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μ^-*SR*-STUDY OF BEHAVIOUR OF IMPURITY ATOMS IN SILICON

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Introduction

At present the μSR-method is successfully used to study various physical processes and chemical reactions in condensed matter and gases[1-4]. This paper considers a possibility of using the μ^-SR-method to study hyperfine interaction of impurity paramagnetic atoms in semiconductors and presents the experimental results for Si. It is rather difficult to use the EPR-method in investigations of this kind with semiconductors of the diamond structure (Si, Ge) as magnetic moments of electrons in paramagnetic centres have a high relaxation rate.

Implanted in a medium, negative muons, are slowed down and captured by high-excited level of the medium atoms. In condensed media the muons get to the ground state through Auger and radiative transitions in less than 10^{-10} s. The muon being about 200 times as heavy as the electron, the radius of its orbit in the 1S-state is about 200 times smaller than that of the electron in the 1S-state. The muon screens a unity of the nuclear charge, so the muon atom can be regarded as an atom consisting of a $(Z+\mu^-)$ pseudonucleus and (Z-1) electrons. In a medium the muon atom simulates an impurity atom with the nuclear charge (Z-1). It is important that initially polarized muons keep part of their initial polarization until they reach the 1S-state. Thus, the $(Z+\mu^-)$ pseudonucleus appears to be polarized (we consider a case with the zero spin of the initial nucleus). One can experimentally follow the changes in its polarization within the $10^{-8} \div 10^{-5}$ s time interval and thus study hyperfine interaction of the pseudonuclear spin with the electron shell. It allows one to investigate processes of scattering of charge carriers by paramagnetic centres and to study fast physico-chemical processes in semiconductors[5,6].

When μ^- stops in silicon, the resulting muon atom is an analogue of the aluminium impurity atom. Replacement of a lattice atom Z by a (Z-1) atom in silicon is known to result in an acceptor centre. The acceptor level for Al in Si is in the forbidden zone above the valence zone at a distance E_a=57 meV[7].

Transition of a muon from the excited to the ground state occurs with emission of Auger electrons and mesic X-rays. As a result, the muon atom gets recoil energy. For example, the recoil energy resulting from a 2p ⇒ 1s transition of a muon in Si $E_r = E^2\cdot(2M_{Si}c^2)^{-1} \approx 3.2$ eV ($E = E(2p \Rightarrow 1s) = 411$ keV). This energy is not enough to displace a muon atom from the lattice node if the electron shell after the Auger transitions is completely restored.

In ref. [8] they observed a decrease in the muon spin precession amplitude in an external magnetic field at temperatures below 30 K and precession in a zero magnetic field at a temperature of 6 K. A conclusion was drawn that displacement of the recoil nucleus during Auger and radiative transitions gives rise to Frenkel pairs, and the muon atom in the form of $_{\mu}Al^{++}$ or $_{\mu}Al$ stays at the interstitial site for a while. As the temperature decreases, the lifetime of the Frenkel pair increases without going beyond 10^{-9} s. So hyperfine interaction of the muon spin with the electron shell in $_{\mu}Al^{++}$ or $_{\mu}Al$ results in smaller polarization of a muon.

The electron moment of an acceptor centre in a nondeformed silicon crystal is known to relax fast[9], which is a serious obstacle for the EPR-study of acceptor centres in silicon. The relaxation rate of the acceptor electron moment increases with temperature, and at $\nu_0 \gg \Omega_{hf}$ (Ω_{hf} is the hyperfine coupling constant) the hyperfine coupling must be observed to break though the impurity centre does not change its charge state in this case. The behaviour of the impurity atom $_{\mu}Al$ will be similar to that of the muonium in doped semiconductors. The only difference is that the moment projection of the acceptor electron shell may have four different values[10] and the relaxation rate of the electron moment must be much higher than that of the muonium.

Under these conditions the relaxation rate of muon polarization at a frequency close to that of free muon spin precession can be estimated as[11]

$$\Lambda \propto \Omega_{hf}^2\cdot(8\nu_0)^{-1}. \qquad (1)$$

Besides, a paramagnetic frequency shift must be observed[6]:

$$\Delta\omega/\omega = |g\mu_B|\cdot h\Omega_{hf}\cdot(|2\mu_\mu|\cdot 4kT)^{-1}, \qquad (2)$$

where g is the Lande factor for the acceptor centre in Si.

Attention should be paid to the fact that for the acceptor centre in Si the g factor is a tensor. In rough estimation one can take $g \propto 1$[9]. Then the expected paramagnetic shift is $\Delta\omega/\omega \propto 10^{-2}$.

Experimental set-up

The experiment was carried in a muon beam of the LNP JINR phasotron[12]. The target was made of p-type silicon with the impurity concentration $\approx 2\cdot 10^{13}$ cm^{-3}. Specific resistance was ≈100 Ω·cm. The target was shaped as a disc 68 mm in diameter and 2.46 g·cm^{-2} thick. The measurements were made in the μSR-installation at the LNP[13] in the temperature range 4.2 ÷ 300 K in an external magnetic field of 0.08 T transverse to the muon spin direction. The external magnetic field was monitored by a NMR sensor. During the measurements the field instability was $\pm 3\cdot 10^{-4}$. The target temperature was stabilized to an accuracy of ±0.1 K. The muon beam hits the target perpendicularly to the disc plane. The rate of stops in the target was about 10^4 s^{-1}. Electrons produced in the decay of μ^- were registered by two telescopes of scintillation counters. In each measurement about $4\cdot 10^7$ events were recorded.

