Depolarization of positive muons in a gallium arsenide single crystal in a perpendicular magnetic field

S. G. Barsov, A. L. Getalov, V. A. Gordeev, V. A. Evseev, R. F. Konopleva, S. P. Kruglov, V. I. Kudinov, L. A. Kuz'min, S. M. Mikirtych'yants, E. V. Minaĭchev, G. G. Myasishcheva, Yu. V. Obukhov, G. I. Savel'ev, V. G. Firsov, and G. V. Shcherbakov

Institute of Technical and Experimental Physics; B. P. Konstantinov Leningrad Institute of Nuclear Physics, Academy of Sciences of the USSR

(Submitted 23 May 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **42**, No. 10, 424–426 (25 November 1985)

Experiments have been carried out to determine the characteristics of the muon component of the polarization in gallium arsenide as a function of the temperature. The behavior observed experimentally agrees qualitatively with model-based predictions advanced previously by the present authors for atomic semiconductors.

Previous measurements in atomic semiconductors (silicon,[1] germanium,[2] and diamond[3]) by the method of spin precession of positive muons in an external magnetic field directed perpendicular to the original spin direction of the particles have revealed three states of the muon, which differ in the nature of the hyperfine interaction of the muon with the electron bound to it in the crystal lattice of the semiconductor. These states have been labeled Mu (a muonium atom, in which the hyperfine interaction of the muon and the electron is isotropic), Mu* ("anomalous" muonium, in which the hyperfine interaction is anisotropic and significantly weaker than in the former case), and μ^+ (the muon component of the polarization, for which there is essentially no hyperfine interaction). In the simple semiconductors listed above, the precession frequencies of each of the states and the temperature regions in which they are stable have been studied in some detail, but the processes by which the states are formed and the appropriate models still cannot be regarded as definitively established, despite repeated discussions in the literature.[1–4]

Preliminary results of corresponding experiments carried out with binary semiconductors—gallium arsenide and gallium phosphide—have recently been reported.[5–7] It has been shown that the states discussed above are also observed in these samples, and the temperature dependence of the relative magnitude of the muon component agrees qualitatively with that for silicon.[4]

In the present letter we report a study of the temperature dependence of the initial amplitude and relaxation rate of the muon polarization component in a perpendicular external magnetic field ~280 Oe. The experiments were carried out in the meson channel of the synchrocyclotron of the Leningrad Institute of Nuclear Physics with a single-crystal semi-insulating sample of chromium-doped gallium arsenide ($\rho \gtrsim 10^8$ Ω·cm, $[p] = 2\times10^{12}$ cm^{-3} at $T = 500$ K with an activation energy of 0.69 eV) over the temperature interval 60–560 K. The experimental procedure and the measurement

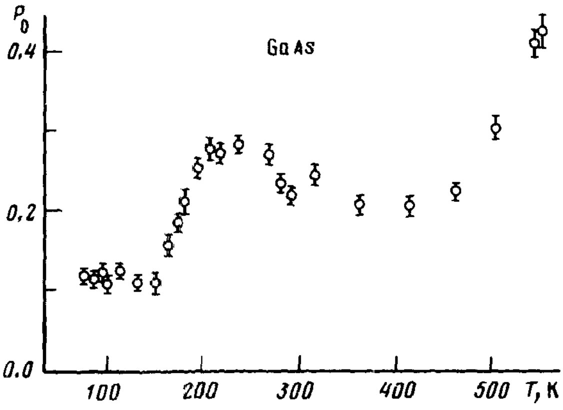

FIG. 1. The initial polarization (P_0) of the muon polarization component versus the temperature in gallium arsenide.

apparatus are basically the same as those used in the silicon experiments.[4] The time interval over which the μe decays are detected is set at 16 μs, longer than in the preliminary experiments,[5] in order to improve the accuracy with which the relaxation rate is measured. The experimental results are shown in the accompanying figures.

