(U) Flat Panel X-Ray Detectors: A Review

Walter Rose
Rachel Benfante

US Army DEVCOM
Armaments Center

Picatinny Arsenal, NJ 07806

(U) Abstract: A broad survey of direct and indirect modalities for x-ray detectors is provided. A review of the current state of research is critical to understanding worthwhile R&D efforts with the goal of pushing state of the art.

(U) Research Innovation and Objective(s): The objective here is to survey relevant materials under investigation for both direct and indirect detectors for radiographic non destructive testing using x-rays.

(U) Impacts on Warfighter Mission: Ensuring that the warfighter has the best materials requires state of the art non-destructive testing equipment. Detectors play a crucial role in non-destructive testing and advances should be noted and pursued when applicable to radiographic inspection.

(U) Keywords: Non-Destructive Testing, X-Radiographic Inspection, Scintillators, Semiconductors, Direct Conversion, Indirect Conversion

1. (U) Introduction

(U) In the context of non-destructive testing, film was ubiquitous up until a decade ago. Digitization of radiographic data can occur in a multitude of ways. The disciplne of digital radiography encompasses digital detector arrays (DDAs) and computed radiography (CR). The DR modality involves the capture of an image by means of a solid state detector and saves the image via an electronic storage medium [1]. There are several immediate advantages DR has over traditional film based imaging. For instance, contrast and brightness can be adjusted using widely available image processing software packages. Radiographs can be further processed via the techniques of image processing which accentuates defects to increase probability of detection.

(U) Two categories of flat panel detectors are available. Direct flat panel detectors are photoconductors that capture incident photons and convert these photons into an electric charge. A typical photoconductor used in direct flat panel detectors is amorphous selenium (a-Se). By contrast, indirect flat panel detectors use a two step process. First, a scintillator is used to change the incoming x-rays into visible light. The most widely used scintillators are cesium iodide and gadolinium oxysulfide. The visible light is then channeled into an amorphpous silicon photodiode for the production of electrical signals [1]. The main strength of direct flat panel detectors, also known as solid state detectors or semiconductor detectors is they provide high speed, superior spatial resolution and increased sensitivity when compared with indirect conversion modalities. However, as we shall explore below, discovering suitable materials for direct conversion detectors along with their subsequent fabrication is a non-trivial task. From a material science point of view, the electronic band structure of photoconductors and phosphors used scintillators exhibit little difference. In each case, the incoming photon energy contributes to the promotion of a electron from the valence band to the conduction band. In general, phosphors have a larger energy gap than photoconductors [2].

(U) For non-destructive testing by way of x-radiation, understanding the limiting factor with regards to spatial resolution is critical. Finding minute defects is critical to performance. Intrinsic losses are present in both direct and indirect modalities. Geometrical blurring arises due to x-rays that don't arrive perpendicular to the detector surface. Electron range blurring arises from a free electron that was liberated due to the interaction with x-radiation that interacts with the detectors materials structure. K-flourescent x-rays are released after an x-ray interacts with an atoms most innermost shell. [2]

(U) It is known that x-ray attenuation is highly dependent on atomic mass. Therefore, it comes as no surprise that many solid state detectors and scintillators that involve the detectionof hard x-rays involve the high atomic number elements.

(U) In a typical photoconductor, an optical photon with energy at least equal to the value of the band gap can excite electron in the valence band into the conduction band. (figure 1) With higher energetic x-rays, the absorption phenomomon is dominated by the photoelectric effect. The production of these energetic electrons causes ionization events within the material. In this regime, the amount of energy required to create an electron hole pair is not simply the gap energy, but approximately three times the energy gap. [3]

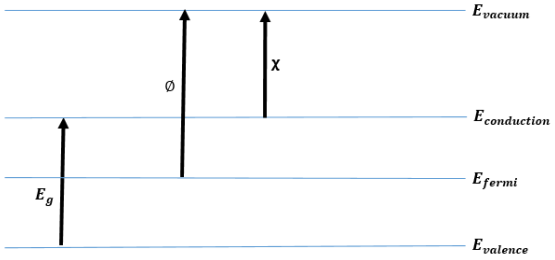

Figure 1. Simple Band Structure of a photoconductor.

(U) The majority of flat panel x-ray detectors are based on the indirect conversion scheme. Optical light produced by a scintillator is detected by amorphous silicon photodiodes that form a matrix on the panel of the detector. Numerous advantages to amorphous silicon photodiodes include small leakage current and a maximum sensitivity to visible light (green wavelengths). Furthermore, each photodiode is connected to a thin film transistor switch which allows for subsequent read-out of the pixel array.

