Resistive quantum oscillations in superconducting aluminum microstructures

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Anomalous, periodic oscillations in the electrical resistance versus applied magnetic field have been found in aluminum ring microstructures at temperatures in the superconducting transition region. At low fields the oscillations, occurring at intervals of the flux quantum $\phi=h/2e$, are characterized by sharp dips in resistance versus field, on a decreasing background. The quantum-interference resistance variations are explained by periodic variations in the length λ_Q for excess density of quasiparticles penetrating from normal-metal regions into superconducting regions of the structure. These length variations are caused by periodic variations in critical current. [S0163-1829(96)51038-6]

INTRODUCTION

In recent years there has been much interest in the investigation of normal-metal–to–superconducting transitions and normal-metal–superconducting (NS) ring microstructures. Quantum interference effects have been reported.[1,2] In the Little-Parks (LP) effect as well as in the anomalous LP effect[1] resistance oscillations are observed in the superconducting transition region of ring structures as a function of magnetic field, and with a period corresponding to successive flux quanta, $n(h/2e)$, penetrating the structure, where n is an integer, h is Planck's constant, and e is the elementary charge. The phase of these oscillations is always such that resistance R is a minimum at $H=0$. The theoretical understanding of the LP effect is firmly established.

However, we have carried out experiments under conditions in the superconducting transition region which to a large extent resemble those of the LP experiment, yet at appropriate choice of field, temperature, current, and size of the ring we have found a behavior which could be described rather as inverted when compared with LP oscillations: The structure of the voltage curves vs field consists of sharp minima, rather than maxima, i.e., the phase of the observed oscillations is opposite of the LP oscillations, including also a maximum at $H=0$, which is just the opposite of the LP case. We propose that this phenomenon is related to the LP effect, but originates in the properties of NS boundaries that arise within the structure.

EXPERIMENTAL

The films were prepared by thermal evaporation, with a resulting film thickness of 65 nm. The typical geometry of measured structures, and the one reported on in subsequent figures, is shown in Fig. 1. The linewidth was 0.2 μm and loop sizes were 2×2 $(\mu m)^2$ or 1.5×1.5 $(\mu m)^2$ in various experiments. The structures were made on silicon substrates by electron beam lithography. Transport measurements were carried out by the standard four-point method. Measurements were repeated on several samples with the same structure. The voltage structure vs magnetic field, $V(H)$, was always observed in the structures which had the best normal-state conductivity, as signified by a resistance per square, R_{sq}, of about 1 Ω or less. In samples with resistance values twice this value or higher only the Little-Parks oscillations were found.

RESULTS

Results are shown in Figs 1–4. All data reported in Figs. 2–4 were taken at the temperature indicated by the arrow in Fig. 1. The voltage difference across the structure, $V(H)=V_+-V_-$, was measured at different μA current levels. The respective current levels are shown next to each curve in Fig. 2. The curves have been arbitrarily displaced in

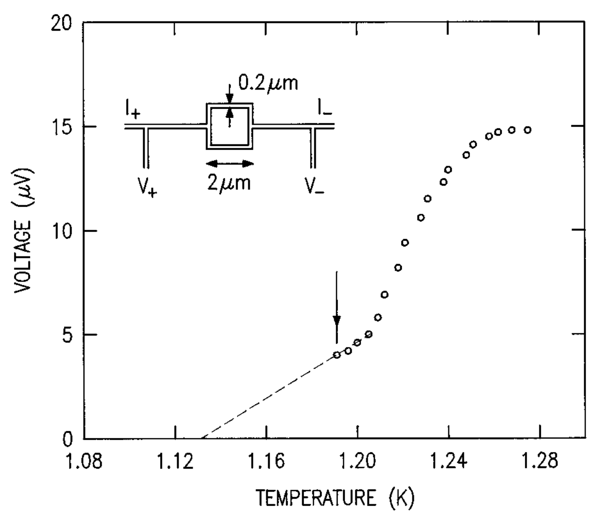

FIG. 1. Measured voltage vs temperature in the superconducting transition region of an Al structure studied in the present work. A typical structure is shown in the inset. The dashed line indicates where the linearly extrapolated resistance would go to zero.

