Giant spin-valve effect in Al/Y₃Fe₅O₁₂ heterostructures

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Abstract. Superconducting phase transition in the aluminium stripes fabricated on yttrium-iron garnet and on oxidized silicon substrates is studied. Reduction of critical temperature, widening of superconducting transition depending upon the mutual current and magnetization orientations as well as on current strength are observed in aluminium on garnet comparing with aluminium on silicon. The proximity and triplet proximity effects, Andreev reflection, exchange interaction, spin-orbit coupling and self YIG magnetic field impacts on the observed effects are discussed. We show that only accounting for the spin-orbit coupling and self-magnetic field of YIG is allowed to explain the observed phenomenon of asymmetric change in the transition under the variation of the current and magnetization alignment. Based on the obtained results, we suggest a new geometry of spin-valve with hundreds percent variation of the resistance controlled by the current.

1. Introduction

Intensive development of cryoelectronics and the prospects for creating a cryogenic quantum computer [1-9] imply the low temperature circuits and elements with the ability to be switched in ultra-short times with low energy losses. These are elements of static and dynamic memory, diodes, transistors, switches and much more. In particular, to create magnetoresistive memory and spin valves, it is proposed to use a superconductor (S) - ferromagnet (F) heterostructure [10-14]. The operation of such devices is based on their ability to change the superconducting properties of the S-layer by reversing the magnetization of the F-layer. Two-layer SF structures and three-layer FSF, SFS, SF₃F structures have been studied. Each of them has its own advantages and disadvantages. For example, Nb/FeNi is capable of switching in a field of only a few Oersted, but the magnetoresistive effect in it is small [15]. Nd/PdFe/Nb switches in the weakest magnetic field of the order of 1 Oe, but its high resistive state turns out to be ambiguous and is realized in a very narrow range of the field [16,17]. The magnetoresistance in such structures is observed when an inhomogeneity of magnetic state appears, e.g. the domain walls in ferromagnet are formed, or vice-versa, when the stray fields vanishes due to demagnetization of the ferromagnetic layer. Resistance of trilayer spin-valve based on two magnetic layers with different coercivity depend upon the magnetization alignment in the ferromagnetic layers [18-20]. The resistance of such structures is low when the magnetization in ferromagnetic layers is aligned. It becomes higher when the magnetization in the layers is misaligned. Advantage of such devices is relatively low switching magnetic field, stability of low and high resistive states in wide enough range of fields determined by the difference in coercivity of the layers. Disadvantage is not high variation of the resistivity. However, not studied till now is the switching rate of SF₃F, which could be too low because of exponential growth of magnetic viscosity with temperature decrease [21-24].
In this work, we suggest a new type of bilayer spin-valve controlled by an alignment of the current and magnetization and report on hundreds percent resistance variation.

2. Experimental
We investigated the resistive properties of aluminum/yttrium iron garnet structures (Al/YIG). Aluminum was chosen as a technologically advanced superconductor with a large coherence length $\xi$ about of 130 nm in 100 nm thick films, which facilitates the fabrication of structures. YIG is a magnetic dielectric with a record low attenuation, with gigahertz rates of magnetization switching by weak magnetic field or light. These properties of the materials determine their choice.

The experiments were carried out on Al stripes 1 µm wide and 80 nm thick, fabricated by magnetron sputtering on relatively large YIG plates with the size about of 5 mm × 5 mm and thickness of 60 µm. Pairs of identical stripes located over the same magnetic domain were made. One of the stripes of each pair was aligned with the direction of magnetization in the domain, while another goes perpendicular to the magnetization. The stripes were located hundreds micrometer away from magnetic domain walls. The location was verified by direct observation in a polarizing optical microscope in transmitted polarized light. In this way we took advantage of YIG's characteristics: transparency, large Faraday rotation and birefringence [25].

Reference Al stripes were fabricated on oxidized Si simultaneously with the samples under the study to illuminate the influence of the YIG vicinity on the Al properties.

The resistance of Al-structures was measured by standard 4-probe method. The distance between potential contacts was about of 100 µm. The current contacts were located outside the potential ones on the distance about of 100 µm from them. The current with the strength 1 - 100 µA was applied during the measurements; the smaller value was determined by the sensitivity of our set-up, the upper value was limited by significant Al overheating appeared at higher current.

3. Results
The temperature dependence of the resistance measured on the Al stripe fabricated on oxidized silicon substrate is shown in figures 1a-1c. Superconducting phase transition occurs at $T_c \approx 1.264$ K when 1 µA current is applied (figure 1a, curve R). The transition takes place at the same $T_c$ when 10 µA current is used (figure 1b, curve R). The transition shifts down to $T_c=1.258$ K under the current of 100 µA (figure 1c, curve R). The 0.006 K shift we ascribe to overheating of the Al under the current.

