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THE INFLUENCE OF THE CRYSTAL LATTICE OF SILICON ON THE HYPERFINE SPLITTING ENERGY OF MUONIUM

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The dependence of the polarization of the μe decay on the intensity of the longitudinal magnetic field was measured in silicon single crystals. The hyperfine splitting energy of the muonium atom in the given crystal lattice differs from the vacuum value and conforms to a muonium dimension of $r = (0.719 \pm 0.016)$Å.

WHEN μ^+ mesons are slowed down in materials with a high electron gas concentration (for example, in metals), the formation of the atomic system muonium (μ^+e^-) does not occur[1-3] and the parameters of the Larmor precession in a transverse magnetic field are given by the magnetic moment and spin of the free μ^+ meson. However, in quartz (SiO_2), which is chemically inert and has a negligible density of conduction electrons, the probability of the formation of muonium is nearly unity[4-5]. We note that under the given conditions muonium behaves like an isolated atom, the wave functions of which are not distorted by the influence of the surrounding crystal lattice. Interest attaches to the investigation of the probability of the formation of muonium and its interactions with the lattice in semiconducting materials with an intermediate value of the free electron density.

One of the basic characteristics of muonium in polarization experiments is the frequency (ω) of the transitions between the hyperfine-structure levels (1, 0) and (0, 0), these transitions causing the depolarization of muonium with the antiparallel directions of the μ^+ meson and electron spins. For the isolated muonium atom $\omega_1 = 2.804 \times 10^{10}$ sec^{-1}[6-7]. In strong longitudinal magnetic fields, in consequence of the break in the coupling of the magnetic moments of the meson and the electron, the above-mentioned transitions are absent, and depolarization does not take place. The critical field at which the change of the magnetic energy of the muonium in an external field, $2H(\mu_e - \mu_\mu)$, becomes equal to the hyperfine splitting energy

$$\Delta W = \omega h \approx 32\mu_e\mu_\mu / 3r^3$$

(μ_μ and μ_e are the magnetic moments of the meson and electron, r is the radius of the Bohr orbit of muonium) is given by the expression

$$H_{cr} = \Delta W / 2(\mu_e - \mu_\mu). \qquad (2)$$

The intensity of the critical magnetic field can be determined by the method of restoration of polarization in longitudinal magnetic fields[5,7]. In the absence of spin-exchange interactions of the muonium with the environment, the connection between the polarization and the intensity of the external field is defined by the relation[8]

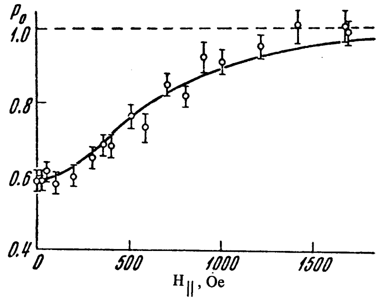
$$P = \frac{1}{2}(1 + P_{\mu^+}) + \frac{1}{2}(1 - P_{\mu^+})\frac{x^2}{1 + x^2}, \qquad (3)$$

where P is the total polarization of the μ_e decay, R_{μ^+} is the contribution of the mesonic component of the precession in the transverse magnetic field, which is independent of the field strength, $x = H/H_{cr}$, and H is the intensity of the longitudinal magnetic field.

We measured the dependence of the polarization of the μe decay on the intensity of the longitudinal magnetic field in silicon. To satisfy the condition of small exchange, materials with a low carrier density are needed[9], therefore we have chosen as the object of investigation single crystals of p-type silicon with an impurity concentration $(1.6 \pm 0.2) \times 10^{13}$ cm^{-3}, $\rho = 260$ ohm-cm at 300°K. The apparatus and measurement procedure have been described earlier[3,5].

The results are presented in the figure. We note that a slow depolarization (on the order of a microsecond) is observed in the course of the observation period both in the transverse and in the weak longitudinal fields. With increasing intensity of the longitudinal field, the rate of depolarization decreases. Values of polarization (P_0) extrapolated to zero time were used. The continuous curve in the drawing was determined with an electronic computer on the basis of (3); the criterion $\chi^2 = 15.05$ with 16 degrees of freedom indicates that the experimental data agree with the theoretical formula and does not contradict the assumption of small spin-exchange interactions in the present case. We shall note that the condition $2P(\parallel) - P(\perp) = 1$[5], satisfaction of which in weak fields indicates the absence of other depolarization channels of the μ^+ meson, is fulfilled in the present experiments with satisfactory accuracy (1.017 ± 0.026). A qualitatively similar dependence of the polarization on the intensity of the longitudinal field (without) analysis of the time dependence) in silicon doped with boron is noted also in[10].

