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Analysis of Quasi-Particle Tunneling Probabilities in a Superconducting Base Transistor Using the Bogoliubov Equations of Motion

Tetsuya YAMAMOTO, Hiroshi SUZUKI, Tatsuro USUKI,
Yorinobu YOSHISATO and Shoichi NAKANO

Functional Materials Research Center, *SANYO* Electric Co., Ltd.
1-18-13, Hashiridani, Hirakata, Osaka 573, Japan

We present a systematic method for calculating the quasi-particle transmission T and reflection R probabilities for the N/I/S emitter-base tunneling junction and base-collector heterojunction in a superconducting base transistor. T and R were calculated from the first principles using the Bogoliubov equations. For the YBCO/n-InGaAs base-collector interface with a Schottky barrier height of 70 meV, it was found that T was greater than 0.5. This suggests that a combination of YBCO and n-InGaAs is suitable for use in the base-collector heterojunction of a superconducting base transistor. We also show the I-V curve for the N/I/S tunneling junction.

1. INTRODUCTION

The exciting technological promise of high-Tc superconductors has given birth to considerable efforts in investigating the fabrication of electronic switching devices using high-Tc superconductors. In recent years, superconducting three-terminal devices have attracted great interest because they make it easy to construct complicated circuits. The low-energy type superconducting base transistor (Fig. 1), proposed by Frank et al.,[1] is one of the promising three-terminal devices. It is expected to enable the realization of both low-power consumption and high-frequency response. This transistor has a junction structure composed of a superconductor (S), a normal-metal (N), an insulator (I), and a semiconductor (SE), i.e., N/I/S (or S/I/S) tunneling emitter-base junction and S/SE base-collector heterojunction, as shown in Fig. 1. Its operating principles are similar to those of a conventional bipolar transistor : minority carriers are quasi-particles and majority carriers are Cooper pairs.

In a previous paper[2], we investigated the quasi-particle transport properties in the superconducting base layer using Monte-Carlo simulation. However, in order to clarify the characteristics of this transistor, it is necessary to calculate the quasi-particle transmission and reflection probabilities at the N/I/S (or S/I/S) and S/SE junction interface. Those probabilities were calculated for restricted potential barrier cases[3,4]. In this paper, we present for the first time a systematic method for calculating the probabilities of quasi-particle transmission (T) and reflection (R) across the arbitrary potential barrier at the N/I/S and S/SE interface in a superconducting base transistor. The T and R were calculated from the first principles using the Bogoliubov-de Gennes[5] equations of motion.

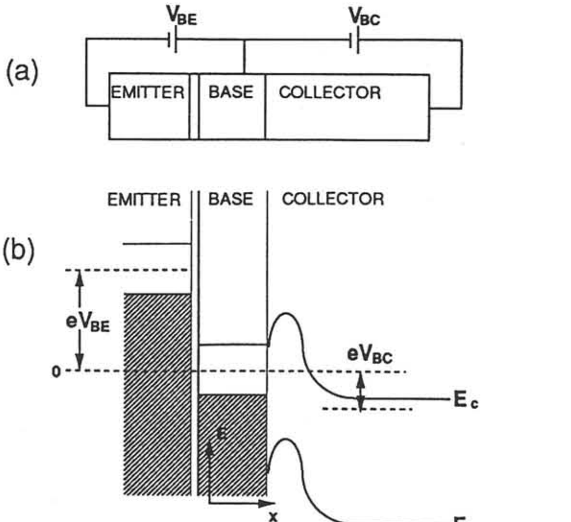

Fig. 1 Superconducting base transistor. (a) is the general structure of the transistor. (b) is the schematic energy diagram.

2. CALCULATION PROCEDURE

In the BCS approximation, the excitations in a superconductor (quasi-particles) are described by the coupled Bogoliubov-de Gennes equations

$$\begin{cases} Eu(x) = \left[-\dfrac{\hbar^2}{2m}\dfrac{\partial^2}{\partial x^2} - \varepsilon_F + U(x) \right] u(x) + \Delta(x)v(x) \\ Ev(x) = \left[\dfrac{\hbar^2}{2m}\dfrac{\partial^2}{\partial x^2} + \varepsilon_F - U(x) \right] v(x) + \Delta(x)u(x) \end{cases}$$

Here, E denotes the quasi-particle energy, u(x) is the electron-like wave function and v(x) is the hole-like wave function. It should be noted that the potential U(x) is measured with respect to the Fermi energy ε_F, and the energy gap $\Delta(x)$ undergoes step-function changes (i.e. $\Delta(x)=\Delta$ for the superconducting region, $\Delta(x)=0$ for the normal region) as shown in Figs. 2 and 5. In the present calculation, instead of dealing with continuous potential energy, we split the potential barrier U(x) into segments, in which potential energy can be regarded as a constant. The potential energy U(x) and effective mass are approximated by the multi-step function[6]. We expanded the method described in Ref. 3 to the case of the multi-step potential. By matching the value and slop of u and v at each boundary, we can determine the quasi-particle transmission T and reflection R probabilities.

