DLTS Characterization of CIGS Cells

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ABSTRACT

Deep Level Transient Spectroscopy (DLTS) and Capacitance-Voltage (C-V) measurements are employed to study deep- level electron and hole traps in CIGS solar cells fabricated at two different locations (EPV and NREL). The activation energy and trap density as well as suggested defect origins are given.

INTRODUCTION

It is well known that $CuInGaSe_2$ (CIGS) has a large homogeneity range, and such deviation from stoichiometry in compound semiconductors is often attributed to antisite defects, vacancies and defect clusters in the material. Zhang [1] has calculated the transition energy for a large number of defects in CIS, and the results are summarized in Figure 1. Knowledge of the defect energies as well as their densities are important inputs to developing meaningful device models. DLTS is a standard diagnostic technique for determining the trap properties such as trap energy level, capture cross section, and trap concentration.

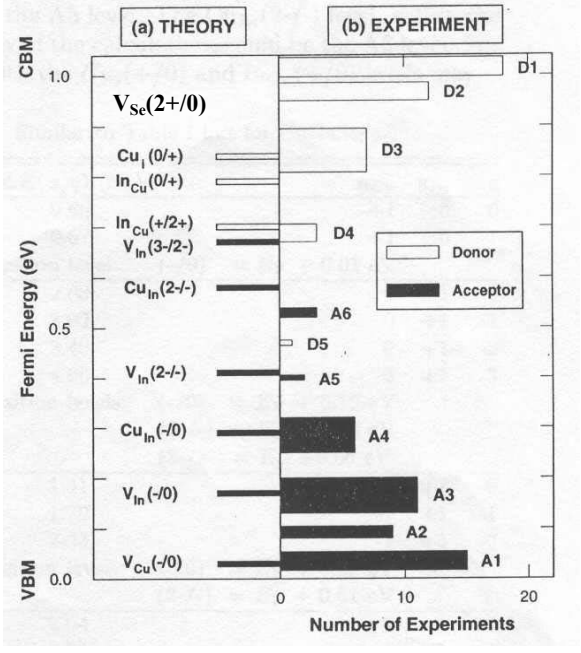

Fig. 1. Defect Transition Energy Diagram of α-$CuInSe_2$ [1]

EXPERIMENTAL PROCEDURE

DLTS is used to measure the transient capacitance change of a junction device after deep- level traps in the space charge region have been filled with either the majority or minority carrier charges, and the trap density and energy levels of these deep level traps can be extracted from DLTS measurements. By scanning the transient capacitance over a range of temperature, the emission rate as a function of temperature can be obtained. The activation energy for an electron trap can be estimated from an Arrhenius plot:

$$e_n = \sigma_n v_{th} N_c \exp(-\frac{E_a}{kT}) \quad (1)$$

where e_n is the electron emission rate, σ_n is the capture cross section, and ν_{th} is the electron thermal velocity. The electron trap density, N_T, can be calculated by

$$N_T = \frac{2\Delta C}{C_0} N_a \quad (2)$$

Equation (2) is valid for $N_T < N_a$. ΔC is the height of capacitance change due to the emission of charge carriers from the trap level, which is proportional to the probed trap concentration. Carrier concentration, N_a, is determined by the C-V meaurements, which give the average carrier concentration in the CIGS absorber layer. C_0 is the zero bias capacitance that is obtained from the C-T data at the corresponding DLTS peak temperature.

RESULTS AND DISCUSSION

1. EPV CIGS sample

The DLTS spectra measured from the EPV sample with a reverse bias voltage, V_R =-0.1V, a trap-filling pulse of 0.3 V, and a saturation pulse width of 10 ms is shown in Fig. 2. The EPV sample showed a deep majority carrier trap (negative signal) at a temperature around 270 K. The DLTS peak shifts to higher temperatures with shorter rate windows. Since the CIGS film is p-type material, the majority carrier trap is referred to as a hole trap, and the minority carrier trap as an electron trap.

