Nuclear Instruments and Methods in Physics Research A 736 (2014) 156–160

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Transient and steady-state dark current mechanisms in polycrystalline mercuric iodide X-ray imaging detectors

M.Z. Kabir *

Department of Electrical and Computer Engineering, Concordia University, 1455 Blvd. de Maisonneuve West, Montreal, Quebec, Canada H3G 1M8

ARTICLE INFO

Article history:
Received 31 January 2013
Received in revised form
13 September 2013
Accepted 1 November 2013
Available online 13 November 2013

Keywords:
X-ray imaging detectors
Polycrystalline mercuric iodide
Dark current
Carrier injections
Thermal generation

ABSTRACT

A theoretical model for describing bias-dependent time transient and steady-state dark current behaviors in polycrystalline mercuric iodide (poly-HgI_2) based X-ray image detectors is developed. The model considers carrier injection from the metal electrode, bulk carrier depletion process, and bulk thermal generation current from the mid-gap states. The transient dark current is mainly determined by the initial carrier depletion process. At a very low applied field (less than 0.05 V/μm), the steady-state dark current is almost equal to the bulk thermal generation current. However, the injection current increases sharply with increasing the applied field. The steady-state dark current in poly-HgI_2 detectors at normal operating field (~ 1 V/μm) is mainly controlled by the Schottky emission of electrons from the metal/HgI_2 contact. The fitting of the physics-based model to the experimental results estimates the effective barrier height and interface defect states for injecting electrons from the metal to poly-HgI_2 layer in various poly-HgI_2 detectors.

1. Introduction

Flat panel digital X-ray image detectors based on using a photoconductor (commonly known as direct conversion detectors) with an active matrix array are commercially available for mammography and under consideration for a number of other medical imaging applications [1,2]. Stabilized amorphous selenium (*a*-Se) is currently the best choice of photoconductor for clinical X-ray image detectors [2]. The main drawback of an *a*-Se detector is its low intrinsic sensitivity, which particularly affects the imaging performance at low exposure imaging such as fluoroscopy [3]. Recently, there has been an active research to find potential X-ray photoconductors to replace *a*-Se because of its substantially higher electron–hole pair (EHP) creation energy W, and operating electric field F_0 ($=V/L$, where V is the bias voltage and L is the photoconductor thickness) compared to other potential X-ray photoconductors such as polycrystalline mercuric iodide (poly-HgI_2), cadmium zinc telluride (poly-CdZnTe), and lead oxide (poly-PbO) [3]. For example, the typical value of F_0 used in *a*-Se devices is ~10 V/μm where the value of W is about 45 eV; the typical F_0 is 1 V/μm and W is ~5–6 eV in poly-HgI_2 and poly-PbO [3]. Among these polycrystalline photoconductors, poly-HgI_2 is the most potential candidate for the large area diagnostic X-ray imaging and radiation therapy detectors, which shows excellent sensitivity, good resolution, and acceptable dark current, homogeneity, and image lag (it is the carry-over of image charge generated by previous X-ray exposures into subsequent image frames) characteristics [4,5].

The HgI_2 layer is deposited onto conductive (indium tin oxide, ITO, or gold coated) glass plates to fabricate a poly-HgI_2 detector structure as shown in Fig. 1. Several hundred angstroms of palladium (Pd) or Au are deposited (by direct evaporation) on top of the HgI_2 layer to form a bias electrode (top electrode). The HgI_2 is grown by either physical vapor deposition (PVD) or particle-in-binder (PIB) methods. The polymer encapsulation surrounding the structure prevents the evaporation of HgI_2 and thus, ensures long-term stability of the detector. The top electrode (radiation-receiving electrode) is negatively biased. HgI_2 tends to react chemically with most metals; hence a thin barrier layer (typically, ~1–3 μm layer of insulating polymer) is used between the HgI_2 layer and the bottom electrode to prevent the reaction and injection of holes from the bottom electrode while allowing transport of X-ray generated electrons from the photoconductor to the bottom electrode [6].

