Superconductor/ferromagnet boundary resistances

1990 J. Phys.: Condens. Matter 2 9701

(http://iopscience.iop.org/0953-8984/2/48/024)

J. Phys.: Condens. Matter **2** (1990) 9701–9706. Printed in the UK

LETTER TO THE EDITOR

Superconductor/ferromagnet boundary resistances

C Fierz, S-F Lee†, J Bass, W P Pratt Jr and P A Schroeder
Department of Physics, Michigan State University, East Lansing, MI 48824, USA

Received 27 September 1990

Abstract. Measurements of $2R_bA$, twice the boundary residual resistance times the cross-sectional area, for superconducting/ferromagnetic (S/F) boundaries in sputtered sandwiches yield values (in fΩ m^2) of (6.1 ± 0.3) for Nb/Co, (4.8 ± 0.6) for Nb/Ni and (12.4 ± 0.7) for NbTi/Co. These values are similar to those previously reported for superconducting/normal (S/N) boundaries in foil-based sandwiches, and smaller than predicted by the standard model.

Ever since the development of Josephson-effect-based detectors, such as the SQUID, made the measurement of very small resistances feasible, there has been interest [1–5] in the boundary resistances between superconductors (S) and normal metals (N). Residual and/or temperature dependent values of such resistances have been reported for a variety of sandwiches consisting of thin foils of *non*-magnetic metals such as Cu, Au, W, and $Cu_{0.97}Al_{0.03}$ between superconductors such as Pb, Al, In, Sn, Pb(Bi), and In(Pb) [1–4]. As described below, the residual boundary resistances were found to be smaller than predicted by the best available model.

It has recently become feasible to measure boundary resistances using sandwiches and multilayers with clean interfaces and controlled layer thicknesses prepared by molecular beam epitaxy or sputtering. In this letter, we report the first residual resistances for three different S/F boundaries in sputtered sandwiches. We undertook these measurements for two reasons. First, to see if the resistances would differ substantially from those found for S/N boundaries, because superconducting electron pairs do not penetrate far into a ferromagnet and the electrons at the Fermi surface of a ferromagnet are highly spin polarized [6]. Second, to be able to use S/F contacts for measuring the perpendicular resistances of multilayer samples of F/N metals, in which case, the S/F boundary resistance must be known to extract the F/N interface resistances.

We focus here upon comparing our values for Nb/Co, Nb/Ni, and NbTi/Co boundaries:

(i) with values previously reported for Pb(Bi)/Cu [1] and In(Pb)/W [4];
(ii) with an as yet unpublished value for Nb/Ni(Cr) [7]; and
(iii) with the best available model of R_bA for S/N boundaries, due to Pippard [5].

A more complete analysis will be given elsewhere [8].

† Present address: Kistler Instrumente AG, Winterthur, Switzerland.

0953-8984/90/489701 + 06 $03.50

If the conductance per unit area of a boundary between two metals is designated as $(1/r)$, then the total conductance, $(1/R_b)$, of an area A, is:

$$1/R_b = \sum_i \delta A_i(1/r) = A/r \tag{1}$$

The 'specific resistance' of the boundary is thus $r = R_bA$.

R_bA for a S/N or S/F boundary is determined by measuring the electrical resistance of an S/N/S or S/F/S sandwich with the current flowing perpendicular to the two boundaries. In our geometry, a 4 mm × 4 mm film of the F metal of thickness t is sandwiched between two longer, crossed, 1 mm wide and 500 nm thick S strips, one above and one below the F metal [9]. The 'effective' sample area, $A \approx 1$ mm^2, is the portion of the F metal film which is bounded by the crossed S strips, since this portion carries almost all of the current passing through the N metal. Because the S strips have zero resistance, the total resistance times area, RA, is related to R_bA by

$$RA = 2R_bA + \rho_0 t \tag{2}$$

with ρ_0 the bulk residual resistivity of the N metal. A plot of RA against t should thus yield a straight line with slope ρ_0 and ordinate intercept $2R_bA$.

In prior work [1–4], residual and temperature dependent (S/N) boundary resistivities were both analysed—mainly in terms of Pippard's model of partial quenching of Andreev reflection by impurities in the superconductor [5], which leads to the equation:

$$(2R_bA)_p = 2(l_a/2l_0)_S)(\rho_0 l_0)_N = (l_a\rho_S/(\rho_0 l_0)_S)(\rho_0 l_0)_N. \tag{3}$$

$l_a = (\pi/2)\xi_0$ is the extinction length in S of the electron evanescent wave from N, ξ_0 is the intrinsic coherence length in S, $\rho_0 l_0$ is the product of ρ_0 and the bulk mean free path l_0, and $\rho_S \approx (\rho_0)_S$ is the resistivity of S in its normal state just above T_c [5].

