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# COMPARATIVE STUDY OF CdTe AND GaAs PHOTOREFRACTIVE PERFORMANCES FROM 1 $\mu$ m TO 1.55 $\mu$ m

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**Abstract.** We present a photorefractive investigation of the Vanadium doped CdTe at different wavelengths from 1.06 $\mu$ m to 1.55 $\mu$ m. The sensitivity and performances of different samples grown with different conditions are deduced. We compare these performances with the ones of the undoped GaAs in the same wavelength range.

**Introduction.** The development of the optical telecommunication networks and metrology systems at the eye safe wavelength of 1.5 $\mu$ m, increases the interest for the extension of the photorefractive effect towards the wavelength region of 1.3-1.5 $\mu$ m. CdTe appears to be a good candidate for such applications as its sensitivity extends beyond 1.5 $\mu$ m and a photorefractive effect can be obtained with the low excitation energies delivered by laser diodes [1, 2]. Previous studies have shown that, in general, semiconductors are very sensitive to the electron-hole competition leading to a strong reduction of the photorefractive gain that varies with optical wavelength [3]. We here study different CdTe samples which present variable electron-hole competitions in the wavelength range 1 - 1.55 $\mu$ m. We compare the performances of these CdTe crystals to the ones of a GaAs sample for which we show a sensitivity at 1.55 $\mu$ m with photorefractive gains, in the diffusion regime, comparable to the absorption losses.

**Experimental set-up and samples.** Photorefractive performances of our samples are analysed in a two beam coupling experiment. The measurement of the strength of the photorefractive energy transfer gain from a pump beam toward a probe beam (from which we deduce the photorefractive gain  $\Gamma$ ) as a function of the grating spacing allows to obtain two important parameters of the photorefractive effect : the electron-hole competition coefficient  $\xi_0$  and the effective trap density  $N_{\text{eff}}$  [4]. The expression of the gain with the grating spacing  $\Lambda$  (or grating wavenumber  $k=2\pi/\Lambda$ ), when considering that the electron-hole competition factor is independent of the grating spacing, as usually admitted in semiconductors, is [5, 6]:

$$\Gamma = \frac{2\pi n_0^3 r_{\text{eff}}}{\lambda \cos \theta} \frac{k_B T}{e} \frac{\xi_0 k}{1 + \frac{k^2}{k_0^2}}$$

with  $k_0^2 = \frac{e^2}{\epsilon k_B T} N_{\text{eff}}$ .  $\theta$  is the half angle between the beams inside the crystal.  $n_0$  the linear refractive index of the material,  $r_{\text{eff}}$  the effective electrooptic coefficient that depends on the

crystal and the beam polarization orientations [7] and  $\epsilon$  is the dielectric constant. All these parameters are known from the literature.

The measurements are performed at the three wavelengths of  $1.06\mu\text{m}$ ,  $1.32\mu\text{m}$  and  $1.55\mu\text{m}$  given by two diode pumped Nd:YAG lasers and a laser diode respectively. The photorefractive gain is verified to be saturated with respect to the illumination for all the samples and wavelengths. The energy transfer direction and then the sign of  $\xi_0$  is measured for the different wavelengths relatively to its sign at  $1.06\mu\text{m}$ . We consider that, in all the cases, we have electrons as majority carriers ( $\xi_0 > 0$ ) at  $1.06\mu\text{m}$  as already measured on two CdTe samples in previous studies [8].

The possible existence of absorption gratings is checked by using the symmetry properties of photorefractive gain. All the measurements presented here are corrected, when necessary, from the absorption component.

We determine the exponential time constant of the build-up of the photorefractive effect in our samples by monitoring the energy transfer kinetics when the pump beam is turned on.

The CdTe samples were grown using the modified Bridgman technique. They were doped with Vanadium at concentrations between  $10^{20}\text{ cm}^{-3}$  and  $5 \times 10^{18}\text{ cm}^{-3}$ . The crystals were generally cut in the classical photorefractive orientation with a beam propagation along (110) direction. However sample (B23-3) was cut with a propagation direction along (111). The absorption spectra of the different samples exhibits similar features with two absorption bands centered at  $1\mu\text{m}$  and  $1.5\mu\text{m}$  (Figure 1), only the absolute value of the absorption changes with the growth conditions.

