ole of normal layer in ferromagnetic osephson junctions

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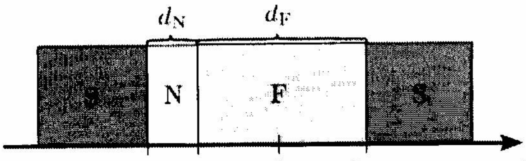
SIsFS в пределе

Using the Usadel equation approach, we have calculated the critical current density in ferromagnetic (F) Josephson junctions of different types containing insulating (I) and normal metal (N) layers in the weak link region. Even a thin additional N layer may change the boundary conditions at the SF or IF interface, where S is a superconducting electrode. We show that inserting an N layer may increase the critical current density Jc and shift the 0-π transition to larger or smaller values of the thickness dF of the ferromagnet, depending on the boundary parameters.

e coexistence and competition of ferromagnetic and erconducting ordering leads to a rich spectrum of sual physical phenomena, intensively studied dur- the recent years [1,2]. One of the consequences is so-called π Josephson junction with phase shift π in ground state. One or two insulating (I) barriers may introduced at the SF interfaces as well, in order to rge the product J_c R_N in the π-phase. Here J_c is the ical current density of the junction and R_N is its mal resistance.

wadays, the development of magnetic memory cells rapid single flux quantum (RSFQ) logics becomes e and more actual [3]. Only recently, a new type of gnetic memory element based on FJJs with a com- x ferromagnet-superconductor-insulator weak link sFS) was proposed [4,5]. These FJJs have a large J_c product in the π-phase, which is required for the ble work of such junctions in devices. The middle erconducting "s" layer is inserted in the weak link ecover the superconducting pairing and increase J_c. thickness of this layer is of the order of the coher- e length so that it may make a transition to the nor- state at different conditions than the thick outer S trodes. One of the aims of our calculation is to y the behavior of such SIsFS FJJs when their mid- superconducting layer is in the normal state.

oducing a normal metal (N) layer between the F r and the S electrode into an FJJ is technologically ssary. Such an additional N layer was used in y FJJs. However, it was not taken into account by theoretical explanation of these experiments. The phson junction we consider consists of two thick S electrodes enclosing a thin N and an F layer (Fig.1). The N layer has a thickness d_N, while the F layer has a thickness d_F. In our model, an additional N layer at the FS interface as well as insulating layers at the SN or FS interfaces can easily be considered.



→ меняет гран. усл.

Fig 1. The sketch of one type of the considered junctions.

We calculate the critical current density J_c of these configurations by determining their Green's functions in the ``dirty" limit. We determine the Green's functions with the help of the Usadel equations, which we use in theta parametrization. The Kupriyanov-Lukichev boundary conditions at all interfaces were used.

It was shown earlier [6-9] that insulating barriers decrease the critical current density and shift the 0-π transitions to smaller values of the ferromagnet thickness d_F. A thin N layer inserted between S and I layers does not significantly influence the Josephson effect. However, if the N layer is inserted between I and F layers, it can have a large effect on the $J_c(d_F)$ curve. If additionally the transport properties of the F and N layers differ significantly (γ_{NF} <<1), the presence of the N layer increases the amplitude of J_c and shifts the first 0-π transition to larger dF, see Figs. 2(b,c,d).

The oscillation period of $J_c(d_F)$ is still determined by the relation of the magnetic exchange energy H and the diffusion coefficient D_F in the dirty limit. If the

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влиян. I слоя } => сдвигает точку 0-π перехода в обл. больших d_F/з transport properties of the N layer are the same as those of the ferromagnet, the $J_c(d_F)$ pattern does not change. This means in particular, that the dead layer plays only a role if its properties differ from the ones of the ferromagnet, not only in terms of the absence of ferromagnetism, but also in terms of its resistance. The smaller the value of γ_{NF}, the larger is the change of the J_c amplitude and the shift of the 0-π transitions, see Figs.2 (f,g,h). The situation is completely different in the case of transparent SF interfaces without an I layer in between. In this case the additional thin normal layer with conductivity much larger than one of the ferromagnet ($\gamma_{NF} << 1$) does not play any role. In the same setup, an N layer with transport properties similar to the ones of the ferromagnet ($\gamma_{NF} \sim 1$) provides a decrease of the J_c amplitude and a shift of the 0-π transition to smaller d_F, see Fig.2(e). This happens because the Josephson phase drops partially across the N layer.