The second form of equation (3) shows that $(R_bA)_p$ should be proportional to ρ_S. In previous studies of foil-based S//N/S sandwiches, impurities were added to superconductors to test this predicted linear dependence of R_b on ρ_S. In one case [1], the data were compatible with a linear dependence up to at least 20×10^{-8} Ω m. In the other [4], the linear dependence extended only up to $\rho_S \approx 2 \times 10^{-8}$ Ω m, above which the data fluctuated widely about an apparent constant value. In both cases, the experimental values of R_bA in the linear regime were *smaller* than predicted by equation (3). Pippard [5] proposed the effects of Fermi surface mismatching between the S and N metals of the sandwich as a partial explanation for the discrepancy.

Our sandwiches were DC sputtered onto cleaned, c-axis oriented, sapphire substrates in an ultra-high-vacuum compatible system that is described elsewhere [9]. The substrates were cooled to just below room temperature during sputtering. To see if changes in the microscopic nature of the S/F boundary would change R_bA, in some cases, thin (10 nm) Ag interlayers were sputtered between the Nb and the sample.

The desired values of t for the F layers were obtained by sputtering for chosen times at calibrated deposition rates. The smallest values were about 9 nm and 50 nm, respectively, for Co and Ni. The uncertainties ranged from ±5% for $t > 100$ nm to ±10% for the thinnest layers [8]. The uncertainty in the cross-sectional area A was generally about 5%, but occasionally larger due to fuzzy edges of the Nb strips. X-ray measurements of the sandwiches revealed polycrystalline films with predominant peaks in the ⟨002⟩ or ⟨111⟩ directions, respectively, for Co and Ni.

To test for the linear dependence of R_bA on ρ_S predicted by equation (3), one set of Co samples was prepared with 200 nm thick superconducting layers composed of

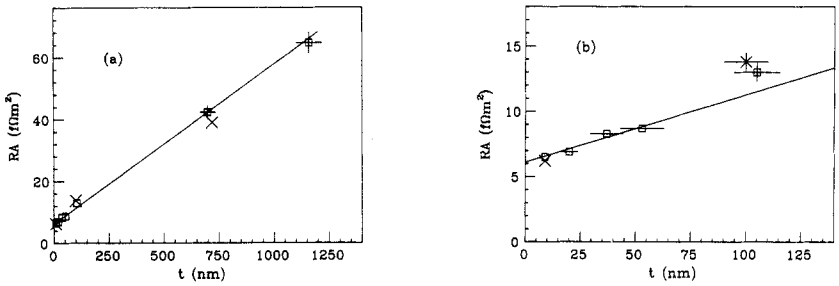

Figure 1. *RA* against sample thickness *t* for Nb/Co/Nb sandwiches: (a) All *t*; (b) expanded scale for $t < 20$ nm. The common straight line is the best least-squares fit to all of the data. The crosses (×) indicate samples with 10 nm Ag interlayers between the Nb and Co layers.

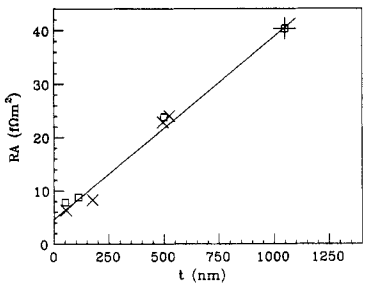

Figure 2. *RA* against sample thickness *t* for Nb/Ni/Nb sandwiches. The straight line is the best least-squares fit to the data. The crosses (×) indicate samples with 10 nm Ag interlayers between the Nb and Co layers.

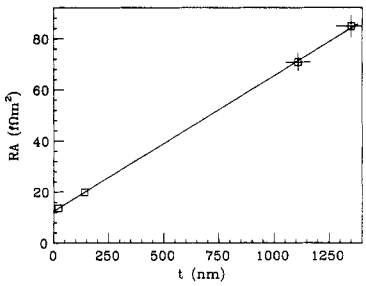

Figure 3. *RA* against sample thickness *t* for NbTi/Co/NbTi sandwiches. The straight line is the best least-squares fit to the data.

alternating 0.5 nm thick layers of Nb and Ti, instead of simply Nb. This procedure was expected to yield a random alloy, but x-ray measurements revealed evidence of residual layering.

