DEFECTS AND ANNEALING STUDIES IN 1-MeV ELECTRON IRRADIATED (AlGa)As-GaAs SOLAR CELLS*

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EXTENDED ABSTRACT

The purpose of this paper is to present the results of our study on the deep-level defects and recombination mechanisms in the one-MeV electron irradiated (AlGa)As-GaAs solar cells under various irradiation and annealing conditions. Deep-level transient spectroscopy (DLTS) and capacitance-voltage (CV) techniques were used to determine the defect and recombination parameters such as energy levels and defect density, carrier capture cross sections and lifetimes for both electron and hole traps as well as hole diffusion lengths in these electron irradiated GaAs solar cells. GaAs solar cells used in this study were prepared by the infinite solution melt liquid phase epitaxial (LPE) technique at Hughes Research Lab., with ($Al_{0.9}Ga_{0.1}$) As window layer, Be-diffused p-GaAs layer on Sn-doped n-GaAs or undoped n-GaAs active layer grown on n^+-GaAs substrate. Mesa structure with area of 5.86×10^{-4} cm^2 was fabricated for our DLTS and CV study. The Sn-doped n-GaAs active layer has a dopant density of 5×10^{16} cm^{-3}, and the undoped n-GaAs layer has a carrier density of 1.5×10^{15} cm^{-3}. Three different irradiation and annealing experiments were performed on these solar cells: (1) one-MeV electron irradiation was done at room temperature on Sn-doped (AlGa)As-GaAs solar cells for electron fluences of 10^{14}, 10^{15}, and 10^{16} cm^{-3}, and subsequently annealed at 230°C for 10, 20, 30, and 60 minutes. (2) Same type of GaAs cells was irradiated at 150°C and 200°C cell's temperature and fluence of 10^{15} cm^{-2} using two different flux rates (4×10^{10} e/cm^2-s and 2×10^{9} e/cm^2-s). (3) one-MeV electron irradiation was performed on the undoped GaAs solar cells at 200°C cell's temperature for fluence of 10^{14} and 10^{15} cm^{-2}. DLTS and C-V measurements were made on the cells described above, and the results are discussed next.

Fig. 1 and Fig. 2 show the DLTS scan of electron and hole traps in the (AlGa)As-GaAs cells irradiated with 10^{16} e/cm^2 electron fluence and annealed at 230°C in vacuum for 20, 30, and 60 minutes, respectively. Three electron traps with energies of E_c-0.31, 0.71, and 0.90 eV and one hole trap with energy of E_V+0.71 eV were observed in these samples. The DLTS data showed that density of each defect level was reduced as a result of the 230°C thermal annealing. Note that the "E_3" electron trap has the largest reduction in its density followed by the 230°C annealing for 60 minutes. Significant reduction in the trap density was also observed for the E_V+0.71 eV hole trap from the 230°C annealing process (see Fig. 2). A similar result for both electron and hole traps was also obtained for cells irradiated by the 10^{15} e/cm^2 electron fluence. Table 1 and table 2 summarize the results deduced from the DLTS and C-V measurements for the Sn-doped GaAs solar cells irradiated at room temperature

