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Giant spin-valve effect in yttrium–ion garnet–aluminum structures

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The nature of resistive switching in structures of yttrium iron garnet-aluminum (YIG/Al) observed when the current direction is changed relative to the direction of YIG magnetization has been studied. It has been established that the effect observed when the magnetic field is rotated increases with an increase in the current passed through the structure and achieves 100 percent switching from the superconducting to the normal resistive state. The magnitude of the effect depends on geometric factors, namely, on the ratio of the lateral dimensions of the YIG plates. Modeling the configuration of the magnetostatic stray fields showed that the effect is partially determined by these fields. It has been established that the inversion of the current flowing through the structures also leads to a variation in their resistance. The effect reaches 20% near the temperature of superconducting transition.

Keywords: magnetic dielectrics, superconductor, proximity effects, spin-orbit coupling, Zeeman field, spin-valve.

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1. Introduction

The intensive development of cryoelectronics and the prospect of creating a cryogenic quantum computer implies the existence of the entire computer architecture capable of operating at low temperatures. These are elements of dynamic memory (i.e. qubits), this is static memory with the ability to rewrite it in ultrashort times, these are also a new type of transistors, switches and much more. New, developing in recent years approach to their creation includes the use of magnetoelectric effects [1,2] in hybrid S/F nanostructures to control the superconductor properties. A wide theoretical and experimental study of such structures is also explained by interesting physics, the prediction of many new physical phenomena [2–8] and due to promising applications in cryoelectronics as non-dissipative switches implemented by rotating a magnetic field, current or ultrashort light pulses, cryogenic memory elements, etc. However, in many cases, experiments allow ambiguous interpretation of the results, just because the states with in-plane and perpendicular magnetization are compared [9]. Of course, such an experimental geometry corresponds to the necessary change in the orientation of the magnetization vector from longitudinal to perpendicular. However, in this case, there is a change in the configuration of the magnetostatic stray fields and the inevitable rearrangement of the magnetic domain structure of the ferromagnetic, a change in its parameters and hardness, which also changes the interaction of the ferromagnetic with the superconductor.

2. Experimental setup

This paper presents the results of experimental studies of the influence of the proximity of the magnetic dielectric of yttrium iron garnet (YIG) on the superconducting properties of aluminum. Aluminum is a technologically advanced superconductor with a long coherence length, which makes it convenient to fabricate structures; it is this material that is used in qubits. YIG is magnetic dielectric with a record low attenuation, gigahertz rates of magnetization switching by a magnetic field or light. In addition, exactly in bilayer structures fabricated on YIG: normal and heavy metals Cr, Fe, Co, Ta, W, Ni, $Fe_{20}Ni_{80}$, Pt, Pd manifestations of spin-orbit interaction were observed at the interface [10,11], which gave reason to expect the observation of this effect in structures with superconductors. The properties of the materials described above determined the choice of them.

The experiments were performed on Al strips 3 and 6 μm wide, $60-100\,\mu$m long and 80 nm thick, fabricated by magnetron sputtering directly onto YIG plates with (112) orientation. Therefore, in the plane of the plates there was only one axis of easy magnetization $\langle 111 \rangle$, along which the magnetization was oriented, alternating in the direction along and against the axis in neighboring magnetic domains having a width of 500 μm. Al strips were deposited along the center of these domains along and across the direction of magnetization (Fig. 1), which was controlled by visual observations of the magnetic domain structure in the polarized-light microscope in transmitted polarized light. We used YIG plates with sizes $\sim 3.6 \times 4$, 8×2.6 and 10.6×2.2 mm, where the first size corresponds to the size along the easy axis, the second — to the size across the axis, with approximately the same thickness $\sim 60\,\mu$m. On every plate were located in fours aluminum strips, two were narrow and two were wide.

YIG/Al samples and reference $Si/SiO_2/Al$ samples were simultaneously fabricated in each cycle.

