# Magnetization of semiconductors with light and NMR in optical pumping in a transverse field

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A nuclear induction signal is obtained upon optical orientation of the spins in the crystal $n$-$GaP_{0.35}As_{0.65}$. The optical pumping was produced by a laser beam modulated in circular polarization at the frequency of the Larmor precession of the nuclei in a magnetic field perpendicular to the beam.

Absorption of circularly polarized light by semiconductor near the absorption edge, in the presence of spin-orbit splitting of the bands, leads to orientation of the electron and nuclear spins and to the appearance of macroscopic magnetic fields. These fields are too weak to be registered directly. The investigations of the optical orientation in semiconductors (to which more than 50 papers have been devoted to date) have developed on the basis of an analysis of the polarization of recombination radiation. Only in the first study[1] was the nuclear magnetization accumulated as the result of prolonged illumination of the semiconductor measured. This study remains so far the only one in which optical orientation was realized in a volume (via an indirect transition in silicon). In the case of direct transitions, the absorption coefficients $k$ reach $10^4$–$10^5$ $cm^{-1}$. The spin orientation is produced in a thin surface layer, where the absolute number of nuclei is small. Investigation of the optical orientation by the NMR signal, in analogy with[1], is either difficult or impossible,

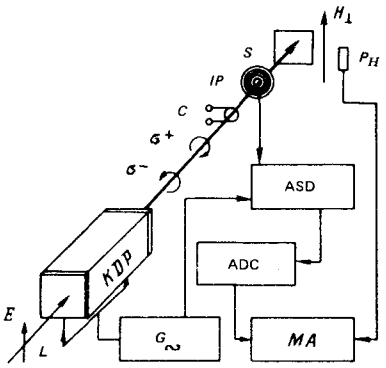


FIG. 1. Simplified diagram of experimental setup: $L$—laser beam polarized in the direction of the vector $E$, KDP—electro-optical crystal modulating the circular polarization ($\sigma^+ \rightleftarrows \sigma^-$) at a frequency 205.6 kHz, IP—inductive pickup, $S$—sample, $C$—calibration turns, $P_H$—magnetic field pickup, ASD—block for resonant amplification and synchronous detection, ADC—analog-digital converter, MA—multichannel pulse-height analyzer, $G_\sim$—driving oscillator for KDP.

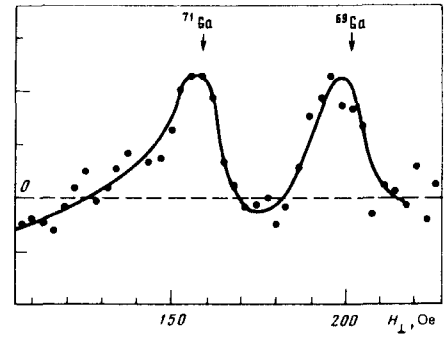


FIG. 2. Spectrum of nuclear-induction signal of the crystal $n$-$GaP_{0.35}As_{0.65}$ at 4.2 °K at the modulation frequency 205.6 kHz of the pump-light circular polarization.

especially in the case of semiconductors with small concentrations of magnetic nuclei.

We describe below a resonant method of detecting weak macroscopic electronic and nuclear fields induced by light, and present the first experimental results. To excite the semiconductor, we used a laser beam modulated in circular polarization with the aid of a KDP crystal (see Fig. 1). The resultant magnetic field, which oscillates at the frequency of polarization modulation, was detected with an induction pickup (IP). The pickup is a coil with inside diameter 2 mm, tightly pressed against the sample. The coil contains 550 turns of wire of 30 micron diameter. The noise of the amplification system, referred to the input, is $1.5\times10^{-9}$ W-Hz$^{-1/2}$ at a working frequency $f_{mod}=206.5$ kHz. At 4.2 °K, the $Q$ of the input circuit is ≈65. The amplified signal is separated by a synchronous-detection circuit, passes through an analog-digital "voltage-frequency" converter, and is accumulated in a multichannel pulse-height analyzer (MA). The nuclear magnetization is revealed by the resonance of the optical pumping, modulated in phase with the precession of the nuclear spins in the transverse magnetic field $H_\perp$. Obviously, all the nuclei oriented during the time $T_2$ of their transverse spin relaxation contribute to the useful signal. The orientation of the nuclear spins results from electron spin relaxation due to the hyperfine interaction. The maximum signal is obtained when the condition $T_1^e \lesssim 1/\omega_L$ is satisfied, where $T_1^e$ is the lifetime of the spin oreintation of the electrons and $\omega_L$ is the angular frequency of their Larmor precession in the field $H_\perp$. The resonance was registered after multiple passage through the chosen range of $H_\perp$. The value of $H_\perp$ determines the number of the MA-analyzer channel in which a number of pulses proportional to the nuclear-induction signal in this field is accumulated.

