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DLTS ANALYSIS OF RADIATION-INDUCED DEFECTS IN ONE-MEV ELECTRON IRRADIATED GERMANIUM AND $AL_{0.17}GA_{0.83}AS$ SOLAR CELLS*

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The purpose of this paper is to investigate the radiation-induced deep-level defects in one-MeV electron-irradiated germanium and $Al_xGa_{1-x}As$ (with x = 0.05 and 0.17) solar cell materials using the Deep-level Transient Spectroscopy (DLTS) and C-V techniques. Defect and recombination parameters such as defect density and energy levels, capture cross sections and lifetimes for both electron and hole traps were determined from these measurements. In this study, both the germanium and AlGaAs p/n junction cells were irradiated by one-MeV electrons with fluences of 10^{14}, 10^{15}, and 10^{16} e/cm^2. DLTS, I-V, and C-V measurements were then performed on these cells. The results are summarized as follows: (1) For the irradiated germanium samples, the dominant electron trap was due to the E_c - 0.24 eV level with density around $4x10^{14}$ cm^{-3}, independent of electron fluence; its origin was attributed to the vacancy-donor complex defect formed during the electron irradiation. In addition two new hole traps with activation energies of E_v + 0.10 and 0.16 eV were observed in the irradiated samples; these two hole traps were attributed to the divacancy-donor complex defects with densities varying from 1.5 to $4x10^{14}$ cm^{-3}. (2) As for the one-MeV electron irradiated $Al_{0.17}Ga_{0.83}As$ sample, two dominant electron traps with energies of E_c-0.19 and -0.29 eV were observed; the density for both electron traps was also found to remain nearly constant, independent of electron fluence. The results of this study show that one-MeV electron irradiation creates very few or no new deep-level traps in both the germanium and $Al_xGa_{1-x}As$ cells, and as such they are suitable for fabricating the radiation-hard high efficiency multijunction solar cells for space applications.

INTRODUCTION

Considerable interests in developing high efficiency cascade junction solar cell using materials such as $Al_xGa_{1-x}As$, GaAs, and germanium or $In_xGa_{1-x}As$ have been reported recently [1-5]. The cascade junction solar cell is particularly attractive for space power generation since it has potential to achieve AMO efficiency of 30 % or higher by using a triple junction structure. To design a

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radiation-hard triple junction solar cell for space power generation, the radiation induced defects in materials to be used for the cascade solar cell fabrication should be studied. Although extensive studies of the radiation damage in GaAs irradiated by one-MeV electrons and low energy protons have been reported in theliterature [6-10], only limited information concerning the radiation induced defects in $Al_xGa_{1-x}As$, $In_xGa_{1-x}As$ and germanium is available at present [11-16]. In order to obtain a detailed information concerning the radiation induced defects in germanium and $Al_xGa_{1-x}As$ for cascade junction solar cell applications, a systematic study of the deep-level defects vs electron or proton fluence must be conducted. In this paper we report the results of our DLTS analysis of the one-MeV electron irradiation induced deep-level traps in germanium and $Al_{0.17}Ga_{0.83}As$ p-n junction cells for different electron fluences. In addition the I-V and C-V measurements were also performed to determine the recombination mechanisms in these electron irradiated samples. From the results of our C-V and DLTS analysis and those reported in the literature, the possible physical origins for the observed electron and hole traps in both germanium and $Al_{0.17}Ga_{0.83}As$ materials are discussed.

EXPERIMENTAL

The $Al_xGa_{1-x}As$ p-n junction solar cells used in this study were fabricated by using infinite solution melt liquid phase epitaxial (LPE) technique for two different aluminum compositions (x = 0.05 and 0.17), while the germanium p-n junction cells were fabricated by using alloying process. The background dopant density for the AlGaAs cells is around 10^{17} cm^{-3}, and is about 10^{15} cm^{-3} for the germanium cells. The one-MeV electron irradiation was performed at room temperature on these cells using three different electron fluences. The I-V, C-V, and DLTS measurements were performed on both germanium and AlGaAs samples before and after electron irradiation, and the results are presented next.

