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Josephson currents in *c*-axis and ab-plane orientated MgB_2/normal-metal/MgB_2 tunnel junction

Bumned Soodchomshom [a,c], Rassmidara Hoonsawat [a], I-Ming Tang [a,b,*]

[a] *Department of Physics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand*
[b] *Institute of Science and Technology for Research and Development, Salaya Campus, Mahidol University, Nakorn Pathom 71730, Thailand*
[c] *Department of General Education, Faculty of Science, Pathumwan Institute of Technology, Bangkok 10330, Thailand*

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Abstract

The critical Josephson currents in a $S_1/N/S_2$ double interfaces tunnel junction are calculated by using the linearized Usadel equation to derive the anomalous Green's function in the normal-metal layer (N). Both of the S_1 and S_2 layers are formed by MgB_2 but due to the proximity effect have different characteristics. Two orientations of the MgB_2 superconductors are considered. In one junction, the *c*-axis of MgB_2 in the S-layer is perpendicular to the interface, while in the other, the ab-plane is perpendicular to the interface. The different transparencies of the two MgB_2/normal-metal interfaces, the normal state resistances of the currents flow from S_1 to S_2 in each band and the N-layer thickness are taken into account. The critical Josephson currents in both the *c*-axis and ab-plane oriented junctions are studied near the critical temperature. The predicted currents are compared with the experimental currents and are seen to fit the data above $0.4T_C$.

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1. Introduction

The importance of the MgB_2 [1] superconductor with a T_c of ~39 K is due to the presence of two types of Cooper pairs (energy gaps) in this superconductors. The two gaps arise from the existence of the two types of electrons in MgB_2, one which exhibits two-dimensional (2D) properties and the other, three-dimensional (3D) properties. The two gaps have been observed in tunneling experiments [2,3]. The 3D band is called the π-band and the other, the 2D band is called the σ-band. The order parameter Δ_π in the π-band is smaller than the order parameter Δ_σ in the σ-band. The two order parameters have the same critical temperature but exhibit different temperature dependences [2,3]. Both gaps have been shown to posses *s*-wave symmetry [4,5]. At $T = 0$ K, the measured energy gap in the σ-band is between 5.6 and 7.8 meV, and that in the π-band, between 1.7 and 3.8 meV.

The quasi-particle tunneling in MgB_2 for the N/S tunnel junctions has been studied by Iavarone et al. [3]. Two-gap behaviors were found in the current flow in a junction where the ab-plane of MgB_2 is perpendicular to the interface. The two peaks in the conductance spectra became smaller as the temperature was increased. The current flow when the *c*-axis is perpendicular to the interface yielded a conductance spectra in which the double peak behavior was absence. Part of this is due to the fact that the electrons carrying the current in this direction are the quasi-particles in the π-band. Experiments on determining the conductance

* Corresponding author. Address: Department of Physics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand. Tel.: +66 2 2015758; fax: +66 2 3547159.
E-mail address: scimt@mahidol.ac.th (I.-M. Tang).

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spectra such as N/MgB_2 tunnel junction have attracted much attention [7–9], especially when comparison with theoretical conductance spectra was made. The theoretical spectra were derived on basis of the BTK theory [2,6].

Additional comparison between experiment and theory regarding superconductivity in a two band superconductor can be made through the study of the Josephson effect in MgB_2. Brinkman et al. [10] have obtained expressions for the critical currents in S/I/S tunnel junctions which takes into account the Josephson effect. Many experimental studies have also been reported [11–15]. In their work, Brinkman et al. assumed that the critical Josephson current along the *c*-axis of an S/I/S tunnel junction having the *c*-axis perpendicular to the interface is carried by the BCS pairs from a single band (π-band). Their expression for the Josephson current exhibited temperature dependence different from that expected of conventional S/I/S tunnel junctions. This is due to the fact that the Josephson current flowing through an MgB_2 Josephson tunnel junction is influenced by the tunneling of electron pairs from the π- and σ-bands. The tunneling causes a change in the superconductivity on the side the tunneling is into (S_2 side).

In this paper, the formula for the critical Josephson current in the MgB_2/normal-metal/MgB_2 junction with double interfaces barriers valid near the critical temperature, are derived. The derivation is achieved by using the linearized Usadel equation [16,17] to derive the anomalous Green's function in N-layer. The proximity effect tunneling causes the MgB_2 superconductors on the two sides of the S/N/S junction to have slightly different properties. These differences in turn cause the transparencies of the two MgB_2/normal-metal interfaces to be different. The difference in the normal state resistances of the currents flow from S_1 to S_2 for each band and the N-layer thickness are also taken in to account. The expressions for the Josephson current in both the *c*-axis and ab-plane oriented directions are then compared with the published experimental data.

