Inversion of nuclear magnetization of compensated silicon in interband absorption of light in weak magnetic fields

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A strong dependence of the degree of dynamic polarization of ^{29}Si nuclei on the external magnetic field has been observed in optically pumped compensated silicon. Two types of interaction between the ^{29}Si nuclei and the electrons captured by different impurity centers have been observed, and this is the reason for the different nuclear-magnetization directions.

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It was shown in[1,2] that doping of silicon with certain impurities can increase appreciably the degree of dynamic polarization of the ^{29}Si nuclei by optical pumping.

We investigate here the influence of the external magnetic field on the degree of optical polarization of ^{29}Si nuclei in compensated silicon.

The experiments were performed with silicon containing $\sim 10^{15}$ cm^{-3} atoms of phosphorus and compensated with gold at a concentration $>10^{16}$ cm^{-3}, so that the resistivity ρ of the sample after the introduction of the gold was $\sim 10^6$ Ω-cm. The sample was illuminated at $T=77\,^\circ$K by circulatory polarized light of wavelength 1 μ. The source of the light was a 1-kW incandescent lamp. To produce an external magnetic field H_0 directed along the light beam and to compensate for the transverse components of the earth's magnetic field we used a system of three mutually perpendicular pairs of Helmholtz coils.

The nuclear magnetization and the degree of polarization of the ^{29}Si produced in the sample by the optical pumping were determined by observing the nuclear magnetic resonance (NMR) signals. These signals were registered by the method of adiabatic fast passage[3] with a radio spectrometer with crossed coils.

The system of crossed coils makes it possible to determine the degree of nuclear polarization and the direction of the nuclear magnetization relative to the external magnetic field from the sign and the magnitude of the NMR.[3] It should be noted that when the sample was moved in our experiments from the external magnetic field H_0 into the NMR radio spectrometer magnetic field, the magnitude and the direction of the nuclear magnetization relative to the external magnetic field remained unchanged, since the nuclear spin-lattice relaxation time greatly exceeded the removal and measurement times. Under these conditions, the transfer of a sample into magnetic fields of different magnitude and direction causes only alignment of the nuclear magnetization with the magnetic field by adiabatic rotation, without a change in the magnitude of the magnetization.[3]

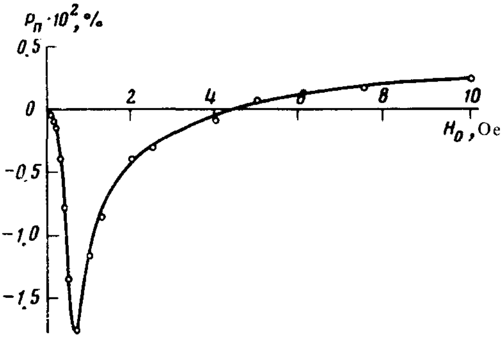

FIG. 1. Dependence of the degree of optical polarization P_n of ^{29}Si nuclei in compensated silicon on the magnitude of the external longitudinal magnetic field H_0.

The experimental dependence of the degree of optical polarization P_n of the ^{29}Si nuclei, on the external magnetic field H_0, extrapolated to an infinite irradiation time, is shown in Fig. 1. The sign of P_n characterizes the direction of the nuclear magnetization relative to the external magnetic field H_0.

As seen from the figure, the nuclear magnetization changes sign with changing H_0. The degree of nuclear polarization P_n is equal to zero at $H_0 = 4.5$ Oe, reaches a maximum absolute value $|P_n| \approx 1.75 \times 10^{-2}\%$ at $H_0 = 0.7$ Oe. This corresponds to equilibrium nuclear polarization in a magnetic field 6.65×10^5 Oe at $T = 77$ °K or 2.65×10^6 Oe at $T = 300$ °K.

When the direction of the external magnetic field H_0 is reversed and the sign of the circular polarization of the pumping light remains the same, the sign of the nuclear magnetization is reversed, i.e., the curve on the figure becomes antisymmetrical with respect to H_0.

The spin-lattice relaxation time of the ^{29}Si nuclei exposed to light was practically the same at all values of H_0 and amounted to ~45 min. The following explanation can be offered for the observed variation of the degree of optical polarization of the ^{29}Si nuclei.

It is known[3] that in dynamic polarization of nuclei the contact and dipole—dipole magnetic interactions between the electrons and the nuclei produce oppositely directed nuclear magnetizations. In silicon containing phosphorus atoms and compensated with gold ($E_v + 0.54$ eV), optical pumping may produce dynamic polarization of the nuclei when the ^{29}Si nuclei interact with photoexcited electrons localized either at the shallow phosphorus donor centers $E_c - 0.045$ eV or at the deep gold donor centers $E_v + 0.35$ eV. Contact interaction predominates in the former case,[4] and dipole—dipole interaction seems to prevail in the latter, for in contrast to a shallow donor center, the wave function of an electron localized on a deep center does not extend over large distances.

To determine which of these interactions causes the positive nuclear polarization P_n and which the negative one on the figure, experiments were performed with n-type silicon containing phosphorus atoms only. In this case the nuclear magnetization had the same sign at all values of the magnetic field H_0 (from 0.1 to 10 Oe), and its direction corresponded to the positive values of P_n.

It can consequently be assumed that the negative branch of the curve shown in Fig. 1 is connected with the dipole-dipole interaction of the ^{29}Si nuclei with electrons captured by the gold donor atoms, while the positive values of P_n at $H_0 > 4.5$ Oe are due to contact interaction with electrons localized on the phosphorus donor atoms.

Each of the considered type of interaction depends on the magnitude of the external magnetic field. This dependence manifests itself in the following manner.

When nuclei interact with electrons, the probability of nuclear spin flip is[3]

$$W \sim (1 + \omega_e^2 \tau_c^2)^{-1}, \tag{1}$$

where $\omega_e = \gamma_e H_0$ is the Larmor frequency of the electron in the magnetic field H_0, and τ_c is the correlation time characterizing the random change of the projection of the electron spin. For a shallow donor center, τ_c is determined by the probability of electron hopping between donor levels and the conduction band ($\tau_c \sim 10^{-10}$ sec for phosphorus in silicon[4]). If the electron is localized on a deep donor center, then τ_c is determined by the spin-relaxation time τ_s of the electron, which increases with increasing depth of level localization.[2] Therefore, as seen from (1), as the field H_0 is increased, the probability of the nuclear spin flip in interactions with the electrons localized on the gold atoms begins to decrease substantially at lower values of H_0 than in the case of interaction with electrons localized on the phosphorus atoms. The nuclear magnetization P_n, is therefore negative in weak magnetic fields, owing to presence of the gold atoms, then decreases rapidly with increasing field, and becomes positive in strong fields on account of the phosphorus atoms. The decrease of the donor polarization at small values $H_0 < 0.5$ Oe is apparently due to the influence of the local magnetic field of the ^{29}Si nuclei.[5]

The increase of the electron spin relaxation time τ_s for the deep gold donor centers is the reason for the large difference between the absolute values of the nuclear polarization caused by the interaction of the ^{29}Si nuclei with the deep gold centers at $H_0 \sim 0.7$ Oe and by the interaction with the shallow phosphorus donor centers $H_0 \sim 4.5$ Oe, since the degree of dynamic polarization of the nuclei increases in optical pumping with decreasing rate of electron spin relaxation.[2]

It follows from the foregoing that the interaction of electrons localized on deep donor centers with the lattice nuclei is most effective in weak magnetic fields. By varying the external magnetic field in the course of optical pumping it is possible to control the mechanisms of the electron-nuclear interactions in compensated silicon, and also the magnitude and direction of the nuclear polarization.

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