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Injection of spin-polarized carriers in ferromagnet/superconductor tunnel junctions

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Abstract
We apply a quantum-mechanical approach to study critical current suppression in a superconductor (SC) due to injection of spin-polarized carriers from a ferromagnet (FM) through a FM/SC tunnel junction. It is found that for a given bias voltage, the superconductivity suppression depends strongly on the polarization of the injection current, on the spin-diffusion length in the SC, and on the insulating barrier strength at the FM/SC interface.

Since the discovery of giant-magnetoresistance (MR) effects in magnetic mutilayers [1], spin-polarized electron transport in various magnetic nanostructured systems has attracted much attention [2]. A tunnel junction consists of two metallic films (electrodes) separated by a thin insulating layer. When the two electrodes are ferromagnetic, the spin-polarized tunnelling conductance depends on whether the electrodes have parallel or antiparallel magnetizations, leading to a tunnelling MR [3–5]. When one electrode is a ferromagnet (FM) and the other is a superconductor (SC), the injection of spin-polarized carriers from the FM to the SC gives rise to interesting physical phenomena. Pioneering experiments on FM/SC tunnelling junctions were carried out in the 1970s by Tedrow and Meservey [6]. The injection of spin-polarized current into the SC was first described theoretically by Aronov [7]. Recently, much attention has been paid to FM/cuprate-SC tunnel junctions; the aim has been to get information on the properties of high-T_c SC and to find applications of new superconducting devices [8–12]. Perovskite FM/SC heterostructures were fabricated [8–10] (where FM is a doped lanthanum manganite film and SC is a high-T_c cuprate film). It has been found that the spin-polarized current injected from the FM film reduces the critical current of the SC significantly. This appears to be associated with some out-of-equilibrium pair breaking. However, this pair-breaking effect has been neglected in many theoretical works on the conductance spectra of FM/SC junctions [11, 12], where the superconductivity of the SC has been assumed not to be affected by the injection of the spin-polarized quasiparticles.

In this paper we study the critical current suppression in an s-wave SC due to the injection of spin-polarized carriers from a FM, taking into account both the spin imbalance and the spin relaxation in the SC. We extend a quantum-mechanical approach of Blonder, Tinkham and Klapwijk (BTK) [13], which was previously used to calculate the differential conductance in normal-metal (NM)/SC tunnel junctions, to study the spin-dependent transport in FM/SC tunnel junctions. For simplicity, the superconducting electrode under consideration is a BCS-like SC with s-wave pairing. If the present approach was extended to the case of the high-T_c SC with d-wave pairing, it would be suitable for application to the perovskite FM/SC heterostructures. Also, we discuss the role of the insulating barrier between the FM and SC films. It is found that the superconductivity suppression depends strongly on the barrier strength. This is attributed to the fact that with increasing barrier strength, the Andreev-reflected pair current [14] is reduced and the spin-polarized quasiparticle current is enhanced, resulting in an increasing pair-breaking effect. The calculated results may be qualitatively comparable with those from existing experiments.

Consider a FM/SC tunnel junction, with the geometry as depicted in figure 1(a). Two currents are fed into the SC film: one is the injection current I_{in} along the z-direction and the other is the transport current I_T through the SC film along the x-direction. I_{in} goes from the FM film to the SC film through an insulating tunnel barrier at the FM/SC interface. Within the Stoner model, the motion of spin-polarized electrons in the FM can be described by an effective single-particle Hamiltonian: $H_{FM} = H_0 - \boldsymbol{h} \cdot \boldsymbol{\sigma}$ where $H_0 = -\hbar^2 \nabla_r^2/2m + V(\boldsymbol{r})$ is the kinetic energy plus the usual static potential, h is the exchange energy and σ is the Pauli spin operator. The insulating barrier is described by a δ-type potential, $H_{IB} = U_0\delta(z)$. This simple model is expected to be able to explain the main features of a real barrier [18], in which U_0 depends on the product of the height and width of the barrier.

