Determining the current polarization in ferromagnet/superconductor point contacts

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Tunneling magnetoresistance (TMR)

\[
TMR = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}}
\]

First observations: Jullière (1975) and Maekawa and Gáfvert (1982).

Jullière’s model (1975):

\[
TMR = \frac{2P_1P_2}{1 - P_1P_2}
\]

\(P_i\) = spin polarization.
**Introduction: Giant magnetoresistance (GMR)**


---

**Origin:** spin-dependent scattering at the interfaces.

**Applications:** nonvolatile memories.
Introduction: Andreev reflection and spin polarization

- **Spintronics** is largely based on the ability of ferromagnetic materials to conduct spin-polarized currents.

- **A key issue:** the experimental determination of the current polarization.

**GOAL:** determination of the current polarization of ferromagnets using Andreev physics

**Andreev Reflection**

\[ eU < \Delta \]

\[ 2\Delta \]

\[ \frac{S}{N} \text{ Interface} \]

\[ \frac{S}{F} \text{ Interface} \]

de Jong and Beenakker, PRL'95
Experimental setup: Fabrication process

Electron-beam lithography

- PMMA (~ 150 nm)
- $e^-$
- $\Phi \sim 50$ nm

RIE (reactive ion etching)

- SF$_6$ plasma
- SF$_6$ etch
- $\Phi_i \sim 50$ nm
- $\Phi_e \sim 5$ nm
- O$_2$ etch

Ralls et al., APL'89
Experimental setup: SEM and TEM characterization

SEM:

TEM:
Experimetal setup: Metallization

Metallization:
- e-beam evaporation
- UHV ($\sim 10^{-9}$ mbar)

- Dilution refrigerator ($\sim 20$ mK)
- $B$: superconducting coil
- Lock-in technique ($I_{ac}$):
  \[ R = G^{-1} = \frac{dU}{dI} \]
- $I_{dc} \rightarrow U_{dc} = U$
Experimental setup: Length scales

- **thermic:** \( l_{in} < a \rightarrow \text{heating of the PC} 
- **diffusive:** \( l_{el} < a < l_{in} 
- **ballistic:** \( a < l_{el}, l_{in} \)

**Ballistic regime:**

- \( R \) is given by geometry: Sharvin resistance
  \[
  R = R_s = \frac{2h}{e^2 k_F^2 a^2}
  \]
  \[
  
  \rightarrow R(T) = R
  \]

- spectroscopy is possible: phonon spectroscopy
  \[
  \alpha^2 F_P(eU) = \frac{3}{32\sqrt{\pi}} \frac{\hbar^{3/2} k_F^2}{m} \frac{1}{\sqrt{R}} \frac{dR}{dU}
  \]
Experimental setup: Phonon spectroscopy (Al)

1 Thz $\leftrightarrow$ 4.14 meV

$R_{RT}/R_{He}$ vs. $R_{He}$ (Ω)

Al (F129B) $d \approx 7$ nm

$R$ (Ω)

$\alpha^2 F_{P}$ vs. $U$ (mV)
Al/Cu point contact:

Al: Type I, BCS superconductor

\[ T_c = 1.2 \, \text{K} \quad \Delta = 1.76 \, k_B T_c = 184 \, \mu eV \]

coherence length: \( \xi \sim 300 \, \text{nm} \)
magnetic penetration depth: \( \Lambda \sim 50 \, \text{nm} \)

Andreev reflection

\[ eU > \Delta \]
\[ eU < \Delta \]
BTK model

Blonder, Tinkham and Klapwijk, PRB '82

\[ I_{S/N} = \frac{G_0}{e} \int_{-\infty}^{\infty} \left[ f(E - eU) - f(E) \right] \left[ 1 + A(E) - B(E) \right] dE \]

\( A(E) \): Prob. for Andreev reflection
\( B(E) \): Prob. for normal reflection
\( \tau \): Transmission \( \tau = \frac{1}{1 + Z^2} \)

