What is the value of the superconducting gap of a F/S/F trilayer?

R. Mélin\(^1\)\(^{(*)}\), D. Feinberg\(^2\)
\(^1\) Centre de Recherches sur les Très Basses Températures (CRTBT\(^{(**)}\)), CNRS, BP 166, 38042 Grenoble Cedex 9, France
\(^2\) Laboratoire d’Étude des Propriétés Electroniques des Solides (LEPES\(^{(***)}\)), CNRS, BP 166, 38042 Grenoble Cedex 9, France

PACS. 74.50.+r – Tunneling phenomena; point contacts, weak links, Josephson effects.
PACS. 74.78.Fk – Multilayers, superlattices, heterostructures.

Abstract. – Based on the model of F/S/F trilayer with atomic thickness \(1\) we discuss the relative roles of pair-breaking and proximity effects, as a function of the exchange field, of disorder and of a finite thickness in the superconducting layer. The exchange field can be small (weak ferromagnets) or large (strong ferromagnets) compared to the superconducting gap. With weak ferromagnets we show the existence of a reentrant superconducting gap for the F/S/F trilayer with atomic thickness in the parallel alignment (equivalent to the F/S bilayer). Qualitatively small disorder is equivalent to reducing the value of the hopping parameters. In the presence of a finite thickness in the superconducting layer the superconducting gap in the antiparallel alignment is larger than in the parallel alignment, meaning that pair breaking dominates over the proximity effect.

Introduction. – Many interesting phenomena take place in mesoscopic devices when superconductors are connected to ferromagnets. For example the superconducting pair amplitude induced in a ferromagnet oscillates in space \(2\)–\(4\) and these oscillations can give rise to the \(\pi\)-coupling. The \(\pi\)-coupling manifests itself in superconductor / ferromagnet (S/F) multilayers as oscillations of the superconducting critical temperature with the thickness of the ferromagnetic layers \(6\)–\(8\). S/F/S \(\pi\)-junctions have been recently probed with various experimental techniques \(9\)–\(11\).

The proximity effect in F/S/F trilayers has recently focused a renewed interest. It was established long ago that with insulating ferromagnets the superconducting transition temperature is larger in the antiparallel alignment because of the exchange field induced in the S layer \(12\) that tends to dissociate Cooper pairs. Following this theoretical prediction two experiments were performed, one with metallic ferromagnets \(13\) and the other with insulating ferromagnets \(14\) and it was shown in both cases that the critical temperature was larger in

\(^{(*)}\) melin@grenoble.cnrs.fr
\(^{(**)}\) U.P.R. 5001 du CNRS, Laboratoire conventionné avec l’Université Joseph Fourier
\(^{(***)}\) U.P.R. 0011 du CNRS, Laboratoire conventionné avec l’Université Joseph Fourier
© EDP Sciences
the antiparallel spin orientation. On the other hand with metallic ferromagnets the theoretical description should also include the proximity effect, namely the possibility that Cooper pairs from the superconductor can delocalize in the ferromagnetic electrodes. The proximity effect in F/S/F trilayers is unusual because it may involve spatially separated superconducting correlations if the S layer is thin enough [15,1]. The basic physics can be understood from considering a model of half-metal ferromagnets: in the parallel spin orientation Cooper pairs from the superconductor cannot be transferred in the ferromagnetic electrodes. As a consequence the zero temperature superconducting gap is not affected by the coupling to the ferromagnetic electrodes [1]. In the antiparallel spin orientation Cooper pairs from the superconductor can delocalize in the ferromagnetic electrodes: the spin-up electron can tunnel in the spin-up electrode and the spin-down electron can tunnel in the spin-down electrode [16]. The zero-temperature superconducting gap is reduced by this proximity effect associated to spatially separated superconducting correlations [15] and the zero-temperature superconducting gap is larger in the parallel alignment ($\Delta_P > \Delta_{AP}$) [1,15]. On the other hand it was shown that the superconducting transition temperature with metallic ferromagnets is, like with insulators, larger in the antiparallel alignment ($T_{Pc} < T_{APc}$) which has been probed in recent experiments [18].

In a recent work Buzdin and Daumens [1] proposed to reconcile these apparently contradictory results for the gap at $T = 0$ and for $T_c$, by calculating the critical temperature of a F/S/F trilayer with atomic thickness within the Stoner model, and the zero temperature gap within a model of half-metal ferromagnet. They indeed found that $T_{Pc} < T_{APc}$ but $\Delta_P > \Delta_{AP}$. This suggests that the proximity effect plays a dominant role in the determination of the zero-temperature superconducting gap and that pair breaking effects play a dominant role in the determination of the critical temperature. The goal of this Letter is to determine whether this picture is robust, including realistic ingredients such as a strong or weak exchange field in the ferromagnets, disorder or a finite thickness in the superconductor.