with fluences of 10^{15} and 10^{16} e/cm^2 and annealed at 230°C for 20, 30, and 60 minutes. Hole diffusion lengths calculated from the DLTS data were found to vary between 1.5 to 2.44 μm for $\phi_e = 10^{15}$ e/cm^2 fluence. The effects of incident flux rate and cell's irradiation temperature on the defect parameters were studied on Sn-doped GaAs cells irradiated with 10^{15} e/cm^2 fluence. Fig. 3 and Fig. 4 show respectively the DLTS scans of electron and hole traps for the Sn-doped GaAs solar cells irradiated by 10^{15} e/cm^2 fluence, with flux rates of 4×10^{10} e/cm^2-s and 2×10^9 e/cm^2-s and irradiated at 150 and 200°C cell's temperature. The results show that the dominant electron trap is due to E_c-0.71 eV level, and the dominant hole trap is due to E_v+0.71 eV. The density for both traps increases with increasing flux rate and reducing cell's temperature. For cells irradiated at 4×10^{10} e/cm^2-s flux rate, two additional electron traps (i.e., E_3 and E_5) were also detected. The defect and recombination parameters calculated from the DLTS data for these cells are summarized in table 3 and table 4. Note that the DLTS data shown in Fig. 1 through Fig. 4 are for the Sn-doped GaAs solar cells. The DLTS scans of electron and hole traps for the undoped GaAs solar cells irradiated at 200°C are shown in Fig. 5 and Fig. 6, respectively. Fig. 5 shows the DLTS scan of electron traps for cells irradiated with 10^{14} and 10^{15} e/cm^2 fluence, respectively; four electron traps with energies of E_c-0.13, 0.41, 0.71, and 0.90 eV were observed in these two cells. Note that E_c-0.13 eV and E_c-0.41 eV electron traps are not detected in the Sn-doped GaAs cells shown in Fig. 1. Fig. 6 shows the DLTS scan of hole traps for the same cells shown in Fig. 5; two hole traps with energies of E_v+0.29 and E_v+0.71 eV were observed for cells irradiated with 10^{15} e/cm^2, and only one hole trap with energy of E_v+0.71 eV was observed in 10^{14} e/cm^2 irradiated cells. In both figures it is noted that increasing electron fluence will increase the density of both electron and hole traps in these cells. Defect and recombination parameters deduced from the DLTS and C-V data for cells shown in Fig. 5 and Fig. 6 are summarized in table 5 and table 6. Fig. 7 shows the defect annealing rate for the "E_3" electron trap for electron fluence of 10^{16} e/cm^2 and for the "E_5" electron trap for electron fluence of 10^{15} e/cm^2, for GaAs cells shown in Fig. 1 and table 1. From the study of deep-level defects and their annealing behavior, it is concluded that (i) one-MeV electron irradiation on GaAs cells grown by the infinite solution melt LPE technique will in general produce three to four electron traps and one to two hole traps if the electron fluence is greater than 10^{14} e/cm^2; (ii) defect density will increase with increasing incident flux rate and fluence; (iii) increasing annealing temperature and annealing time will reduce the density of both electron and hole traps; (iv) increasing the cell's temperature during electron irradiation will effectively reduce the trap density; (v) low temperature thermal annealing is more effective in annealing out the shallower traps than the deeper traps; (vi) the recombination enhanced annealing[1] was found to be effective for reducing the density of deep-level recombination centers; (vii) the activation energy for the "E_3" electron trap was found slightly different in the undoped GaAs than that of the Sn-doped GaAs solar cells (i.e., E_c-0.41 eV vs. E_c-0.31 eV), and (viii) the (E_v+0.29 eV) hole trap observed in the undoped GaAs cells was not detected in the Sn-doped GaAs solar cells under same irradiation conditions.

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[1] J. D. Weeks, J. C. Tully, and L. C. Kimerling, Phys. Rev. B, 12, 3286 (1975).

