DLTS study of extended defects in HgCdTe photodiodes

P Guinedor 1,*, T Broult 1, A Brunner 1, L Rubaldo 1, D Bauza 2, G Reimbold 3, A Kerlain 1 and V Desteфанis 1

1 SOFRADIR, Actipole - 364 Route de Valence, CS – 10021 – 38113 Veyre-Voroize, France
2 IMEP-LAHC, Minatec - 3 Parvis Louis Néel, CS 50257 - 38016 Grenoble Cedex 1, France
3 CEA-LETI, 17 avenue des Martyrs – 38054 Grenoble, France
* e-mail: pierre.guinedor@sofradir.com

Abstract: Extended electrically active defects have been investigated in Short Wave InfraRed (SWIR) HgCdTe n on p photodiodes, using the Deep Level Transient Spectroscopy (DLTS) technique. Three localized defects have been found in the dislocations core or in their close environment. DLTS studies have also been performed before and after indentation, a technique which generates dislocations in the material. DLTS spectra are discussed and dislocations generated by indentation have been found to be electrically active only after annealing.

1. Introduction

The Hg1-xCd,xTe alloy is widely used in high performance infrared detection since it covers the whole infrared range (from 1 µm up to 18 µm cut-off wavelengths) with very small lattice parameter variation (below 0.3%), when changing its Cd composition.

With the current necessity to increase the operating temperature, infrared detectors are faced today to extra low frequency noises which degrade global performances. Both 1/f noise [1] and Random Telegraph Signal (RTS) noise [2] are present in HgCdTe photodiodes and need to be addressed. To that end, bulk defects have to be studied. Indeed, a better comprehension of point defects, and extended defects like dislocations easily introduced in HgCdTe epitaxial layers [3], are necessary to understand noise mechanisms and thus improve the image quality of the detectors.

In this work, we are interested in the Short Wave InfraRed (SWIR) HgCdTe n on p technology with a cut-off wavelength of λc = 2.5 µm, based on bulk mercury vacancy doped p-type material in the 10^16 cm^-3 range. The Deep Level Transient Spectroscopy (DLTS) studies have been performed on single photodiodes with an area of 271 * 271 µm².

We report the presence of a dislocation related peak, made up of three localized defects in the dislocation core or its close surroundings. Energy levels in the bandgap as well as capture cross sections have been extracted for each defect. DLTS measurements have also been realized before and after micro-indentation, a technique which generates extra dislocations in the material [4].

2. The DLTS technique

Introduced by D. V. Lang, DLTS is one of the most powerful techniques for studying electrically active defects in semiconductor devices. The basic principle, which is well known, can be found in the following reference [5]. This DLTS technique has already been successfully applied in several materials such as Si [6], Si-deformed [7-8], GaAs [9] or HgCdTe [10-12] over years.

In this work, Deep Level Transient Fourier Spectroscopy (DLTFS) [13], a variant of the DLTS technique where emission time constants are extracted using different Fourier correlators, has been used to characterize electrically active defects. With this technique, dissociating close time constants is easier and a better energy resolution is obtained. For all these studies, the sine b1 correlator has been used because it offers a good compromise between energy resolution and defects concentration.
sensibility. The discrete Fourier’s coefficient \( b_1 \) \([F]\) is described by equation (1), where \( \Delta C_0 \) \([F]\) is the transient amplitude, \( \tau \) [s] the transient time constant, \( t_0 \) [s] the waiting time before recording the transient, \( T_w \) [s] the transient recording time and \( w_0 \) \([s^{-1}]\) given by \( 2\pi / T_w \).

\[
b_1 = \frac{2\Delta C_0}{T_w} \exp \left( -\frac{t_0}{\tau} \right) \left( 1 - \exp \left( -\frac{T_w}{\tau} \right) \right) - \frac{w_0}{1 + \frac{1}{\tau^2} + w_0^2}
\]

From equation (1), it is possible to go back to the transient amplitude \( \Delta C_0 \) and therefore to extract the defect concentration in the material.

3. Results and discussions

DLTFS measurements have been performed over twelve n on p HgCdTe photodiodes from several wafers. A good reproducibility has been found for all the samples. The defect concentration, extracted from the sine \( b_1 \) correlator, is plotted in Figure 1 for several tp pulse durations on the same diode.

Three peaks have been identified on Figure 1. Two positive which indicate they are majority (hole) carrier traps, and a negative so a minority (electron) carrier trap. Furthermore, it can also be observed that the higher temperature peak is broadened and that its maximum is increasing with tp pulse duration over several orders of magnitude. Therefore it can’t be the response of a single defect which has a finite concentration. According to literature on the subject [7-8, 14-15], this is a signature of extended defects and more precisely of dislocations. So we are probably observing here their electrical activity in SWIR HgCdTe n on p photodiodes.