The model. – Let us start with the F/S/F trilayer with atomic thickness [1]. The superconducting layer is described by the BCS Hamiltonian

$$\mathcal{H}_{BCS} = \sum_{\langle \alpha, \beta \rangle, \sigma} -t \left( c_{\alpha, \sigma}^+ c_{\beta, \sigma}^+ + c_{\beta, \sigma}^+ c_{\alpha, \sigma}^+ \right) + \sum_\alpha \left( \Delta_\alpha c_{\alpha, \uparrow}^+ c_{\alpha, \downarrow}^+ + \Delta_\alpha^* c_{\alpha, \downarrow}^+ c_{\alpha, \uparrow}^+ \right),$$

(1)

where $\alpha$ and $\beta$ correspond to neighboring sites on a square lattice. The ferromagnetic electrodes are described by the Stoner model

$$\mathcal{H}_{Stoner} = \sum_{\langle \alpha, \beta \rangle, \sigma} -t \left( c_{\alpha, \sigma}^+ c_{\beta, \sigma} + c_{\beta, \sigma}^+ c_{\alpha, \sigma} \right) - h_{ex} \sum_i \left( c_{\alpha, \uparrow}^+ c_{\alpha, \uparrow} - c_{\alpha, \downarrow}^+ c_{\alpha, \downarrow} \right),$$

(2)

where $h_{ex}$ is the exchange field. The ferromagnetic layers a and b are connected to the superconducting layer by the Hamiltonian

$$\mathcal{W}_{a(b)} = \sum_{\alpha, \sigma} -t_{a(b)} \left( c_{\alpha, \sigma, a(b)}^+ c_{\alpha, \sigma, S} + c_{\alpha, \sigma, S}^+ c_{\alpha, \sigma, a(b)} \right).$$

(3)

Strickly speaking the individual layers of the F/S/F trilayer with atomic thickness might be unstable against charge or spin density wave ordering. We view the F/S/F trilayer with atomic thickness as a toy model for more realistic models involving a finite thickness in the F and S layers so that we can safely neglect these instabilities.

The Green’s functions of the superconductor are given by [19]

$$g^{11}_{\alpha, \alpha}(\xi, \omega) = \frac{u_p^2}{\omega - \epsilon(p) + i\delta + \frac{v_p^2}{\omega + \epsilon(p) - i\delta}}$$

(4)
and similar expressions are obtained for \( g^{2,2}_{\alpha,\alpha} \) and \( f^{2,1}_{\alpha,\alpha} \). The labels “1” and “2” in (11) and (12) correspond to the Nambu indexes. \( \epsilon(p) \) corresponds to the quasiparticle energy \( \epsilon(p)=\sqrt{\Delta^2+\xi^2} \), with \( \xi=\hbar^2p^2/(2m)-\epsilon_F \) the kinetic energy determined with respect to the Fermi level. The coherence factors are given by \( u_\alpha^2=(1+\xi/\epsilon(p))/2 \) and \( v_\alpha^2=(1-\xi/\epsilon(p))/2 \). The “11” Green’s function of a spin-up ferromagnetic electrode is given by \( g^{1,1}_{\alpha,\alpha}=1/|\omega-\xi-\hbar_{\text{ex}}+i\delta\text{sgn} (\xi+\hbar_{\text{ex}})| \) , and a similar expression is obtained for the “22” component.

**Perturbative expansions.** The fully dressed Green’s function corresponding to the F/S/F trilayer with atomic thickness is determined through the Dyson equation \( \hat{G}_{\alpha,\alpha}=g_{\alpha,\alpha}+\hat{t}_{\alpha,\alpha}g_{\alpha,\alpha}\hat{G}_{\alpha,\alpha}+\hat{g}_{\alpha,\alpha}\hat{t}_{\alpha,b}\hat{g}_{\alpha,b}\hat{G}_{\alpha,\alpha} \). The self-consistency relation takes the form \[ 19 \]

\[ \Delta=\lambda\int\frac{d\omega}{2\pi}\frac{d^2k}{(2\pi)^2}G_{\alpha,\alpha}^{1,2}(k,\omega). \] (6)