Annealing time & Temperature	$\phi_e = 10^{16}$ e/cm^2				10^{15} e/cm^2			
	E_T (eV)	N_T (cm^{-3})	σ_n (cm^2)	τ_n (s)	E_T (eV)	N_T (cm^{-3})	σ_n (cm^2)	τ_n (s)
Unannealed	$E_2=E_c-0.20$ $E_3=E_c-0.31$ $E_4=E_c-0.71$ $E_5=E_c-0.90$	$9\text{x}10^{12}$ $2.9\text{x}10^{14}$ $3.2\text{x}10^{14}$ $3.4\text{x}10^{14}$	$1\text{x}10^{-16}$ $1.8\text{x}10^{-14}$ $5.1\text{x}10^{-14}$ $5.8\text{x}10^{-14}$	$2.77\text{x}10^{-5}$ $4.26\text{x}10^{-9}$ $1.25\text{x}10^{-9}$ $1.04\text{x}10^{-9}$	230°C ,10 min.) E_2 E_3 E_4 E_5	$7.9\text{x}10^{12}$ - $5.7\text{x}10^{13}$ $1.1\text{x}10^{14}$	$1\text{x}10^{-16}$ - $5.1\text{x}10^{-14}$ $5.8\text{x}10^{-14}$	- - $7.64\text{x}10^{-9}$ $3.2\text{x}10^{-9}$
230°C for 20 min.	E_3 E_4 E_5	$1.4\text{x}10^{14}$ $9.5\text{x}10^{13}$ $1.2\text{x}10^{14}$	$1.8\text{x}10^{-14}$ $5.1\text{x}10^{-14}$ $5.8\text{x}10^{-14}$	$9.92\text{x}10^{-9}$ $4.39\text{x}10^{-9}$ $2.93\text{x}10^{-9}$	E_3 E_4 E_5	$2.6\text{x}10^{13}$ $5.4\text{x}10^{13}$ $6.1\text{x}10^{13}$	$1.8\text{x}10^{-14}$ $5.1\text{x}10^{-14}$ $5.8\text{x}10^{-14}$	$4.75\text{x}10^{-8}$ $8.07\text{x}10^{-9}$ $5.77\text{x}10^{-9}$
230°C for 30 min.	E_3 E_4 E_5	$1.2\text{x}10^{14}$ $7.7\text{x}10^{13}$ $6.2\text{x}10^{13}$	$1.8\text{x}10^{-14}$ $5.1\text{x}10^{-14}$ $5.8\text{x}10^{-14}$	$1.01\text{x}10^{-8}$ $5.41\text{x}10^{-9}$ $5.68\text{x}10^{-9}$	E_3 E_4 E_5	$2.4\text{x}10^{13}$ $2.5\text{x}10^{13}$ $3.1\text{x}10^{13}$	$1.8\text{x}10^{-14}$ $5.1\text{x}10^{-14}$ $5.8\text{x}10^{-14}$	$5.1\text{x}10^{-8}$ $1.6\text{x}10^{-8}$ $1.14\text{x}10^{-8}$
230°C for 60 min.	E_3 E_4 E_5	$2.7\text{x}10^{13}$ $6.2\text{x}10^{13}$ $1.6\text{x}10^{14}$	$1.8\text{x}10^{-14}$ $5.1\text{x}10^{-14}$ $5.8\text{x}10^{-14}$	$4.57\text{x}10^{-8}$ $6.45\text{x}10^{-9}$ $2.19\text{x}10^{-9}$	E_3 E_4 E_5	$7.2\text{x}10^{12}$ $1.8\text{x}10^{13}$ $2.2\text{x}10^{13}$	$1.8\text{x}10^{-14}$ $5.1\text{x}10^{-14}$ $5.8\text{x}10^{-14}$	$5.6\text{x}10^{-7}$ $2.22\text{x}10^{-8}$ $1.6\text{x}10^{-8}$

Table. 1 Electron trap parameters in one-MeV electron irradiated (AlGa)As-GaAs solar cells annealed at 230 °C for 10,20,30, and 60 min. $N_D = 5\text{x}10^{16}$ cm^{-3} (Sn-doped n-GaAs)

Table .2 Defect parameters of Hole Traps in one-MeV Electron Irradiated (AlGa)As-GaAs Solar Cells vs. Annealing Time

Fluence (e/cm^2)	N_D (cm^{-3})	Annealing Time & Temp.	Hole Trap				
			E_T (eV)	N_T (cm^{-3})	σ_p (cm^2)	τ_p (ns)	L_p (μm)
10^{15}	$5.5\text{x}10^{16}$	20 min. at 230°C	E_v+0.71	$9\text{x}10^{13}$	$4.01\text{x}10^{-13}$	2.25	1.50
		30 " "	"	$6.8\text{x}10^{13}$	"	2.65	1.72
		60 " "	"	$3.4\text{x}10^{13}$	"	5.30	2.44
10^{16}	$3.5\text{x}10^{16}$	20 min. at 230°C	E_v+0.71	$9\text{x}10^{14}$	$4.01\text{x}10^{-13}$	0.20	0.47
		30 " "	"	$6.2\text{x}10^{14}$	"	0.29	0.57
		60 " "	"	$1.1\text{x}10^{14}$	"	1.64	1.35

Table .3 Electron Trap Parameters vs. Flux Rate in one-MeV Electron Irradiated (AlGa)As-GaAs Solar Cells for $\phi_e = 10^{15}$ e/cm^2

