Spin-echo effect in a variable-gap semiconductor

A. S. Volkov, A. L. Lipko, Sh. M. Meretliev, and B. V. Tsarenkov
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

(Submitted 16 April 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 11, 458–460 (10 June 1985)

A new spin effect has been detected in a semiconductor in whose interior the electron g-factor changes sign: Oriented electrons excited at the surface, whose spins precess in a magnetic field, reacquire their original orientation at a certain distance from the surface, regardless of the strength of the field.

1. We know that during the optical pumping of spin-oriented electrons during their transport in the absence of a magnetic field, the spin-density vector **S** will retain its orientation at any point in the semiconductor. When a transverse magnetic field is imposed, the spin density vector precesses. In the case of surface pumping, the effect of this precession is that the projection of the vector onto the transport direction becomes an oscillating, sign-changing function of the coordinate, with an amplitude that is damped by recombination and spin relaxation. If the g-factor of the electrons is independent of the coordinate, these oscillations will be sinusoidal. If the g-factor instead does depend on the coordinate, the oscillations will not be sinusoidal, and if the g-factor changes sign, there will be an "echo" spin effect.

2. We consider a variable-gap semiconductor in which the g-factor of the electrons and the gap width E_g depend linearly on the coordinate x, and the g-factor changes at some point x_0. We assume that circularly polarized light σ^- excites spin-oriented electrons at the wide-gap surface ($x = 0$), so that the spin-density vector **S** is directed along the x axis (Fig. 1).

In this case the transport of spins in the magnetic field H occurs in the following way. As the electrons drift away from the wide-gap surface, the precession of **S** initially slows down; later, after changing rotation direction at the point x_0, it accelerates with a constant angular acceleration. As a result, the phase of the spin-density vector becomes the same as the original value at the point x_e, which is the mirror image of the initial coordinate with respect to the point x_0. This alignment of spins in phase with the excitation may be interpreted as a sort of spin echo. We stress that the phase of **S** at the point x_e always corresponds to the phase of **S** at the surface, while at all other points in the semiconductor this phase depends on the magnetic field. When **S** is

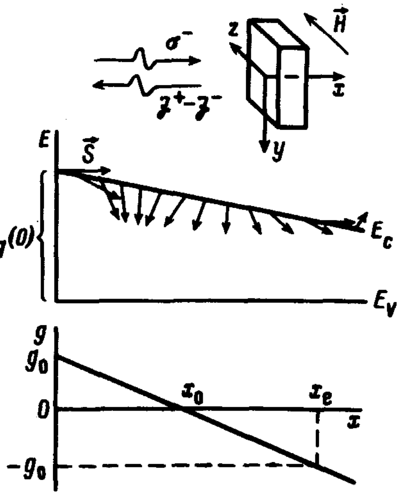

FIG. 1. Energy diagram of the variable-gap semiconductor; profile of the g-factor along the coordinate x. The inset shows the geometry of the problem.

averaged in a time-varying magnetic field, we should of course observe a peak in the amplitude of **S** at x_e.

3. A rigorous solution of the problem of spin transport reduces to the solution of a system of equations for the projections S_x and S_y:

$$L_s^2 \frac{d^2 S_{x,y}}{dx^2} - l_s \frac{dS_{x,y}}{dx} - S_{x,y} \mp \Omega T S_{y,x} = 0.$$

Here L_s and l_s are respectively the diffusion and drift lengths of the spin density, T is the spin lifetime, and the angular precession velocity of the spins, Ω, is a linear function of the coordinate x: $\Omega = \Omega_0(1 + g_0^{-1}(dg/dx)x)$, where $\Omega_0 = g_0 \mu_B H/\hbar$ and $dg/dx = \text{const}$.

Figures 2a and 2b show two series of calculated curves of $S_x(x)$ for various magnetic fields. The different series of curves correspond to different values of the coordinate x_0. In these calculations it was assumed that dE_g/dx, T, and the mobility of the electrons are all independent of the coordinate. The boundary conditions correspond to the generation of S_x at $x = 0$ and to the decay of **S** at infinity. We see from these figures that a change in the coordinate x_0 results in a corresponding displacement of the spin-echo coordinate x_e.

4. One of the fundamental properties of a variable-gap semiconductor is that the photon energy of the recombination radiation, $h\nu$, corresponds to the coordinate (x_ν) of that point at which the radiative recombination occurs. For example, with $dE_g/dx = \text{const}$ and for interband radiative recombination, we have $h\nu = E_g(0) - x|dE_g/dx|$. This property makes it possible to study the transport of nonequilibrium charge carriers and of their spins in the direction of decreasing E_g by luminescence methods.[1]

Measurements[2] of the polarized photoluminescence spectra $J^+(h\nu) - J^-(h\nu)$ of a p-GaAlAs structure in a transverse magnetic field have revealed sign-changing oscillations corresponding to an oscillatory $S_x(x)$. However, since the change in the composition over the structure was of such a nature (a change from 28% to 16% AlAs) that

