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Current Applied Physics 8 (2008) 383–387

Current Applied Physics
An official journal of the K@S

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Dependence of the electrical properties of stabilized a-Se on the preparation conditions and the development of a double layer X-ray detector structure

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Available online 1 November 2007

Abstract

Stabilized a-Se films deposited at sufficiently low substrate temperatures are *n*-like in which electrons can drift but holes are deeply trapped. Such layers can be conveniently incorporated in a multilayer a-Se detector structure to block the injection of holes from the positive electrode. We have shown that a simple double-layer detector structure based on a cold deposited *n*-layer (which is then annealed) on which an *i*-like layer is grown can have dark current densities lower than 10^{-10} A cm^{-2} at a field of 10 V/μm. The dark current depends on the thickness of the *n*-like layer. An a-Se X-ray detector for slot scanning was fabricated by having the *i*–*n* a-Se photoconductor structure coated onto a CCD chip. The latter detector was shown to have excellent resolution with a modulation transfer function remaining above 0.5 up to a spatial frequency of 11–14 lp mm^{-1}.

PACS: 07.85.Fv; 07.57.Kp; 81.05.Gc; 42.79.Pw

Keywords: X-ray image detector; X-ray sensor; Radiation detector; Amorphous selenium; X-ray photoconductive detector

1. Introduction

Direct conversion X-ray image detectors based on amorphous selenium (a-Se) have already been commercialized and shown to provide excellent X-ray images, especially for mammographic applications [1]. To obtain a reasonable sensitivity, the a-Se photoconductor needs an applied field of 5–10 V μm^{-1} and, at these fields, the dark current I_d in simple metal/a-Se/metal devices is higher than acceptable limits of 1–10 nA cm^{-2} [2]. The dark current is reduced by either using a thin insulating dielectric layer between the a-Se layer and the positive electrode [3] or resorting to "*p*–*i*–*n*"-like multilayer structures [4]. In the latter, an intrinsic-like (*i*-layer) thick a-Se (with both hole and electron transport) is sandwiched between two thin layers of *p*-like (doped a-Se that has good hole transport but negligible electron transport) and *n*-like a-Se (doped material that has good electron transport but negligible hole transport) as illustrated in Fig. 1a. The *p*- and *n*-like layers act as *blocking layers* to reduce dark current through the multilayer structure. The *i*-like layer transports both holes and electrons and therefore functions as an efficient X-ray photoconductor. The *p*-like and *n*-like definitions for a-Se do not follow conventional semiconductor physics definitions. They are based on the relative magnitudes of the mobility-lifetime product $\mu\tau$; e.g. $\mu_h\tau_h >> \mu_e\tau_e$ implies a *p*-type like a-Se even though the exact position of the Fermi level is not well known. The thin *n*-layer consists of a-Se doped with an alkali element (typically Na) and alloyed together with up to 10%As to *stabilize* a-Se (i.e. prevent crystallization). The *n*-like layer is the most important blocking layer in the multilayer structure because the

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doi:10.1016/j.cap.2007.10.064

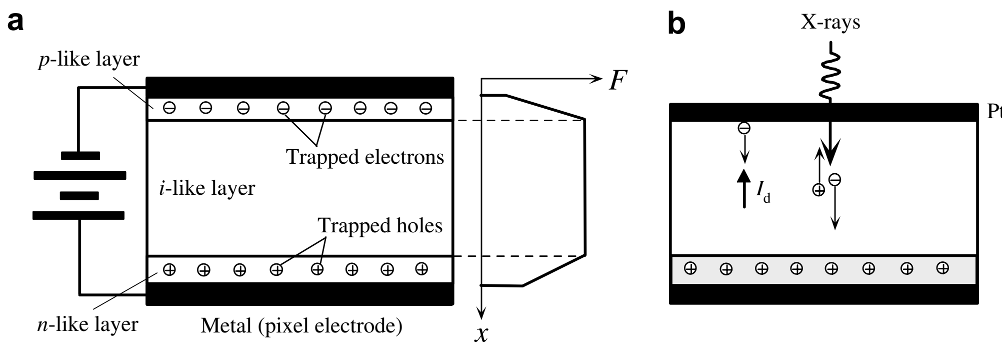

Fig. 1. (a) A simplified schematic diagram of the a-Se *p–i–n* detector structure. (b) The double layer *i–n* detector structure as developed in this work.

dark current is primarily controlled by hole injection [5]. Holes injected into the *n*-like layer become deeply trapped, and the resulting positive bulk space charge in this hole trapping layer reduces the actual field at the metal to *n*-type a-Se interface. The latter reduces the rate of hole injection from the contact as depicted in Fig. 1a. We use the term "carrier range" to represent the average distance a carrier drifts before it is deeply trapped per unit field, i.e. range is the mobility and lifetime product, $\mu\tau$. The schubweg on the other hand is usually defined as the actual distance drifted $\mu\tau F$, where F is the field.