To order \( t^2 \) and for strong ferromagnets \( (\Delta_0\ll t\ll \hbar_{\text{ex}}) \) we obtain:

\[ \ln\left(\frac{\Delta}{\Delta_0}\right)=-2\frac{t^2_a+\xi^2}{\hbar_{\text{ex}}^2}\left[\ln\left(\frac{\hbar_{\text{ex}}}{\Delta_0}\right)-\frac{1}{2}\right], \] (7)

where \( \Delta_0 \) is the superconducting gap of the isolated superconductor. In the case of weak ferromagnets \( (t\ll \hbar_{\text{ex}} < \Delta_0) \) we obtain

\[ \ln\left(\frac{\Delta}{\Delta_0}\right)=-\frac{1}{2}\frac{(t^2_a+\xi^2)\hbar_{\text{ex}}^2}{\Delta_0^2}. \] (8)

We deduce that in both cases the superconducting gap at order \( t^2 \) is reduced by the proximity with the ferromagnetic layers, independently of the relative spin polarizations of the F layers.

In the case of strong ferromagnets a perturbation theory to fourth order in \( t \) leads to

\[ \ln\left(\frac{\Delta_{\text{P}}}{\Delta_{\text{AP}}}\right)=2\frac{t^2_a}{\hbar_{\text{ex}}^2}\left[3\ln\left(\frac{\hbar_{\text{ex}}}{\Delta_0}\right)-4+\ln\left(\frac{\Delta_0}{\eta}\right)\right], \] (9)

where we introduced a small cut-off \( \eta \) to regularize the logarithmic divergence of the integral over \( \xi \). The (positive) difference between the superconducting gap in the parallel and antiparallel alignments is of order \( (t/\hbar_{\text{ex}})^4 \) and is thus very small compared to \( \Delta_0 \).

For weak ferromagnets a perturbation theory to order \( t^4 \) leads to

\[ \ln\left(\frac{\Delta_{\text{P}}}{\Delta_{\text{AP}}}\right)=2\frac{t^2_a}{\Delta_0^2}\left[\frac{3}{2}+\ln\left(\frac{4\hbar_{\text{ex}}\eta}{\Delta_0^2}\right)\right]+2\frac{t^2_a^2}{\Delta_0^2}\left[-\frac{1}{6}+2\ln\left(\frac{2\hbar_{\text{ex}}^2}{\Delta_0^2\eta}\right)\right]+... \] (10)

In this case there are two small parameters in perturbation theory: \( t^2/\Delta_0^2 \) and \( \hbar_{\text{ex}}^2/\Delta_0^2 \). Perturbation theory is well suited for understanding the small parameters in the problem but is not quantitatively reliable because of logarithmic divergences in the limit \( \eta \to 0 \).

**Numerical simulations of the F/S/F trilayer with atomic thickness.** Non-perturbative solutions valid for arbitrary interface transparencies and for finite temperatures can be implemented numerically. For a F/S/F trilayer with atomic thickness we can solve explicitly the Dyson equation and obtain the expression of the dressed propagator \( G_{\alpha,\alpha}^{1,2} : G_{\alpha,\alpha}^{1,2} = f_{\alpha,\alpha}^{1,2}/\mathcal{D} \), with

\[ \mathcal{D} = 1 - g_{\alpha,\alpha}^{1,1} + g_{\alpha,\alpha}^{2,2} + [g_{\alpha,\alpha}^{1,1} - f_{\alpha,\alpha}^{1,2}] \Sigma_{\alpha,\alpha}^{1,1} \Sigma_{\alpha,\alpha}^{2,2}, \] (11)
where the self-energy $\Sigma_t$ is diagonal in Nambu space: $\Sigma_t^{\tau_1,\tau_2} = (t_{a,a}^2 g_{\tau_1,\tau_2} + t_{b,b}^2 g_{\tau_1,\tau_2}) \delta_{\tau_1,\tau_2}$, where $\tau = 1, 2$ is a Nambu index.