![Figure 1. Defect concentration at different tp pulse durations for SWIR n on p HgCdTe photodiode](image)

In this work, we focus on the broadened high temperature peak because, for all the previously mentioned reasons, it seems a good candidate to make the link with dislocations. The two other peaks will not be discussed in this paper.

Doing isothermal measurements leads to better resolution in energy. In contrary to the standard approach, the temperature of the sample is set to a fixed value while the Tw recording time is now varying. This method is plotted in Figure 2 for several tp pulse durations at 245 K. Some peaks can be observed at different Tw times. That means there is more than one contribution to the broadened peak.

To extract these different contributions, defect concentration is plotted in Figure 3 as a function of tp in a logarithmic scale. Three slopes can be observed, which means that at least three defects contribute to this broadened peak. If each slope is plotted again in a linear scale, using the following equations (2) and (3), it is possible to extract the apparent capture cross section for each defect from the slope.

\[
n_{tc}(t_p) = N_t \left( 1 - \exp \left( -\frac{t_p}{\tau_{tp}} \right) \right)
\]

(2)
With \( n_c(t_p) \) the number of filled traps during the capture process, \( \tau_{cp} \) [s] the hole capture time constant, \( t_p \) [s] the pulse duration and \( N_t \) [cm\(^{-3}\)] the total number of traps.

\[
c_p = \frac{1}{\tau_{cp}} = \sigma_p v_{th,p} p
\]

With \( c_p \) [s\(^{-1}\)] the hole capture rate, \( \sigma_p \) [cm\(^2\)] and \( v_{th,p} \) [cm.s\(^{-1}\)] respectively the apparent capture cross section and the thermal velocity for holes and \( p \) [cm\(^{-3}\)] the hole concentration.

**Figure 2.** Defect concentration as a function of Tw recording time for different pulse durations

**Figure 3.** Defect concentration as a function of the logarithm of the \( t_p \) pulse duration for Tw = 15 s

Extracted capture cross sections are resumed in Table 1.

| defect   | \( \sigma_p \) (cm\(^2\)) |
|----------|---------------------------|
| defect 1 | \( 4.1 \times 10^{-18} \) |
| defect 2 | \( 2.0 \times 10^{-20} \) |
| defect 3 | \( 6.9 \times 10^{-24} \) |

**Table 1.** Extracted capture cross sections for the three contributions of the broadened peak
Capture cross section values are found to be very small, way lower than $1 \text{Å}^2 = 10^{-16} \text{cm}^2$. Small capture cross section means more a capture probability. This could be typical of capture cross section of defects localized around or in the core of dislocations, where potential barrier around dislocations increases when carriers are captured [8], and induces very small capture cross sections. Then the three defects found could be localized in the dislocation environment.

Both activation energy and defect concentration have also been extracted for the three contributions, using isothermal direct high energy resolution analysis evaluations. The methods, based on DISCRETE [16] and CONTIN [17] algorithms developed by S. W. Provencher, use multi-exponential decay to estimate the (amplitude, emission rate) couple of each contribution in the experimental transients.

These extracted parameters (capture cross section, activation energy and defect concentration) for the three contributions have been used to model experimental data. The method, consisting in rebuilding the global transient of capacitance for each temperature, is explained below. Both experimental measurement and model are plotted in Figure 4 and are in good agreement.

If capture cross section as well as activation energy are known, going back to the hole emission rate $e_p [\text{s}^{-1}]$ of each defect is possible, following the equation (4).

$$
e_p = \frac{1}{\tau_{ep}} = K_p \sigma_p T^2 \exp\left(\frac{E_v - E_t}{k_B T}\right)$$

(4)

$e_p [\text{s}^{-1}]$ is the hole emission rate, $\tau_{ep} [\text{s}]$ the transient time constant, $K_p [\text{m}^2,\text{K}^{-2},\text{s}^{-1}]$ a constant which takes into account hole effective mass, thermal velocity, the degeneracy level and effective states density in the valence band, $E_v [\text{eV}]$ the valence band and $E_t [\text{eV}]$ the position of the trap in the bandgap.

