Mesoscopic Ferromagnet/Superconductor Junctions and the Proximity Effect

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We have measured the electrical transport of submicron ferrimagnets (Ni) in contact with a mesoscopic superconductor (Al) for a range of interface resistances. In the geometry measured, the interface and the ferromagnet are measured separately. The ferromagnet itself shows no appreciable superconducting proximity effect, but the ferromagnet/superconductor interface exhibits strong temperature, field and current bias dependences. These effects are dependent on the local magnetic field distribution near the interface arising from the ferromagnet. We find that the temperature dependences may be fit to a modified version of the Blonder-Tinkham-Klapwijk theory for normal-superconductor transport.

There has been much interest recently about the possibility of observing the superconducting proximity effect in a ferromagnetic metal \[l_{ex}\]. In general, one does not expect to see the proximity effect in a ferromagnet due to the large internal exchange field which is expected to destroy superconducting correlations in the ferromagnet at distances greater than the exchange length \(l_{ex}\) (typically a few nanometers for the transition metal ferromagnets). This point of view has been reinforced by many experiments on ferromagnet/superconductor (FS) multilayers, where it was found that two superconducting layers are effectively decoupled if the thickness of the ferromagnet between them is much greater than \(l_{ex}\).

More recently, attention has focused on mesoscopic FS structures, where experimental results seem to indicate that superconducting correlations can penetrate into the ferromagnet at distances much greater than \(l_{ex}\). Giroud et al. [6] measured the temperature dependent resistance of mesoscopic Co rings in contact with a superconducting Al film, and found a small but significant temperature and bias dependent differential resistance, reminiscent of the reentrant proximity effect observed in normal metal/superconductor (NS) structures. Petrashov et al. [7] measured Ni wires in contact with Al films, and observed an anomalously large change in the resistance of the devices below the transition temperature of the superconductor. This change was also reflected in the differential resistance of the devices as a function of dc current below the superconducting transition.

In this Letter, we present results of our measurements of the resistance of mesoscopic Ni/Al structures as a function of temperature, dc current and magnetic field. In contrast to previous experiments, the devices have multiple non-magnetic Au probes which allow us to separately probe the resistance of different regions of the sample. In agreement with previous experiments, we find large changes in resistance below the superconducting transition of the Al. However, the multiprobe nature of our devices allows us to determine that the primary contribution to this resistance change in our samples arises from the FS interface itself, with essentially no contribution from the ferromagnet, indicating the absence of long range superconducting correlations in the ferromagnet. In addition, we find that the interface resistances of our devices are sensitive to the magnetic state of the ferromagnetic particle. The resistance of the interface can be reasonably well described by the model of Blonder, Tinkham and Klapwijk (BTK) [8], taking into account the effects of partial spin polarization of the conduction electrons in the ferromagnet.

Our samples are fabricated in three separate e-beam lithography steps with the metals deposited by e-gun deposition. Seven different samples were measured, but we present here results on only a few representative samples. Figures 1(a) and (b) show a scanning electron micrograph of one of our samples along with a sample schematic. The majority of our devices consist of an elliptical Ni particle in contact with a superconducting Al film [11]. To ensure predictable magnetic behavior, the Ni elements are patterned and deposited first so that they lay flat on the substrate, and the elliptical shape of the Ni particles ensures that the magnetic shape anisotropy aligns the magnetization of the particle in-plane along the major...
The thickness of the Ni films is approximately 2 Ω, which corresponds to the resistance of the Ni particle itself. The temperature dependence of $R_3$ is reminiscent of the reentrant proximity effect seen in normal metal mesoscopic structures in contact with superconductors [14], and if one had access to these data alone, one might conclude that the ferromagnet exhibits a strong superconducting proximity effect. However, a similar resistance change is not seen in the Ni particle by itself (Fig. 2(b)), indicating that the resistance change arises in the region of the sample between the voltage probes of configuration “2”, i.e., the FS interface. Similar behavior is also observed in our other samples with barrier resistances ranging from 19 Ω to 1.3 MΩ. We therefore conclude that no long range superconducting coherence effects are present in the ferromagnet.

We believe that the peak in the resistance observed near the superconducting transition in Fig. 2(a) is associated with charge imbalance effects in the Al films. This can be seen by comparing the data for low and high interface resistance samples. Figure 3(a) shows the resistance normalized to the normal state value ($r_2 = R_2/R_{2,n}$) of four samples with interface resistances ranging from $\sim 23.8$ Ω to 1.4 MΩ as a function of temperature in zero applied magnetic field. The peak in resistance observed in the low interface resistance sample disappears as the resistance of the interface increases. Below the resistance peak, the data can be reasonably well described by the BTK theory with suitable modifications to account for spin polarization as we describe below.
The normalized conductance of an NS point contact in the BTK model is:

\[ g(Z,T) = (1 + Z^2) \int_{-\infty}^{+\infty} \left( -\frac{\partial f_0}{\partial E} \right) [1 + A(E) - B(E)] dE, \]

where \( f_0 \) is the Fermi function, and \( A(E) \) and \( B(E) \) are the BTK parameters which describe Andreev and normal reflection processes respectively. \( A(E) \) and \( B(E) \) depend on the gap in the superconductor \( \Delta \) and the BTK parameter \( Z \) which parameterizes the strength of the interface. In the case when the normal metal is a ferromagnet (FS transport), the spin-polarization \( P = \frac{\langle N_{\uparrow}(E_F) \rangle - \langle N_{\downarrow}(E_F) \rangle}{\langle N_{\uparrow}(E_F) \rangle + \langle N_{\downarrow}(E_F) \rangle} \) of the electrons in the ferromagnet must be considered. Since Andreev reflection processes can only occur between pairs of spin-up and spin-down electrons, the fraction of the electrons that can participate in such a process is \((1 - P)\) of the total population. To account for this in the BTK model, one may replace the factor \( A(E) \) in equation (1) with \( A'(E) = (1 - P)A(E) \). This substitution was performed by Soulen et al. to determine the polarization of various ferromagnetic metals using point contact spectroscopy in clean contacts. Using this same substitution, one may fit the temperature dependence for arbitrary values of \( Z \) and \( P \).

