Fast High-Flux Response of CdZnTe X-Ray Detectors by Optical Manipulation of Deep Level Defect Occupations

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***Abstract*—We experimentally investigate the possible correlation between high hole-trap concentrations in wide-bandgap semiconductors and delayed temporal response of high-flux x-ray detector devices to changing photon fluxes. We show that fast photo-current response can be achieved with (1) CdZnTe detectors with high hole mobility-lifetime products, (2) temperature increased detrapping, and (3) constant below-bandgap energy light illumination that modifies the dark defect occupation towards a steady-state with a reduced concentration of active hole traps. This way, the detector signal stabilizes immediately upon flux onset, independent of details of the semiconductor's point defect structure. Quasi-instantaneous response stabilization (<3 ms) to x-ray flux changes $>10^7$ photons mm^{-2} s^{-1} is demonstrated.**

***Index Terms*—CdZnTe, infra-red, photocurrent, semiconductor radiation detectors, temporal response, X-ray detectors.**

I. Introduction

UTILIZATION of energy-discriminating (pulse mode) room-temperature semiconductor detectors like CdZnTe for fast scanning, high-flux x-ray applications can significantly simplify and improve the multi-energy imaging potential of systems like those for medical computed tomography [1]. Referring to the detector, this requires high-flux photon counting capability on the order of hundred million photons mm^{-2} s^{-1} or higher. This calls for detectors in which the electric field does not collapse due to excessive space charge accumulation under high-flux operation (polarization), and which exhibit fast charge transits in the device. It also requires fast response stabilization in the millisecond range upon rapid changes of the x-ray flux.

In general, the response time to flux-changes is controlled by the charge carrier dynamics, i.e., the response undergoes a transient upon the initial charge injection from the x-ray photons and eventually stabilizes when the final steady-state defect occupation (thereby, steady-state electric field) is established. The dynamics for counting-rate in pulse-mode and photocurrent response in integrating detectors are equivalent.

Manuscript received October 13, 2009; accepted January 21, 2010. Date of publication June 01, 2010; date of current version August 18, 2010.

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Digital Object Identifier 10.1109/TNS.2010.2049120

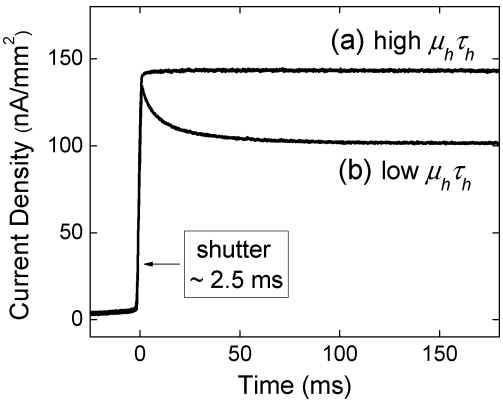

Fig. 1. X-ray photocurrent temporal response from planar, 2 mm thick CdZnTe detectors at 300 V bias: (a) high $\mu_h\tau_h$ material, (b) low $\mu_h\tau_h$ material.

II. Experimental Results and Discussion

A. Hole Transport

We extensively investigated the photocurrent temporal response for test devices fabricated from CdZnTe ingots with significantly different charge transport properties, i.e., different defect structures. The $\sim$2 mm thick Pt/CdZnTe/Pt parallel plate devices were x-ray irradiated from the cathode side and the photocurrents were directly converted into voltage signals by a transimpedance amplifier (gain: 5×10^4 V/A, bandwidth: 100 MHz). The voltage signals were recorded with a digital oscilloscope. The 24 mm thick brass shutter with collimator hole took $\sim$2.5 ms to effectively open the x-ray beam to the detector and the applied flux was typically in the (10–100) $\times 10^6$ photons mm^{-2} s^{-1} range at 120 kVp.

Fig. 1 shows typical room temperature photocurrent temporal response curves of fast and slow responding CdZnTe detectors. The electron mobility-lifetime products $\mu_e\tau_e$ were similar for all detectors used in this study: (4-6) $\times 10^{-3}$ cm^2/V. In general, quasi-instantaneous response stabilization (curve a) was only observed from CdZnTe detectors with high hole mobility-lifetime products $(\mu_h\tau_h)$. According to our rough estimates based on charge induction efficiency measurements, this material may have $\mu_h\tau_h \geq 5 \times 10^{-5}$ cm^2/V.