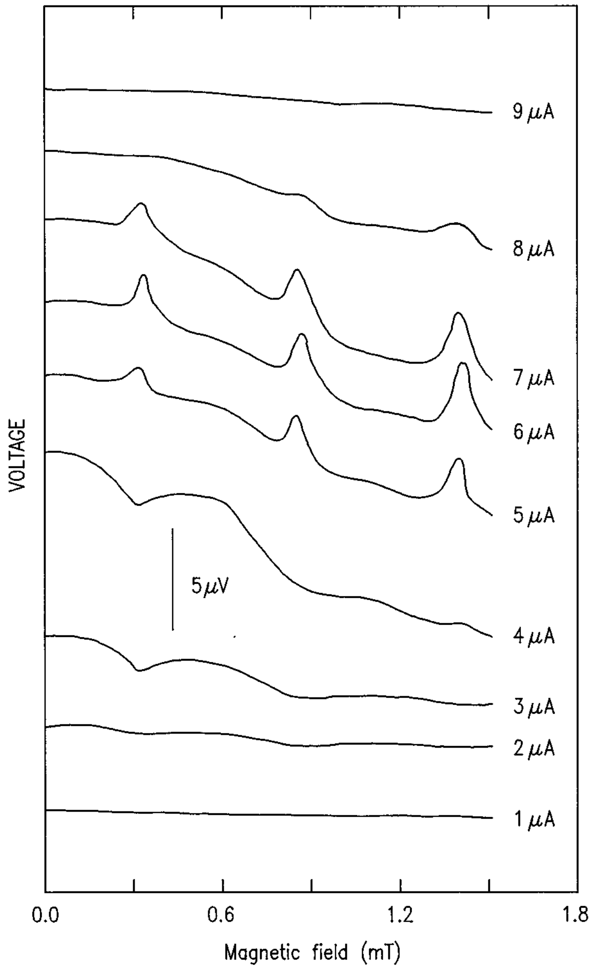

FIG. 2. Observations of voltage vs magnetic field at various current levels, given in μA at each curve. The curves are displaced vertically to allow display of all data. The voltage scale is shown by the vertical bar. A peaked structure is seen both at low and high current levels, but the phase of the oscillations is opposite in the two regimes. The upper regime is that of LP oscillations.

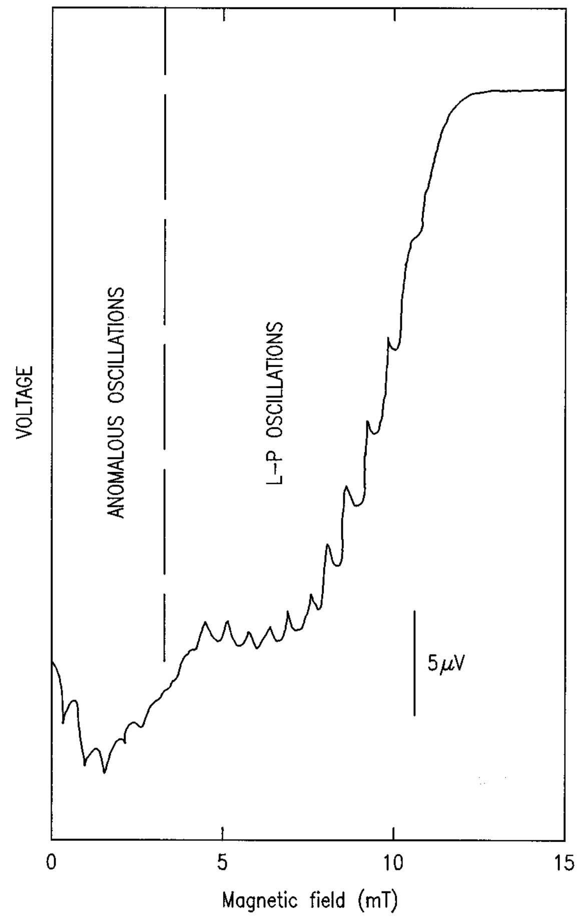

FIG. 3. Observations of voltage vs magnetic field in the structure of Fig. 1, on a wider field scale than in Fig. 2. The current is $I=3$ μA. Here the inversion of the peak structure occurs as a function of applied field. The high-field part is the LP regime.

the vertical direction for clarity, and the vertical bar gives the voltage scale which applied to all curves in Fig. 2. Measurements at negative fields are not shown, but $V(H)$ was found to be a symmetrical function of H. It was also checked that $V(H)$ changed sign with change of sign of current I, and that the oscillations were present in the same manner. The distance between peaks corresponds to one flux quantum, $\phi=h/2e$.