Samples	N_D (cm^{-3})	Flux Rate (e/cm^2-s)	Annealing Temp. (°C)	Electron Traps			
				E_T (eV)	N_T (cm^{-3})	σ_n (cm^2)	τ_n (s)*
1	$5.35\text{x}10^{16}$	$4\text{x}10^{10}$	200	$E_3=E_c-0.31$ $E_4=E_c-0.71$ $E_5=E_c-0.90$	$1.24\text{x}10^{13}$ $5.84\text{x}10^{13}$ $1.35\text{x}10^{13}$	$1.8\text{x}10^{-14}$ $5.1\text{x}10^{-14}$ $5.8\text{x}10^{-14}$	$1\text{x}10^{-7}$ $6.85\text{x}10^{-9}$ $2.6\text{x}10^{-8}$
2	$5.56\text{x}10^{16}$	$2\text{x}10^{9}$	150	E_4	$4.85\text{x}10^{13}$	$5.1\text{x}10^{-14}$	$8.25\text{x}10^{-9}$
3	$5.69\text{x}10^{16}$	$2\text{x}10^{9}$	200	E_4	$3.61\text{x}10^{13}$	$5.1\text{x}10^{-14}$	$1.11\text{x}10^{-8}$

Table. 4 Hole Trap Parameters vs. Flux Rate in one-MeV Electron Irradiated (AlGa)As-GaAs Solar Cells for $\phi_e = 10^{15}\ e/cm^2$

Samples	N_D (cm^{-3})	Flux Rate (e/cm^2-s)	Annealing Temp. (°C)	Hole Traps				
				E_T (eV)	N_T (cm^{-3})	σ_p (cm^2)	τ_p (s)*	L_p (μm)*
1	5.35×10^{16}	4×10^{10}	200	EB=E_v+0.71	4.94×10^{13}	4.0×10^{-13}	3.6×10^{-9}	2.01
2	5.56×10^{16}	2×10^{9}	150	E_v+0.71	4.02×10^{13}	4.0×10^{-13}	4.46×10^{-9}	2.23
3	5.69×10^{16}	2×10^{9}	200	E_v+0.71	3.06×10^{13}	4.0×10^{-13}	5.84×10^{-9}	2.58

$*\tau_p = (N_T\sigma_p V_{th})^{-1}$, $L_p = (\tau_p D_p)^{1/2}$; $D_p = 11.2\ cm^2/s$.

Table. 5 Electron and Hole Traps in one-MeV Electron Irradiated (at 200°C) (AlGa)As-GaAs Solar Cells.☆

Electron Fluence (cm^{-3})	N_D^* (cm^{-3})	Electron Traps		Hole Traps	
		E_T (ev)	N_T (cm^{-3})	E_T (eV)	N_T (cm^{-3})
0	1.5×10^{15}	-	-	-	-
10^{14}	1.45×10^{15}	E_c-0.13	3.2×10^{13}	E_v+0.29	0
		E_c-0.41	1.3×10^{13}	-	-
		E_c-0.71	1.2×10^{12}	E_v+0.71	6.4×10^{12}
		E_c-0.90	1.6×10^{12}	-	-
10^{15}	1.05×10^{15}	E_c-0.13	2.2×10^{14}	E_v+0.29	6.9×10^{12}
		E_c-0.41	1.3×10^{13}	-	-
		E_c-0.71	7.8×10^{12}	E_v+0.71	2.0×10^{13}
		E_c-0.90	9.5×10^{12}	-	-

*Carrier removal rate = $\Delta n/\phi_e = 0.5\ cm^{-1}$.

☆ undoped n-GaAs LPE layer.

