Experimental and Monte Carlo Analyses of a-Se and CsI:Na/a-Se for X-ray Imaging

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\textbf{Abstract}-- In this paper, the pertinence of a solution using thin coplanar selenium as a photosensitive converter requiring only a few tens of volts of bias, associated with a thick columnar coating of sodium-doped cesium iodide scintillator, was evaluated. A new evaporation process for direct CsI:Na deposition on an a-Se layer substrate was developed. The photoluminescence characterization of this scintillator shows a light emission peak centered at 420 nm, as expected, which matches the sensitivity spectrum of selenium. In addition, to optimize the thickness of the CsI:Na/a-Se structure, the X-ray absorption was investigated at various diagnostic X-ray energy levels using the MCNP 4C code. The Monte Carlo simulation results showed that the absorption fraction of 500 \( \mu \text{m} \)-Se film and 180 \( \mu \text{m} \)-CsI(Na) film is about 80\% at 60 kVp. The simulation results were verified by comparing these with experimental measurements and results. The measured dark currents were below 300 pA/cm\textsuperscript{2} at an electric field of 10 V/\( \mu \text{m} \) for a-Se and CsI:Na/a-Se. The preliminary sensitivity measurements give a signal in the range of about 7.31 and 3.95 nC/cm\textsuperscript{2}/mR for 180 \( \mu \text{m} \)-CsI:Tl/a-Se and 500 \( \mu \text{m} \)-Se at the exposure conditions of 60 kVp and 2-mm aluminum filter, respectively.

I. INTRODUCTION

A new digital X-ray imager for flat-panel X-ray detectors has been studied for application in various medical modalities [1-5]. This new digital detector has many advantages over conventional radiography, such as a high dynamic range, fast image acquisition and display, digital archiving and retrieval systems, teleradiography, display of stored images with degradation, and extended capabilities of data analysis and image processing. Currently, two types of detection methods have been realized in digital radiography [6]. One is an indirect conversion method, and the other is a direct conversion method. The indirect conversion method is composed of a scintillation layer and a-Si photodiode. The incident X-ray photons are converted into visible light on a scintillator layer that is mainly composed of cesium iodide (CsI). The visible light is converted to an electrical signal by a photodiode array with PIN structure. Although the indirect conversion method has a good detective quantum efficiency (DQE), however, it has a low spatial resolution due to the spreading of light on the scintillator layer.

In the direct conversion method, the absorbed X-ray photons are directly converted into electron hole pairs on a photoconductor layer and collected as electric charges in storage capacitors. In general, superior spatial resolution is expected from the direct detection type, in which amorphous selenium (e.g., a-Se) is most commonly used as the conversion layer because of its simple conversion process [7-8]. However, a-Se layers have low X-ray sensitivity because they have an ineffectual X-ray stopping power and a high creation energy of about 50 eV for the generation of an electron hole pair. Moreover, a-Se has disadvantages, such as the breakdown of the TFT array due to the high electric field of 10 V/\( \mu \text{m} \), namely, several kV, because of the thickness (usually 500 \( \mu \text{m} \)) of a-Se-based X-ray detectors [9-10].

In this paper, a new X-ray detector that combines a columnar CsI:Na scintillation layer with a photosensitive amorphous selenium layer was investigated. In this structure, X-rays are converted into visible light on a 180 \( \mu \text{m} \)-CsI:Na scintillation layer, which is then converted to electric charges in a 30 \( \mu \text{m} \)-Se layer. The electron-hole pairs can also be generated from X-ray interaction in the a-Se photoconductor, which can improve the detection efficiency of electric charges. Using the MCNP 4C code, the X-ray absorption according to the CsI:Na thickness was simulated. In addition, the photoluminescence and electrical measurements of a-Se and CsI:Na/a-Se were evaluated. The results of this research suggest that the new CsI:Na/a-Se X-ray detector with a hybrid-type structure can resolve the following problems: high voltage from the direct conversion method, and low conversion efficiency from the indirect conversion method.

