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Proximity effects in superconductor–ferromagnet junctions

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Abstract. We have studied electron transport in Sn–Ni–Sn structures, in which the Ni had the form of a narrow (∼400 Å wide) wire. The behaviour is very sensitive to the quality of the Ni–Sn interface. With a clean interface, there appears to be a significant proximity effect in the Ni, and the results imply an unexpectedly long proximity length. However, when an oxide layer is present at the Sn–Ni interface, the effective resistance of the Ni *increases* as the temperature is reduced below the critical temperature, T_c, of the Sn. It does not appear that these observations can be explained by current theories.

Over the past few decades there have been a very large number of studies of electrical conduction through superconducting thin-film structures. One's general impression might well be that this is a mature field, in which the central issues are understood from both experimental and theoretical viewpoints. Even so, recent interest in mesoscopic physics has led to a number of new studies of superconductivity in such systems [1], and in many cases the results have been unexpected. In this paper we describe some experiments involving transport through narrow Ni wires, to which contact is made using superconducting leads composed of Sn. Our results suggest that when the Ni–Sn interface is clean, a substantial, and strongly temperature-dependent proximity effect is observed. When an oxide layer is allowed to form at the Ni–Sn interface, so that electrons are injected/removed via tunnelling, this proximity effect is suppressed, and the resistance of the Ni is found to *increase* as the temperature is reduced. It does not appear that either of these results can be explained by current theories [2].

The sample geometry is sketched in the inset to figure 1(a). A thin Ni wire was first prepared on a glass substrate using a step-edge technique [3]. This method produces very narrow strips whose cross-sections are approximately triangular. For convenience we will characterize the widths of these strips by $\sqrt{A}$, where A is the cross-sectional area. Typical values of $\sqrt{A}$ were 300–1000 Å. The Ni was thermally evaporated, and had a low-temperature resistivity of $\sim 10\ \mu\Omega$ cm, which corresponds to an elastic mean free path of ∼80 Å. After preparation of the Ni wire, subsequent optical lithography and lift-off was used to form Sn contact pads. These pads were made triangular in shape, as indicated in figure 1(a), to improve the lift-off yield. The Sn was sputtered, with a thickness of 1000 Å, and had a low-temperature, normal-state sheet resistance of typically $\sim 2\ \Omega$. While the Ni wires were initially 10–1000 μm long, the effective length of the Ni, for the purposes of the conductance, was determined by the separation of the Sn pads. This separation ranged from 1–50 μm.

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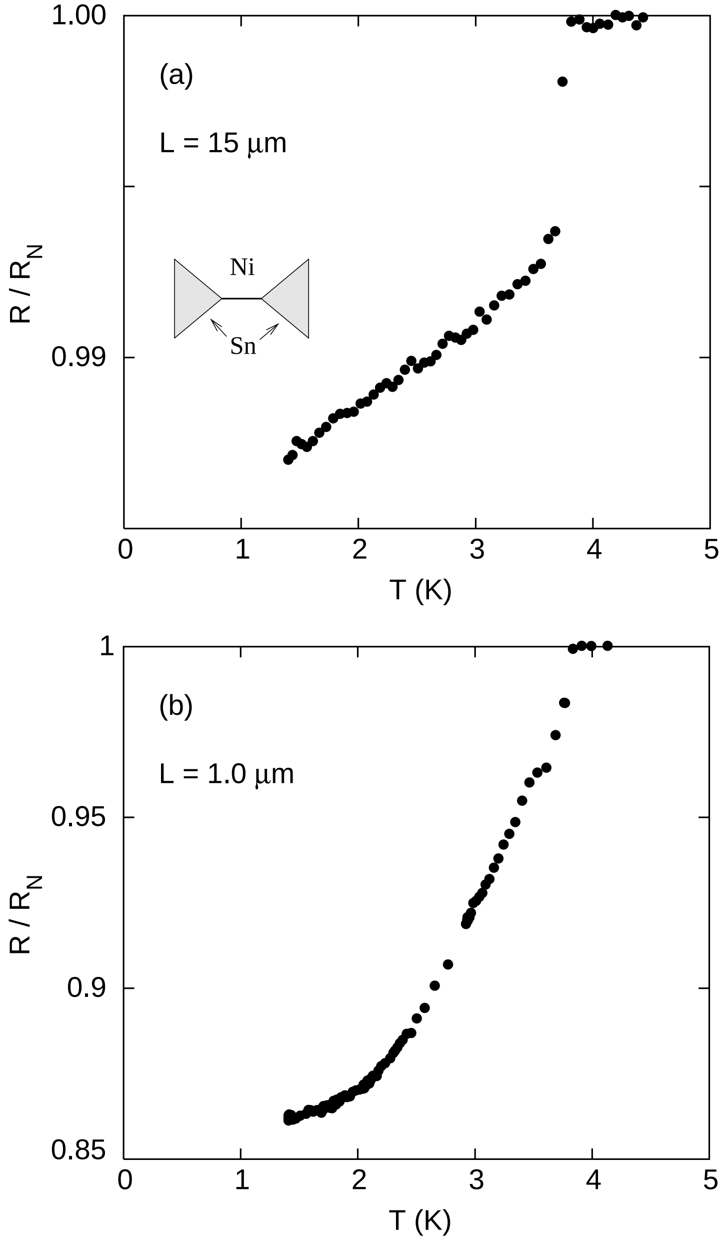