\( \Delta, \tau, \Gamma \)

\( \Gamma \): Dynes parameter
Al/Cu experiment

Best $\chi^2$ fit for $T \approx 100$ mK

$$\chi^2 = \frac{1}{N} \sum_{i=1}^{N} \left[ G^*(U_i) - G_{\text{theo}}^*(U_i) \right]^2$$

$G^*$: normalized $G$

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<tr>
<th>sample</th>
<th>$R_N$ (Ω)</th>
<th>$T$ (mK)</th>
<th>$\Delta$ (μeV)</th>
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<td>F95A</td>
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$\tau_{\text{Al/Cu}} = 0.77$
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$\tau_{\text{Al/Cu}} = 0.77$

$T \neq 100$ mK: $\Delta(T) = \Delta_{\text{BCS}}(T)$
**Role of a FM?**

\[
P_N = \frac{N_{\uparrow}(E_F) - N_{\downarrow}(E_F)}{N_{\uparrow}(E_F) + N_{\downarrow}(E_F)}
\]

Co: Exchange energy \( \sim 1.4 \, eV \)

\[
P = \frac{I_{\uparrow} - I_{\downarrow}}{I_{\uparrow} + I_{\downarrow}}
\]

**P = 1**

\( eU < \Delta \)

\( 2\Delta \)

\[ P = 1 \Rightarrow A(E) = 0 \]

\[ \rightarrow \text{FM suppresses Andreev reflection.} \]

\[ \Rightarrow \text{Do Andreev reflections contain information on the current polarization } P? \]
Previous work

Soulen et al., Science’98
*Measuring the Spin Polarization of a Metal with a Superconducting Point Contact.*

- “spear-anvil” geometry
- $P$ was determined for several FM

Upadhyay et al., PRL’98
*Probing Ferromagnets with Andreev Reflection.*

- nanostructured PC
- Pb/Co, Pb/Ni PC

$$g(V) = \frac{G_{FS}(V) - G_{FN}(V)}{G_{FN}(0)}$$
Previous work

Modified BTK model:

\[ G = (1 - P) G_{\text{unpol}} + PG_{\text{pol}}. \]

but...

\[ G_{\text{unpol}}: \text{from BTK theory} \]
\[ G_{\text{pol}}: A(E) = 0 \]

\( P \) is a phenomenological parameter.

Spin-Dependent Transparency of Ferromagnet/Superconductor Interfaces

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2Department of NanoScience, Delft University of Technology, 2628 CJ Delft, The Netherlands
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We combine parameter-free calculations of the transmission and reflection matrices for clean and dirty interfaces with a scattering-theory formulation of Andreev reflection (AR) generalized to spin-polarized systems in order to critically evaluate the use of an extended Blonder-Tinkham-Klapwijk (BTK) model to extract values of the spin polarization for ferromagnetic metals from measurements of point-contact AR. Excellent agreement with the experimental conductance data is found for Pb/Cu but it is less good for Pb/Ni and poor for Pb/Co, indicating that the BTK formalism does not describe transport through superconducting/ferromagnetic interfaces correctly.
Our theoretical model is based on quasiclassical Green functions \((g\text{ and } f)\) and adequate boundary conditions for spin-active interfaces (Cuevas and Fogelström, PRB’01; Eschrig, Kopu, Cuevas and Schönh, PRL’03).

Scattering matrix \(\hat{S}\) for an S/F interface:

\[
\hat{S} = \begin{pmatrix}
\hat{r} & \hat{t} \\
\hat{t}^\dagger & \hat{r}^\dagger
\end{pmatrix};
\hat{t} = \begin{pmatrix}
t_\uparrow & 0 \\
0 & t_\downarrow
\end{pmatrix},
\hat{r} = \begin{pmatrix}
r_\uparrow & 0 \\
0 & r_\downarrow
\end{pmatrix},
\]

where \(\tau_{\uparrow,\downarrow} = |t_{\uparrow,\downarrow}|^2\) are the spin-dependent transmission coefficients.

