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Study of transport properties in superconducting junctions of double insulating barrier

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ABSTRACT

In this work we analyze the Tomasch effect in double barrier insulating superconducting N_1ISIN_2 (N: normal metal, I: insulator and S: superconductor) junctions. From the solution of the Bogoliubov–de Gennes equations we find that the differential conductance presents resonances when the applied voltage changes. These resonances are originated by the formation of quasibound states in the superconducting region and depend on the symmetry of the pair potential. We develop an analytical model in order to find the quasibound states energies and its lifetimes. This model allows us to calculate the voltage at which each resonance appears and the resonance widths. We calculate and analyze the dependence of the transmission coefficients with the thickness of the superconducting layer.

1. Introduction

In high critical temperature superconductivity the symmetry of the pair potential is one of the most widely studied aspects. In a NIS junction with d-symmetry, for instance, the differential conductance has a peak at zero voltage, called zero bias conductance peak (ZBCP) [1–5]. In a N_1ISIN_2, oscillations in the differential conductance called Tomasch effect appear [6]. Andreev reflections [7,8] have been used to explain the oscillations in the differential conductance in graphene and isotropic NISIN junctions [9,10]. Recently the Tomasch effect has been observed in ramp-type junctions [11,12]. Complete studies on the Tomasch effect have been carried out in anisotropic NISN junctions [13]. On the other hand there are not theoretical model for NISIN junctions. In this article we find the differential conductance in terms of the applied voltage for s, $d_{x^2-y^2}$ and d_{xy} symmetries. We solve the Bogoliubov–de Gennes equations (BdGE) in NISIN junctions and we find the differential conductance from electron–electron and electron–hole reflection coefficients. Since the oscillations in the differential conductance are due to the formation of quasibound states, we analyze the energy spectrum and the lifetime of quasiparticles in these states.

2. Differential conductance

If a voltage is applied to an NS interface, it is possible to find the differential conductance at zero temperature by using the BTK model [14] as

$$G_R = \frac{1}{G_N}\frac{dI_S}{dV} = \frac{1}{T}(1 + R_{e-h}(E) - R_{e-e}(E)), \tag{1}$$

where $R_{e-h}(E)$ and $R_{e-e}(E)$ are, respectively, the reflection coefficients electron–hole and electron–electron and G_N is the differential conductance for an NIN junction characterized by a transparency T as defined below.

The system under consideration is illustrated in Fig. 1, where a superconductor is located between two normal regions N_1 and N_2, in $x = 0$ and a. We have included two insulating barriers modeled by potentials $V_1(x) = \gamma\delta(x)$ and $V_2(x) = \gamma\delta(x-a)$ with $\delta(x)$ the Delta Dirac function and γ a parameter that characterizes each barrier, for this model we assume that the planes of CuO_2 of the superconductor are in the $x-y$ plane.

In order to find the coefficients R_{e-h} and R_{e-e} we solve the BdGE when an electron is injected from the normal N_1 with E energy and replace these coefficients on Eq. (1). We find the differential conductance for the double barrier insulating as

$$G_R = \frac{(1+Z^2)}{|D|^2}(|D|^2 + \Gamma + C^2 - Z^2(1+Z^2)|A + CB|^2), \tag{2}$$

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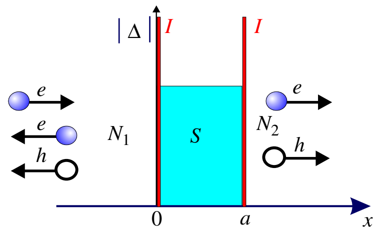

Fig. 1. Double barrier insulating superconducting junction N_1ISIN_2, the electron injected on the junction from normal state metal N_1 can be reflected as an electron, as hole or can be transmitted as an electron or as a hole in the normal metal N_2.

with

$$A = 1 - e^{-i\delta\varphi}\Gamma Q - e^{2ik^+a}(1 - \Gamma Q),$$

$$B = \Gamma - e^{-i\delta\varphi}Q - e^{i(k^+-k^-)a}\Gamma(1 - \Gamma Q),$$

$$C = -\frac{\frac{e^{i(k^-+k^+)a}}{(1-\Gamma Q)}(\Gamma(1+Z^2) - Z^2Qe^{i\delta\varphi}) - Z^2\Gamma}{\frac{e^{2ik^-a}}{(1-\Gamma Q)}((1+Z^2) - Z^2Q\Gamma e^{i\delta\varphi}) - Z^2} \tag{3}$$

and

$$D = 1 + Z^2A + C(\Gamma + Z^2B),$$

$$\Gamma = E - \sqrt{E^2 - |\Delta|^2}, \quad Q = \frac{\Gamma(1 - e^{i(k^+-k^-)a})}{(1 - \Gamma^2 e^{i(k^+-k^-)a})},$$

$$k^{\pm} = \sqrt{k_{0xF}^2 \pm \frac{2m}{\hbar^2}\sqrt{E^2 - |\Delta|^2}},$$

$$k_{0xF} = \sqrt{k_F^2 - k_y^2} \quad \text{and} \quad Z = \frac{m\gamma}{\hbar^2 k_{0xF}}. \tag{4}$$

In these equations $k_{0xF} = k_F\cos\theta$, k_F is the Fermi wave number, Z is the insulating barrier strength, so that transparency is given by $T = 1/(1+Z^2)$ and Δ is the pair potential of the superconductor modeled as $\Delta(\mathbf{k},\mathbf{r}) = \Theta(x)\Theta(x,a)\Delta(\mathbf{k},x)$, where $\mathbf{k}$ is the quasiparticles wave vector and $\Theta(x)$ is the Heaveside function. For a d-symmetry it is possible to write the pair potential $\Delta(\theta) = \Delta_0\cos(2\theta - 2\alpha)$, where α is the angle between the a axis of the CuO_2 planes and the vector normal to the interface, θ is the angle of the injected electron respect to the x axis. When $\alpha = 0$ we have a $d_{x^2-y^2}$ symmetry, $\Delta(\theta) = \Delta_0\cos(2\theta)$ and for $\alpha = \pi/4$ we have a d_{xy} symmetry, $\Delta(\theta) = \Delta_0\sin(2\theta)$.