RESULTS AND DISCUSSION

The arsenic-doped germanium p-n junction cells were irradiated by one-MeV electrons with fluences of 10^{14}, 10^{15} and 10^{16} cm^{-2} in the room temperature. DLTS and C-V measurements were made on these samples to determine the defect parameters such as activation energy, defect density, capture cross sections and the lifetimes for both the electron and hole traps. The results are summarized in table 1. Fig. 1 and Fig. 2 show respectively the DLTS scans of electron and hole trap in the unirradiated germanium cells. The E_c - 0.26 eV electron trap and the E_v + 0.33 eV hole trap observed in the unirradiated cells were attributed to the copper impurity related defect [15], and the density for both trap levels is nearly identical (3.8×10^{14} cm^{-3}). Fig. 3 shows the DLTS scan of the E_v + 0.26 eV hole trap observed in the 10^{15} e/cm^2 irradiated sample. The annealing experiments were performed on these germanium samples, and the results are shown in Fig. 4 through Fig. 6. Fig.4 shows the effect of thermal annealing on the E_c - 0.27 eV electron trap observed in the 10^{15} cm^{-2} electron irradiated cell. In this sample, the thermal annealing was carried out by repeating the DLTS scans between 77 and 435 K. Significant reduction in defect density was observed in the first three annealing cycles, and showed little or no reduction in defect density after the fifth annealing cycle. Fig. 5 shows the DLTS scans of E_c - 0.26 eV electron trap observed in the unirradiated germanium sample. The effect of thermal annealing (annealed at 162 ^{o}C for 12 hours) is negligibly small in this case, indicating that this electron trap is indeed the impurity (Cu^{3-}) related defect. Fig.6 shows the effect of thermal annealing on the hole traps observed in the 10^{14} cm^{-3} electron irradiated sample. The $E_v + 0.10$ eV hole trap level was disappeared after 45 min. of annealing at 162 °C. The results of our DLTS measurements on the irradiated germanium samples clearly show that one-MeV electron irradiation induced defects can be reduced drastically via low temperature (less than 200 °) thermal annealing process. The results show that germanium possesses good radiation resistance; this is consistent with our I-V data and those reported by others in the literature. Fig. 7 shows the current-voltage relationship under the forward bias conditon for four germanium cells irradiated by different electron fluences. The results show little or no correlation between the dark forward current and the electron fluence in these irradiated germanium samples.

The DLTS analysis of deep-level defects in one-MeV electron irradiated $Al_xGa_{1-x}As$ with x=0.05 and 0.17 was also carried out in this study. Fig.8 shows a typical DLTS scan of electron traps observed in the one-MeV electron irradiated AlGaAs cell. Defect parameters deduced from our C-V and DLTS measurements for the $Al_{0.17}Ga_{0.83}As$ samples irradiated by one-MeV electrons with 10^{15} and 10^{16} e/cm^2 fluences are summarized in table 2. No deep-level defects were detected by our DLTS measurements in the $Al_{0.05}Ga_{0.95}As$ sample, while two electron traps with energies of $E_c-0.19$ eV and $E_c-0.29$ eV were observed in the $Al_{0.17}Ga_{0.83}$ samples. It is interesting to note that both electron traps observed in the one-MeV electron irradiated $Al_{0.17}Ga_{0.83}As$ sample have also been observed in the unirradiated AlGaAs specimen with $x > 0.15$. This result clearly indicates that no new defect levels were introduced in the $Al_xGa_{1-x}As$ specimen by the one-MeV electron irradiation.

In summary, the results of our DLTS and C-V analysis on the one-MeV electron irradiation induced defects in germanium and $Al_{0.17}Ga_{0.83}As$ materials clearly show that both of these two materials possess good radiation resistance characteristics, and may be suitable for use as the top and bottom cell materials in a triple junction structure with GaAs as the middle cell material. The possible physical origins for the observed deep-level traps in the germanium samples are also listed in table.1.

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Table 1. Defect parameters in one-MeV electron irradiated germanium.

Samples	Φ_e(e/cm^2)	E_T(eV)	N_D(cm^{-3})	N_t(cm^{-3})	σ_n(cm^2)	σ_p(cm^2)	τ_n	τ_p	Defect origin
GE-B A=2.65x10^{-5}cm^2	0	E_c-0.26	1x10^{15}	3.73x10^{14}	4.23x10^{-16}		6.33x10^{-7}		Cu^{3-}
		E_v+0.33		3.89x10^{14}		8.52x10^{-15}		3.02x10^{-8}	Cu^{2-}
GE13	10^{14}	E_c-0.24	7.45x10^{14}	3.55x10^{14}	5.55x10^{-16}		5.10x10^{-7}		VD Complex
		E_v+0.10		3.51x10^{14}		3.6x10^{-17}		7.91x10^{-6}	VVD Complex
		E_v+0.17		1.33x10^{14}		1.22x10^{-16}		6.16x10^{-6}	VVD Complex
GE12	10^{15}	E_c-0.27	8.9x10^{14}	4.51x10^{14}	4.47x10^{-15}		4.96x10^{-8}		VD Complex
		E_v+0.26		2.92x10^{14}		4.24x10^{-14}		8.08x10^{-9}	VVD Complex
GE11	10^{16}	E_c-0.24	7.46x10^{14}	3.54x10^{14}	5.55x10^{-16}		5.09x10^{-7}		VD Complex
		E_v+0.10		2.69x10^{14}		3.60x10^{-17}		1.03x10^{-5}	VVD Complex
		E_v+0.17		1.72x10^{14}		1.22x10^{-16}		4.77x10^{-6}	VVD Complex

