weak link (as compared to the coherence length) with a large mean free path of the electrons, Kulik and Omelyanchuk [4] showed that, in the classical limit of constriction width much greater than Fermi wavelength, the product of critical current and normal resistance, I_cR_N, is constant and independent of R_N, with a value $\pi\Delta/e$. In a recent paper [5] it was shown that this relation survives under conditions where the transport through a narrow constriction is quantized by conduction of a limited number of modes. As a result, I_c was predicted to increase stepwise, as a function of the constriction diameter, with steps equal to $e\Delta/\hbar$ (Δ is the superconducting energy gap).

A problem related to metallic point contacts is how to continuously adjust the constriction radius on the scale of the Fermi wavelength, which is of the same order as the interatomic distance. Recently we have developed a method for finely adjusting the constriction diameter of a mechanically controllable break (MCB) junction [6]. The stability of the system is such that contacts of a single atom or even a vacuum barrier of a subatomic dimension can be established between the two electrodes. A schematic drawing of the sample mounting is presented in the inset of Fig. 1. A filament of the material under investigation is broken in vacuum at liquid-helium temperature by bending a glass substrate (bending beam) with an external mechanically applied force. After the breaking process the two freshly prepared electrodes are brought into contact, and the piezo element is used for fine adjustment of the constriction diameter. Here we report on results in our effort to look for possible conductance and critical-current quantization.

All experiments reported here are in vacuum at 1.2 K. Standard four-probe measurements are made by current biasing the sample. Figure 1 shows two examples of the variation of the conductance G of the same Pt point contact as a function of the voltage V_p on the piezo element, i.e., as a function of constriction diameter. For a piezo voltage scan over a large range as in Fig. 1 the fine structure does not reproduce in detail, but the overall shape of

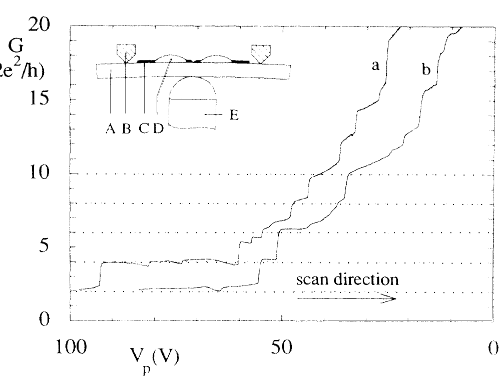

FIG. 1. Two examples of traces of the conductance G as a function of decreasing piezo voltage, i.e., increasing constriction diameter of a Pt sample. The full scan was recorded in about 20 min. We estimate that 10 V$\sim$1 Å. Conductance steps are of the order of $2e^2/h$, but no quantization is observed. Curve *a* is offset in the horizontal direction by +10 V for clarity. The inset is a schematic drawing of the sample mounting in a three-point bending configuration with *A* the bending beam; *B*, counter support; *C*, notched metal filament; *D*, epoxy adhesive, and *E*, piezo element.

the conductance does. We will show below for Nb that for a smaller V_p range the fine structure is reproducible. Although steps are observed with the expected magnitude [7] of the order of $2e^2/h$, no conductance quantization similar to 2DEG point contacts is found. We stress that the jumps in conductance are a result of changes in the point contact and do not result from a nonuniform displacement of the bending beam on which the electrodes are mounted. The latter can be excluded, since we are able to monitor the conductance in the tunnel regime, where the electrodes are separated by a finite vacuum barrier, and we observe a smooth and continuous change in conductance over comparable V_p ranges as reported here.

The nature of the steps is clarified by tuning V_p to coincide with a step and recording the I-V characteristic; see Fig. 2. The contact switches between two conductance values, and the characteristic time between jumps decreases strongly with increasing bias current, or equivalently, the voltage over the point contact (Fig. 3). Similar, so called, two-level fluctuations (TLF's) have been observed in nanometer-sized constrictions of larger contact diameter by Ralls, Ralph, and Buhrman [8] and Holweg *et al.* [9]. Here, the magnitude of the fluctuations can be as large as the total conductance, and it is possible to reproducibly create the TLF's. The TLF's are believed to be related to switching of a defect in the constriction region between two stable positions. An expression for the average time τ_i spent in a position i ($i=1,2$) is $\tau_i = \tau_{0i}\exp[(\varepsilon_{0i}-\zeta_i V)/k_B T_d]$, with τ_{0i} the attempt time of state i, ε_{0i} the energy barrier between the two metastable positions, and ζ_i a parameter describing current-induced migration of the defect [8]. The defect temperature T_d is presumed to be much higher than the environment temperature due to excitation by the current. Holweg *et al.* derived the expression $T_d = 5e|V|/16k_B$ for the defect temperature in the low-temperature limit. Analysis of switching times in our experiments give τ_0 as high as 10^{-7} s and barrier energies ε/k_B of the order of 10^3 K. The energy barrier is comparable but τ_0 is long compared to values obtained in Refs. [8,9].