(U) This review paper is not the focus of the amorphous silicon photodiode. However, since it is integral part of the flat panel detector, we will briefly describe some of the current research topics in improving the performance of this array for radiographic applications. Driven by the medical industry there is a desire to improve the signal to noise ratio at low X-ray doses. Efforts to improve the signal to noise ratio are focused on increasing the fill factor of a pixel. So called diode-on-top technologies and infinite photodiode layers have been explored. There have also been efforts to increase the signal in an individual pixel by means of advanced circuit in pixel amplifiers. Its important to note that a-Si technology is not the only means of large area electronics being investigated. The most obvious alternative being CMOS array detectors. [4]

2. (U) Materials

2.1 (U) Direct Conversion

(U) As mentioned previously, there are several advantages that solid state detectors have over scintillator or gas based detectors. One of the big challenges in using the semiconductor based detectors lies in the multitude of challenges arising in their manufacturing. Defects in the materials can result in trapping of the free electrons and holes which would result in a loss of the signal. In addition to this, defects can alter the intrinsic electric field resulting in distortions or other nonuniformities in the final image. Desirable qualities of solid state detectors are good carrier transport usually expressed as mu-tau, (a product of mobility times recombination time tau) and high resisitivity which translates into a low dark current. The generated charge carriers can reach the electrodes when the recombination lifetime is greater or equal to the transit time,τ_t. The transit time is given by $\tau_t = \frac{L}{\mu E}$, where L is the distance between the two electrodes and E is the electric field due to the bias voltage. Since we must have $\tau \geq \tau_t$, it follows that $\mu\tau \geq \frac{L^2}{V}$. Qualitatively, the larger the value of $\mu\tau$ the larger the detector efficiency. The mobility-lifetime is influenced by the crystalline quality and the density of impurities as mentioned above.

In the introduction, it was described that an incoming photon with an energy equal to that of the band gap of the detector material can promote an electron from the condunction band into the valence band. When an incoming photon possesses an energy much larger than the energy gap, a different physical mechanism is responsible. The presence of a high atomic number Z in a photoconductor is indicative that x-rays will be transformed via the photoelectric effect whereby energetic photoelectrons are produced. These photoelectrons move throughout the crystal structure of the detector material causing further ionization. It was found empiraclly that the amount of energy necessary to create an electron hole pair under these

circumstances is about three times the energy gap. [2]

Although silicon is considered to be a mature semiconductor technology with some excellent characterstics, it has relatively low stopping power for X-rays and therefore is restricted to low energy applications.

2.1.1 Germanium (Ge)

Elemental germanium is a naturally occuring semiconductor and therefore circumvents some of the general manufacturing challenges described previously. High purity germanium crystals are grown via the Czocharlski process. Typical dimensions of these crystals are about 100mm in length and diameter. Germanium posseses a low bandgap energy and therefore require cooling in order to be unaffected by thermal processes. Historically liquid nitrogen was used but today there are other methods of using integrated mechanical cooling that are preferable. Prototype pixel detectors have been fabricated using 1mm thick germanium with 55 micron pixel size. One protype imaging array covered an area of 256 x 256 pixels. Compared to other semiconductors discussed, high purity germanium offers superior resolution and efficiency for the spectroscopy of hard x-rays and gamma rays. Germanium has excellent mobility for both electrons and holes, and has a relatively high atomic number and density. Lastly, large pure single crystals are available for use in detectors which makes this material an excellent candidate. [5]

2.1.2 Gallium Arsenide (GaAs)

(U) Gallium Arsenide is widely used throughout the semiconductor industry and can be fabricated in large wafers. Sufficient thickness of GaAs has been difficult to achieve in combination with efficient electron hole transport and high resistivity. Recently, it has been shown that n-type GaAs with chromium doping might be able to compensate for these shortfalls. [5]

(U) GaAs pixel detectors have been produced with 55 micron pixel pitch and 768x512 pixel array. These systems can be operated at 2000 frames per second. It has also been demonstrated that this material possesses a high degree of radiation hardness which is important in the context of non-destructive testing where greater energies are required to sufficiently inspect larger manufactured items. [5]

2.1.3 Amorphous Selenium (a-Se)

(U) Amorphous selenium is typically quoted as a promising candidate for direct conversion. A thick layer, from 0.5-1mm is typically used. The band gap for a-Se is 2.2 eV. Amorphous Selenium (a-Se) is a photoconductive material which when coupled with a thin film transistor based active matrix arrays is promising for X-ray imaging. First, amorphous selenium provides excellent conductivity. Second, amorphous selenium can be applied in thick uniform layers due to its low melting point and high vapor pressure. A-Se is also known to undergo an avalanche process whereby intrinsic gain is achieved. Due to this materials high resistivity, low dark current and low thermal noise are additional advantangeous properties compared to other candidates. Lastly, amorphous selenium based detectors have superior spatial resolution. Despite the numerous advantages amorphous selenium has a number of challenges. A-Se possesses low charge carrier mobility a low charge conversion efficiency and although possesses a low intrinsic dark current, this is increased considerably under the influence of a bias voltage. [6] For large area flat panel applications, a-Se has usable sensitivities of up to 30 keV. As of 2020, this is the only commericially available direct conversion material. [8]