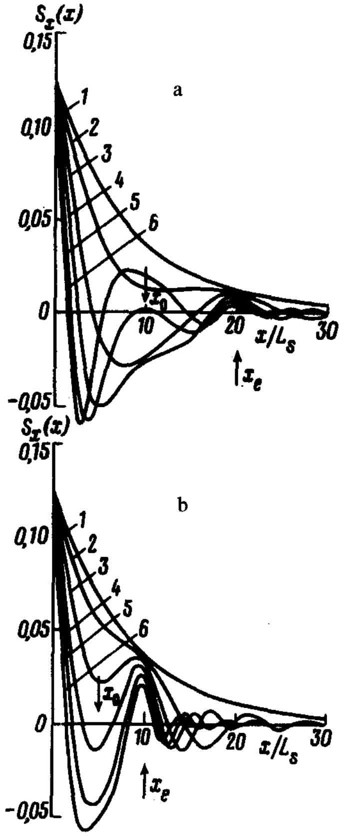

FIG. 2. The x component of the spin density, S_x, versus the dimensionless coordinate x/L_s for $l_s/2L_s = 4$ and for various values of $\Omega_0 T$: 1—0; 2—2; 3—4; 4—6; 5—8; 6—10. $g_0^{-1}(dg/dx)L_s$: a—0.1; b—0.2.

the g-factor did not change sign, no spin echo arose.

5. In an effort to experimentally detect the spin-echo effect in the present experiments, we fabricated a variable-gap p-GaAlAs:Zn structure in which the composition of the solid solution varied from 25% to 1% AlAs, so that the g-factor of the electrons varied from 0.35 to -0.4 (Ref. 3). Here the derivative dE_g/dx varied from 250 eV/cm at the wide-gap surface to 100 eV/cm at the narrow-gap surface, and the average gradient of the g-factor was 380 cm^{-1}. The structure was excited by the beam from a He-Ne laser ($h\nu = 1.96$ eV).

Figure 3, a and b, shows two series of spectra of the polarized photoluminescence in various magnetic fields. The spectra in Fig. 3b were obtained after a three-μm layer was etched off the wide-gap surface of the original structure (the spectra in Fig. 3a). We see that the etching, which shifts the energy of the maximum of the photoluminescence spectra in the long-wave direction, leads to a short-wave displacement of the photon energy corresponding to the echo coordinate x_e. However, since dE_g/dx and dg/dx were not constant in this structure, the position of x_e with respect to x_0 is no longer the point of the mirror image of the origin of coordinates.

On each series of curves we observe yet another maximum, at $h\nu = 1.49$ eV, in the absence of a magnetic field. This maximum is due to an accumulation near the

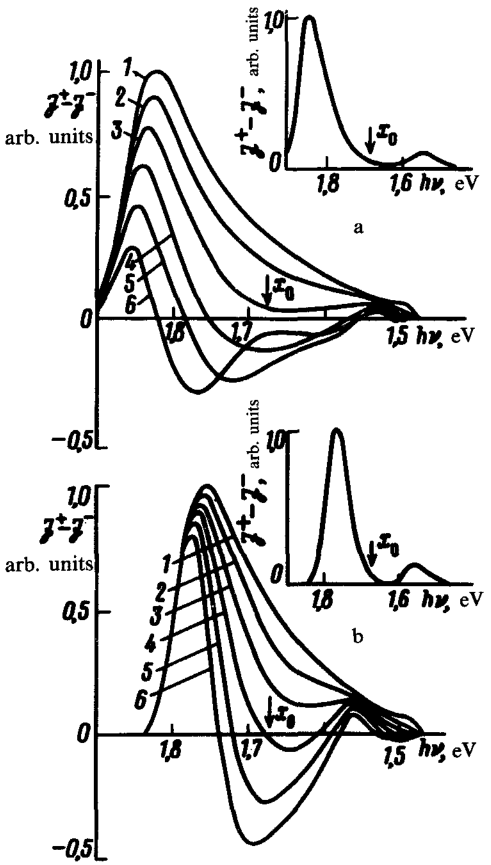

FIG. 3. Polarized photoluminescence spectra (a) before and (b) after etching of the structure at 14 K in various magnetic fields *H*, kOe: 1—0; 2—2; 3—3; 4—4; 5—5; 6—6.

narrow-gap surface of electron spins that have drifted across the entire structure.

The insets in Fig. 3, a and b, show the polarized photoluminescence spectra obtained by integrating the luminescence signal over the entire time during a sinusoidal variation of the magnetic field with an amplitude of 6 kOe. The spin echo is seen as a spike in the polarized emission at the corresponding photon energy.

We wish to thank V. I. Perel' and A. A. Rogachev for a discussion of these results.

[1] A. S. Volkov and G. V. Tsarenkov, Fiz. Tekh. Poluprovodn. **11**, 1709 (1977) [Sov. Phys. Semicond. **11**, 1004 (1977)].

[2] A. S. Volkov, A. I. Ekimov, S. A. Nikishin, V. I. Safarov, B. V. Tsarenkov, and G. V. Tsarenkov, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 560 (1977) [JETP Lett. **25**, 526 (1977)].

[3] C. Weisbuch and C. Hermann, Phys. Rev. **15**, 1850 (1977)

Translated by Dave Parsons