Detection of the magnetization of a ferromagnetic film in a Ni/GaAs structure from the polarization of electrons of the semiconductor

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It has been found that a ferromagnetic nickel film deposited on an n-GaAs surface by ion sputtering affects the polarization of optically oriented electrons in the semiconductor. The film gives rise to magnetic fields in the semiconductor which fluctuate in space. These fields stem from the domain structure of the material. The film also gives rise to a regular magnetic field, which is proportional to the magnetic moment of the film. A photoinduced change in the coercive force of a nickel film has been observed. The use of a semiconductor as a magnetization detector opens up new opportunities for monitoring the state of ferromagnetic films. © *1994 American Institute of Physics.*

Systems consisting of a ferromagnet and a paramagnetic metal have recently attracted considerable interest.[1,2] There have also been studies of ferromagnet/semiconductor structures.[3] It was observed in Ref. 3 that a semiconductor affects the magnetic properties of a ferromagnetic Fe film in the Fe/GaAs system. At the same time, we would expect that a ferromagnetic film would in turn affect the magnetic processes which occur in the semiconductor. Magnetic interactions in semiconductors are widely studied by an optical-orientation method.[4]

In the present letter we show that a ferromagnetic nickel film on a gallium arsenide surface causes an additional spin relaxation of optically oriented electrons of the semiconductor. This relaxation is the result of a precession of the electron spins in the spatially fluctuating magnetic fields resulting from the domain structure of the ferromagnet. The effect of the nickel film is seen in the dependence of the average spin of the polarized electrons and also in the dependence of the curves of the magnetic depolarization of the photoluminescence on the magnetization of the ferromagnet. It becomes possible to utilize the semiconductor as a detector of the magnetization of ferromagnetic films.

Illumination of the Ni/GaAs structure leads in turn to a radical change in the magnetic characteristics of the ferromagnetic film. Illumination of a test sample with a laser beam at an intensity ≈ 5 W/cm^2 causes a decrease in the coercive force of a nickel film by a factor of more than 3.

Electrons with spin oriented along the exciting beam give rise to circularly polarized light in the semiconductor in the course of interband absorption. If, during their lifetime, the photoexcited carriers do not completely lose their spin orientation, the photoluminescence will be partially circularly polarized. The degree of the circular polarization (ρ) of

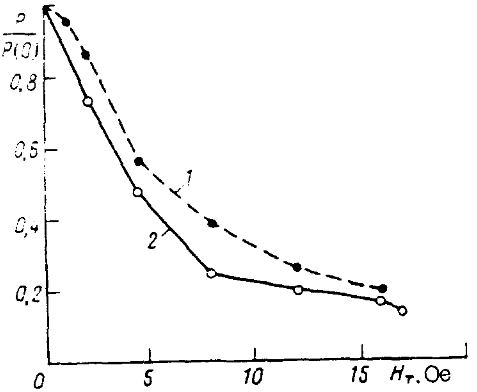

FIG. 1. Depolarization of the luminescence in a Ni/GaAs sample in a transverse magnetic field. 1—After demagnetization of the sample; 2—after magnetization in a field $H = 350$ Oe. The measurement errors do not exceed the size of the points.

the photoluminescence in GaAs is numerically equal to the projection of the average spin of the electrons onto the exciting beam.[4]

It is of interest to use the optical-orientation method to study ferromagnet/semiconductor structures. We have studied a Ni/GaAs sample. The n-type GaAs (Si, 2×10^{15} cm^{-3}) was grown in the [001] direction by liquid-phase epitaxy to a thickness of 35 μm on a gallium arsenide substrate 400 μm thick. A nickel film ≈ 2000 Å thick was grown on the surface of the GaAs layer by ion sputtering.

The experiment was carried out at liquid-helium temperature. The carriers were generated by light which passed through the nickel film along the normal to the surface of the sample. The source of the exciting light was the line at $\lambda = 7525$ Å from a cw Kr^+ laser. The polarization of the edge luminescence was measured at the peak of the line corresponding to the recombination of an exciton trapped by a donor impurity. The procedure for measuring the polarization of the photoluminescence is described in Ref. 5. In order to eliminate the polarization of the nuclear spins of the semiconductor, which affects the electron spin,[4] we carried out the excitation with light, whose circular polarization changed in sign at a high frequency (26 kHz). For this purpose we used a photoelastic light-polarization modulator.[6] We measured ρ as a function of the external magnetic field H, which was directed either along the beam of exciting light (this was the case of a longitudinal field, H_L) or across it (a transverse field, H_T, parallel to the plane of the film).