On the other hand, CdZnTe with lower $\mu_h\tau_h$ (usually, this material is slightly n-type), shows a characteristic decaying photocurrent overshot upon x-ray flux onset (Fig. 1, curve b), a behavior similar to transients previously reported for CdZnTe x-ray detectors by Du *et al.* [2]. At room temperature, we observe a fast $\sim$(2–5) ms and a slow >15 ms timescale during

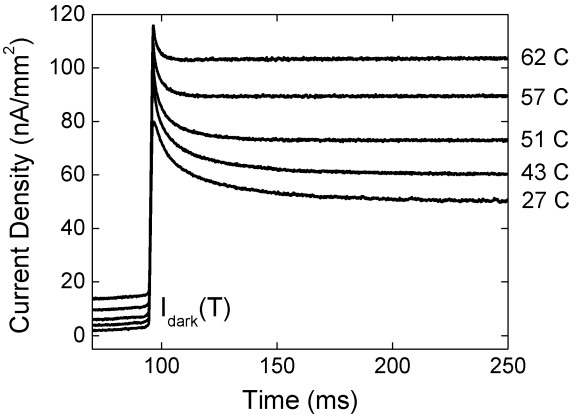

Fig. 2. Temperature dependence of the X-ray photocurrent temporal response from a planar, 2 mm thick CdZnTe detectors at 200 V.

TABLE I
TIME CONSTANTS TO FIT THE PHOTO-CURRENT DECAY IN FIG. 2

T (°C)	τ_1 (ms)	τ_2 (ms)
27	31	5
43	24	4
51	14	3
57	-	4
62	-	3

the initial photocurrent response transient. Both may be explainable by the defect structure of the lower $\mu_h\tau_h$ material in the sense that it controls the dynamics that eventually leads to a steady-state balance between a significant positive space charge profile (trapped holes) and a high-flux concentration of x-ray generated free electrons and holes. During this initial transient, the electric field, the number of available charge carriers, and hence, the photo-current change simultaneously in time. Simulating several cycles of hole trapping and detrapping, we were able to numerically obtain the correct time scale for the longer component directly from the time evolution of the hole trap population, but other charging and recombination mechanisms may contribute too (fast component). For this reason, no detailed interpretation (which would necessarily require concentrations, ionization energies, and capture cross sections of the trapping defects) will be attempted at this point.

B. Temperature

Fig. 2 shows measured response curves of a low $\mu_h\tau_h$ detector at different temperatures. The detector temperatures were estimated using the measured barrier-blocked dark leakage currents during a slow temperature ramp, i.e., the radiation detector served as its own temperature sensor [3]. The photo-current stabilization after opening the x-ray shutter could be fit with two exponential decay terms. Though, the actual time evolution of the transients is unlikely to be physically described by a simple double exponential, the fact that there are, at least, two timescales involved remains true. The time constants that fit this particular case are listed in Table I.

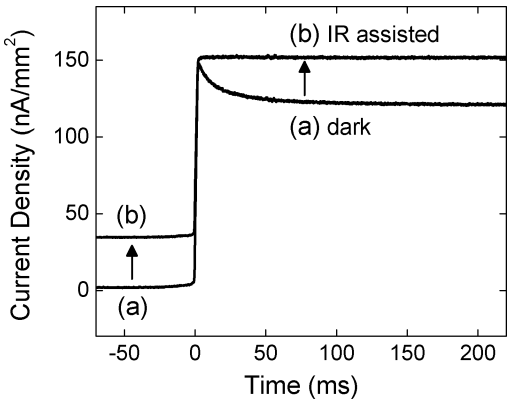

Fig. 3. X-ray photocurrent temporal response from a low $\mu_h\tau_h$, planar, 2 mm thick CdZnTe detectors at 600 V bias: (a) operated in dark, (b) with 880 nm IR illumination.

The observed behavior may be explained by the bulk defect structure as follows: In a situation, where the average de-trapping time τ_d^h controls the effective hole velocity [4]

$$v_{\text{eff}}^h = \frac{\mu_h\tau_h E}{\tau_h + \tau_d^h}, \tag{1}$$

it also dominates its temperature dependence (E is the local electric field). The hole emission rates from the traps increase roughly exponentially with the temperature but note, that an exact quantitative description of the initial dynamics is not straight-forward because the electron and hole concentrations, as well as the average defect occupations keep changing during the transient (no detailed balance). However, independent of the exact time evolution, the effective hole drift velocity in (1) increases with temperature, hence, the steady-state is reached faster and also the final electric field deterioration is reduced because of the overall shorter residence time of the trapped holes. At the same time, the recombination rates at high injection (concentrations of photo-generated carriers are much larger than their equilibrium values) increase only weakly with temperature. As a result, the fast component in the delayed photo-current response of low $\mu_h\tau_h$ detectors can still be observed at elevated temperatures, whereas the long component gradually disappears.

