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Asymmetric differential resistance of point contacts on normal-metal–superconductor bilayers

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Abstract. Point-contact junctions on normal-metal–superconductor bilayers show asymmetries of different magnitudes and signs in the differential resistance versus voltage curves for opposite-bias voltages. In the absence of Andreev reflection (i.e. for energies outside the energy gap) no asymmetry is found. The asymmetries are investigated with Ag, Cu, Pd, Pt, Ni, and Co as point-contact material on Ag–Pb bilayers. For all materials we provide the statistics of the asymmetries. We discuss effects that may be responsible for this new phenomenon.

1. Introduction

An electron that arrives at a normal-metal–superconductor (N–S) interface cannot enter the superconductor as a quasiparticle as long as its energy is within the energy gap. However, in combination with a second electron from the normal metal with opposite momentum and spin it may condense in a Cooper pair and be added to the superconducting condensate (Andreev reflection [1]). The hole (or missing electron) that is created in the normal metal travels away from the N–S interface along the same trajectory that was followed by the incident electron (retroreflection). A single point contact on an N–S bilayer provides a well defined geometry for the study of Andreev reflection because only Andreev-reflected holes arrive back at the point contact [2, 3]. In this way the effect of Andreev reflection and specular reflection at the N–S interface can be clearly separated (see figure 1). When the point contact is in the Sharvin regime [4] and a voltage V is applied to the junction, electrons are injected with energies between 0 and eV relative to the Fermi energy. The electrons can be used for spectroscopy [5] and the point contact can be regarded as an isotropic source. The voltage dependence of the differential resistance of the point contact $R(V)/R_S$ reflects the energy dependence of Andreev reflection $A(eV)$ and its simplest expression is

$$R(V)/R_S = 1/[1 + A(eV)] \tag{1}$$

with R_S the Sharvin resistance of the point contact in the absence of a superconductor. The energy dependence of A is well described by the model of Blonder, Tinkham, and Klapwijk (BTK) [6] for an N–S interface. The differential resistance of the point contact

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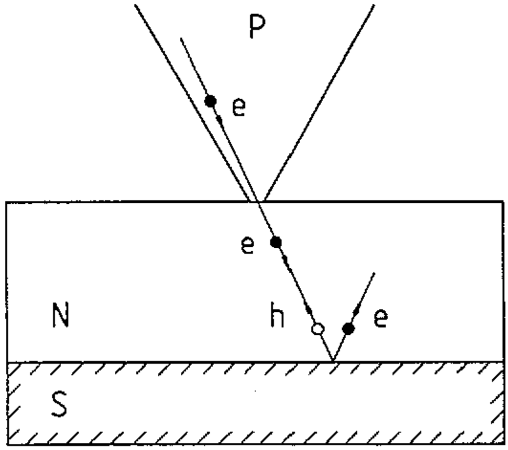

Figure 1. Experimental geometry with a single point contact P on an N–S bilayer. An injected electron (filled circle) is Andreev reflected as a hole (open circle) and detected with the same point contact. Electrons that reflect specularly at the N–S interface do not arrive at the point contact because the point-contact radius is always much smaller than the thickness of the normal metal layer.

drops (to maximally half the Sharvin resistance, see equation (1)) because the sign of the charge carriers is reversed after Andreev reflection. Figure 2 shows a set of calculated $R(V)/R_S$–V curves (based on the BTK model) for a point contact on an N–S bilayer.

The BTK model as well as a calculation that explicitly includes the dispersion of wave vectors in the normal metal and the superconductor [7] does not predict differences in the $R(V)/R_S$–V curves at opposite-bias voltages (asymmetries). The experimental data reported on N–S point contacts in the literature are in general either symmetric or show only the positive-voltage part of the curve. However, we regularly observe asymmetric $R(V)/R_S$–V curves. We will introduce the experimental data, give the statistics, and discuss this new effect.