The temperature dependence of the superconducting gap in the case of strong ferromagnets is shown on Fig. 1(a). We obtain $\Delta_P(0) \simeq \Delta_{AP}(0)$ but $T_c^{AP} > T_c^P$. Because electrons in the S layer can make excursions in the F layers an exchange field of order $(t_{a,a}^2 + t_{b,b}^2)/h_{ex}$ is induced in the superconducting layer in the parallel alignment. This pair-breaking mechanism is absent in the antiparallel case. The order of magnitude of the exchange field is obtained by evaluating the density of spin-up and spin-down electrons in the superconductor. Superconductivity breaks down at zero temperature if the exchange field in the F layer becomes smaller than a critical exchange field $h_{ex}(0)$ of order $h_{ex}(0) \simeq (t_{a,a}^2 + t_{b,b}^2)/\Delta_0(0)$. For the parameters corresponding to Fig. 1(a) we obtain from the numerical simulation $h_{ex}(0) = 0.092 \pm 0.002$ which is of order $2t^2/\Delta_0$. The F/S/F trilayer in the parallel alignment with the parameters on Fig. 1(a) is close to the breakdown of superconductivity and this is why we obtain large values of $T_c^P - T_c^{AP}$. This regime may be of interest from the point of view of realizing a superconducting spin valve. Yet, this would require a fine tuning of some parameters such as the interface transparencies.

With weak ferromagnets (see Fig. 1(b)) the most interesting case corresponds to $h_{ex}$ slightly smaller than $\Delta_0(0)$. We obtain $\Delta_P(0) > \Delta_{AP}(0)$ for small values of $t = t_a = t_b$ and a crossing between $\Delta_P(T)$ and $\Delta_{AP}(T)$. For larger values of $t$ we obtain $\Delta_P(T) < \Delta_{AP}(T)$ for all values of the temperature. If the interface transparencies are sufficiently large the gap $\Delta_P(T)$ in the parallel alignment is minimal at $T = T^*$ and reenters at a lower temperature. This behavior is apparently due to a cross-over between two regimes: $\Delta_0(T) > h_{ex}$ for $T < T^*$ (weak ferromagnets) where the small parameter in perturbation theory is $h_{ex}/\Delta_0(T)$ and $\Delta_0(T) < h_{ex}$ for $T > T^*$ (strong ferromagnets), where the small parameter in perturbation theory is $\Delta_0(T)/h_{ex}$. Given the perturbative expansion like (5) we see that the pair-breaking effect of magnetism onto superconductivity is maximal for $h_{ex} \simeq \Delta_0(T)$. We also verified

![Image of Fig. 1](image-url)

Fig. 1 – Variation of the superconducting gap $\Delta(T)$ as a function of temperature $T$ for the F/S/F trilayer with atomic thickness (a) for strong ferromagnets and (b) for weak ferromagnets and with the parameters $h = 1$, $m = 2$, $k_F = 1$, $\lambda = 0.32$. The Debye frequency is set to $\omega_D = h^2 k_F^2/(2m)$. For both figures we use $t = t_a = t_b$. For strong ferromagnets we used $t = 0.01$. For weak ferromagnets we used $h = 0.003$ and $t = 0.00235$ (1), $t = 0.00230$ (2), $t = 0.00225$ (3) and $t = 0.00175$ (4). The open symbols correspond to the parallel alignment and the filled symbols correspond to the antiparallel alignment.
R. Mélin, D. Feinberg: Superconducting gap of a F/S/F trilayer

Fig. 2 – (a) Variation of the critical temperature as a function of disorder in the S layer for strong ferromagnets. (b) Variation of the superconducting gap as a function of disorder in the S layer for weak ferromagnets. Both cases correspond to the F/S/F trilayer with atomic thickness. We used the parameters $\bar{h} = 1$, $m = 2$, $k_F = 1$, $\lambda = 0.32$. The Debye frequency is set to $\omega_D = \bar{h}^2 k_F^2 / (2m)$. For strong ferromagnets we used $t = t_a = t_b = 0.01$. For weak ferromagnets we used $h = 0.003$ and the temperature is set to $T = 0.00025$. In (a) the open symbols correspond to the parallel alignment and the filled symbols correspond to the antiparallel alignment. In (b) the open symbols correspond to the parallel alignment. The solid line corresponds to the antiparallel alignment with $t = 0.0220$ and the dashed line corresponds to the antiparallel alignment with $t = 0.0235$. Disorder is measured by $\Sigma_1^{1,1}(\omega)$ for $\omega \gg \Delta$. That for smaller values of $h_{ex}$ we obtain larger values of $T^*$ which is in agreement with this scenario.