The goal of the present work is to develop a detector structure with a low dark current without alkali dopants because they tend to induce crystallization of a-Se [6]. As we have shown recently [7], the hole range $\mu_h\tau_h$ depends on the substrate temperature during fabrication, and an a-Se layer deposited at a low substrate temperature can be *n*-like, i.e. $\mu_h\tau_h << \mu_e\tau_e$, and can therefore act as a hole trapping layer. We apply this concept to the design of an X-ray imaging system.

Our proposed new a-Se detector uses a simplified two-layer structure rather than the conventional three-layer by the elimination of the *p*-like layer, as shown in Fig. 1b [8]. The *i*-layer has good hole and electron ranges that allow this layer to function as an efficient X-ray photoconductor, whereas the *n*-layer has good electron transport but traps holes. The most significant aspect of the proposed new structure is that the same material composition can be used for both the *n*-like and the photoconductive layers. This eliminates the difficult problem of synthesizing *n* and *p*-layers by alloying and doping of a-Se. We present results on the development of the double layer a-Se detector and the choice for the metal contact for the negative radiation receiving electrode. We emphasize that the current structure is designed to have the radiation receiving electrode negatively biased because the photoconductor was designed to be used with an electron channel CCD.

2. Experimental procedure

The vacuum deposition of a-Se layers has been described previously [7]. The a-Se materials were alloyed with 0.2–0.5 wt.% As and doped with 0–5 ppm Cl. During the layer evaporation the substrate temperature $T_{substrate}$ was kept constant at a desired value in the range 0–80 °C. The boat temperature was about 250 °C. The thickness of the film was controlled by a quartz thickness monitor and finally measured by a micrometer with a precision of ±3 μm. Some of the films deposited at low substrate temperatures, $T_{substrate} < T_g$ (the glass transition temperature of the material), were annealed in vacuum for about 1 h at approximately T_g. Annealing does not affect the hole range but slightly improves the electron range. Samples that are deposited with $T_{substrate} > T_g$ are called *hot deposited* and those with $T_{substrate} < T_g$ are called *cold deposited.* The double *i–n* layer devices were fabricated by first cold depositing a thin *n*-layer, annealing it, and finally hot depositing a thicker *i*-layer. Three top electrodes were tried: Al, Au and Pt (listed in order of increasing work function).

A semitransparent Au or Pt top electrode was deposited on top of the a-Se layer in a DC sputtering unit to complete a metal/a-Se/metal sandwich structure for time-of-flight (TOF) transient photoconductivity and dark current measurements. The carrier drift mobility μ was measured by TOF experiments and the lifetime (deep trapping time) τ

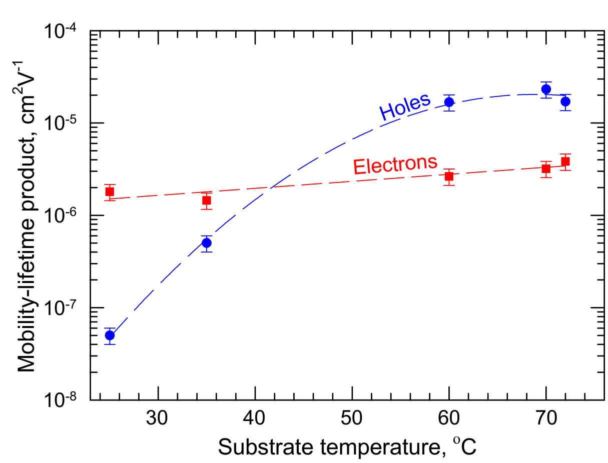

Fig. 2. Hole and electron ranges as a function of substrate temperature $T_{substrate}$ for various vacuum deposited a-Se layers of composition a-Se:0.5%As with no Cl.