C. Infra-Red Illumination

In this work, we demonstrate a technical solution to obtain quasi-instantaneous ($<$3 ms) high-flux response, practically independent of the hole transport properties of the semiconductor (patent application [5]). Fig. 3 shows the temporal photocurrent response of a low $\mu_h\tau_h$ detector to a sudden high-flux x-ray exposure: Curve (a) has been measured under standard conditions in the dark and curve (b) was obtained when the same detector was conditioned by constant below-bandgap infrared (IR) illumination. At a wavelength of 880 nm ($\sim$1.41 eV), this illumination uniformly excites the entire detector volume and transfers carriers from, and to the deep levels, thereby balancing the ionized fractions of the deep levels with the free carrier concentrations in the bands to a steady-state of reduced active hole

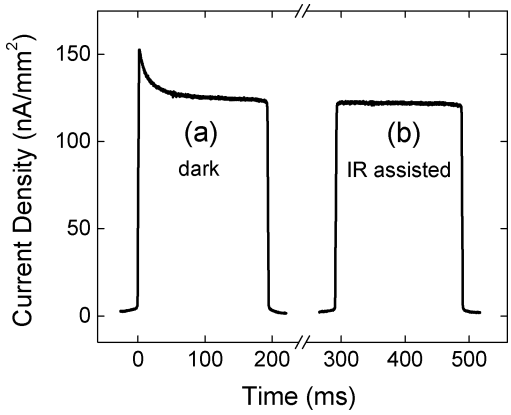

Fig. 4. Baseline corrected x-ray photocurrent temporal response to full high-flux steps from a low $\mu_h\tau_h$, planar, 2 mm thick CdZnTe detectors at 600 V bias: (a) operated in dark, (b) with 880 nm IR illumination.

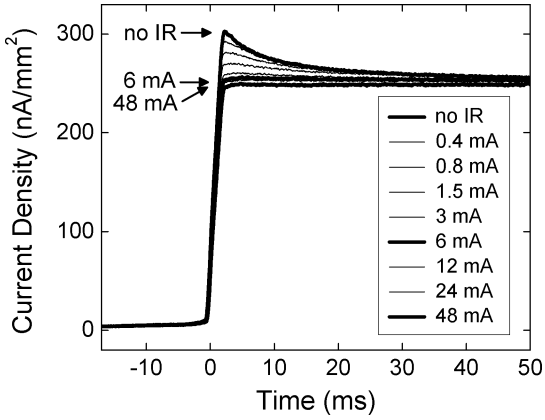

Fig. 5. Baseline corrected x-ray photocurrent temporal response from a low $\mu_h\tau_h$, planar, 2 mm thick CdZnTe detectors at 600 V bias. The curves are for different IR baseline excitations. The legend shows the IR photodiode currents, which are proportional to the IR light intensity.

trap concentrations and increased conductivity. Fig. 3 shows that under IR stimulation, the detector response instantaneously follows the x-ray flux onset but from a constant IR photo-current baseline. The detector response is stable as soon as the shutter is fully open, i.e., the response speed is indistinguishable from the high $\mu_h\tau_h$ material (Fig. 1) with the additional advantage, that lower $\mu_h\tau_h$ (slightly n-type) detectors can be operated at higher bias, which is essential to satisfy the requirement for fast charge transients. The constant IR photo-current baseline can be simply subtracted from the signal if required. Fig. 4 compares the baseline corrected response from the same detector to full x-ray flux steps operated in the dark (curve a) with the IR assisted response (curve b) under otherwise identical conditions. It is to be noted that the detectors also show nearly instantaneous photocurrent decay upon the termination of the x-ray irradiation as shown in Fig. 4. The absence of such delayed components or "afterglow" -as called for scintillator detectors- is an equally important requirement for computed tomography.

The IR light intensity needed to facilitate instantaneous response depends on the concentrations and capture cross sections of the hole traps in the relevant detector volume. This puts a minimum light intensity requirement on the IR illumination as shown in Fig. 5: In this example, the 6 mA (IR photo-diode current) ensures already a fast response. Further increase of the IR intensity does not deteriorate the response speed. Technologically, this is beneficial because it provides a broad experimental window, as one illumination configuration can be used for a multitude of detectors with a wide range of CdZnTe crystal charge transport properties, and exposed to different x-ray flux and energy ranges: There is no need to provide exactly the same illumination or separate tuning to all individual detectors.

III. Summary

The millisecond timescale response dynamics of CdZnTe x-ray detectors is controlled by the bulk defect structure of the semiconductor, which also determines the $\mu_h\tau_h$ products. Though, this provides -in principle- a materials selection criterion, it is hard to engineer and to implement such an approach during crystal growth. We show that below-bandgap illumination of CdZnTe detectors with IR light can establish a steady-state defect occupation baseline from which quasi-instantaneous response (<3 ms) to abrupt changes of a high x-ray flux ($>10^7$ photons mm^{-2} s^{-1}) can be achieved independent of the details of the semiconductor's defect structure.

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