The data of Fig. 2 are interesting for several reasons. First of all, an oscillatory voltage structure is apparent in almost all curves, at different current levels. Second, a characteristic difference is seen in the oscillatory voltage structure at low current levels ($I\leqslant 4$ μA) as compared to that at higher current ($I\geqslant 5$ μA). In the former case the oscillations have the character of successive minima, in the latter case maxima appear in the same field positions as the minima. A noticeable feature of the data in Fig. 2 is also that the overall field dependence is the opposite of that normally observed in the LP effect: Here we find a maximum of voltage at $H=0$, followed by a sequence of diminishing minima (for $I\leqslant 4$ μA), or maxima (for $I\geqslant 5$ μA), on a decreasing background as a function of field. The latter effect, i.e., a negative slope, was observed in aluminum microstructures previously.[3] In that same study it was also shown that at sufficiently large currents the structure becomes an *NS* structure, i.e., an *NS* boundary arises when the total width of the current-transporting structure varies along the current direction. In our case the total width along the current direction varied by a factor of 2, as can be seen in Fig. 1: The sum of the widths of two lines in the ring is twice that of the connecting lines. It was shown in Ref. 3 that the superconducting transition of such structures in a magnetic field takes place in two regimes, as could be expected. In Fig. 3 we show corresponding measurements on the structure reported here, i.e., how the voltage across the ring varies with magnetic field on a larger field scale than in Fig. 2. Here, we see again the contrast described above, but this time in voltage V versus B field at *one* current level ($I=3$ μA). The field dependence changes from the type of voltage structure observed at the lowest fields, to ordinary LP oscillations at higher field. The dependence of V on H can be described broadly as occurring in two regimes, and connected with this is a transition from sharp minima on a downward sloping background at low fields to sharp maxima on an upward sloping background at higher fields, the latter being the LP oscillations.

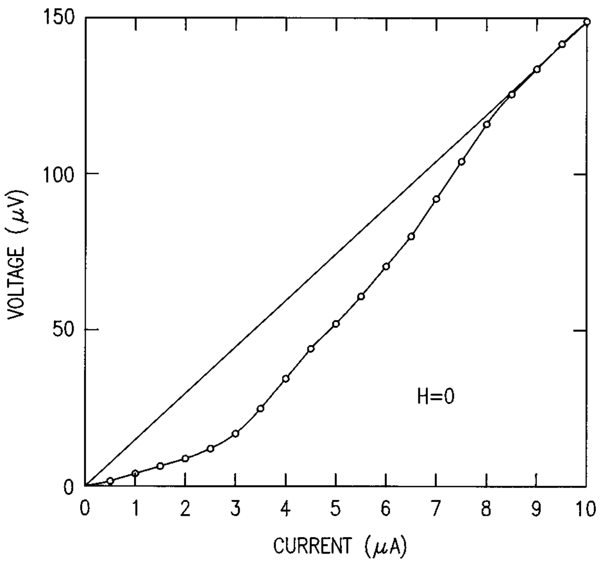

FIG. 4. Voltage-current characteristics for a typical structure as shown in the inset of Fig. 1. The applied field is $H=0$. The $V(I)$ is nonlinear, and can be interpreted as a superposition of two broad steps below a linear region.

We remark that although the data of Fig. 2 seem to indicate an abrupt transition from minima to maxima vs field when going from 4 to 5 μA current, in reality there is a continuous, although rather sharp, transition from one behavior to the other. This was checked out in separate measurements. In this transition regime one could find a superposition of the two types of voltage structures.

We have also measured the V-I characteristics of the structure, as shown in Fig. 4. The characteristic is nonlinear up to a certain current (in the case shown, to about 8.5 μA), and linear above. Although the signature is relatively weak, it seems that the data can be broadly interpreted as occurring in two regimes within the nonlinear range. The linear dependence above 8.5 μA shows that there was no heating of the structure. We emphasize that the interference effect is observed only in the nonlinear region.

The experiments show that the effect is largest where there is a negative background slope connected with NS boundary effects. This also points towards a mechanism for the oscillations connected with the existence of NS boundaries.