2. Experimental results

The experimental data concerning differences in the $R(V)/R_S$–V curves for opposite-bias voltages can be summarized as follows. We have performed a large number of point-contact experiments on N–S bilayers using Ag, Cu (noble metals), Pd, Pt (d-band metals), Ni, and Co (ferromagnets) as point-contact material on Ag–Pb bilayers. For all types of point-contact material we have used high-purity wire with a sharp etched tip and we could establish metallic point contacts with resistances between 1 and 100 Ω (i.e. well within the Sharvin regime). The Ag–Pb bilayers were evaporated in a single run to ensure a high-quality N–S interface [3] (the thickness of the Ag layer was chosen to be 50, 100, or 200 nm; the thickness of the Pb layer was in all experiments 400 nm). All experiments were performed at a temperature of 1.2 K. The differential resistance of the point contact was measured as a function of the voltage using phase-sensitive detection (with modulation voltages of 0.1 or 0.2 meV).

We were able to observe differences in the $R(V)/R_S$–V curves at opposite-bias voltages with all types of point-contact material. The magnitude and sign of the asymmetry could

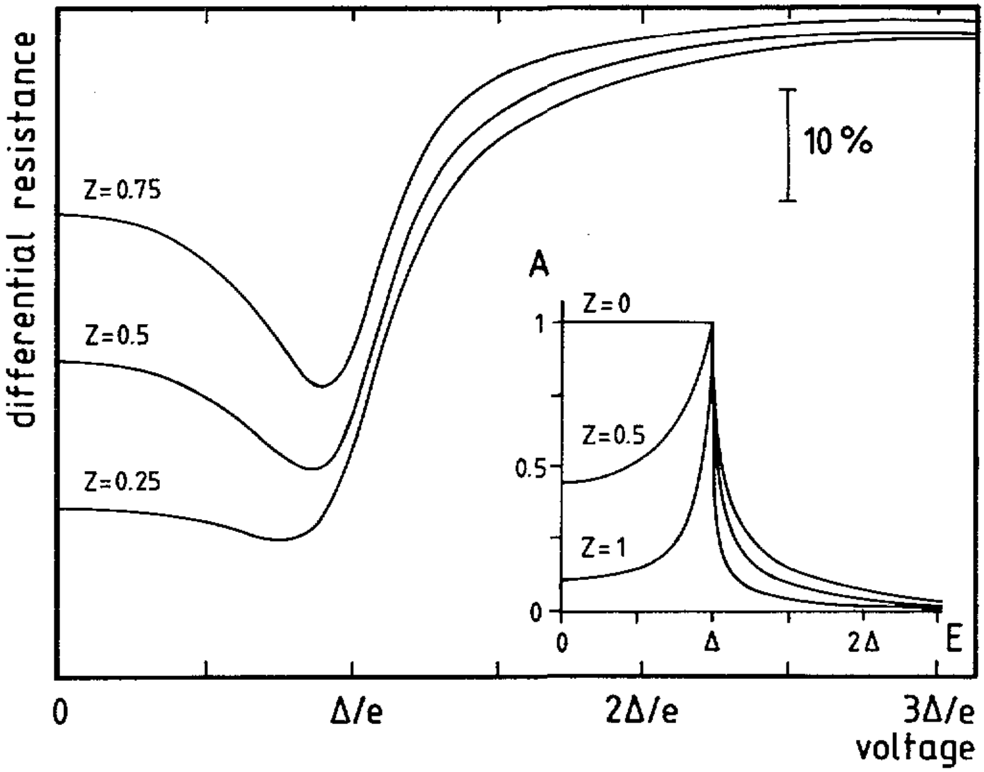

Figure 2. Calculated $R(V)/R_S$–V curves for three values of the scattering parameter Z at the N–S interface ($Z = 0.25, 0.50$ and 0.75). The curves include broadening due to thermal smearing and voltage modulation (calculations for $\Delta_{Pb} = 1.40$ meV, $T = 1.2$ K, and $V_{mod} = 0.1$ meV). The inset shows the energy dependence of the Andreev reflection probability A for $Z = 0, 0.5$, and 1.

change when the point-contact wire was lifted and placed again on the N–S bilayer in order to make a new point-contact junction. The experiments presented have been performed over a span of several years using different experimental and electronic set-ups, ruling out instrumental effects. Moreover, we have always used freshly prepared samples. We do not find a dependence between the magnitude of the asymmetry and the layer thickness. The only effect of increasing the layer thickness is a small change of $R(V)/R_S$ due to a larger scattering probability in the normal-metal layer. There exists no systematic dependence of the asymmetry on the point-contact resistance.