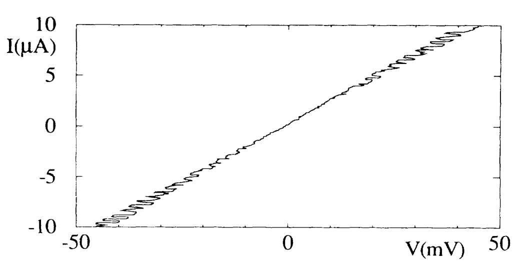

FIG. 2. An I-V curve with the piezo voltage tuned at a conductance step. The total recording time of this curve was 0.1 s. Switching occurs at random between two different conductance values. The switching frequency increases with increasing bias voltage, as shown in Fig. 3.

The contact areas for the measurements presented here are only a few atoms across. An estimate of the contact area S can be obtained from the Landauer formula for the conductance G:

$$G = \frac{2e^2}{h}\sum_{n=1}^{N} T_n ,$$

where T_n is the transmission probability of subband n and $N \simeq k_F^2 S/4\pi$ is the total number of occupied subbands. We have $S=\frac{1}{4}\pi d^2$ and $k_F \simeq \pi/a$ so that $N \simeq (d/a)^2$ (d and a are the constriction diameter and interatomic distance, respectively). Since G is only a few times $2e^2/h$ we find that our contacts are of atomic dimensions. Quantized conductance is observed under conditions where a well-defined number N of subbands is occupied, and the transmission probabilities are unity. However, it is easy to imagine that the contact is far from ideal, spoiling the regular quantization of the plateaus. In particular back scattering from defects in the constriction region is known to destroy the quantization.

We interpret the jumps in G (Fig. 1) as being due to

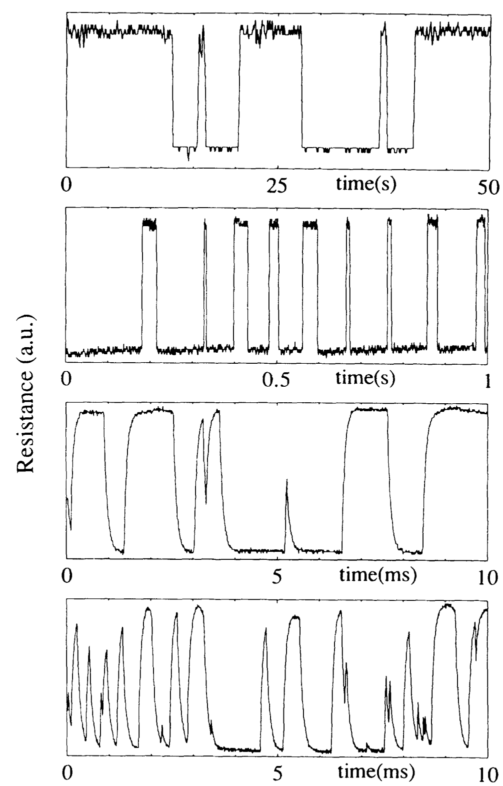

FIG. 3. Time traces at different bias currents at the same conductance step as Fig. 2. The conductance change between upper and lower level is the same in all panels, and is about $0.3\times(2e^2/h)$. The voltages of the higher-conductance state are (from top to bottom panel) 15.6, 20.1, 32.8, and 38.5 mV. The rounding of the curves in the lower panels is due to the finite time resolution of the equipment.

the sudden transition of an atom from one position to the next in the direct vicinity of the point contact. For V_p very close to the value at which the jump in G occurs, the atom is free to choose between two nearly equal sites. When changing V_p away from this value, one of the sites becomes more favorable. The remarkable aspect of our experiment is that the motion of a single atom can have an effect of order $2e^2/h$ on the conductance. Since in a metallic point contact the number of subbands is of the same order as the number of atoms making up the contact, this finding is consistent with the notion of a conductance of $2e^2/h$ per subband in the ballistic regime, even though no conductance quantization could be observed.

We now turn to point contacts of superconducting Nb. In a superconducting constriction an additional parameter, I_c, can be monitored as a function of the constriction diameter. Here, the critical current is defined as the current value at a setpoint voltage near $V=0$. This setpoint current value coincides with the zero-voltage critical current within 0.1%. The equipment automatically ramps the current until the preset voltage is reached. The current value at this setpoint voltage is held at an output terminal while the current switches back to zero. This procedure is repeated periodically, enabling us to monitor the setpoint current value continuously. In Fig. 4 the variation of the critical current with the piezo voltage is shown over two periods of a triangular V_p variation. Pronounced steps in the critical current are observed. The scans for rising voltage are very different for those of falling voltage but the steps for falling V_p roughly reproduce. Note that the step size is of the order of $e\Delta/\hbar \simeq 0.5$ μA, consistent with the theoretical prediction of a critical current of $e\Delta/\hbar$ per subband in a superconducting quantum point contact [5].