Results and discussion

The time distribution of decays electrons is described by the following function:

$$N(t) = N_0 \cdot e^{-t/\tau} \cdot [1 + \alpha \cdot e^{-\Lambda t} \cdot Cos(\omega t + \phi)] + \Phi(t) + N_C, \qquad (3)$$

where τ is the lifetime of the muon μ^- in the 1S-state of Si; ω, ϕ are the frequency and initial phase of muon spin

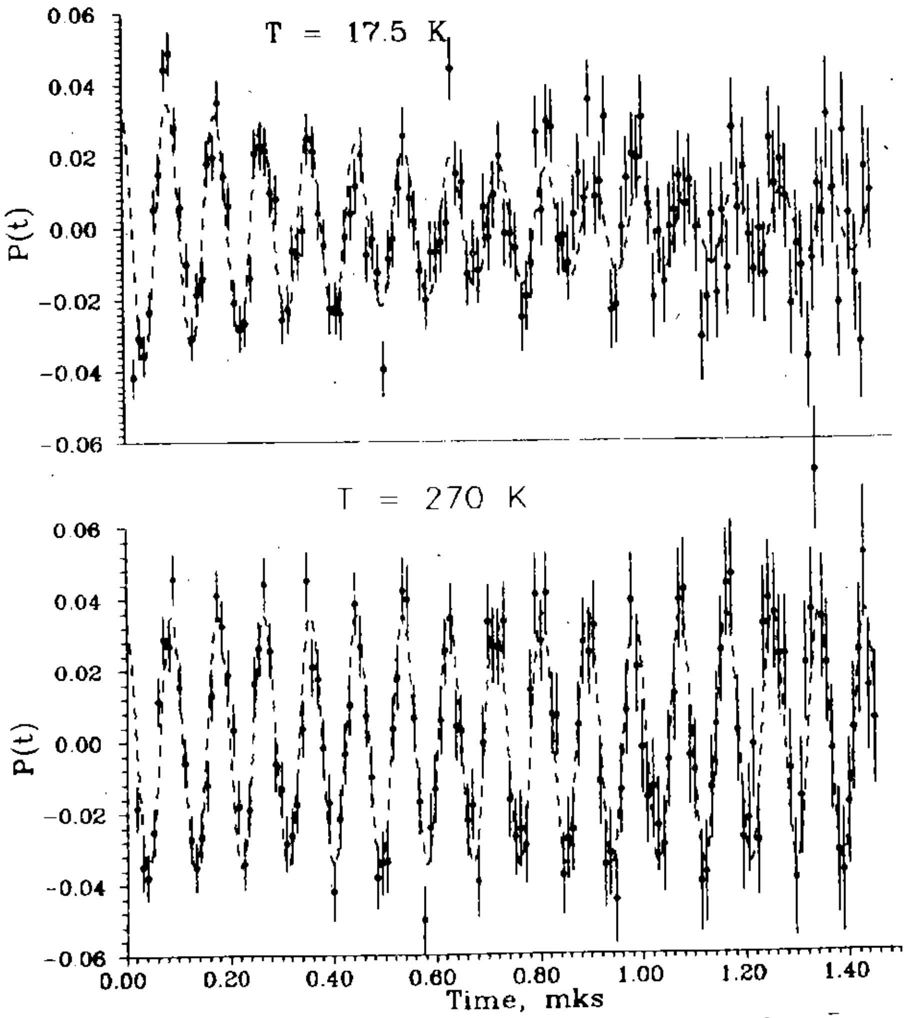

Fig. 1. Time distribution of electrons from the $\mu^- \Rightarrow e$ decay in Si at T = 17.5 K and 270 K. The experimental data are corrected for the decay exponent, contributions from components with no relation to Si are eliminated. The curves are plotted by the least squares method.

precession in the magnetic field; α is the asymmetry coefficient of decay electrons; $\Phi(t)$ is term to take into account electrons arising from the decay of muons stopped in a counter before the target and in a copper container; N_C is the constant background.

In fig. 1 there are recorded spectra of electrons from the μ^- decay in Si at room temperature and at 17.5 K. The data are corrected for the finite lifetime of the muon, and the $\Phi_1(t)$, N_C contributions are removed from them. The curve corresponds to the parameters obtained from the experimental data by the least squares method.