Table 2. One-MeV Electron Irradiation Induced Defects in $Al_{0.17}Ga_{0.83}As$ Materials.

Electron Fluence (e/cm^2)	N_d (cm^{-3})	E_T(eV)	N_T (cm^{-3})	σ_n (cm^{-2})
ϕ_e= 10^{15}	3.7x10^{17}	E_c- 0.19	1.12x10^{16}	6.99x10^{-14}
		E_c- 0.29	1.3x10^{16}	5.14x10^{-14}
ϕ_e= 10^{16}	2.9x10^{17}	E_c- 0.19	1.08x10^{16}	6.99x10^{-14}
		E_c- 0.29	1.13x10^{16}	5.14x10^{-14}

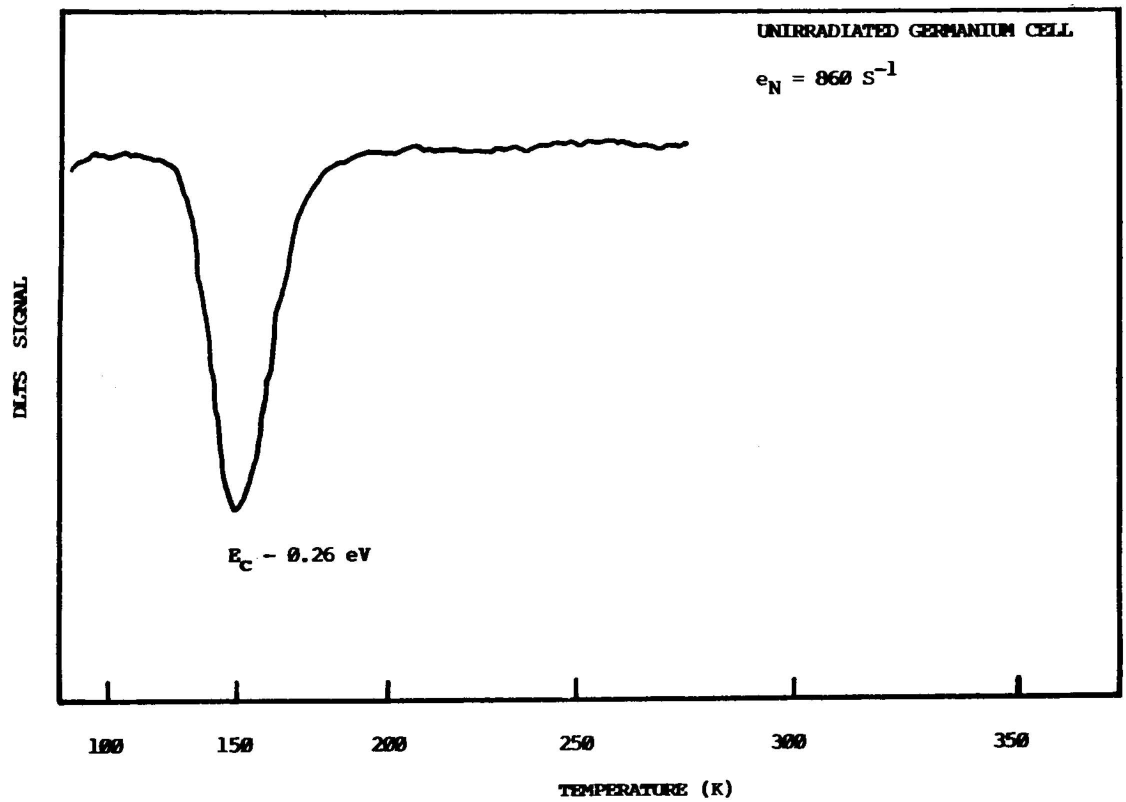

Fig. 1 DLTS scan of electron trap in unirradiated germanium cell.

