Microwave absorption at a junction between the ferromagnetic semiconductor $HgCr_2Se_4$ and the semiconductor InSb

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The microwave absorption at a junction between the ferromagnetic semiconductor $HgCr_2Se_4$ and the semiconductor InSb has been studied. A huge intensification of the magnetoplasma absorption was observed in the semiconductor during the flow of a current across the junction. An attempt is made to explain the results in terms of a polarization of the charge carriers in the semiconductor.

The charge carriers in a ferromagnet at $T < T_c$ are known to be spin-polarized by virtue of the exchange interaction. The magnitude of this polarization ranges from $\sim 100\%$ in a ferromagnetic semiconductor to ~ 1–10% in a ferromagnetic metal.[1] It has been shown theoretically[2] that the injection of polarized carriers from a ferromagnet into a semiconductor during the flow of a current across a junction formed by the two materials should result in a change in the physical properties of the semiconductor. In particular, it was shown that a polarized luminescence may arise during exposure of a system with spin-polarized carriers to unpolarized light. We have also suggested that the microwave properties of the semiconductor should be altered during this "magnetization" of the free carriers; in particular, the intensity of the ESR involving conduction electrons should increase.

We used a standard-production ERS-230 3-cm-range ESR spectrometer to study the microwave absorption at an $HgCr_2Se_4$–InSb (ferromagnetic semiconductor)–

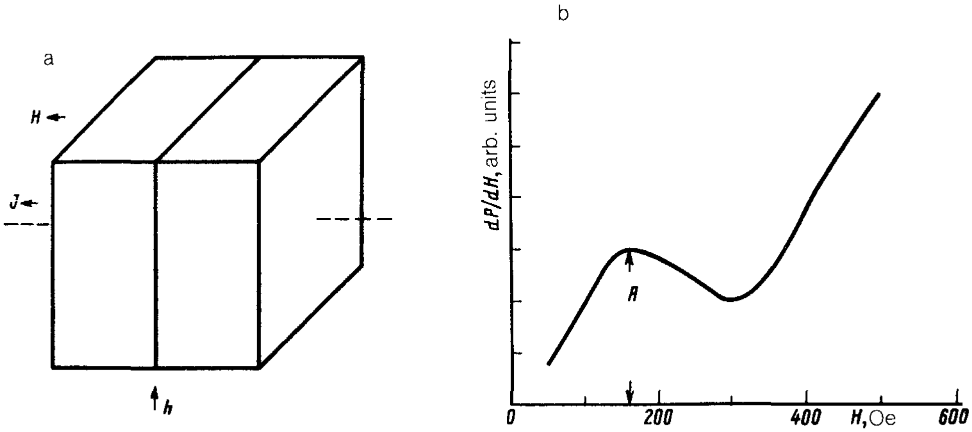

FIG. 1. a—Experimental layout; b—part of the magnetoplasma absorption line.

semiconductor junction during the flow of a current across the junction in an external magnetic field. The g-factor of the free electrons in InSb is known to be $g = -50$, so at a frequency of 10 GHz the ESR line of the carriers is observed at $H \approx 130$ Oe, against the background of a far more intense, broad magnetoplasma line.[3] The characteristics of magnetoplasma absorption depend on the carrier density, the carrier mobility, and the shape of the sample.[4]

The junction was formed by mechanically squeezing together two polished and etched plates of $HgCr_2Se_4$ and InSb, cut from single crystals. The $HgCr_2Se_4$ samples were annealed in mercury vapor to achieve a high conductivity, $\sigma \approx 10^2$ S/cm, of n type. The InSb samples were also of n type, doped with Te to a concentration $\approx 10^{15}$ cm^{-3}. Indium conducting contacts were soldered to both the $HgCr_2Se_4$ and the InSb.

Figure 1b shows part of a magnetoplasma line near the resonance for free carriers. The passage of a current $J = 100$ mA increases the amplitude of the magnetoplasma line, A, by a factor of about 100. Against the background of this large increase in the magnetoplasma line, we did not observe an ESR signal corresponding to the carriers, probably because the demagnetizing field from the ferromagnetic semiconductor was nonuniform. Figure 2 shows the amplitude of the magnetoplasma line as a function of the current for junction structure 1. We see that A is a linear function of J, increasing by a factor of about 100 from its value at $J = 0$. Figure 3 shows the temperature dependence $A(T)/A(4.2\ \mathrm{K})$ for two junction structures. We see that this behavior approximately reproduces the dependence of the magnetization, with a sharp decay near $T = 100$ K, although T_c for $HgCr_2Se_4$ is 120 K. When the current flow through the junction is reversed, no change occurs in the value of A. A test showed that the passage of a current through an InSb sample by itself (not forming a junction with $HgCr_2Se_4$) had no effect on the amplitude A. A change in the temperature for an isolated InSb sample also had only a slight effect on A. The (ferromagnetic semiconductor)–semiconductor structure was magnetized in the direction perpendicular to the plane of the junction. The application of a magnetic field in the direction parallel to