II. SIMULATION OF A-SE AND CDI:NA DETECTOR

A. Simulation Method

For the interaction between X-rays and detector materials, MCNP 4C from Los Alamos was used. In the MCNP simulation, an X-ray spectrum corresponding to 60-kV and 100-kV diagnostic X-ray source with 2-mm Al filtering was used, as shown in Fig. 1. All X-ray photons were assumed to be incident vertically from above the sample. Table 1 shows the parameters of the MCNP input file.
TABLE I
DATA OF MCNP INPUT FILE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<td>X-ray Source(kVp)</td>
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<td>Surface size(cm²)</td>
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<tr>
<td>Thickness(µm)</td>
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<tr>
<td>Material density(g/cm³)</td>
<td>CsI:Na(4.51)</td>
</tr>
<tr>
<td>History</td>
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</tbody>
</table>

Fig. 1. X-ray source spectrum obtained by x-ray tube

After incident X-ray photons interacted with the CsI:Na bulk layer, the energy spectrum and the photon number of the transmitted X-ray photons were obtained. From the transmitted total energy, the absorbed X-ray energy was calculated according to the thickness of the CsI:Na layer.

B. X-ray absorption of a-Se and CsI:Na detectors

Fig. 2 shows the X-ray transmission spectra as a function of a-Se and CsI:Na thickness at 60 kVp and 100 kVp. Continuous X-rays interacted with a-Se and CsI:Na. CsI:Na generated the characteristic X-ray peaks (29 keV, 30.5 keV, 34 keV, 36 keV, 59 keV). The characteristic X-ray peak observed in 59 keV shows that low X-ray energy is absorbed. Fig. 3 shows the X-ray energy absorption fraction with various CsI:Na thicknesses. For CsI:Na with 300 µm thickness, the X-ray energy absorption fraction was 0.9 at 60 kVp and 0.8 at 100 kVp.

Fig. 2. X-ray transmission spectrum versus the thickness of CsI:Na at (a) 60 kVp and (b) 100 kVp
III. Experiments

A. Preparation of detector

As a bottom electrode for collecting electric charges, indium tin oxide (ITO) was evaporated on a slide glass (2 × 2 cm$^2$) through the DC sputtering technique. The selenium used in this study was prepared by alloying 0.3%-wt As and 30-ppm Cl to a-Se (99.999%, Nippon Rare Metal Co., Japan), in which the electronic transport properties have been optimized [11]. Prior to CsI:Na deposition, an a-Se layer was coated on an ITO electrode using a thermal evaporator, under 10$^{-6}$ Torr. The a-Se layers have an area of 2 × 2 cm$^2$ and a thickness of 500 µm. A transparent ITO layer (1.5 × 1.5 cm$^2$) was also evaporated on an a-Se layer as an upper electrode.

The raw materials for the CsI:Na scintillation layer were prepared by mixing 99.99% CsI (Cerac Co., Japan) and 99.9% Na (Cerac Co., Japan). Sodium doping was added to match the spectral emission of the CsI:Na scintillator with the absorption spectrum of the selenium. The CsI:Na scintillation layer was obtained on the surface of an upper ITO electrode through a thermal evaporation method, under 10$^{-6}$ Torr. An evaporated CsI:Na scintillation layer has an area of 2 × 2 cm$^2$ and a thickness of 65 µm. To guide light toward a photosensitive a-Se layer, an Al material was coated on the top surface of the CsI:Na scintillation layer as a reflective layer.

B. Optical properties of a-Se and CsI:Na

The photo-luminescent spectrum of CsI:Na was measured in the wavelength range of 200-800 nm by using a double monochromator (SPEX 1403, USA) equipped with an R943-02 photomultiplier tube. The excitation source was a 325-nm line of He-Cd Laser (Spirox Holding, USA). The absorption spectrum of the a-Se layer was measured in the wavelength range of 200-800 nm using a UV-VIS-NIR Spectrophotometer (Varian Cary 5E, USA).

Fig. 3 shows the absorption fraction according to CsI:Na thickness obtained by MCNP.

Fig. 4 shows the photoluminescence emission spectrum of a CsI:Na scintillation layer (180 µm) and the absorption spectrum of an a-Se layer (30 µm). The CsI:Na layers showed a single intensity centered at around 420 nm. This emission peak is in agreement with data reported in other studies [13]. The a-Se film, on the other hand, showed a broad absorption spectra since the impurities of 0.3%-wt As and 30-ppm Cl were added to a-Se to improve the electrical properties.