![Figure 1](image-url). $R(T)$ measured on Al stripes which are parallel with YIG magnetization ($R_\parallel$) and perpendicular to it ($R_\perp$) and $R(T)$ on Al/Si ($R$). The dependences measured under the current about of 1, 10 and 100 µA are shown in figure a, b and c, correspondingly.
Temperature dependences of the resistance measured on identical Al stripe fabricated on YIG differs remarkably from those on Al/Si. Four specific features can be seen from figures 1a-1c, in which $R_\parallel$ marks the curves showing the resistance of the stripe aligned with magnetization and $R_\perp$ is used as notation of the resistance of perpendicular stripe. First, the phase transition begins at lower temperature. Second, the transition becomes much wider. Next, the orientation of Al stripe relative to magnetization of YIG turns out to be important: the transition widening is larger when the current flow parallel to magnetization of YIG than in perpendicular direction. Further, temperature of the transition depends upon the strength of the current. We see that reduction of the beginning of the transition: measured at level $R = 0.9 R(1.4K)$, it occurs at 1.236 K for 1 μA current, 1.234 K for 10 μA current, and 1.157 K or 1.247 K for 100 μA current of perpendicular directions. The transition temperature measured at level $R = 0.1 R(1.4K)$ is 1.163 K and 1.192 K for 1 μA, 1.160 K and 1.192 K for 10 μA, 1.10 K and 1.212 K for 100 μA currents. It is definitely seen that the difference between $R_\parallel(T)$ and $R_\perp(T)$ increases with the current strength. Besides, the transition temperature increases with current strength when the current is directed perpendicular to magnetization and decreases when the current flow parallel with it. As a result, large interval of temperature appears in which the resistance depends upon mutual orientation of the current and magnetization. Difference in resistivity between $R_\parallel(T)$ and $R_\perp(T)$ measured under the 100 μA current, $\Delta R = R_\parallel(T) - R_\perp(T)$, corresponds now to the difference in the Al resistivity in the superconducting state and in the normal state, figure 2. Determined as $\Delta R / R_\perp(T)$, it turns to be infinitely large.

Listed above features were observed in all studied Al/YIG samples, although some details in $R(T)$ differ, e.g. the value of the reduction of $T_c$ and the value of $\Delta R$ could be a little different.

We also found that the effect depends upon the width of Al stripe. Comparing the results obtained under the same applied current for stripes with the width of 1 and 3 μm, we have established that in wider stripes the effects are less pronounced. For example, the $\Delta R$ changes by only 0.2 from $R(1.4K)$, the temperature range with the effect shrinks from 0.15 K down to 0.07 K (compare curves in figure 2).
One more very important feature was found in the manifestations of the influence of the perpendicular current on the superconducting transition. The switching the current on 180 degrees led to different shift of the transition, figure 3. This showed that the resistance in Al/YIG can be switched using just the current inversion. Unfortunately, the resistance variation in this case was less than when the current was turned by 90 degrees, and took place in a narrower temperature range.

4. Discussion
Reduction of superconducting transition temperature in superconductor-ferromagnet structures can be caused by many reasons. The proximity effect [9,26,27], i.e. the decay of Cooper pairs penetrating into ferromagnet, does not matter in our case, because we are using a ferromagnetic insulator. In the same time, the decay of Cooper pairs due to the Andreev reflection [28,29] from SF interface could contribute to the observed superconductivity suppression. However, it cannot explain the observed dependence of the superconducting transition from the alignment of magnetization and the current.

The effect of triplet proximity in SF structures is sensitive to gradients of magnetic induction [11,12,30,31] but it is invariant of current-magnetization disorientation. We did not see magnetic inhomogeneity in YIG. Differently from [32], we do not have any domain walls under the Al-structure; we paid special attention to fabricate the Al-structures over the domain wall-free region in YIG. Therefore, we could not refer to appearance of triplet states in the Al.

Exchange interaction [33,34] is considered as an important factor, which could influence the \( T_c \), but exchange is isotropic, so it cannot be responsible for the difference in \( R_{||}(T) \) and \( R_{\perp}(T) \) seen in figures 1a-1c and 3.