The dotted traces in Fig. 3(b)–(e) show numerical fits of our data (solid traces) to the normalized resistance (or conductance) predicted by the modified BTK theory for different values of \( Z \), \( P \). In our model we also allow for magnetic flux penetration into the superconductor from the field generated by the ferromagnet near the interface. This necessitates another free parameter in the fitting routine since it is difficult to predict the exact flux penetration profile near the interface. We found that fixing \( P \) at zero nearly always gave inferior fits to those performed with \( P \) as a free parameter. For the traces shown in Fig. 3(b)–(d), the \( Z \) values were all similar \((0.38 < Z < 0.50)\), while the best fits where found with \( 0.21 < P < 0.30 \), in rough agreement with the value, \( P_{Ni} \sim 0.23 \) found by FS tunnelling spectroscopy. Our highest resistance sample (Fig. 3(e)) fit with a higher value of \( Z = 2.1 \), while also yielding a polarization \( P = 0.28 \). We also observe evidence for a finite spin polarization in the differential resistance as a function of dc current, although these data are not discussed here.

In contrast to previous FS experiments, in many of our devices two or more distinct states were seen in the temperature dependence of the interface (see Fig. 3(a)); the samples frequently showed switching between these states while the sample temperature was swept. These multiple states were also seen in the magnetic field dependence of the interface at fixed temperature. Figure 3(b) shows a number of magnetoresistance (MR) traces for both the interface \( R_2 \) and the overlapping Al \( (R_{Al}) \), with field sweeps in both positive and negative directions. There is a strong low-field dependence with sharp jumps at \(+350 \text{ G} \) and \(-300 \text{ G} \). A MR trace of the Ni ellipse by itself shows standard AMR behavior (see Ref. 12) with sharp jumps at exactly the same fields (see Fig. 3(c)). Since these jumps are due to the switching of the magnetization from positive to negative orientation (and vice versa), it is clear that the interface resistance, \( R_2 \), is sensitive to the local field generated by the ferromagnet itself. Even with no applied field, the ferromagnet may generate a substantial amount of flux and should never be assumed to vanish, especially in this geometry. Furthermore, the absence of multiple states in the Ni MR (for positive or negative magnetization orientation) suggests that the states seen in the temperature and field dependences of the interface are due to multiple magnetic screening states in the superconductor itself.
form at which the field penetration in the superconductor is uni-

mately to establish as uniform a field distribution as perconductive coherence length. Although we have at-

current may not be homogeneous with respect to the su-

terface. This is further complicated by the fact that such

field generated by the ferromagnet very close to the in-

ence, a complete theory of FS transport will need to include the nonequilibrium superconductivity, spin-accumulation in both F and S, and spin-

splitting of $N_s$.

In summary, our results are in agreement with recent

oretical work which suggest that a proximity effect within the ferromagnet is negligible, while the main con-

tribution to the resistance change is due to the interface. However, the effects of finite field and charge-imbalance may be important in constructing a comprehensive the-

ory of FS transport in mesoscopic structures.

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FIG. 4. (a) Multiple states in the temperature dependence

of the 556 $\Omega$ interface resistance sample; MRs (at $T =$300

K): (b) interface resistance, $R_2$, showing multiple states(left

axis, solid trace), overlapping Al wire, $R_M$ (right axis, dashed

trace). (c) Ni ellipse, $R_1$ (arrows indicate sweep direction).

Although we have restricted the above analysis to a

modified BTK model, recent work by Golubov [16] has

modified the BTK model to account for charge-imbalance and diffusive interfaces, while Belzig et al. [7] have anal-
yzed dirty and diffusive FS interfaces within the fram-

work of nonequilibrium Green’s function theory. While

ese approaches are certainly more sophisticated than our simple approach, qualitatively they predict behavior similar to our experimental results for the temperature
dependence. However, to our knowledge there is no avail-
able published work which includes charge-imbalance, spin-accumulation, and the effect of field penetration into the superconductor. In addition to these effects, a complete

tory should include effects of spin-splitting in $N_s(E)$, since even at zero applied magnetic field, the superconductor may be subjected to a substantial magnetic field generated by the ferromagnet very close to the in-

terface. This is further complicated by the fact that such a field may not be homogeneous with respect to the superconductor coherence length. Although we have at-

tempted to establish as uniform a field distribution as possible (by carefully selecting an elliptical geometry), ultimately it is very difficult to construct a device in

which the field penetration in the superconductor is uniform at $H_{\text{applied}} \ll H_c$. Furthermore, at finite voltage or current bias it is possible that the charge-imbalance is strongly modified by the spin-polarized quasiparticle cur-

rent that is generated at the interface. Since these quasi-

particle excitations are expected to decay into Cooper

pairs, matching spin-up and spin-down electrons equally, the spin-imbalance may prolong the quasiparticle decay time $\tau_{Qs}$ substantially if the spin-scattering lifetime $\tau_s$ is much larger. In essence, a complete theory of FS trans-

port will need to include the nonequilibrium superconductivity, spin-accumulation in both F and S, and spin-

splitting of $N_s$.

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