DISCUSSION

We propose that the observations can be understood as an effect caused by penetration of quasiparticles (and hence also of electrical field) from a normal region of the thin-film structure into the superconducting region. Under conditions of nonequilibrium the electric field penetrates from N into S on a length scale λ_Q. This length, when added to the length of the N region is a source of additional resistance. Theory[4] predicts the following expression for λ_Q:

$$\frac{1}{\lambda_Q}=\left(\frac{\pi\Delta(T)}{4kT}\right)^{1/2}\frac{1}{l_i(T)}\left\{1+\frac{l_i^2(T)}{\xi^2(T)}\left[\frac{1}{3}\left(\frac{I}{I_c(T)}\right)^2+\left(\frac{H}{H_{c2}(T)}\right)^2\right]\right\}^{1/4}. \quad (1)$$

The corresponding resistance, R_Q, related to this length is

$$R_Q=\frac{2R_{\text{sq}}}{w}\left(1-\frac{\pi\Delta(T)}{4kT}\right)\lambda_Q. \quad (2)$$

In Eqs. (1) and (2) the following notation is used: $\Delta(T)$ is the superconducting energy gap, l_i is the inelastic diffusion length of quasiparticles, ξ is the superconducting coherence length, $I_c(T)$ is the critical current in zero magnetic field, and H_{c2} is the upper critical field of the superconductor. w is the width of the line structure, and R_{sq} is the resistance per square. We seek the explanation for the observed dependencies $V(I,H)$ in the dependence of λ_Q on current and magnetic field. The total width of the structure is typically a factor of 2 lower in the connecting lines as compared to the ring. Therefore at appropriate current levels the connecting lines may be in the normal state at the same time as the ring is superconducting. It should be noted here that when we speak about part of the structure as being in the N state or S state this is a simplification, a model description. In reality we are dealing with a structure consisting of two parts which are at different stages of the superconducting transition. Therefore, there is no contradiction in stating that the LP oscillations are still present when the system is driven hard enough to remove the voltage structure, or at high enough magnetic fields. Our model description of the physical mechanism responsible for the effect is based on adoption and interpretation of Eqs. (1) and (2). Since the resistance of an NS boundary is directly proportional to the charge-imbalance length λ_Q for conversion of quasiparticles to Cooper pairs, the interpretation is based on the dependence of λ_Q on the ratios $i=I/I_c$ and $h=H/H_{c2}$. Now compare the observed field dependence in Fig. 2, i.e., the initial overall fall of resistance from $H=0$, and the superposed inverted peak structure, with that expected on the basis of Eqs. (1) and (2): The background variation comes from the h dependence in Eq. (1). But when H is changed at fixed I, i is also changed due to the dependence of I_c on T_c. Since T_c has cusplike, periodic variations as a function of magnetic field these will result in precisely the kind of minima seen in Fig. 2. This is similar to the LP effect, but in that case the oscillations are of opposite phase, and the critical current is not directly involved. In addition, we see that the h term and the i term in Eq. (1) have different weight, giving a relative weight of only 1/3 to the i dependence. This is also consistent with our observations, as can be seen in the data of Fig. 3, when comparing the fall of resistance which is caused by h, and the amplitude of the anomalous oscillations caused by the current i. The ratio of these is roughly 3:1.

In support of these arguments we make the following estimates of relevant quantities involved: Let us first look at the penetration length for quasiparticles, and hence also for electrical field, λ_Q. In the case when both field h and current i are small, an estimate can be made on the basis of the simplified expression

$$\frac{1}{\lambda_Q} \approx \left[\frac{\pi\Delta(T)}{4kT}\right]^{1/2} \frac{1}{l_i(T)}. \tag{3}$$

For T near T_c in Al l_i is known to be about 5 μm,[5] and $2\Delta(0)/kT_c$ is 3.4.[6] This gives a value for the quantity λ_Q of about 4.5 μm or more because $\Delta(T) \leqslant \Delta(0)$. This length is comparable to or larger than the size of the ring of our structure. Further, to estimate R_Q we refer to Eq. (2), and approximate R_Q by $(2R_{\rm sq}/w)\lambda_Q$. For our structures $R_{\rm sq} = 0.37\ \Omega$, hence we find R_Q approximately equal to 17 Ω using directly the full $\Delta(0)$ value. This is comparable with the total resistance of the structure, including the ring, of 15 Ω. Since our measurements were made close to T_c the gap value is reduced, and the estimate of R_Q should be increased correspondingly. Still, the obtained value seems in close enough agreement with that measured to be acceptable. The main discrepancy may be in the value used for l_i from Ref. 5, since this quantity can be expected to be sample dependent.

To check further the consistency of the NS boundary effect interpretation when the connecting lines are normal and the ring is superconducting we have also performed experiments with wider lines connecting the ring in Fig. 1, so that the ring is normal and the connecting lines are superconducting at appropriate currents through the structure. With these wider contact lines the oscillations reported here did not appear.

We point out finally that the authors of Ref. 1 observed an additional peak in the voltage structure which may possibly be interpreted as an effect of the same kind as reported here.

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