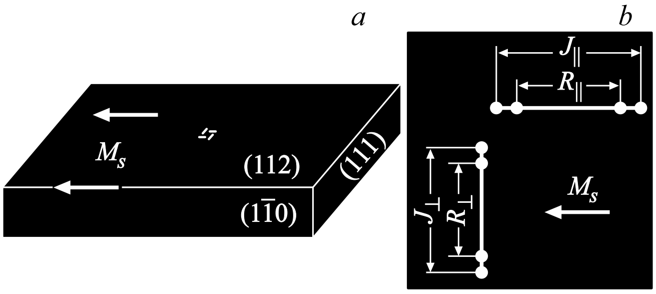

Figure 1. *a* is schematic representation of YIG plate, the orientations of its faces are given, the direction of spontaneous magnetization M_s is shown, and the arrangement of aluminum strips is also schematically shown. It should be noted that the aluminum strips are much smaller than the YIG plates, and all the strips are located in the central region of the plates outside the domain boundaries. *b* is a diagram of the central part of the sample, showing the orientation of the aluminum strips on the (112) YIG plane, parallel and perpendicular to the M_s direction, indicating the location of the contacts.

Resistance measurements were carried out by the standard 4-point method with a constant current of 1 to 100 μA, passed along the strips of aluminum, as shown in Fig. 1.

3. Experimental results

As in our previous experiments [12,13], due to the proximity of the ferromagnetic layer, the superconducting transition temperature T_c of all Al structures prepared on garnet noticeably decreased compared to similar structures prepared on oxidized silicon substrates, and the transition itself was significantly expanded. This is clearly seen in Fig. 2, *a* and *b*, where the plots show the $R(T)$ dependences measured on aluminum strips deposited on oxidized silicon (curves R), on aluminum strips deposited on the YIG and oriented perpendicular to the M_s direction in the YIG plate (curves $R_\perp$) and parallel to the M_s direction (curves $R_{\|}$). It is also seen that the dependences $R(T)$ are different for aluminum strips perpendicular and parallel to M_s, i.e. $R(T)$ depends on the orientation of the current J with respect to M_s: the transition to the superconducting state at $J \times M_s = 0$ ends at temperatures lower than at $J \times M_s \neq 0$.

In this work, we explored the issue: what other factors influence the magnitudes of the effects. First, we have established that the current strength turns out important to be: the larger the current flowing through the structure, the more noticeable the differences in the form of the $R(T)$ dependence for different misorientations of the current and field. Figure 2, *a* shows $R(T)$ for current with strength 1 μA, Figure 2, *b* — for 10 μA. It can be seen that at the current of 10 μA, there is a slight suppression of the beginning of the transition, moderate decrease T_c if defined as the temperature at which the resistance drops by a factor of two relating the normal value, but the distinction between $R_\perp$ and $R_{\|}$ is more than at current $J = 1\,\mu$A. Experiment shows that the stronger the current, the stronger this distinction. Two plots showing the largest difference in $R_\perp$ and $R_{\|}$ observed by us at two currents, $J = 10$ and $100\,\mu$A are given in fig. 3. It can be seen that $\Delta R = R_\perp - R_{\|}$ reaches 100% change in resistance in fairly wide temperature range near T_c, $\Delta T = 1.15{-}1.21$ K at $J = 100\,\mu$A. The impressing of larger currents is undesirable, because overheating of the structures becomes noticeable.

Secondly, we found that the shape of the garnet plate on which the structures are prepared affects the magnitude of the observed effects. As can be seen from Fig. 4, the suppression of T_c in nearly square sample with the