C. The x-ray response characteristics

I-V characteristics of the a-Se detector and CsI:Na detector were measured to investigate their electrical properties. Even in the absence of ionizing radiation, all detectors show some finite conductivity and steady-state dark currents. The dark currents flowing through the a-Se layer were measured at a dark state after applying an electric field at an interval of 1 V/µm from 1 to 10 V/µm. The experimental setup for measuring the dark currents was composed of a high-voltage generator (EG & G 558H, USA) and an electrometer (Keithley 6517A, USA). The measurement of X-ray sensitivity was similar to that of the dark current, except for X-ray exposure [12]. A Shimadzu TR-500-125 was used as the X-ray generator to measure X-ray sensitivity. The waveform of the induced voltage generated by X-ray exposure was acquired using an oscilloscope. The total charges were calculated by integrating an acquired waveform using AcqKnowledge 3.0. The radiation dose was monitored using an Ion Chamber 2060 (Radical Cooperation, USA) during measurement.
The dark current of the CsI:Na/a-Se detector shows a similar behavior compared with that of the a-Se detector. The CsI:Na/a-Se detector exhibits a low dark current of 300 pA/cm² at an electric field of 10 V/µm. This value is as low as the value measured on a conventional X-ray detector. In digital X-ray imaging applications, the dark current must not exceed a few nA to avoid significant resolution degradation.

The interaction of incident X-ray or light photons with the atoms in a-Se produces an energetic primary electron, which then goes on to create many electron hole pairs. Fig. 5 shows the X-ray sensitivity of the a-Se detector and CsI:Na/a-Se detector as an electric field function. The irradiation conditions of the X-ray were 60 kVp, 100 mA, and 0.03 sec. The X-ray sensitivities of the CsI:Na/a-Se detector and the a-Se detector were 7.31 nC/mR/cm² and 3.95 nC/mR/cm² at an electric field of 10 V/µm, respectively. The CsI:Na/a-Se detector exhibits higher X-ray sensitivity compared with the a-Se detector, especially as the biased electric field is increased. The CsI:Na/a-Se X-ray detector, composed of CsI:Na and a-Se, has a potential capability for reducing the a-Se thickness and, therefore, the high voltage of the a-Se layer, since a direct a-Se detector uses a thick film (typically 500-1000 µm) and an extremely high electric field of above 10 V/µm, namely, several kV, for collecting charges.

In Fig. 6, the X-ray sensitivity of the a-Se detector and the hybrid detector were plotted as a function of the exposure doses. An applied electric field was fixed at 10 V/µm for both samples. The output charges are linearly increasing with the increasing intensity of incident X-rays. Furthermore, for a low X-ray intensity of below 5µR, the a-Se detector was not measured due to electronic noise, but the hybrid detector was measured to be at 1µR. Therefore, the hybrid detector presented in this study suggests its significant potential for application in digital mammography and digital fluoroscopy system.

IV. CONCLUSION

To evaluate the imaging performance of the digital detector to solve the problems inherent in a conventional X-ray detector, a new X-ray detector was made and its performance (e.g., morphology, dark current, X-ray sensitivity, linearity) was evaluated. This detector consisted of a CsI:Na scintillation layer with an a-Se photoconductor layer. An MCNP 4C input code and estimated X-ray absorption fraction according to various CsI:Na thicknesses were developed. From SEM and spectrum measurements, the morphology of CsI:Na with pillar structure, the emission spectrum of CsI:Na, and the absorption spectrum of a-Se were revealed and examined. The 180 µm-CsI:Na-coupled 30 µm-Se detector proposed in this work exhibited a low dark current and high X-ray sensitivity, and in particular, excellent linearity to X-ray exposure dose. The research presented herein reveals that a high detection efficiency is achieved by increasing the thickness of the CsI:Na layer and by fabricating the CsI:Na layer of the columnar structure.

V. ACKNOWLEDGEMENTS

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VI. Reference