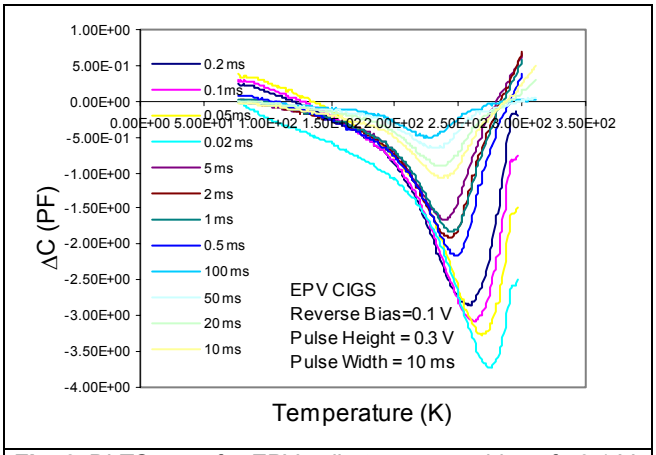

Fig. 2. DLTS scan for EPV cell at a reverse bias of –0.1 V, a pulse height of 0.3 V, and pulse width of 10 ms.

The activation energy calculated from the Arrhenius plot is 0.94 eV, which may be attributed to the Se vacancy according to the diagram shown in Figure 1.

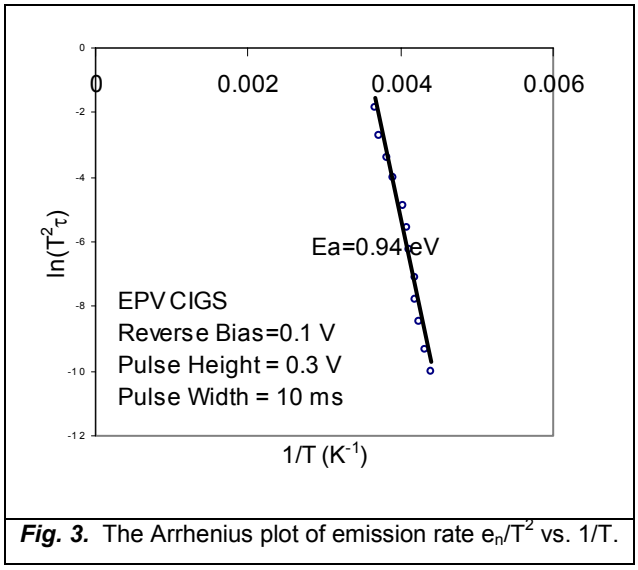

Fig. 3. The Arrhenius plot of emission rate e_n/T^2 vs. 1/T.

Figure 4 shows the C-V data measured on the same EPV cell as that used in the DLTS measurement. The average carrier concentration at 270 K from the C-V measurements is 3×10^{15} cm^{-3}.

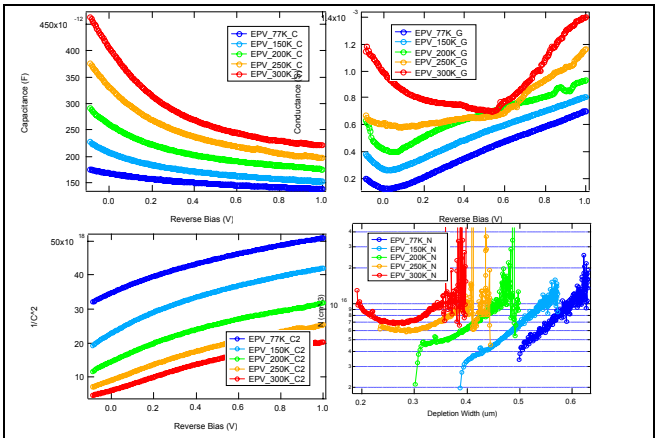

Fig. 4. C-V data of EPV sample at different temperatures.

From the C-T scan (Fig. 5), C_0 in Eq. (2) was found to be 3.01×10^{15} cm^{-3}, and N_T was determined to be 6.5×10^{13} cm^{-3}.