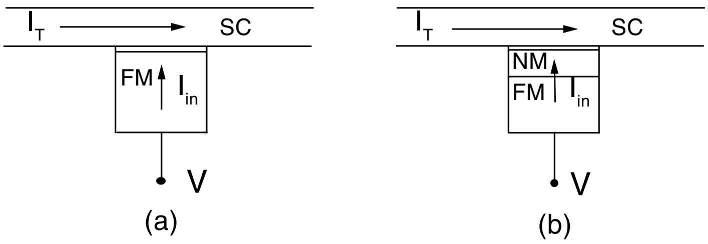


Figure 1. Structures of FM/SC (a) and FM/NM/SC (b) tunnel junctions. I_{in} is the injection current and I_T is the transport current through a SC film.

As a bias voltage V is applied to the FM/SC tunnel junction, the spin-polarized injection current I_{in} will give rise to an imbalance of spin density in the junction region of the SC film (the population of spin-up quasiparticles being greater than that of spin-down ones), so the chemical potentials for the spin-up and spin-down quasiparticles will be shifted oppositely by $\delta\mu$ from the equilibrium value E_F. In this work, the thickness of the SC film is considered to be shorter than the spin-relaxation length, and so spin-flip effects in the SC film may be neglected along the z-direction. As a result, $\delta\mu$ is then independent of z but is x-dependent, decreasing with distance from the junction region of the SC film due to spin-flip effects in the x-direction. As will be shown, such a spin imbalance plays a part in breaking Cooper pairs in the SC film. The Hamiltonian of the SC film can be written as

$$H_{SC} = H_{BCS} + \sum_k \delta\mu(0)(c_{k\uparrow}^\dagger c_{k\uparrow} - c_{k\downarrow}^\dagger c_{k\downarrow}) \tag{1}$$

where H_{BCS} is the Hamiltonian in the BCS theory and $\delta\mu(0)$ is the shift of the chemical potential in the junction region of the SC film. By means of the Bogoliubov transformation: $\gamma_{k\sigma} = u_k c_{k\sigma} - \eta_\sigma v_k c_{-k\bar{\sigma}}^\dagger$, where $\bar{\sigma}$ is the spin opposite to σ, $\eta_\sigma = 1$ for $\sigma = \uparrow$ and $\eta_\sigma = -1$

for $\sigma = \downarrow$, Hamiltonian (1) is diagonalized to give

$$H_{SC} = \sum_k E_{k\uparrow}\gamma^{\dagger}_{k\uparrow}\gamma_{k\uparrow} + \sum_k E_{k\downarrow}\gamma^{\dagger}_{k\downarrow}\gamma_{k\downarrow} \tag{2}$$

with

$$E_{k\sigma} = \xi_k + \eta_\sigma\,\delta\mu. \tag{3}$$

Here

$$\xi_k = \sqrt{\epsilon_k^2 + \Delta^2}$$

is the excitation energy, with ϵ_k the one-electron energy relative to E_F and Δ the gap parameter, and

$$u_k^2 = \frac{1}{2}(1 + \epsilon_k/\xi_k) \qquad v_k^2 = \frac{1}{2}(1 - \epsilon_k/\xi_k).$$

The gap parameter Δ can be determined from the self-consistent equation

$$\Delta = g\sum_k u_k v_k(1 - \langle\gamma^{\dagger}_{k\uparrow}\gamma_{k\uparrow}\rangle - \langle\gamma^{\dagger}_{k\downarrow}\gamma_{k\downarrow}\rangle) \tag{4}$$

where g is the effective attractive potential between electrons. Comparing equation (4) with the gap equation in the absence of $\delta\mu$, one gets [18]

$$\ln\left(\frac{\Delta_0}{\Delta}\right) = \int_0^{\hbar\omega_D}\frac{\mathrm{d}\epsilon_k}{\xi_k}\,(f_{k\uparrow} + f_{k\downarrow}) \tag{5}$$

where Δ_0 is the zero-temperature gap parameter in the absence of $\delta\mu(0)$, ω_D is the Debye frequency and

