ptical orientation of Si^{29} nuclei in compensated ilicon

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Dynamic polarization of the Si^{29} nuclei in n-type silicon compensated with gold was obtained by optical pumping. The times of nuclear spin-lattice relaxation following exposure to light were measured. The effectivenesses of optical polarization of Si^{29} nuclei in compensated silicon and in silicon containing only donor impurities are compared.

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Dynamic polarization of Si^{29} nuclei in silicon, due to photo-excited electrons, ıs first obtained in[1]. The object of the investigation was n-type silicon with osphorous-atom concentration $N(\mathrm{P}) \approx 10^{13}$ cm^{-3}. The Si^{29} nuclei in such sames have a long spin-lattice relaxation time in the absence of light ($T_{1\,\mathrm{dark}}$ 200 hours). This time was reduced to approximately 20 hr by illuminating e silicon. Since the time required to establish a nuclear magnetization $\langle I_z \rangle$ equal to the relaxation time of the Si^{29} nuclei when exposed to illumination, follows that an appreciable polarization of the Si^{29} nuclei can be obtained only prolonged illumination of the sample. The values of the degree of polarizaэn of the Si^{29} nuclei, extrapolated to an infinite irradiation time, and the nes of the nuclear spin-lattice relaxation time, are listed in the table. Same 1 was silicon doped with phosphorus and having $N(\mathrm{P}) \approx 10^{13}$ cm^{-3}. When mped with unpolarized and circularly-polarized light, the density of the oto-excited electrons was 2×10^{14} cm^{-3}. The degree of polarization of the ^{29} nuclei was calculated for this sample on the basis of the data of[1].

It was shown in[1] that when the conduction electrons are generated by light the degree of nuclear polarization $\langle I_z \rangle$ depends on the ratio of the time τ_s of the spin relaxation of the electrons to the lifetime τ of the photo-excited electrons. In the case of pumping with unpolarized light, the ratio of the nuclear polarization to its equilibrium value I_0 in the absence of optical illumination, is given by[1]

$$\frac{\langle I_z \rangle}{I_0} = 1 - \frac{\gamma_e}{\gamma_n} \frac{\tau_s}{\tau + \tau_s} f. \quad (1)$$

Here γ_e and γ_n are the gyromagnetic ratios of the electron and the Si^{29} nucleus, respectively; $f = T_1/T_{1e}$ is the leakage factor of the nuclear polarization,[2] where T_1 is the total time of the spin-lattice relaxation of the Si^{29} nuclei and T_{1e} is the spin-lattice relaxation time due only to the interaction with the photo-excited electrons.

In the case of optical pumping with circularly polarized light, the maximum degree of the nuclear polarization $\langle I_z \rangle$ is given by[1]

$$\langle I_z \rangle = \frac{1}{2} \frac{g_+ - g_-}{g_+ + g_-} \frac{\tau_s}{\tau + \tau_s} f, \quad (2)$$

where g_+ and g_- are the rates of generation of electrons with spin projections $+\frac{1}{2}$ and $-\frac{1}{2}$, respectively.

In phosphorus-doped silicon, the time ratio $\tau_s/\tau \sim 10^{-3}$ is small and this, as seen from (1) and (2), leads to a decrease of the degree of nuclear polarization

To obtain an appreciable degree of polarization of the Si^{29} nuclei and to decrease the time in which it can be attained, it is of interest to use as the optical-pumping object compensated silicon containing deep impurities, which can greatly decrease the lifetime τ of the nonequilibrium carriers. For example, introduction of gold atoms into n-type silicon makes it possible to decrease the lifetime of the photo-excited electrons by approximately two orders of magnitude.[3]

We have performed experiments on optical polarization of Si^{29} nuclei in silicon with phosphorous-atom density $N(P) \approx 10^{15}$ cm^{-3}, containing also gold atoms [$N(Au) > 10^{16}$ cm^{-3}] (sample 2 in the table). Experiments were also performed with n-type silicon containing only phosphorus atoms at approximately the same density as in sample 2 [$N(P) \approx 1.1 \times 10^{15}$ cm^{-3}] (sample 3 in the table).