The undoped GaAs crystal was grown by the Liquid Encapsulated Czochralski technique. Conversely to CdTe, the deep defect responsible for the photorefractive effect between 1 and  $1.55\mu\text{m}$  is identified [9], it is the EL2 native defect, which optical characteristics are known [10]. Concentrations of the different states of charge of this defect are determined from absorption and Electron Paramagnetic Resonance (EPR) measurements. Absorption at  $\lambda=1.19\mu\text{m}$  (Figure 2) gives a total concentration of the EL2 defect [11, 9] :  $[\text{EL2}]=1.3 \times 10^{16}\text{ cm}^{-3}$ .  $[\text{EL2}^+]=6 \times 10^{15}\text{ cm}^{-3}$  is given by EPR measurements [9].

**Experimental results in CdTe.** We study four CdTe samples (called H1, B6, B9-1, B23-3). Typical curves of variation of the gain with the grating spacing are obtained in these samples as it is shown in Figure 3 for sample B23-3. The adjustment of the theoretical curve to the experimental points gives us the two parameters  $\xi_0$  and  $N_{\text{eff}}$ . For these adjustments we take for the  $n_0^3 r_{41}$  coefficient the same value for the three wavelengths :  $120\text{pm.V}^{-1}$  [1, 12]. The parameters deduced from these experiments are summed up in Table 1. All CdTe samples present high photorefractive gain at  $1.06\mu\text{m}$ , at least as strong as in GaAs (as will be seen below). According to the results in Table 1, it appears that all samples present a strong electron-hole competition at  $1.32\mu\text{m}$  or  $1.55\mu\text{m}$ . Photorefractive gains of different signs are observed at  $1.32\mu\text{m}$ . This change in majority carrier with wavelength is very different from

what was previously observed in others studies [13] where the same dominant carriers (electrons) were observed at the three wavelengths. The effective trap density is of the same order of magnitude for the different samples (Table 1).

The photorefractive gain we measure is always lower than the absorption coefficient, i.e. no net gain is observed in these two beam coupling experiments without applied electric field.

**Experimental results in GaAs.** In GaAs, conversely to CdTe, the knowledge of photoionization cross-sections ( $S_n$ ,  $S_p$ ) [10] and concentrations allows to calculate the

expected photorefractive gain for each wavelength. As  $\xi_0 = \frac{S_n [EL2^0] - S_p [EL2^+]}{S_n [EL2^0] + S_p [EL2^+]}$ , we

calculate  $\xi_0=0.49$  at  $\lambda=1.06\mu\text{m}$ ,  $\xi_0=-0.48$  at  $\lambda=1.32\mu\text{m}$  and  $\xi_0=-0.55$  at  $\lambda=1.55\mu\text{m}$  with an effective trap density  $N_{\text{eff}}=3.2 \times 10^{15} \text{ cm}^{-3}$ . The accordance between theoretical calculations and experimental results is good (Figure 4). It shows that the photorefractive model of one defect coupled with both valence and conduction bands well explains the photorefractive behavior of undoped GaAs. The photorefractive gain changes its sign between  $1.06\mu\text{m}$  and  $1.32\mu\text{m}$  going from electrons to holes as majority carriers. As for CdTe, the sensitivity range of GaAs extends to  $1.55\mu\text{m}$  with a photorefractive gain of the order of magnitude of the absorption ( $\Gamma \approx \alpha \approx 0.1 \text{ cm}^{-1}$ ).

**Comparison between CdTe and GaAs.** If we compare the photorefractive gain obtained in CdTe and GaAs, we see that higher gains are obtained in CdTe for each of the three wavelengths. This is mainly due to the higher value of the electrooptic coefficient of CdTe that leads to a higher  $n_0^3 r_{41}$  (Table 2). Nevertheless only GaAs currently exhibits a net gain at  $1.55\mu\text{m}$  without applied electric field. Work has to be done to decrease the background absorption of CdTe samples in order to observe this net gain.

