# Influence of the depth of location of donor levels on the degree of optical orientation of $^{29}$Si nuclei in silicon

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We investigated the optical orientation of the nuclear moments of $^{29}$Si in silicon containing phosphorus and doped with gadolinium, which shifts the donor levels of the phosphorus into the interior of the forbidden band. It is shown that by increasing the depth of the donor levels it is possible to obtain very large degrees of optical polarization of the nuclei.

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We have demonstrated in[1] the possibility of increasing the degree of polarization of $^{29}$Si nuclei in silicon via optical pumping by introducing gold atoms, which decrease the lifetimes of the photoexcited electrons.

In the present study we investigate the influence of the depth of localization of donor impurities on the polarization of $^{29}$Si nuclei. The investigations were carried out on silicon doped with gadolinium to $\sim 10^{17}$ cm$^{-3}$ and containing phosphorus with concentration $\sim 2\times10^{13}$ cm$^{-3}$. The introduction of rare-earth impurities into the silicon shifts the donor level of the phosphorus into the interior of the forbidden band, increasing the ionization energy by an approximate factor of 1.5.[2]

The experiments were performed by the procedure described in[3]. The degree of polarization of the $^{29}$Si nuclei was measured by the NMR method. Exposure to circularly polarized light in a magnetic field $H_0 \sim 5$ Oe at $T=77$ °K for 10 hours produces in silicon doped with gadolinium and phosphorus a polarization of the $^{29}$Si nuclei equal to $2.6\times10^{-3}$%, corresponding to an equilibrium polarization in a magnetic field of $10^5$ Oe at $T=77$ °K. The time of the spin-lattice relaxation of the $^{29}$Si nuclei in the presence of light is estimated at $T_1 = 13.5$ hr. The value of the nuclear polarization extrapolated to infinite irradiation time turned out to be $6.8\times10^{-3}$%.

TABLE I.

| Sample | | $P$, % | $T_1$, hr | $\tau$, sec | $\tau_s$, sec |
|---|---|---|---|---|---|
| Si < $P$ > | expt | $3{,}6\cdot10^{-4}$ | 8,5 | $7\cdot10^{-5}$ | $6{,}1\cdot10^{-9}$ |
| Si < $P$ + Gd > | theor | $8{,}7\cdot10^{-3}$ | – | – | $1{,}3\cdot10^{-7}$ |
| | expr | $6{,}8\cdot10^{-3}$ | 13.5 | $1.2\cdot10^{-4}$ | $1{,}0\cdot10^{-7}$ |

  

The degree of nuclear polarization $P$ produced in a semiconductor following optical pumping with circularly polarized light is determined by the relation[1]

$$P = \frac{g_+ - g_-}{g_+ + g_-} \frac{\tau_s}{\tau + \tau_s}, \qquad (1)$$

where $\tau_s$ is the electron spin relaxation time; $\tau$ is the lifetime of the photoexcited electrons; $g_+$ and $g_-$ are the rates of generation, in the conduction band, of electrons with spin projections $S_z = 1/2$ and $S_z = -1/2$, respectively; $P$ is connected with the average projection of the nuclear spin $\langle I_z \rangle$ by the expression $P = 2\langle I_z \rangle$.

In our experiments we obtained $(g_+ - g_-)/(g_+ + g_-) = 0.08$. This value was obtained by determining the probabilities of the transitions from the valence band to the conduction band under the influence of circularly polarized light with production of electrons with spin projections 1/2 and $-1/2$, respectively. Account was taken here of the degree of ellipticity of the circularly polarized pump light, which in our experiments was 12%. To compare the efficiencies of optical pumping in silicon with and without Gd, we performed experiments with silicon containing only phosphorus atoms ($\sim 2 \times 10^{13}$ cm$^{-3}$). The results of measurements of the degree of polarization $P$ of the nuclei in $^{29}$Si and of the spin-lattice relaxation time $T_1$ are listed in Table I. Table I gives also the values of the lifetime $\tau$ measured for our samples at $T = 77$ °K.

It follows from (1) that the degree of polarization of the $^{29}$Si nuclei depends on $\tau$ and $\tau_s$, and that with increasing $\tau$ the value of $P$ should decrease. In gadolinium-doped silicon we have $\tau = 120$ μsec, but the degree of polarization of the nuclei turned out to be much larger than in silicon with phosphorus, where $\tau \approx 70$ μsec, and also larger than in silicon compensated with gold, where $\tau \sim 10^{-8}$ sec and $P = 1.3 \times 10^{-3}$%.[1] The observed increase of the polarization of the $^{29}$Si nuclei in silicon with Gd is attributed to the considerable increase of the electron spin relaxation time $\tau_s$ (see the table), which in turn has the following explanation:

With increasing depth of localization of the donor level, the frequencies of the jumps between the donor levels and the conduction bands decreases. In addition, the degree of filling of the donor centers by electrons following exposure to light increases. The ensuing increase of $\tau_s$ allows us to assume that the spin relaxation of the electrons occurs mainly on the donor centers. In this case the rate of spin relaxation can be determined from the relation[4]

$$\frac{1}{\tau_s} = \frac{2}{3} \frac{\omega_c^2 \gamma}{\gamma^2 + \Omega_e^2}, \qquad (2)$$

where $\Omega_e = \gamma_e H_0$ is the Larmor frequency of the localized electron in a magnetic field $H_0$, $\gamma_e \approx 1.75 \times 10^7$ Hz/Oe; $\gamma$ is the frequency of the electron jumps between the conduction band and the donor level (with allowance for the donor-level shift we have $\gamma \approx 1.5 \times 10^8$ sec$^{-1}$); $\omega_c^2 = \gamma^2 e^2 \overline{H_n^2}$, where $H_n$ is the effective field of the $^{29}$Si nuclei at the electrons.[4]

We have calculated $\overline{H_n^2}$ for the case of contact interaction between an electron localized on a donor center and the surrounding $^{29}$Si nuclei and used (2) to estimate the time $\tau_s$ (see Table I.) The calculated time $\tau_s$ agreed well with the value $\tau_{s\,\mathrm{exp}}$ determined from the experimental value of $P$ and the measured time $\tau$ (see (1)).

We have thus shown that by increasing the depth of the donor levels we can obtain very large degrees of polarization of the nuclear moments in optical pumping, owing to the increase in the time of the electron spin relaxation.


[1]N. T. Bagraev, L. S. Vlasenko, and R. A. Zhitnikov, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 639 (1976) [JETP Lett. **23**, 586 (1976)].
[2]G. I. Voronkova, M. I. Iglitsyn, and A. R. Salmanov, Fiz. Tekh. Poluprovodn. **8**, 1607 (1974) [Sov. Phys. Semicond. **8**, 1043 (1975)].
[3]G. Lampel, Phys. Rev. Lett. **20**, 491 (1968).
[4]M. I. D'yakonov and V. I. Perel', Zh. Eksp. Teor. Fiz. **65**, 362 (1973) [Sov. Phys. JETP **38**, 177 (1974)].