Plots of $R(3K)A$ against t are given in figure 1 for Nb/Co/Nb, figure 2 for Nb/Ni/Nb, and figure 3 for NbTi/Co/NbTi. Since the temperature dependent resistances below 3K were only a few percent of the total resistances, $R(3K)$ is an appropriate measure of the residual resistance. The crosses (×) in several of the figures indicate data for samples with 10 nm buffer layers of Ag between the S and F layers; these buffer layers produce no systematic changes. The straight lines are least squares fits to each set of data. These lines intercept the ordinate axes at non-zero values, which represent our best estimates of the measured quantity $(2R_bA)_m$ for each of the sandwiches.

From equation (2), the slope of each line in figures 1–3 should yield ρ_0 for the central constituent of the corresponding sandwich. Table 1 shows that these values agree with independent estimates—designated $\rho_{0\|}$—from parallel resistivity measurements on sputtered single films of Co and Ni with $t = 500$ nm.

Table 1 contains our values for $(2R_bA)_m$ plus reported values from other studies [10] for the values of ρ_S indicated. The listed uncertainties for our data are standard deviations from the least squares fits. We also list our best estimates of the predictions for $(2R_bA)_p$

Table 1. $(R_bA)_m$, $(R_bA)_p$, ρ_0, $\rho_{0\parallel}$ and the parameters for the S/F/S and S/N/S sandwiches. The symbols are defined in the text.

	$(2R_bA)_m$ $10^{-15}\,\Omega\,m^2$	ρ_S $10^{-8}\,\Omega\,m$	$l_a = (\pi/2)\xi_0$ $10^{-8}\,m$	$(\rho_0 l_0)_S$ $10^{-15}\,\Omega\,m^2$	$(\rho_0 l_0)_N$ $10^{-15}\,\Omega\,m^2$	$(2R_bA)_P$ $10^{-15}\,\Omega\,m^2$	ρ_0 $10^{-8}\,\Omega\,m$	$\rho_{0\parallel}$ $10^{-8}\,\Omega\,m$
Co/Nb	6.1 ± 0.3	~6	6	0.37	0.7 → 2.3	7 → 22	5.2 ± 0.3	5.8 ± 0.6
Ni/Nb	4.8 ± 0.6	~6	6	0.37	0.7 → 2.3	7 → 22	3.5 ± 0.3	3.0 ± 0.3
Co/NbTi	12.4 ± 0.7	~57	6	0.37	0.7 → 2.3	65 → 210	5.3 ± 0.3	5.8 ± 0.6
NiCr/Nb [7]	15 ± 4	~6	6	0.37	0.7 → 2.3	7 → 22		
Cu/Pb(Bi) [1]	3.5†	~5	13	1.0	0.66	4.3		
W/In(Pb) [4]	7†	2	77	0.6 → 1.1	0.9 → 2.2	13 → 56		

† See [10] for comments.

from equation (3); a more detailed analysis of these estimates will be given elsewhere [8]. Our values of l_a for Nb, Pb, and In are from [11], and l_a for NbTi is taken to be the same as for Nb. The values (or ranges) of $(\rho_0 l_0)_S$ for Nb, Pb, and In, and $(\rho_0 l_0)_N$ for Cu and W, are from [12]; in each case, anomalous skin effect (ASE) measurements supplement direct thin-film determinations. For Ni and Co, no ASE data are available, and it is not obvious that for these metals $(\rho_0 l_0)_N$ can be reliably estimated from the standard equation involving simply the Fermi surface area [5]. The derivation of that equation requires l_0 to be constant over this area, an assumption likely to be strongly violated for the complex Fermi surfaces of Ni or Co. For Ni, with a Fermi surface consisting of sheets of 'light' s-electrons and 'heavy' s–d hybrids, the lower limit of $(\rho_0 l_0)_N$ listed in table 1 is estimated using the total Fermi surface area from [13]. The upper limit involves only the s-electron portion of this surface. Both values are much smaller than those listed in [12]; we believe that those of [12] are too large because of the increasing importance of grain boundary scattering as the test films become thinner. $(\rho_0 l_0)_N$ for NiCr is taken to be the same as for Ni. Due to our inability to find Fermi surface information for Co, its $(\rho_0 l_0)_N$ was chosen to be the same as for Ni.

