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Spectrum of Constrained Electronic States in Heterostructures Formed with Superconductor and Ferromagnetic Metals

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Abstract—The dependence of ballistic Josephson’s current though heterostructures superconductor–ferromagnetic metal–isolator–ferromagnetic metal–superconductor (SF$_1$–I–F$_2$S) on the heterostructure’s parameters is calculated. The conditions, under which a significant increase in the considered Josephson’s current may be observed, are suggested.

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INTRODUCTION

Research of transport characteristics of multilayered structures consisting of thin superconducting (S) and ferromagnetic (F) films represents a vital problem with direct practical output [1]. One example of such device is a hybrid system composed of two SF-bilayers separated by a thin isolator (I). Similar SFIFS heterostructure may serve as a switch in various radio-electronic devices since the value of the Josephson’s current, passing through it, significantly depends on the direction of magnetizations in two ferromagnetic layers [1]. The aim of this paper is a sequential quantum-mechanical calculation of influence of mutual magnetizations orientation on the superconducting current in the SFIFS heterostructure.

ELECTRON IN THE BARRIER OF THE JOSEPHSON’S CONTACT

It is a well known fact [2] that electron in a single-dimensional potential pit (isolator–normal metal–isolator I–N–I), i.e. in a thin metal film (N) bounded on two sides with a semifinite isolator spaces, forms at least one constrained state with energy $\varepsilon < U$, where electron’s energy ε is calculated with respect to a unarychemical potential of the heterostructure, while ε is the distance from μ to the bottom of the conductivity zone of the isolator. A constrained state may be formed for electron when $\varepsilon < \Delta_0$ (Δ_0 is the superconductor’s slot) and in the heterostructure superconductor–normal metal–superconductor (S–N–S) while the differences between the two types of reflections (Andreyevskiy [3] and common) are easily demonstrated using quasiclassical description. Under common reflection of electron from isolator (I) which occupies half space, a normal to which is the axis, the *x*-component of the wave vector for electron with energy $\varepsilon < U$ changes its sign while its longitudinal component remains unchanged. However, if we speak about superconductor, then electron with energy $\varepsilon < \Delta_0$ reflects from the N/S-boundary as a hole while the produced Cooper pair goes to superconductor. In this case the wave vector for the hole $k_{\rm h}$ practically coincides with the one for electron $k_{\rm e}$, though it moves in the opposite direction with respect to $k_{\rm e}$. There are two waves in metal: forward $\exp(\mathrm{i}k_{\rm e}x)/\sqrt{k_{\rm e}}$ and reflected $\exp(-\mathrm{i}k_{\rm e}x)/\sqrt{k_{\rm e}}$, where $\hbar k_{\rm e} = \sqrt{2m(\mu+\varepsilon)}$. Their linear combination should equal zero at the boundary metal–isolator for $x = 0$, i.e. the coefficient for the reflected wave should be equal –1 (amplitude of the reflection in this case equals to the product of the reflection coefficient $r_{\rm e} = -1$, which corresponds to a full reflection, and the wave function $\exp(-\mathrm{i}k_{\rm e}x)/\sqrt{k_{\rm e}}$). If the isolator is substituted with a superconductor, then the reflection’s nature will become radically different. The wave functions of quasipartial states in the superconductor are a combination of the hole and electron excitations and, as known [3], represent two-component wave functions