Onset of a nuclear polarization front due to optical spin orientation in a semiconductor

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The nuclei of a semiconductor near the donors can be polarized optically [$T_{1e}(0) \lesssim 10^{-4}$ sec]. This leads to the formation of a nuclear polarization front, which is displaced from the donor within the limits of the diffusion radius, similarly to a shock wavefront. An effective method of optical cooling of the nuclear spin system to $\sim 10^{-6}$ K is used.

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Optical orientation of electrons in a semiconductor is accompanied by polarization of the nuclei.[1] The fluctuating electron field at the nuclei near a donor causes nuclear relaxation with a time[2] T_{1e}:

$$T_{1e}^{-1} \approx 2F\omega^2(r)\gamma/(\gamma^2+\Omega^2), \tag{1}$$

where $\omega(r)$ is the Larmor precession frequency of the nuclei in the field of the electrons at a distance r from the donor, γ is the frequency of the fluctuations of the electron field, Ω is the Larmor precession frequency of the electrons, and F is the donor filling factor. In the case of n-type crystals we have $F = 1$.

The dependence of T_{1e} on r is determined by the square of the modulus of the wave function of a donor-localized electron $|\Psi(r)|^2 \sim \exp(2r/a_B)$:

$$T_{1e}^{-1} = T_{1e}^{-1}(0)\exp(-4r/a_B). \tag{2}$$

Here a_B is the Bohr radius, and $T_{1e}(0)$ corresponds to $r = 0$.

The overwhelming majority of experiments on optical orientation of electrons and nuclei in semiconductors have been carried out for steady-state conditions. We now examine the process of establishing the steady-state condition.

Suppose that a change in the external conditions causes a transition between the steady states corresponding to the values $\langle I_1 \rangle$ and $\langle I_2 \rangle$ of the average spin of the nuclei. Incorporating Eqs. (1) and (2), we can represent the process of establishing $\langle I(r) \rangle$ in the form

$$< I(r,t) > = < I_2 > - (< I_2 > - < I_1 >)\exp[-\tau\exp(-4r/a_B)], \tag{3}$$

where $\tau = t/T_{1e}(0)$.

Equation (3) describes the location of the spherically symmetrical nuclear polarization front as a function of t. Figure 1 illustrates the displacement of the front after circularly polarized light is turned on at the time $t = 0$. As seen from this figure, the length of the front is $\sim(3/4)a_B$.

In experiments the optical polarization of the nuclei is usually determined from the effective field $\mathbf{H}_N = h_N \langle I \rangle$, where $h_N = H_N$ for $\langle I \rangle = 1$. This field acts on the electron spins and can be detected from the change in the degree ρ of circular polarization of the recombination radiation with the participation of these electrons.[2] The time dependence of H_N can be found by integrating Eq. (3) with respect to r and taking into account the r dependence of the electron density at the nucleus. For $t \gg T_{1e}(0)$ we obtain

$$H_N(\tau) = A \int_0^\infty < I(r,\tau) > |\Psi(r)|^2 r^2 dr \approx B - \frac{C}{\sqrt{\tau}}(\ln^2\tau + 3.93\ln\tau + 8.79). \tag{4}$$

Here A B, and C are constants.

The front can exist only if the time $T_{1e}(0)$ is small. The influence of diffusion and dissipation of the nuclear polarization in this case is insignificant. The n-type crystals should have small values of T_{1e}.

The experiment was carried out under conditions that combine optical cooling of the nuclear-spin system[3-5] with its cooling by means of adiabatic demagnetization. Such a combination makes it possible to obtain the minimum spin temperature β^{-1} and a high nuclear polarization in weak magnetic fields, where T_{1e}^{-1} is a maximum.

The experiment has three steps. 1) Optical pumping with a circularly polarized light during a time t_p in a longitudinal magnetic field $H_\parallel > H_L$, where H_L is the local field of the nuclei. At a sufficiently large value of t_p for a lattice of identical nuclei $\beta_1 = (4I/\mu_I)\langle S \rangle H_\parallel :(H_\parallel^2 + H_L^2)$, where μ_I and I are the magnetic moment and spin of the nucleus, and ξ is a numerical coefficient $(2 < \xi < 3)$. 2) Adiabatic demagnetization. A temperature $\beta_2 \approx \beta_1 H_\parallel / H_L$ is reached as a result of demagnetization. 3) Optical measurement of the nuclear polarization in a transverse field $H_\perp \ll H_L$ which makes possible a direct study of the spin–lattice relaxation process in a weak magnetic field at a small time T_{1e}. The equilibrium nuclear polarization along the field $H_\perp$ at β_2 is characterized by an average spin $\langle \mathbf{I} \rangle = (1/3)(I+1)\beta_2\mu_I \mathbf{H}_\perp$. In this case there is a transverse nuclear field H_N which causes depolarization of the electrons (Henley effect)

$$\mathbf{H}_N = h_N (4/3)(I+1) I < S > \mathbf{H}_\perp / H_L. \tag{5}$$

Figure 2 shows the variation of $\rho = \langle S \rangle_z$ in a field $H_\perp = 0.1$ Oe after optical pumping of n-type GaAs at 4.2 K in a field $H_\parallel = 100$ Oe for 5 min (the earth's field is