**Effect of disorder.** – To include disorder in the superconducting and ferromagnetic layers we cannot use Usadel equations since we want to describe spatially separated superconducting correlations. Instead we use a perturbative treatment of disorder based on Ref. [19]. It is well known that the superconducting gap of an isolated superconductor is not affected by non magnetic impurities [19] and we could verify this in our simulations. We show here that this is not the case in the F/S/F trilayer and that introducing non magnetic impurities has the same effect as reducing the value of the hopping parameters. The self-energy associated to disorder in the superconductor takes the form $\Sigma_1^{1,1} = n_\alpha u_\alpha^2 g_1^{1,1}(0)$, where $n_\alpha$ denotes the concentration of impurities, $u_\alpha$ is the scattering potential, supposed to be isotropic, and $g_1^{1,1}(0)$ is equal to the propagator of the superconductor evaluated at $R = 0$. The '11' component of the total self-energy is given by $\Sigma_1^{1,1,\text{tot}} = \Sigma_1^{1,1} + t^2_a g^{1,1}_a + t^2_b g^{1,1}_b + t^2 a (g^{1,1}_a)^2 \Sigma^{1,1}_a + t^2 b (g^{1,1}_b)^2 \Sigma^{1,1}_b$, and a similar expressions are obtained for $\Sigma_2^{1,2,\text{tot}}$. The '12' component of the total self-energy is given by $\Sigma_1^{1,2,\text{tot}} = \Sigma_1^{1,2}$, with $\Sigma_1^{1,2} = n_\alpha u_\alpha^2 g_2^{1,2}(0)$. $\Sigma_a$ and $\Sigma_b$ correspond to the self-energies due to disorder in the ferromagnetic electrodes. The expression of the '12' component of the averaged dressed propagator is given by

$$G_1^{1,2}_{a,a} = \frac{1}{D} \left\{ t_1^{1,2} a - \left[ g_{a,a}^{1,1} g_{a,a}^{2,2} - (t_1^{1,2})^2 \right] \Sigma_{a}^{1,2} \right\},$$

where $D$ is given by [11] with $\Sigma_1$ being replaced by $\Sigma_{1,\text{tot}}$. We implement the simplest approximation: we neglect the corrections to the tunnel vertex in which a quasiparticle from S scatters...
on an impurity, tunnels in a ferromagnetic electrode, tunnels back in the superconductor and scatters on the same impurity. In the case of strong ferromagnets we find that a small disorder tends to increase the value of \( T_P^c \), which means a reduction of pair-breaking effects (analogous to a reduction of \( t \)). This is absent in the antiparallel case where disorder reduces the value of \( T_{AP}^c \) (see Fig. 2(a)). For larger values of disorder we have \( T_{AP}^c \approx T_P^c \). For weak ferromagnets we carried out a simulation at a temperature close to the minimum on Fig. 1(b). We find that a small disorder tends to increase the value of the superconducting gap in the parallel and antiparallel alignments (see Fig. 2(b)). The increase of the superconducting gap is larger in the parallel alignment so that there exists a value of disorder above which the superconducting gap in the parallel alignment is larger than the superconducting gap in the antiparallel alignment (see Fig. 2(b)). For larger values of disorder we have \( \Delta_P(T) \approx \Delta_{AP}(T) \).

**Effect of a finite thickness in the \( S \) layer.** — The model of trilayer can be generalized to incorporate a finite thickness in the superconductor. This is done by inverting numerically the Dyson matrix associated to a chain of \( L \) coupled superconducting layers \( \alpha_0 , \ldots, \alpha_{L−1} \). The layer \( \alpha_i \) and \( \alpha_{i+1} \) are coupled by a tunnel amplitude \( t' \). The layer \( \alpha_0 \) (\( \alpha_{L−1} \)) is coupled to the left (right) to a ferromagnetic layer a (b) by a tunnel amplitude \( t \).