$$f_{k\sigma} = 1/[\exp(\beta E_{k\sigma}) + 1]$$

is the Fermi distribution function for the spin-σ quasiparticles with $\beta = 1/k_B T$ the inverse temperature. From equation (5), it follows that with increasing $\delta\mu(0)$, Δ is suppressed with respect to Δ_0, which arises from pair-breaking effects of the spin-polarized current. For an s-wave SC, the critical current density j_c is proportional to Δ, so $j_c/j_{c0} = \Delta/\Delta_0$ where j_{c0} is the critical current density at zero temperature and with $\delta\mu = 0$. As the spin-polarized injection current is increased, $\delta\mu(0)$ is increased and Δ is decreased, leading to a reduction of j_c. In the junction region of the SC film, whose centre is at $x = 0$, $\delta\mu(0)$ is maximal and Δ exhibits its minimum. With x increasing away from the junction region, $\delta\mu(x)$ decreases gradually due to spin-flip effects, and so $\Delta(x)$ increases. The critical current density passing through the SC film is determined by that in the junction region where j_c is minimal.

Next, we focus our attention on the FM/SC tunnel junction with the aim of finding the relationship between $\delta\mu(x = 0)$ and the spin-polarized injection current I_{in}, from which Δ in the junction region of the SC film can be determined by means of equation (5). As shown in figure 2, a spin-up electron is incident on the interface at $z = 0$ from the FM at an angle θ_N to the interface normal; there are four possible trajectories: the normal reflection (NR) at angle θ_N; the Andreev reflection (AR) at an angle θ_A; transmission to the SC as electron-like and hole-like quasi-particles (ELQ and HLQ) at an angle θ_S. For a FM/SC tunnel junction, the Bogoliubov–de Gennes (BdG) equations have four components: ELQ and HLQ with up and down spins, respectively. However, in the absence of spin-flip tunnelling, the spin-dependent (four-component) BdG equations can be decoupled into two sets of (two-component) equations: one for the spin-up ELQ and spin-down HLQ wave functions ($u_\uparrow$, $v_\downarrow$); the other for the spin-down ELQ and spin-up HLQ wave functions ($u_\downarrow$, $v_\uparrow$) [11]. With the solutions of the BdG equations, for the spin-up electron incident on the interface, the wave functions in the FM and SC have the following form:

$$\Psi_{FM} = \mathrm{e}^{\mathrm{i}q_{e\uparrow}z\cos\theta_N}\begin{pmatrix}1\\0\end{pmatrix} + a_\downarrow \mathrm{e}^{\mathrm{i}q_{h\downarrow}z\cos\theta_A}\begin{pmatrix}0\\1\end{pmatrix} + b_\uparrow \mathrm{e}^{-\mathrm{i}q_{e\uparrow}z\cos\theta_N}\begin{pmatrix}1\\0\end{pmatrix} \tag{6}$$

for $z < 0$ and

$$\Psi_{SC} = c_\uparrow \mathrm{e}^{\mathrm{i}k_{e\uparrow}z\cos\theta_S}\begin{pmatrix}u_k\\v_k\end{pmatrix} + d_\downarrow \mathrm{e}^{\mathrm{i}k_{h\downarrow}z\cos\theta_S}\begin{pmatrix}v_k\\u_k\end{pmatrix} \tag{7}$$

for $z > 0$. Here the three terms on the right-hand side of equation (6) stand for the incident electron wave function, the Andreev reflection and the normal reflection, respectively, with

$$q_{e\uparrow} \simeq \sqrt{2m(E_F + h)}/\hbar \qquad q_{h\downarrow} \simeq \sqrt{2m(E_F - h)}/\hbar.$$

In the ELQ and HLQ wave functions of equation (7), both wave vectors $\boldsymbol{k}_{e\uparrow}$ and $\boldsymbol{k}_{h\downarrow}$ can be approximated by the Fermi wave vector $k_F = \sqrt{2mE_F}/\hbar$. In the BTK model [13], the wave-vector component parallel to the interface is assumed to remain unchanged in the AR and transmission processes, i.e.,

$$q_{e\uparrow}\sin\theta_N = q_{h\downarrow}\sin\theta_A = k_F\sin\theta_S.$$

Since $q_{e\uparrow} > k_F > q_{h\downarrow}$, we have $\theta_N < \theta_S < \theta_A$ for the incident electrons with spin up. In this case, a virtual AR will occur if

$$\theta_N > \sin^{-1}(q_{h\downarrow}/q_{e\uparrow}) \equiv \theta_{c2}$$

where the z-component of the wave vector in the AR process becomes purely imaginary and so the AR quasiparticles do not propagate [12]. Further, as

$$\theta_N > \sin^{-1}(k_F/q_{e\uparrow}) \equiv \theta_{c1}$$

the z-component of the wave vector in either ELQ or HLQ transmission also becomes purely imaginary, so a total reflection occurs and the net current from the FM to the SC film vanishes. There is an opposite result, $\theta_N > \theta_S > \theta_A$, for the incident electrons with spin down. In this case, neither virtual AR nor total reflection can take place.

