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Deep Defect States in High-Purity Germanium Irradiated with Electrons

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Deep defect levels produced in high-purity n-type and p-type germanium by irradiation with 1.0 MeV, 1.5 MeV and 2.0 MeV electrons were studied by DLTS technique. Two electron traps located at $E_c-0.36$ eV and $E_c-0.41$ eV found to be formed in n-type material and two hole traps at $E_v+0.22$ eV and $E_v+0.31$ eV in p-type. Introduction rates of the traps at $E_c-0.41$ eV and $E_v+0.22$ eV depended on irradiation energies of electrons. Capture cross sections of the two electron traps were estimated to be $1.8\times10^{-11}\text{cm}^2$ for the level at E_c- 0.36 eV and 8.4×10^{-13} cm^2 for the $E_c-0.41$ eV level, and those of the two hole traps were 1.8×10^{-13} cm^2 for the $E_v+0.22$ eV level and 5.5×10^{-14} cm^2 for the $E_v+0.31$ eV level.

§1. Introduction

Deep level transient spectroscopy (DLTS) measurement of defects introduced in n-type doped germainum by electron irradiation have revealed a number of deep traps, which were related to many vacancy-type defects associated with oxygen and with doping impurities.[1–4] Pearton *et al.*[5] have studied γ-induced defect centers in p-type high-purity germanium crystals grown under widely varying conditions of dopant, crucible material, gas ambient and post-growth annealing. They observed the most common levels associated with defects containing oxygen.

This paper describes the DLTS measurements of the deep defect states created in n-type and p-type high-purity undoped germanium as a consequence of irradiation with varying energies of electrons.

§2. Experimental Procedure

Two kinds of undoped germanium crystal were used in this study. Carrier concentrations of the samples were about 4×10^{12}– 6×10^{12} cm^{-3} for n-type material and 1×10^{12}–3×10^{12} cm^{-3} for p-type before irradiation. For the DLTS measurement, Schottky diodes were prepared by evaporating a thin layer of gold on n-type germanium crystal and aluminum on p-type one. The diodes were irradiated with electrons of 1.0 MeV or 1.5 MeV from a Van de Graaff accelerator under a cooling jet of nitrogen gas evaporated from liquid nitrogen and with 1.5 MeV or 2.0 MeV electrons from a Dynamitron accelerator at room temperature. Energy level positions, capture cross sections and trap concentrations were measured using the DLTS technique. The assembly for the DLTS measurement was composed of a capacitance meter and a dual-channel boxcar averager.

§3. Results and Discussion

DLTS spectra for the undoped p-type samples irradiated with 1.5 MeV and 2.0 MeV electrons of 5.0×10^{15} cm^{-2} under a reverse bias of 2 V and $\tau_m = 3.64$ ms are shown in Fig. 1, where τ_m is the time constant of emission rate corresponding to the maximum of a trap peak observed in a DLTS thermal scan. These curves show that two hole traps are formed by electron irradiation. The two peaks at 115 K and 160 K were observed in the sample irradiated with 2.0 MeV electrons, whereas single peak at 160 K with 1.5 MeV electrons.

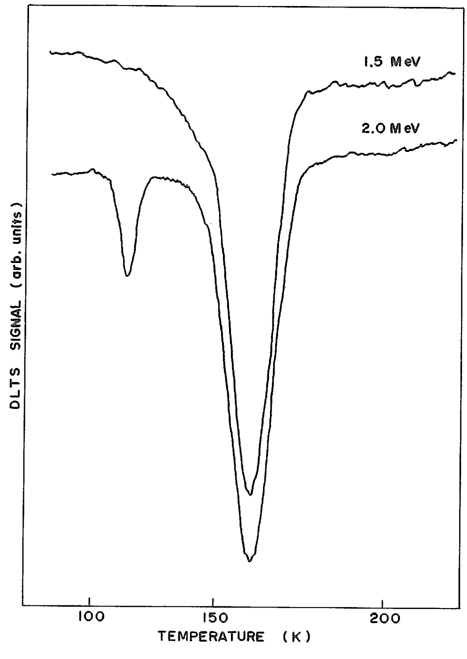

Fig. 1. DLTS spectra for undoped p-type germanium crystals irradiated with 1.5 MeV and 2.0 MeV electrons.

