Development of Flat-Panel X-ray Image Sensors

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Abstract

New flat-panel X-ray image sensors are being studied for medical imaging applications. The combination of a thin film transistor (TFT) array and X-ray detection material constitutes the basis of the flat-panel X-ray image sensor.
We developed two prototypes of direct-detection sensors with an amorphous Se film and poly-crystalline CdTe film as the X-ray detection materials. We achieved high spatial resolution and good linear sensitivity with wide dynamic range. These image sensors have great promise as high-performance digital radiography and fluoroscopy systems for the next generation.

Introduction

In the field of medical diagnostics, a variety of imaging systems have traditionally been used to generate X-ray images, including screen/film (S/F) systems utilizing a phosphor screen and film, computed radiography (CR) systems using laser scanning to capture a latent image recorded on an imaging plate, and image-intensifier TV (II-TV) systems combining a photomultiplier tube with a CCD. Recently, however, development has been accelerating of flat-panel digital X-ray image sensors, a new type of imaging system that has the potential to supersede these[1)2)]. The key devices used in these flat-panel X-ray image sensors are a large-area thin-film transistor (TFT) array commonly used in active-matrix LCDs, and an X-ray photoconductor that converts X-rays into electrical signals. This new system offers a variety of advantages over traditional X-ray imaging systems. Compared to conventional S/F systems, a film-less system can be achieved, facilitating improved image quality based on digital image processing, diagnostic support, electronic filing, and networking. Compared to CR systems, imaging results can be instantly converted to screen-image signals. And compared to II-TV systems, a significantly thinner form is achieved, which enables high-resolution X-ray images to be obtained over a large area.

These flat-panel X-ray image sensors can be classified into "indirect conversion" and "direct conversion" systems differentiated by the X-ray detection principle. The "indirect conversion" system first converts X-ray information to visible light using scintillators and then converts the visible light into electrical signals using photodiodes. In contrast, the "direct conversion" system converts the X-ray information directly to electrical signals using an X-ray conversion film (X-ray photoconductor). In general, although the former (indirect conversion system) can take advantage of the excellent photodetection capabilities of photodiodes, it has problems such as inherent deterioration of spatial resolution due to optical scattering and the need to build a photodiode into each pixel of the TFT array on the process side. For this reason, we focused on "direct conversion systems" which eliminate the need for photodiode arrays and for which the TFT arrays used for LCDs are readily adaptable, and in which there is theoretically little deterioration in resolution. We developed two types of flat-panel X-ray image sensors-one using an amorphous Se (a-Se) film and the other using a polycrystalline CdTe film as X-ray photoconductors[3]. In this paper, we report on the structure of the sensor panel, captured image characteristics, and status of recent developments.

1. Structure of the sensor panel

1.1 Principle of operation

Fig. 1 is a schematic diagram of a direct-conversion flat-panel X-ray image sensor illustrating the principle of operation. An X-ray photoconductor and a bias electrode cover almost the entire surface of the TFT array. X-rays emitted from an X-ray generator pass through a subject such as the human body and strike the X-ray photoconductor. An electrical charge (an electron-hole pair) corresponding to the incident X-ray dose is induced. The generated charge migrates to the pixel electrode in accordance with the polarity of the bias being applied to the X-ray photoconductor, and is stored in a storage capacitor (Cs) within the TFT array. By subsequently scanning the TFTs line by line, the charge information stored in the storage capacitors can be read out from the data bus lines. The data bus line terminations connect to a charge-sensitive amplifiers (CSAs) and A/D converters, and the scanned charge information is converted to digital image signals and output sequentially.

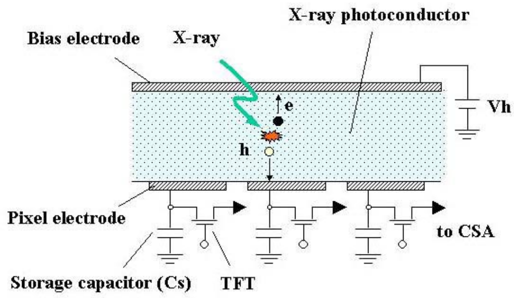

Fig. 1 Scheme of a direct-detection flat-panel X-ray image sensor.