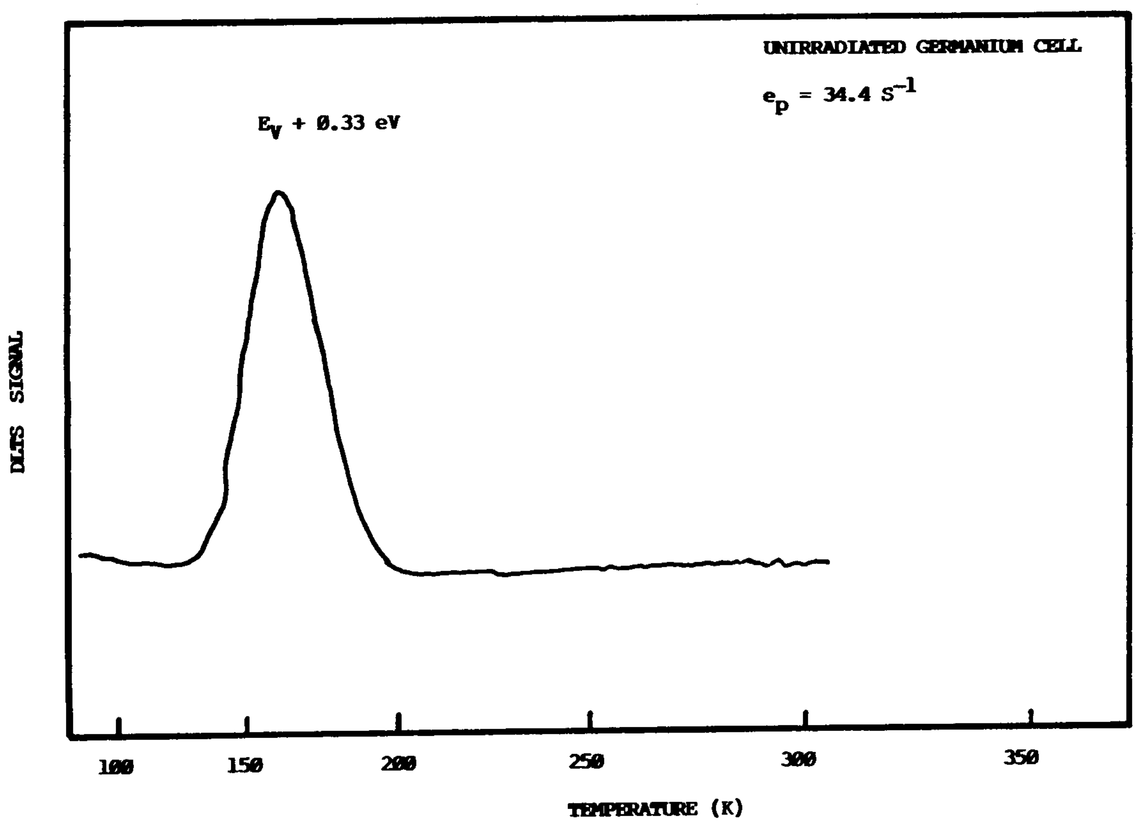

Fig. 2 DLTS scan of hole trap for the unirradiated germanium cell.

