An Indirect-Conversion Flat-Panel X-Ray Detector Based on Amorphous Silicon 3-D One-Transistor Active Pixel Sensor

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ABSTRACT

An active pixel sensor (APS) has been proposed for achieving high signal-to-noise (SNR) ratio in indirect-conversion flat-panel X-ray detectors and usually consists of multiple thin-film transistors (TFTs). Since 2015, we have developed a dual-gate three-dimensional (3-D) photosensitive one-TFT APS to obtain both high resolution and high gain. In this work, a flat panel detector with an array of 3840×3072 was developed with an image sensitivity of 281.6 lsb/μGy and a spatial resolution of 6.7 lp/mm, enabling mammographic imaging application at a low dose.

1 Introduction

TFTs with active matrix have become ubiquitous for flat-panel display and large-area X-ray imaging. Initially, for an indirect-conversion flat-panel X-ray detector, a passive pixel sensor (PPS) with a combination of a TFT and a photodiode (PD), normally, a PIN structure is used [1]. However, its low SNR value limits its applications in some low-dose X-ray imaging modalities, for example, mammography. Hence, an APS with multiple TFTs has been proposed and leads to a high SNR as a result of using an in-pixel TFT amplifier. Conventionally, three-transistor (3T) APS was commonly used [2], nevertheless, it dramatically decreases fill factor or increases pixel size and consequently leads to a low spatial resolution. Alternatively, an APS composed of two transistors and one capacitor (2T1C) was proposed to improve resolution to some extent but it suffers from low readout speed [3]. Therefore, there exists a tradeoff between high resolution (small pixel) and high SNR. In order to resolve it, we have developed a one-TFT APS formed by a 3-D dual-gate photosensitive TFT [4-11]. Until recently, a 14.5-inch flat-panel X-ray detector has been prototyped and the 3-D 1-T APS concept was therefore fully proved.

2 Detector Design and Characteristics

The cross-sectional schematic structure of the 3-D dual-gate photosensitive TFT is shown in Fig. 1(a). The traditional planar a-Si:H channel is replaced by a 3-D π-shape active layer to improve the light absorption. When the device is under light illumination, the photogenerated electron-hole pairs will be separated by the electric field between the top and the bottom gate electrodes. Then the electrons will be accumulated at the bottom interface of the channel and the holes will be on the top interface. In this way, a “virtual” PIN-like photodiode is formed inside the structure and will tune the threshold voltage of the bottom TFT under light illumination. The equivalent circuit model of the photosensitive TFT are shown in Fig.1 (b).

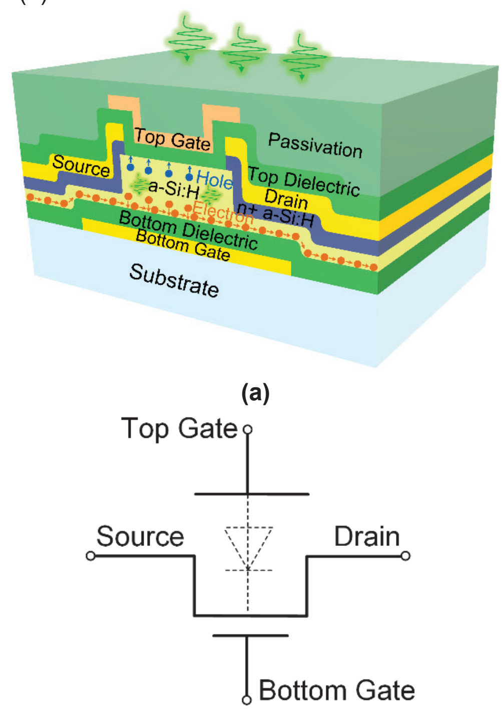
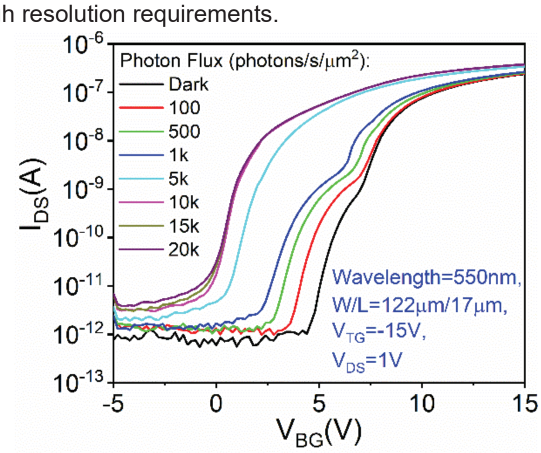