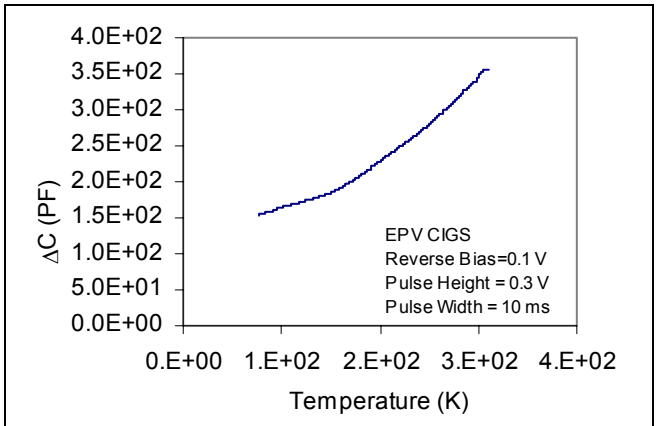

Fig. 5. The C-T scan for EPV cell at a reversed bias -0.1V.

2. NREL CIGS sample

A pulse amplitude equal to 0.4V was applied to the NREL CIGS sample at a reverse set-off voltage of -0.5 V. A minority carrier trap peak was observed at a lower temperature of around 100 K as shown in Figure 6. The activation energy is 0.067 eV below the conduction band as shown in Figure 7. A possible physical origin of this electron trap is the Se vacancy (V_{se}).[1] The trap density is estimated to be 4.2×10^{13} cm^{-3}. The DLTS scan at higher temperature showed another possible positive peak, however, the activation energy for this trap could not be resolved by heating sample above 300 K.

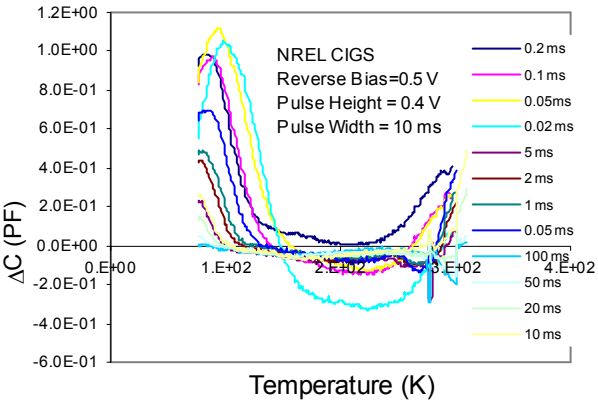

Fig. 6. DLTS data for NREL sample measured at a reverse bias -0.5 V, pulse amplitude 0.4 V, and pulse width 10 ms.

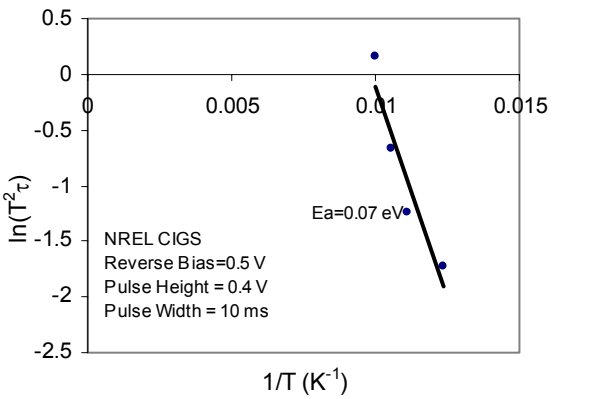

Fig. 7. Arrhenius plot of the emission rate e_n/T^2 vs. 1/T.

Therefore, it is noted that the minority traps are likely the dominant traps in the NREL sample. To detect other possible minority traps, a small forward bias (0.1 V) was applied and the sample cooled to 77 K to freeze the minority carriers. The sample was then heated with V_R =-0.5 V, trap-filling pulse amplitude of 0.7 V, and a saturation pulse width of 10ms to observe the capacitance change due to the minority carrier emission. Figure 8 shows three minority carrier traps with the addition of a small peak around 250 K, which was not apparent in the DLTS spectra of the 0.4 V pulse amplitude. The Arrhenius plot in Figure 9 showed that the activation energy for the trap at 80 K is 0.14 eV. The trap density is estimated to be 2.54×10^{13} cm^{-3}. The electron trap observed at 80 K is possibly related to a vacancy on a Se site, which might be the same trap level as the one observed with the 0.4 V pulse amplitude as shown in Figure 6. The activation energy at 335 K could not be estimated since the peak shift does not follow the trend; the shorter the rate window, the higher the temperature at which the peak appears.

