MUONIUM FORMATION IN SEMICONDUCTORS*

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(Received November 4, 1960)

A well-known consequence of parity nonconservation in π - μ decay[1] is the longitudinal spin polarization of muons in meson beams emerging from synchrocyclotrons.[2] The residual polarization of positive muons before decaying in various solids in which they have been stopped has been measured by several groups.[3-5] In some substances (e.g., graphite, metals) no depolarization occurs; in others (e.g., nuclear emulsions, polyethylene) a partial depolarization has been observed; while in a few (e.g., SiO_2) there is complete depolarization. The details of the processes involved are at present not understood. However, measurements including the quenching of depolarization in external longitudinal fields[6-11] are consistent with a mechanism in which the muon undergoes short-lived attachments to electrons; i.e., μ^+e^- systems called muonium are formed. In order to gain a better understanding of these processes we have studied the depolarization in semiconductors, the electronic structure of which is well understood, and the electronic concentration of which can be easily varied. In this Letter we report on the depolarization of muons in silicon and germanium, and in particular show that by varying the concentration of impurities, the entire range between maximum and essentially zero polarization can be covered.

The polarization of the muons is detected by measuring the asymmetry in the angular distribution of positrons from the muon decay. This is accomplished by a standard precession-type experiment, as illustrated in Fig. 1. Five scintillation counters were placed in the "85-Mev" external positive-meson beam of the Nevis synchrocyclotron. Sufficient absorber was placed between counters 1 and 2 to absorb the pions and allow the muons in the beam to stop in the target material placed between counters 3 and 4. Forward decay positrons in counter pair 23 and backward positrons in 45 were counted during a gate 1.2 μsec long, which was started 0.6 μsec after each stopped muon. Alternate measurements were taken in one case with no applied external field and in another where the muon spins were pre-

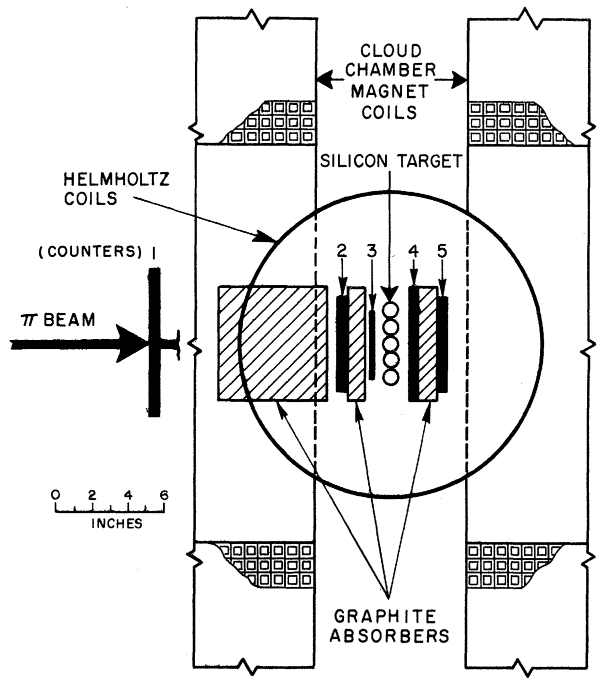

FIG. 1. Experimental arrangement for measuring the depolarization of muons. Cloud-chamber magnet coils are used in experiments to measure the quenching of muon depolarization in large longitudinal fields. Helmholtz coils provide the transverse field in which the muons precess through 180 deg.

cessed through an average angle of 180 deg in a 40-gauss vertical field provided by a set of Helmholtz coils.

Each target was assembled from cylindrical samples with the desired impurity concentration. The effective target sizes ranged from $2\frac{1}{2}$in. $\times 2\frac{1}{2}$in. $\times\frac{1}{2}$in. to 5in. $\times$ 5in. $\times$ 1in. The targets were imbedded in Styrofoam holders which positioned the samples in addition to serving as Dewars for cooling to liquid nitrogen temperatures.