Figure 1. R/R_N as a function of temperature for samples in which the Ni–Sn interfaces were clean. In (a) the Ni strip was 15 μm long with $A = (600\ \text{Å})^2$ and $R_N = 610\ \Omega$, while in (b) it was 1.0 μm long with $A = (900\ \text{Å})^2$, and $R_N = 180\ \Omega$. The inset in (a) shows the sample geometry.

Since the Ni wires were prepared first, the surface of the Ni was exposed to solvents and other possible contamination in several of the subsequent fabrication steps. This led to a significant contamination layer, presumably an oxide, on the Ni surface, which was apparent from its contribution to the resistance. This contribution (which was found to be ohmic) was typically 100 Ω, which was comparable to the Ni resistance for a sample several μm long.

As we will see below, these samples exhibit behaviour which is quite different from that of samples in which this oxide layer is removed, by ion milling, just prior to the deposition of the Sn. Samples in which the oxide was removed in this way had a total resistance whose value was consistent with the measured resistivity and dimensions of the Ni wire.

A standard dc method was used, with separate current and voltage leads attached to each Sn pad; hence the pads contributed to the overall resistance. We measured R as a function of both temperature and magnetic field, although in this paper we will focus only on the behaviour as a function of T.

Figure 1 shows the behaviour of two samples in which the Ni–Sn interfaces were clean; i.e., the Ni surface was cleaned just prior to depositing the Sn. In both measurements the resistive transition of the Sn pads at $T_c \sim 3.7$ K is clearly visible, while at lower temperatures there are long 'tails.' That is, the resistance is temperature dependent, and decreasing, over a broad range of T below the T_c of the Sn. Such tails were not found in codeposited Sn films. Moreover,the magnitude of this resistance change is too large to be caused by the Sn; the Sn contact films simply do not have enough resistance to produce a change of this magnitude in the overall resistance of the structure. This means that the resistance change here must be taking place in the Ni. The resistance of a Ni wire with normal-metal leads is (on this scale) independent of T in this range [6]. Hence, the decrease of R as T is lowered in figure 1 would appear to be due to a proximity effect in the Ni. Such behaviour seems qualitatively reasonable; we will consider it quantitatively below.

While the samples considered in figure 1 both exhibit a proximity effect reduction of R below the T_c of the Sn, there is an important difference between the two results. In the shorter sample, figure 1(b), R begins to flatten off at the lowest temperatures, while this is not observed in the longer sample. This suggests that in the shorter sample there is a coherent coupling across the entire length of the Ni.