1.2 X-ray photoconductors

Table 1 shows the physical properties of typical semiconductor materials usable as X-ray photoconductors[4]. Although a-Se is inferior in the W value (the amount of energy required to generate an electron-hole pair) and the $\mu\gamma$ product (carrier transfer property) to other materials, it is considered a promising candidate because of its attractive features such as low dark (leakage) current and low-temperature deposition over large-area substrates. On the other hand, CdTe has a high temperature of crystallization above 500°C, and its application in flat-panel X-ray image sensors has heretofore been considered difficult. However, as shown in **Table 1**, it has a smaller W value than a-Se and consequently offers high sensitivity, and it has a large $\mu\gamma$ product, and thus it can be inferred that a lower bias voltage can be used. So, it, too, is an attractive material for a high-performance X-ray photoconductor. Accordingly, we selected two types of X-ray photoconductors; a-Se

Table 1 Property of X-ray photoconductors.

Materials	State	Resistivity (Ω cm)	$\mu\tau$ product (cm^2/V)	W value (eV)
a-Se	film	1.E+12	1.E-06	50
PbI_2	crystal	1.E+13	1.E-05	5
HgI_2	crystal	1.E+13	1.E-04	4
CdTe	crystal	1.E+09	4.E-03	5

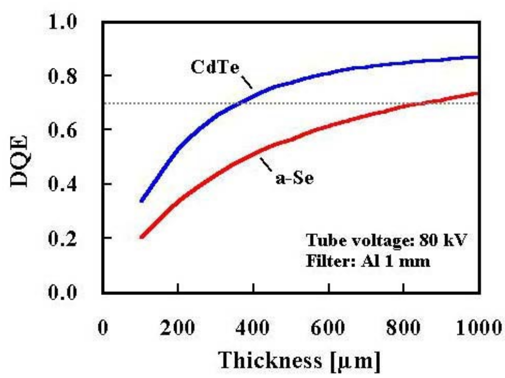

Fig. 2 Detective quantum efficiency of a-Se and CdTe.

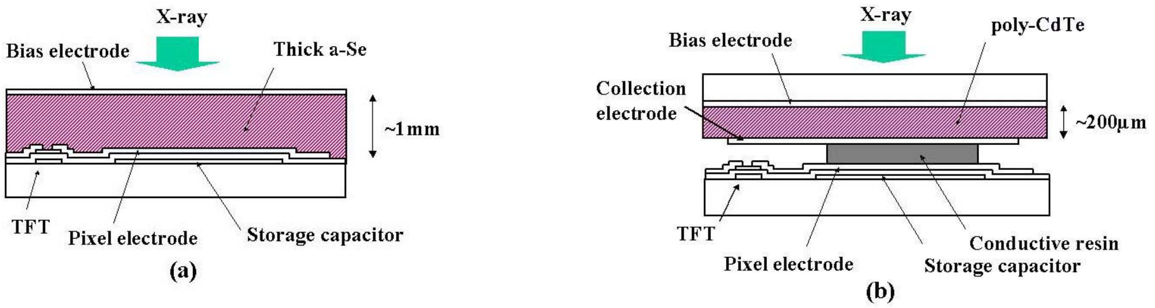

Fig. 3 Panel structure: (a) a-Se and (b) CdTe.

with its easy film deposition over large areas, and CdTe which we anticipated would offer better sensitivity.

Next, **Fig. 2** shows the dependency of the detective quantum efficiency (DQE) on the film thickness for a-Se and CdTe. We set a goal of attaining a DQE better than existing II-TV imaging systems (target value: approximately 0.7), and decided that a film thickness of approximately 1,000 μm when using a-Se and approximately 300 μm when using CdTe would be required.