The dc current that flows through the detector in absence of light is called the *dark current*, I_d. The dark current should be as small as possible (smaller than 10 pA/cm^2 [3]), since it is a source of noise and reduces dynamic range of the detector. It is one of the most important factors for the selection of the photoconductor for X-ray imaging applications [2]. The dark current in poly-HgI_2 detectors is considerably higher than that in *a*-Se detectors [3]. The dark current in the PIB sample is an order of magnitude

* Tel.: +1 514 8482424x5688.
E-mail address: kabir@encs.concordia.ca

0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.11.014

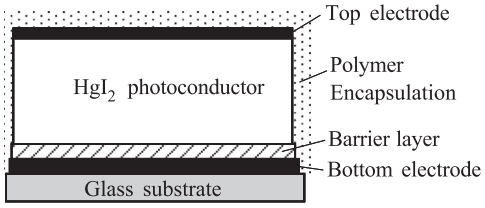

Fig. 1. Schematic diagram of a poly-HgI_2 X-ray detector structure.

smaller than in the PVD sample. It is usually very high right after applying the bias voltage and decays with time [7]. It reaches a plateau within ~60–3600 s [7]. Su et al. [8] suggested that the carrier depletion from the bulk is responsible for this transient behavior. Both the transient and steady-state dark currents depend on the applied field and electrode contacts. As per our knowledge, no attempt has been made to investigate the sources of dark current in poly-HgI_2 detectors by physics-based quantitative modeling. In this paper, we have performed a detailed analysis on quantitative dark current contributions from the bulk thermal generation, transient carrier depletion, and the electron injection through the top electrode. We propose a carrier trapping/detrapping model in the energy distributed interface states at the metal–semiconductor contacts, which can be partly responsible for the initial transient dark current behavior. The results of the proposed model are compared with the published experimental data.

2. Theoretical model

The bulk HgI_2 is slightly n-type [9] and thus there is a depletion of electrons from the defect states in the mid-gap after applying the bias. The dark current in poly-HgI_2 detectors may have three origins; (i) the depletion of electrons from the defect states within the band gap, (ii) thermal generation of carriers in the bulk, and (iii) electron injections from the metal contacts towards HgI_2 layer and subsequent trapping/detrapping of electrons in the distributed interface states at the metal/HgI_2 layer. The hole injection from the bottom electrode is neglected because of the polymer barrier layer between ITO and poly-HgI_2, and much lower hole mobility in poly-HgI_2.

The Fermi level E_F in HgI_2 at zero bias is above the midgap [9]. After applying the bias to the poly-HgI_2, electrons are depleted from the bulk and the steady state quasi-Fermi level E_{FD} lies below E_F. The temporal behavior of the carrier depletion process is determined by the detrapping time constants. The time-dependent electron depletion rate due to carrier detrapping is,

$$g_d(t)=\int_{E_v}^{E_c}\frac{N(E)}{\tau_d(E)}\left\{\frac{1}{1+\exp[(E-E_F)/kT]}-\frac{1}{1+\exp[(E-E_{FD})/kT]}\right\}\exp\left[-\frac{t}{\tau_d(E)}\right]dE \tag{1}$$

with mean detrapping time constant,

$$\tau_d(E)=\omega_0^{-1}\exp[(E_C-E-\beta_{pf}\sqrt{F_0})/kT], \tag{2}$$

where, $N(E)$ is the density of states of poly-HgI_2 at energy E in the mid-gap, F_0 ($=V/L$) is the applied field, V is the bias voltage, L is the photoconductor thickness, e is the elementary charge, ε_s ($=\varepsilon_0\varepsilon_r$) is the permittivity of HgI_2, k is the Boltzmann constant, T is the absolute temperature, t is the instantaneous time (in seconds), $\beta_{pf}=\sqrt{e^3/\pi\varepsilon_s}$ is the Poole–Frenkel coefficient, and E_C and E_v are the conduction and valance band edges. The quantity ω_0 is the attempt-to-escape frequency, defined as the product of the maximum lattice frequency and a factor, equal to or less than 1, describing the probability of the electron entering the conduction band after receiving sufficient energy [10]. Eq. (1) represents the rate of electron depletion per unit volume, which decays with time. The depletion of electron results a positive space charge $N_d(t)$ in the bulk of HgI_2.

