Density of states oscillations in a ferromagnetic metal in contact with a superconductor

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It is demonstrated that in a ferromagnetic metal near the boundary with a superconductor the local density of states at energies close to the Fermi energy E_F has a damped-oscillatory behavior similar to the decaying of the Cooper's pair density. However at energies $E_F \pm I$ (where I is the exchange field in the ferromagnet) the decaying length is strongly increased and the proximity effect becomes a long-ranged one.

The proximity effect between a superconductor (S) and a ferromagnet (F) is a rather special one. Various effects have been predicted to occur in S/F structures.[1–6] The usually exponentially decaying Cooper's pair density in the ferromagnet has a damped-oscillatory behavior.[1–4] This causes the oscillatory type dependence of the critical temperature in S/F structures as a function of the ferromagnetic layer thickness,[2,3] as well as the formation of π junction[7] and spin-orientation-dependent superconductivity in $F/S/F$ structures.[8,9] The damped-oscillatory behavior of the critical temperature as a function of the ferromagnetic layer thickness has been observed experimentally in Nb/Gd (Refs. 10,11) and in Nb/CuMn multilayers.[12] Very recently the unambiguous proof of π-phase formation in S-F-S junctions has been obtained experimentally.[13]

Now the progress of the STM technique provides a powerful tool to a direct tracing of the damped-oscillatory decaying of Cooper's pair density in ferromagnet. The purpose of this work is to calculate the electron density of states' variation (mediated by the superconductivity) in the F layer as a function of the distance from the S/F boundary.

We examine the behavior of the density of states in the F region $(x>0)$ assuming that the dirty-limit conditions are held. Then we may use the Usadel equations.[14] The local density of states near the S/N boundary has been studied in this framework in Ref. 15.

To concentrate on the physics of the phenomenon (for the calculations in the general case see (Ref. 16) and to avoid an overloading of our presentation by the unnecessary mathematical details, we suppose that the superconductor is at the temperature slightly below T_c, the boundary resistance between S and F regions is very small and $\sigma_n \ll \sigma_s$, where σ_n and σ_s are the conductivities in the F and S regions in the normal state. The first condition justifies the possibility to use the equation for the anomalous Green's function (F function) in the linearized form. The second and the third ones assure that the proximity of F metal affects superconductivity in S region only slightly and at the S/F boundary, the F function is equal to its unperturbed value in the S region[6,17]

$$F(x=0)=F_{s0}=\frac{\Delta}{\sqrt{|\Delta|^2+\omega_n^2}}. \qquad (1)$$

Here $|\Delta|$ is the uniform superconducting gap in the S region. In fact, the same boundary condition describes also the case of a thin ferromagnetic wire attached to the bulk superconductor.

The Hamiltonian we use to describe the proximity effect in the F region is the same as used previously and described in more details in Refs. 1–4, 6–9, and takes into account the presence of a constant exchange field I in the ferromagnetic region creating by the localized moments of magnetic atoms. This exchange field is strong comparing to T_c but supposed to be much smaller than the Fermi energy and then we neglect the change of density of states at the Fermi energy due to spin polarization. Note that the situation when the spin polarization effect is important, as well as the case of itinerant ferromagnets deserves a special consideration—in particular due to a very peculiar Andreev reflection on the S/F boundary(see for example Refs. 18,19). Supposing that the Cooper pairing constant $\lambda=0$ in F regions we may write the Usadel equation for positive Matsubara frequencies $\omega_n=\pi T(2n+1)>0$ in its linearized form as[2–4]

$$(\omega_n+iI)F(x,\omega_n)-\frac{1}{2}D\frac{\partial^2}{\partial x^2}F(x,\omega_n)=0, \qquad (2)$$

$$G^2(\vec{r},\omega_n)+F(\vec{r},\omega_n)\tilde{F}(\vec{r},\omega_n)=1, \qquad (3)$$

where G and F are normal and anomalous Green's functions integrated over the velocity direction and energy; the function $\tilde{F}$ is determined by the condition $\tilde{F}(\omega_n,I)=F^*(\omega_n,-I)$; D is the diffusion coefficient in the F region. Note that we have written the equations only for the Green's function G with spin orientation along the exchange field (up) and $\omega_n>0$. For the opposite spin orientation (down) or $\omega_n<0$, the Green function is obtained simply by the substitution of I by $-I$.