1.3 Panel structure

Fig. 3 is a cross-sectional block diagram of the two sensor panels using, respectively, (a) an a-Se film and (b) a CdTe film, as the X-ray photoconductor. In the a-Se film sensor panel shown in (a), an a-Se film having a thickness of approximately 1,000 μm and a bias electrode of Au are formed directly on the TFT array by vacuum evaporation method. The TFT array is based on those used in LCD applications, and is designed so that its storage capacitors will have a value one order of magnitude higher. In contrast, because a CdTe film cannot be deposited directly onto the TFT array, the CdTe film sensor panel shown in (b) newly adopts what we call a "hybrid panel structure" in which the CdTe film and TFT array are first formed separately and then later bonded together[5]. This technique enabled us to readily utilize a CdTe film which requires a film deposition temperature in excess of 500°C as the X-ray photoconductor. As the method of depositing the CdTe film, we adopted the close-spaced sublimation method (**Fig. 4**), originally developed for solar cells. This method enables the formation of a polycrystalline-structured CdTe film at high speeds (greater than 5 μm/min), and is expected to be applicable to larger surface areas in the near future.

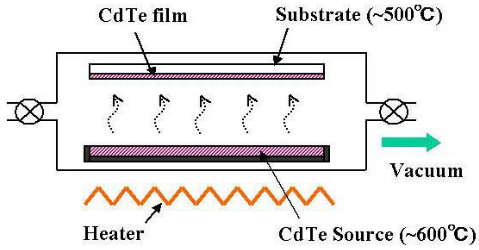

Fig. 4 Close-spaced sublimation.

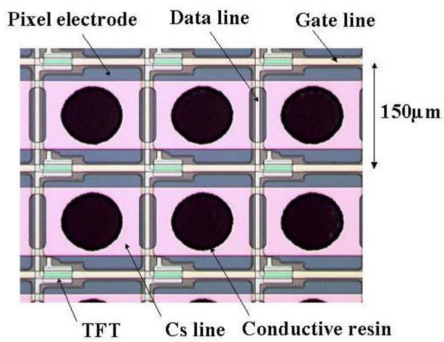

Fig. 5 Patterned conductive resin.

For electrical connections between the CdTe film and the TFT array, we adopted a conductive resin with adhesive properties. **Fig. 5** is a photograph showing the conductive resin in a patterned configuration on top of the TFT array. This conductive resin is a dry film in which a conductive pigment is dispersed in photosensitive resin, and can be formed as bumps on the top of the pixel electrodes of the TFT array using standard photolithography techniques. The TFT array on which the bumps of conductive resin are formed and the CdTe film can be joined by using the hot pressing methods employed in the bonding process for LCD panels.

The interconnect resistance of the conductive resin is approximately 10^5 Ω/pixel, but if we take account of the capacitance (1 to 1.5 pF) of the storage capacitor (Cs), the value of the CR time constant relative to the readout rate (33 ms per scan period) will be sufficiently low.

1.4 Specifications of 3-inch prototypes

Table 2 gives the specifications for a 3-inch prototype for each type of panel using an a-Se film and a CdTe film for the X-ray photoconductor.

Table 2 Specification of 3" prototypes.

Description	Specification		Unit
Detector film	a-Se	CdTe	
Panel structure	Conventional	Hybrid	
Film thickness	1,130	200	μm
Electric field	5.0	0.1	V/μm
Array format	512 x 512		dots
Array dimensions	76.8 x 76.8		mm^2
Pixel pitch	150		μm

2. Captured image characteristics

2.1 Sensitivity

Fig. 6 shows the X-ray sensitivity of the 3-inch prototypes profiled in **Table 2**. It confirms that both the a-Se film and CdTe film sensor panels have excellent linearity over at least three orders of magnitude for X-ray doses in the fluoroscopic to radiographic range. In addition, it was confirmed that the CdTe has roughly four times the sensitivity, in spite of the smaller bias field of this X-ray photoconductor, compared to the a-Se film.

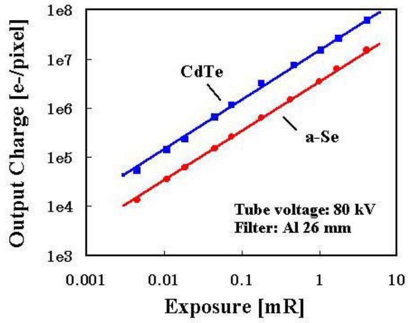

Fig. 6 X-ray sensitivity of 3" prototypes.

