Magnetoresistance of proximity coupled Au wires

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We report measurements of the magnetoresistance (MR) of narrow Au wires coupled to a superconducting Al contact on one end, and a normal Au contact on the other. The MR at low magnetic field \( B \) is quadratic in \( B \), with a characteristic field scale \( B_c \) determined by phase coherent paths which encompass not only the wire, but also the two contacts. \( B_c \) is essentially temperature independent at low temperatures, indicating that the area of the phase coherent paths is not determined by the superconducting coherence length \( L_T \) in the normal metal, which is strongly temperature dependent at low temperatures. We identify the relevant length scale as a combination of the electron phase coherence length \( L_\phi \) in the normal metal and the coherence length \( \xi_S \) in the superconductor.

The properties of a normal metal (N) in contact with a superconductor (S) have been an active subject of interest in recent years [1]. The proximity of a normal metal with a superconductor induces pair correlations which can extend appreciable distances into the normal metal. In dirty normal metals (the case of interest here), where the motion of the electrons is diffusive, the relevant length scale is the normal metal coherence length \( L_T = \frac{\sqrt{\hbar D}}{k_B T} \), where \( D \) is the electronic diffusion coefficient [2]. For typical metallic films, \( L_T \) can be as long as 0.5 \( \mu m \) at \( T = 1 \) K. With modern lithographic techniques, this now represents an experimentally accessible length scale, and many experiments in the past few years have investigated the proximity effect in mesoscopic NS structures. An overview of these experiments can be found in the recent article by Courtois and Pannetier [3].

The microscopic basis of the superconducting proximity effect is Andreev reflection (AR) [4], whereby an electron in the normal metal incident on the NS interface with an energy \( \epsilon \) less than the gap \( \Delta \) of the superconductor is reflected as a hole, with the simultaneous generation of a Cooper pair in the superconductor. AR is a phase coherent process; the phases of the incident electron and the reflected hole are related through the macroscopic phase \( \phi \) of the superconductor. This has been elegantly demonstrated by recent interference experiments in so-called Andreev interferometers [5], which are NS loops where one arm is fabricated from a superconductor, and the other from a normal metal. The electrical [6] and thermoelectric properties [7] of these doubly-connected devices have been found to oscillate periodically with the magnetic flux coupled to the area of the loop, with a fundamental period corresponding to one flux quantum \( \Phi_0 = \hbar/2e \).

In spite of the tremendous amount of work on the proximity effect, the relevant length \( L_p \) that sets the scale for quantum interference in the proximity regime is not entirely clear. One might argue that \( L_p \) should be set by \( L_T \), the length which determines how far superconducting pair correlations can diffuse at a temperature \( T \) in the proximity-coupled normal metal before breaking apart. However, experiments which measure the amplitude of the magnetoresistance (MR) oscillations in Andreev interferometers indicate that \( L_p \) can be much longer than \( L_T \). For example, Courtois et al. [8] measured the temperature dependence of the MR oscillations in an Andreev interferometer and found that the oscillation amplitude decreased only gradually with increasing temperature. According to their analysis, the relevant length scale is \( L_T \) with the electron phase coherence length \( L_\phi \) providing an upper cutoff. Only pair correlations with a coherence length greater than the length \( L \) of the normal arm of the Andreev interferometer can contribute to the interference. The fraction of such correlations is given by \( E_c/k_BT = L_\phi^2/L^2 \), where \( E_c = \hbar D/L^2 \), giving rise to an oscillation amplitude which decreases with temperature as \( 1/T \), in agreement with experiment.

In this Letter, we describe our measurements on the proximity effect magnetoresistance of short, narrow Au wires. The wires are connected on one end to a large Al contact, and on the other to a large Au contact. The MR is quadratic at low magnetic fields; however, the characteristic field scale \( B_c \) is much smaller than that expected from the dimensions of the wire, but agrees with what one would expect from contributions of phase-coherent paths which encompass the wire as well as the normal and superconducting contacts, indicating that the contacts cannot be considered ideal reservoirs. Furthermore, at temperatures \( T \leq 0.5T_c \), \( B_c \) is essentially temperature independent. This indicates that the relevant length scale for interference is not determined by \( L_T \), which varies as \( \sqrt{1/T} \). At higher temperatures, \( B_c \) decreases with increasing temperatures, evidence that the interference is associated with phase coherent paths whose lengths increase with increasing temperature. We identify the relevant length for interference as a combination of \( L_\phi \) in the normal metal, and the superconducting coherence length \( \xi_S \) in the superconductor.