The solution of Usadel equation (2) satisfying the boundary condition (1) may be easily written as:[2,3]

$$F(x,\omega_n)=\frac{\Delta}{\sqrt{|\Delta|^2+\omega_n^2}}\exp(-k_\omega x), \qquad (4)$$

where $k_\omega=\sqrt{2(\omega_n+iI)/D}$ and $\mathrm{Re}(k_\omega)>0$.

To calculate the electronic density of states, we need to perform the analytical continuation $\omega_n \to i\omega$ of the normal Green function. In the result the density of state for spin up orientation is

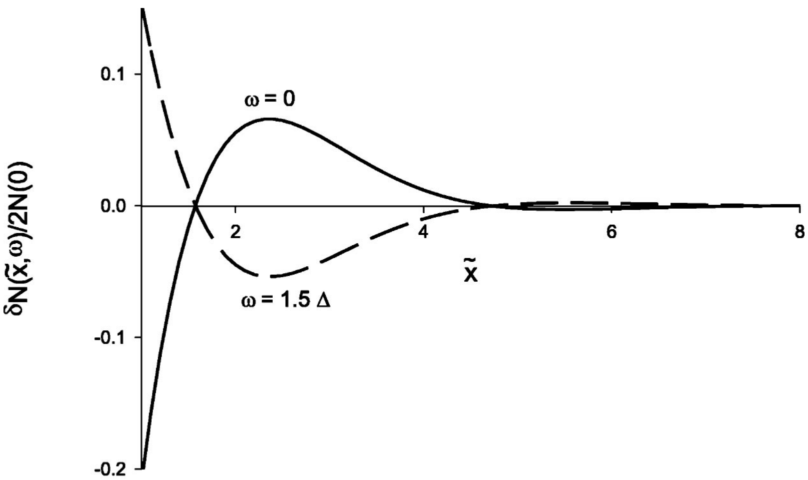

FIG. 1. Spatial variation of the normalized local density of states $\delta N(x,\omega)/2N(0)$ for different energies (the solid line corresponds to $\omega=0$ and the dashed one to $\omega=1.5\Delta$) near the S/F interface $(x=0)$. The dimensionless coordinate $\tilde{x}=x\sqrt{2}/\xi_F=2x\sqrt{I/D}$, and parameter Δ/I is chosen to be 0.05.

$$N_{\uparrow}(x,\omega)=N(0)\,\mathrm{Re}\,G(\omega_n\rightarrow i\omega)$$
$$=N(0)\sqrt{1-\frac{|\Delta|^2}{|\Delta|^2-\omega^2}\exp\left(-2x(1+i)\sqrt{\frac{I+\omega}{D}}\right)},\tag{5}$$

where $N(0)$ is the density of states per spin in the normal state. The density of states for spin down orientation $N_{\downarrow}(\omega)$ is obtained by the substitution $I\rightarrow -I$ in Eq. (5).

The main characteristic feature of the spatial dependence of $N(x)$ for small energy $\omega\ll I$, is a damped-oscillatory behavior with the characteristic length $\xi_F=\sqrt{D/(2I)}$, which is much smaller than the superconducting coherence length (typically $I/T_c>10-10^2$). The distance ξ_F is the same that characterizes the oscillatory type dependence of the critical temperature in S/F structures as a function of the ferromagnetic layer thickness.[2,3]

