μSR IN SEMICONDUCTORS

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I. INTRODUCTION

The purpose of this lecture is to give an introduction to the behaviour of muonium (μ⁺e⁻) in solids and to acquaint you with the present status of the μSR research in semiconductors. Most of the first applications of positive muons in solid state physics dealt with muonium and only a few experiments were made on muons in metals. Today this ratio has changed since the major part of μSR studies is concerned with metals, as you can see from the program of this school. Owing to the Fermi-Dirac distribution of the conduction electrons the muon magnetic moment reacts in metals quite differently on internal and external magnetic fields than in the paramagnetic muonium state where the interaction is dominated by the large magnetic moment of the unpaired electron.

The electronic properties of muonium are very similar to those of a hydrogen atom since the reduced masses are almost equal (m*Mu = 0.995 m*H). For the ground state in vacuum the binding energy is 13.539 eV and the Bohr radius is a₀ = 0.532 Å. In a solid, the electron wave-function may be distorted due to the interaction with the electronic structure of the environment. This distortion is particularly strong for muonium in semiconductors. The change in the electron wave-function leads to a change in the hyperfine interaction which is directly measured by the μSR technique.

Although hydrogen is known to be present in various chemical forms in most semiconductors, only indirect information on the nature of the hydrogen centers in Si and Ge has been obtained by

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infrared absorption techniques. From μSR measurements one therefore hopes to get more information as to the nature of the hydrogen impurities. Just as the muon or proton in metals can be regarded as the simplest impurity problem in conductors, the muonium, as a substitute for hydrogen, is a prototype of an impurity center in a non-metal.

Since measurements in Si\(^1\) have revealed the existence of two different muonium states the μSR activity has concentrated on the investigations of these states in Si and Ge. I am going to report on these studies in a way which seems most appropriate for a pedagogical presentation. Thereby, the historical developments and the individual achievements of the various groups are not properly accounted for. These aspects can be found in the review articles about this topic\(^2,3,4\).

II. SPIN–HAMILTONIAN FOR MUONIUM

The Fermi contact interaction between the magnetic moments of a muon and an electron is given by

\[
H_{\text{cont}} = -\frac{8\pi}{3} |\psi(0)|^2 \vec{\mu}_\mu \cdot \vec{\mu}_e
\]  

where \(|\psi(0)|^2\) is the electron density at the muon and where the operators for the magnetic moments are

\[
\vec{\mu}_\mu = -g_\mu \mu_\mu \hat{S}_\mu \\
\vec{\mu}_e = -g_e \mu_B \hat{S}_e
\]

\(g_\mu \simeq +2\) and \(g_e \simeq -2\) are the g-factors of the electron and the muon in the muonium state. The contact term is a special case of the general hyperfine interaction between two particles with magnetic moments which results if the electron wave-function around the muon is spherically symmetric. The general interaction can be written as

\[
H_{\text{hf}} = -\vec{\mu}_\mu \cdot \hat{B}_{\text{hf}}(\vec{r}, \hat{S}_e)
\]

where \(\hat{B}_{\text{hf}}\) is an operator and depends on the electron coordinate \(\vec{r}\) and its orbital momentum \(\hat{l}\):

\[
\hat{B}_{\text{hf}}(\vec{r}, \hat{S}_e) = -2\mu_B \left\{ \frac{8\pi}{3} \hat{S}_e \delta(\vec{r}) + \frac{\hat{l}}{r^3} + \frac{3\hat{l}(\hat{S}_e \cdot \hat{r})}{r^5} - \frac{\hat{S}_e}{r^3} \right\}
\]