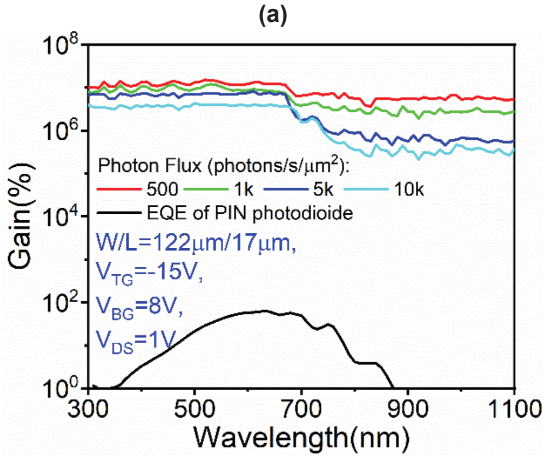
Fig. 1 (a) Schematic diagram of 3-D dual-gate photosensitive TFT. (b) Equivalent device circuit model.

The photocurrent of the device under various photon flux is shown in Fig.2 (a) and the transfer curves of the TFT shift negatively when there is a certain photon flux. The threshold voltage of the TFT is therefore modulated because of the accumulation of the photogenerated electrons and holes on the bottom and top interface of the active layer and it decreases under the light illumination. When the TFT works in the subthreshold region, the output current of the TFT is in an exponential relationship with the threshold voltage. Hence, a small change of the threshold voltage induced by the light illumination will cause an exponential change of the output current, and the photoconductive gain can reach 10^3~10^5 as presented in Fig. 2(b). The achieved high gain is several-order-of-magnitude higher than that of the traditional PIN-type photodiode (PD). Fig.2 (b) also unveils that the 3-D dual-gate photosensitive TFT is able to detect a wide range of light with wavelengths in the experiments ranging from 300nm to 1100nm. These characteristics help the sensor fully utilize all the possible income photons and greatly increase the gain of the device.

Fig.3 plots the calculated SNR as a function of pixel size. This 3-D dual-gate photosensitive TFT has much higher SNR than other conventional designs with the pixel size ranging from 50μm to 140μm. The dependence of SNR on pixel size in Fig. 3 verifies that the proposed novel one-TFT APS has the potential to tackle the tradeoff between high spatial resolution (small pixel) and high SNR. Taking advantages of this performance characteristics, the 3-D 1T APS design is suitable for image sensors especially with high resolution requirements.



(a)



(b)

Fig.2 (a) Transfer curves of the 3-D dual-gate photosensitive TFT under photon flux from 0 to 10k photons/s/μm².

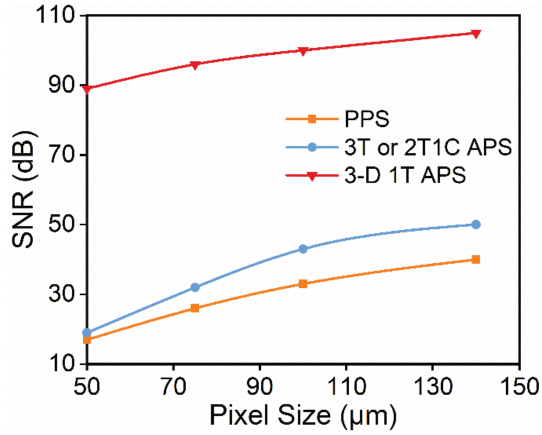


Fig.3 Dependence of pixel SNR on pixel size between prior arts and this work. The SNR here is calculated using 20log(I_{photo}/I_{dark}).

3 Flat Panel X-ray Detector

A sensor array of 3840×3072 with the pixel size of 75μm integrated with cesium iodide (CsI:T1) scintillator for converting X-ray photons into visible light was then fabricated in an industrial-standard G2.5 TFT production line as shown in Fig. 4(a). Top gate and bottom gate driver ICs and several 256-channel readout ICs were connected to the sensor array to acquire light-induced current and output digital signal. Subsequently, a 14.5-inch indirect-conversion flat panel X-ray detector based on the sensor array was assembled as illustrated in Fig. 4(b). The image acquisition user interface was also developed to capture gray-scale images. Fig. 5 depicts the image of a tissue-equivalent breast phantom for mammography obtained from the detector, where the simulated calcifications, hemispheric masses and step wedge inserts of the phantom can be clearly identified. The dose condition used here is 32kVp and 20mAs.