The critical magnetic field in our experiments was found to equal $H_{cr} = 643 \pm 42$ Oe, which is ~2.5 times less than the vacuum value ($H_0 = 1585$ Oe[6]). Analysis of experimental errors showed that the contribution of systematic errors included in the root mean square deviation is insignificant. Using expressions (1) and (2) for the calculation of the effective dimension of atomic muonium in the crystal lattice of silicon, we obtain the value $r = (0.719 \pm 0.016)$ Å. An analogous increase in the dimensions of muonium (~1.2 times the vacuum value) was found by the method of beats in



The dependence of the initial polarization (P_0) of the μe decay on the intensity of the longitudinal magnetic field in single crystals of silicon.

single crystals of germanium[11]. We thus get the relation

$$r_0 < r < a, \qquad (4)$$

where r_0 is the radius of the Bohr orbit of muonium in a vacuum (0.532 Å) and a is the crystal lattice parameter of silicon (5.43 Å). The left part of the inequality indicates the existence of interactions of muonium with the crystal lattice. It is significant, however, that this interaction cannot be described on the basis of the usual macroscopic dielectric constant (ϵ), for then the value $r/r_0 = \epsilon m_0/m^*$, taking account of the effective mass of the electron (m^*), should be equal to ~30. In addition, the right side of inequality (4) shows that the expected influence of the crystal lattice on the distribution of the electron density of muonium should be significantly weaker than, for example, in the case of hydrogen-like impurity atoms located at the lattice sites. In the last case the value of r is of the order of several a[12].

The data obtained allow one to surmise that muonium (and consequently also atomic hydrogen), apparently, is located in the interstices of silicon. We note additionally that the formation of valence bonds in the case of the occurrence of muonium at a lattice site would lead to a significant contribution of the polarization $P(\perp)$ at the mesonic frequency, an event, which did not occur in the present work. The increase in the dimensions of muonium in the lattice of silicon is apparently a specific property of semiconducting crystals since, for example, in quartz (SiO_2) one observes the vacuum value of the transition frequency ω[4]. The concrete mechanism of the interaction of muonium with the crystal lattice of a semiconductor remains unclear at the present time. Therefore there is interest in the further study of the behavior of muonium in other semiconducting materials with chemical bonds of a different nature.

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[1] R. L. Garwin, L. M. Lederman, and M. Weinrich, Phys. Rev. 105, 1415 (1957).

[2] R. A. Swanson, Phys. Rev. 112, 580 (1958).

[3] G. G. Myasishcheva, Yu. V. Obukhov, V. S. Roganov, and V. G. Firsov, Zh. Eksp. Teor. Fiz. 53, 451 (1967) [Sov. Phys.-JETP 26, 298].

[4] I. I. Gurevich, I. G. Ivanter, L. A. Makar'ina, E. A. Meleshko, B. A. Nikol'skiĭ, V. S. Roganov, V. I. Selivanov, V. P. Smigla, B. V. Sokolov, V. D. Shestakov, I. B. Yakovlena. Preprint IAÉ-1788, 1969; Phys. Lett. 29B, 387 (1969).

[5] E. V. Minaichev, G. G. Myasishcheva, Yu. V. Obukhov, V. S. Roganov, G. I. Savel'ev, and V. G. Firsov, Zh. Eksp. Teor. Fiz. 57, 421 (1969) [Sov. Phys.-JETP 30, 230].

[6] A. O. Vaĭsenberg, Myu-mezon (Mu Mesons), Nauka, 1964.

[7] V. W. Hughes, Ann. Rev. Nucl. Sci. 16, 445 (1966).

[8] R. A. Ferrell and F. Chaos, Phys. Rev. 107, 1322 (1957).

[9] D. G. Andrianov, G. G. Myasishcheva, Yu. V. Obukhov, V. S. Roganov, V. G. Firsov, and V. I. Fistul', Zh. Eksp. Teor. Fiz. 56, 1195 (1969) [Sov. Phys.-JETP 29, 643].

[10] B. Eisenstein, R. Prepost, and A. M. Sachs, Phys. Rev. 142, 217 (1966).

[11] B. A. Nikol'skiĭ. Report at the Franco-Soviet Colloquium on Solid State Physics, October, 1969, Lumini, France.

[12] R. A. Smith, Semiconductors.

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231