A way to determine the activation energy of a deep level is to construct an Arrhenius plot such as in Fig. 2. The Arrhenius plot is constructed from the data plotting log of rate window vs inverse temperature of the DLTS peak. The data points in Fig. 2 correspond to the rate-window vs peak-temperature data in Fig. 3. As a result it was evident that the levels are located at $E_v + 0.22$ eV and $E_v + 0.31$ eV for the two

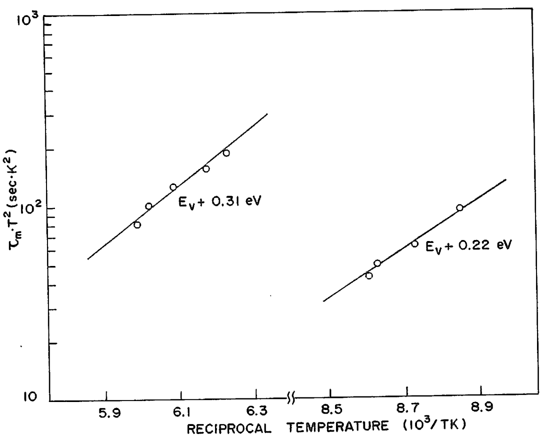

Fig. 2. Variation of $\tau_m T^2$ vs $10^3/T$ for the two hold traps.

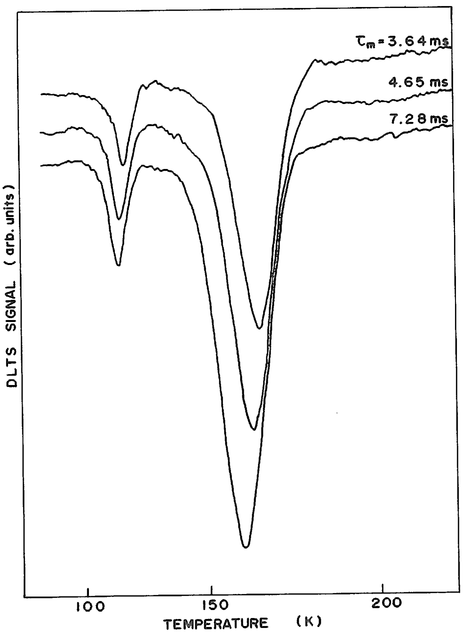

Fig. 3. DLTS spectra of the two hole traps as a function of τ_m.

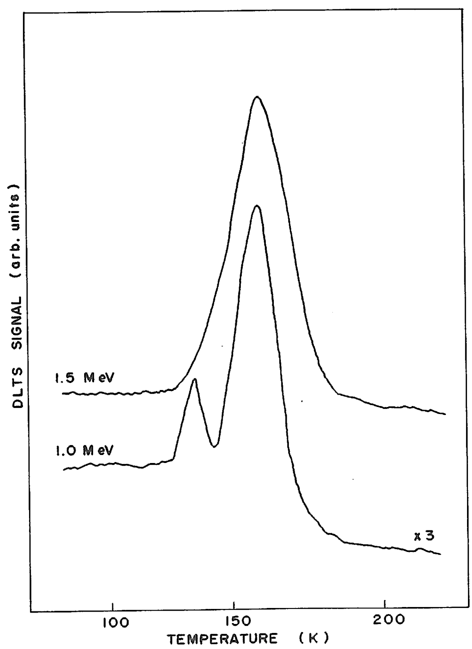

Fig. 4. DLTS spectra for undoped n-type germanium crystals irradiated with 1.0 MeV and 1.5 MeV electrons.

hole traps. From the extrapolation of τ_m at $T^{-1}=0$, the cross sections are estimated to be 1.8×10^{-13} cm^2 and 5.5×10^{-14} cm^2 respectively. For the measurement of defect concentration, we used the capacitance change due to completely filling a trap in the depletion layer. The concentration of the $E_v+0.22$ eV level was determined to be 2.3×10^{11} cm^{-3} and 1.1×10^{12} cm^{-3} for the $E_v+0.31$ eV level.

Three hole traps located at $E_v+0.21$ eV, $E_v+0.24$ eV and $E_v+0.31$ eV in indium or gallium-doped samples irradiated with 10 MeV electrons were observed by Fukuoka *et al.*[6] In n-type sample doped with arsenic or antimony, they found two hole traps at $E_v+0.29$ eV and $E_v+0.24$ eV. The $E_v+0.31$ eV level in a p-type sample and the $E_v+0.29$ eV level in a n-type sample were concluded to be associated with the same defect. Bourgoin *et al.*[3,4] reported four hole traps (H_1–H_4) in doped n-type samples. Two energy levels among these traps were located at $E_v+0.16$ eV (H_1) and $E_v+0.30$ eV (H_2). Pearton *et al.*[5] observed two deep hole-trapping levels located at $E_v+0.23$ eV and $E_v+0.38$ eV induced by γ-irradiation in all p-type high-purity germanium crystals grown under widely varying conditions. With regard to the traps in our samples, there are good agreement of level location with the results obtained by Fukuoka *et al.*[6] The small discrepancy in the level positions between the results obtained by varying workers regards to be caused by the experimental conditions. The characteristics of electron traps in n-type germanium have been fully described by Poulin and Bourgoin[7]. Using their experession for the temperature dependence of the cross section, we can write $(\Delta H+\Delta E)$ for level position, where ΔH is the enthalpy associated with the free energy of ionization and ΔE is the activation energy for hole capture.