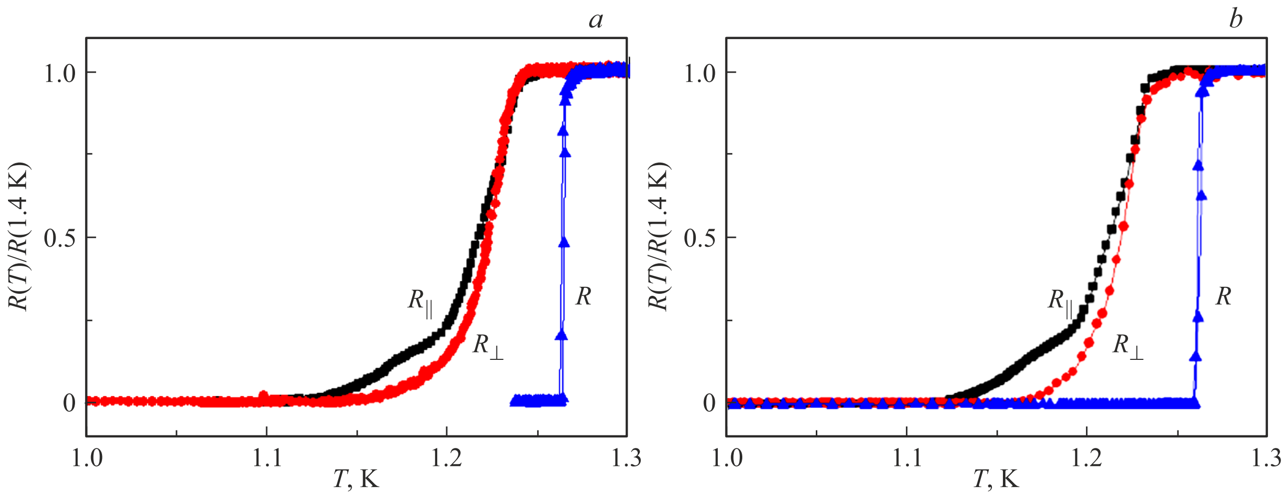

Figure 2. Temperature dependences of the resistance of aluminum structures fabricated on oxidized silicon (curves marked as R) and on YIG with the structures oriented perpendicularly (curves $R_\perp$) and parallel (curves $R_\perp$) to magnetization; *a* are measurements at $J = 1\,\mu$A, *b* are measurements at $J = 10\,\mu$A. The YIG plate, on which aluminum structures are fabricated, has a size of 10.6×2.2 mm. Aluminum strip width is 6 μm.

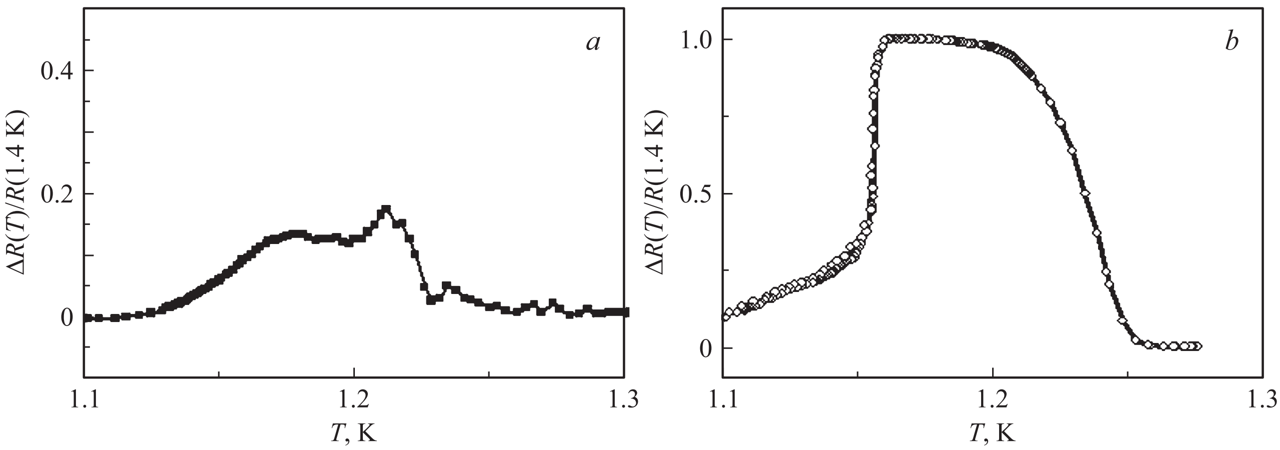

Figure 3. Difference in $R_\perp$ and $R_\parallel$ for $J = 10\,\mu$A and $J = 100\,\mu$A is shown in *a* and *b*. The YIG plate, on which aluminum structures are fabricated, has a size of 10.6×2.2 mm. Al strip width is $3\,\mu$m.

