# Effect of radiation-induced lattice defects in silicon single crystals on the characteristic states of an interstitial muonium atom

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It is observed experimentally that radiation defects affect normal and anomalous muonium in silicon differently. It is shown that the mobilities of these two states of muonium in the lattice of the specimen differ considerably.

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As shown in our previous work,[1,2] the temperature dependence of the magnitude of polarization and the relaxation rate of the polarization of an ensemble of $\mu^+$ mesons in perpendicular and longitudinal magnetic fields give information both on the probability for the formation of different bound states of the $\mu^+$ meson and on the dynamics of transitions between them. In order to describe all of the experimental data on the states of the $\mu^+$ meson in semiconductors, we proposed a model representation of the three possible states of the $\mu^+$ meson in matter,[1] in which anomalous muonium (Mu*) is taken to mean the bound system in the silicon lattice with an unpaired electron localized on one of the atoms in the lattice neighboring the muonium atom (chemical bond model).

A systematic phenomenological theory describing the states of Mu and Mu* in lattices of solids with the diamond structure was developed by Belousov, Gorelkin, and Smilga.[3]

The research described in this paper was performed in order to check the chemical bond model and to obtain new experimental data for further development of the theory and of our ideas concerning the behavior of $\mu^+$ mesons in matter.

The most complete information about the three different states of the $\mu^+$ meson in matter can apparently be obtained by studying the probability of their formation and the dynamics of the changes over time of the existence of these states with different (known) parameters of the surrounding medium. Thus, for example, it is known that hydrogen atoms injected into silicon by ion implantation actively interact with radiation defects in the lattice with the formation of Si–H type bonds.[4]

Free muonium atoms (Mu), which rapidly find a point defect and interact with it just as hydrogen does, are an analog of the hydrogen atom in silicon.

As far as the behavior of anomalous muonium as a function of the number of radiation defects in the specimen is concerned, it largely depends on the structure of this state. If we view Mu* as a free atom $(\mu^+e^-)^*$ differing from Mu only in its hyperfine structure, then the condition for interaction of this system with radiation defects in the specimen should not differ strongly from interactions of the Mu atom. If, on the other hand, the Mu* system is viewed as a complex rigidly fixed to the crystal lattice, then, on the contrary, due to the absence of diffusion over the bulk of the specimen radiation defects cannot change the dynamics of the Mu* system in silicon.

In order to clarify this problem, we investigated the effect of radiation damage in a single crystal of silicon and its subsequent annealing on the ratio of the amplitudes of normal and anomalous muonium and the $\mu^+$ meson. For this purpose, the specimen of $p$-type silicon studied by us previously in detail ($p = 5\times10^{12}$ cm$^{-3}$) was irradiated by fast neutrons in the experimental channels of the reactor at the Leningrad Institute of Nuclear Physics, Academy of Sciences of the USSR. Three series of irradiations were performed with different neutron doses, which created, according to estimates, concentrations of defects (substituted atoms) equal to $2\times10^{18}$, $10^{17}$, and $10^{16}$ cm$^{-3}$.

After each irradiation, a $\mu SR$ investigation was performed with the irradiated specimen and with the same specimen after complete thermal annealing of the radiation defects. The experiments were performed on the "Myuoniĭ" setup in a beam in the $\mu$-meson channel of the synchrocyclotron at the Leningrad Institute of Nuclear Physics.[5] The results of the investigations are presented in Figs. 1 and 2. Figure 1 shows the temperature dependence of the initial ($t = 0$) polarization of the ensemble of $\mu^+$ mesons in longitudinal ($H_\parallel = 250$ Oe) and in perpendicular ($H_\perp = 350$ Oe) magnetic fields for the unirradiated specimen (dashed lines[2]), for radiation-defect concentrations $1\times10^{17}$ cm$^{-3}$ (triangles) and $2\times10^{18}$ cm$^{-3}$ (dark circles) and after complete thermal annealing of defects (open circles). It is evident from these dependences that the initial (at $t = 0$) polarization of $\mu^+$ mesons depends weakly on the concentration of defects in the specimen; this indicates that radiation defects do not change the probability of formation of the three states Mu, Mu*, and $\mu^+$ initially.