The experimental results are shown in Fig. 2, where the usual positron asymmetry parameter, a, is plotted against the concentration of free electrons and holes in silicon. The results on a single sample of n-type germanium and of graph-

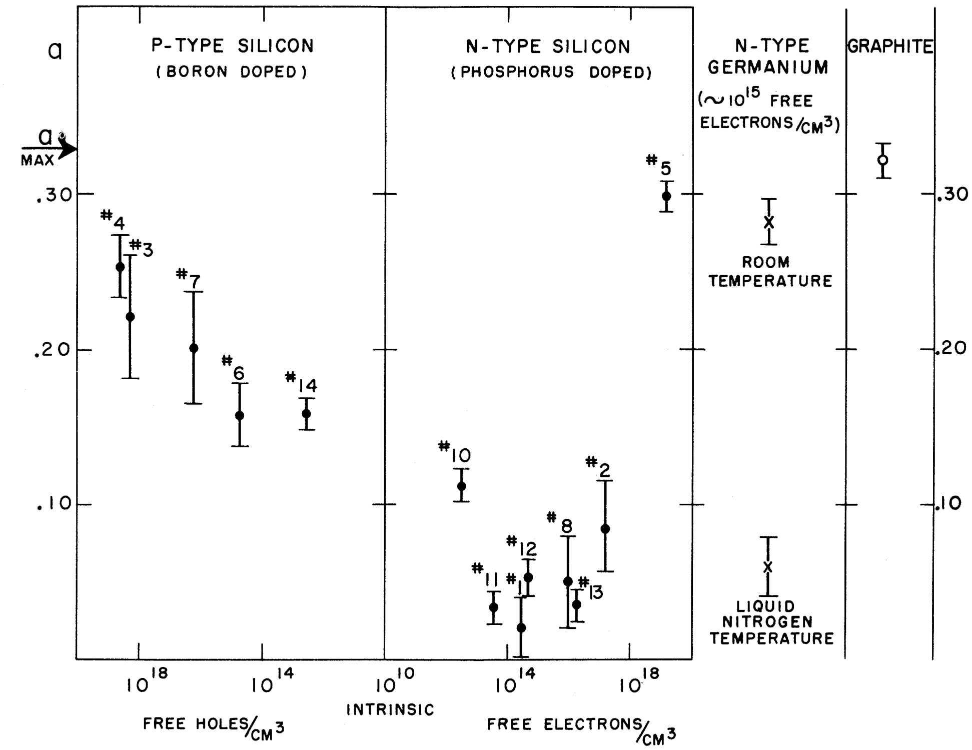

FIG. 2. Experimental values of the asymmetry parameter, a, for decay positrons from stopped muons (a) versus free electron concentration in n-type silicon and free hole concentration in p-type silicon; (b) in one sample of n-type germanium (phosphorus-doped) at room temperature and liquid nitrogen temperature; and (c) in a graphite sample for which the maximum value of $a = 0.33$ is assumed to correspond to full muon polarization. The abscissas for n-type and p-type silicon have been joined at the value of the intrinsic concentration for room temperature ($\sim 10^{10}$ cm^{-3}). Since the product of the numbers of free holes and electrons in thermal equilibrium with the lattice is constant at a given temperature (i.e., $\sim 10^{20}$ for silicon at room temperature), the entire abscissa represents an increasing free electron concentration to the right (or an increasing hole concentration to the left).

ite are shown on the same graph. The angular distribution of decay positrons is of the form $1 - a\cos\theta$, where θ is the angle between the directions of the incident muons and the emitted positrons. In order to obtain a from the measured peak-to-valley ratios for forward and backward positrons, corrections have been made for accidental counts, for positrons not originating in the target, and for smearing caused by the finite gate width used and acceptance angle subtended by the detectors.