The depleted electrons drift under the influence of the electric field and induce a current in the detector. Currents resulting from the drifting of carriers in the photoconductive detectors are due entirely to induction, which can conveniently be calculated by the Shockley–Ramo theorem [11]. Assuming that the electron lifetime is longer than the carrier transit time (in fact, the electron lifetime is longer than the carrier transit time in HgI_2 [3]) so that the retrapping may be ignored. According to Shockley–Ramo theorem the instantaneous rate of collected charge per unit area (i.e., the induced current) due to electrons liberated from traps within dx' at a distance x' from the collecting electrode is [12,13],

$$dJ_{dep}(t)=eg_d(t)\frac{x'dx'}{L} \tag{3}$$

The dependence on x' arises because the displacement current from the detrapped carrier depends on the distance x'/L. Integrating Eq. (3) over the HgI_2 layer of thickness L gives the total transient current density due to electron depletion,

$$J_{dep}(t)=\frac{eL}{2}g_d(t). \tag{4}$$

The steady-state thermal generation current in poly-HgI_2 detectors arises from the carriers excited from the deep states near E_{FD} to the band edges. The perturbation of applied electric field in the HgI_2 layer due to the space charge is negligible because the charge concentrations under dark condition is quite low (small signal case). The diffusion of carriers is negligible compared to their drift because of very high applied voltage [14]. Considering uniform thermal generation of carriers from the bulk and assuming constant drift mobility μ and carrier lifetime τ, the continuity equation of electrons with negative bias applied to the radiation receiving electrode can be written as,

$$\frac{\partial n}{\partial t}=-\mu_e F_0\frac{\partial n}{\partial x}-\frac{n}{\tau_e}+g \tag{5}$$

where, μ_e is the drift mobility of electrons, τ_e is the effective carrier lifetime, x is the distance from the top metal/semiconductor interface, and n is the free electron concentration. The states close to the middle of the bandgap of poly-HgI_2 have a high probability for thermal excitation of both types of carrier. Therefore, the thermal generation rate g is dominated by the emission from traps within kT of E_{FD}. If the excitation rates for electrons and holes are equal, E_{FD} is very close to the middle of bandgap. The generation rate for a fully depleted sample is determined by the average carrier release time and can be written as [15],

$$g=N(E_{FD})kT\omega_0\exp[-(E_C-E_{FD}-\beta_{pf}\sqrt{F_0})/kT] \tag{6}$$

where, $N(E_{FD})$ is the density of states of poly-HgI_2 at energy E_{FD} in the midgap. It is assumed in Eq. (6) that the density of states is constant over kT near E_{FD}.

Since the generation rate is uniform and equal for electrons and holes, we need to derive the expression of current for one type of carrier only. The thermally generated electrons immediately start drifting towards the back contact (i.e., $n=0$ at $x=0$) due to the applied electric field. At steady-state, the solution of (5) is,

$$n(x)=g\tau_e\left[1-\exp\left(-\frac{x}{\mu_e\tau_e F_0}\right)\right]. \tag{7}$$

The current density in the detector can be written as,

$$J_{th}=J'_e(x)+J'_h(x)+J'_D(x), \tag{8}$$

Where, $J'_D(x)$ is the displacement current density, $J'_e(x)$ and $J'_h(x)$ are the conduction current densities for electrons and holes, respectively. Considering the spatial invariant property of the total current density and integrating Eq. (8) over L, the expression of the