Near-surface muonium states in semiconductors

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We used the low-energy μSR technique (LE-μSR) to extend our previous studies on the energy dependence of muonium (Mu) states in Si and insulators [1] by investigating shallow Mu states in undoped, 0.5-mm thick ZnO and CdS <0001> crystals. The Mu formation in the near-surface region from about 10 nm to 200 nm is probed with mean implantation energies between 1 and 30 keV. The number of track electron-hole pairs varies in this energy range between about hundred and several thousand [2]. In ZnO at energies larger than 15 keV (mean depth of about 70 nm), we observed shallow Mu for the first time by LE-μSR. At 5 K the Mu fraction is about 50%, which is in agreement with previous bulk μSR measurements [3]. On lowering the energy, this fraction continuously decreases to 20% at 1 keV. This demonstrates that also the formation of shallow Mu clearly depends on the availability of excess charge carriers which the muon creates during the stopping process. In CdS shallow Mu has not been observed by LE-μSR up to 30 keV implantation energy ($\sim$ 200 nm depth). However, in bulk μSR studies at the GPS spectrometer on the same samples shallow Mu is detected in both CdS and ZnO. The origin of the discrepancy in CdS is probably the near-surface crystal quality: RBS-channeling measurements reveal a poor crystal quality with high defect concentration for the CdS samples up to 1 μm depth, whereas the ZnO crystals exhibit very good crystal quality in this region [4].

Additionally, we present recent data on undoped, 0.25-mm thick Ge <100> crystals which we investigated by LE-μSR and bulk μSR. At low energies similar behavior as in Si is observed between 30 K and 150 K, i.e. a doubling of the diamagnetic fraction F_D on lowering the energy from 12.5 keV to 2.5 keV. Surprisingly, below 30 K F_D starts to increase again for $E > 4keV$. In bulk μSR studies on a piece cut from the same sample F_D shows the opposite trend below 30 K. More investigations are necessary to clarify this difference.

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