The asymmetry of the $R(V)/R_S$–V curves is most notable at energies where the probability of Andreev reflection is high, i.e. close to the gap edge ($|V| = \Delta/e$, with Δ the gap energy of the superconductor). For energies well above the energy gap (where the contribution of Andreev reflection is negligible) the asymmetry is absent and well known point-contact spectroscopy characteristics are measured [5]. The magnitude of the asymmetry ($R(+V)/R_S - R(-V)/R_S$) can be several per cent, which implies quite a large effect because $R(V)/R_S$ changes by 50% at most. In figure 3 we have plotted a set of representative examples of asymmetric $R(V)/R_S$–V curves (using a noble metal, a d-band metal, and a ferromagnet as point-contact material). Note that the voltage dependence of the measured curves is in good agreement with the result of the calculations shown in figure 2 (for each polarity of the applied voltage). The interfacial scattering Z in the experimental curves is about 0.5, as is expected for a clean N–S interface with scattering due only to wave-vector mismatch. The insets show the magnitude of the asymmetry as a function of the voltage for each of the curves. It is clear that the asymmetry is prominent when $|V| \leqslant \Delta/e$ and that the asymmetry vanishes for voltages that exceed Δ/e.

Figure 4 shows the distribution of the magnitude of the asymmetry $(R(\Delta/e)/R_S - R(-\Delta/e)/R_S)$ at the gap edge, as obtained from a large number of experimental data. As mentioned before, asymmetries occur for all types of point-contact material and figure 4 shows that the sign of the asymmetry is not unique, i.e. we measure $R(V)/R_S$–V curves with $R(+V)/R_S \geqslant R(-V)/R_S$ and with $R(+V)/R_S \leqslant R(-V)/R_S$. In the experiments we find that (for the same thickness of the normal metal layer) the maximal change of $R(V)/R_S$ for Ni and Co is smaller than for Ag, Cu, Pd, or Pt. As a result, asymmetries appear to be more prominent with ferromagnetic point-contact materials. The accuracy to which the magnitude of the asymmetry can be measured is of the order of 0.2% or better and determines the width of the interval in figure 4.

3. Discussion

First, we note that for energies that exceed the gap energy of the superconductor no asymmetry is found. This regime, where Andreev reflection is absent, is also studied in conventional point-contact spectroscopy and the curves presented here are consistent with the results obtained there. Moreover we remark that, even if one goes beyond the original BTK calculation and takes the dispersion of the wave vectors at the N–S interface into account, the probability of Andreev reflection is equal for opposite-bias voltages $(A(-eV) = A(+eV))$ [7] so the Andreev reflection process itself cannot be responsible for the asymmetries.

Second, we consider the role of the point-contact–normal-metal (P–N) interface. Since the magnitude and sign of the asymmetry change from contact to contact the cause of the asymmetries may originate at the P–N interface. For example, due to deformation caused by making the point contact, the bandstructure at the point-contact interface may change. Consequently the coupling of the wave functions on either side of the interface changes and results in a different transmission probability for subsequent contacts. This argument can also be used in the case that the point contact is made at a different spot of the (polycrystalline) normal-metal layer, which has a different crystallographic orientation. The experiments show, however, that Andreev reflection is an essential factor because asymmetries are only observed when Andreev reflection is present. An explanation solely in terms of a transmission coefficient at the P–N interface is therefore ruled out. It cannot give rise to large asymmetries within the energy gap and to negligible asymmetries outside the energy gap at the same time (this also remains valid if the dispersion of the wave vectors at the P–N interface is taken into account [7]).

An effect that combines Andreev reflection and specular reflection at the P–N interface is the interference of an electron with itself. Then, an electron is injected and Andreev reflected as a hole. Next the hole is specularly reflected at the P–N interface where it will arrive, after a second Andreev process, as an electron again and interferes with itself (geometrical resonances [8]). The phase difference between the initial electron and the returning electron is twice the phase difference between the initial electron and the Andreev-reflected hole (because the electron and hole are at a slightly different energy their wavelengths are different and a phase difference results). Despite the fact that this phase difference is