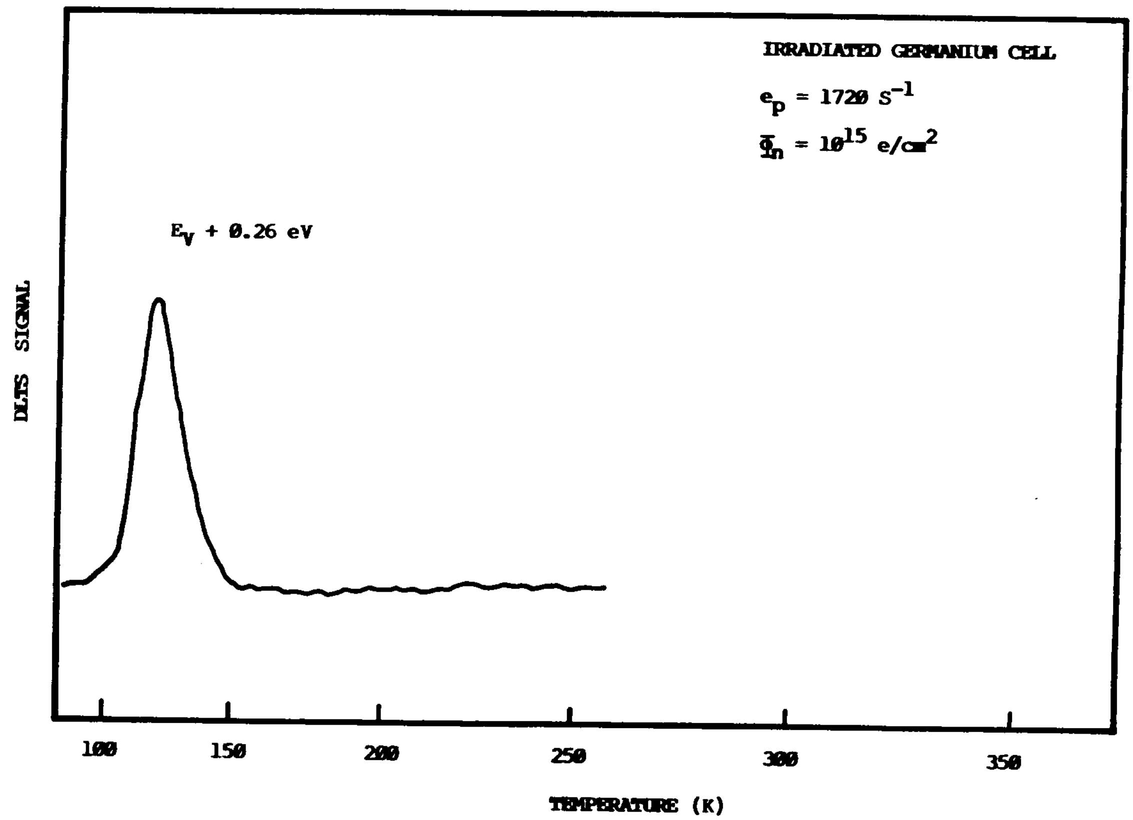

Fig.3 DLTS scan of hole trap for the irradiated germanium cell.

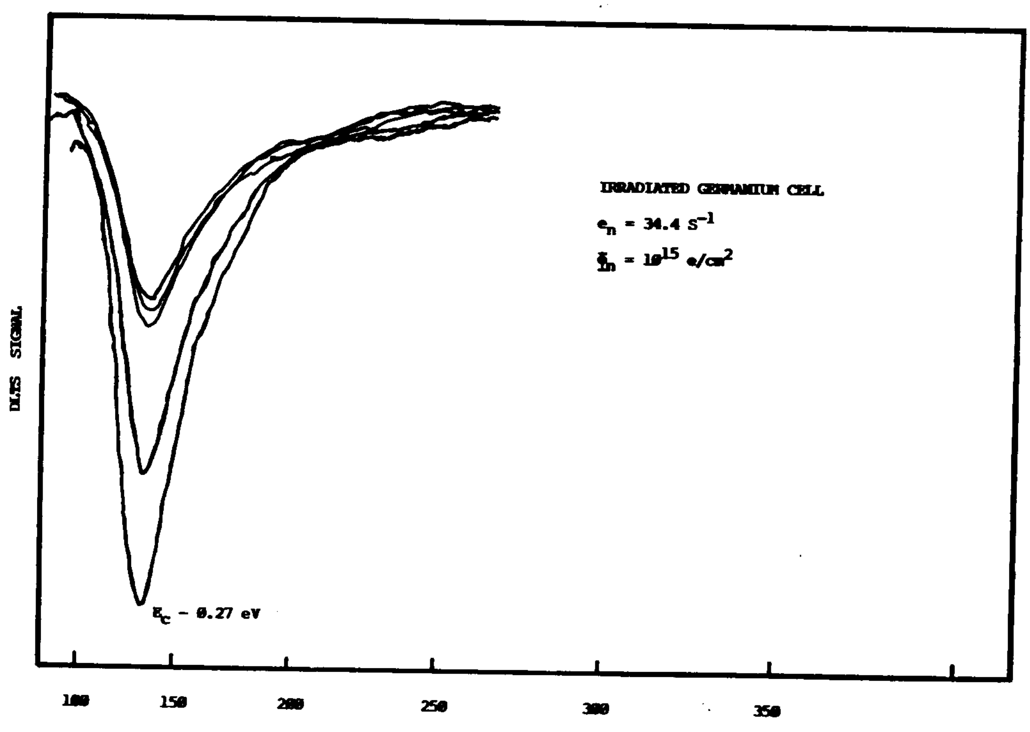

Fig.4 DLTS scans of electron trap for the irradiated germanium cell by repeating thermal scan between 77 and 435 K, showing the effect of thermal annealing.

