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Spin supercurrent injection by magnetization precession

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Abstract

In this work we theoretically investigate the spin dynamics of superconducting condensate proximity coupled with the single FMR mode uniform periodical precessing magnetization. The theoretical model of the inverse proximity effect is built within quasicalssical formalism using time-dependent Usadel equations. Frequency representation of Usadel equations allows to turn non-stationary periodic problem to the stationary one. We numerically solve the derived frequency-dependent Usadel equations and calculate non-stationary distributions of the spin supercurrent and induced magnetization inside the superconductor/ferromagnetic insulator hybrid structure.

Keywords

superconducting spintronics; proximity effect; ferromagnetic resonance

Introduction

Spin flow creation and manipulation in superconducting hybrid systems became a very active research area during the last decade because of possibility of creation spin supercurrents with much larger relaxation lengths and spin lifetimes [1]. Creation of persistent spin currents in superconductors opens new ways for the development of prospective spintronic devices like magnon transistors [2,3] and superconducting magnon crystals [4]. In this context, the challenge of the superconductor spin injection is one of the central problems in modern superconducting spintronics. There are several ways of spin current injection into the superconductor, for example spin Hall effect [5] , spin Seebek [6] effect, ferromagnetic resonance spin pumping [7,8]. The spin pumping technique in hybrid structure, consisting of ferromagnetic insulator and superconductor, is considered to be the most preferable way to inject spin current, due to the absence of Joule heating. Moreover, proximity coupling between magnetic excitations plays a crucial role in ferromagnetic Josephson junctions [9-12] and mesoscopic structures [13]. The latest experimental researches [5,8,14] show that the interaction between the superconducting correlations and spin waves, influences both dynamics of superconducting and magnetic films. Interfacial exchange interaction between cooper pairs and magnons results in non-stationary induced magnetization and spin currents in superconducting film and changes the magnetic excitations spectrum inside the ferromagnetic insulator [15]. Despite the large number of discussions in experimental works, there is no clear understanding of the interplay between superconducting and magnetic excitations inside proximity coupled hybrid structures. That is why developing a consistent theory of the inverse proximity effect is one of the central topics of modern superconducting spintronics. There is a series of theoretical papers [7,16-19] describing the spin current injection and induced magnetization generation in microscopic [7,16] and quasiclassical [17-19] frameworks. However, the main subject of this works is the magnetic excitation spectrum in hybrid structures. Most of the works ignore the dynamics of non-uniform distributions of induced magnetization and spin current inside the superconducting film, which can be called the inverse proximity effect. Distributions of spin-current and induced magnetization were calculated in recent works [20,21], where the authors investigate spin current flow through the Josephson-like trilayer structures.

The quasiclassical theory of proximity effect in superconductor/ferromagnetic insulator hybrid structures was applied to describe non-uniform phenomena, like generation of spin transfer torques, non-uniform thermoelectric effects, domain wall movement, etc. The theoretical description of the dynamic proximity effect is the more complex task because of the double time structure of non-stationary Usadel equation. The recent successes in quasiclassical boundary conditions theory [22,23] make it possible to develop adequate models of the proximity effect in the different types of superconducting hybrid structures. Quasicalssical boundary conditions can successfully describe the interfaces between the superconductor and weak or strong ferromagnets [22-24], normal metals [25-27], half-metals [28], etc. The first attempts to implement non-stationary, adiabatic, quasicalssical boundary conditions were done in the works [18,19]. In this work, we develop a theory based on Usadel equations, combined with the adiabatic, non-stationary boundary conditions. We show that adiabatic approximation is useful in the wide range of magnetization precession frequencies. The main goal of our theory is to describe the dynamics of the spin current and induced magnetization inside the superconducting film, which is in contact with the ferromagnetic insulator layer. We calculate spin current and induced magnetization, not only at the interface of the hybrid structure, but also inside the superconducting metal film.