Furthermore if the total concentration in defects is extracted, the transient amplitude can be model at each temperature, using (4) and (5). Where $C_r [\text{F}]$ is the reverse bias capacitance, $N_t [\text{cm}^{-3}]$ the defect concentration and $N_a [\text{cm}^{-3}]$ the doping concentration.

$$
\Delta C_0 = \frac{C_r}{2} \frac{N_t}{N_a} \left(\exp\left(-e_p \tau_0\right) - \exp\left(-e_p T_w\right)\right)
$$

(5)

**Figure 4.** Experimental measurement and model of the broadened high temperature peak

To confirm the link between this broadened high temperature peak and dislocation, micro-indentation technique has been performed on four diodes from two different wafers. Micro-indentation is a mechanical technique which generates dislocations in the material and has been successfully applied in literature on II-VI compounds such as CdZnTe [18-19] and HgCdTe [19-20].
In Figure 5 is presented an indentation pitch in the close neighbouring of the diode. The four indentations were done at room temperature with a Vickers diamond pyramid. The effective radius is about 100 µm.

![Figure 5](image.png)

Figure 5. Indentation pitch at room temperature, close to a 271*271 µm² photodiode.

Referring to micro-indentation literature on HgCdTe material [20], there is evidence in Figure 5 that dislocations have been generated inside the diode. Defect concentrations before and after indentation are displayed in Figure 6 (a) for the same diode. It can be seen that indentation and the induced dislocations have no impact on the signal. Two hypotheses can be suggested. The broadened peak is not related to dislocations or the generated dislocations are not electrically active after indentation. Note that this phenomenon has been found for the four indented diodes.

To confirm or not the hypotheses, a soft annealing (130°C – 4h) has been realized on the four indented diodes and two not indented reference diodes. Defect concentrations are shown in Figure 6 (a)-(b). For both indented and non-indented diodes, annealing has been found to shift the broadened peak maximum of about 4 K to lower temperatures. Furthermore, in the indented diodes cases the broadened peak maximum increased. This could suggest either a migration of the dislocation in the space charge region or its electrical activation. The shape of the broadened high temperature peak suggests an electrical activity from a decorated dislocation [15]. And this thermal electrical activation of dislocations could be ascribed to impurities diffusion enhanced in the vicinity of dislocations [21] or defects reconfiguration in the dislocation core.

![Figure 6 (a)](image.png)

Figure 6 (a). Defect concentration before and after indentation / annealing for indented diode
Figure 6 (b). Defect concentration before and after annealing for non-indentated diode

4. Conclusion
DLTS studies on SWIR n on p HgCdTe photodiodes have shown a broadened peak related to dislocations. Its electrical activity is due to three defects localized in the dislocation core or in its close environment. Indentations have been performed to confirm the link between the broadened peak and the dislocations. New generated dislocations seem to be electrically active only after soft annealing.

References
[1] Tobin S, Iwasa S and Tredwell T 1980 IEEE T. Electron. Dev. 27 p 43
[2] Brunner A, Rubaldo L et al 2014 J. Electron. Mat. 43 p 3060
[3] Basson J H et al 1983 Phys. Stat. Sol. (a) 80 p 663
[4] Guergouri K, Brihi N and Triboulet R 2000 J. Cryst. Growth 209 p 709
[5] Lang D V 1974 J. Appl. Phys. 45 p 3023
[6] Schröter W, Kveder V et al 2000 Mat. Sci. Eng. B 72 p 80
[7] Kveder V V, Osipyan Yu A et al 1982 Phys. Stat. Sol. (a) 72 p 701
[8] Cavalcoli D and Cavallini A 1997 Phys. Review B 56 p 10208
[9] Wosinski T 1989 J. Appl. Phys. 65 p 1566
[10] Rubaldo L, Brunner A et al 2014 J. Electron. Mat. 43 p 3065
[11] Barbot J F 1991 Phys. Stat. Sol. (a) 123 p 513
[12] Polla D L and Jones C E 1981 J. Applied. Phys. 52 p 5118
[13] Weiss S and Kassing R 1988 Solid State Electron. 31 p 1733
[14] Kimerling L C, Patel J R et al 1979 Appl. Phys. Lett. 34 p 73
[15] Schröter W, Kronewitz J et al 1995 Phys. Review B 52 p 13726
[16] Provencher S W 1976 J. Chem. Phys. 64 p 2772
[17] Provencher S W 1982 Comput. Phys. Commun. 27 p 229
[18] Fu X, Xu Y et al 2016 CrystEngComm 18 p 5667
[19] Fissel A and Schenk M 1992 J. Mat. Sci.: Materials in Electronics 3 p 147
[20] Gopal V and Gupta S 2004 IEEE T. Electron. Dev. 51 p 1078
[21] Bubulac L O and Viswanathan C R 1992 J. Cryst. Growth 123 p 555