3. RESULTS

Assuming that the high-Tc superconductor YBCO obeyed the BCS theory and that the system was isotropic, we calculated T and R using the YBCO parameters (Δ=20 meV, ε_F=2 eV). The N/I/S tunneling junction (Fig. 2) and the S/SE heterojunction (Fig. 5) were analyzed.

(i) N/I/S tunneling junction (emitter-base)

The T and R were calculated as functions of quasi-particle energy E, potential barrier height U_0 and width L in the N/I/S tunneling junction under the biasing condition as shown in Fig. 2. To examine the validity of the present method, we calculated the T and R in the two limited cases. Within the limits of $L \rightarrow 0$, we found that T and R fit smoothly into the expression obtained by Andreev[7] for the N/S junction. Moreover, within the limits of $E \ll U_0$, we found that our results were reduced to the expression obtained by Griffin and Demers[3].

The T and R for the N/I/S tunneling junction under biasing conditions are plotted in Fig. 3, where "A" shows the probability of Andreev reflection, "B" the probability of ordinary reflection, "C" the probability of ordinary transmission without branch crossing, and "D" the probability of transmission with branch crossing. The transmission probabilities "C" and "D" rise at E=Δ. For low-energy quasi-particles (E~Δ), "C" is markedly different from the normal-electron transmission probability calculated by the Schrödinger equation (dotted lines in Figs. 3 and 6). Andreev reflection probability "A" is also observed as well as the case of the N/S junction[7].

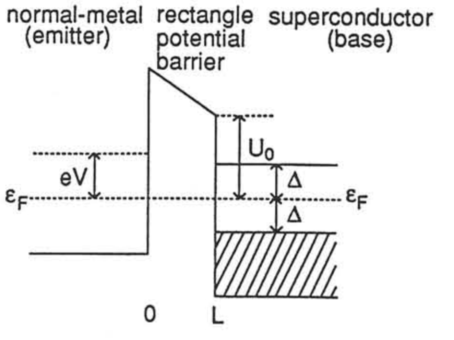

Fig. 2 Potential barrier shape for the N/I/S emitter-base tunneling junction under biasing conditions. V is the applied voltage at the junction.

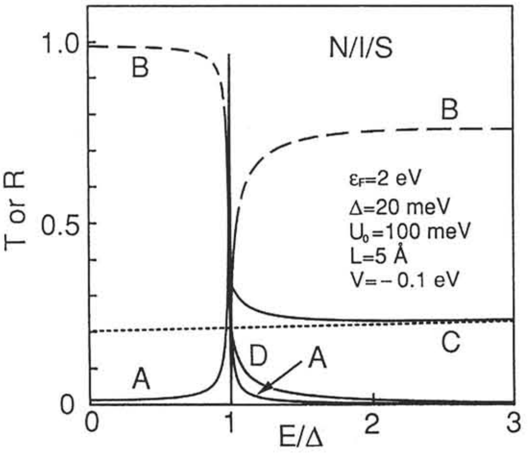

Fig. 3 Plots of transmission and reflection probabilities as a function of the quasi-particle energy. The dotted line indicates the transmission probability calculated by Schrödinger equation.

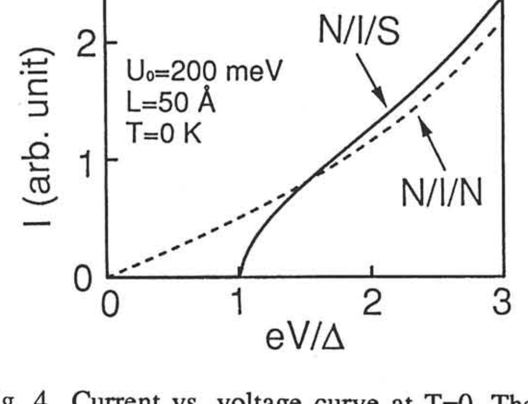

Fig. 4 Current vs. voltage curve at T=0. The dotted line denotes the I-V curve for N/I/S tunneling junction.

