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Reconstruction of the DOS at the end of a S/F bilayer

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Active development of superconducting spintronics, caloritronics and spin caloritronics raised a renewed interest in studying hybrid structures of superconductors and ferromagnets. In the present work we study the reconstruction of the density of states (DOS) at the closed end of the superconductor when it is a part of a S/F bilayer. It is very well known that for a conventional s-wave superconductor the DOS is of the bulk BCS-like shape even in the vicinity of the surface. It is also known that for s-wave superconductivity a magnetic surface or interface with a magnetic insulator is pair breaking and the Andreev surface bound states can arise at such a surface or interface [1–4].

In the present paper we investigate the influence of a conventional nonmagnetic surface on the DOS in a spin-split superconductor. It is easily seen that for a case of homogeneous spin-splitting the surface of the closed end is not pair-breaking just like the case of a surface of a conventional s-wave BCS superconductor. However, this is not the case if the exchange field of the ferromagnet is spin textured. For concreteness we study the magnetic inhomogeneity in the form of a domain wall (DW). If the magnetic DW is close enough (at the distances of several coherence lengths) to the end of the bilayer, the DOS at the end is modified. The most striking feature of the DOS reconstruction is the appearance of the Andreev resonances in the region between the DW and the end of the bilayer. We unveil the mechanism of these quasi-bound states formation and demonstrate that it does not connected to pair breaking of superconductivity by the surface. It is a direct consequence of the spatially-dependent spin-splitting of the DOS in the system. The interest of these characteristic DOS features is manifold. They can be used as a spectroscopic probe of the DW presence and as a spectroscopic detector of the DW motion. The DOS reconstruction also should be taken into account if one thinks about operating the device by nonequilibrium spin injection.

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The model system consists of the spin-textured ferromagnet with a spatially dependent exchange field $\mathbf{h}(\mathbf{r})$ and a spin-singlet superconductor. It is assumed that the S film is in the ballistic limit and its thickness d_t is small as compared to the superconducting coherence length $\xi_s = \Delta/v_F$. The ferromagnet can be a metal or an insulator. It is widely accepted in the literature that if $d_t \lesssim \xi_s$ the magnetic proximity effect, that is the influence of the adjacent ferromagnet on the S film can be described by adding the effective exchange field $h_{\rm eff}(\mathbf{r})$ [5] to the quasiclassical Eilenberger or Usadel equation, which is used for treating the superconductor. While for the ferromagnetic insulators the magnetic proximity effect is not so simple and in general is not reduced to the effective exchange only [6, 7], we neglect the other terms (which can be viewed as additional magnetic impurities in the superconductor) in the framework of the present study and focus on the effect of the spin texture. The S film is described by the Eilenberger equation for the retarded Green's function:

$$i\mathbf{v}_F\nabla\check g(\mathbf{r},\mathbf{p}_F) + \Big[\varepsilon\tau_z + \mathbf{h}_{\rm eff}(\mathbf{r})\boldsymbol{\sigma}\tau_z - \check\Delta, \check g\Big] = 0, \quad (1)$$

where Δ is the effective order parameter in the film, which is reduced to some extent with respect to the bulk value due to the suppression by the proximity to the ferromagnet. In this work we neglect the spatial variations of the order parameter and assume $\Delta = \text{const}$. Having the Geen's functions at hand it is possible to calculate the DOS (normalized to the normal state DOS) as follows:

$$N = N_F {\rm Re}\Big\{{\rm Tr}\langle\hat g\rangle\Big\}, \quad (2)$$

where $\langle ...\rangle$ means averaging over the 2D Fermi surface of the superconducting film. For concreteness we consider the head-to-head DW here. It is convenient to parametrize the spin texture of the effective exchange field by

$$\mathbf{h}_{\rm eff} = h_{\rm eff}(\cos\theta, \sin\theta\cos\delta, \sin\theta\sin\delta), \quad (3)$$

where in general the both angles depend on x-coordinate. The equilibrium shape of the DW is dictated by the interplay between the magnetic anisotropy energy and the exchange energy and is given by

$$\cos\theta = -\tanh[(x - x_0)/d_W], \tag{4}$$

where x_0 is the position of the DW and $\delta = \text{const}$ for the classical in-plane DW.