In order to compare the different samples, we use a figure of merit which is the index change per absorbed energy per unit volume. This sensitivity is defined as  $S = \frac{\Delta n}{F \alpha}$ .  $\Delta n$  is the index

change at saturation which is deduced from the photorefractive gain  $\Gamma$  with expression  $\Gamma = \frac{4\pi}{\lambda \cos \theta} \Delta n$ .  $F$  is the grating formation fluence  $F=I \cdot \tau(I)$  ( $\tau(I)$  is the time constant of the

photorefractive effect at the incident illumination  $I$ ),  $\alpha$  is the sample absorption. For example, for sample B9-1 at  $1.06\mu\text{m}$ , we measure a time constant  $\tau = 580\mu\text{s}$  at an illumination of  $24 \text{ mW.cm}^{-2}$ , which gives  $F = 14 \mu\text{J.cm}^{-2}$ . At the same grating spacing ( $\Lambda = 1.44 \mu\text{m}$ ), the gain  $\Gamma$  is  $0.4 \text{ cm}^{-1}$  for an absorption  $\alpha = 6 \text{ cm}^{-1}$ . We have then for sample B9-1 a sensitivity  $S = 0.04 \text{ cm}^3.\text{J}^{-1}$ . The same calculation conducted for sample B23-3 gives  $S = 0.005 \text{ cm}^3.\text{J}^{-1}$  (see Table 2).

For the GaAs sample at  $1.06\mu\text{m}$ , we measure, at a grating spacing of  $1.44\mu\text{m}$ , a gain  $\Gamma = 0.2 \text{ cm}^{-1}$  with an absorption  $\alpha = 1 \text{ cm}^{-1}$ . The response time is  $\tau = 1 \text{ ms}$  at an illumination of  $110 \text{ mW.cm}^{-2}$ . We have then a sensitivity  $S = 0.015 \text{ cm}^3.\text{J}^{-1}$ .

We see on these results that, regarding the sensitivity, CdTe and GaAs are comparable. The sensitivity of CdTe is very dependant on the samples with a variation of a factor of 10 between samples B9-1 and B23-3.

**Conclusion.** We have presented a photorefractive study of two of the most important photorefractive materials for the wavelength range between 1 and  $1.55\mu\text{m}$  : GaAs and CdTe. Both of these crystals present an electron-hole competition that can lead to an annulation of the gain at  $1.32\mu\text{m}$  or  $1.55\mu\text{m}$ , depending on the sample. If CdTe presents the highest gain due to its higher electrooptic coefficient, only GaAs presents net gain at  $1.55\mu\text{m}$  due to its smaller absorption. The sensitivity of these two crystals are similar with a strong variation from sample to sample for CdTe.

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## Figure captions

Figure 1 : Absorption spectrum of CdTe sample B6.

Figure 2 : Absorption spectrum of GaAs sample D2. The slightly negative value is due to a small overestimation of the refractive index [9], in all the paper we consider the crystal absorption to be zero at  $\lambda=2\mu\text{m}$ .

Figure 3 : Photorefractive gain as a function of the grating spacing at wavelegths  $\lambda=1.06\mu\text{m}$  and  $1.55\mu\text{m}$  for CdTe sample B23-3. Lines are the theoretical adjustments. The photorefractive gain at  $1.32\mu\text{m}$  is nearly zero.

Figure 4 : Photorefractive gain as a function of the grating spacing at  $\lambda=1.06\mu\text{m}$ ,  $1.32\mu\text{m}$  and  $1.55\mu\text{m}$  for the GaAs sample D2. Lines represent the calculated photorefractive gain.

|                                      | H1                   | B6                   | B9-1                 | B23-3              |
|--------------------------------------|----------------------|----------------------|----------------------|--------------------|
| V doping (cm <sup>-3</sup> )         | 5x10 <sup>19</sup>   | 1.5x10 <sup>19</sup> | 10 <sup>20</sup>     | 5x10 <sup>18</sup> |
| $\lambda=1.06 \mu\text{m}$           | $\xi_0 = 0.62$       | $\xi_0 = 0.51$       | $\xi_0 = 0.5$        | $\xi_0 = 0.83$     |
| $\lambda=1.32 \mu\text{m}$           | $\xi_0 = -0.1$       | $\xi_0 = 0.03$       | $\xi_0 = 0.27$       | $\xi_0 = 0$        |
| $\lambda=1.55 \mu\text{m}$           | x                    | $\xi_0 = -0.35$      | $\xi_0 = 0$          | $\xi_0 = -0.7$     |
| N <sub>eff</sub> (cm <sup>-3</sup> ) | 4.3x10 <sup>15</sup> | 1.2x10 <sup>15</sup> | 3.5x10 <sup>15</sup> | 3x10 <sup>15</sup> |