2.2 Spatial resolution

Fig. 7 shows the resolution chart patterns imaged by the respective prototype units. For a-Se, a resolution of 3.2 lp/mm was confirmed, equivalent to the pixel pitch of the TFT array (0.15 mm). For the CdTe film, it appears that the resolution is somewhat inferior compared to the a-Se film. Accordingly, we evaluated the frequency response of the spatial resolution of both (MTF: modulation transfer function). The results are shown in **Fig. 8**. The MTF of the a-Se film shows a response

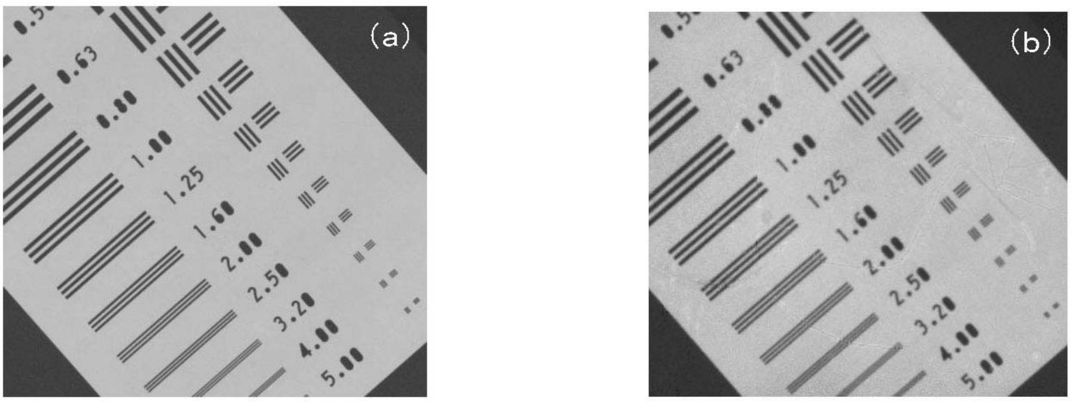

Fig. 7 Resolution pattern: (a) a-Se, (b) CdTe.

that follows theoretical values, but the MTF of the CdTe film deviates from theoretical values. Therefore it is confirmed that the resolution is reduced with the CdTe film. The primary cause is thought to be the low sheet resistivity of CdTe films.

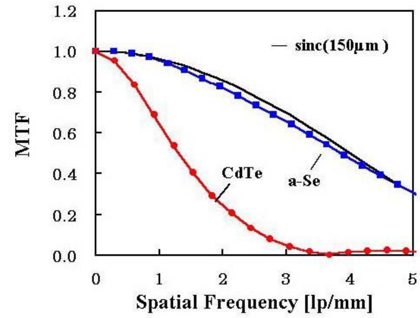

Fig. 8 Modulation transfer function of 3" prototypes.

2.3 Images

Figs. 9 and **10** are radiographic images generated by each of the prototype units. In **Fig. 9**, the fibrous structure of the bone is clearly evident, which illustrates the superior resolving power of the a-Se film. Meanwhile, the example in which the image was acquired using a CdTe film as the X-ray photoconductor is unprecedented, and **Fig. 10** is the world's first X-ray image obtained from a CdTe film. It should also be noted that it has been confirmed that both sensor panels are capable of capturing real-time video images at 30 frames/second.

3. The challenges of larger surface areas and performance improvements

3.1 a-Se sensor panel

The feasibility study described above confirmed that the a-Se sensor panel has excellent resolution as well as sensitivity usable on the practical level. Accordingly, as a step toward practical application, we decided to develop a new prototype sensor panel with an enlarged image area of 9" x 9" [6].


Fig. 9 X-ray image of a hand phantom (3" a-Se).

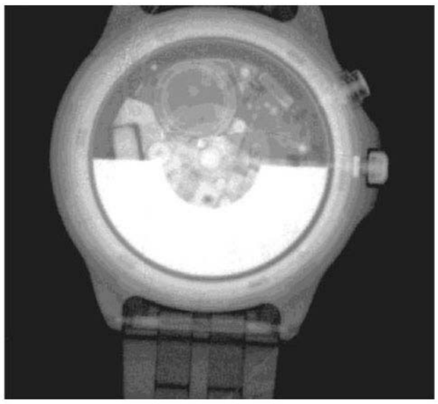
Fig. 10 X-ray image of a watch (3" CdTe).