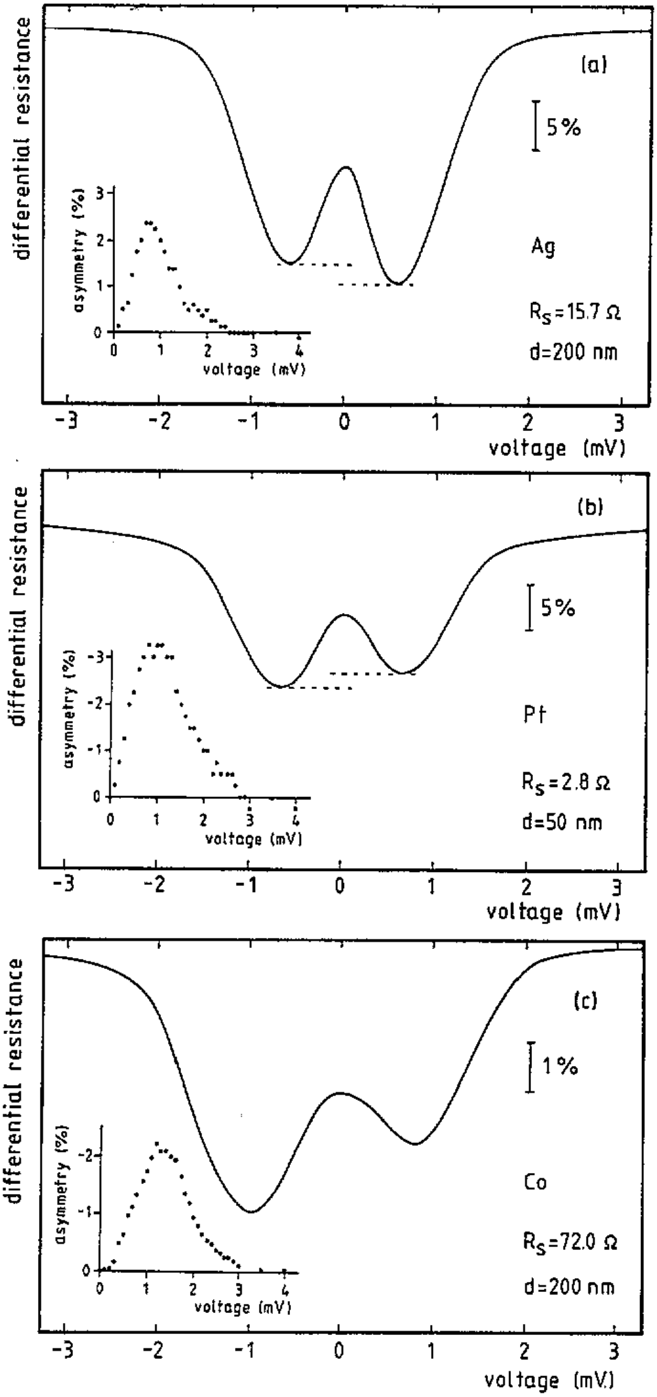

Figure 3. Point-contact characteristics of Ag, Pt, and Co point contacts on an Ag–Pb bilayer (a–c respectively). The Sharvin resistance and the thickness of the Ag layer are indicated. The insets show the voltage dependence of the asymmetry (obtained by measuring the difference between the positive- and negative-voltage part of the displayed point-contact characteristic).

