Optical cooling of a nuclear spin system of a conductor in a weak oscillating magnetic field

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The spin temperature Θ of an n-type semiconductor was lowered to the range 10^{-4}–10^{-3} °K with synchronous modulation of the circular polarization of the exciting laser beam and of the longitudinal magnetic field (which was lower than the local fields) at a frequency 30 kHz. The cooling was detected by the increase of the equilibrium nuclear polarization along the weak transverse field at positive and negative.

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The interaction of spin-oriented electrons with nuclei of a semiconductor leads to nuclear polarization.[1-3] When the semiconductor is continuously excited with light, the nuclear spin system is practically in thermodynamic equilibrium corresponding to a temperature Θ_0. The equilibrium within the system is established within a transverse-relaxation time T_2 on the order of 10^{-4} sec, and the time T_1 in which Θ_0 sets in is determined by the slow spin-lattice relaxation. The nonequilibrium part of the nuclear polarization is, in the case of optical orientation, $T_2/T_1 = 10^{-5} - 10^{-7}$ of the equilibrium orientation and was registered in[4].

D'yakonov and Perel' obtained a general expression for Θ_0 under optical-orientation conditions.[5] With certain restrictions, it can be written in the form

$$\Theta_0^{-1} = 4I(\mathbf{H} \times \mathbf{S}) / \mu_I (H^2 + 3H_L^2). \quad (1)$$

Here μ_I and I are the magnetic moment and spin of the nucleus, H and H_L are the intensities of the external and local magnetic fields, and S is the average spin of the optically oriented electrons. Equation (1) is valid for nondegenerate electrons if the thermodynamic-equilibrium value is $S_T \ll S$; $\mu_0 H \ll T$, where μ_0 is the magnetic moment of the electron and T is the lattice temperature (Θ and T are in energy units). The nuclear spin temperature manifests itself in nontrivial fashion in the range of fields $H \lesssim H_L$. From (1) follows also the nonobvious result that cooling is possible in an oscillating field $H_\sim = H_0 \sin\omega t$ if S is synchronously modulated. In this case the cooling is attained in the absence of constant nuclear polarization. If $\omega T_2 \ll 1$, then $\Theta_0^{-1} \sim (1/2) S_0 H_0 \cos\phi$, where S_0 is the maximum amplitude of $S_\sim$ and ϕ is the phase difference between the oscillations of S and H. At $\pi/2 < \phi < \pi$ we have $\Theta_0 < 0$. Then the Zeeman energy of the nuclei (which is proportional to S_0 and H_0) goes over to the spin-spin interaction energy, increases the latter, and causes cooling at negative temperatures (since the nuclear spin-system spectrum is bounded from above). At $0 < \phi < \pi/2$ we have $\Theta_0 > 0$ and cooling takes place in the region of positive temperatures. It follows from the theory that Θ_0^{-1} decreases with increasing ω. In

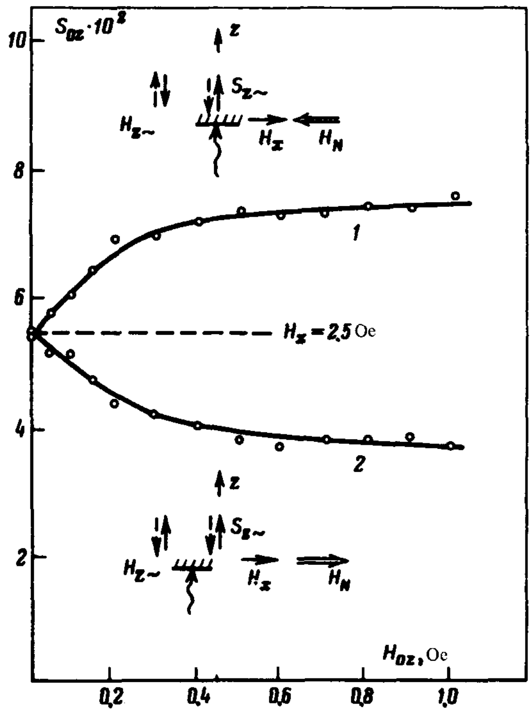

FIG. 1. Plot of S_{0z} against H_{0z} at 4.2 °K. Curve 1 corresponds to a choice of ϕ maximizing $N_N \downarrow\uparrow H_x$. In Curve 2 the phase is changed by π and $H_N \uparrow\uparrow H_x$.

addition, if $\omega T_2 \gtrsim 1$, then the maximum values of Θ_0^{-1} may be reached at $\phi_1 = \phi_m \neq 0$ and $\phi_2 = \phi_m \pm \pi$ (a phase shift appears).

