PHYSICAL REVIEW B VOLUME 56, NUMBER 14 1 OCTOBER 1997-II

ac effect in the conductance of mesoscopic normal-metal–superconductor structures

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(Received 22 May 1997; revised manuscript received 4 August 1997)

Resonant peaks in the *resistance* of a mesoscopic normal-metal wire in contact with two superconductors under rf irradiation are detected. The peaks occur when a potential difference $V_S = \hbar\omega/2e$ is applied between the superconductors. The peaks can be interpreted as an ac phase-coherent phenomenon in the conductance of mesoscopic normal-metal–superconductor structures. This effect is observed although the critical Josephson current is negligibly small and the Shapiro steps are absent. [S0163-1829(97)51138-6]

Recently, a great deal of attention has been devoted to the effect of a superconductor on the normal resistance of mesoscopic normal-metal–superconductor (NS) structures. It turns out that the behavior of the proximity correction to the resistance (PCR) differs drastically, in some aspects, from that of the Josephson current, another consequence of the proximity effect. For instance, the PCR and Josephson current have a different temperature dependences. The Josephson current has a maximum amplitude at low temperature and decreases exponentially at high temperature when the coherence length in the normal region, ξ_N, becomes smaller than the spacing between the superconductors. In contrast, the PCR has a maximum amplitude at a temperature corresponding to the Thouless energy, $E_{\mathrm{Th}} = \hbar D/L^2$ (L is the length of the normal part, and D is the diffusion coefficient), and disappears at low temperature.[1] The PCR and the Josephson current also have different sensitivity to the phase of the superconducting order parameter, φ. The Josephson current is related to the phase through the equation $I_J = I_C \sin\varphi$, whereas the PCR depends on the phase such that $\delta R/R \sim \cos\varphi$. The latter was demonstrated recently in experiments performed with an Andreev interferometer, where the phase is controlled by means of magnetic field or the supercurrent.[2–5] The question still remains as to whether the ac phenomenon exists in the PCR. In the case of the Josephson current, the ac effect results in Shapiro steps in the I-V characteristic of the superconductor–normal-metal–superconductor (SNS) junctions. Recently Volkov and Takaynagi showed that the resistance of mesoscopic NS structures exposed to rf irradiation, $V_\omega \cos\omega t$, should display peaks at $V_S = n\hbar\omega/2e$, where $n = 1,2\ldots$ and V_S is the constant bias voltage between the superconductors (the geometry of the structure was similar to that shown in Fig. 1).[6] The peaks were caused by resonant suppression of the PCR when V_S satisfies the Josephson relation. It was predicted that the amplitude of the peaks should be of the order of the PCR, and that they should exist even when the spacing between the two superconductors greatly exceeds ξ_N and the Josephson current is negligible. In this paper, we follow the arguments presented in Ref. 6 to seek the ac phase coherent effects in the resistance of NS structures. We study the response of a normal silver wire in contact with two superconductors on rf irradiation in the gigahertz range. We observe the phase-coherent ac effect. Under rf irradiation, resonant peaks in the wire resistance emerge when a potential difference is applied to the superconductors. The position of the peaks corresponds to those predicted by the Josephson relation $V_S = n\hbar\omega/2e$. However, the amplitude of the effect is much smaller than expected and is only 2% of the total proximity correction.

Plan view of the sample and experimental configuration are presented in the inset of Fig. 1. The normal 0.8 μm long silver wire is placed in contact with two superconducting aluminum stripes at the stubs. The distance between the two NS boundaries is about 0.6 μm. The silver wire is 40 nm thick and 120 nm wide. The sheet resistance of the silver is 0.2 Ω, which corresponds to a diffusion coefficient for the electrons, D, of about 180 cm^2/s, and a coherence length $\xi_N = (\hbar D/2\pi k_B T)^{1/2} \approx 0.25\ \mu$m at $T = 0.35$ K. The phase breaking length in the silver film, L_φ, is $\sim 0.5\ \mu$m. The aluminum stripes are 300 nm wide and 45 nm thick. The normal and superconducting parts are defined in two successive electron-beam lithography steps. The silver surface is cleaned with Ar ions just before the evaporation of the aluminum. Typical NS interface resistance varies from 0.5 to 1 Ω.

Measurements are performed in a shielded He^3 refrigerator in the temperature range of 0.3 to 1 K. The resistance of the silver wire is studied as a function of rf radiation ampli-

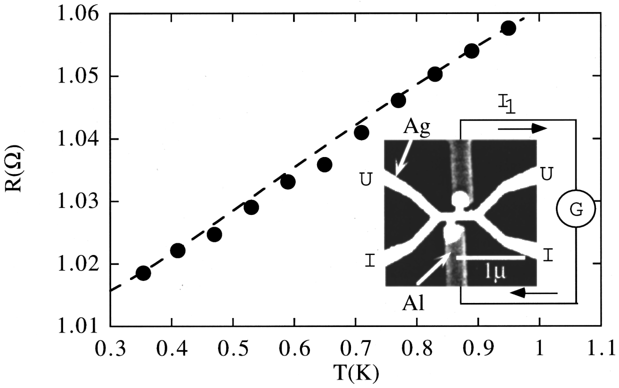

FIG. 1. Temperature dependence of the resistance of the silver wire (filled circles) and a fit given by quasiclassical proximity theory (dashed line). Inset: scanning electron microscopy picture of the structure studied; I-I and U-U denote current and potential leads for the resistance measurement. The dc current I_1 induces a potential difference between the superconductors.