First of all, we consider a toy model of infinitely thin DW $\mathbf{h}_{\text{eff}}(x) = -h_{\text{eff}}\text{sign}(x)\mathbf{e}_x$. The bulk DOS for a given spin subband has a conventional BCS-like shape shifted down (up) by h_{eff} for the spin-up (down) subband. In the region $0 < x < d$ the direction of the exchange field is reversed and, consequently, the DOS seen by spin-up quasiparticle is of the bulk spin-down form. Therefore, at $-(\Delta + h_{\text{eff}}) < \varepsilon < -(\Delta - h_{\text{eff}})$ the region $0 < x < d$ forms a quantum well for spin-up quasiparticles, where the bound states appear as a result of dimensional quantization. For spin-down quasiparticles the same picture is valid at $\Delta - h < \varepsilon < \Delta + h$. This quantum well can be called "the Andreev quantum well" because the bound state is formed by the combination of the ordinary reflection from the closed end of the superconductor and the Andreev reflection process at $x = 0$. Then the bound state energies are solutions of the following equation:

$$\tan[2\kappa_{1,\sigma} d/|v_x|] = \frac{\kappa_{1,\sigma}\kappa_{2,\sigma}}{\varepsilon^2 - h_{\text{eff}}^2 - \Delta^2}, \tag{5}$$

where $\kappa_{1,\sigma} = \sqrt{(\varepsilon - \sigma h_{\text{eff}})^2 - \Delta^2}$ and $\kappa_{2,\sigma} = \sqrt{\Delta^2 - (\varepsilon + \sigma h_{\text{eff}})^2}$ are real quantities because the bound states only exist in the range $-(\Delta + h) < \varepsilon < -(\Delta - h)$ for spin-up and in the range $\Delta - h < \varepsilon < \Delta + h$ for spin-down quasiparticles.

The mechanism of the bound states formation resembles the mechanism of the well-known de Gennes–Saint-James bound states formation due to the inhomogeneity of the superconducting order parameter near the surface (or in the hybrid superconductor/normal metal/insulator structures) [8]. However, we would like to note that the physical nature of the bound states discussed here is different because they do not require an order parameter inhomogeneity at the closed end. Having this physical mechanism of the bound states formation at hand, below we calculate numerically the DOS near the closed end of the superconductor taking into account the realistic profile of the DW magnetization.

The bulk DOS of a spin-split superconductor has a typical two-peak shape. The Andreev resonances can be seen as features at constant energies between these peaks, localized between the DW and the superconductor edge. It is seen that the peak height at a given peak energy oscillates along the x-axis. The broadening of the peaks is due to the averaging of the bound state energies over different momenta at the Fermi surface and also due to the finite DW width. It can be shown that the resonances smear for wider walls. It is natural because the appearance of the z-component of $\mathbf{h}_{\text{eff}}$ at the DW leads to the nonzero probability for a quasiparticle to reverse its spin at the wall region. Therefore, after the transition through the wall region the spin-up quasiparticle is partially converted to the spin-down one. This spin-down quasiparticle can freely move inside the superconductor. This process provides a leakage channel for the quasiparticles from the quantum well region. As it should be expected the Andreev resonances for very wide walls practically disappear and the DOS approaches the bulk shape. Upon increasing d more and more resonances appear in the quantum well according to Eq. (5), but their heights get lower and the DOS approaches the bulk form when the DW center goes far from the end of the superconductor.

In conclusion, the DOS at the end of the superconductor, which is a part of a S/F bilayer, is considered. We study the case when the ferromagnet magnetization has a defect in the form of a DW in the vicinity of the superconductor end. It is shown that in this case the superconducting DOS is reconstructed near the end manifesting spin-split Andreev resonances in the spatial region between the DW and the superconducting end. So far, all types of surface bound states at nonmagnetic surfaces discussed in the literature are known to be formed due to the order parameter absolute value or phase variations along the quasiparticle trajectory near the surface. On the contrary, these states are formed as a combination of the specular reflection from the closed end and the Andreev reflection from the spin-split gap position shift, which arises due to the DW presence.

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