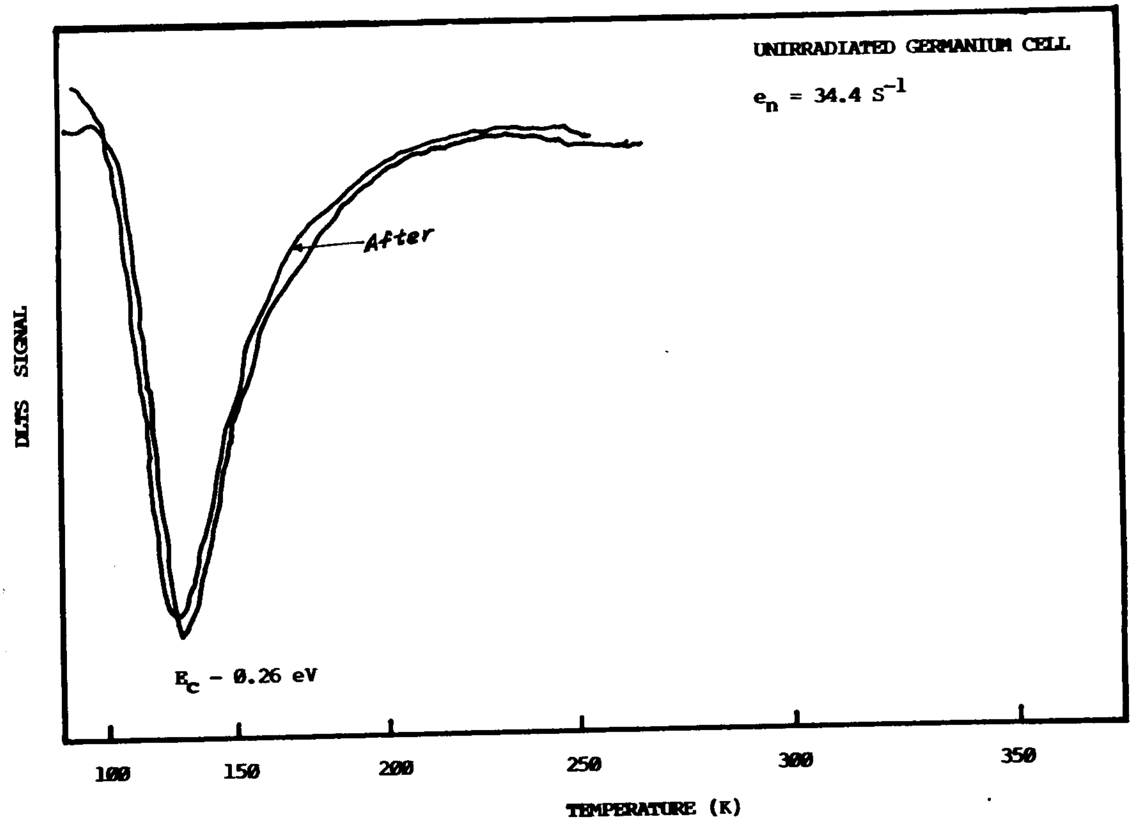

Fig.5 DLTS scans of electron trap for the unirradiated germanium cell by thermal annealing at 162 C for 12 hours.