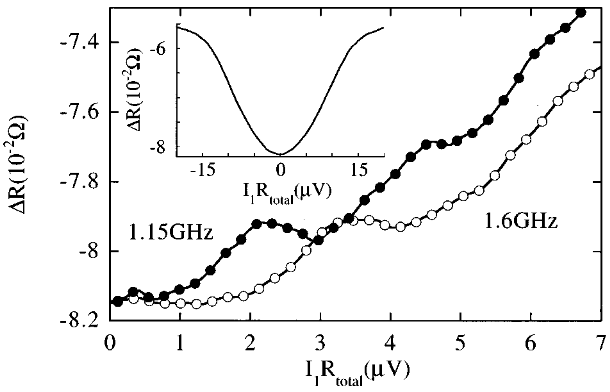

FIG. 2. The proximity correction to the resistance as a function of the potential difference between the superconductors in the presence of 1.15 GHz (curve with filled circles) and 1.6 GHz (curve with empty circles) radiation. The rf power at the top of the refrigerator, P_{ω}, has the corresponding amplitude of ~ 1 and 0.3 mW. Inset: the proximity correction as a function of potential difference between the superconductors at $P_{\omega}=0$ W.

tude and potential difference between the superconductors. A lock-in technique with a low frequency ($f=183$ Hz) probe current is used for the resistance measurements. The current and potential leads are identified in Fig. 1. The typical magnitude of the probe current is $I_{\text{probe}}\sim 0.5\ \mu$A. A potential difference between the superconductors, $V_S=I_1R_{\text{total}}$, is induced by the dc current I_1 (R_{total} is the total resistance between the superconductors; this includes the resistances of two NS interfaces, and the silver wire). We estimate R_{total} from the I-V curves measured between the superconductors. In different samples, R_{total} is found to be between 2 and 3.5 Ω. The I-V curves demonstrate the absence of the dc Josephson current in the samples. This should be expected because of the large distance between the superconductors compared with ξ_N. rf irradiation in the frequency range from 0.8 to 1.6 GHz is fed from the top of the refrigerator by coaxial cable, and is coupled to the sample capacitively.

We have investigated five samples. They show qualitatively the same behavior and in this paper we present the data for just one of them. Below the superconducting transition of the aluminum stripes, $T_C\sim 1.5$ K, we observe a gradual decrease in the resistance of the silver wire (Fig. 1). The amplitude of the effect at $T=0.3$ K is about 5% of the normal state resistance. This phenomenon has a fruitful explanation in the framework of the quasiclassical proximity theory.[7] We can approximate the experimental curve by assuming a temperature-independent phase breaking rate in the normal conductor, and using the NS interface resistance, R_b, as a fitting parameter.[7] The theoretical curve is plotted in Fig. 1 as a dashed line. R_b deduced from this approximation is $\sim 2\ \Omega$, which is in reasonable agreement with the experimental value of $\sim 0.9\ \Omega$.

We are able to influence the induced proximity correction in a number of ways: by exposing the sample to rf radiation, by altering the current I_1 between the superconductors, and by applying a magnetic field. In the parameter range of our experiments, all these factors weakly affect the normal properties of the silver metal itself. In Fig. 2 the dependencies of ΔR vs I_1R_{total} are shown (the total resistance is $R_{\text{total}}\approx 2.2\ \Omega$). In the absence of rf radiation, I_1R_{total} suppresses the proximity correction monotonously with saturation occurring at 20 μV (inset of Fig. 2). Under rf radiation peaklike features are superimposed on the smooth curve. For the curve corresponding to radiation of 1.15 GHz two peaks are situated at 2.3 and 4.7 μV, and for the curve corresponding to radiation of 1.6 GHz one can distinguish a peak at 3.3 μV. The peak positions satisfy the Josephson relation $V_S=R_{\text{total}}I_1=n\hbar\omega/2e$ with $n=1$ for the first peak and $n=2$ for the second peak. The amplitude of the peaks accounts for only 2% of the total proximity correction. The effect has also been observed in an experiment with radiation of 0.825 GHz (not shown). These observations reassured us that we did detect the ac phase-coherent effect discussed by Volkov and Takayanagi. Nevertheless, the *amplitude* of the effect is much smaller than expected from the theory. The theory predicts an amplitude comparable to the total proximity correction, which occurs in the Andreev-type interferometers (in both cases, a phase dependent part of the proximity correction is affected).[2–5] In our experiments the amplitude is two orders of magnitude weaker. Although there is no complete explanation of this suppression, we suggest three reasons that can be important. One is the rough tuning of the rf radiation power. As with the usual Shapiro effect, the amplitude of the nth peak should be proportional to the Bessel function of the nth order, $J_n[2eV_{\omega}/\hbar\omega]$.[6] Therefore, the first peak should have a maximum value when $2eV_{\omega}/\hbar\omega\approx 1.9$, and should disappear at a higher or lower rf power. Qualitatively this is observed in the experiment, but we are not able to precisely trace the power dependence of the amplitude and adjust it to the maximum value. Due to this reason we can expect a suppression of the peak amplitude by a factor of 2. Another possible source is the effect of the probe current. This current produces an alternative potential difference between the superconductors $I_{\text{prob}}R_{\text{eff}}$ (R_{eff} is the resistance of the silver wire between the stubs), which should broaden and smear the peaks. We estimated $I_{\text{prob}}R_{\text{eff}}\sim 0.2\ \mu$V in the experiment. One should note that the broadening of the peaks in Fig. 2 is larger than this value, hence this mechanism cannot be the only source of the suppression. Temperature can serve as a third cause of the peak amplitude suppression. In our experiment, the thermal energy k_BT greatly exceeds the energy of the rf quanta, which determines the scale of the effect. One can expect a smearing of the resonant peaks for this condition.[8] We believe that this is the main reason for the suppression of the peak amplitude.

