

TITLE: TEMPERATURE DEPENDENCE OF ANOMALOUS MUONIUM HYPERFINE INTERACTIONS IN SILICON

**MASTER**

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TEMPERATURE DEPENDENCE OF ANOMALOUS MUONIUM  
HYPERFINE INTERACTIONS IN SILICON

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The temperature dependence of the anomalous muonium hyperfine interaction has been measured in silicon. Between 5 and 150 K, an approximately 1% decrease is observed and attributed to interaction with the silicon host phonons.

The temperature dependence of the hyperfine interaction of paramagnetic centers in solids may be due to lattice dilation and to interaction with phonons.<sup>(1)</sup> The combined effect of these two processes may be either an increasing or decreasing hyperfine interaction with increasing temperature. We report here measurements of the hyperfine interaction,  $A$ , of anomalous muonium in silicon. Our results show a decreasing  $A$  with increasing temperature that is attributed to interaction with the host phonons. We find no evidence for any large effect due to the small nonmonotonic lattice expansion characteristic of tetrahedral semiconductors like silicon.<sup>(2)</sup> Neither do we find evidence of local phonon modes due to the light muon particle.

The measurements were made at the Stopped Muon Channel of the Clinton P. Anderson Meson Physics Facility at Los Alamos on a p-type silicon single crystal with approximately  $10^{13}$  electrically active carriers per cc at room temperature. The crystal was mounted in a variable temperature cryostat with the magnetic field fixed at 150 G along  $\langle 110 \rangle$  to determine  $A_{\perp}$  and set to 1000 G along  $\langle 111 \rangle$  to determine  $A_{\parallel}$ . The quantities  $A_{\perp}$  and  $A_{\parallel}$  of the highly anisotropic anomalous muonium center<sup>(3)</sup> are given by the sum and the difference of the frequencies due to the perpendicular and parallel centers, respectively, in each arrangement. The results are shown in Fig. 1.

Since the results show a monotonic decrease of both  $A_{\perp}$  and  $A_{\parallel}$  with increasing temperature and no large nonmonotonic variation that could be attributed to lattice dilation, the effect of the latter was neglected in the data analysis. Two phonon interaction models were fit to the data. Firstly, if an equal interaction is assumed with the long wavelength part of a Debye phonon spectrum, then the hyperfine interaction should vary as<sup>(4)</sup>

$$A(T) = A(0) \left[ 1 - cT^4 \int_0^{D/T} \frac{x^3}{e^x - 1} dx \right],$$

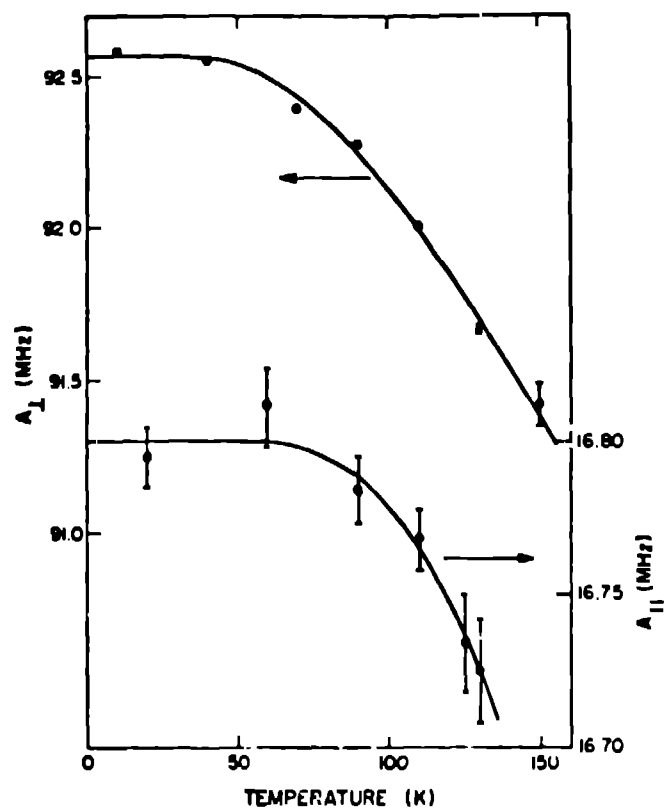


Fig. 1

Temperature dependence of  $A_I$  and  $A_{II}$  of anomalous muonium in silicon. The lines are the best fit to a Coth law. The best fits to the integral equation do not differ significantly from these lines.