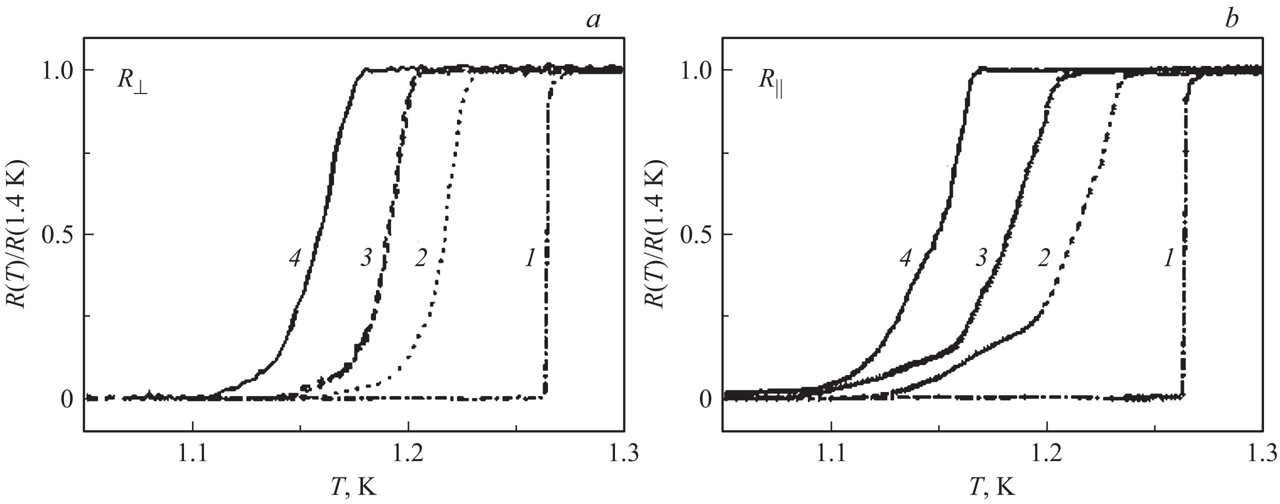

Figure 4. Temperature dependences of the resistance of aluminum structures fabricated on oxidized silicon (curve *1*) and on YIG (curves *2, 3, 4*) with structure orientation and current flow perpendicular to magnetization in *a* and parallel to the magnetization in *b*. For YIG samples, plate sizes vary and the aspect ratio of YIG samples changes: 4.8 (curve *2*), 3.1 (curve *3*) and 0.9 (curve *4*). Measurements at current $10\,\mu$A. Al strip width is $6\,\mu$m.

aspect ratio of $k = 0.9$ (curve *4* in Fig. 4) is much stronger than in long strips with $k = 3.1$ or 4.8 (curves *3* and *2*, respectively, in Fig. 4). However, the difference between $R(T)$ for current flow parallel and perpendicular to the magnetization is more significant in long samples than in nearly square ones, which can be seen from a comparison of the corresponding curves in Figs. 4*a* and *b*. At the same time, $R(T)$ in the perpendicular geometry remains a function smoothly decayed with decreasing temperature, while in the longitudinal geometry, the kink is clearly seen, which increases as the sample lengthens (from the curve *4* to the curve *2* in Fig. 4). It should be emphasized again that the maximum difference between curves $R_\perp(T)$ and $R_\parallel(T)$ is observed exactly on a long sample (Fig. 3, curves *2*).