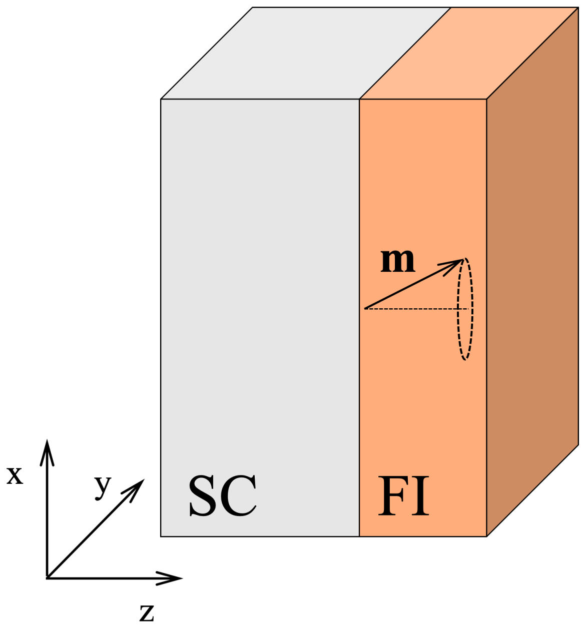

Figure 1: Investigated hybrid superconducting structure: ferromagneic insulator(FI) adjacent to superconductor (SC). Magnetization **m** in ferromagnetic insulator layer is uniform and it direction precess with the cyclic frequency Ω, z coordinate of the interface is equal to the the superconductive layer thickness.

Model

The structure is schematically depicted in Figure 1. The spin current is injected from the ferromagnetic insulator (FI) to the superconducting film (SC). The thickness of the ferromagnetic insulator doesn't matter because the superconducting correlations do not penetrate inside the insulating material. Uniform magnetization periodically precesses inside the ferromagnetic insulator with a cyclic frequency Ω. To describe the non-stationary state of the superconducting condensate we use the formalism of two-time quasicalssical Green functions in Nambu-Spin-Keldysh space[28]. We expand the Green function assuming the weak proximity effect [28] with the ferromagnetic insulator: $\check{g}\left(t_1, t_2\right) \approx \check{g}^{(0)} + \check{g}^{(1)}$. To handle the expansion of the order parameter correctly, we should cancel the odd orders of the perturbation, because the triplet Green function components do not contribute to the order parameter. Only even orders of the perturbation series determine its correction. Thus, the superconducting order parameter in the linear regime, has only a zero-order term in expansion. The resulting dynamics of the superconducting condensate in weak proximity effect regime, can be described via the non-stationary Usadel equation [18,19,29]:

$$\hbar\{\check{\rho}_4 \partial_t, \check{g}\}_t - \hbar D \partial_z \left(\check{g} \circ \partial_z \check{g}\right) = i\left[\check{\Delta}^{(0)}, \check{g}\right], \tag{1}$$

where $\check{\Delta}^{(0)}$ - the stationary, BCS superconducting order parameter matrix [28], D - the diffusion constant, $\check{\rho}_4 = \sigma_0 \otimes \sigma_x \otimes i\sigma_y$ -the auxiliary matrix in Nambu-spin-Keldysh space, $\circ$ - the time convolution operator, the anticommutator $\{f, g\}_t = f\left(t_1\right) g\left(t_1, t_2\right) + g\left(t_1, t_2\right) f\left(t_2\right)$. We have dropped the coordinate dependence of Green functions and of the order parameter for the simplicity of notation. We consider time-dependent magnetization at the interface as a adiabatic perturbation which changes slowly compared to the timescale of the superconducting system : $\hbar\Omega << \Delta$.

In general, the equation can be solved numerically within the mixed representation formalism. The time-periodicity condition allows us to represent spin-current and induced magnetization as time-harmonic variables:

$$\mathbf{j}_z^s(z, t) = \mathbf{j}_z^s(z) e^{i\Omega t} \tag{2}$$

$$\mathbf{M}\,(z,t) = \mathbf{M}\,(z)\, e^{i\Omega t} \tag{3}$$

where $t = (t_1 + t_2)/2$ is the centre-of-mass time argument. To form a closed set of equations we should add the equation for the normalization condition [29] in mixed representation.