When $Z = 0$ we have an NSN junction. From Eq. (2) the differential conductance is given by

$$G_R = 1 + \left|\frac{\Gamma(1 - e^{i(k^+-k^-)a})}{1 - \Gamma^2 e^{i(k^+-k^-)a}}\right|^2. \tag{5}$$

Resonances for different voltage values appear in G_R, as shown in Fig. 2 for $Z = 0$. These resonances are due to interference of the transmitted quasiparticles at $x = 0$ and the reflected quasiparticles at $x = a$ and can be found from

$$eV = (\pi(2n+1)E_F)^2(k_Fa)^{-2}\cos^2(\theta) + |\Delta(\theta)|^2. \tag{6}$$

The energy values in (6) agree with the values found in [13]. Fig. 2 shows the differential conductance as a function of the applied voltage for an NISIN junction and for different values of Z. For $Z = 1$ and $eV > \Delta_0$, we find that the number of resonances is greater for a d_{xy} symmetry than for $d_{x^2-y^2}$ symmetry. In addition one resonance to zero voltage appeared for the conductance on d_{xy} symmetry. These differences are due to the resonant states energy are affected by the pair potential anisotropy. For the two considered symmetries the width of resonances diminishes as Z increases.

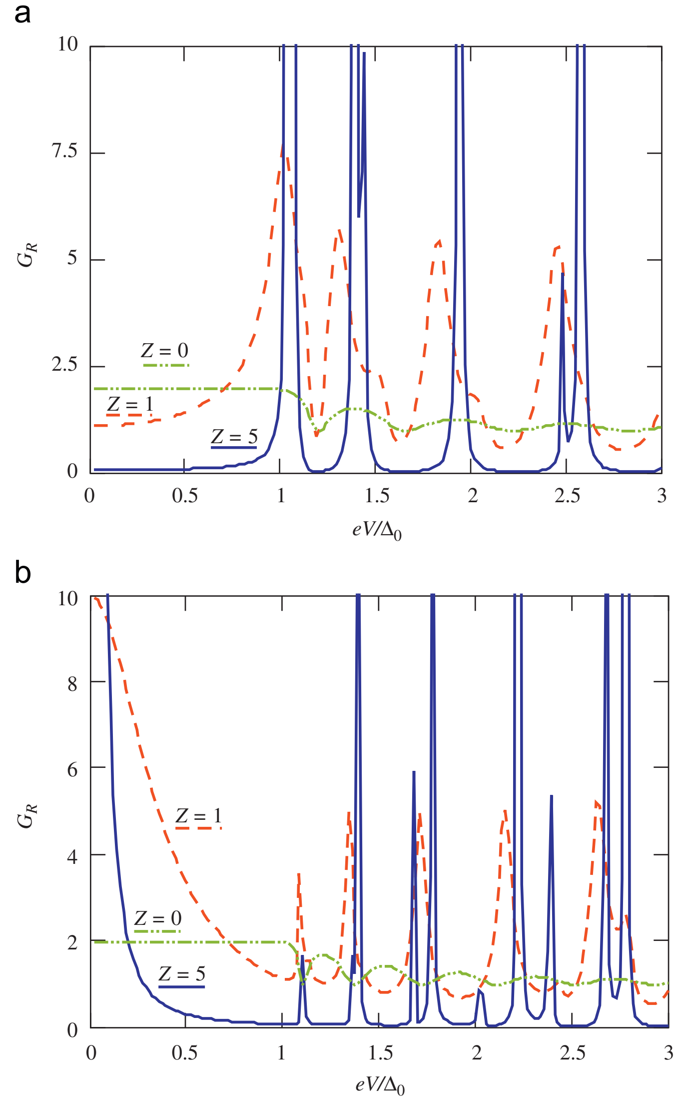

Fig. 2. Differential conductance $G_R(E = eV)$ in an NISIN junction for different values of the insulating barrier strength Z. (a) $d_{x^2-y^2}$ symmetry, (b) d_{xy} symmetry. In both cases the superconducting region width is $a = 15\xi_0$, where ξ_0 is the coherence length.

3. Resonances in the differential conductance

The voltage for which the differential conductance presents oscillations can be found from the poles in the denominators of the transmission coefficients. For the tunnel limit ($Z \gg 0$) this voltage can be found from the energy spectrum of a superconductor film. From the solution of the BdGE the energy spectrum for s and $d_{x^2-y^2}$ symmetries is the same

$$E_n = \sqrt{|\Delta|^2 + \left(\frac{\hbar^2}{2m}\left(\left(\frac{n\pi}{2a}\right)^2\right) - k_{0xF}^2\right)^2}, \tag{7}$$

where n is a whole number. In Fig. 3a we show the resonant energy values for G_R and the energies obtained from Eq. (7). It is seen that the resonances are caused by the formation of quasibound states in the superconducting region.