Finally, we found that the inversion of the current direction leads to the shift in the transition temperature and the change in resistance of the structure, Fig. 5,*a* (T_1 and T_2). This change is especially significant on long specimens when measured on narrow aluminum strips, Fig. 5. Although this effect is weaker than when the current is reoriented by 90 degrees, it is quite observable at current of $50-100\,\mu$A.

4. Discussion of results

Thus, we have determined that the transition temperature of aluminum deposited onto the YIG plate to the superconducting state and the behavior of the dependence $R(T)$ are depending on the mutual orientation of the magnetization and the current flowing through the structure, on the current strength, on the geometric factor, and also are changing at current inversion.

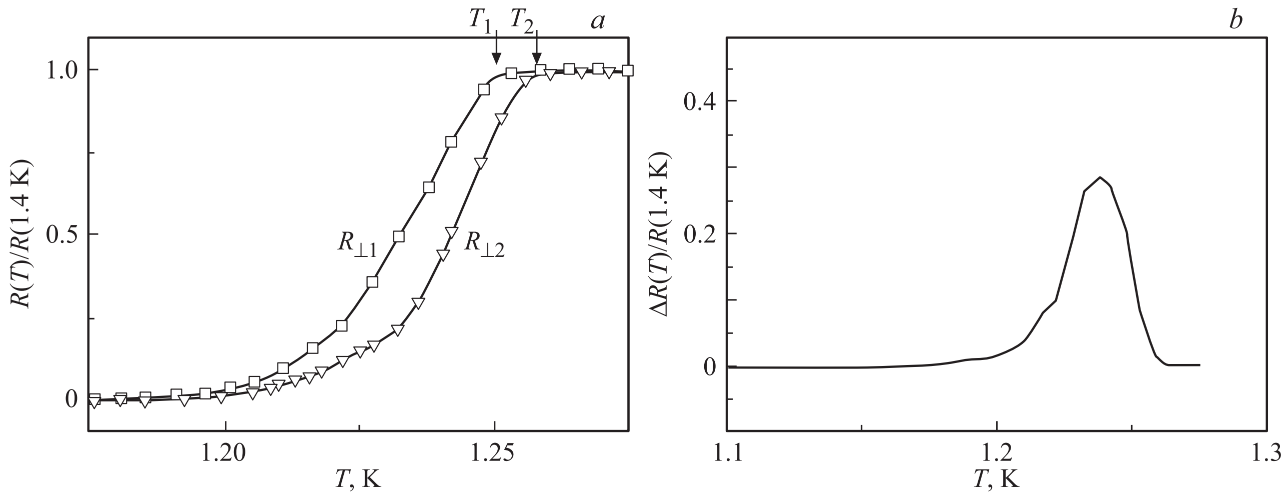

Figure 5. Changes in the resistance of the structure in cases of current with the strength of $100\,\mu$A flowing transverse to the YIG magnetization and its inversion; *a* are experimental dependences of $R_\perp(T)$ for two current directions, T_1 and T_2 are temperature of the beginning of the superconducting transition; *b* is difference between the curves shown in Figure *a*. The YIG plate has the size 10.6×2.2 mm, the width of the Al strip is $3\,\mu$m.