The samples for this experiment were produced by multi-level electron beam lithography techniques on oxidized silicon substrates. Figure 1(a) shows a scanning electron micrograph of the sample discussed in this paper. It consists of 5 Au wires of different lengths, each connected to a separate 3×3 \( \mu m^2 \) Au reservoir on one
end, and to the same Al reservoir on the other. All 5 wires are connected to the same Au strip of width $\sim 0.3$ $\mu$m just underneath the Al film at the Al/Au interface to ensure as much as possible uniform interface resistance for all samples. Two additional fine Au probes on each wire permit us to make four-terminal resistance measurements on the wire by itself, without including any explicit contributions from the superconductor or the NS interface (see Fig. 1(b)). Additional contacts let us directly measure the four terminal resistance of the Al film and the NS interface as well. The 50 nm thick Au wires and contacts were patterned and evaporated first, after which the 80 nm thick Al contact was evaporated following an Ar$^+$ etch to ensure good interfaces between the Au and Al films, as evidenced by a measured interface resistance of less than 0.1 $\Omega$. The area of the Al contact was $3 \times 20$ $\mu$m$^2$, and its transition temperature was $T_c = 1.24$ K. In addition to the sample itself, a Au meander wire was fabricated simultaneously to characterize the material properties. From weak localization (WL) measurements on this control sample, $L_0 \cong 3.8$ $\mu$m at $T = 35$ mK, and the diffusion constant in the Au was determined to be $D \cong 3.0 \times 10^{-3}$ m$^2$/sec, giving $L_T \cong 0.48$ $\mu$m at $T = 1$ K. The samples were measured in a dilution refrigerator using standard ac lock-in techniques in a magnetic field perpendicular to the sample substrate. Of the 5 wires shown in Fig. 1(a), two had one or more contacts disconnected and could not be measured. The lengths of the remaining three were $L = 1.0$, 1.2 and 1.5 $\mu$m, and their widths were $W = 120$ nm.

The temperature dependence of the resistance of this and similar samples was studied in detail, and has been reported elsewhere [9]. Here we shall concentrate on the low field MR of the proximity coupled Au wires. Figure 2 shows the MR of the $L = 1.5$ $\mu$m wire at $T = 37$ mK. The most noticeable aspect of these data is the fact that there is not just one MR curve, but a number of distinct curves which are almost identical, except that they are offset from each other by a magnetic field of $\sim 1.4$ G. The sample switches spontaneously between these curves on sweeping the magnetic field. Similar behavior is observed for the 1.0 and 1.2 $\mu$m wires as well. Since this metastability appears only on measurements of the proximity coupled wires below $T_c$ of the Al film, and not the Au control wire which was measured simultaneously, it is not an experimental artifact, associated for example with the superconducting solenoid used for the external magnetic field. This hysteretic behavior appears to be due to metastable screening states in the superconducting contact which correspond to a paramagnetic response to the external magnetic field. However, this behavior is not the focus of this paper, and will be discussed in a later publication. For the remainder of the paper, we will turn our attention to a single MR curve in order to discuss its magnetic field dependence in detail.

Figure 3 shows the MR of the $L = 1.5$ $\mu$m wire at 35 mK and 1.06 K, along with the MR of the superconducting bank by itself. At low magnetic fields, the MR of the wire is quadratic, with the resistance increasing rapidly to its normal state value within $\sim 7$ G. The superconductor, on the other hand, remains in a resistanceless state until a magnetic field of $\sim 70$ G (at 35 mK), where there is a rapid transition to the normal state resistance. This indicates that, at low temperatures, the field scale of the proximity wires is not restricted by the critical field of the superconductor. We shall now attempt to understand the magnetic field scale of the MR of the proximity wire.

In analogy with quantum interference effects such as WL in normal metals, the Aharonov-Bohm (AB) phase generated by the presence of a magnetic field also leads to measurable effects in singly connected structures such as films and wires. For WL, which arises from the interference of electrons traversing pairs of time reversed paths, the application of a magnetic field destroys this interference and leads to a decrease in resistance [11]. An estimate of the characteristic field required to destroy this interference can be obtained from the physical argument that this field should correspond to one flux quantum through the area of the largest possible phase coherent path. For WL, it is $L_0$ that determines the length of the phase coherent paths. For two dimensional (2D) films, in which both lateral dimensions (but not the thickness) are larger than $L_0$, the characteristic field is consequently $B_c \sim \Phi_0/L_0^2$. For one dimensional (1D) wires, where motion in the transverse direction is restricted by the finite width $W$ of the wire, the corresponding expression is $B_c \sim \Phi_0/(L_0 W)$. In the intermediate case, where a 1D wire of width $L \ll L_0$ is connected to 2D probes, the electrons in the wire can sample regions in the 2D probes in a phase coherence time. In this case, the characteristic field is not given by either the 1D or the 2D form, but something in between which depends on the ratio $L/L_0$. These physical arguments are supported by more quantitative calculations for WL [13], and have also been confirmed by experiment [12].