The current through an SF point contact can be written as:

\[
I_{SF} = I_\uparrow + I_\downarrow; \quad I_\sigma = \frac{e}{h} \int_{-\infty}^{\infty} d\epsilon \ [n_F(\epsilon - eV) - n_F(\epsilon)] [1 + A_\sigma(\epsilon) - B_\sigma(\epsilon)]
\]

\(A_\sigma(\epsilon)\) and \(B_\sigma(\epsilon)\) are the Andreev reflection and normal reflection probabilities, respectively.

\[
A_\sigma = \tau_\sigma \tau_{-\sigma} |f/D|^2 \quad B_\sigma = |(r_\sigma + r_{-\sigma}) + (r_\sigma - r_{-\sigma})g|^2 / |D|^2
\]

where \(r_\sigma = \sqrt{1 - \tau_\sigma}\) and \(D = (1 + r_\sigma r_{-\sigma}) + (1 - r_\sigma r_{-\sigma})g\).
Theoretical model II

\[ P \equiv \text{current polarization} \]
\[ P = \frac{|\tau_\uparrow - \tau_\downarrow|}{(\tau_\uparrow + \tau_\downarrow)} \]
\[ G_{SF} = \frac{4e^2}{\hbar} \left\{ \frac{\tau_\uparrow\tau_\downarrow}{(1+r_\uparrow r_\downarrow)^2 - 4r_\uparrow r_\downarrow (eV/\Delta)^2} \right\} ; \quad eV \leq \Delta \]
\[ \left[ (1-r_\uparrow r_\downarrow) + (1+r_\uparrow r_\downarrow) \sqrt{1 - (\Delta/eV)^2} \right]^2 \]
\[ G_{SF} = \frac{4e^2}{\hbar} \left\{ \frac{\tau_\uparrow\tau_\downarrow}{(1+r_\uparrow r_\downarrow)^2 - 4r_\uparrow r_\downarrow (eV/\Delta)^2} \right\} ; \quad eV \geq \Delta \]

- In the absence of spin polarization (\( \tau_\uparrow = \tau_\downarrow \)) this formula reduces to the BTK result.
- \( \tau_\uparrow \) and \( \tau_\downarrow \) are used as fit parameters.
- They contain the microscopic properties relevant for transport, i.e. the spin-split band structure of the ferromagnet, the electronic structure of the superconductor and the interface properties.
- The modified BTK model cannot be mapped onto ours, it is not rigorously founded, and misses the fundamental ingredient of a spin-dependent transmission.
Al/Co experiment

F110D
X = 12 nm
T = 100 mK

G / G_N

eU (mV)

F105A (Al/Cu)
Al/Co experiment

F110D
X = 12 nm
T = 100 mK

<table>
<thead>
<tr>
<th>Fit</th>
<th>$\Delta$ (meV)</th>
<th>$\tau$</th>
<th>$\tau_\uparrow$</th>
<th>$\tau_\downarrow$</th>
<th>$P$</th>
<th>$\chi^2 \left( 10^{-4} \cdot \Omega^{-2} \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P'$ model</td>
<td>0.185</td>
<td>0.878</td>
<td>–</td>
<td>–</td>
<td>0.348</td>
<td>1.42</td>
</tr>
<tr>
<td>$\tau_\uparrow \tau_\downarrow$ model</td>
<td>0.188</td>
<td>0</td>
<td>0.415</td>
<td>0.970</td>
<td>(0.401)</td>
<td>0.73</td>
</tr>
</tbody>
</table>
Determination of \(\{\tau_\uparrow, \tau_\downarrow\}\)

\(\{\tau_\uparrow, \tau_\downarrow\}\) are independent of \(X\)