Furthermore, Fig. 6 shows the measured modulation transfer function (MTF) of the detector by 60kVp and 6.3mAs. The extracted spatial resolution of the detector reaches around 6.7lp/mm based on the data in Fig.6. Fig. 7 illustrates the relationship between the gray and X-ray dose implying that the image sensitivity can be up to 281.6 lsb/μGy.

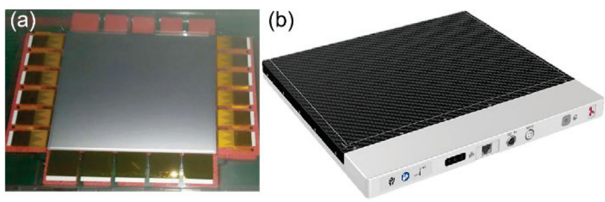


Fig.4 (a) Photos of the detector module including the sensor array and external ICs and (b) the flat-panel detector prototype.

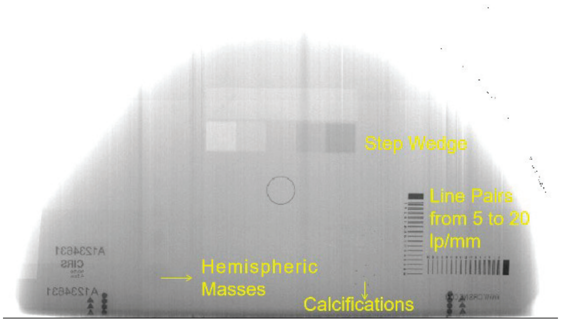


Fig.5 Image of a tissue-equivalent phantom for mammography captured by the detector.

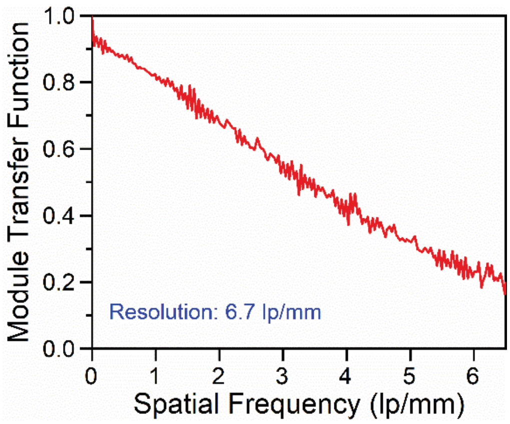


Fig.6 MTF dependence of spatial frequency.

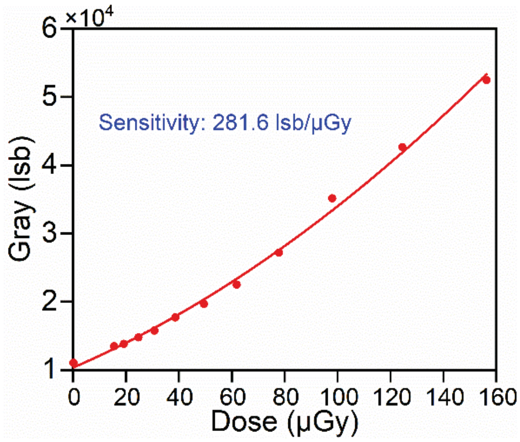


Fig. 7 Relationship between image gray level and X-ray dose, implying that the image sensitivity is 281.6 lsb/μGy, one-fold increase as compared with the commercial product.

4 Conclusion

In this work, we demonstrate a 14.5-inch flat-panel X-ray detector consisting of 3840×3072 sensor array with a pixel size of 75μm. Thanks to a 3-D dual-gate photosensitive TFT, such a one-transistor has a gain of 10^3~10^5 and resolves the tradeoff between high resolution and high sensitivity. Thus, the proposed detector achieves an image sensitivity of 281.6 lsb/μGy and a spatial resolution of 6.7lp/mm, promising for large-area low-dose imaging applications.

Acknowledgment

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