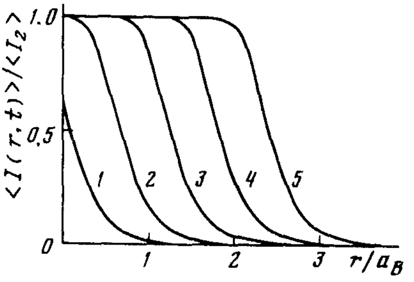
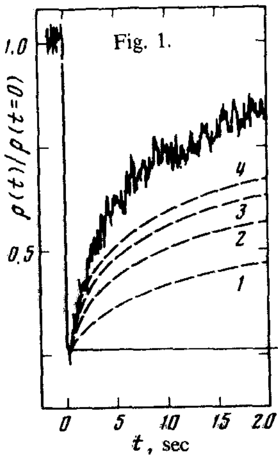


FIG. 1. Location of the nuclear polarization front after a time $T_{1e}(0)$ (1), $10T_{1e}(0)$ (2), $10^2T_{1e}(0)$ (3), $10^3T_{1e}(0)$ (4), and $10^4T_{1e}(0)$ (5) after switching on the light σ.



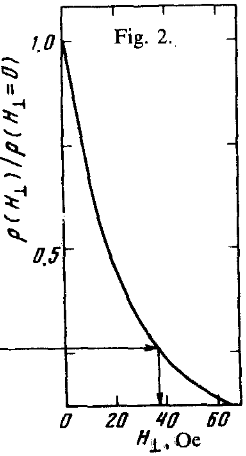


FIG. 1. $\rho(t)$ dependence for a GaAs crystal after switching off the field $H_\parallel = 100$ Oe and turning on the field $H_\perp = 0.1$ Oe at a temperature of 4.2 K. The dashed curves were obtained from Eq. (4) for $T_{1e}(0) = 10^{-1}$ sec (1), $10 - ^2$ sec (2), 10^{-3} sec (3), and 10^{-4} sec (4).

FIG. 2. $\rho(H_\perp)$ dependence for a varying polarization of the excited light with a frequency of 50 kHz. The vertical arrow denotes the value of the field $H_\perp$ equal to the field H_N at the point of the $\rho(t)$ curve in Fig. 2 that corresponds to $t = 0.4$ sec.

compensated for). The values of H_N at different points on the $\rho(t)$ curve in Fig. 2 can be determined from the Henley curve for fast modulation of the polarization of the excitation light (in order to eliminate H_N) (see Fig. 3). Identical values of ρ in Figs. 2 and 3 correspond to the equality $H_N = H_\perp$. Thus, at $t = 0.4$ sec the deviation of ρ in Fig. 2 corresponds to $H_N^{\text{exp}} \approx 38$ Oe. An estimate of H_N from Eq. (5) gives $H_N^{\text{theor}} \approx 200$ Oe ($h_N = 35.3$ kOe^5, $I = \frac{3}{2}$, $H_L \approx 2$ Oe, and $\langle S \rangle = 0.025$). This estimate corresponds to $\beta_2{}^{-1}$ 1μK. The value of the ratio $\delta = H_N^{\text{exp}}/H_N^{\text{theor}} \sim 0.2$ is determined by a rapid warming of the nuclear-spin system near the donor and by the motion of the temperature front (similar to the front in Fig. 1) during the recording. The fast recording of the variations of the small values of ρ is limited by fluctuations of the light flux. The experimental curve in Fig. 2 was obtained with a time constant of 0.1 sec. The quantity δ corresponds to the contribution of the peripheral nuclei outside a sphere with radius $R \sim 2a_B$. The temperature front is displaced this distance at $\tau \sim 10^4$; consequently, $T_{1e}(0) \lesssim 10^{-4}$ sec. The quantity β can be determined rigorously only at those r values for which $T_{1e}(r) \gg T_2$ (T_2 is the spin-spin relaxation time of the nuclei). The region of r (large τ), for which this condition is satisfied, has been observed in the experiment.

The calculated $\rho(t)$ curves in Fig. 2, which are obtained with the aid of Eq. (4) and the curve in Fig. 3, are normalized at $t = 0.4$ sec. An estimate shows that during the time t_f of diffusion of the nuclear spins a distance equal to the length of the front it has no effect (within measurement error limits) on the $\rho(t)$ curve. For GaAs $t_f \sim 5$ sec. The diffusion transport of polarization in the direction of the donor center causes an additional decrease of H_N and a rise of the $\rho(t)$ curve. An estimate of $T_{1e}(0) \lesssim 10^{-4}$ sec has been obtained from a comparison of the calculated $\rho(t)$ curves with the experimental curve for $t < 5$ sec. In this case $\gamma \lesssim 2 \times 10^8$ rad/sec ($\omega \sim 10^6$ rad/sec and $F = 1$) in Eq. (1), and even weak fields (tens of oersteds) should slow the relaxation considerably, as observed in the experiment. The value of γ corresponds in order of magnitude to the half-width of the Henley curve in Fig. 3. This means that the fluctuations of the electron field are determined by the recombination and spin relaxation processes.

A weak varying field ($H_1 = 0.5$ Oe) with a frequency of 7 kHz warms the nuclear-spin system far from the donors, where T_{1e} is relatively large. In this case the spike of $\rho(t)$, shown in Fig. 2, is reduced to ~ 0.2 sec.

An interesting consequence of the smallness of $T_{1e}(0)$ and the formation of a nuclear polarization front is the possibility of obtaining a given $\langle I(r) \rangle$ distribution near a donor during a time that is limited by the diffusion process. For example, by using an alternating-polarity sequence of circularly polarized light pulses with a duration that decreases logarithmically, we can obtain around a donor a set of spherical shells of equal thickness with opposite nuclear-orientation directions in adjacent shells.

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