2. Formalism

The junctions considered in this paper are of two types; junctions where the *c*-axis or the ab-plane of the MgB_2 superconductor is perpendicular to the interface (see Fig. 1). For the *c*-axis orientation (Fig. 1a), the Josephson tunneling current, I_s, assumed to be carried by the π-band BCS pairs on the S_1 side as they tunnel into the BCS pairs in the π′-band on the S_2 side, is derived. For this, I_s can be expressed as $I_s \sim I_{\pi\pi'}$. The normal state resistance R_N for this case is due to the BCS pairs in π-band and so $R_N \sim R_{N\pi}$. We denote γ_{B1} and γ_{B2} as the transparency of the interfaces at S_1/N and at N/S_2, respectively. For the ab-plane orientation (Fig. 1b), the Josephson tunneling current is due to the tunneling of the π-band BCS pairs of S_1 into the π′-band BCS pairs of S_2 and by the tunneling of the σ-band BCS pairs of S_1 into the σ′-band BCS pairs of S_2. We note that there is no tunneling of the π (σ) BCS pairs of S_1 into the σ′(π′) BCS pairs of S_2. The

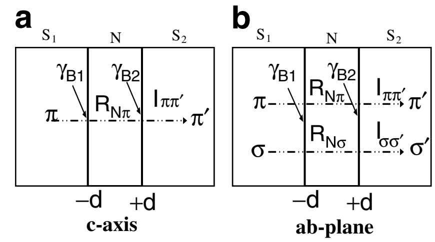

Fig. 1. Schematic presentation of tunneling currents carried by electrons from π-band in S_1 (a) and from both π- and σ-bands in S_1 (b) tunneling into each respective band in $S_1/N/S_2$ Josephson junctions for *c*-axis and ab-plane orientations respectively. Geometries of the considered $S_1/N/S_2$ constructed by the different MgB_2. The N-layer thicknesses in both systems are 2*d*.

normal state resistance in the ab-plane orientation can be expressed as $R_N \sim (R_{N\pi} + R_{N\sigma})/R_{N\sigma}R_{N\pi}$ [18], where $R_{N\pi}$ is the normal state resistance for the electrons flowing from the π-band of S_1 to the π′-band of S_2 in normal states, and $R_{N\sigma}$ is the normal state resistance for the electrons flowing from the σ-band of S_1 to σ′-band of S_2 in normal states. The Josephson current for this orientation can be expressed as $I_s \sim I_{\pi\pi'} + I_{\sigma\sigma'}$.

The electron scattering mean free paths in a $S_1/N/S_2$ junction are usually small. In the dirty limit, the angular dependence of the Green's function is weak [17]. We adopt the Usadel equation to describe the normal Green's functions $G(x,\omega)$ and the anomalous Green's functions $F(x,\omega)$ averaged over the Fermi surface in $S_1/N/S_2$ system [16,17]. The Usadel equations are given by

$$-\frac{D(x)}{2}\left[G(x,\omega)\frac{\partial^2}{\partial x^2}F(x,\omega) - F(x,\omega)\frac{\partial^2}{\partial x^2}G(x,\omega)\right] + \omega F(x,\omega) = \Delta(x)G(x,\omega) : G^2(x,\omega) + F(x,\omega)F^*(x,\omega) = 1, \quad (1)$$

where $D(x)$ is the diffusion coefficient in N-layer (in this study, we let $D(x) \sim D_N$); $\Delta(x)$, the order parameter and ω is the Matsubara frequency defined by $\omega_n = \pi k_B T(2n+1)$. In the low transparency case, i.e., $\gamma_{B1,2} \gg 1$ and where the temperature T of S_1 and S_2 is close to T_c and $F(x,\omega)$ within the N-layer is small and $G(x,\omega_n) \sim \mathrm{sgn}(\omega_n)$, the Usadel equation in N-layer becomes linearized [17], i.e.,

$$\left[-\frac{D_N}{2}\frac{\partial^2}{\partial x^2} + |\omega|\right]F_N(x,\omega) = 0 \quad (2)$$

To derive the anomalous Green's function in Eq. (2), the boundary conditions [17,19] are matched at the S_1/N and N/S_2 interfaces ($x = \mp d$). This yields

$$\gamma_{B1}\xi_{n1}\partial_x F_N(x,\omega)|_{-d} = -G_{S1}\left\{\frac{\Delta_1}{\omega} - F_N(-d,\omega)\right\}\mathrm{sgn}(\omega) \quad (3)$$

$$\gamma_{B2}\xi_{n2}\partial_x F_N(x,\omega)|_{+d} = +G_{S2}\left\{\frac{\Delta_2}{\omega} - F_N(+d,\omega)\right\}\mathrm{sgn}(\omega), \quad (4)$$

where $G_{S1,2} = \omega/\sqrt{\omega^2 + \Delta_{1,2}^2}$, where $\Delta_{1,2} = |\Delta_{1,2}|\exp[\mp i\varphi/2]$, with ϕ being the phase difference between S_1 and S_2,