The behaviour of samples in which an oxide is present at the Ni–Sn interface is shown in figure 2. The superconducting transition of the Sn pads is again evident at $T_c \sim 3.7$ K, and the resistance again begins to develop a tail immediately below T_c. However, this tail appears to be pre-empted by another effect, as the resistance well below T_c increases as the temperature is reduced.

The results in figure 2 were obtained at measuring currents sufficiently low that the behaviour of R was independent of the current. It is interesting to consider also the behaviour at different currents, as shown in figure 3, which shows results for the 9.0 μm long sample from figure 2 at several different currents. We see that at measuring currents below 1 μA, the behaviour is independent of the current. However, at larger currents R is independent of T at the lowest temperatures, as Joule heating becomes important. From much previous work on metal strips with similar dimensions, we know that this current density is of the correct size to cause Joule heating in such a narrow Ni wire. Moreover, it is far too small to give any Joule heating (or to exceed the critical current) in the Sn pads, or to produce significant Joule heating in the oxide layer at the Sn–Ni interface (since this layer is thermally very well connected to a thick Sn film). These results thus demonstrate that the increase in R at the lowest temperatures is occurring in the Ni, and not in the Sn pads.

Let us now consider these results somewhat more quantitatively, beginning with the behaviour of the samples with clean Ni–Sn interfaces, figure 1. We have already argued that the decrease in R below the T_c of the Sn pads is due to a proximity effect in the Ni. Let us assume, for simplicity, that a length L_{prox} of the Ni wire becomes superconducting (i.e., has a vanishing resistance) due to proximity coupling with the Sn. We can then estimate L_{prox} from the change in R starting from just below T_c, since it is the growth of L_{prox} as T is lowered which causes the resistance to decrease. If we make the rather drastic assumption

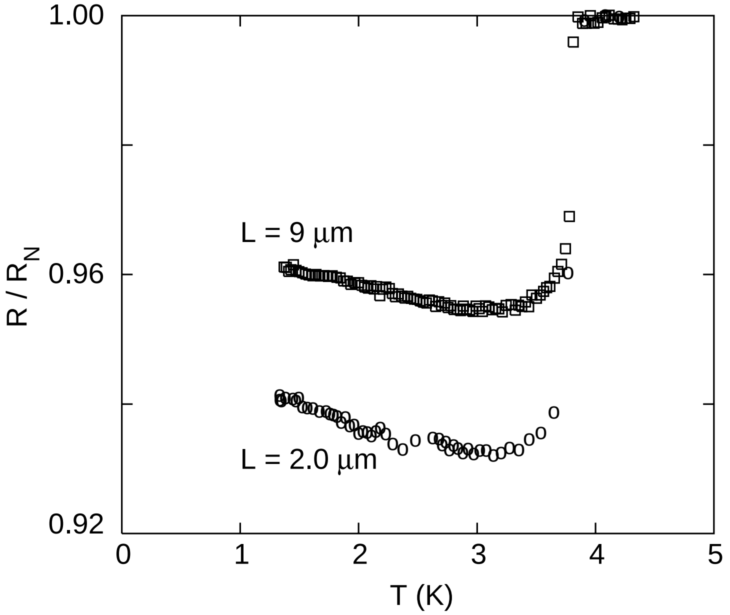

Figure 2. R/R_N as a function of temperature for two samples in which there was an oxide layer at the Ni–Sn interface. The lengths of each of the Ni wires are given in the figure. In both samples the Ni had $A \approx (400\ \text{Å})^2$. Note that for these samples R_N includes the resistances of the oxide layers at the two Ni–Sn interfaces.

