Doped Chalcogenide Glasses in Digital Direct Conversion Flat Panel X-Ray Imagers for Mammography: A Review

Safa Kasap
Department of Electrical Engineering, University of Saskatchewan, Saskatoon, S7N 5A9, Canada
safa.kasap@usask.ca

ABSTRACT

The majority of the flat panel x-ray imagers currently used in mammography are based on doped amorphous selenium (a-Se) alloys. They are multilayer photoconductive detector structures with doped a-Se alloy layers and convert the absorbed x-ray radiation into collectable charges by various propriety technologies. The paper examines the research and development at the materials level of a-Se detector structures that have achieved low dark currents, high detective quantum efficiency and high resolution.

Key words: Doped chalcogenide glasses, doped amorphous selenium alloys, x-ray photoconductors

1. INTRODUCTION TO a-Se X-RAY DETECTORS

At present the majority of flat panel x-ray imagers (FPXIs) that are used in digital mammographic x-ray imaging are based on doped a-Se alloys. One of the first demonstrations of an a-Se FPXI was given by Zhao and Wei in 1995, which is considered as one of the pioneering reports on the development of a-Se FPXIs [1]. The research and development essentially involved four components: (a) Materials research based on doped and alloyed chalcogenide glasses. (b) The fabrication, characterization and modeling of multilayer photoconductors, and detectors fabricated from such photoconductors. (c) The fabrication, testing and modeling and flat panel x-ray imagers based on structures in (b). (d) The evaluation of the medical imaging performance of a-Se x-ray imagers. There are three distinctly different detector structures in use, with each technology having its own advantages and disadvantages, including the overall cost of production [2,3].

The basic requirements for an x-ray photoconductor can be summarized as follows [2]: (A) Nearly all incident x-ray photons must be absorbed, which means that the attenuation depth δ of x-ray radiation in the medium must be smaller than the photoconductor thickness L; the fraction A_Q of attenuated radiation is given as $A_Q = [1-\exp(-L/\delta)]$. (B) The intrinsic x-ray sensitivity should be as high as possible, that is, the electron and hole creation energy (ionization energy) W_{EHP} should be as small as possible. (C) The x-ray generated electrons and holes must be transported through the photoconductor without recombining, or being trapped; and become collected. The total charge collection efficiency η_{CC} should be as close to 1 as possible. This means that the schubweg $\mu\tau F$, where μ is the drift mobility, τ is the carrier lifetime and F is the applied field, must be much greater than the photoconductor thickness L for both holes and electrons. (D) The dark current I_d must be as small as possible. The noise in I_d deteriorates the DQE and restricts the dynamic range. A typical allowed dark current density is roughly 1 pA cm^{-2} [4]. (E) The longest transit time (usually x-ray generated electrons) should be shorter than the pixel access time. (F) The above photoconductor characteristics should not change or deteriorate with time and also as a result of repeated x-ray exposure; that is x-ray fatigue should be as small as possible. (G) The photoconductor layers should be readily coated onto *large area* active matrix array substrates by convenient or cost-effective deposition techniques; such as conventional vacuum deposition techniques. Special fabrication processes are generally more expensive. A large-area detector is essential in radiography inasmuch as there is no practical (and inexpensive) means to focus X-rays. Doped a-Se alloys in multilayer photoconductor structure fulfill all these requirements in the mammographic energy range and represent probably the best large area photoconductive material to date for this modality.

2. AMORPHOUS SELENIUM MULTILAYER PHOTOCONDUCTORS

One of the most important steps in the development of a-Se x-ray photoconductors was the suppression of the dark current to an innocuous level below 1 pA mm^{-2}. This was achieved by using thin blocking layers next to the bias electrodes as shown Figure 1. This three layer structure, patented in 1999, serves as the basic technology in Analogic's mammographic FPXIs shown in Figure 2. The thin layer next to the positive electrode is called an *n*-like layer. It has an alkaline doped a-$Se_{1-x}As_x$ alloy structure with the right amount of As alloying and just the right type of alkaline element and the right amount of doping to allow the electrons to have a much higher schubweg than the thickness L_n of this layer; but the holes are totally trapped. This layer is effectively an *n*-layer because only electrons can drift – holes are immediately trapped. Note that the Fermi level has not necessarily been shifted by any significant amount from midgap because the conductivity is very small. The thickness L_n of this layer is critical to the resolution of the detector and has to be much less than the thickness L_i of the bulk photoconductive layer where carriers are generated and transported. The bulk photoconductive layer must transport all x-ray generated electrons and holes. It is called an *i*-like layer because the layer is engineered by As-alloying and halogen doping of a-Se to have good electron and hole transport; $\mu_h\tau_h F >> L_i$ and $\mu_h\tau_h F >> L_i$. The thin *p*-like layer next to the negative electrode traps electrons but allows hole transport. The most common choice is a thin As_2Se_3 layer (halogen doped) but other choices have been also used such as a Cl-doped a-$Se_{1-x}As_x$ alloy. In the absence of any radiation, the thin *n*-like layer has trapped holes and *p*-As_2Se_3 has trapped electrons. The *i*-like layer is free of any trapped carriers. Thus, the electric field is uniform in the *i*-layer but it is reduced (significantly) at the electrodes. Consequently the fields that cause hole injection from the positive electrode and electron injection from the negative electrode become so suppressed that the dark current is orders of magnitude smaller than a device with an *i*-layer alone. The success of the a-Se detector is intimately linked to the development of stable *n*-like a-Se layers in which electrons would drift and holes would be totally trapped. The design of an a-Se detector involves not only choosing the compositions of the three layers and the thickness of each layer, but also the operating field F in Figure 1. Inasmuch as W_{EHP} in a-Se decreases with the field, typical operating fields are 10 V/μm or greater to achieve a respectable radiation to charge conversion efficiency. The whole detector design can be quite complicated and must also consider x-ray induced defects in the photoconductor structure and also how the structure recovers from x-ray irradiation.