2.1.4. Mercury Iodide (HgI_2)

A promising candidate as a direct conversion material. This photoconductor has a number of useful fundamental properties that make it an attractive candidate for direct conversion detector. The high atomic number lends itself to great absorption of x-rays. A wide bandgap allows for the detector to perform at room temperature and the work function to create electron hole pairs is relatively small. In addition to this, a low operating voltage and processing temperature make this material a desirable candidate for direct conversion. A film mercury iodide was fabricated via the so called screen printing method. A 139 micron pixel pitch was achieved with this methodology. HIZO oxide layer was used as the thin film transistor as opposed to the conventional a-Si which was grown by the radio-frequency sputtering technique.

2.1.5. Cadmium Telluride ($CdTe$)

Cadmium telluride is a wide bandgap semiconductor with a high resistance , high atomic number and high density. These characteristcs theoretically justify the desire to

use cadmium telluride as a highly efficient room temperature detector of x rays. When compared to silcon, germanium, and GaAs, the detection efficiency for 140 keV gamma rays was found to to be superior for cadmium telluride. Epitaxial growth techniques were employed for producing large area detectors on Si substrates. It was found that metalorganic vapor phase epitaxy produced large areas with high growth rates and homogeneity. The presence of defects due to the fragility of the material and manufacturing are one of the biggest impedements to using this material. The largest size detectors have been fabricated by Dectris up to 2 megapixels with a pixel size of 172 micron reported. Long exposures coupled with high flux can cause polarization effects which can affect the performance of the detector adversely [5].

2.1.6. Cadmium Zinc Telluride ($CdZnTe$)

Cadmium zinc telluride detectors, CZT, is very simiar to the cadmium telluride detectors discussed previously. The introduction of zinc increases the bandgap which leads to better spectroscopic response. The spectroscopic resolution of CZT greatly outperforms any commeriially available scintillator. The operational temperature of this large band gap semiconductor is around room temperature. However, the material is expensive and cannot be made arbitrarily large. High pressure Bridgman techniques can produce large ingots of CZT for spectroscopic applications but THM methods are needed for imaging applications. Improvements in device fabrication have now allowed for more wide spread use of CZT detectors in computed tomography and non-destructive testing in a host of applications [5].

2.2 (U) Indirect Conversion

Materials that possess a wideband gap are usually employed for converting x-rays into ultraviolet/visible photons. Scintillation has been described by the following three subprocesses; conversion, trainsport and luminescence. In the converison stage, the photon interacts with the scintillator through the photoelectric effect and the compton scattering effect. The interaction mechanisms of the photon with the conversion material is highly dependent upon incident photon energy. The maxmium number of electron-hole pairs created can be estimated by the following equation,

$$N_{e-h} = \frac{E_\gamma}{bE_g}$$

Where E_γ, is the energy of the incoming X-ray, E_g, is the band gap energy of the detector material and b is a number whos value depends on the host matrix. The net result of this stage is the production of electron-hole pairs via excitation of electrons from the valence band to the conduction band. Followng conversion is the transport stage whereby the electron-hole pairs migrate to a luminecence center. The third stage, luminescence, is where the electron-hole pair is trapped at a luminescence center and a photon is produced upon their recombination. Electrons will return to the valence band through a local state which is created by a small amount of impurities known as activators. There is a reciprocal relationship between spatial resolution and x-ray detection. This reciporical relationship is the central weakness of all detectors that employ scintillator technology [7].

2.2.1. Cesium Iodide (CsI)

Growing cesium iodide in a columnar structure allows for a fine spatial resolution. This structure limits the lateral spread of scintillation light. When paired with amorphous silicon photodiode, CsI is doped with traces of thallium which shifts the light spectrum in order to achieve the maximum detector efficiency by the photodiode. The deposition onto a-Si is done directly by thermal evaporation which avoids any secondary optical coupling agents between the scintillator and the readout array. It is also known that CsI:tl scintillator gives the highest light output of many of the known scintillators [8].

2.2.2. Gadolinium Oxysulfide (Gd_2O_2S)

It is common to dope the gadolinium oxysulfide with terbium in order to shift its spectrum to match the photodiode TFT array for maximum efficiency. This material is a granular phosphor which can be manufactured in large sizes with the appropriate thickness [8].

4. (U) Conclusion

(U) There are numerous choices for flat panel detectors on the market today. Considerable advances have been made in the fabrication of cadmium zinc telluride detectors which might be

advantageous in certain DoD applications. This review article touched upon a host of materials for direct conversion modality and also discussed two of the most widely used indirect conversion materials. This guide should provide the necessary resources for personnel to understand important parameters when choosing a detector for both direct and indirect conversion based x-ray detectors.

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