Table 1 : Photorefractive parameters of CdTe crystals at different wavelengths

|                                       | CdTe                 |                      | GaAs                 |
|---------------------------------------|----------------------|----------------------|----------------------|
|                                       | B9-1                 | B23-3                |                      |
| $n_0^3 r_{41}$ (pm.V <sup>-1</sup> )  | 120                  |                      | 72                   |
| F (μJ.cm <sup>-2</sup> )              | 14                   | 214                  | 110                  |
| α (cm <sup>-1</sup> )                 | 6                    | 2.9                  | 1                    |
| Δn (at Λ≈1.5μm)                       | 3.4x10 <sup>-6</sup> | 2.9x10 <sup>-6</sup> | 1.7x10 <sup>-6</sup> |
| S (cm <sup>3</sup> .J <sup>-1</sup> ) | 0.04                 | 0.005                | 0.015                |

Table 2 : Sensitivity of CdTe samples and GaAs at 1.06μm

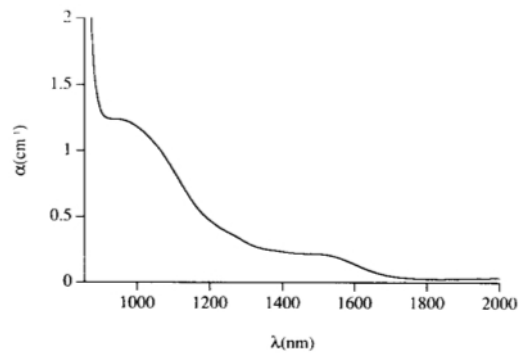


Figure 1

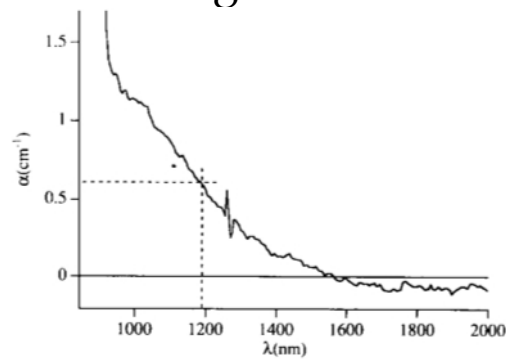


Figure 2



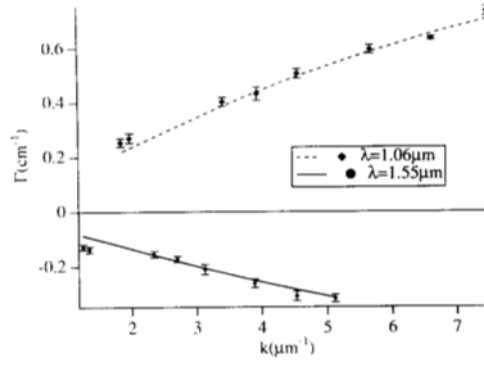


Figure 3

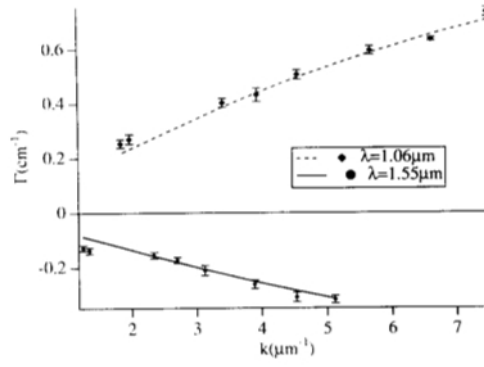


Figure 4