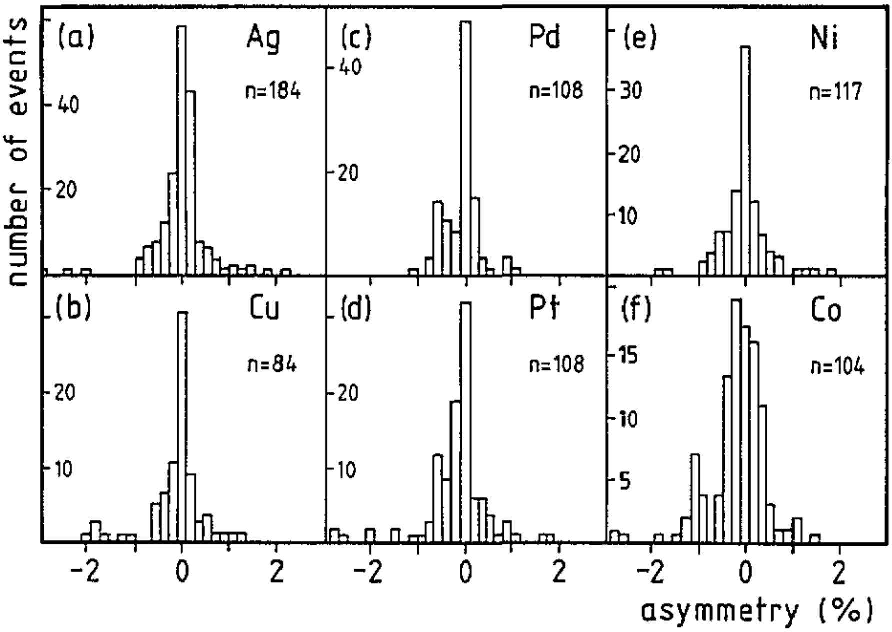

Figure 4. Distribution of the magnitude and sign of the asymmetry as observed with Ag, Cu, Pd, Pt, Ni, and Co point contacts on Ag–Pb bilayers (the thicknesses of the Ag layer are 50, 100 and 200 nm). For each point-contact material the number of experiments is indicated.

energy dependent and only occurs when Andreev reflection is present, its effect is similar for opposite-bias voltages (i.e. in the case of hole–hole interference). Therefore, no asymmetries are expected at opposite-bias voltages. A similar reasoning can be used when the incident electron scatters at an impurity at some distance from the N–S interface and continues in the form of partial waves in different directions. After Andreev reflection the partial hole waves interfere at the position of the scatterer and the resulting hole wave may again be detected [9, 10]. The magnitude of the phase difference (after Andreev reflection) at the position of the scatterer is not changed when the polarity of the voltage is reversed. Therefore, no asymmetry is expected in this situation either.

The previous discussion shows that potential explanations fail to give an asymmetry for opposite-bias voltages as long as the Andreev process is assumed to give perfect retroreflection. However, on closer examination this is only true for electrons (and holes) at the Fermi energy. In all other situations there is a deviation from perfect retroreflection, which has opposite sign for electrons and holes. Therefore, these deviations combined with sample-specific effects (such as any type of scattering in the normal-metal layer, at the P–N or at the N–S interface) may provide an explanation for the observed asymmetries. As an illustration we consider an electron with energy E relative to the Fermi energy that arrives at the N–S interface. Upon Andreev reflection it couples with a second electron with energy $-E$ relative to the Fermi energy. The missing second electron (or hole) has a wave vector parallel to the N–S interface that is exactly opposite to that of the incoming electron. However, the perpendicular component of the wave vector is not perfectly reversed due to the momentum taken up by the Cooper pair. As a result there is no perfect retroreflection so the trajectory of the hole deviates slightly from the initial electron trajectory; dependent on the energy the difference angle between the electron and hole trajectories is positive or negative. Since the trajectories are slightly different, sample-specific properties may affect the electron and hole trajectories differently and can possibly give cause to energy-dependent effects (particularly asymmetries) that are exclusively related to Andreev reflection.

Under the implicit assumption of a spherical Fermi surface this energy-dependent effect is only significant for electrons at grazing incidence and a limited volume of the phase-space will contribute. The effect may however actually be larger since for a real Fermi surface of Ag with necks, a larger part of the phase space will show this energy-dependent deviation of the trajectories. Therefore, the microscopic orientation of the Fermi surface at the N–S interface will determine the magnitude of the effect. Since we lack this knowledge of the N–S interface we are presently not able to quantify this possible explanation. For this reason future experiments should preferably be carried out with systems that are crystallographically well defined. This may be achieved using a combination of point-contact junctions prepared with electron-beam lithography and epitaxially grown N–S bilayers. With this type of structure the microscopic environment of the point contact is better defined as well and deformation and stress may be avoided.

4. Conclusions

In conclusion, we have observed asymmetries in the resistance versus voltage curves of different types of point-contact material on N–S bilayers. The asymmetry is present in the excess current resulting from Andreev reflection. Different effects concerning the P–N interface, the N–S interface, and the transport in between the interfaces are inadequate to explain the asymmetries. We speculate that, in addition, the non-ideality of retroreflection and deviations from the spherical Fermi surface of the point-contact material or the normal-metal layer should be considered.

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