Let us first consider the decrease in the superconducting transition temperature in structures prepared on garnet compared to the same structures prepared on oxidized silicon. In the work [13], it was shown that the effect can be associated with the influence of the demagnetizing field, which is inevitably present near the surface of the magnetic. Indeed, if the magnetic moment of the garnet is oriented along the surface of the plate, then the demagnetizing field H_m is also directed along this surface, but in a way opposite to the magnetization. Due to the invariance of the tangential component of the field strength when transiting through the garnet–aluminum interface, the same field is applied to a thin layer of aluminum, and in its presence the structure is cooled. It is clear that this field can lower the transition temperature slightly. Let us estimate how significant this lowering is for our samples. Aluminum structures were prepared on rectangular garnet plates with different aspect ratios, i.e. characterized by various demagnetizing factors N that determine the scattering fields $H_m \sim 4\pi N M_s$, where $4\pi M_s = 2400$ Oe is the low-temperature saturation magnetization of YIG [14]. This formula is true for H_m in a uniformly magnetized sample. In the work [13] it was proposed to use it taking into account the specific domain structure in the following way. A specific domain is considered in which the aluminum structure is located, its specific dimensions are taken into account: length, width, thickness, which in our case coincides with the thickness of the plate, since the domains are through. Ellipsoid is inscribed in this domain, and the demagnetizing factor is calculated by numerical method, and then the demagnetizing field H_m is calculated. Equating H_m to $H_c(T)$ in the formula relating critical field to temperature, [16]: $H_c(T) = H_c(0)[1 - (T/T_c)^2]$, and assuming for aluminum $H_c(0) = 104.9$ Oe, as for bulk material, and $T_c = 1.26$ K, determined in our experiments for strips of aluminum prepared on oxidized silicon, the expected temperatures of the superconducting transition, $T_c \sim 1.23$, 1.22, 1.16 K, are calculated, which agrees quite well with the experimentally observed $T_c \sim 1.23$, 1.20, 1.17 K, Fig. 4. It should be noted that such agreement does not mean that other mechanisms of suppression of superconductivity, for example, through an exchange field suppressing superconductivity near the S/F interface [17–19] or Andreev reflection from a spin-polarized interface [20,21] do not contribute to the observed effect, but shows that in the case of Al, the direct suppression of superconductivity by the magnetostatic field of the magnetic turns out to be significant even for in-plane magnetization in YIG.

Two other features of the presented results are noteworthy. First, it is the $R(T)$ anisotropy, Fig. 2, observed when the current is turned by 90 degrees. Secondly, nonreciprocity, i.e. $R(T)$ sensitivity to current inversion, Fig. 5.

In thick films, the $R(T)$ anisotropy could be explained by the different interaction of vortices formed in the film in process of cooling in the presence of the field H_m, with the measuring current, which in one case is parallel, and in the other case is perpendicular to the vortices. However, this model works well in films thicker than ξ, which is not fulfilled in our case, so the applicability of the model is not entirely clear. In addition, the difference between the dependences $R(T)$ for parallel and perpendicular orientations of the current and field can be determined by different hydrodynamics of the current in the presence of a field, but this requires theoretical consideration.

Breaking of reciprocity in any physical properties of a system is often associated with the breaking of spatial symmetry of this system. For example, it was predicted in the works [2,22–24] that the symmetry breaking in the direction of the normal to the flat surfaces of a conductor (superconductor) can lead to the dependence of the resistance on the direction of the current relative to the field. The direction can be set, for example, by the one-sided proximity of the superconducting film to the magnetic. Another cause of symmetry breaking in our system may be the film deformation gradient due to the van der Waals interaction of the film with the substrate. Such a gradient makes directions from or to the film-substrate interface nonequivalent. It would be interesting to find a concrete mechanism for the effect of such a symmetry disarrangement on the conductivity of superconductor.

5. Conclusion

The superconducting properties of YIG/Al structures fabricated on YIG plates of various sizes have been studied, and it has been determined that in all samples the lowering the superconducting transition temperature and the expansion of the transition take place. The effect depends on the orientation of the conductor relative to the magnetization of the YIG, on the strength of the current passed through the conductor, and on the dimensions of the YIG plates. In a perpendicular geometry, the change in the resistance of structures upon current inversion was found.

It is important to note that near T_c, in the temperature range of the order of $0.1T_c$, the change in resistance with current rotating reaches 100%, and with current inversion reaches 20%. Switching the resistance due to current inversion does not require the application or switching of an additional magnetic field, it is enough to pass a relatively weak current through the structure, with density of no more than 4×10^4 A/cm^2. This effect can be used to create a new type of low temperature resistance switchers or current direction sensors.

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Conflict of interest

The authors declare that they have no conflict of interest.

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