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EFFECTS OF ELECTRONICALLY NEUTRAL IMPURITIES ON MUONIUM IN GERMANIUM

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Low-temperature measurements of muonium parameters in various germanium crystals have been performed. We have measured crystals with different levels of neutral impruities, with and without dislocations, and with different annealing histories. The most striking result is the apparent trapping of Mu by silicon impurities in germanium.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

That the behavior of the μ^+ states in semiconductors is effected by the type and concentration of electronically active dopants is well known [1,2]. Arguments based on expected depolarization mechanisms agree at least semi-quantitatively with the observed relaxation rates [2].

But the history of μSR has shown time and time again the sensitivity of relaxation rates to the presence of minute amounts of impurities or defects in metals, and we cannot a priori assume that isoelectronic impurities in semiconductors are unimportant. Indeed, such impurities are now known to form complexes with hydrogen in germanium [3]. If the thermalized muonium is highly mobile, one may expect the μSR signals to be affected by the presence of such impurities. Divacancies, also known to be present in dislocation-free germanium, have also been found to form complexes with hydrogen [4].

We reported earlier [5] on our studies of Mu in germanium. Our principal results were that the Mu asymmetry was the same for all samples, and that the only dislocation-free crystal studied showed a much larger Mu relaxation rate than the others.

We interpreted the fast relaxation in the dislocation-free sample as evidence for the trapping of Mu by the divacancy, but further work showed that not all dislocation free samples showed such a strong relaxation. To see whether this was because the divacanices in some of the samples were already filled with hydrogen, we annealed them at 500°C for 2 hours to drive out the hydrogen.

The Mu relaxation rates, before and after anneling, for two dislocation-free samples at 5 K are shown in Table 1. One (# 498-5.5) is the sample reported previously [5] and the other (# 571-12.7u) is one which did not show a strong relaxation. No significant effect of annelaing is apparent, indicating that the presence of hydrogen does not influcence Mu in these samples. Similar results are seen in other samples.

The trapping of Mu by Si dissolved in Ge has been reported [6] recently. We too have observed strong relaxation of the Mu signal in Si-doped Ge. In a sample containing $\approx 10^{16}\ cm^{-3}$ Si we found $\lambda_{Mu} = 8 \pm 3 \mu s^{-1}$, and in one containing $\approx 10^{17}\ cm^{-3}$ Si we found $\lambda_{Mu} > 30\ \mu s^{-1}$. These results are substantially in agreement with those reported in Ref. [6].

It is possible that the higher than normal Mu relaxation rate in sample #498-5.5 is due to silicon impurities. From the data of Ref. [6], it appears that a concentration of Si near $10^{14} - 10^{15} cm^{-3}$ could cause a relaxation of the strength we see. Quartz-grown germanium crystals contain typically $10^{14}\ cm^{-3}$ Si [7], with the concentration being highest near the seed end of the crystal [3] from where our sample was taken.

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Table 1

Mu relaxation rates at 5 K, in μs^{-1}

Sample	λ_{Mu} Before anneal	λ_{Mu} After anneal
498-5.5	2.1(2)	2.3(3)
571-12.7u	0.59(7)	0.59(5)

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