where  $\Theta_D$  is the Debye temperature of Si taken as 640 K and C is a coupling constant. This expression should apply to low-temperature measurements and was found to give a least squares fit to the data with

$$A_I(0) = 92.549 \pm 0.004 \text{ MHz}$$

$$C_I(0) = 7.136 \pm 0.974 \times 10^{-12} \text{ K}^{-4}$$

and

$$A_{II}(0) = 16.804 \pm 0.007 \text{ MHz}$$

$$C_{II}(0) = 3.128 \pm 0.624 \times 10^{-12} \text{ K}^{-4}$$

A better fit to  $A_I$  could be obtained with a smaller  $\Theta_D = 415$  K but not for  $A_{II}$ .

The second model of phonon interaction includes only coupling to a single phonon mode. In this case, the temperature dependence is given by<sup>(5)</sup>

$$A(T) = A(0)[1 - C'(\text{Coth } \frac{h\nu}{kT} - 1)] ,$$

where  $h\nu$  is the energy of the phonon mode and again  $C'$  is a coupling constant.

A least squares fit to the data yields

$$A_1(0) = 92.569 \pm 0.005 \text{ MHz}$$

$$C_1' = 0.0300 \pm 0.002$$

$$h\nu_1 = 260 \pm 8 \text{ K}$$

and

$$A_2(0) = 16.800 \pm 0.008 \text{ MHz}$$

$$C_2' = 0.1705 \pm 0.302$$

$$h\nu_2 = 565 \pm 223 \text{ K} .$$

Both models fit the data equally well and the lines in fig. 1 show the Coth law fit. Hence, we conclude that interaction with the silicon host phonon spectrum is the dominant cause of the temperature dependence of A and that the neglect of the effect due to lattice dilation is justified. The actual phonons involved are not determined with sufficient accuracy to associate them with any particular singular point of the silicon phonon spectrum.

The experimental data also give the temperature dependence of the depolarization rate,  $\lambda$ , of the muons. Up to nearly 100 K there is very little change in  $\lambda$ , but above this it starts increasing rapidly. This increase at high temperature has been observed at SiH.<sup>(6)</sup> The combined data may be described by a thermally activated depolarization process such as the liberation of charge carriers where

$$\lambda(T) = \lambda(0) \exp(-E/kT) .$$

We find the activation energy  $E = 110 \pm 35 \text{ meV}$  which is in the range of half center acceptor ionization energies. Alternatively, the data may be explained by a Raman relaxation process for a  $S = \frac{1}{2}$  center. This model predicts  $\lambda \propto T^9$  which also fits the experimental results within the same accuracy as the exponential law.

In conclusion, contrary to earlier reports,<sup>(7)</sup> we have found a temperature dependence of the hyperfine interactions of anomalous muonium in silicon. Furthermore, it is attributed to interaction with the silicon host phonon modes. The high temperature depolarization rate may be either thermally activated or due to a Raman process.

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#### REFERENCES

1. W. T. Doyle and A. B. Wolbarst, J. Phys. Chem. Solids 36, 549 (1975).
2. D. N. Batchelder and R. O. Simmons, J. Chem. Phys. 41, 2324 (1964).
3. B. D. Patterson, A. Hintermann, W. Kündig, P. F. Meier, F. Waldner, H. Graf, E. Recknagel, A. Weidinger, and I. Wichert, Phys. Rev. Lett. 40, 1347 (1978).
4. E. Simanek and R. Orbach, Phys. Rev. 145, 191 (1966).

5. W. Dreybrodt, Phys. Stat. Sol. 21, 99 (1967).
6. C. Boekema et al., Proceedings of this conference.
7. C. Boekema, A. Denison, W. Kündig, W. Reichert, and K. Rüegg, Helv. Phys. Acta 52, 376 (1979).

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