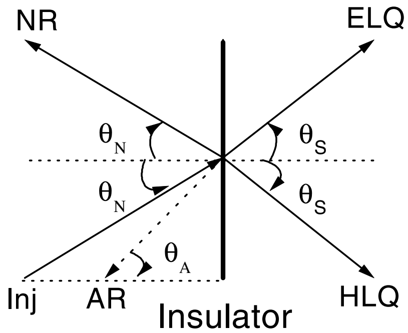


Figure 2. A schematic illustration of reflections and transmissions of spin-up electrons in a FM/SC junction.

All the coefficients in equations (6) and (7) can be determined by matching the boundary conditions at $x = 0$:

$$\Psi_{SC}(x=0) = \Psi_{FM}(x=0)$$

and

$$(\partial\Psi_{SC}/\partial x)_{x=0} - (\partial\Psi_{FM}/\partial x)_{x=0} = (2mU_0/\hbar^2)\Psi_{FM}(0).$$

Using the above conditions on the wave functions and carrying out a little tedious algebra, we obtain $a_\downarrow = 4\lambda_1 u_k v_k/D$ and $b_\uparrow = B/D$, where

$$B = v_k^2(\lambda_1 + 1 - 2iZ)(\lambda_2 - 1 - 2iZ) - u_k^2(\lambda_1 - 1 - 2iZ)(\lambda_2 + 1 - 2iZ) \quad (8)$$

$$D = v_k^2(\lambda_1 - 1 + 2iZ)(\lambda_2 - 1 - 2iZ) - u_k^2(\lambda_1 + 1 + 2iZ)(\lambda_2 + 1 - 2iZ) \quad (9)$$

with

$$\lambda_1 = q_{e\uparrow}\cos\theta_N/(k_F\cos\theta_S) \qquad \lambda_2 = q_{h\downarrow}\cos\theta_A/(k_F\cos\theta_S)$$

for $\theta_N < \theta_{c2}$; $a_\downarrow = 0$ and $b_\uparrow = B/D$ with

$$\lambda_2 = -i\sqrt{k_F^2\sin^2\theta_S - q_{h\downarrow}^2}/(k_F\cos\theta_S)$$

for $\theta_{c2} < |\theta_N| < \theta_{c1}$; $a_\downarrow = 0$ and $b_\uparrow = 1$ for $|\theta_N| > \theta_{c1}$. The dimensionless parameter $Z = Z_0/\cos\theta_S$, with $Z_0 = mU_0/(\hbar^2 k_F)$ representing the interfacial barrier strength. Note that in the case of the spin-down electron injection, the expressions for $a_\uparrow$ and $b_\downarrow$ can be obtained by replacing h by $-h$ in the equations above. Besides, since $\theta_N > \theta_S > \theta_A$, the AR and transmission always take place for arbitrary incident angle.

The tunnelling current is the sum of the spin-up and spin-down currents, $I_{in} = I_\uparrow + I_\downarrow$. Following the BTK theory, they are given by

$$I_\sigma = N_\sigma(0)ev_{F\sigma}A\int_{-\infty}^{\infty}\int_0^{\pi/2} dE\, d\theta_N\,\sin\theta_N\cos\theta_N[B_\sigma(E) + A_\sigma(E)] \times [f(E - eV) - f(E - \eta_\sigma\,\delta\mu(0))] \quad (10)$$

where $N_\sigma(0)$ is the density of states for the spin-σ electrons and A is the effective-neck cross-section area. $A_\sigma(E)$ and $B_\sigma(E)$ are the contributions of the AR and transmission to the tunnelling currents:

$$A_{\bar\sigma}(E) = |a_{\bar\sigma}(E)|^2\,\mathrm{Re}\left(\frac{q_{h\bar\sigma}\cos\theta_A}{q_{e\sigma}\cos\theta_N}\right) \quad (11)$$

$$B_\sigma(E) = 1 - |b_\sigma(E)|^2. \quad (12)$$

If the two electrodes of a tunnel junction are the same normal-metal films, i.e., $u_k = 1$, $v_k = 0$, $\lambda_1 = 1$, $a_\sigma = 0$ and $1 - |b_\sigma|^2 = 1/(1 + Z^2)$, the tunnelling current is given by $I = V/R_N$ where

$$1/R_N = N(0)v_F e^2 A[1 - Z_0^2\ln(1 + Z_0^{-2})]$$

with $N(0)$ the density of states at E_F in the normal metal and v_F the Fermi velocity.

In equations (5) and (10), there are three unknowns: $\Delta(0)$, $\delta\mu(0)$ and I_{in} for a given bias voltage V. It is necessary to find a new relation between the injection current I_{in} and the chemical difference $2\,\delta\mu(0)$ between the spin-up and spin-down subbands. As a bias voltage is applied to the FM/SC tunnel junction, while the spin-polarized injection induces a spin imbalance in the SC film, the resulting $\delta\mu(x = 0)$ prevents I_{in} from increasing further. Such a competition gives a balance between I_{in} and $\delta\mu$. We introduce a spin current density

$$j_{spin} = \frac{\mu_B}{eA}(I_\uparrow - I_\downarrow) \quad (13)$$

to denote the net spin injection from the FM to the SC film, where μ_B is the Bohr magneton. This spin current comes only from the single-particle current; the AR makes no contribution to it because the AR current is carried by the Cooper pairs. At the same time, the local magnetic moment in the SC film is defined as

$$m(x) = -\mu_B[n_\uparrow(x) - n_\downarrow(x)] \quad (14)$$

where $n_\sigma(x)$ is the average density for the spin-σ electrons, and given by [15]

$$n_\sigma(x) = N_\sigma(0)\int_{-\infty}^{\infty} \mathrm{d}E\ [u_k^2 f_{k\sigma} + v_k^2(1 - f_{k\sigma})] \tag{15}$$

so we get

$$m(0) = 2N(0)\mu_B\,\delta\mu(0). \tag{16}$$

Evidently, $m(x)$ depends on $\delta\mu(x)$, decreasing with x, and satisfies [16]

$$\frac{\partial^2 m(x)}{\partial x^2} = \frac{m(x)}{L_s^2} \tag{17}$$

where $L_s = \sqrt{D_s\tau_s}$ is the spin-diffusion length in the SC film with D_s the spin-diffusion constant and τ_s the longitudinal spin-relaxation time. The boundary condition for $m(x)$ is given by

$$-\partial m(x)/\partial x|_{x=0} = I_{spin}/D_s \qquad \partial m(x)/\partial x|_{x\to\infty} = 0$$

from which one gets $m(x) = m(0)\exp(-x/L_s)$, where

$$m(0) = \chi j_{spin}/v_F \tag{18}$$

stands for the spin magnetization in the junction region of the SC film with $\chi = v_F L_s/D_s$. Note that I_{spin} is a function of $\delta\mu(0)$, as given in equation (13), and $m(0)$ is proportional to $\delta\mu$, as given in equation (16); they are linked with each other via equation (18), yielding $\delta\mu(0)$ self-consistently. For example, if $L_s = 0$ ($\tau_s = 0$), $m(0)$ is always equal to zero and so $\delta\mu = 0$. This implies that as soon as the spin-polarized currents enter into the SC film, the very short τ_s or the very fast spin flip may lead to a balance between spin-up and spin-down electrons. In this case, there is neither spin imbalance nor a pair-breaking effect. As a result, the superconducting properties of the SC film remain unchanged. In most studies of the FM/SC tunnel junctions, the effects of the spin-polarized injection on the superconducting properties have been neglected [11, 12], corresponding to the above approximation of taking $L_s = 0$.