The illumination of samples 2 and 3 and the measurement of the nuclear magnetization were carried by a procedure similar to that described in[1]. The light source was a 1-kW incandescent lamp. The pumping was at 77 °K with circularly polarized light in a magnetic field ~ 1 G and with unpolarized light in a magnetic field $H_0 \approx 4.9$ kG. The density of the photo-excited electrons in the illuminated samples was $\sim 5 \times 10^{14}$ cm^{-3}. The polarization of the Si^{29} nuclei and the spin-lattice relaxation times were measured with an NMR radio-spectrometer with crossed coils by the fast adiabatic passage method.[2]

The results of the experiments on the optical polarization of the nuclei Si^{29} in samples 2 and 3 are also given in the table.

Optical pumping of compensated silicon (sample 2) with circularly polarized light yielded a polarization 1.3×10^{-2}% of the Si^{29} nuclei, corresponding to

mple	Circularly polarized light nuclear polarization, %	T_1, hr	Unpolarized light nuclear polarization, %	T_1, hr
Si⟨P⟩ $N(P) \approx 10^{13}$ cm^{-3} from the data of[1]	0.74×10^{-3}	27	2.4×10^{-4}	22
Si⟨P+Au⟩ $N(P) \approx 10^{15}$ cm^{-3} $N(Au) \approx 10^{16}$ cm^{-3}	1.3×10^{-3}	1.3	3.0×10^{-4}	3.0
Si⟨P⟩ $N(P) \approx 1.1 \times 10^{15}$ cm^{-3}	4.2×10^{-5}	2.2	7.7×10^{-5}	4.2

uilibrium polarization in a magnetic field ≈ 50 kG at $T = 77$ °K. The nuclear laxation time T_1 for this sample was much shorter than for sample 1. For mples 2 and 3 measurements were made of the nuclear relaxation times $_{\rm dark}$ in the absence of optical irradiation. The shorter relaxation time for mple 3 ($T_{1\,\rm dark} \approx 11.5$ hr) in comparison with sample 1 ($T_{1\,\rm dark} \approx 200$ hr) is due the higher concentration of the electrons localized on the donor atoms; these ectrons are the relaxation centers for the Si^{29} nuclei. The relaxation rate of Si^{29} nuclei in sample 2 ($T_{1\,\rm dark} \approx 8.5$ hr) was increased in comparison with mple 3, owing to the possible presence of neutral paramagnetic gold atoms.

It is seen from the results of the experiments and from their comparison th the results of[1] that in the case of optical pumping of silicon containing a rge amount of donor atoms (sample 3) the nuclear polarization is established thin a shorter time than in silicon with low donor impurity density, but the gree of polarization of the Si^{29} nuclei is strongly decreased. The reason is it the degree of polarization of the electrons in the conduction bands is deeased by the presence in it of thermal electrons having an equilibrium poization and having a density comparable with or even larger than the density the photo-excited electrons.

In samples with an appreciable content of paramagnetic impurities, an essen-l role in the process of dynamic polarization is played by the leakage factor the nuclear polarization due to the nuclear relaxation on these impurities.[2] r sample 3, the leakage factor f turns out to be equal to 0.61.

When sample 2 was illuminated with unpolarized light with a photon energy ver than the width of the forbidden band, a decrease was observed in the laxation time of the Si^{29} without optical orientation, and this was apparently e to the change of the charge state of the gold with formation of paramagnetic nters. In this case in a magnetic field $H_0 = 4.9$ kG at $T = 77$ °K, the equilibrium clear polarization is established with a relaxation time $T_1 \approx 4$ hr, which leads a leakage factor $f \approx 0.25$. However, despite the small value of f, a considerle degree of nuclear polarization is reached in sample 2 within a short time.

As noted above, this is connected with the increase of the degree of polarizati of the electrons in the conduction band, due to the decrease of their lifetime, and also due to the absence of thermal electrons.

Thus, the use of n-type silicon compensated with deep acceptor impurities, such as gold, makes it possible to obtain an appreciable degree of polarizatio of Si^{29} nuclei within a short time.

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