Even a thin additional N layer may change the boundary conditions at the IF boundary depending on the value of γ_{NF}. It effectively mitigates the effect of the insulating barrier on the decaying oscillations of the critical current density Jc (d_F). Even technological thin N layers, which almost do not suppress the superconducting correlation, have to be taken into account for the explanation of experimental results for FJJs. For example, the 0 and π states in FJJs proposed recently [10] for a cryogenic magnetic memory, should be determined very carefully.

References

1. A. I. Buzdin, Rev. Mod. Phys. 77, 935 (2005).
2. A. A. Golubov, M. Y. Kupriyanov, and E. Il'ichev, Rev. Mod. Phys. 76, 411 (2004).
3. E. Goldobin, H. Sickinger, M. Weides, et. al. Appl. Phys. Lett. 102, 242602 (2013).
4. S. V. Bakurskiy, N. V. Klenov, I. I. Soloviev, et. al. Appl. Phys. Lett. 102, 192603 (2013).
5. T. I. Larkin, V. V. Bol'ginov, V. S. Stolyarov, et. al. Appl. Phys. Lett. 100, 222601 (2012).
6. A. S. Vasenko, A. A. Golubov, M. Y. Kupriyanov, et. al. Phys. Rev. B 77, 134507 (2008).
7. A. Buzdin, JETP Lett. 78, 1073 (2003).
8. A. Buzdin, I.Baladie, Phys. Rev. B 67, 184519 2003.
9. M. Faure, A. I. Buzdin, A. A. Golubov, et. al. Phys. Rev. B 73, 064505 (2006).
10. Y. Wang, W. P. Pratt, and N. O. Birge, Phys. Rev. B 85, 214522 (2012).

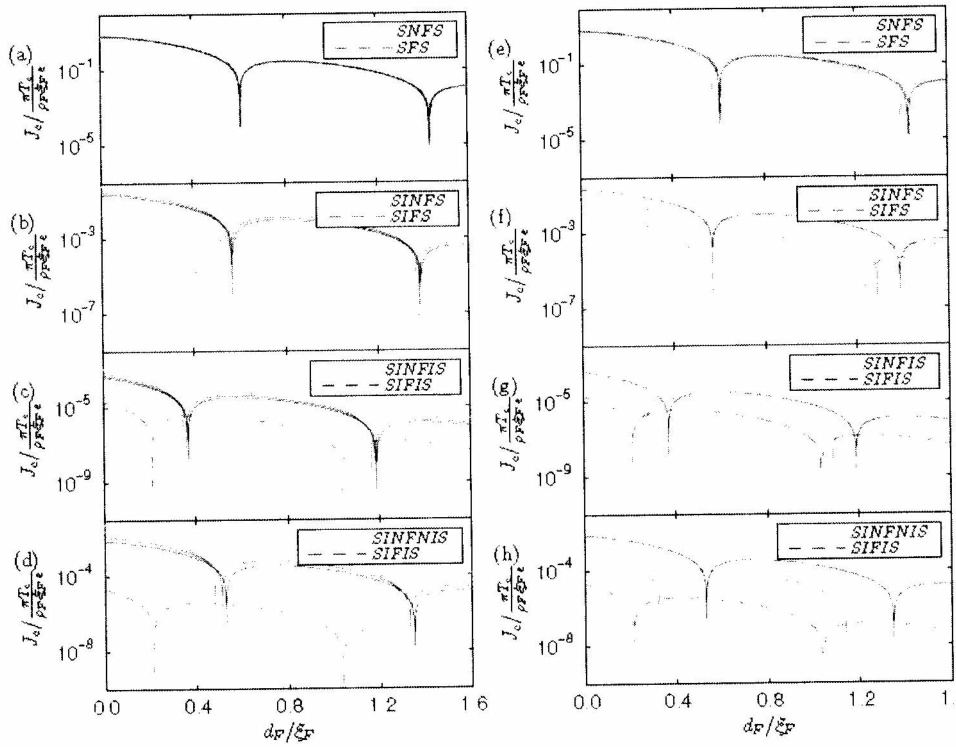

Fig 2. The critical current density Jc(dF) for different FJJs. Solid lines are for the structures with different thicknesses of N layer, th dashed lines are the solutions without the N layer. In Figs. (a-d) the solid lines are getting darker as dN becomes thicker. In Figs.2 (h) the solid lines are getting darker with decreasing the suppression boundary parameter γNF =1, 0.1, 0.01.