Results and Discussion

For the numerical calculations, we have considered niobium as a superconducting metal with the following parameters $T_c = 9.2$ K, $\Delta^{(0)} \approx 1.76 k_B \cdot T_c = 14$ meV, $D = 0.8 \cdot 10^{-3}$ m^2/s, $\epsilon_F \approx 5.32$ eV, we approximate DOS on the Fermi level with the free electron gas value $N_0 \approx 4.9 \cdot 10^{46} J^{-1} m^{-3}$, the coherence length has been estimated using $\xi_0 = \sqrt{\hbar D / 2\pi k_B T_c}$ where k$_B$ is the Boltzmann constant, $\xi_0 \approx 1.1 \cdot 10^{-8}$ m. We numerically solve the mixed representation of the equation (1) with the normalization condition. To obtain physical observables from the quasiclassical, Green functions, we should find the harmonic coefficients (2),(3) and directly calculate observable values at the space-time points. In this work, we are interested in the calculation of spin currents and induced magnetization distributions along the thickness of the superconducting film. The dynamics of any observable will be periodic and can be characterized by its amplitude value. Thus, we only need to calculate the doubled, absolute value of the coefficients (2) and (3), which are exactly the amplitudes of the spin current and magnetization in the linear regime. Now let us consider the doubled Fourier coefficients for the induced magnetization. One can see that the curves for the different precession frequencies coincide. This happens because the absolute value of the projection of the magnetization vector at the interface does not change with the changing of the precession frequency. However, a more complicated picture is anticipated, if we take into account the non-adiabatic process at the interface. At first glance, there is no possibility of the non-adiabatic processes, because the ratio $\Delta/\hbar\Omega \sim 50$ for the Nb / YIG hybrid structure. But the superconducting order parameter can be dramatically reduced at the interface between the superconductor and ferromagnetic due to the strong proximity effect. If the order parameter at the interface is suppressed by the proximity effect, this ratio can move close enough to 1 and non-adiabatic effects will come into play. These complex dynamics can affect the quasiparticle generation at the interface. and also cause significant suppression of the superconductivity. We do not explore the stationary component of the induced magnetization because it was done in [30]. In this work, we are interested in the dynamic components of the induced magnetization and spin current. Both spin current and induced magnetization in the superconductor are originated from the singlet-triplet Cooper pairs conversion mechanism. The spin current can be induced only by the non-stationary flow of triplet Cooper pairs, just as in the conventional spin-pumping bilayer structure with normal metal [31]. Thus, spin currents cannot emerge when the magnetization is stationary inside the ferromagnetic insulator layer. However, there is a possibility to induce stationary pure spin currents inside trilayer superconducting structures [1].

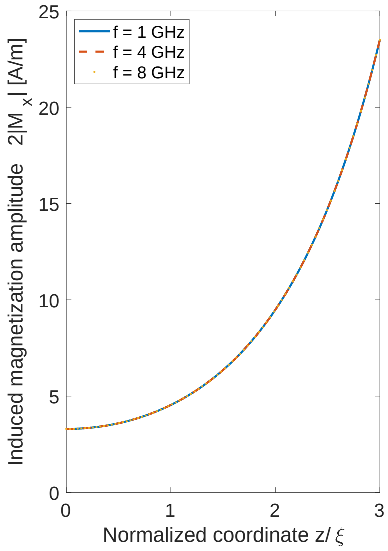

Figure 2: Distribution of the induced magnetization inside the superconducting layer at different frequencies of the magnetization precession

Figure 2 displays the exponential-like decay of the induced magnetization inside the superconducting film. The induced magnetization is created by the triplet superconducting correlations, whose concentration reaches the maximum value at the interface due to the singlet-triplet conversion process. Suppression of superconductivity at the interface can give rise to some interesting, non-adiabatic spin dynamics. In Figure 3, one can see the amplitude of the induced magnetization at the interface between the superconductor and ferromagnetic insulator.

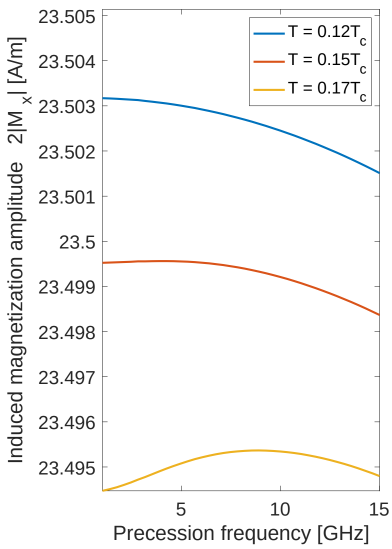

Figure 3: Induced magnetization at the interface between the superconductor and ferromagnetic insulator

As one can see from Figure 3, the induced magnetization distribution depends non-monotonically on the precession frequency. Moreover, the peak becomes more visible with the increasing of the temperature, even if we do not take into account the thermal suppression of the superconducting order parameter. We predict that the competition between two different spin pumping mechanisms can explain this interesting behaviour. The first mechanism is the adiabatic spin pumping of the superconducting condensate and the second one is the spin pumping of the thermally-generated quasiparticles e. g. normal electrons and holes. We should remember that increasing the excitation frequency can cause the suppression or destruction of superconductivity at the interface. This means that the induced magnetization of the triplet correlations will also decrease. However, the spin pumping in normal metals goes exactly in the opposite way: the spin density is growing with the increasing of the excitation frequency. According to different spin pumping mechanisms, the induced magnetization is the sum of the quasiparticle spin density and triplet Cooper-pairs magnetization. In general, the interplay between the magnetization precession and proximity effect can completely destroy superconductivity at the interface. During the interaction with the time-dependent magnetization at the interface, electrons from the superconductor can gain or lose additional magnon energy quanta $\hbar\Omega$. If $\hbar\Omega \sim \Delta$ at the interface, the inelastic electron scattering causes the breaking of the Cooper pairs and generates quasiparticles above and below the Fermi surface. That is why the non-adiabatic effects can potentially play extremely important role in the spin dynamics of the superconductor/ferromagnetic hybrid structures.