Before discussing the results, it may be recalled that embedding impurity atoms such as phosphorus in a material with a large dielectric constant ϵ, such as silicon, creates what are called "shallow donors."[12] The donor impurities have hydrogen-like orbits of greatly expanded radius, an ionization energy reduced by $\sim\epsilon^2$, and markedly reduced hyperfine interactions. For example, phosphorus in silicon has an ionization energy $E_i = 0.045$ ev, and the hyperfine interaction of its electron is approximately 30 times smaller than it would be if ϵ were unity.[13] Therefore, if muonium is formed in silicon or germanium, one might expect it to behave like a shallow donor, with reduced ionization energy and hyperfine interaction. The experimental results will be discussed with this point of view in mind.

The free electrons and holes are supplied by the added impurities which are almost all ionized at room temperature.[14] The time τ_B that the electron is bound to a donor (i.e., the lifetime of the muonium state) can be shown to be

$$\tau_B = (\sigma v N_C)^{-1} \exp(E_i/kT), \tag{1}$$

where σ is the capture cross section of an ionized donor, v is the velocity of an electron, N_C is the density of states in the conduction band, E_i is the ionization energy of the impurity, and kT is the thermal energy of the carriers.[15] For donor concentrations exceeding 10^{18} per cm^3, the donor wave functions overlap, the electrons are no longer localized, the effective τ_B becomes much shorter than given by Eq. (1), and one approaches a state similar to a metal (see Fig. 16 of reference 8). This situation is exemplified by sample No. 5 which like graphite shows no depolarization, corresponding to the lack of muonium formation. As the donor concentration is reduced, the electrons are able to attach themselves for a time τ_B to the muon. This results in the depolarization exhibited by samples 2, 13, 8, 12, 1, and 11. As the donor concentration is further decreased and acceptors are added, the equilibrium number of electrons becomes too small to have a significant probability to form muonium.[16] The partial depolarization observed (see samples 10, 14, and 6) must therefore be due to the capture of electrons that are not in equilibrium with the lattice but may be created, for example, by the muon passing through the sample. The weak dependence of a on the hole concentration is at present not understood.

A germanium sample with $\sim 10^{15}$ elec/cm^3 showed only a very small degree of depolarization (see Fig. 2). This presumably results from the fact that the ionization energy of donors in germanium is four times smaller than in silicon, resulting in a decrease in τ_B [see Eq. (1)]. By going to 77°K, the relevant ratio of E_i/kT equals that of silicon at room temperature and indeed an almost complete depolarization (similar to that for silicon) is observed (see Fig. 2).

The polarization may be re-established by applying a longitudinal magnetic field to the sample.[6-11] We have performed a preliminary experiment on sample 11 and found that a field of approximately 1000 gauss quenched half of the muon depolarization. This is consistent with the idea of shallow donor formations if the number of (μ^+e^-) attachments with the reduced hyperfine interaction formed in a muon lifetime is of the order of a hundred.[17] Further depolarization experiments at low temperatures are in progress.

We would like to thank T. Benedict of Merck & Company, Inc. and several members of the Bell Telephone Laboratories for supplying the samples used in these experiments, and would also like to thank P. W. Anderson for stimulating discussions. We are indebted to L. Levine, P. Nemethy, and J. Sunderland for aid in the measurements.

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*This research is supported by the Office of Naval Research and the U. S. Atomic Energy Commission.

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[14]The fraction of un-ionized impurities is given by $(N_D{}^+/N_C)\exp(E_i/kT)$, where $N_D{}^+$ is the number of ionized donors (or acceptors), the rest of the symbols being defined in the text.

[15]Taking $\sigma = 10^{-15}$ cm^2 [see M. Lax, Phys. Rev. 119, 1502 (1960)] one obtains for silicon at room temperature $\tau_B \simeq 4\times10^{-11}$ sec.

[16]The trapping time τ_t for an electron is given by $\tau_t = (\sigma v n)^{-1}$, where n is the number of available electrons. For an intrinsic silicon sample with $\sim 10^{10}$ elec/cm^3, τ_t becomes $\sim 10^{-2}$ sec too long to account for the observed depolarization.

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