Let $\mathbf{S}_\sim$ and $\mathbf{H}_\sim$ be directed along z. A constant field $H_x \perp S_z$ does not change Θ if S_z is constant, but produces a polarization along x. The average projection of the nuclear spin is

$$I_x = \mu_I (I+1) H_x / 3\Theta . \tag{2}$$

The nuclear field $H_{Nx} = A_N I_x$ produced in this case at the electrons (A_N is a constant) is then added to or subtracted from the external field, depending on the sign of Θ. The appearance of H_N can be detected by the change of the degree ρ_σ of the circular polarization of the luminescence (the Hanle effect). Numerically, ρ_σ is equal to S_z. We used an n-$Ga_{0.78}Al_{0.22}As$ crystal with a narrow Hanle curve.[6] The experimental geometry is clear from the schemes of Fig. 1, which correspond to in-phase ($\Theta_0 > 0$) and counterphase ($\Theta_0 < 0$) modulation (ϕ_m is assumed small). The circular polarization of a He-Ne laser beam directed along z was modulated, normal to the sample surface ($\sigma^+ \rightleftharpoons \sigma^-$) at a frequency 30.265 kHz by a quartz modulator. Since the lifetime of the electron spin orientation is $\lesssim 10^{-8}$ sec, S_z "follows" without lag the variation of the light polarization. A two-channel photon-counting system made it possible to accumulate separately the numbers N^+ and N^- of the recombination-radiation quanta (along $-z$) passing through the polarization analyzer in the half-periods corresponding to the excitation by the σ^+ and σ^- light. The value of S_{0z} was determined from the formula $S_{0z} = \alpha (N^+ - N^-)/(N^+ + N^-)$, where α is the constant

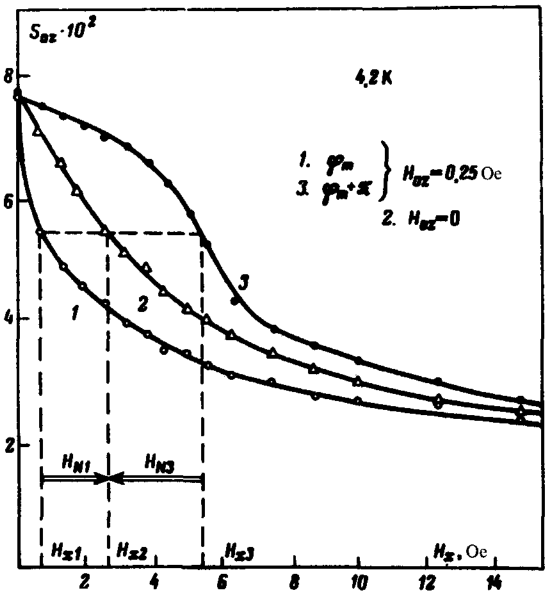

FIG. 2. Plots of $S_{0z}(H_x)$ (Hanle effect) for phases ϕ that differ by π at $H_{0z}=0.25$ Oe (Curves 1 and 2). Curve 2 shows the Hanle effect in the absence of an oscillating magnetic field.

of the instrument. The voltage from the output of the quartz-modulator generator was also fed through an amplifier and a phase shifter to the Helmholtz coils that produced the field $H_\sim$ along z.