Table 3 lists the specifications for this 9-inch sensor panel, and **Fig. 11** shows an external view of the resulting sensor module. Six driver ICs are TAB-mounted along the top edge, and 12 amplifier ICs mounted the same way on the left and right edges (for a total of 24) enable readout data to be output from both the right and left sides. When a bias of 10 V/μm was applied to this sensor panel, a DQE of approximately 0.75 was measured at an X-ray tube

Table 3 Specification of a 9" a-Se prototype.

Parameter	Specification	Unit
Array dimensions	230 x 230	mm^2
Array format	1536 x 1536	dots
Pixel pitch	150	μm
Film thickness	1000	μm
Readout rate	30	fps

voltage of 80 kV. This high value exceeds that of conventional II-TV imaging systems.

Fig. 12 shows a radiographic image of a head phantom taken using this sensor panel. Superb resolution and wide dynamic range resulted in clear, distinct image quality over the entire area. Of course, real-time video imaging at 30 frames/second is also possible.

In the future, as a step toward commercialization, we plan improvements in low-noise amplifier ICs, reliability evaluations such as tolerance to ambient temperatures, and development of a sensor panel designed for general-purpose radiographic systems capable of taking thoracic images (imaging area: 17" x 17"), and are working toward eventual evaluation in the clinical setting.

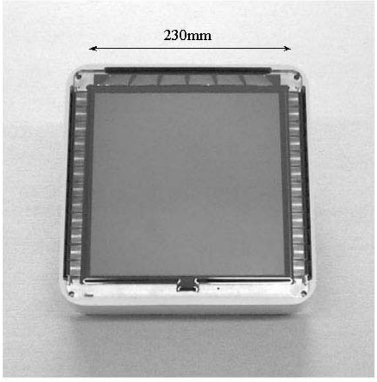

Fig. 11 Appearance of a 9" a-Se prototype.

Fig. 12 X-ray image of a head phantom (9" a-Se).

3.2 CdTe sensor panel

The previously noted feasibility study demonstrated that CdTe sensor panels exhibit higher sensitivity than a-Se sensor panels. This indicates that using a CdTe sensor panel would enable a reduction in the X-ray dosage the body would be exposed to, and therefore, reduced risk during fluoroscopic (moving) imaging.

At present, the problem with the resolution of CdTe films has been identified, and as a solution, we think that, by doping the CdTe film with Zn, it would be possible to widen the bandgap, or increase the film resistance and reduce the leakage (dark) current. When we actually constructed a prototype sensor panel using a Zn-doped Cd(Zn)Te film, we confirmed that the MTF (at 1 lp/mm) was improved from 0.6 to 0.8. In addition, no deterioration was apparent in the X-ray detection characteristics even though we omitted the collection electrode formed in the pattern on the CdTe film in the panel structure shown in **Fig. 3(b)**, which means that it is possible to simplify the panel design[7].

In view of above-mentioned results, we think that Cd(Zn)Te sensor panels have great promise for next-generation high-performance sensor panels.

Conclusions

We developed direct-conversion flat-panel X-ray image sensors that combine an X-ray photoconductor (a-Se film or polycrystalline CdTe film) with TFT array technology, the key technology in active-matrix LCDs. We constructed a 9-inch-square prototype sensor panel using a-Se, and confirmed excellent resolution as well as sensitivity usable on the practical level. Meanwhile, by adopting a novel and original hybrid panel structure, we demonstrated for the first time that a polycrystalline CdTe film can be utilized as an extremely high-sensitive X-ray photoconductor. These flat-panel X-ray sensor panels hold out promise as digital imaging devices that can be used for both real-time imaging (fluoroscopy) and static imaging (radiography) in the near future, and new diagnostic systems taking advantage of telecommunications networks can be anticipated.

In addition, through this research, we confirmed that the TFT arrays used in LCDs can be applied to input devices, and in the near future, new applications for TFT arrays beyond the display field can be expected.

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