We also computed the I-V curves using the transmission and reflection probabilities ("A","B", "C" and "D") within a generalized semiconductor model[4]. The I-V curve of the N/I/S tunneling junction, where U_0=200 meV, L=50 Å and T=0 K, is shown in Fig. 4. We found excess current generated by Andreev reflection and non-linear I-V characteristics, due to the finiteness of U_0 and L, in the high voltage (eV>2Δ) region.

(ii) S/SE heterojunction (base-collector)

We worked out the quasi-particle transmission probability (corresponding to "C" in Fig. 3) from the superconducting to the semiconducting region across the Schottky barrier (Fig. 5), which was formed at the S/SE interface. The result is shown in Fig. 6. For a YBCO/n-$In_{0.53}Ga_{0.47}As$ base-collector interface with a Schottky barrier height of U_0=70 meV[8], the transmission probability is greater than 0.5 for E>Δ, as shown in Fig. 6. On the other hand, for Nb, the transmission probability is under 0.1 for E<5Δ. This suggests that a combination of YBCO and n-$In_{0.53}Ga_{0.47}As$ is suitable for use in the base-collector heterojunction of a superconducting base transistor.

We also took into consideration the effect of the image-force potential which lowers the Schottky barrier height U_0. We adopted a "MacColl" type[9] potential barrier (solid-line in Fig. 6) for calculations. In the YBCO/n-$In_{0.53}Ga_{0.47}As$ case, the barrier lowering due to the image-force potential energy is about 30 meV. The transmission probability increases, except for the low energy part, by introducing the image-force potential energy. It was found that the image-force potential energy plays an important role in obtaining a high current gain in the transistor.

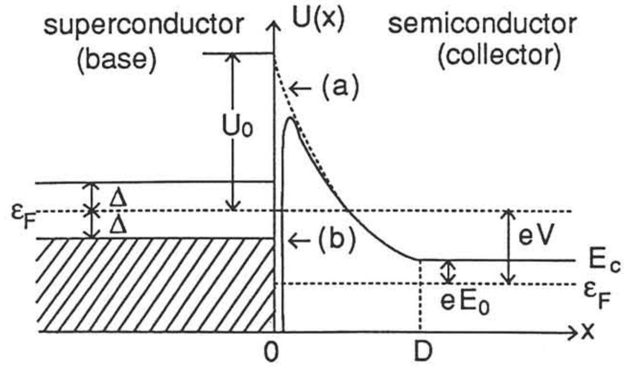

Fig. 5 Schottky barrier model at the interface between the superconducting base and the semiconducting collector. (a) denotes the Schottky barrier without image-force potential. (b) denotes the Schottky barrier with image-force potential.

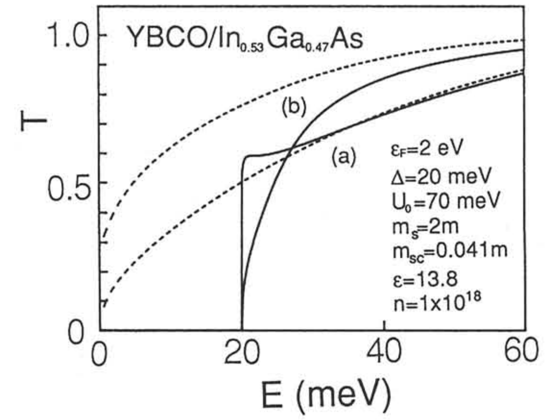

Fig. 6 Transmission probability T for YBCO/n-InGaAs heterojunction. (a) is the case without image-force potential, (b) is the case including the image-force potential. ε is the dielectric constant of the semiconductor, n the density of the donor, and m_s and m_{sc} the effective masses of the superconductor and semiconductor,respectively. The dotted line indicates the transmission probability calculated by Schrödinger equation.

4. CONCLUSION

We proposed a systematic method for calculating the quasi-particle transmission T and reflection R probabilities across an arbitrary potential barrier using the Bogoliubov equations of motion. Applying the present method, we analyzed the N/I/S emitter-base tunneling junction and S/SE base-collector heterojunction. The I-V curve for the N/I/S junction was computed within a generalized semiconductor model. For a YBCO/n-$In_{0.53}Ga_{0.47}As$ heterojunction with a Schottky barrier height of 70 meV, quasi-particle transmission probability was greater than 0.5 for E>Δ. It was clarified that high-Tc superconductors were suitable materials for transistor activity.

ACKNOWLEDGMENT

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