Figure 1 shows the measurements of the photoluminescence depolarization in a transverse magnetic field (the Hanle effect). The experimental points, through which curve 1 is drawn, were found after a preliminary demagnetization of the Ni/GaAs sample by a transverse magnetic field. In this case, the curve of $\rho(H_T)$ is symmetric under a change in the sign of the external magnetic field. Curve 2 was recorded after a preliminary magnetization of the nickel in the plane of the film in a field $H = 350$ Oe (the field H_T was parallel to the magnetizing field H). This curve is not symmetric with respect to the coordinate axes, and it is shifted 0.3 Oe in the direction of the magnetizing field. The asymmetry was found through precise measurements of the values of $\rho(+H_T)$ and $\rho(-H_T)$ for a given sign of the magnetizing field H (the geomagnetic field was cancelled within 0.02 Oe by means of Helmholtz coils). At the scale of the fields H_T in Fig. 1, this asymmetry is seen only weakly, so we do not show values of $\rho(-H_T)$. The direction in which the curve shifts changes with the direction of the magnetizing field. In a zero magnetic field, the degree of circular polarization of the luminescence is $\rho(0)\approx 1.9\%$ in the case of a magnetized film, while it becomes $\rho(0)\approx 1.5\%$ after demagnetization. The half-width of curve 2 is less than that of curve 1. Note that the curves of the magnetic depolarization in Fig. 1 do not depend on the direction in which the magnetic field H_T is scanned if the range over which this field is varied does not exceed 30 Oe.

These results indicate that an additional mechanism for spin relaxation of electrons of the semiconductor comes into play during demagnetization of the nickel. This new mechanism leads to a decrease in ρ and to a broadening of the magnetic-depolarization curves. The photoexcited electrons lose their initial spin orientation during their lifetime, as a result of spin-relaxation processes. The onset of the additional mechanism for spin relaxation leads to a decrease in the average spin of these electrons and to a decrease in ρ. In a transverse magnetic field, the depolarization of the light occurs if the period of the spin precession in this field becomes shorter than the time over which the spin disappears, T_S (Ref. 4). As T_S decreases, the depolarization of the light occurs in progressively stronger fields, leading to a broadening of the $\rho(H_T)$ curve. The onset of the additional spin-relaxation mechanism reduces the time T_S and thus reduces the broadening of the depolarization curve in a transverse magnetic field. The decrease in ρ in a zero magnetic field and the broadening of the Hanle curve in the case of demagnetized nickel are thus evidence that an additional spin-relaxation mechanism has come into play.

We believe that the additional depolarization of the electrons in GaAs occurs because of a precession of the electron spin in spatially fluctuating magnetic fields caused by the domain structure of the demagnetized nickel. Since a fully demagnetized film consists of a single domain, the spatially fluctuating random magnetic fields disappear, and the spin relaxation is suppressed. A regular magnetic field $\mathbf{H}_0$ arises in the semiconductor in this case. It is caused by the magnetized film, and it adds to the external field $\mathbf{H}_T$. The results are a directed precession of the electron spin and a shift of the magnetic-depolarization curve by an amount equal to the field H_0. Estimating the strength of this regular field, H_0, from the formula $4\pi Md/L$, where M is the saturation magnetization of Ni, d is the film thickness, and $L=4$ mm is the size of the sample, we find $H_0=0.3$ Oe. This result agrees with the shift of 0.3 Oe observed experimentally and mentioned above.

Further support for the fluctuating-field model comes from our measurements of ρ in a longitudinal magnetic field. We found that, as the field H_L was increased, the value of ρ increased in the Ni/GaAs test sample, reaching a constant level of 2.5% in a field $H_L\approx 100$ Oe. In the same GaAs sample without the nickel we found $\rho=3\%$; this value is independent of H_L over the same field range. The increase in the degree of circular polarization in a longitudinal magnetic field has been studied in several semiconductors.[4] It has been shown that this increase stems from a suppression of the electron spin relaxation in random magnetic fields. A quantitative description of this effect depends strongly on the relation between the length scales of the domains of the ferromagnet and the electron diffusion length in the semiconductor; that topic lies outside the scope of the present letter.