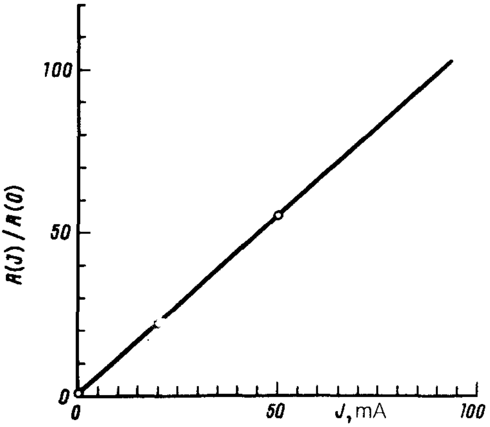

FIG. 2. The $A(J)/A(0)$ dependence for $T = 4.2$ K.

the plane of the junction changed the dependence $\frac{dP}{dH}$ (H) and reduced the change in $A(J)$ by a factor of several units. We should point out that we studied a part of the magnetoplasma line in weak magnetic fields, up to 400–500 Oe—well below the field of the ferromagnetic resonance in $HgCr_2Se_4$ at a frequency of 10 GHz. In addition, we used a separate plate of the ferromagnetic semiconductor to verify the absence of lines of a natural and nonuniform ferromagnetic resonance in fields up to 500 Oe, both with and without a current flow through the sample.

These results—the linear $A(J)$ dependence, which arises only when the semiconductor forms a junction with the ferromagnetic semiconductor, and the disappearance of the effect upon the transition from the ferromagnetic region to the paramagnetic region—may be evidence in favor of spin injection and a corresponding spin polarization of the carriers in the semiconductor during the flow of a current across the junction. The layer of polarized carriers may reach a large thickness. In InSb, for example, the relaxation time found for the spin polarization of the charge carriers

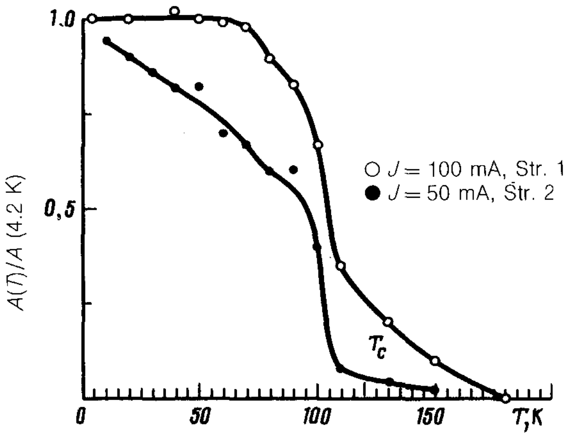

FIG. 3. The $A(T)/A(4.2\ K)$ dependence for two current values.

from the ESR experiments is 10^{-6}–10^{-7} s. At a density of 10^{15} cm^{-3}, a mobility of 10^5 cm^2/(V·s) and a current of 100 mA, the drift velocity would be 10^5–10^6 cm/s, and the carriers would be polarized in a layer ≈ 1 mm thick. It is also obvious that as the electrons move from the semiconductor into the ferromagnetic semiconductor a spin polarization will again occur, but with the opposite sign: The carriers with a spin corresponding to the polarization of the ferromagnetic semiconductor will pass into it, while the carriers with the opposite spin polarization will be reflected from the junction. They will accumulate near it, since the conduction band for the electrons with the opposite spin polarization is 1 eV higher in the ferromagnetic semiconductor. This interpretation might explain why the effect is independent of the current direction. One possible mechanism for explaining the change in the intensity of the magnetoplasma resonance might be as follows: At the transition from polarization to depolarization at a fixed concentration, the radius of the Fermi-energy surface of a free electron gas decreases by a factor of $2^{1/3}$. Such a transition would evidently be accompanied by an additional appearance of a gradient of the electric potential in the semiconductor and thus by the appearance of a space charge in the semiconductor. The corresponding electric dipole moment would also be proportional to the current. This effect could obviously influence the amplitude of the magnetoplasma oscillations, which are known to be of an electric dipole nature.[4]

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