Positive-muon depolarization processes in silicon single crystals

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We investigate experimentally the dependences of the initial polarization and of the rate of the slow relaxation of μ^+-meson spins in silicon single crystals on the temperature in the interval 300–720 K. The data are analyzed on the basis of the theory of muonium depolarization of μ^+ mesons. The results are compared with the data for germanium.

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Interactions of μ^+ mesons with silicon single crystals (n-type conductivity, donor concentration 1.6×10^{13} cm^{-3}) were investigated with the beam of the muon channel of the synchrocyclotron of the Leningrad Institute of Nuclear Physics. The beam characteristics were: initial momentum 110 MeV/c, initial μ^+-meson polarization 84%, counting rate of the particles stopped in the target $\sim 8\times10^3$ sec^{-1} (for graphite 4 g/cm^2 thick), admixture of π^+ mesons and positrons at the exit from the channel not higher than 0.5%.

We investigated in the experiment the distribution of the μe-decay times in a perpendicular (relative to the initial direction of the μ^+-meson spin) external magnetic field, when the decay-registration probability was modulated in time as a result of the spatial asymmetry of the decay and of the presence of precession of the μ^+-meson spin. The experimental program included the determination of the initial ($t=0$) amplitude of the meson precession and its relaxation rate (λ) as the target temperature and the magnetic-field intensity were varied. The experimental results are shown Fig. 1. The normalization of the values of the asymmetry coefficient to obtain the initial polarization (P_0), and the monitoring of the absence of systematic errors, were carried out with allowance for the energy spectrum of the decay positrons from measurements in a standard target of graphite, where there is practically no depolarization of the μ^+ mesons.[1]

In the analysis of the possible manners whereby the μ^+-meson can interact with the crystal lattice of the silicon, account must be taken of the fact that the parameters $P_0(T)$ and $\lambda(T)$ characterize different temporal stages of the process. In fact, $P_0(T)$ gives an idea of the relation between the diamagnetic (P_0) and paramagnetic ($1-P_0$) interaction products, which took place within times $\tau\sim10^{-9}$–10^{-10} sec ($\tau\lesssim1/\omega'$ and $\tau\lesssim1/\omega_0$), where $\omega'=(2–4)\times10^9$ sec^{-1} is the frequency of the muonium precession in the employed magnetic fields, and $\omega_0=1.14\times10^{10}$ sec^{-1} is the frequency of the hyper-