Figure 2 shows the Fourier transformations of the $\mu SR$ spectra for the silicon

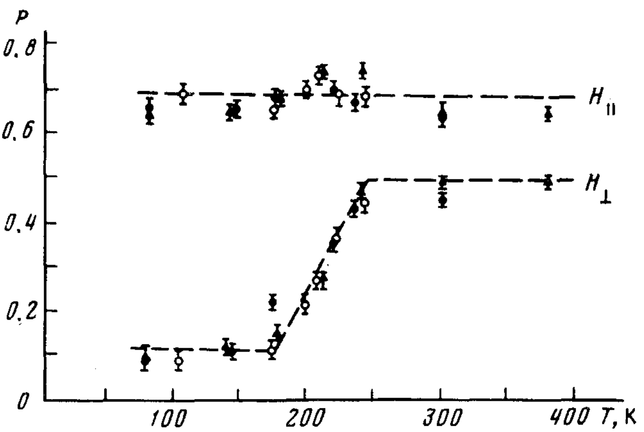


FIG. 1. Temperature dependence of the initial polarization of $\mu^+$ mesons in silicon ($p = 5\times10^{12}$ cm$^{-3}$) for longitudinal ($H_\parallel = 250$ Oe) and perpendicular ($H_\perp = 350$ Oe) magnetic fields.

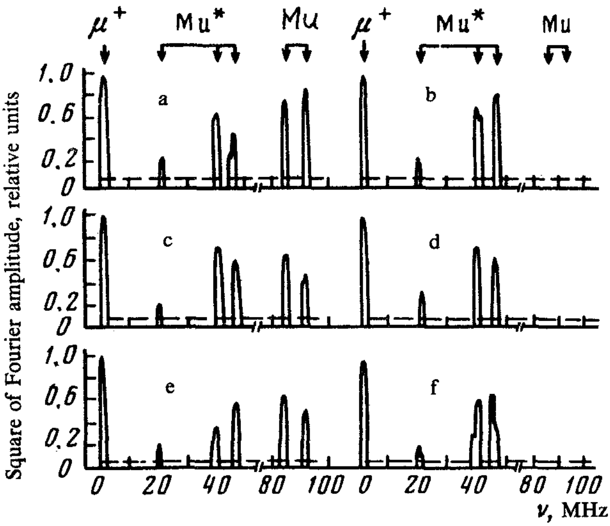


FIG. 2. Results of a Fourier analysis of the experimental $\mu SR$ spectra ($H_{\perp} = 60$ Oe, $T = 80$ K). a—Unirradiated specimen; b—defect concentration after first irradiation, $2\times10^{18}$ $cm^{-3}$; c—after first thermal annealing; d—defect concentration after second irradiation, $1\times10^{17}$ $cm^{-3}$; e—after second thermal annealing; f—defect concentration after third irradiation, $1\times10^{16}$ $cm^{-3}$. Dashed lines represent the white noise level.

specimen studied at $T = 80$ K in a field $H_{\perp} = 60$ Oe at different stages of irradiation and subsequent annealing. It is evident from the figure that the radiation defects that are formed have different effects on the normal and anomalous muonium in silicon (for $t > 0$). For defect concentrations in the range $10^{16}$–$2\times10^{18}$ $cm^{-3}$ normal muonium is not observed experimentally from the precession at the muonium frequency. At the same time, the amplitude and rate of relaxation of the polarization of $\mu^+$ in the composition of the anomalous muonium remained essentially the same. This indicates that the normal and anomalous muonium have very different mobilities in the silicon crystal lattice. Subsequent thermal annealing of the specimen restores the starting characteristics of the spin polarization of the $\mu^+$ meson in the composition of normal muonium.

The investigations performed show that radiation defects considerably change the dynamics of the state of normal muonium in silicon and have virtually no effect on the anomalous muonium. This phenomenon can be used to study in greater detail the states of anomalous muonium in semiconductors and to observe with the help of $\mu SR$ defectoscopy radiation defects in weakly doped specimens of silicon and germanium. The data obtained qualitatively confirm the mechanism of interaction of the $\mu^+$ meson in the lattice of atomic semiconductors, as presented in the chemical-bond model.[1]

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