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Interface spin-flip scattering model for point contact Andreev reflection

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Point contact Andreev reflection measurements show a correlation between measured spin polarization and the interface scattering parameter Z extracted from fits of the modified Blonder–Tinkham–Klapwijk model to the conductance–voltage curves of superconductor/ferromagnet point contacts. We present a simple spin-flip scattering model which identifies Z^2 as the effective scattering parameter and explains the observed exponential decay of the spin polarization. © 2003 American Institute of Physics. [DOI: 10.1063/1.1558664]

Point contact Andreev reflection (PCAR) has emerged as an approach for direct measurement of the degree of spin polarization of transport electrons in various ferromagnetic materials.^{1–8} This polarization parameter is the key ingredient to transport phenomena exploited in spin-electronic devices. PCAR involves transport through a superconductor/metal (S/N) point contact in which the superconductor serves as the probe for the spin polarization.

The transport in S/N contacts, in which N is a nonmagnetic metal, was originally described by the Blonder–Tinkham–Klapwijk (BTK) model.⁹ Interface transparency is accounted for by a planar delta potential with dimensionless strength Z . The BTK model has been modified^{2,4} to describe S/N contacts in which N is a magnetic metal. By fitting this modified BTK model to measured conductance–voltage (dI/dV – V) curves, of which typical examples are shown in Fig. 1, the spin polarization P and interface scattering strength Z are extracted, systematically revealing a decrease in P with increasing Z .

In this article, we present a simple model to explain the decrease of P with Z by incorporating spin-flip scattering in an extended interface region, and we compare it with existing experimental data on Co, Fe, and Gd,^{4,8} CrO_2 , and $\text{La}_x\text{Sr}_{1-x}\text{MnO}_3$.^{6,7} We suggest with the present model that with an appropriate experimental approach, providing a defined control of Z , PCAR can be used to study spin-flip scattering at interfaces in addition to the spin polarization P .

Before we introduce the role of spin-flip scattering, it is important to realize that in a model in which interface scattering is incorporated with a delta potential, the scattering is localized in the sense that an incoming electron is reflected or transmitted as a result of at most a single scattering event. In practice, however, an electron may be transmitted or reflected as a result of multiple scattering events in forward and backward direction within an extended scattering region. Thus, the fitted Z values obtained from the BTK model represent an “effective” scattering parameter measured over an extended region.

A quantitative identification of Z with classical scattering parameters, such as the electron mean free path, can be obtained by calculating the transmission T of electrons through a scattering region of width ℓ . We consider an electron traveling only in the x direction, which enters the scattering region at $x=0$ and is transmitted when it reaches $x=\ell$. Within a distance dx the probability for scattering is dx/λ , where λ is the mean free path. At a particular scattering site, the electron can be scattered while it maintains its direction of traveling, i.e., scattering in forward direction, or it can be backward reflected. The parameter ψ is the ratio between the probability for forward and backward scattering. A differential equation for $T(x)$ can be deduced by calculating $T(x+dx)$ in terms of $T(x)$ by considering all possibilities for transmission through dx and adding their probabilities. That is, the electron is transmitted through dx without being scattered with probability

$$1 - \frac{dx}{\lambda}$$

or via one forward scattering event with probability

FIG. 1. Typical examples of measurements performed on Pb/Co point contacts at 4.2 K (open symbols) with fits of the modified BTK model (solid lines). The maxima in the curves mark the edge of the superconducting band gap and the relatively deep minimum at zero bias in the top curve reflects the high interface scattering strength Z as compared to the bottom curve (see Ref. 8).

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$$\frac{dx}{\lambda} \left(\frac{\psi}{1+\psi} \right),$$

or via two backscattering events with probability

$$\frac{dx}{\lambda} \left(\frac{1}{1+\psi} \right) (1-T(x))$$

etc. Summarizing all the probabilities leads to

$$\frac{dT}{dx} = -\frac{1}{\lambda} \frac{1}{1+\psi} T^2, \quad (1)$$

with the solution at $x=\ell$

$$T = \frac{1}{1 + \frac{1}{1+\psi} \frac{\ell}{\lambda}}. \quad (2)$$

Interestingly enough, this expression has the same form as the expression for the delta potential⁹

$$T = \frac{1}{1 + Z^2}, \quad (3)$$

which shows that T depends explicitly on Z^2 . This suggests that Z^2 is the relevant scattering parameter rather than Z , and that it can be written as

$$Z^2 = \frac{1}{1+\psi} \frac{\ell}{\lambda}. \quad (4)$$

The quantity Z^2 scales with ℓ/λ , which is a measure for the average number of scattering events of a transmitted electron. If the electrons scatter mostly in the forward direction, ψ is large and Z^2 is small. In the fully backward scattering limit, ψ is zero and $Z^2 = \ell/\lambda$.