Drawing on the similarity between the equation of motion for the Cooperon, which determines the WL correction, and the Usadel equation for the anomalous superconducting Green’s function parameter $\Theta$, which determines the proximity effect corrections in a diffusive normal metal [13], one would expect a similar situation to occur for the superconducting proximity effect. Figure 1(c) shows a schematic of a diffusive quasiparticle trajectory in a normal metal wire with a normal contact on one end, and a superconducting contact on the other. An electron diffusing in the normal metal is Andreev reflected as a hole at point (1) on the NS interface. The hole picks up an additional phase factor corresponding to the macroscopic phase $\phi$ of the superconductor. This hole retraces the trajectory of the incident electron in the opposite direction, eventually intersecting the NS interface at point (2), where it in turn is Andreev reflected as an electron with the accumulation of an additional phase factor of $-\phi$. Since the AR process is phase-coherent, this second electron, which retraces the trajectory of the hole,
can interfere with the first electron. In the absence of a magnetic field, the additional phase shifts introduced by the two AR processes cancel. To simplify the theoretical analysis, the phase $\phi$ of the singly-connected superconducting contact is usually assumed to be a constant along the NS interface, even in the presence of a magnetic field. In addition, the normal contact is considered to be an ideal ‘reservoir,’ in that $\Theta$ vanishes. This is equivalent to a quasiparticle immediately losing phase memory on entering the normal contact.

Let us assume for the moment that the relevant phase coherence length $L_p$ in the proximity coupled metal is longer than the length $L$ of the wire. If the normal contact is an ideal reservoir, and the superconducting contact has a uniform phase $\phi$, then the expected field scale is given by $B_c \sim \Phi_0/(LW)$. Applying this to the $L = 1.5$ $\mu$m wire whose MR is shown in Fig. 3, we obtain an expected field scale of $B_c \sim 120$ G, more than a factor of 10 larger than the experimentally observed field scale. This implies that the area of some of the trajectories contributing to the MR are not restricted to the proximity wire alone, but encompass a much larger area. For example, if we now relax the assumption that the normal contact is a phase-randomizing reservoir, one can consider trajectories in which the quasiparticles diffuse coherently into the normal contact and return to the proximity wire, leading to nonlocal contributions to the MR of the wire. In fact, the measured $B_c$ corresponds roughly to a phase coherent area comparable to the area of the normal contact. In the absence of a theory which includes the effects of phase coherence in normal metal contacts, a more quantitative comparison to calculations based on the quasiclassical theory is difficult.

Further information about $L_p$ can be obtained by investigating $B_c(T)$ as a function of $T$ in the proximity wires. Figure 4(a) shows these data for the three proximity wires, as well as the superconducting contact by itself. (Experimentally, we define $B_c$ as the field at which the extrapolated low field quadratic behavior intersects the saturation value of the MR, as shown in Fig. 3). $B_c(T)$ reflects the temperature dependence of $L_p$, since $B_c \sim 1/L_pW$ in the 1D wire and $\sim 1/L_p^2$ in the normal contact (2D case), when $L_p$ is shorter than the contact dimensions. At low temperatures $B_c$ for all three wires is essentially constant. At higher temperatures, $B_c$ decreases as $T$ increases, indicating that $L_p$ increases as $T$ increases. Figure 4(b) shows the temperature dependence of $L_p$ obtained from WL measurements on the Au control wire, along with the calculated dependence of $L_T \sim \sqrt{1/T}$. Both lengths decrease as a function of temperature, exactly opposite to the expected temperature dependence of $L_p$. Some understanding of this dependence of $B_c(T)$ for the proximity wires can be obtained by examining $B_{cS}(T)$ for the superconducting contact, shown in Fig. 4(a). $B_{cS}(T)$ for a 2D superconductor is determined by the superconducting phase coherence length $\xi_s(T)$, i.e., $B_{cS} \sim \Phi_0/\xi_s^2(T)$. The difference for a superconductor, however, is that $\xi_s(T)$ increases as $T \to T_c$, so $B_{cS}$ decreases, as observed experimentally. This suggests that $\xi_s(T)$ also plays a role in determining the interference in the proximity coupled normal metal.