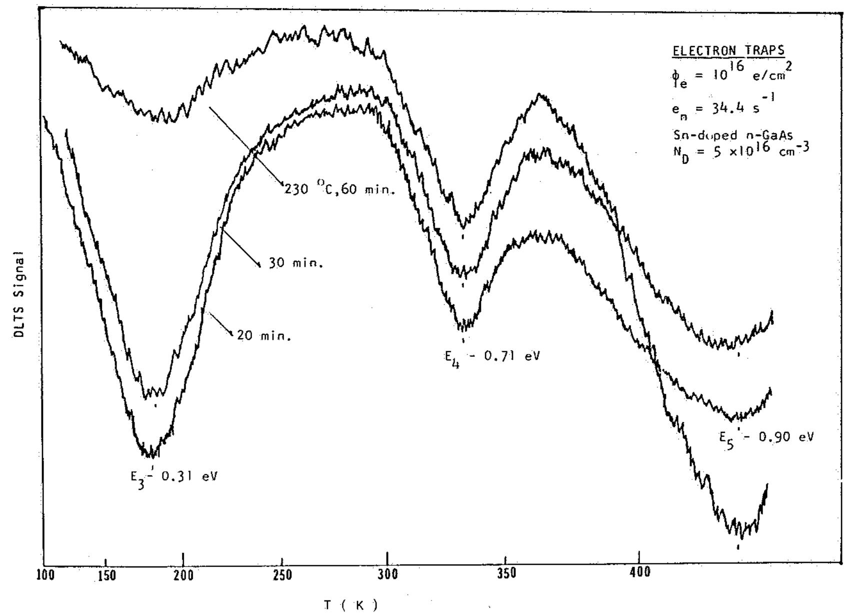

Fig. 1 DLTS scan of electron traps in one-MeV electron irradiated (AlGa)As-GaAs solar cells as a function of annealing (230 °C) time.

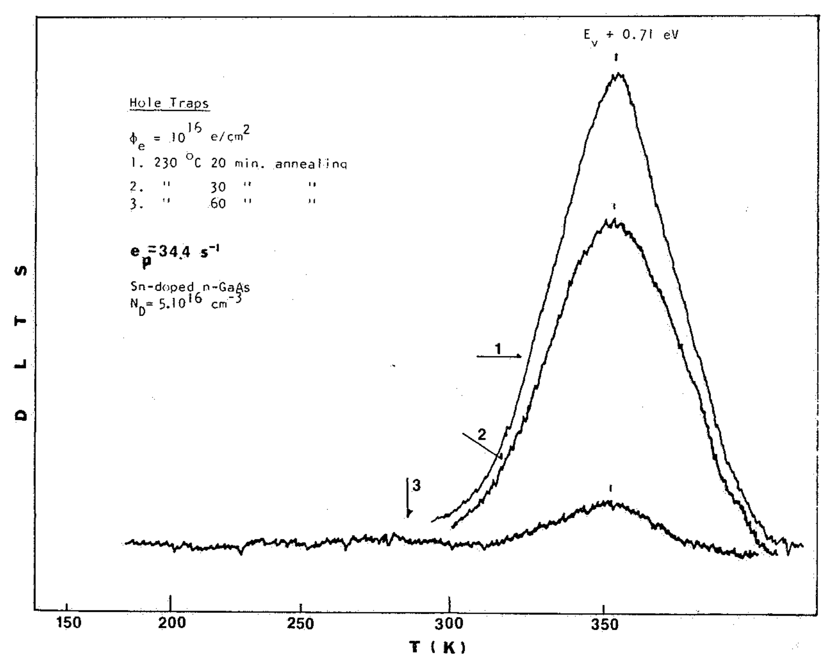

Fig. 2 DLTS scan of hole traps in one-MeV electron irradiated (AlGa)As-GaAs solar cells for different annealing times.

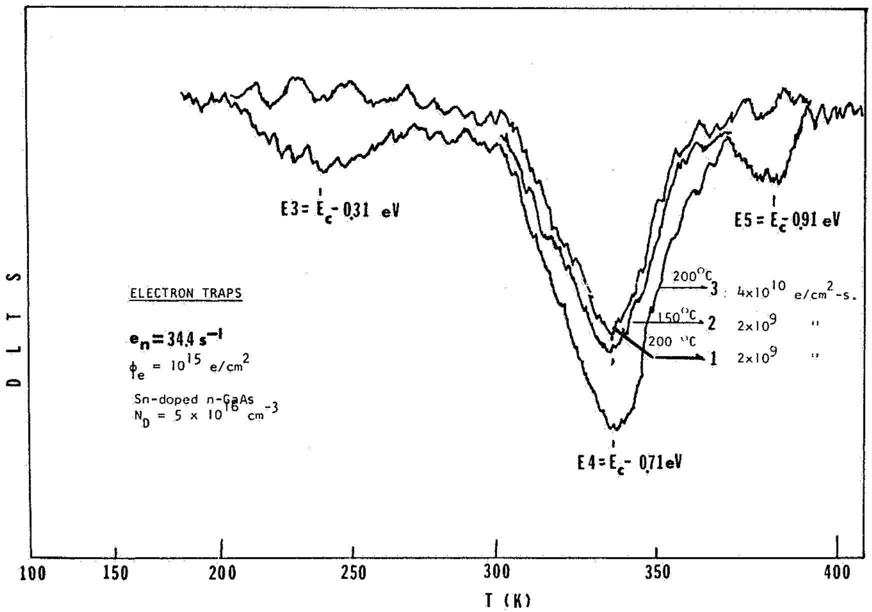

Fig. 3 DLTS scan of electron traps in one-MeV electron irradiated (AlGa)As-GaAs solar cells vs incident flux rate and annealing temperature.