For nonzero L_s, $\delta\mu(0)$ is determined by equation (18), and a graphical solution is shown in figure 3. For a given bias voltage, the magnetic moment $m(0)$ in the junction region increases linearly with $\delta\mu(0)$, while $\chi j_{spin}/v_F$ decreases with $\delta\mu(0)$. The intersection of the two curves yields the solution for $\delta\mu(0)$. Evidently, the magnitude of $\delta\mu(0)$ depends on L_s; the value of $\delta\mu(0)$ is increased with L_s. If the sample size is much smaller than L_s—such as in the case of the SC film in a FM/SC/FM double tunnel junction [17, 18]—all of the physical quantities will be uniform, including suppression effects of the spin imbalance on the superconductivity and critical current density. Figure 4 shows the critical current density j_c as a function of the injection current I_{in} for different values of χ. With increasing I_{in}, $\delta\mu(0)$ is enhanced and Δ is decreased, resulting in a decrease in j_c. As L_s is increased, the variation rates of $\delta\mu(0)$ and Δ become large, as discussed above. As a result, there is a bigger drop of j_c for a larger L_s. Figure 5 shows I_{spin} ($=j_{spin}A$) and j_c as functions of I_{in} for different barrier strengths. It is found that for a fixed injection current, with increasing barrier strength, j_{spin} becomes large and j_c is decreased. As has been pointed out above, only the single-particle transmission process makes a contribution to the spin current into the SC film. The total current is the sum of the AR current and the single-particle current. As the barrier strength is increased, the AR will be reduced and the single-particle current will make a larger contribution to the total current. As a result, j_{spin} is enhanced and the suppression of j_c becomes substantial.

Finally, we wish to discuss the slightly more complicated structure of the FM/NM/SC tunnel junction, as depicted in figure 1(b). Such a structure has been realized experimentally and the Cooper-pair-breaking effect in the SC due to the injection of spin-polarized quasiparticles

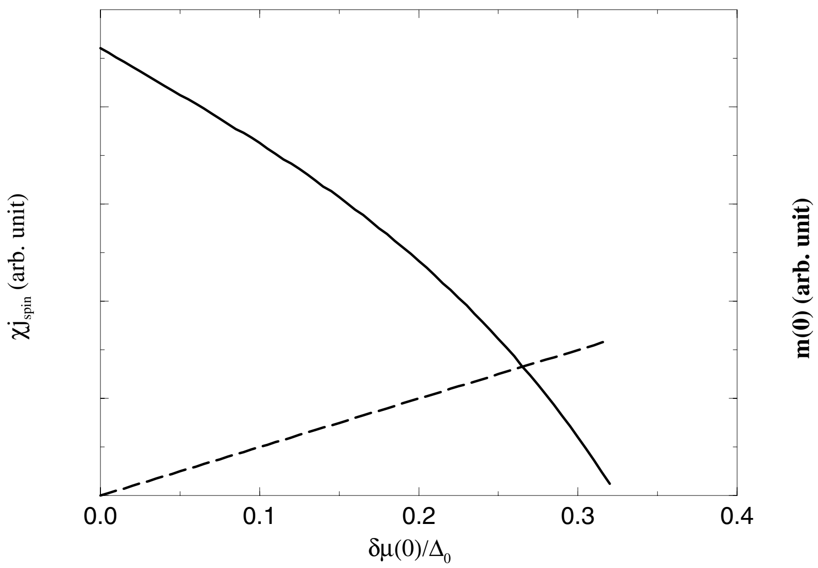


Figure 3. Spin current (solid curve) and spin magnetization (dashed curve) as functions of the chemical difference $\delta\mu(0)$ in the junction region of the SC film, with $eV = 0.5\Delta_0$, $Z_0 = 3$, $P_0 = 0.2$ and $k_B T = 0.2\Delta_0$.