Curves 2 and 1 of Fig. 1 show the variation of S_{0z} with the alternating field amplitude at $H_x=2.5$ Oe for two values ϕ_1 and ϕ_2 that differ by $\pi(\phi_1=\phi_m\approx\pi/6)$. In the case of Curve 1, the field H_N is subtracted from H_x and the electron depolarization decreases. For Curve 2, H_N is added to H_x and S_{0z} decreases. Figure 2 shows the Hanle curves $S_{0z}(H_x)$ at $H_{0z}=0$ (Curve 2) and $H_{0z}=0.25$ Oe (Curve 1 for $\phi=\phi_m$ and Curve 3 for $\phi=\phi_m+\pi$). We note that an oscillating 30-kHz field ($H_{0z}=2.5$ Oe), not synchronized with the modulation of the light polarization does not lead to noticeable deviations from Curve 2. The statement that the additional field H_N is due to the nuclear spin is confirmed by the inertia of the transient processes. Furthermore, since the nuclei are polarized along x, a saturating RF field along y at NMR frequencies for the field H_x should lead to a depolarization of the nuclei and to a "constriction" of the Curves 1 and 3 towards Curve 2. The "constriction" effect is observed not only at NMR frequencies, but in a wide range up to 60 kHz. The shape of the frequency spectrum is complicated and depends on the field amplitudes along z and y. The value of H_N is determined by the shifts of Curves 3 and 1 relative to 2, namely $H_{n1,3}=H_{x_2}-H_{x_3}$. Here $H_{x1,2,3}$ are the values of the external fields at points with identical S_{0z} on Curves 1, 2, and 3 of Fig. 2. The values of $H_{N1,3}$ at constant S_{0z} are determined by the behavior of $S_{0z}(H_x)$ and the ratio of H_{N_1} to H_{N_3} at different points of this curve is different.

By determining H_N from experiment we can estimate Θ_0 with the aid of (2).

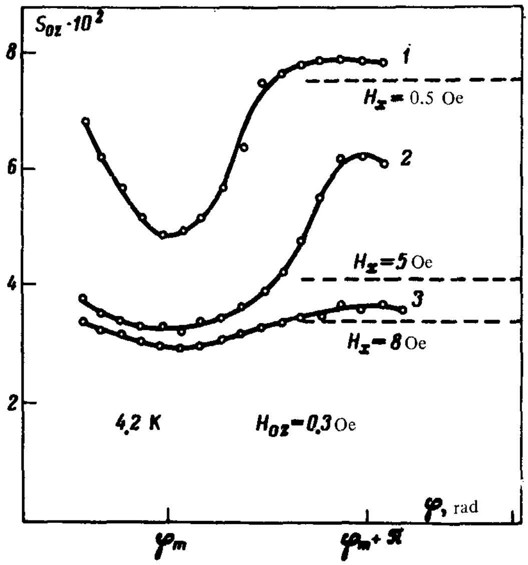

FIG. 3. Plot of $S_{0z}(\phi)$: 1) $H_x=0.5$ Oe, 2) $H_x=5$ Oe, 3) $H_x=8$ Oe. Dashed—values of S_{0z} for the same H_x at $H_{0z}=0$.

Thus, for example, for the points of Curves 1 and 3 with the abscissas H_{x1} and H_{x2} on Fig. 2 we obtain $|\Theta_0|_1^{exp}\approx 0.25A_N\mu_I$ and $|\Theta_0|_3^{exp}\approx 1.5A_N\mu_I$. Here A_N and μ_I stand for values averaged over the different lattice nuclei. The quantity A_N determines the field produced by the fully oriented nuclei. In crystals $Ga_{1-x}Al_xAs$ the order of magnitude of A_N is 10^4 Oe. The corresponding values of $|\Theta_0|^{exp}$ lie in the range $10^{-4}-10^{-3}$ °K. Thus, in spite of the relatively high modulation frequency ($\omega T_2 \gtrsim 1$), an appreciable lowering of Θ_0 is observed.[1)] Deeper cooling occurs at constant S_z and H_z. The strong mutual dependence of **S** and **I** leads to a qualitatively new behavior of the function $S_z(H_x)$ in weak fields (a strong narrowing of the Hanle line, instability, and so on[6,7]). The manifestation of the cooling is less obvious in this case. We emphasize that in an oscillating field the spin system of the lattice nuclei is cooled in the absence of a stationary nuclear polarization. This experiment proves that the entire action of the light reduces to a cooling of the spin system of the lattice nuclei, and the nuclear polarization is the result of establishment of thermodynamic equilibrium in the external field. By varying the phase ϕ it is easy to change from positive to negative temperatures, at which the sign of the field H_N is reversed and ΔS_{0z} is increased (see (Fig. 3)).

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[1)]M. I. D'yakonov and V. I. Perel' have noted the possibility of cooling optically-oriented electrons in an oscillating field when there is no external field.

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