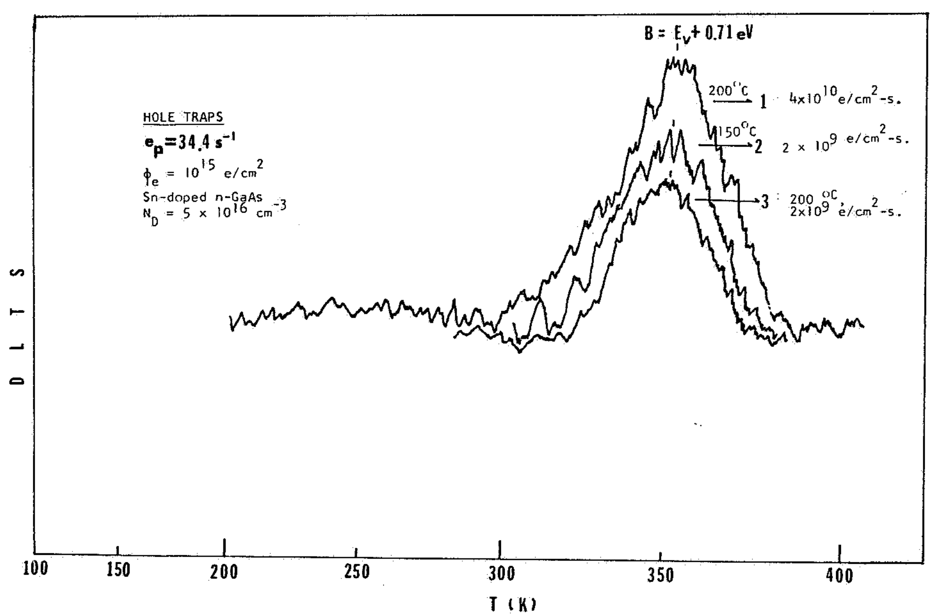

Fig. 4 DLTS scan of hole traps in one-MeV electron irradiated (AlGa)As-GaAs solar cells vs incident electron flux rate and annealing temperature.

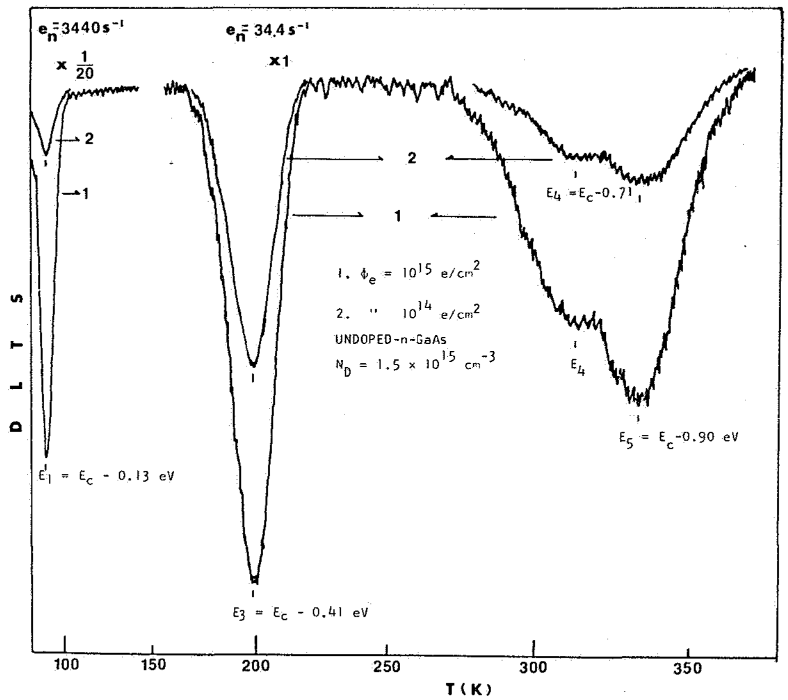

Fig.5 DLTS scan of electron traps in one-MeV electron irradiated (at 200 °C) (AlGa)As-GaAs solar cells as a function of electron fluence.