\(\Rightarrow\) Andreev processes local

Co: \(N_\downarrow(E_F) \gg N_\uparrow(E_F)\)

\(\Rightarrow\) \(\downarrow\): Minority band

\(\bar{\Delta} = (190 \pm 10\%) \mu eV\)

\(\bar{\tau}_\downarrow = 0.40 \pm 0.03\)

\(\bar{\tau}_\uparrow = 0.98 \pm 0.02\)

\(\bar{P} = 0.42 \pm 0.04\)

<table>
<thead>
<tr>
<th>Sample</th>
<th>(X) (nm)</th>
<th>(R_N) ((\Omega))</th>
<th>(\Delta) ((\mu eV))</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F116C</td>
<td>6</td>
<td>10.4</td>
<td>189</td>
<td>0.42</td>
</tr>
<tr>
<td>F117A</td>
<td>6</td>
<td>6.69</td>
<td>199</td>
<td>0.42</td>
</tr>
<tr>
<td>F110C</td>
<td>12</td>
<td>33.2</td>
<td>199</td>
<td>0.39</td>
</tr>
<tr>
<td>F110D</td>
<td>12</td>
<td>13.3</td>
<td>188</td>
<td>0.40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>(X) (nm)</th>
<th>(R_N) ((\Omega))</th>
<th>(\Delta) ((\mu eV))</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F120A</td>
<td>24</td>
<td>6.00</td>
<td>180</td>
<td>0.44</td>
</tr>
<tr>
<td>F120B</td>
<td>24</td>
<td>3.58</td>
<td>193</td>
<td>0.42</td>
</tr>
<tr>
<td>F121A</td>
<td>50</td>
<td>15.7</td>
<td>172</td>
<td>0.46</td>
</tr>
<tr>
<td>F121B</td>
<td>50</td>
<td>3.59</td>
<td>198</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Temperature dependence of the Andreev spectra

**Graph 1:**
- **Title:** F117A, X = 6 nm
- **Axes:**
  - X-axis: eU/\Delta
  - Y-axis: G/G_N
- **Legend:**
  - Multiple curves for different T (mK) values

**Graph 2:**
- **Title:**
- **Axes:**
  - X-axis: T / T_c
  - Y-axis: R / R_N
- **Legend:**
  - Multiple curves for different samples

**Table:**

<table>
<thead>
<tr>
<th>Sample</th>
<th>(\tau_1)</th>
<th>(\tau_2)</th>
<th>(\tau_1^{\text{int}})</th>
<th>(\tau_2^{\text{int}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>F117A</td>
<td>0.403</td>
<td>0.979</td>
<td>0.408</td>
<td>0.978</td>
</tr>
<tr>
<td>F110C</td>
<td>0.420</td>
<td>0.968</td>
<td>0.422</td>
<td>0.968</td>
</tr>
<tr>
<td>F120A</td>
<td>0.382</td>
<td>0.989</td>
<td>0.384</td>
<td>0.989</td>
</tr>
<tr>
<td>F121A</td>
<td>0.370</td>
<td>0.994</td>
<td>0.371</td>
<td>0.994</td>
</tr>
</tbody>
</table>
The Andreev spectrum disappears abruptly for $13 \text{ mT} < B < 16 \text{ mT}$.

→ 1st order PT for $B = B_c$

R(B)-Measurement: $B_c = 15.2 \text{ mT}$  

$G(U = 0, B) \approx \text{const.}$

• A description with the modified BTK model is not possible.
Magnetic field dependence of the Andreev spectra II

**Thin films:**
1. $l \ll \xi$ in the Al electrode (diffusive S)
2. $\xi > d \Rightarrow \Delta(\vec{r}) = \Delta$
3. $d/\Lambda \rightarrow 0$: $B$ penetrates completely in S. Pair-breaking parameter $\alpha \propto B^2$

$\rightarrow$ The shape of the spectrum is determined by the DOS. ($\Omega \neq \Delta$!)