Finally we would like to discuss two side effects which accompany the resonant peaks and are important for a complete physical picture. They are the effects of the voltage I_1R_{total} and rf radiation on the PCR. Both gradually suppress the PCR (Figs. 2 and 3). We have performed out independent experiments on samples of similar geometry to rule out the heating effect.[9] One possible explanation of the PCR suppression comes from the phase-coherent nature of the proximity correction. The potential difference between the superconductors, I_1R_{total} results in a time dependence of the phase difference φ, $\varphi=\varphi_0+(2eV_S/\hbar)t$. To find a stationary PCR, one should time average the equations containing φ. This results in a gradual suppression of the proximity correction with I_1R_{total}. It is straightforward to show that the phase-dependent part of the PCR should disappear when the potential difference becomes larger than $I_{1C}R_{\text{total}}=(\hbar D/L^2)/2e$.

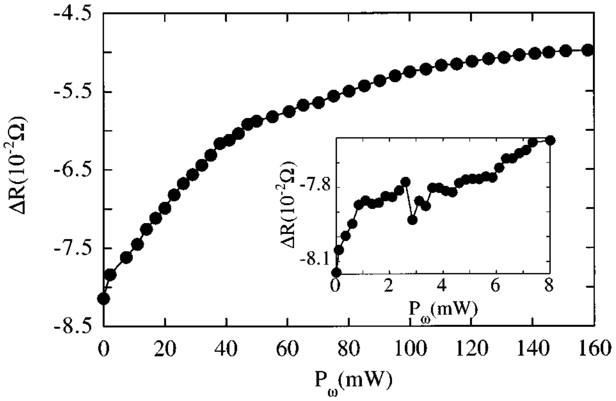

FIG. 3. The suppression of the proximity correction to the resistance in the presence of rf radiation at $I_1R_{\text{total}}=0$ V. P_ω is the power at the top of the refrigerator. The inset: enlargement showing the suppression at low power.

We estimate $I_{1C}R_{\text{total}}\approx 20\ \mu$V in the sample under consideration, which is in agreement with the experimental value (see inset of Fig. 2). The presence of this suppression mechanism substantially limits the range of the frequencies which can be used for the detection of the ac phase-coherent effect in the PCR. The effect of rf radiation is twofold. On one hand, the radiation influences the phase dependent part of the proximity correction in a similar fashion to the voltage (we think this mechanism is effective for low power of rf radiation, see inset of Fig. 3). On the other hand, it suppresses the proximity correction by dumping the superconducting order parameter near the NS interfaces. The first mechanism is slightly different from the case of the dc potential difference. Because of the oscillating voltage $V_\omega\cos(\omega t)$, the proximity correction has a stationary term after time averaging, which is proportional to $J_0[2eV_\omega/\hbar\omega]$, where J_0 is a zero-order Bessel function. Therefore, one can expect a modulation of the PCR with rf power. The experimental curve in the inset of Fig. 3 does not evidently display a modulation larger than 5% of the total PCR, which is consistent with the amplitude of resonant peaks. The remaining suppression effect we attribute to the second mechanism. We did not study in detail the latter, and so we limit ourselves to presentation of the experimental data.

In conclusion, we have described the observation of the phase-coherent effect in the resistance of mesoscopic NS structures exposed to rf radiation. We find a resonant suppression of the proximity correction to the resistance, which occurs when the potential difference satisfying the Josephson relation $V_S=\hbar\omega/2e$ is applied between the superconductors. This effect is in agreement with the recent prediction by Volkov and Takayanagi.[6] The amplitude of the effect, however, is much smaller than expected from theory being only 2% of the total proximity correction. We attribute the latter to temperature smearing.

We acknowledge useful discussion with Professor C. J. P. M. Harmans, Professor T. M. Klapwijk, Dr. U. Gunsenheimer, and Dr. A. Korotkov. We are grateful to Dr. T. Izawa and Dr. N. Matsumoto of NTT Basic Research Laboratories for their encouragement throughout this work.

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