MUONIUM DEPOLARIZATION PROCESSES IN GERMANIUM SINGLE CRYSTALS

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The temperature dependence of μ^+ polarization was studied in germanium single crystals having different concentrations of a dopant. Precession with 0.16 ± 0.07 μsec relaxation time was observed at a frequency corresponding to muonium atoms. Possible mechanisms are discussed for muonium interactions in media having different electron densities.

IN media containing a highly dense electron gas (metals) very little μ^+ depolarization occurs.[1,2] This situation is associated with the high frequency that characterizes the exchange interaction of the muonium electron spin; the principal factor in the depolarization, that resulting from hyperfine interaction, is thus effectively absent. On the other hand, in materials lacking conduction electrons the formation of a stable muonium state (with probability near unity) can be detected.[3]

The behavior of muonium (μ^+) in intermediate cases is of considerable interest. Semiconductors are suitable objects of study for this purpose, since the type and concentration of charge carriers can be varied easily by doping and sometimes by changes of temperature. We have measured polarization and its time dependence at muon and muonium frequencies, at temperatures from +90° to −196°C, in germanium single crystals having different dopant concentrations. The apparatus and experimental technique have been described in[2,3]. The polarization of the initial μ^+ beam was determined using bromoform; $c'(CHBr_3) = 0.286 \pm 0.004$ was the experimental asymmetry coefficient for the given experimental series. We used single crystals of pure germanium (p-type, with impurity concentration $1 \times 10^{14}/cm^3$, and ρ varying monotonically from 25.4 Ω-cm at 21°C to 1.76 Ω-cm at −195°C) and single crystals of arsenic-doped germanium (n-type, with $2 \times 10^{19}/cm^3$ arsenic concentration, and $\rho = (1.1 \pm 0.2) \times 10^{-3}$ Ω-cm in the entire investigated temperature interval).

Our results are given in the table. The initial asymmetry coefficient c_0' varies over a broad range, from a maximum to a minimum, as a function of temperature in pure germanium. The polarization remains close to the maximum (exhibiting weak temperature dependence) in the doped germanium. In addition, the time dependence of the polarization (the relaxation time τ) varies for pure germanium (down to the interval +14°—−11°C), with no relaxation at lower temperatures (Fig. 2). The temperature dependence of the polarization (without analyzing the time dependence) for germanium (n-type with $10^{15}/cm^3$ concentration) has been noted in[4]. Doped germanium exhibits no time dependence of the polarization except close to the

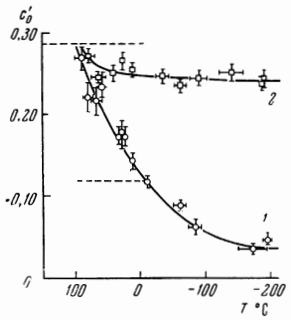

FIG. 1

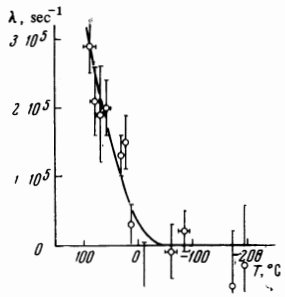

FIG. 2

FIG. 1. Temperature dependence of the initial experimental asymmetry coefficient in germanium single crystals (Curve 1) and in arsenic-doped germanium (Curve 2). The lower dashed straight line corresponds to the residual μ^+ polarization.

FIG. 2. Temperature dependence of depolarization rate ($\lambda = 1/\tau$) in undoped gernamium.

Ge, $p = 1 \cdot 10^{14}$ cm^{-3}				Ge (As), $n = 2 \cdot 10^{19}$ cm^{-3}			
H, Oe	T, °C	c_0'	$10^{-3}\lambda$, sec^{-1}	H. Oe	T, °C	c_0'	$10^{-3}\lambda$, sec^{-1}
$H_\perp = 7.03$	−196	0.123±0.026*	62±27	$H_\perp = 50.0$	+78±10	0.270±0.012	—
$H_\perp = 50.1$	+90±10	0.269±0.015	2.9±0.4	»	+63±9	0.245±0.010	—
$H_\perp = 49.9$	+81±5	0.221±0.018	2.1±0.5	»	+43±3	0.249±0.008	—
»	+69±3	0.216±0.018	1.9±0.7	»	+27±1	0.269±0.008	—
»	+61±3	0.235±0.017	2.0±0.4	»	+12±1	0.254±0.008	—
»	+32±1	0.173±0.011	1.3±0.3	»	−34±11	0.245±0.008	—
$H_\parallel = 0.84$	+31±1	0.175±0.019	1.3±0.3	»	−62± 8	0.233±0.009	—
$H_\perp = 50.3$	+25±2	0.172±0.012	1.5±0.4	»	−90±14	0.243±0.009	—
$H_\perp = 49,9$	+14±1	0.142±0.010	0.3±0.3	»	−139±21	0.250±0.009	—
»	−11±3	0.116±0.006	0	»	−192±4	0.242±0.012	0.3±0.2
»	−61±10	0.087±0.006	−(0.1±0.4)	$H_\parallel = 0.90$	−191±5	0.238±0.009	0.5±0.4
»	−86±8	0.061±0.008	0.2±0.3				
»	−172±22	0.033±0.006	−(0.6±0.8)				
$H_\perp = 50.3$	−193±3	0.048±0.006	−(0.3±0.9)				