that $L_{prox} = 0$ at the completion of the Sn transition at 3.7 K, we find $L_{prox} \approx 500$ Å at 1.5 K for the 15 μm sample in figure 1, and $L_{prox} \approx 460$ Å at the same temperature for the 1.0 μm sample. Our assumption that $L_{prox} = 0$ at the completion of the Sn transition most probably underestimates L_{prox} at this point; these values of the proximity must be regarded as lower limits on its value. As far as we know, there is no microscopic theory for the proximity effect in a ferromagnet. It is often quoted (or suggested) [4, 5] that the proximity length for a ferromagnet should be $L_{\text{theory}} = \sqrt{D\hbar/k_b T_{\text{Curie}}}$, where D is the diffusion constant for the ferromagnet, and T_{Curie} is the Curie temperature of the ferromagnet. For our case this yields $L_{\text{theory}} = 40$ Å. Not only is this is an order of magnitude smaller than our estimate of L_{prox}, but this 'theoretical' prediction is also independent of temperature, which is clearly not the case for our L_{prox}. Our result is thus in conflict with this expression for L_{theory}, and emphasizes the need for a careful microscopic theory of the proximity effect in a ferromagnet. The apparent coherent coupling across the entire length of the Ni wire is also surprising in view of the values that we have inferred for L_{prox}. However, these values are, at best, lower limits; it also seems quite possible that our assumption that the resistance of the Ni is precisely zero within a proximity length of the Sn is too simple. If the resistance in this region were reduced, but not to zero, the derived value of L_{prox} would be longer. It is interesting to note that the thermal length $L_T = \sqrt{D\hbar/k_B T}$, which plays a role in many phase-coherent effects [7], has a value close to L_{prox} (the two agree to within a factor of 2 or better, given the uncertainties in D). It seems possible, at least intuitively, that L_T may control the proximity effect in our structures.

Let us now consider the behaviour found with an oxide layer at the Ni–Sn interface, figure 2. The increase in R at low temperatures occurs in rather long samples, so it does not appear to be due to coherent coupling across the Ni. This increase in R is reminiscent of the

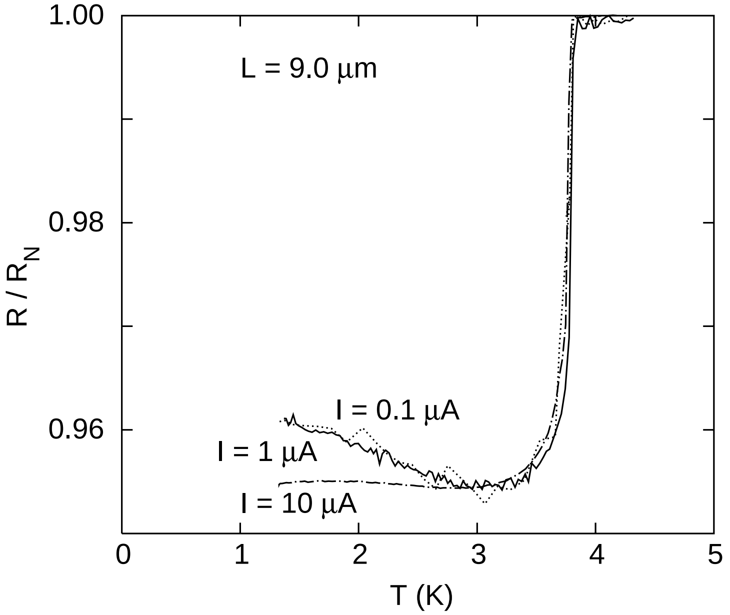

Figure 3. R/R_N as a function of temperature for the 9 μm sample from figure 2, at several different sample currents.

re-entrant proximity behaviour predicted and observed in mesoscopic superconductor–normal-metal structures [8]. However, it is not clear to us how such an effect would be modified in a ferromagnet. Moreover, we would expect the oxide layer at the interface to suppress any proximity effect in our case.

In summary, we have observed unexpected proximity-like effects in Sn–Ni–Sn structures. When the Ni–Sn interfaces are clean, the inferred proximity lengths are much longer and more strongly temperature dependent than expected from previous work. When an oxide layer is allowed to form at this interface, there is re-entrant behaviour, with the resistance of the Ni increasing at the lowest temperatures. It appears that the proximity behaviour of superconductor–ferromagnet interfaces is much richer than previously suspected.

Acknowledgments

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