Figure 2 shows the expression obtained with an $n$-$GaP_{0.35}As_{0.65}$ crystal with a forbidden band 1.89 eV at 4.2 °K and with a donor density $\approx10^{16}$ cm$^{-3}$. The crystal was excited with an He-Ne laser (1.96 eV). The shown section of the spectrum, corresponding to the isotopes of Ga, was obtained as a result of $\approx10^3$ passages in nine hours.

Let us estimate the values of the expected magnetic field. The amplitude of the oscillating field on the axis of a laser beam of radius $R$ is, directly at the sample surface, $H_\sim = 2\pi I_\sim/kR$, if the light is absorbed in the surface layer of thickness much smaller than $R$. Here $I_\sim$ is the amplitude of the magnetization component along the axis of the IP coil. With increasing distance $d$ from the surface of the sample, this field falls off like $R^2/(R^2+d^2)^{3/2}$. The value of the field on the axis of the magnetic lobe made up by the nuclei is $H^N = 2P\alpha GT_2\mu_B/R^3$. Here $P$ is the degree of orientation of the photo-excited electrons, $G$ is the rate of their generation, $\mu_B$ is the nuclear magneton, and $\alpha$ is the ratio of the probability of the spin relaxation of the electrons due to exchange with nuclei to the total probability $1/T_1^e$. The nuclear orientation is preserved during the time $T_2$, which determines completely the line widths in Fig. 2 and amounts to $\approx10^{-4}$ sec. The value of $P$ for solid solutions based on GaAs is 0.5. Using an He-Ne laser with beam diameter 1 mm, we have $PG\approx10^{17}$ cm$^{-3}$ sec$^{-1}$, and $H^N \approx \alpha\cdot10^{-6}$ Oe. If $\alpha \lesssim 10^{-2}$, then $H^N \lesssim 10^{-8}$ Oe. The sensitivity of the installation was checked with the aid of a two-turn coil placed on the IP on the side opposite to the sample. When an alternating current of $0.5\times10^{-9}$ A, with frequency 205.6 kHz and integration constant 1 sec was passed, the output signal corresponding to $H_\sim \approx 6\times10^{-9}$ Oe noticeably exceeded the noise. Measurement of the absolute nuclear magnetization with the aid of such a calibration is difficult because of the inhomogeneous distribution of the intensity on the illuminated area of the sample, and because the resultant magnetic lobe is not equivalent to that due to the current in the turn.

We note in conclusion that the macroscopic magnetic fields outside the semiconductor are smaller by many orders of magnitude than the local fields acting only on the electron spin in contact hyperfine interaction in the semiconductor. The contact fields become manifest in the optical channel and are revealed by the change of the polarization of the recombination radiation.[2] The method described above for measuring the macroscopic magnetization is promising for the investigation of optical orientation in cases when the recombination radiation is weak or is completely absent, or when the background of the transition with participation of nonoriented equilib-

rium electrons is large ($n$-type semiconductors). For magnetically diluted crystals one can expect an increase in the sensitivity if $T_2$ increases quadratically with decreasing concentration of the magnetic nuclei, and $H^N$ increases linearly when $\alpha$ decreases linearly. The use of the described method to measure the electronic magnetization is advantageous at large $T_1^e$. The corresponding signal should vary monotonically in a transverse magnetic field (in analogy with the Hanle effect). The increase of this signal with increasing $T_1^e$ is limited by the condition $T_1^e < 1/f_{mod}$. Obviously, the sensitivity of registration of magnetization by light increases when volume pumping is used.

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[1]G. Lampel, Phys. Rev. Lett. **20**, 491 (1968).
[2]V. L. Berkovits, A. I. Ekimov, and V. I. Safarov, Zh. Eksp. Teor. Fiz. **65**, 346 (1973) [Sov. Phys.-JETP **38**, 169 (1974)].