On further reduction of the range of the V_p scan the structures on both slopes reproduce in detail, as seen in the top graph of Fig. 5. Repeating the same scan and measuring R_N, the second graph of Fig. 5 was recorded, where the minimum piezo voltage served as a zero time reference. Here R_N is the normal-state resistance of the contact measured at a constant bias current by a lock-in technique at voltages well above 2Δ. We observe steps in R_N at exactly the positions of steps in I_c. The third panel in Fig. 5 shows the product of I_cR_N. The variations of 50% in I_c and R_N separately are reduced to 7% variations in the product. In particular, the indicated 15% jumps in I_c are reduced to 3% jumps in the product with R_N. The residual variations in I_cR_N have a fine structure that is still periodic with V_p, which remains to be explained.

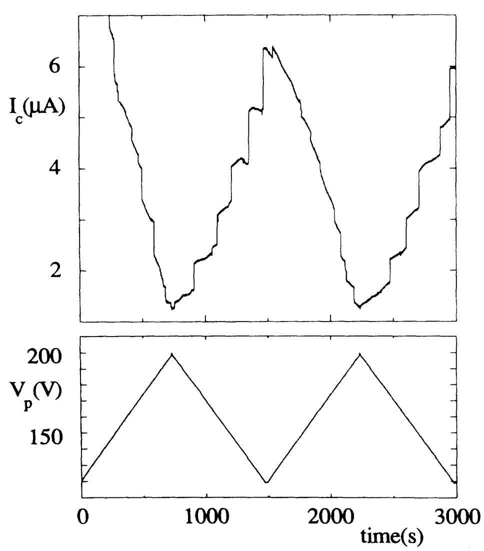

FIG. 4. Critical current measurement of a Nb point contact over two periods of the triangular piezo voltage scan. For an increasing constriction diameter (decreasing V_p) steps in I_c of the order of $e\Delta/\hbar \simeq 0.5$ μA are observed.

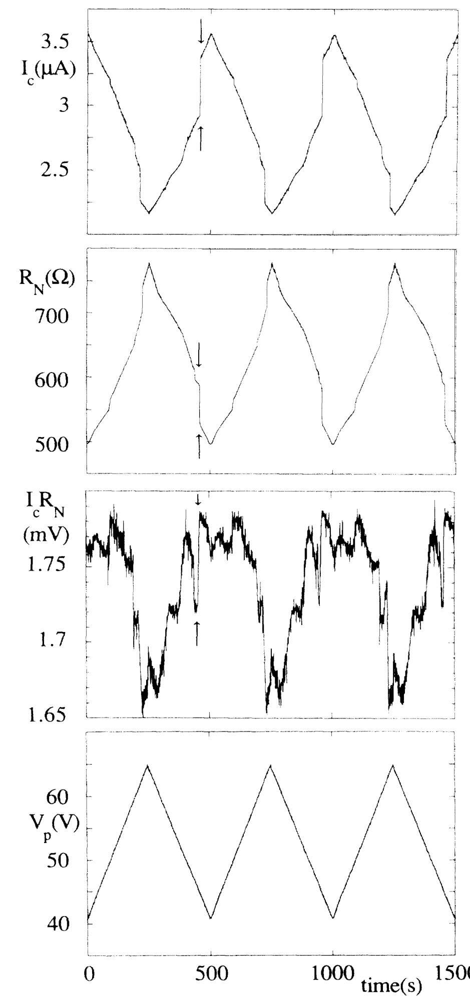

FIG. 5. Critical current and normal-state resistance measurement on a smaller piezo voltage range as compared to Fig. 4. The fine structure in I_c lines up with that in R_N. The relatively large changes in I_c and R_N at the steps almost compensate each other in the product I_cR_N.

The average value amounts to $I_cR_N = 1.73 \pm 0.05$ mV, which is somewhat smaller than, but of the same order as the theoretical value, $\pi\Delta/e = 4.5$ mV, in Ref. [5].

A reduction of I_cR_N, for R_N exceeding 80 Ω, to values well below the theoretical Ambegaokar-Baratoff value [10] was observed in a systematic study [6]. The origin of this reduction has not yet been clarified; ingredients to the interpretation might involve such aspects as thermal fluctuations, quantum fluctuations, and macroscopic quantum tunneling. These aspects are, of course, not taken into account in the theory of Beenakker and van Houten [5].

In conclusion, normal and superconducting metallic quantum constrictions show a stepwise increase of the conductance and supercurrent when the constriction diameter is increased. These phenomena are interpreted as an atom-by-atom change in size of the constriction. The magnitudes of the steps in G and I_c are of order $2e^2/h$ and $e\Delta/\hbar$, respectively, consistent with the theories of conductance and supercurrent quantization in ballistic point contacts.

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