The results presented here are unambiguous evidence that a ferromagnetic film

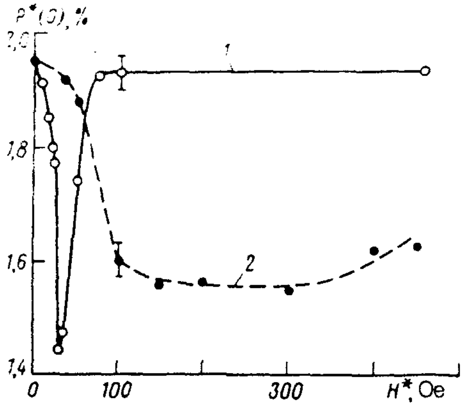

FIG. 2. Degree of circular polarization of the luminescence, $\rho^*(0)$, in a zero magnetic field versus the strength of the magnetization-reversing field H^*. 1—The magnetization reversal of the film was carried out during illumination of the sample; 2—the exciting light was blocked during magnetization reversal of the nickel film.

affects the optical orientation of electrons in the semiconductor in a Ni/GaAs structure. We can make use of the electron polarization in GaAs to monitor the state of the ferromagnetic film, in particular, to monitor the changes in its domain structure during magnetization and demagnetization in an external magnetic field.

We have also observed a photoinduced change in the coercive force of a ferromagnetic film in a Ni/GaAs structure. Illumination of a test sample with laser light at an intensity ≈ 5 W/cm^2 leads to a decrease in this coercive force by a factor of more than 3. This conclusion is demonstrated by the results of an experiment in which we studied the effect of the remanent magnetization of a nickel film on the degree of polarization of the luminescence in GaAs. The sample was magnetized in an external field $H = -350$ Oe, directed parallel to the plane of the film. The magnetizing film was then lowered to zero, and a transverse magnetization-reversing field H^* of the given strength was imposed. The latter field was directed opposite the magnetizing field. The magnetization-reversing field was then also turned off, and we measured $\rho^*(0)$ for the circular polarization of the luminescence corresponding to the remanent magnetization of the film after the application of the external field H^* to it. The procedure described above was then repeated for each value of the field H^*. Curve 1 in Fig. 2 shows $\rho^*(0)$ versus H^* in the case in which the magnetization and magnetization reversal of the film are carried out during illumination of the sample with laser light. The energy flux density of the light incident on the surface of the sample was ≈ 5 W/cm^2. The area of the light spot did not exceed 10^{-3} cm^2. In fields H^* such that the remanent magnetization of the nickel is high, the electron spin relaxation caused in GaAs by the domain structure of the film is suppressed, and $\rho^*(0)$ is at a maximum. At $H^* \approx 30$ Oe, the remanent magnetization is at a minimum, the rate of spin relaxation is high, and $\rho^*(0)$ is at a minimum. At values $H^* > 30$ Oe, the film undergoes magnetization reversal, leading to an increase in $\rho^*(0)$. If the magnetization-reversing field H^* has the same direction as the magnetizing field, we find $\rho^*(0) \approx 1.94 \pm 0.03$, and this value is independent of the strength of the field H^*. Curve 2 in Fig. 2 was derived under conditions such that the magnetization reversal of the film by the field H^* was carried out after the exciting light was turned off. It was then turned on for measurements of $\rho^*(0)$ in a zero external magnetic field. Under these conditions, $\rho^*(0)$ falls off substantially in fields $H^* \geqslant 100$ Oe. Consequently, the values of H^* corresponding to the minimum value of $\rho^*(0)$ (the film is demagnetized) differ by a factor of more than 3 in these two cases (see curves 1 and 2). This difference indicates a substantial decrease in the coercive force during illumination of the test sample. When the sign of the magnetizing field and thus the sign of the field H^* are changed, the two curves in Fig. 2 are mirror reflections with respect to the ordinate axis.

In the case at hand, this huge photoinduced decrease in the coercive force is difficult to explain in terms of a local heating of the sample. Measurements of the hysteresis in the magnetization, carried out with a SQUID on a similar structure in darkness, showed that the coercive force falls off by a factor of about 3 as the temperature is raised from 4.2 to 75 K. The heating of a sample immersed in liquid helium in optical measurements of the magnetization curve does not exceed a few degrees. The change in the magnetic properties of the nickel may be due to the effect of the semiconductor in contact with the ferromagnetic film. Further research is necessary in order to clarify the nature of this effect.

In summary, this study has revealed that a ferromagnetic film deposited on a semiconductor has a substantial influence on the optical polarization of electrons in the semiconductor. The presence of the ferromagnet leads to the onset of an additional relaxation of the electron spin in the semiconductor; this additional relaxation depends on the magnetization of the film. The use of a semiconductor as a magnetization detector opens up a new opportunity for monitoring the state of ferromagnetic films. At the same time, the semiconductor may also influence the magnetic properties of the ferromagnetic film, as is indicated by the photoinduced change in the coercive force of nickel in the Ni/GaAs structure.

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