*At the precession frequency of muonium atoms. The experimental value was corrected by taking the μ^+ polarization into account (with −180° geometry of the electron telescope.

boiling point of liquid nitrogen, where as the limit of the experimental errors dependence of the polarization on the observation time was observed.

The aforementioned case of metallic conduction occurs at the given concentration of the electron gas. An analysis of the data indicates that in the absence of a dopant the frequencies of electron exchanges correspond, with decreasing temperature, to a transition to a low probability of muonium charge exchange in the thermal region (as in the cases of nonmetals and insulators). In this case the polarization relaxation time at muon frequency corresponds to the probability of muonium formation, i.e., the inclusion of μ^+ in a system having an extremely different gyromagnetic ratio (by a factor ~ 103). Since muonium formation occurs at any time during μ^+ precession, the muonium is statistically depolarized from an experimental point of view. When the probability of electron exchange is substantially increased (with considerable temperature rise, for example) μ^+ depolarization via the channel of muonium formation should diminish and the "slow" depolarization constant ($\lambda = 1/\tau$) should drop to zero. These conditions are fulfilled for heavily doped germanium above 78°K and should evidently exist in pure germanium at temperatures above the investigated interval.

It should be noted that depolarization in pure germanium at low temperatures is temperature dependent even when the polarization does not vary in time, i.e., when $c_0' \equiv c'$. For a qualitative explanation of the analogous weak effect in doped germanium (the high-temperature region of curve 2 in Fig. 1) two causes can be suggested: First, electron mobility decreases because scattering by phonons plays a large role[5] (the probability of the process $\mu^+ + e^- \rightarrow$ Mu decreases); secondly, higher temperatures increase the probability of the inverse process due to thermal ionization of muonium. It is difficult at the present time to decide between these two hypotheses. For this purpose we would have to know the state of muonium in the germanium lattice; this knowledge could possibly be obtained through additional experimental work. Information about the state of muonium in germanium is also of independent interest, since the behavior of muonium should in first approximation resemble the analogous interaction between the hydrogen atom and germanium.

In connection with the foregoing discussion there exists an interesting possibility of observing muonium atoms at low temperatures. The corresponding experiment at −196°C with undoped germanium at the muonium precession frequency showed that the formation of the muonium triplet state (with parallel electron and μ^+ spins) proceeds with a probability corresponding to the combined balance of μ^+ and muonium polarizations, i.e., depolarization is negligible during periods $< 2 \times 10^{-8}$ sec. However, the probability of conversion exchange, and possibly other factors, results in the depolarization of triplet muonium with $\tau = 0.16 \pm 0.07$ μsec (Fig. 3). We note that for materials with negligible densities of conduction electrons (such as quartz and carbon dioxide) the depolarization rate is considerably slower.[3]

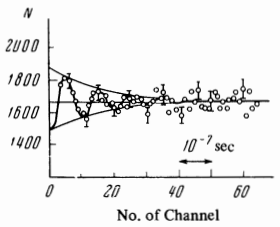

FIG. 3. Precession curve of muonium in germanium single crystals. Abscissas—channels (each 10.2 nsec wide); ordinates—counts corrected for the exponential muon decay. The characteristic ranges of statistical errors are indicated. T = −196°C.

The existence of stable muonium atoms in germanium at low temperatures is of fundamental significance, providing evidence that exchange interactions between muonium and electrons of the medium play only a small part. The frequency dispersion of the dielectric constant plays an important part.[6,7] Indeed, the value of the dielectric constant $\epsilon(\omega)$ for the frequency of the electron-generated field at a Coulomb center (at the μ^+ in the present instance) leads to changes in the radius of the electron orbit and in the ionization potential of muonium inside the medium. We are preparing to verify this effect by means of the variation of muonium depolarization at low temperatures as a function of the longitudinal magnetic field. The hfs splitting interval of the muonium atom can be determined in this way.

Very promising further work includes investigations of μ^+ depolarization as a function of impurity concentration and type in semiconductors, and of the relation between the magnetic properties of heavily doped semiconductors and the spin-spin and spin-lattice interactions of muonium.

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