$\rightarrow$ $d/\Lambda \rightarrow 0$: “Smooth” 2nd order Phase Transition for $\alpha_c = 0.5$

Exp.: $d_{Al} \approx 200\text{ nm, } \Lambda_{Al} \sim 50\text{ nm} \rightarrow d/\Lambda \sim 4 \Rightarrow B$ is partially screened.
The thickness of the Al film, $d$, is probably larger than the penetration depth, $\Lambda \rightarrow$ we have to determine how the magnetic field is screened.

Diffusive regime ($l \ll \xi$): Usadel equation with space-independent order parameter

$$\epsilon + i\Gamma(B)g(\epsilon, B) = i\Delta \frac{g(\epsilon, B)}{f(\epsilon, B)} \quad \text{where} \quad \Gamma = \frac{2De^2}{\hbar c^2} \langle A^2 \rangle$$

- $\Delta$ has to be determined self-consistently (gap equation).
- The vector potential is calculated solving the Maxwell equation:

$$\nabla^2 \vec{A} = -(4\pi/c)\vec{j} \quad \text{where} \quad \vec{j}(\vec{r}) = -(2\sigma_N/\hbar c)\vec{A}(\vec{r}) \int_0^\infty d\epsilon \tanh(\beta\epsilon/2) \Im(f^2)$$

where $\sigma_N$ is the normal conductivity of the Al sample and $\beta = (k_B T)^{-1}$

- The solution of the Maxwell equation yields:

$$\Gamma(B) = \frac{6\alpha}{r^2 \cosh^2(r/2)} \left( \frac{\sinh(r)}{r} - 1 \right) \quad ; \quad \alpha = \frac{De^2d^2B^2}{6\hbar c^2}$$

where $r = (d/\Lambda) \left( \frac{2}{\pi} \int_0^\infty d\epsilon' \tanh \left( \frac{\beta\epsilon'}{2} \right) \Im(f^2) \right)^{1/2}$.
Additionally we calculate the free energy to determine the transition to the normal state.

The ratio \( d/\Lambda \) is the only parameter that enters our analysis.

Since \( d/\Lambda \) determines the critical field of the Al films, \( B_c \), we fix its value by means of an independent measurement of \( R(B) \) at \( T \approx 100 \text{ mK} \).

In our samples \( B_c \approx 1.5 B_{cb} \), which in our theory corresponds to \( d \approx 4 \lambda_0 \).
Magnetic field dependence of the Andreev spectra V

Assumptions:

- $l \ll \xi$ in the Al electrode (diffusive S)
- $\xi > d \Rightarrow \Delta(\vec{r}) = \Delta$

\[
B_c \rightarrow d/\Lambda \\
\Rightarrow \text{"parameter-free" comparison}
\]

F110D: $R(B)$: $B_c = 15 \text{ mT}$,  
$\tau_{\uparrow} = 0.415$, $\tau_{\downarrow} = 0.970$  
$\Delta = 188 \mu\text{eV}$

$B_c = 1.5 B_{c}^{\text{bulk}} \rightarrow d/\Lambda = 3.8$
Magnetic field dependence of the Andreev spectra V

- Sometimes we observe some deviations between theory and experiment close to the critical temperature.

- We attribute them to the existence of a stray field \((\sim 4mT)\) created by the Co film. This idea is supported by the calculations.
Conclusions


- By means of nanostructuring techniques we have fabricated Al/Co point contacts, which are well-defined in geometry and mechanically very stable.

- We have introduced a model for the description of the Andreev reflection in F/S interfaces. While retaining the simplicity of BTK-type theories, our model includes the effect of a spin-dependent transmission and allows the analysis of a great variety of realistic ingredients.

- We have shown that our model consistently describes the whole set of measurements for arbitrary voltage, temperature and magnetic field, which clearly demonstrates that the current polarization in ferromagnets can be determined using Andreev physics.