If we introduce the dimensionless coordinate $\tilde{x}=x\sqrt{2}/\xi_F$ and the energy $\tilde{\omega}=\omega/I$ we may write down the total density of states as

$$N(x,\omega)=N_{\uparrow}(x,\omega)+N_{\downarrow}(x,\omega)=N(0)\sqrt{1-\frac{(|\Delta|/I)^2}{(|\Delta|/I)^2-\tilde{\omega}^2}\exp(-\tilde{x}\sqrt{|1+\tilde{\omega}|})\cos(\tilde{x}\sqrt{|1+\tilde{\omega}|})}$$
$$+N(0)\sqrt{1-\frac{(|\Delta|/I)^2}{(|\Delta|/I)^2-\tilde{\omega}^2}\exp(-\tilde{x}\sqrt{|1-\tilde{\omega}|})\cos(\tilde{x}\sqrt{|1-\tilde{\omega}|})}.\tag{6}$$

As it can be readily seen from Eq. (6) for $\omega=0$, the variation of the density of states $\delta N(x,\omega=0)=N_{\uparrow}(x,\omega=0)+N_{\downarrow}(x,\omega=0)-2N(0)$ at large $\tilde{x}$ has the following simple damped-oscillatory behavior:

$$\frac{\delta N(x,\omega=0)}{2N(0)}=-\frac{1}{2}\exp(-\tilde{x})\cos(\tilde{x}).\tag{7}$$

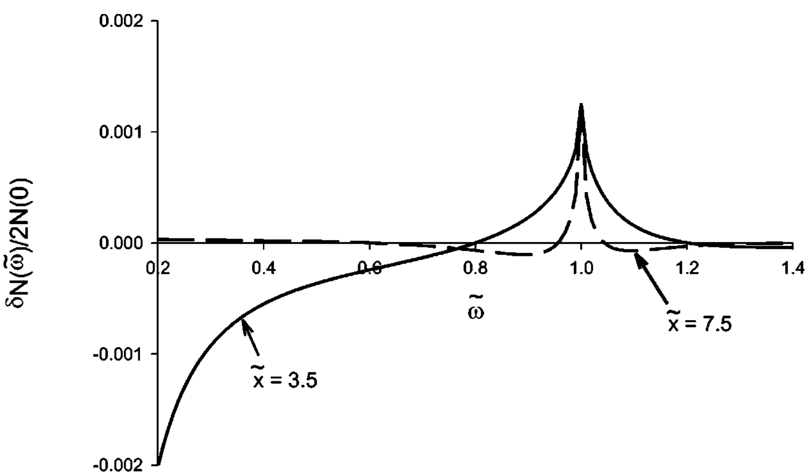

FIG. 2. Energy dependence (as a function of dimensionless energy $\tilde{\omega}=\omega/I$) of normalized local density of states at different distances from S/F interface, parameter Δ/I is chosen to be 0.05. The solid line corresponds to the distance $\tilde{x}=2x\sqrt{I/D}=3.5$ and the dashed one to $\tilde{x}=7.5$. The peak at $\omega=I$ remains rather pronounced even at large distances.

The spatial variation of the density of states for different energies $\tilde{\omega}$ is illustrated in Fig. 1. The very interesting characteristic of the proximity effect in ferromagnetic is the strong increase of the decaying length for $\omega=\pm I$. It can be clearly demonstrated in the ω dependence of $\delta N(x,\omega)$ presented in Fig. 2. Formally, at $\omega=\pm I$, the decaying length diverges. Such a divergency is in fact limited by the inelastic processes destroying the phase coherence. The peak of the density of states at $\omega=\pm I$ somewhere reminds the singularity predicted to exist in the fluctuational regime in superconductors above paramagnetic limit.[20] Its presence also has been noted for superconductor-ferromagnetic hybrid system in Ref. 21.

In conclusion, we have demonstrated the rich variety of the spatial and energy dependence of the local density of states in ferromagnet near the S/F interface. Systems such as the Josephson ''π-phase'' structures[13] or superconductor-ferromagnet multilayers where the damped-oscillatory behavior of the critical temperature as a function of the F layer thickness has been observed[10,11] seem to be quite appropriate to observe the predicted effects. Finally note that the very long-range anomaly of the density of states at $\omega=\pm I$ could be of some relevance with the anomalous proximity effect observed recently in S/F nanostructures.[22,23]

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