Next, we consider the distribution of the spin current. The amplitude of spin current is normalized by the factor $j_{s0} = (\hbar/2e)\, j_{e0}$. The charge current density normalization factor is $j_{e0} = 2eN_0D\Delta^{(0)}/\xi = 6.26210^6 A/cm^2$. The spin current distribution amplitudes are depicted in Figure 4.

One can see that the spin current amplitudes decay similarly to the induced magnetization. However, the amplitude of the spin current strongly depends on the frequency of the magnetization precession. This effect is similar to ferromagnetic resonance spin pumping in the normal metal/ferromagnetic insulator structures. In the case of spin pumping into normal metal, the decay of the spin current is a consequence of the spin relaxation processes, but we do not take into account any of the spin relaxation mechanisms within our model. Therefore, we conclude that the main mechanism of the spin current reduction is similar to that for the induced magnetization: the decay of the spin current density corresponds to the lowering of the triplet pairs density away from the magnetic interface, because of singlet-triplet conversion weakening.

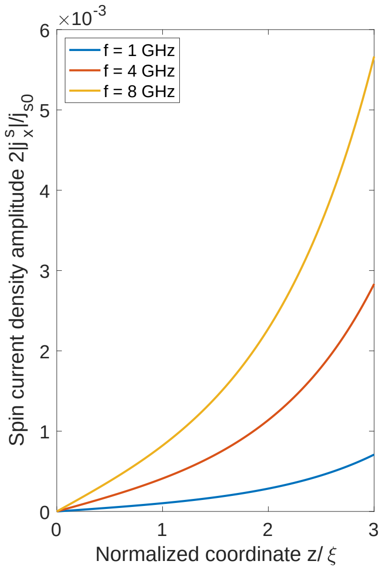

Figure 4: The distribution of the spin current density inside the superconducting layer at the different frequencies of the magnetization precession

Conclusion

In this work, we have investigated the simplest case of the linear adiabatic dynamics caused by the proximity of the superconductor with the ferromagnetic insulator. It was found that the spin current density amplitude is proportional to the frequency of the magnetization precession. Distributions of the induced magnetization and spin supercurrent are similar to those of the spin pumping in normal metal / ferromagnetic insulator hybrid structures. But the spin current and spin density penetrate inside superconducting film on the distances much longer than in normal metals. This behaviour is a result of the adiabatic singlet-triplet cooper pair conversion process at the interface. However, we have pointed out that the spin current generation at the interface can be largely affected by the non-adiabatic effects, which can arise due to the significant suppression of the superconducting order parameter near the ferromagnetic insulator. That is why the non-perturbative description of the dynamic inverse proximity effect must include both adiabatical and non-adiabatical processes. In other words, we should take into account the inelastic electron scattering at the interface. The time-dependent inelastic scattering leads to the breaking of the superconducting correlations at the interface and the injection of the quasiparticles inside the superconducting film. The results reported in this work, demonstrate the rich potential of the dynamic inverse proximity effect in hybrid superconductor / ferromagnetic insulator structures, making them promising candidates for novel spintronic devices.

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References

1. Linder, J.; Robinson, J. W. *Nature Physics* **2015**, *11* (4), 307–315.

2. Chumak, A. V.; Serga, A. A.; Hillebrands, B. *Nature communications* **2014**, *5* (1), 1–8.

3. Cornelissen, L.; Liu, J.; Van Wees, B.; Duine, R. *Physical review letters* **2018**, *120* (9), 097702.

4. Golovchanskiy, I. A.; Abramov, N. N.; Stolyarov, V. S.; Bolginov, V. V.; Ryazanov, V. V.; Golubov, A. A.; Ustinov, A. V. *Advanced functional materials* **2018**, *28* (33), 1802375.

5. Jeon, K.-R.; Ciccarelli, C.; Kurebayashi, H.; Wunderlich, J.; Cohen, L. F.; Komori, S.; Robinson, J. W.; Blamire, M. G. *Physical Review Applied* **2018**, *10* (1), 014029.