The spin polarization of electrons traveling through the scattering region will decrease when for each scattering event there is a spin-flip probability α . For a given spin polarization P_0 of the incoming electrons at $x=0$, the transmitted spin polarization P and reflected spin polarization Q can be calculated. A system of two differential equations for P and Q can be deduced in a similar approach as is done for obtaining the equation for T . This system can be formulated in a compact form by using the quantities $\mathcal{P}=TP$ and $\mathcal{Q}=(1-T)Q$:

$$\frac{d\mathcal{Q}}{d\zeta} = 1 - 2\rho\mathcal{Q} + \mathcal{Q}^2, \quad (5)$$

and

$$\frac{d\mathcal{P}}{d\zeta} = (\mathcal{Q} - \rho)\mathcal{P}, \quad (6)$$

where $\rho = (1+2\alpha\psi)/(1-2\alpha)$ and $\zeta = (1-2\alpha)Z^2$. Equation (6) can be solved to find P when $\mathcal{Q}$ is known from Eq. (5). However, in the case of dominant forward scattering ($\psi \rightarrow \infty$), $\mathcal{Q}$ in Eq. (6) can be neglected and the solution for P is approximately an exponential decay

$$P \approx P_0 \exp(-2\alpha\psi Z^2), \quad \psi \rightarrow \infty. \quad (7)$$

For arbitrary ψ the solutions are

FIG. 2. Transmission of polarization calculated with Eq. (8).

$$P = P_0 \frac{(1+Z^2)\eta}{(1+2\alpha\psi)\sinh(\eta Z^2) + \eta \cosh(\eta Z^2)} \quad (8)$$

and

$$Q = P_0 \frac{1+Z^2}{Z^2} \frac{(1-2\alpha)\sinh(\eta Z^2)}{(1+2\alpha\psi)\sinh(\eta Z^2) + \eta \cosh(\eta Z^2)}, \quad (9)$$

where $\eta^2 = 4\alpha(1+\psi) + 4\alpha^2(\psi^2 - 1)$. Figure 2 shows P/P_0 calculated from Eq. (8) for the backward scattering regime ($\psi=0$) and for dominant forward scattering ($\psi=100$). The transmitted polarization is higher in the backward scattering regime. This is due to the fact that for a given Z^2 the transmitted electrons experience less scattering events.

In application of the model with the PCAR experiments, the width ℓ in Eq. (4) relates to the characteristic dimension of the region where Andreev reflection occurs. Since this is an extended region, the measured P is not necessarily the polarization of the electrons at $x=\ell$ alone. As a consequence, the simple interface spin-flip scattering model, which calculates the P for electrons at $x=\ell$, is formally not applicable and should be extended by considering weighted contributions of P s at different positions. Nevertheless, our simple approach captures the essential physics involved and we apply the model to experimental data.

All the considered data are obtained by a similar experimental approach in which a superconducting tip is pressed onto a sample by means of a mechanically driven mechanism. Conductance (dI/dV) is measured with a standard lock-in technique at liquid helium temperatures. Both Nb and Pb are used as superconducting tips. Tip and sample are brought into physical contact while immersed in liquid helium. In general, changes in contact resistance and Z^2 are obtained by applying a short voltage pulse or due to mechanical drift over a time scale long compared to the measurement time.

Figure 3 shows the measured polarization as a function of Z^2 for various materials. Co, Fe, and Gd (open symbols)⁸ show a clear exponential-like decay in P . The measured spin polarization obtained by Ji et al.^{6,7} on CrO_2 and $\text{La}_x\text{Sr}_{1-x}\text{MnO}_3$ shows a much weaker decay in comparison with Co, Fe, and Gd. Under the assumption that forward results (solid lines). The fitted parameters P_0 , which are

FIG. 3. P plotted as a function of Z^2 for Co, Fe, and Gd (open symbols). For comparison data of Co, Fe (see Ref. 4), CrO_2 , and $\text{La}_x\text{Sr}_{1-x}\text{MnO}_3$ (see Refs. 6 and 7, respectively) are included (closed symbols). The solid lines are fits of an exponential decay.

consistent with the earlier reported values, and $\alpha\psi$ are listed in Table I.

The considerable spread in P for a given Z^2 , which is not caused by limited accuracy of the BTK model fits, reflects the coarse experimental approach used. With tip and sample exposed to air prior to the formation of the contact, control of the interface is poor. We point out that with a cleaner experimental approach the decay of P with Z^2 can be studied more accurately, potentially enabling a quantitative experimental study of spin-flip scattering. A cleaner experiment can be performed using a low temperature ultrahigh vacuum scanning tunneling microscope with *in situ* deposi-

TABLE I. Fit results.

Material	P_0	$\alpha\psi$
Co	0.47 ± 0.02	1.8 ± 0.1
Fe	0.46 ± 0.03	1.2 ± 0.2
Gd	0.45 ± 0.04	2.1 ± 0.3
CrO_2^a	0.96 ± 0.02	0.16 ± 0.03
$\text{La}_x\text{Sr}_{1-x}\text{MnO}_3^b$	0.80 ± 0.01	0.27 ± 0.01

^aSee Ref. 6.

^bSee Ref. 7.

tion facilities. Another approach, similar to what is followed by Upadhyay *et al.*,³ might be the fabrication of contacts formed by deposition in combination with nanostructuring enabling controlled variation of Z^2 .

For the present contacts, the interface might be atomically intermixed due to electromigration triggered by the applied short voltage pulses during the contacting procedure. The clear weaker decay with Z^2 for CrO_2 and $\text{La}_x\text{Sr}_{1-x}\text{MnO}_3$, as compared to Co, Fe, and Gd, can be explained by the physical properties of the sample. Possibly, during formation of the contact, there is a significantly smaller amount of atomic intermixing at the interface due to the relatively strong bonds in the ionic CrO_2 and $\text{La}_x\text{Sr}_{1-x}\text{MnO}_3$ crystals as compared to the bonding in the other materials.

In conclusion, we have presented a simple model, involving spin-flip scattering in an extended interface region, to explain the observed decrease of P with interface scattering strength Z as measured with PCAR.

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