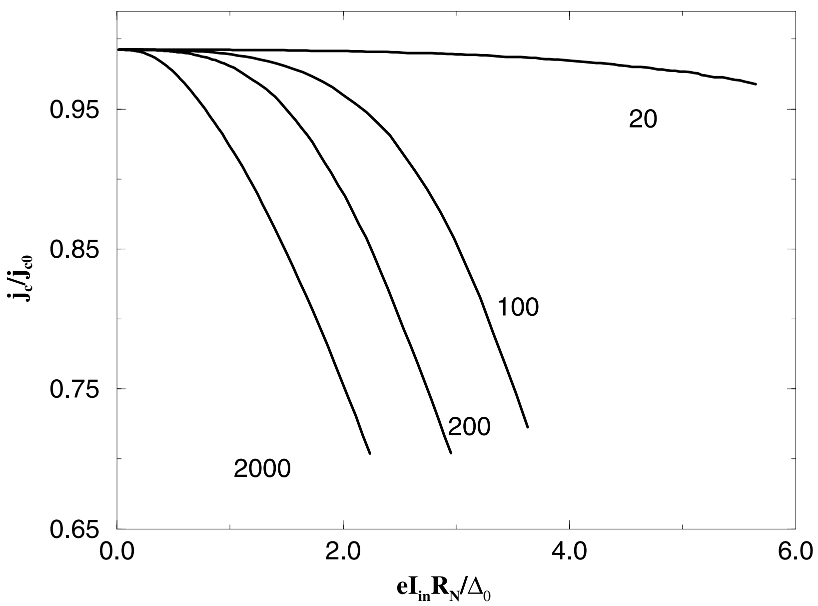
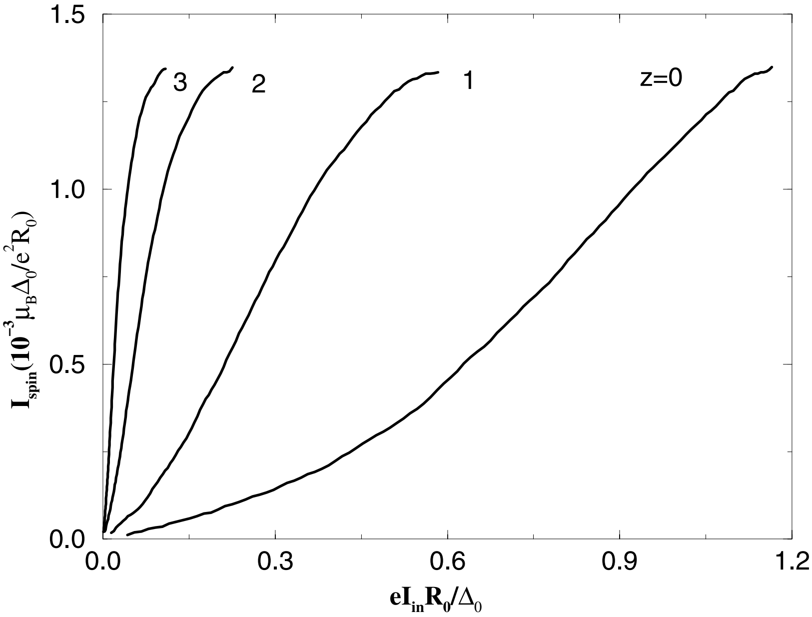
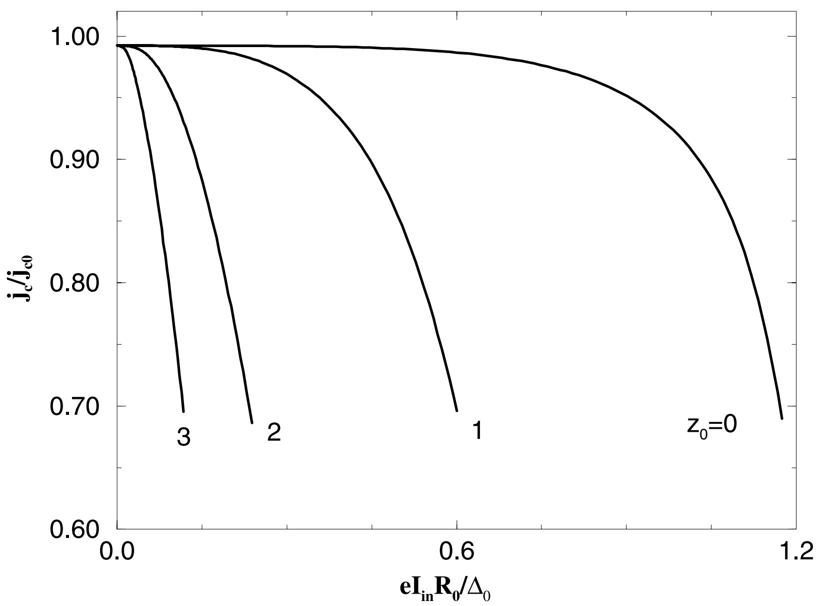