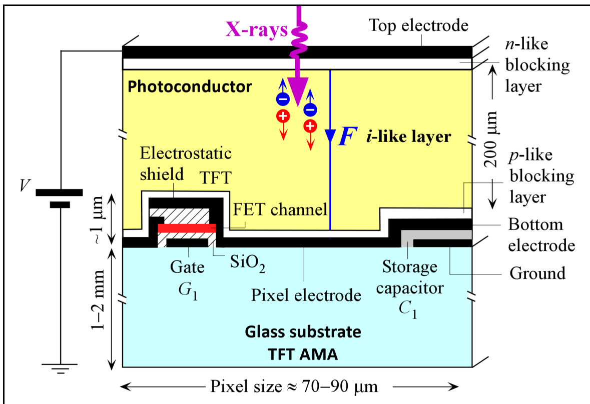

Figure 1 A simplified sketch of the cross section of a single pixel with a thin film transistor switch. The charges generated by the absorption of x-rays drift towards their respective electrodes. C_1 integrates the induced current due to the drift of the carriers, which results in a stored charge Q_1 on C_1. (Not to scale.)

Figure 2 Typical a-Se based commercial flat panel x-ray imagers as marketed by Anrad Corporation, now Analogic Canada. The shiny gray surface on the right detector (without the cover) is the top metal electrode. The multilayer a-Se photoconductor is below this electrode.

3. DEVICE AND IMAGING PERFORMANCE

There have been numerous papers that have compared the imaging performance of a-Se FPXIs with not only other photoconductive imagers but also indirect conversion based imagers.

Basically, in the mammographic energy range where the mean photon energy is very roughly 20 keV, a 200 μm thick a-Se detector attenuates 98% of the incident radiation. At an operating field F = 10 V/μm, $W_{EHP} \approx 50$ eV so that an incident 20 keV photon generates roughly 400 electrons and holes. In an electronic quality a-Se layer with long schubwegs, this represents a sensitivity of 220 pC cm^{-2} mR^{-1} at a dark current density less than 1 pA mm^{-2}. There are large area semiconductors such as HgI_2 or PbI_2 that can do much better in terms of incident radiation energy to charge conversion efficiency but the small dark current requirement usually means that they need to be operated under low fields, where the charge collection efficiency limits their sensitivity. One distinct advantage of a-Se FPXIs is their superior resolution performance compared to indirect detectors, which use scintillators. When an x-ray photon is absorbed in a scintillator, visible photons are emitted in all directions, which spreads the original line of information. This spread is overcome by using columnar scintillators, resembling bunched needles of scintillator crystals, coming out from pixels of the active matrix array. Scintillator columns guide the light toward the pixels but there is still some spread of information as light couples from one column to a neighboring column. Present a-Se mammographic imagers have a resolution that is only limited by the pixel size, currently about 50–90 μm. Moreover, the ultimate limit to the intrinsic resolution of an a-Se photoconductor is actually the range of the primary photoelectron, a few microns, all other factors being ideal. Research to date essentially confirms that a-Se is almost a perfect large area photoconductor for mammography. The a-Se photoconductive medium can, of course, experience "damage" or x-ray induced effects (deterioration). Recent work by the author's group shows that even with large accumulative doses, the changes in the x-ray sensitivity and hence the detector performance are quite small and temporary. Further, the x-ray induced defects almost always anneal out and disappear on a time scale of several hours, which depends on the temperature.

4. CONCLUSIONS

The development of a-Se flat panel x-ray imagers involved extensive research over nearly fifteen years not only at the fundamental materials level to find stable *n*-like doped a-Se alloys but also the design of three layer photoconductive detector structures in which the dark current density is below ~1 pA mm^{-2}. Today's a-Se detectors have a high detective quantum efficiency and exceptional resolution limited only by the pixel size; and dominate the mammographic detector market.

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Biography

The Ovshinsky Lectureship Award, E\PCOS 2016

Safa Kasap holds the title of Distinguished Professor of Optoelectronic Materials and Devices at the University of Saskatchewan in Canada. He is a Fellow of the Royal Society of Canada and the American Physical Society.