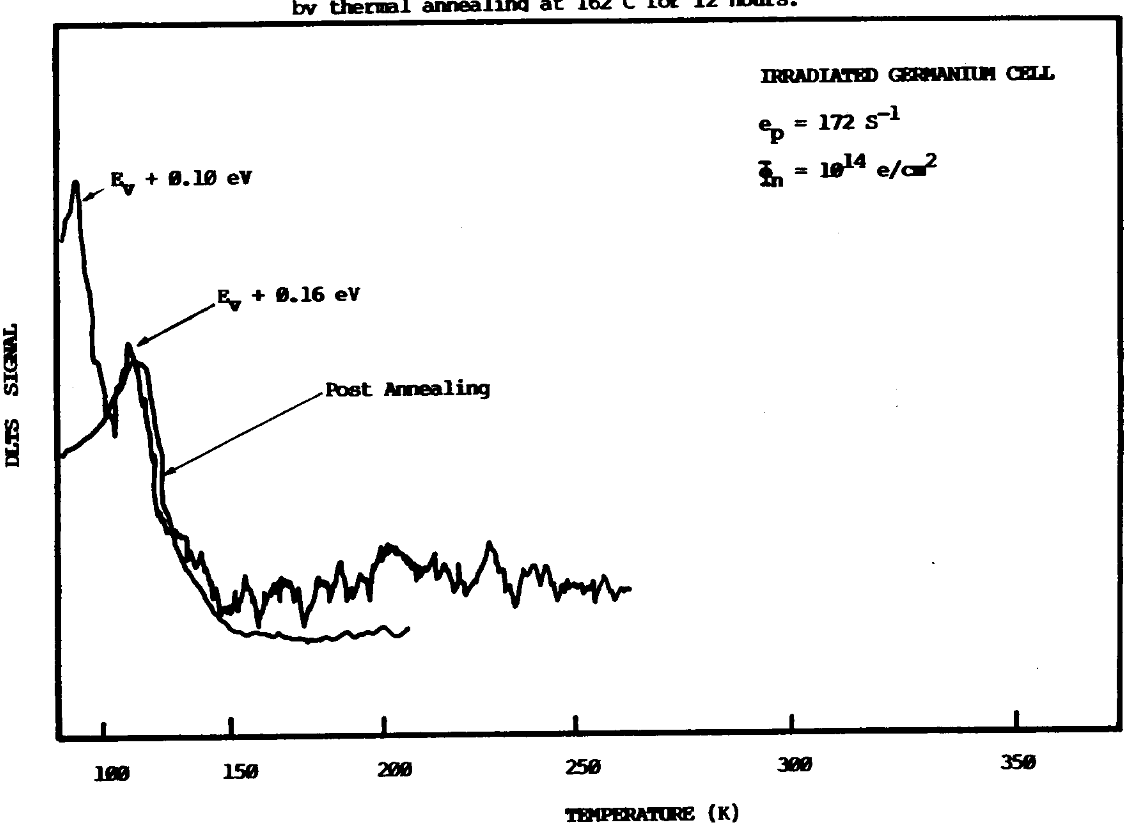

Fig.6 DLTS scans of hole traps for the irradiated germanium cell before and after thermal annealing at 162 C for 45 min.