It can be seen from Figs. 1 and 2 that the temperature dependence of the relative size of the muon polarization component in gallium arsenide, like that in silicon, can be partitioned into four intervals along the temperature scale, with different values of the initial polarization:

I) 60–160 K; the polarization is constant at $P_0 = 0.12 \pm 0.02$;

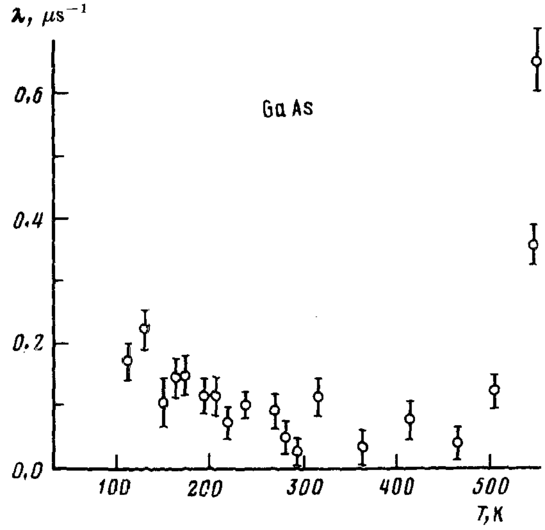

FIG. 2. Relaxation rate of the muon polarization component versus the temperature in gallium arsenide.

II) 160–200 K; a sharp increase in P_0 to the value $P_0 = 0.30 \pm 0.02$;

III) 200–500 K; a monotonic decrease in P_0 to $P_0 = 0.20 \pm 0.02$ (for silicon, constant values of P_0, within the experimental errors, have been observed in region III);

IV) $T > 500$ K; a sharp increase in the initial polarization and in the relaxation rate of the muon precession (Fig. 2).

Analysis of these results in comparison with corresponding results and on the basis of the physical picture constructed by us previously for silicon,[4] with allowance for the preliminary experiments in longitudinal magnetic fields[5] and the fact that precession frequencies of normal and anomalous muonium are observed in gallium arsenide,[6,7] suggests that the characteristic increase in the muon polarization component in temperature regions II and IV is caused by transitions between states, specifically,

$$\mathrm{Mu}^* \rightarrow \mu^+ \text{ (II) and } \mathrm{Mu} \rightarrow \mu^+ \text{ (IV).}$$

The apparent reason why there is no plateau in the plot of the initial polarization in region III in that the μ^+ state that forms is not stable in binary semiconductors. These results are evidence that the mechanism for the interaction of the muonium atom with the crystal lattice is of universal applicability to both atomic and binary semiconductors. A more comprehensive analysis of the picture of the interaction of positive muons with binary semiconductors will become possible when the data obtained are compared with the results of studies in longitudinal magnetic fields.

[1]B. D. Patterson, A. Hintermann, W. Kündig, P. F. Meier, G. Waldner, H. Graf, E. Recknagel, A. Weidinger, and Th. Wichert, Phys. Rev. Lett. **40**, 1347 (1978).

[2]E. Holzschuh, H. Graf, E. Recknagel, A. Weidinger, and Th. Wichert, Phys. Rev. B **20**, 4391 (1979).

[3]E. Holzschuh, W. Kündig, P. F. Meier, B. D. Patterson, J. P. F. Sellschop, M. C. Stemmet, H. Appel, Phys. Rev. A **25**, 1272 (1982).

[4]S. G. Barsov, A. L. Getalov, V. A. Gordeev, R. F. Konopleva, S. P. Kruglov, V. I. Kudinov, L. A. Kuz'min, S. M. Mikirtych'yants, E. V. Minaichev, G. G. Mysisheva, Yu. V. Obukhov, G. I. Savel'ev, V. G. Firsov, and G. V. Shcherbakov, Zh. Eksp. Teor. Fiz. **76**, 2198 (1979) [Sov. Phys. JETP **49**, 1110 (1979)]; Zh. Eksp. Teor. Fiz. **79**, 1461 (1980) [Sov. Phys. JETP **52**, 738 (1980)].

[5]S. G. Barsov, A. L. Getalov, V. A. Gordeev, S. P. Kruglov, V. I. Kudinov, L. A. Kuz'min, S. M. Mikirtychyants, E. V. Minaichev, G. G. Myashishcheva, Y. V. Obukhov, G. I. Savel'ev, V. G. Firsov, and G. V. Shcherbakov, Hyperfine Interact. **17**, 634 (1984); Yamada Conference on Muon Spin Rotation and Associated Problems, Shimoda, Japan, April 18–22, 1983, p. 82.

[6]K. W. Blazey, T. L. Estle, J. Felber, E. Holzschuh, H. Keller, R. F. Kiefl, W. Kündig, P. F. Meier, W. Odermatt, D. B. Patterson, S. L. Rudaz, and J. W. Schneider, SIN Newsletter **16**, 105 (1984).

[7]R. F. Kiefl, E. Holzschuh, H. Keller, W. Kündig, P. F. Meier, B. D. Patterson, J. W. Schneider, K. W. Blazey, S. L. Rudaz, and A. B. Denison, Phys. Rev. Lett. **53**, 90 (1984).

Translated by Dave Parsons