Figure 4. Critical current density j_c as a function of the injection current I_{in} for different values of χ as indicated, with $Z_0 = 3$, $P_0 = 0.2$ and $k_B T = 0.2\Delta_0$.

has been studied [19]. In this case, the spin-polarized current injected from the FM to the NM film undergoes spin relaxation when it passes through the NM film, leading to a decrease of the polarization of the injected current. This relaxation process may be described by $P = P_0 \exp(-d/L_s)$ where P_0 is the polarization of the FM film and d is the thickness



(a)



(b)

Figure 5. Critical current density I_{spin} (a) and spin current j_c (b) as functions of I_{in} for different values of the barrier strength Z_0, with $1/R_0 = N(0)v_F e^2 A$, $\chi = 2000$, $P_0 = 0.2$ and $k_B T = 0.2\Delta_0$.

of the NM film. As a result, the NM film plays a part in reducing the polarization of the current injected into the SC film, replacing P_0 by $P = P_0 \exp(-d/L_s)$. Figure 6 shows j_c as a function of I_{in} for different values of d/L_s. As d is increased, P is reduced due to spin-flip effects

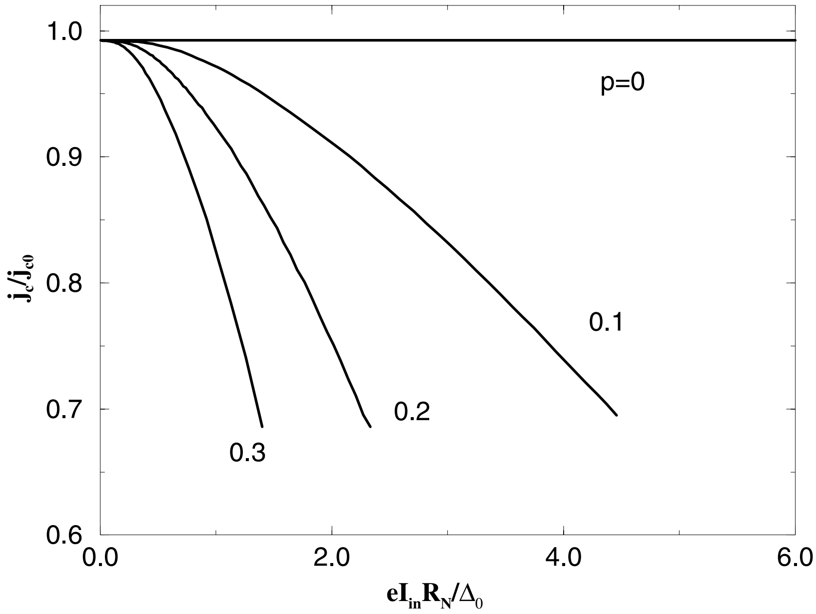


Figure 6. Critical current density j_c as a function of I_{in} for different values of d/L_s as indicated, with $Z_0 = 3$, $\chi = 2000$ and $k_B T = 0.2\Delta_0$.

in the NM film, and so the suppression of j_c becomes small. Since the present calculations are performed in accordance with an s-wave SC, the calculated result cannot be quantitatively compared with experiment [19], where the SC film is a high-T_c system with d-wave pairing. However, the theoretical and experimental results are found to be qualitatively consistent with each other.

In summary, we have studied the spin-polarized transport in FM/SC junctions. The spin-polarized current injected into the SC gives rise to a spin imbalance and a chemical potential difference $2\,\delta\mu$ between spin-up and spin-down electron subbands. The increase of $\delta\mu$ in turn obstructs the injection of the spin-polarized current. A balance of I_{in} and $\delta\mu$ results in a steady nonequilibrium state in the SC and a superconductivity suppression. It is found that the magnitude of $\delta\mu$ depends not only on the bias voltage and the polarization of the injection current, but also on the spin-diffusion length in the SC and the insulating barrier strength at the FM/SC interface.

Acknowledgments

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