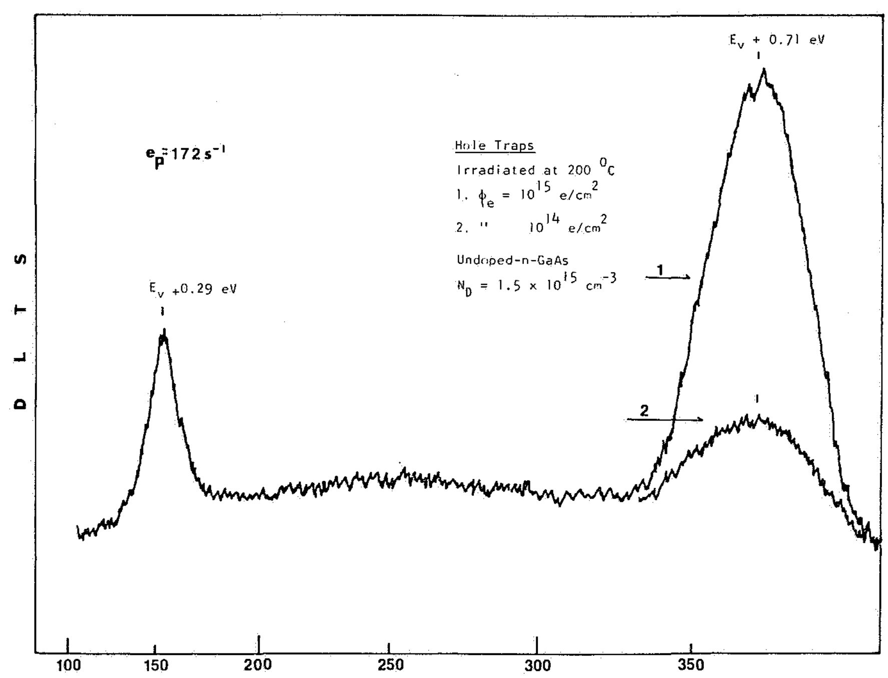

Fig.6 DLTS scan of hole traps in one-MeV electron irradiated (at 200 °C) (AlGa)As-GaAs solar cells as a function of electron fluence.

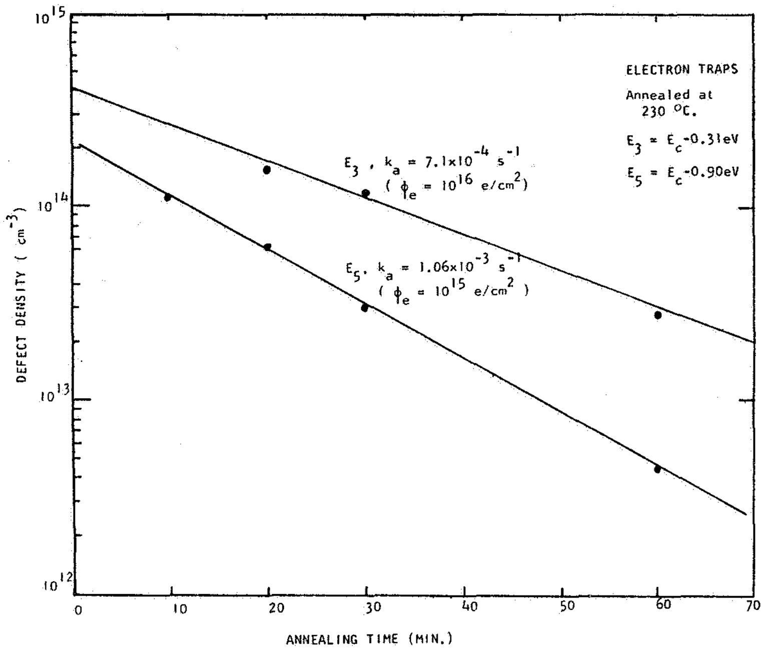

Fig.7 Annealing rate of E_3 and E_5 electron traps in one-MeV electron irradiated (AlGa)As-GaAs solar cells.