Spin-orbit coupling (SOC) [35,36] in superconductor-magnetic isolator structures was supposed to be confirmed in the experiments [37-39]. They observed the resistance variation under the field rotation from perpendicular to planar orientation and even observed the anisotropy in the effect, which was strictly correlated with crystallographic anisotropy of the ferromagnet. However, the change in the direction of magnetization in these experiments was accompanied by a change in the demagnetizing factor and a complex transformation of the magnetic domain structure. These effects, in turn, could change the interaction of the superconductor and the ferromagnet. We were changed the current-magnetization off-orientation in the plane of the ferromagnet and observed the effect. However the SOC should give larger influence on the resistance of that Al stripe which is perpendicular to the magnetization because of non-zero vector product of \( \mathbf{n} \times \mathbf{j} \times \mathbf{m} \), where \( \mathbf{n} \) is the normal to the interface, \( \mathbf{j} \) - current direction and \( \mathbf{m} \) is magnetization direction. We get quite opposite; the effect was larger in the stripe with aligned \( \mathbf{j} \) and \( \mathbf{m} \). However, the amplification of the current applied to the structure made it possible to notice the difference in the shift of \( R_{\perp}(T) \) for oppositely directed current, figure3, and the shift of \( R_{\perp}(T) \) to higher temperature, while \( R_{||}(T) \) was shifted to lower temperature, figure2c. Therefore, we believe that we have some signatures of the SOC of superconducting Al with YIG.

However the effect is too large to be attributed to SOC only. Large demagnetizing field \( H_m \) always exists in and around the YIG plate. If YIG has an in-plane magnetization, the out-of-sample field \( H_m \) has maximum on YIG surface decreasing slowly with distance from it. The Al layer fabricated on YIG is very thin relative to the thickness of YIG plate. Therefore, \( H_m \) penetrates the whole Al layer without changing its strength. The estimations show that for YIG with magnetization value \( 4\pi M_s = 2400 \) Oe, which is table low temperature value, the demagnetizing field \( H_m \) is \( \sim 8 \) Oe [34]. Table value of critical field for Al film is \( H_L \sim 100 \) Oe. This field completely destroys the superconductivity. The \( H_m \) is smaller than \( H_L \). Therefore it does not destroy superconductivity but reduces critical temperature \( T_c \) by appropriate value. Roughly estimated [40] temperature reduction \( \Delta T \) is about of \( \sim 0.05 \) K, which is in reasonable agreement with our experiments. Further, the current flowing through the Al stripe produces some field \( H_f \), which is summarised with \( H_m \); the \( H_m \) slightly deviates from stripe direction by \( H_f \) for parallel with magnetization stripe and the strength of summarised field varies between \( H_f = H_f + H_m \) and \( H_f = H_f - H_m \) for perpendicular stripe, namely, the field is increased on one stripe surface
and decreased on opposite one. Thus, self-field of the YIG together with current field could bring asymmetric responses in differently oriented Al stripes upon variations of an applied current.

The widening of superconducting transition in SF structures is ascribed usually to the enhanced flux flow states which are described in many publications, e.g. in [41-44]. Different from our observations (compare curves 1 with 2,3 in figure 2), the expected broadening is independent upon mutual orientation of the current and magnetization. The spatial fluctuations of superconductivity or normal phase can be differently oriented in parallel and perpendicular stripes because of the interaction with considered above field $H_m$ and these would cause their different drift (in directions and velocity). The field $H_m$ can introduce vortices in Al stripe, orientation of which and as a consequence motion under the current flow would be different; as a consequence, the energy losses in two types of stripes as well as $R(T)$ would be different. Unfortunately, we cannot define exactly what impact gives each of discussed above mechanisms in large orientation dependent variation of $R(T)$ that we observe. New experiments are needed.

Finally, we suggest the using of the observed effects in some low-temperature applications. For example, the resistance of a structure consisting of two crossed stripes or squared shaped can be switched between low and high resistance by changing the strength or direction of the current. Otherwise, relatively weak rotating magnetic field, below 10 Oe, can be applied for switching of the resistance of Al/YIG. We believe that similar effects can take place in any SF structures where the equilibrium magnetization of the ferromagnet is oriented in the structure plane.

5. Conclusions

We compared the superconducting phase transitions in Al stripes fabricated on plates of oxidized silicon and yttrium-iron garnet which is ferrimagnet dielectric. In accordance with the known literature data, we observed a decrease in the temperature of the superconducting transition and its widening due to the proximity of the magnetic dielectric. Studying the influence of orientation of the magnetization in the plane of the structure, we discovered unexpected phenomena. We found that the widening of the superconducting phase transition largely depended on the mutual orientation of the magnetization $m$ and testing current $j$. The transition was remarkably wider at parallel orientation, i.e when $|j \times m| = 0$. We also found that the transition depends both on the strength of the current and on the direction of vector product $|j \times m|$, being shifted towards higher or lower temperature when the product change the sign in the case of $|j \times m| \neq 0$. Considering the generally accepted mechanisms of the influence of the proximity of a ferromagnet on the properties of a superconductor, we came to the conclusion that the interface spin-orbit coupling along with the influence of self-field of ferromagnet on the flux-flow state and on the nucleation and drift of vortices could explain the found asymmetry. We believe that similar effects can be observed in any SF structures. Finally, we suggest the circuits of low-temperature resistive devices, the resistance of which can be switched by changing the strength or direction of the current or otherwise by the rotation of magnetic field.

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