Drawing on this information, one can come up with a physical picture for the MR of the proximity wire. In our discussion above, we assumed that the phase of the superconducting contact was constant at all points on the NS interface, even in the presence of a magnetic field. In reality, however, one should take into account the AB phase that can be accumulated along the paths in the superconductor. Figure 1(c) shows an example of one such path. The AB phase accumulated along the path will result in an additional contribution to the phase of the interfering quasiparticles corresponding to the magnetic flux enclosed by the superconducting path, the same physics that gives rise to MR oscillations in Andreev interferometers. This means that $B_c$ is now determined by the area of the largest phase coherent trajectory which encompasses both the normal metal and the superconductor, i.e., a dependence given by something of the form $B_c(\xi_s, L_p) \sim \Phi_0/(\xi_s(T)^2 + A_{L_p})$, where $A_{L_p} = L_p^2$ if $L_p \gg L$, and $A_{L_p} = L_pW$ if $L_p \leq L$. At low temperatures, $L_p \gg \xi_s$, since $B_{cS} \gg B_c$. (This is also in agreement with the fact that $\xi_s(0)$ for Al is about 190 nm.) Hence $B_c$ is determined primarily by $L_p$ at low temperatures. Near $T_c$, however, $\xi_s(T)$ diverges and can be much longer than $L_p$, so that $B_c$ is determined essentially by $\xi_s(T)$. Consequently, $B_c$ for the proximity wires is much smaller than $B_{cS}$ at low temperatures, but the field scales merge near $T_c$.

What determines $L_p$, the coherence length in the normal metal? This question can be answered by plotting $B_c(\xi_s, L_p)$, with $L_p$ replaced by $L_T$ or $L_\phi$. In order to compare $B_c(\xi_s, L_p)$ to our experimental results, we rewrite this function in the form $B_c(\xi_s, L_p) = (1/L_{cS} + A_{L_p}/\Phi_0)^{-1}$. Since $L_\phi \gg L$ at all temperatures while $L_T \leq L$ above 100 mK, we take $A_{L_p} = L_p^2$ and $A_{L_T} = L_TW$. Figure 4(a) shows the resulting curves, along with the measured $B_c$. While $B_c(\xi_s, L_T)$ closely follows the experimental curve, $B_c(\xi_s, L_T)$ is nonmonotonic, showing a maximum of $\approx 50$ G at a temperature of 300 mK. This clearly shows that $L_\phi$ is the relevant length scale for interference in the normal metal, not $L_T$.

In conclusion, our results show the relevant length scale that determines Aharonov-Bohm type interference in proximity coupled normal metals is the electron phase coherence length $L_\phi$. A detailed quantitative analysis of the MR needs to take into account the contributions of nonlocal phase coherent transport in both the superconducting and normal contacts of a proximity effect device.

This work was supported by the NSF through DMR-9801982, and by the David and Lucile Packard Foundation.
FIG. 1. (a) Scanning electron micrograph of sample: the light areas are normal metal (Au) and the dark rectangular is superconductor (Al). (b) Schematic of one of the wires with current (I) and voltage (V) probes. (c) Schematic representation of Andreev reflection and a quasiparticle trajectory in vicinity of the NS interface. See text for details.

FIG. 2. Resistance versus magnetic field for the 1.5 µm long proximity wire at 37 mK. Vertical solid lines indicate the points of MR jumps from one branch to another. The three dashed curves are quadratic fits to the low field behavior.

FIG. 3. Resistance versus magnetic field for the 1.5 µm wire and superconducting film at \( T = 35 \) mK (curves 1) and \( T = 1.06 \) K (curves 2). Left axis: 1.5 µm wire, open symbols; right axis: superconducting film, solid line. Probe configuration for proximity wire: current \( I_1-I_3, V_1-V_2 \); for superconductor: current \( I_3-I_4, V_3-V_4 \). The values of the characteristic fields \( B_c \) and \( B_{cS} \) are shown.

FIG. 4. (a) Temperature dependences of \( B_{cS} (\circ) \) and \( B_c \) for the 1.5 (\( \circ \)), 1.2 (\( \triangle \)) and 1.0 (\( \square \)) µm long wires. Calculated \( B_c (T) \) for \( L_p = L_T \) (dashed curve) and \( L_p = L_\phi \) (dotted curve), as described in the text. The solid line is a guide to the eye. (b) Measured temperature dependence of \( L_\phi \), and calculated dependence of \( L_T \). The temperature dependence of \( \xi_S \) near \( T_c \) is also shown.