To compare our data with equation (3), we measured ρ_S (10 K) directly on the Nb strips of sandwiches from different sputtering runs. Mostly, we found $\rho_S \approx 6 \times 10^{-8}\ \Omega$ m. However, values for samples from one particular Nb/Co/Nb run were $\approx 14 \times 10^{-8}\ \Omega$ m. In this letter, we omit the Nb/Co/Nb data for that run, and assume that $\rho_S = 6 \times 10^{-8}\ \Omega$ m for the remaining Nb strips. The omitted data were included in a preliminary publication on Nb/Co/Nb [14], and will be discussed separately elsewhere [8]. The value of $(2R_bA)_m$ for those data alone is $(8.3 \pm 0.5) \times 10^{-15}\ \Omega\ m^2$, much smaller than predicted by equation 3, from which a linear increase with ρ_S is expected.

From figures 1–3 and table 1 we see that:

(i) For each of our S/F/S sandwiches RA against t has the form of equation (2), and the ρ_0 obtained from the slope of the line agrees with $\rho_{0\|}$.

(ii) 10 nm Ag interlayers produce no systematic changes in RA.

(iii) For each sandwich, we obtain non-zero values of $(2R_bA)_m$, with values for the S/F interfaces similar in size to those for S/N interfaces having similar values of ρ_S [1, 4].

From comparisons of the data in table 1 with equation (3) we find that:

(i) Our values of $(2R_bA)_m$ for Nb/Co, Nb/Ni, and NbTi/Co boundaries are all smaller than predicted.

(ii) Our value of $(2R_bA)_m$ for Nb/Ni/Nb is only about $\frac{1}{3}$ that reported for Nb/CiCr/Nb sandwiches with similar values of ρ_S for Nb [7], whereas the two values are predicted to be the same.

(iii) Our value of $(2R_bA)_m$ for NbTi/Co/NbTi is only twice as large as that for Nb/Co/Nb, instead of the predicted ten times larger.

We conclude that our values of $(R_bA)_m$ for sputtered S/F sandwiches are similar in size to those published for foil-based S/N sandwiches, and that all but one of the published values for $(R_bA)_m$ are smaller than predicted by equation (3). The behaviour described in item (ii) immediately above is also incompatible with equation (3) which thus appears to require modifications or additions.

This work was supported in part by the US National Science Foundation under grant DMR-88-13287, and in part by the Swiss National Science Foundation. The authors thank S Renfrow for experimental assistance.

References

[1] Harding G L, Pippard A B and Tomlinson J R 1974 *Proc. Roy. Soc.* A **340** 1

[2] Hsiang T Y and Clarke J 1980 *Phys. Rev.* B **21** 945

[3] Battersby S J and Waldram J R 1984 *J. Phys. F: Met. Phys.* **14** L109

[4] Lean H W and Waldram J R 1989 *J. Phys.: Condens. Matter* **1** 1299; 1989 *J. Phys.: Condens. Matter* **1** 1285

[5] Pippard A B 1984 *Proc. Roy. Soc.* A **391** 255; 1981 *NATO Advanced Study Institute on Non-Equilibrium Superconductors* ed K Gray (New York: Plenum)

[6] van Son P C, van Kempen H and Wyder P 1987 *Phys. Rev. Lett.* **58** 2271; 1988 *Phys. Rev. Lett.* **60** 378 Johnson M and Silsbee R H 1988 *Phys. Rev. Lett.* **60** 377

[7] Schwarzbek S M and Ruggiero S T 1989 *Bull. Am. Phys. Soc.* **34** 1020 and to be published

[8] Fierz C, Lee S-F, Bass J, Pratt W P Jr and Schroeder P A to be published

[9] Slaughter J M, Pratt W P Jr and Schroeder P A 1989 *Rev. Sci. Inst.* **60** 127

[10] For the Cu/Pb(Bi) interface Pippard [5] has been followed in subtracting off the measured boundary resistance for a Cu/Pb sandwich. For high purity Pb, ρ_S is so small that the $(R_bA)_p$ predicted by equation (3) should be negligible, and Pippard argued that any residual boundary resistance due to 'dirt' at the interface should not be included in the comparison with equation (3). For the W/In(Pb) interface, the value measured on an In/W/In(Pb) sandwich has been doubled, since the boundary resistance predicted by equation (3) for the W/In interface is also negligible.

[11] Van Duzer T and Turner C W 1981 *Principles of Superconductive Devices and Circuits* (New York: Elsevier)

[12] Bass J 1982 *Landolt–Bornstein Tables* new series **15a** 1

[13] Wakoh S and Yamashita J 1964 *J. Phys. Soc. Japan* **19** 1342

[14] Fierz C, Lee S-F, Bass J, Pratt W P Jr and Schroeder P A 1990 *Proc. LT-19, Physica* B at press