We have shown on Fig. 3(a) the variations of the superconducting gap for different values of the thickness of the superconducting layer. We have \( \Delta_P(T) < \Delta_{AP}(T) \) meaning that pair breaking dominates at any temperature for sufficiently large thicknesses. In the case of weak ferromagnets with \( h_{ex} \) of order \( \Delta_0 \) we find also \( \Delta_P(T) < \Delta_{AP}(T) \) for \( t \gg h_{ex} \) (see Fig. 3(b)). We calculated the temperature dependence of the superconducting gap for weak ferromagnets with \( L_S = 2 \) layers in the superconductor and \( L_F = 2 \) layers in the ferromagnets and found a reentrant behavior. By contrast we found no reentrant behavior for \( (L_S, L_F) = (2, 1) \). A systematic study of reentrance as a function of \( L_S \) and \( L_F \) will be presented elsewhere.
Conclusions. – To summarize we found that two regimes of parameters are relevant from the point of view of possible experiments: strong ferromagnets with tunnel interfaces such that $\Delta_0 \ll t \ll h_{\text{ex}}$ and weak ferromagnets with tunnel interfaces such that $t \ll h_{\text{ex}} < \Delta_0$ for F/S/F trilayers with atomic thickness, or $h_{\text{ex}} \approx \Delta_0 \ll t$ with a finite thickness in the S layer. Quantitative predictions can be obtained from the numerical determination of the superconducting gap at finite temperature. For the F/S/F trilayer with atomic thickness and with strong ferromagnets we obtain $\Delta_P(0) \approx \Delta_{\text{AP}}(0)$ but $T_{Pc} < T_{\text{AP}c}$. With weak ferromagnets we obtain a reentrant superconducting gap in the F/S bilayer with atomic thickness. We discussed the effect of disorder within the simplest approximation in which we neglect vertex corrections. In the ferromagnetic alignment and close to the breakdown of superconductivity we find that disorder increases $T_{Pc}$ in the case of strong ferromagnets, and $\Delta_P$ in the case of weak ferromagnets. In the presence of a finite thickness in the superconducting layer pair breaking effects dominate and we find $\Delta_P(T) < \Delta_{\text{AP}}(T)$.

***

The authors acknowledge fruitful discussions with A. Buzdin.

REFERENCES

[1] A. Buzdin and M. Daumens, cond-mat/0305320, Europhysics Letters to appear
[2] P. Fulde and A. Ferrel, Phys. Rev. 135, A550 (1964).
[3] A. Larkin and Y. Ovchinnikov, Sov. Phys. JETP 20, 762 (1965).
[4] M.A. Clogston, Phys. Rev. Lett. 9, 266 (1962).
[5] E.A. Demler, G.B. Arnold and M.R. Beasley, Phys. Rev. B 55, 15174 (1997).
[6] A.I. Buzdin and M. Yu. Kupriyanov, JETP Lett. 52, 487 (1990); A.I. Buzdin, M. Yu. Kupriyanov and B. Vujicic, Physica C 185 - 189, 2025 (1991).
[7] J.S. Jiang, D. Davidovic, D.H. Reich, and C.L. Chien, Phys. Rev. Lett. 74, 314 (1995).
[8] Th. Muhge, N.N. Garif’yanov, Yu. V. Goryunov, G.G. Khalullin, L.R. Tagirov, K. Westerholt, I.A. Garifullin, and H. Zabel, Phys. Rev. Lett. 77, 1857 (1996).
[9] V.V. Ryazanov, V.A. Oboznov, A. Yu. Rusanov, A.V. Veretennikov, A.A. Golubov, J. Aarts, Phys. Rev. Lett. 86, 2427 (2001).
[10] T. Kontos, M. Aprili, J. Lesueur, and X. Grison, Phys. Rev. Lett. 86, 304 (2001).
[11] W. Guichard, M. Aprili, O. Bourgeois, T. Kontos, J. Lesueur and P. Gandit, Phys. Rev. Lett. 90, 167001 (2003).
[12] P.G. de Gennes, Phys. Letters 23, 10 (1966).
[13] G. Deutscher and F. Meunier, Phys. Rev. Lett. 22, 395 (1969).
[14] J.J. Hauser, Phys. Rev. Lett. 23, 374 (1969).
[15] R. Mélín, J. Phys.: Condens. Matter 13, 6445 (2001); V. Apinyan and R. Mélín, Eur. Phys. J. B 25, 373 (2002); H. Jirari, R. Mélín and N. Stefanakis, Eur. Phys. J. B 31, 125 (2003).
[16] G. Deutcher and D. Feinberg, Appl. Phys. Lett. 76, 487 (2000).
[17] I. Baladié and A. Buzdin, Phys. Rev. B 67, 014523 (2003).
[18] I. Baladié, A. Buzdin, N. Ryzhanova, and A. Vedyayev, Phys. Rev. B 63, 054518 (2001). A. Buzdin, A.V. Vedyayev, and N. Ryzhanova, Europhys. Lett. 48, 686 (1999).
[19] J. Y. Gu, C.-Y. You, J. S. Jiang, J. Pearson, Ya. B. Bazaliy, and S. D. Bader, Phys. Rev. Lett. 89, 267001 (2002).
[20] A.A. Abrikosov, L.P. Gorkov and I.E. Dzyaloshinski, Methods of quantum field theory in statistical physics, Dover Publications, Inc, New York (1963).
[21] F.S. Bergeret, A.F. Volkov and K.B. Efetov, cond-mat/0307468.