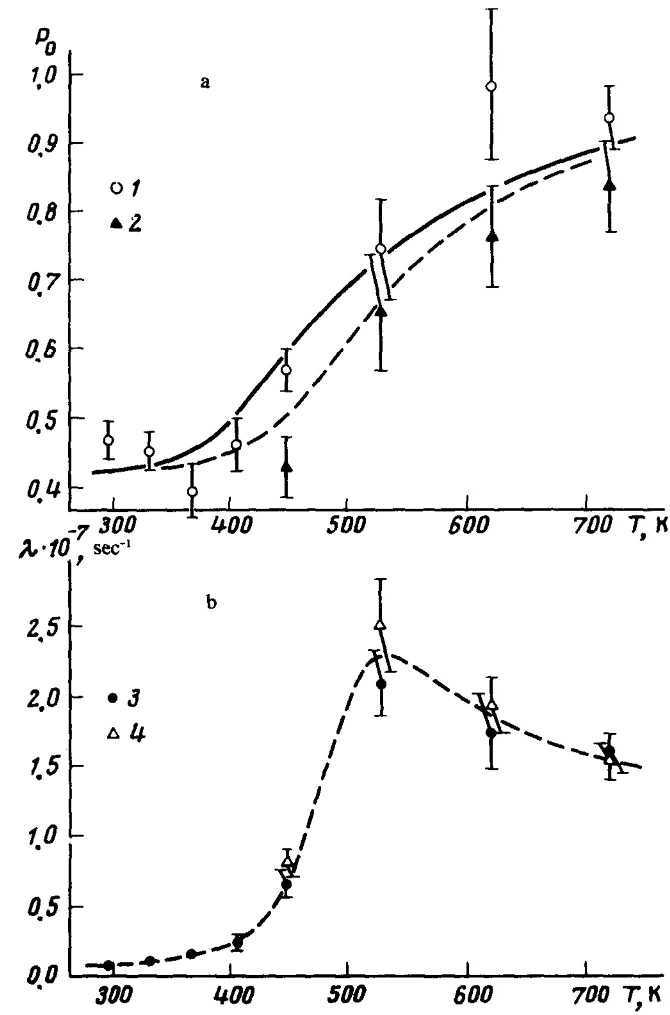

FIG. 1. Dependence of the initial polarization (*a*) and of the relaxation rate (*b*) of the μ^+-meson spins in silicon on the temperature. Abscissas-absolute temperature, ordinates-*a*) initial polarization P_0, *b*) relaxation rate λ. Curves 1,3-at a magnetic field intensity 236 Oe, curves 2 and 4-at 472 Oe. Smooth curves of Fig. *a*-calculation by muonium depolarization theory.

fine splitting of the muonium in silicon[2,3]). On the other hand, the relaxation of the μ^+-meson spin takes place within characteristic times $\sim 10^{-7}$ sec (see Fig. 1), thus evidencing a subsequent slower onset of the electronic paramagnetism of the medium in the immediate vicinity of the μ^+ meson. It is seen that this process takes place more intensely in the region of high (>500 K) temperatures, thus distinguishing it from the known dipole-interaction between the magnetic moments of the μ^+ mesons and the nuclei of the crystal lattice.[4,5]

The hereafter-considered mechanism of the μ^+-meson interaction in the silicon lattice is based on the concepts developed in[6,7] for germanium, where μ^+-meson depolarization processes were investigated in greater detail.[8,9] In the temperature region 300–400 K, the polarization value $P_0 \approx 0.42$ (see Fig. 1) is apparently due to the end result of the superthermal or intra-track processes, inasmuch as for the same silicon sample, at 350 K, the presence of muonium was demonstrated[2] by the method of restoration, in longitudinal magnetic fields, of the missing polarization of the μ^+ mesons. The precession at meson frequency is due to the μ^+ mesons that joined to the atoms of the crystal lattice by a diamagnetic chemical bond of the hydride Si–H type.[10] The relaxation of the μ^+-meson spins was due to the breaking of the diamagnetism of the bond, resulting from the thermal vibrations of the lattice.[7]

The average height of the activation barrier for the interaction of muonium in lightly doped germanium samples was obtained in[6], namely $\Delta E\,(\mathrm{Ge}) = 0.17$ eV. Analogous calculations are of interest also for the interactions of muonium in the silicon crystal lattice. The parameters of the theory[11] of the muonium stage of depolarization of μ^+-mesons were calculated in[6] on the basis of the $P_0(T)$ dependences and the phase shift of the meson precession, namely: the duration τ of the muonium stage, the frequency ν of the spin-exchange interactions, the fraction β of the polarization due to the μ^+ mesons that enter in the diamagnetic state. The experimental material shown in Fig. 1 does not make it possible to determine separately all the parameters, and we therefore calculated one parameter τ, at values $\nu\tau \ll 1$ [2]; $\beta = 0.42 \pm 0.02$; $\omega_0(\mathrm{Si}) = 1.14 \times 10^{10}\ \mathrm{sec}^{-1}$.[2,3] The smooth $P_0(T)$ curves in the figure reflect an exponential temperature dependence $\tau \sim T^{-1.2} \exp(\Delta E/kT)$ at an activation-barrier height $\Delta E = 0.18$ eV.

The causes of the maximum in the function $\lambda(T)$ can be, for example, the abrupt increase of the concentration of the free electrons in the conduction band of the semiconductor, on account of the appearance of intrinsic conductivity of the material. Estimates show that the last quantity becomes noticeable at a temperature above 500 K. A qualitatively similar $\lambda(T)$ dependence was obtained for germanium,[7] where it was also shown that the rate of slow relaxation decreases with increasing impurity donor concentration. Further accumulation of experimental data is quite important for a detailed comparison of the interaction of the μ^+ mesons with the crystal lattice of substances as close in their physical and chemical properties as silicon and germanium.

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