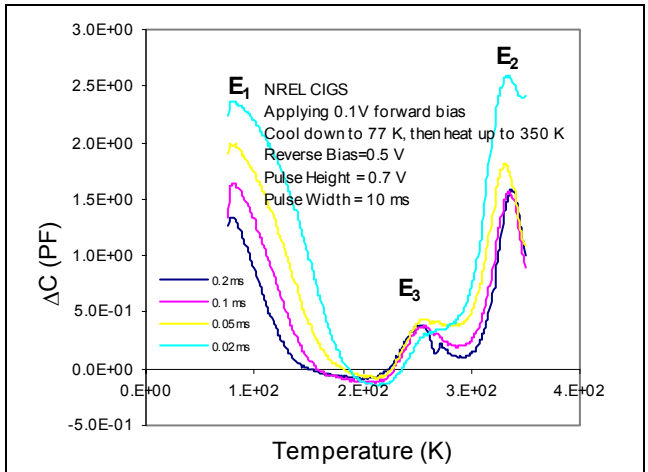

Fig. 8. DLTS scan for the NREL sample under forward bias (0.1 V) injection, and heat up with reverse bias of -0.5V, pulse height of 0.7V, and pulse width of 10 ms.

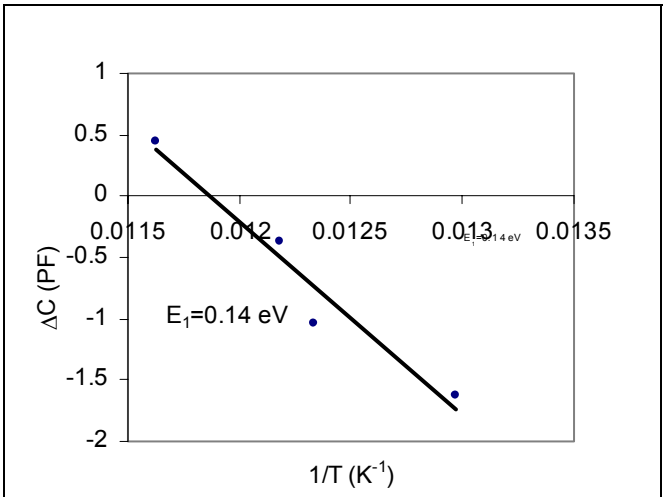

Fig.9. Arrhenius plot of emission rate e_n/T^2 vs. 1/T for the electron trap E_1.

CONCLUSIONS

The DLTS and C-V measurements have been performed on both EPV and NREL CIGS samples, and defect activation energy and density were determined from these measurements. The EPV sample showed a majority carrier (hole) trap with activation energy and trap density determined. The NREL CIGS sample showed three minority carrier traps. Possible defect origins were depicted from this DLTS study. A summary of the DLTS and C-V results is given in Table 1.

Table 1. Summary of DLTS and C-V data for the EPV and NREL samples.

	EPV	NREL		
Approximate Peak Temperature	270 K	100K	250 K	335 K
Activation Energy (eV)	E_v+0.94	E_c-0.067		
DLTS peak	Negative	Positive	Positive	Positive
Trap Carrier Type	Majority	Minority	Minority	Minority
N_a (cm^{-3})	3×10^{15}	2.25×10^{15}		
N_T (cm^{-3})	6.5×10^{13}	4.2×10^{13}		
Possible defect I.D.	E_{D2} V_{Se}	E_{D2} V_{Se}		
Capture Cross Section σ (cm^2)		6×10^{-18}		

ACKNOWLEDGEMENTS

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REFERENCES

[1] S.B. Zhang, S-H Wei, and A. Zunger, Phys. Rev. B, Vol 57, No. 16 pp 9642-9668 (1998).