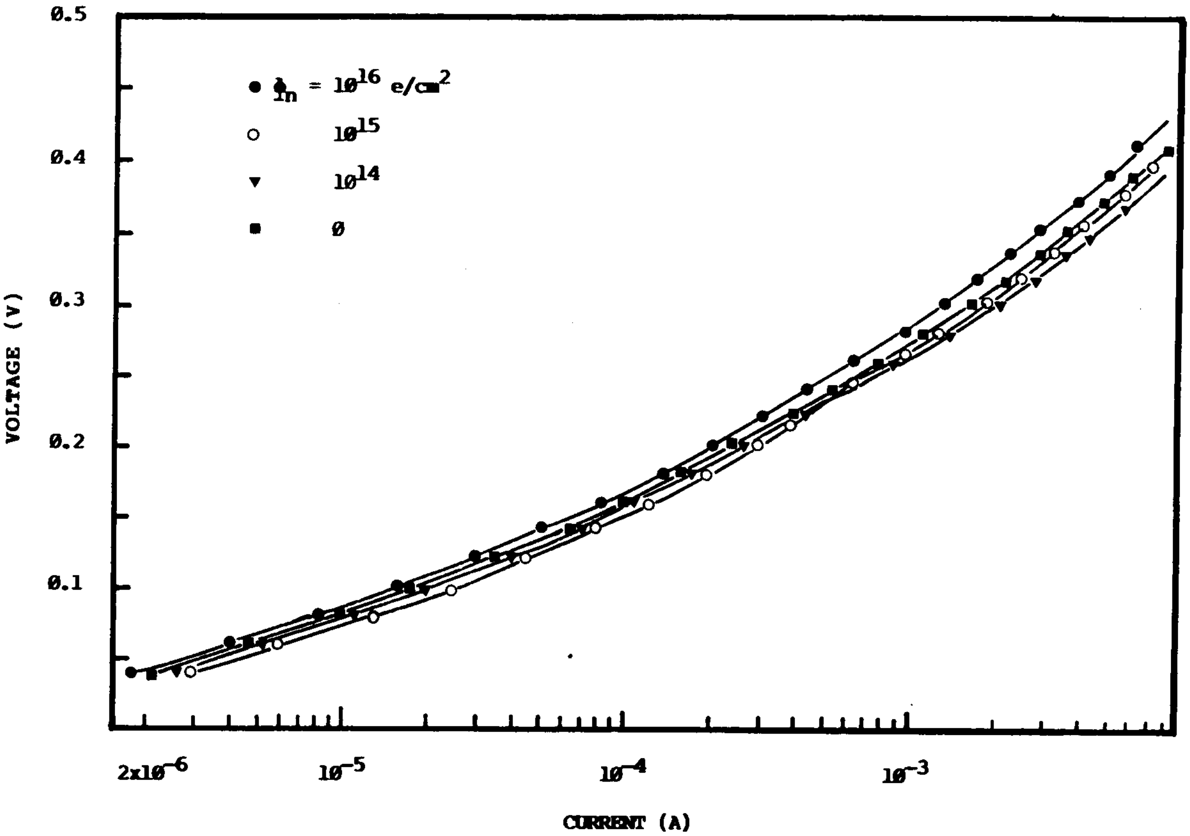

Fig. 7 Forward I-V curves in germanium p/n junction cells irradiated by one-MeV electrons of different fluences.

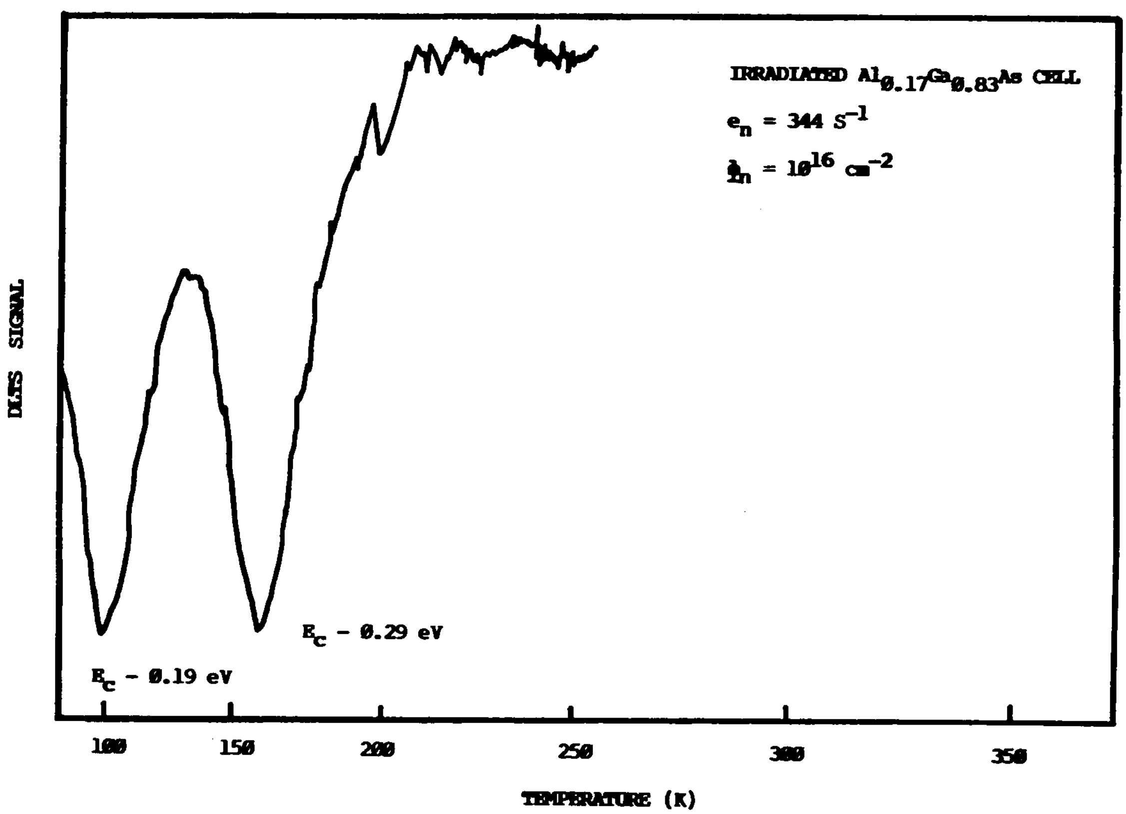

Fig.8 DLTS scan of electron traps for the one-MeV electron irradiated $Al_{0.17}Ga_{0.83}As$ solar cell.