6. Ozaeta, A.; Virtanen, P.; Bergeret, F.; Heikkilä, T. *Physical review letters* **2014**, *112* (5), 057001.

7. Inoue, M.; Ichioka, M.; Adachi, H. *Physical Review B* **2017**, *96* (2), 024414.

8. Yao, Y.; Song, Q.; Takamura, Y.; Cascales, J. P.; Yuan, W.; Ma, Y.; Yun, Y.; Xie, X.; Moodera, J. S.; Han, W. *Physical Review B* **2018**, *97* (22), 224414.

9. Stoutimore, M.; Rossolenko, A.; Bolginov, V.; Oboznov, V.; Rusanov, A.; Baranov, D.; Pugach, N.; Frolov, S.; Ryazanov, V.; Van Harlingen, D. *Physical review letters* **2018**, *121* (17), 177702.

10. Heim, D.; Pugach, N.; Kupriyanov, M. Y.; Goldobin, E.; Koelle, D.; Kleiner, R.; Ruppelt, N.; Weides, M.; Kohlstedt, H. *New Journal of Physics* **2015**, *17* (11), 113022.

11. Heim, D.; Pugach, N.; Kupriyanov, M. Y.; Goldobin, E.; Koelle, D.; Kleiner, R. *Journal of Physics: Condensed Matter* **2013**, *25* (21), 215701.

12. Pugach, N.; Kupriyanov, M. Y.; Vedyayev, A.; Lacroix, C.; Goldobin, E.; Koelle, D.; Kleiner, R.; Sidorenko, A. *Physical Review B* **2009**, *80* (13), 134516.

13. Holmqvist, C.; Fogelström, M.; Belzig, W. *Physical Review B* **2014**, *90* (1), 014516.

14. Jeon, K.-R.; Ciccarelli, C.; Kurebayashi, H.; Cohen, L. F.; Montiel, X.; Eschrig, M.; Wagner, T.; Komori, S.; Srivastava, A.; Robinson, J. W. et al. *Physical Review Applied* **2019**, *11* (1), 014061.

15. Golovchanskiy, I.; Abramov, N.; Stolyarov, V.; Golubov, A.; Ryazanov, V.; Ustinov, A. *Journal of Applied Physics* **2020**, *127* (9), 093903.

16. Kato, T.; Ohnuma, Y.; Matsuo, M.; Rech, J.; Jonckheere, T.; Martin, T. *Physical Review B* **2019**, *99* (14), 144411.

17. Ojajärvi, R.; Heikkilä, T. T.; Virtanen, P.; Silaev, M. *Physical Review B* **2021**, *103* (22), 224524.

18. Silaev, M. *Physical Review B* **2020**, *102* (14), 144521.

19. Silaev, M. *Physical Review B* **2020**, *102* (18), 180502.

20. Simensen, H. T.; Johnsen, L. G.; Linder, J.; Brataas, A. *Physical Review B* **2021**, *103* (2), 024524.

21. Ojajärvi, R.; Bergeret, F.; Silaev, M.; Heikkilä, T. T. *Physical Review Letters* **2022**, *128* (16), 167701.

22. Cottet, A.; Huertas-Hernando, D.; Belzig, W.; Nazarov, Y. V. *Physical Review B* **2009**, *80* (18), 184511.

23. Eschrig, M.; Cottet, A.; Belzig, W.; Linder, J. *New Journal of Physics* **2015**, *17* (8), 083037.

24. Tokuyasu, T.; Sauls, J. A.; Rainer, D. *Physical Review B* **1988**, *38* (13), 8823.

25. Zaitsev, A. *Zh. Eksp. Teor. Fiz* **1984**, *86*, 1742–1758.

26. Kuprianov, M. Y.; Lukichev, V. *Zh. Eksp. Teor. Fiz* **1988**, *94*, 149.

27. Nazarov, Y. V. *Superlattices and microstructures* **1999**, *25* (5-6), 1221–1231.

28. Fyhn, E. H.; Linder, J. *Physical Review B* **2019**, *100* (22), 224508.

29. Brinkman, A.; Golubov, A. A.; Rogalla, H.; Wilhelm, F.; Kupriyanov, M. Y. *Physical Review B* **2003**, *68* (22), 224513.

30. Yagovtsev, V.; Gusev, N.; Pugach, N.; Eschrig, M. *Superconductor Science and Technology* **2021**, *34* (2), 025003.

31. Xu, Y.; Awschalom, D. D.; Nitta, J. *Handbook of spintronics*; Springer: Berlin, 2016.