Figure 4 illustrates typical DLTS spectra for an undoped n-type sample, whose carrier concentration was about 4×10^{12} cm^{-3}, irradiated with 1.0 MeV and 1.5 MeV

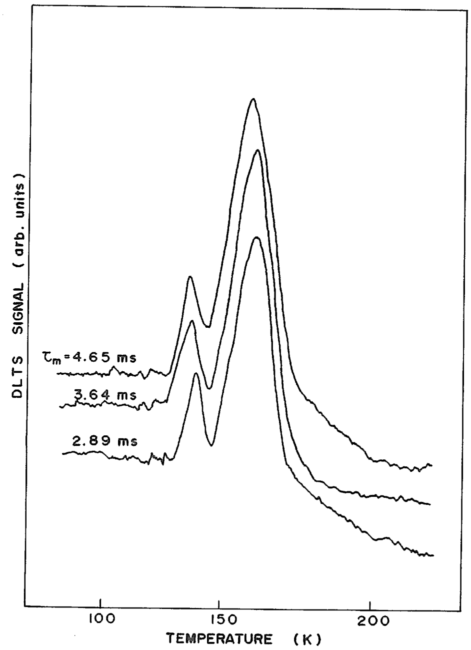

Fig. 5. DLTS spectra of the two electron traps as a function of τ_m.

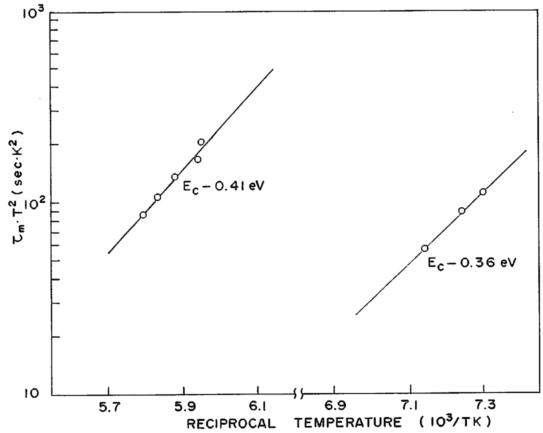

Fig. 6. Variation of $\tau_m T^2$ vs $10^3/T$ for the two electron traps.

electrons of 1.0×10^{15} cm^{-2} under a reverse bias of 2 V and $\tau_m = 3.64$ ms. It is obvious that two deep electron trapping centers are predominant in high-purity n-type germinaum after electron irradiation. The DLTS spectrum for irradiation at low energy of 1.0 MeV exhibted two peaks at 140 K and 162 K. When the energy of irradiation increased, the 162 K peak grew up to masking the 140 K peak. An analysis of the data on the undoped n-type samples is given in Fig. 5 and Fig. 6. The levels causing the peaks in Fig. 4 were located at 0.36 eV and 0.41 eV from the conduction band for the two electron traps. The cross sections were estimated to be 1.8×10^{-11} cm^2 for the level at E_c–0.36 eV and 8.4×10^{-13} cm^2 for the level at E_c– 0.41 eV.

Defect levels produced in doped n-type germanium by irradiation with 1.5 MeV electrons have been studied by Fukuoka *et al.*[1] They observed four electron traps at E_c– 0.20 eV, E_c– 0.23 eV, E_c– 0.27 eV and E_c– 0.40 eV, and suggested that the E_c– 0.40 eV and the E_c– 0.23 eV levels are associated with defects containing antimony atoms. The E_c– 0.27 eV level causing the peak at 160 K has been unidentified. They have also observed the E_c– 0.25 eV level in oxygen doped germanium irraidated with 1.5 MeV electrons.[8] The level was considered to be associated with the germanium A-center. Bourgoin *et al.*[2–4,7,9] have studied doped n-type germanium crystals irradiated with electrons at liquid-helium and room temperaperatures. A number of electron and hole traps have been observed using the DLTS technique. The energy levels associated with these traps in the sample irradiated at room temperature were the following: E_1(E_c– 0.32 eV), E_2(E_c– 0.53 eV), E_4(E_c– 0.46 eV) and E_5(E_c– 0.42 eV). The defect associated with the E_1 level thought to be formed by association of impurity atoms with vacancy. The traps E_4 and E_5 were believed to be associated with the divacancy for the following reason: the variation of their introduction rates induced by electron irradiation are characteristic of two times the threshold energy for atomic displacement.

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