The values of the asymmetry coefficient α and the relaxation rate Λ obtained for different temperatures are shown in tab. 1 and fig. 2. As follows from the data, the value of the asymmetry coefficient is close to the one predicted by the cascade theory of depolarization /14/ and is practically independent of the temperature. Muon spin relaxation was not found at room temperature while it was observed at temperatures below 30 K. Its rate increased as the temperature decreased, and at liquid helium temperature the apparatus resolution did not allow it to be measured. In the region T < 30 K the relaxation rate data are well described by the relationship $\Lambda = B \cdot T^{-q}$, where $q = 2.75$. The power dependence of Λ with q close to 3 may indicate an essential role of the phonon mechanism in relaxation of the electron moment of the acceptor centre.

Our results for p-type Si with the impurity concentration $2 \cdot 10^{13}$ cm^{-3} essentially differ from the results /8/ for p-type and n-type Si with the impurity concentration $1.4 \cdot 10^{14}$ cm^{-3} and $2.5 \cdot 10^{14}$ cm^{-3} respectively. In ref. [8] muon spin relaxation was not observed, the asymmetry coefficient in the range from room temperature to 30 K was constant, then decreased with the temperature.

If we take $\Omega_{hf} = 2\pi \cdot 6.5 \cdot 10^8$ s^{-1} $\approx 4 \cdot 10^9$ s^{-1} (experimental value of the muon spin precession frequency in a zero external magnetic field is equal to 650 MHz /8/), and the muon spin relaxation rate to be equal to our value of Λ at 15 K,

Table 1

T, K	$\alpha \cdot 10^2$	Λ, μs^{-1}
10	4.2 ± 0.7	4.90 ± 1.00
15	3.6 ± 0.2	1.05 ± 0.17
17.5	3.8 ± 0.2	1.07 ± 0.16
20	3.8 ± 0.2	0.66 ± 0.07
25	3.7 ± 0.2	0.48 ± 0.10
30	3.9 ± 0.2	0.18 ± 0.08
270	3.8 ± 0.1	0.04 ± 0.04

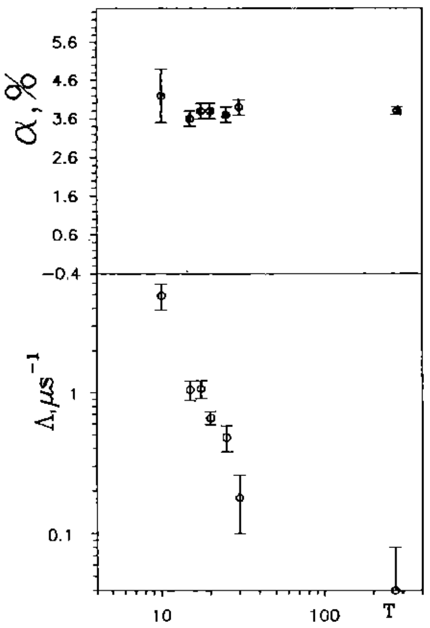

Fig. 2. Asymmetry coefficient α of the $\mu^- \to e$ decay electrons and muon spin relaxation rate Λ as a function of temperature in Si.

then from formula (1) we obtain the relaxation rate for the electron shell moment of the impurity muon atom to be $\nu_o \propto 10^{12}$ cm^{-1}. This value of ν_o for the impurity acceptor in silicon seems to be quite reasonable.

Determining $\Delta\omega$ we did not use the data for T = 10 K because the accuracy in determination of ω decreases as the muon spin relaxation rate increases. From the $(\Delta\omega/\omega)$ data in fig. 3 one can draw a conclusion that the possible value of the paramagnetic shift does not exceed 10^{-3}. This value does not contradict the above-mentioned rough estimation. Actually, formula (2) involves an averaged value of g-factors, which in their turn depend on local deformations in the crystal and orientation of its axes with respect to the magnetic field. Besides, both the g-factor and Ω_{hf} may depend on the temperature.

Thus, our results are in quite good agreement with the assumption that the muon atom $_{\mu}Al$ occupies the acceptor level in silicon. The fact that in ref. [8] there was only one distinct frequency in the spectrum obtained with a zero external magnetic field points to isotropic hyperfine coupling. It poorly agrees with the statement that the impurity atom $_{\mu}Al$ is displaced from the lattice node. The behaviour of the relationship between temperature and the asymmetry coefficient obtained in ref. [8] can be explained by local elastic stresses in the lattice with deformation tensor components $\propto 10^{-4}$.

To clear up the physical nature of the impurity centre resulting from capture of negative muons in silicon, one must

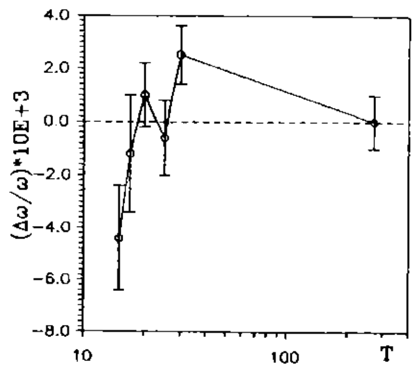

Fig. 3. Paramagnetic shift of the muon spin precession frequency in Si as a function of temperature.

study the temperature dependence of the paramagnetic shift and recovery of polarization in strong longitudinal magnetic fields. The latter will allow independent determination of Ω_{hf} at a given temperature and a possibility of judging from polarization damping whether it is isotropic or tensor interaction.

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