Magnetization of a planar (type II superconductor)-(ferromagnetic semiconductor) structure

A. S. Borukhovich, V. G. Bamburov, E. A. Antonova, V. A. Sukhov, and B. P. Khrustalev

L. V. Kirenskiĭ Institute of Physics, Siberian Branch, Academy of Sciences of the USSR; Moscow Institute of Steel and Alloys; Institute of Chemistry, Ural Science Center, Academy of Sciences of the USSR

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The magnetization in the easy direction has been studied in a contact planar structure consisting of a hard superconductor and a ferromagnetic semiconductor. The results reveal an open hysteresis loop and switchings of an approximately threshold nature on this loop in partial cycles. The behavior of the low-temperature part of the $M(T)$ curve is observed to depend on the junction magnetization conditions.

The contact planar superconductor-(ferromagnetic semiconductor) (SFS) structure is an interesting physical entity. The results of Refs. 1 and 2 show that a superconductor in a junction of this sort experiences an "effective" magnetic field consisting of the external field H and the self-magnetic field H^* of the film of the ferromagnetic

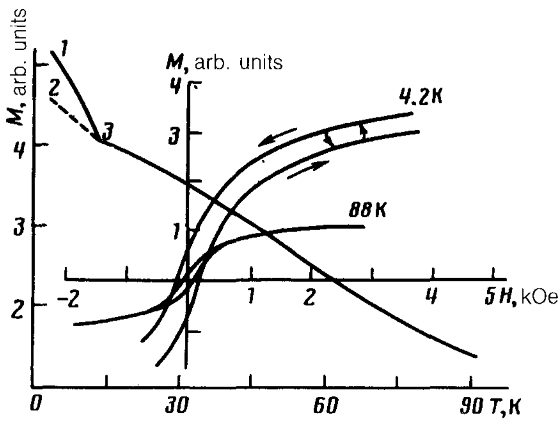

FIG. 1. Hysteresis loops and curve of $M(T)$ of a planar NbN-EuO junction structure ($\mathbf{H} \perp \mathbf{n}$).

semiconductor. The latter field is induced by the external field. This circumstance should affect primarily the magnetic behavior of the junction of a ferromagnetic semiconductor with a hard type II superconductor, with a strong pinning. As a result, irreversible processes occur during the magnetization reversal of a superconductor of this sort. For example, partial hysteresis effects occur at[3] $H < H_{c2}$. Planar SIIFS structures of this sort might find use as elements in cryoelectronic instruments. This application would also require a study of their magnetization reversal. However, the literature reveals no information on the magnetic behavior of SIIFS junctions.

In this letter we report a study of planar SIIFS structures, in which the superconductor is niobium nitride with $T_c = 15$–16.5 K, and the ferromagnetic semiconductor is europium monoxide (the characteristics of (separate) EuO and NbN films are given in Refs. 4 and 5, respectively). For the measurements of the $M(H,T)$ curves we used a vibration magnetometer with a superconducting solenoid in fields up to 70 kOe along the easy magnetization axis of the planar structure in the orientation $\mathbf{n} \perp \mathbf{H}$, where $\mathbf{n}$ is the normal to the plane of the sample. Measurements were carried out in both comparison and direct-amplification regimes. Results are shown in Fig. 1.

A distinctive feature of the $M(H)$ dependence in this case is the presence of an open hysteresis loop. Another is the absence of partial magnetization-reversal loops at fields up to $H \approx 70$ kOe at $T = 4.2$ K. The effective coercive force of this SIIFS junction at $T = 4.2$ K is $H_k \approx 100$ Oe. This figure is close to the value of H_c of a NbN film, and it is 1.6 times the coercive force of a EuO film. The magnetization and demagnetization curves which make up the hysteresis loop lie quite far apart, approaching each other only in a strong field $H \approx 70$ kOe. Attempts to obtain partial magnetization-reversal loops of the junction revealed a transition between the curves upon a change in the sign of the increment in the external magnetic field, ΔH: a transition from the lower curve to the upper curve when the solenoid field was reduced ($\Delta H < 0$) and the inverse transition from the upper curve to the lower one in the case $\Delta H > 0$. This change in the magnetization of the junction is essentially of a threshold nature, and it is reproducible as we move along any partial closed circuit of the loop. When the temperature is raised to $T > T_c$ for the NbN film, the magnetization curve of the SIIFS junction assumes the form typical of a ferromagnet, becoming degenerate in terms of $H_k(T)$. Also shown in Fig. 1 is the large hysteresis loop of the junction at $T = 88$ K, which is of course characteristic of the EuO film exclusively and which indicates that the Curie temperature of this film is in the region ~90 K.

Another distinctive feature of the magnetization of the SIIFS junction is its temperature dependence. While the behavior $M(T)$ of the NbN film at $T > T_c$ is characteristic of a ferromagnet, at temperatures $T < T_c$ the behavior of the magnetization of the junction is determined by its magnetization conditions. For example, when the junction is magnetized from its initial (unmagnetized) state by a strong field ($H \approx 50$–70 kOe), followed by a reduction of the field and a recording of the $M(T)$ curve at 20 kOe (Fig. 1), the behavior of the low-temperature part of this curve corresponds to region 1–3. If, on the other hand, the junction is magnetized by gradually increasing the external field from 0 to 20 kOe, the low-temperature part of the $M(T)$ curve takes path 2–3. Point 3 on the curve corresponds to a temperature ~10–12 K, which in turn corresponds to the value of T_c of the NbN film in a magnetic field of 30–40 kOe (Ref. 5). In the case at hand, this "effective" field in the junction is apparently produced because of the ferromagnetic semiconductor (EuO) film.

The difference ΔM corresponding to the ordinates of points 1 and 2 on the $M(T)$ curves at 4.2 K results from the thickness of the superconducting film. In the case in which the thicknesses of the NbN and EuO films are small and comparable to each other, we have $\Delta M = 0$ at the junction, and the superconducting properties of the junction upon magnetization are suppressed. The apparent reason is the depth to which the magnetic flux penetrates into the SII film.

In summary, the results of this study of the magnetization of a planar (type II superconductor)-(ferromagnetic semiconductor) junction demonstrate that the properties of this junction are rather unusual, because the ferromagnetic semiconducting film is capable of "freezing" the magnetic flux which enters the fairly thick layer of the hard superconductor, while its superconductivity is retained. The superconducting film experiences an "effective" field caused by the presence of the ferromagnetic semiconductor in the junction. Working from the experimentally established difference ΔM at 4.2 K and from the value of ΔT_c of the niobium nitride film, we estimate the strength of this additional field to be 1–2 T.

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