Dual-gate photo thin-film transistor: a “smart” pixel for high-resolution and low-dose X-ray imaging

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Abstract. Since its emergence a decade ago, amorphous silicon flat panel X-ray detector has established itself as a ubiquitous platform for an array of digital radiography modalities. The fundamental building block of a flat panel detector is called a pixel. In all current pixel architectures, sensing, storage, and readout are unanimously kept separate, inevitably compromising resolution by increasing pixel size. To address this issue, we hereby propose a “smart” pixel architecture where the aforementioned three components are combined in a single dual-gate photo thin-film transistor (TFT). In other words, the dual-gate photo TFT itself functions as a sensor, a storage capacitor, and a switch concurrently. Additionally, by harnessing the amplification effect of such a thin-film transistor, we for the first time created a single-transistor active pixel sensor. The proof-of-concept device had a W/L ratio of 250µm/20µm and was fabricated using a simple five-mask photolithography process, where a 130nm transparent ITO was used as the top photo gate, and a 200nm amorphous silicon as the absorbing channel layer. The preliminary results demonstrated that the photocurrent had been increased by four orders of magnitude due to light-induced threshold voltage shift in the sub-threshold region. The device sensitivity could be simply tuned by photo gate bias to specifically target low-level light detection. The dependence of threshold voltage on light illumination indicated that a dynamic range of at least 80dB could be achieved. The "smart" pixel technology holds tremendous promise for developing high-resolution and low-dose X-ray imaging and may potentially lower the cancer risk imposed by radiation, especially among paediatric patients.

1. Introduction
Over the last two decades, flat panel X-ray detector (FPD) has become commercially available for various medical imaging modalities including chest radiography and mammography[1]. Silicon thin-film transistor (TFT) technology which has gained increasing popularity in large area manufacture is widely utilized in making FPDs. An FPD is essentially an amorphous silicon (a-Si:H) imaging sensor array containing millions of pixels. As a fundamental building block, a pixel typically consists of three components: sensor, storage, and switch to meet the needs of signal generation and collection, storage and readout. In terms of pixel architecture, a passive pixel sensor (PPS) is simple and includes a
switching TFT and storage capacitor while an active pixel sensor (APS) differs by embedding an additional in-pixel amplifier TFT and thereby, leading to a higher signal to noise ratio (SNR) and reduced exposure dose requirement[2][3]. Nevertheless, in all current pixel architectures, either passive or active, the abovementioned three components are unanimously kept separate with a major disadvantage being trade off spatial resolution for a decent SNR.

In this work, we proposed and studied a “smart” pixel architecture that combines sensor, storage, and readout into one single dual-gate photo TFT, which apparently outperforms all conventional structures, not only for being much more space-efficient, especially for high-resolution X-ray imaging, but also for making a higher SNR possible upon TFT amplification.

Most previous reports on dual-gate TFTs were mainly focused on switching performance and applications in circuits, biosensors, and displays[4]. Such a device was primarily designed to allow for better control and reliability in threshold voltage operation. Recently, Kim et al. demonstrated a dual-gate HIZO/IZO Photo TFT intended for a transparent imager[5]. To our best knowledge, this was one of the few works to address photosensing applications of dual-gate TFTs. However, it still works as a passive pixel sensor and was only sensitive to short-wavelength light given the wide band gap of HIZO/IZO semiconductors.

Compared with existing works, our dual-gate TFT was set apart by its ease of production and the possibility of forming a compact single transistor APS so that in-pixel amplification can be readily achieved. This is of particular interest to low-dose X-ray detection such as pediatric imaging where patients are more susceptible to radiation dose.

2. Pixel Architecture

Fig. 1 depicts a schematic representation of the cross-sectional structure of an X-ray imaging pixel using an amorphous silicon dual-gate photo TFT. At the top of the pixel, there lies an X-ray scintillator (e.g. CsI) that converts X-ray to visible light. Underneath the scintillator, it is a four-terminal a-Si:H dual-gate photo TFT composed of a photo gate (Photo G-PG), a dark gate (Dark G-DG), a source electrode (S) and a drain electrode (D) to complete the whole signal collection, storage, and readout operation. In order to enhance photo absorption, a thick a-Si:H layer is generally used.

3. Results and Discussion

3.1. Device Fabrication

We set out to design and fabricate a dual-gate photo TFT using a five-mask process: first of all, a 120 nm Cr film was sputtered and patterned on Corning 1737 glass substrate to form gate electrodes (Mask No. 1); a 220 nm SiNx/240nm a-Si:H/60nm n⁺-a-Si:H triple-layer was then deposited consecutively at 200°C by using conventional PECVD consecutively without breaking vacuum and this was followed by the deposition of a 130 nm Cr film by sputtering; thirdly, Cr and n⁺-a-Si:H layers were patterned.
by wet etching and dry etching to form source and drain electrodes (Mask No. 2); subsequently, a TFT island was created through etching the a-Si:H (Mask No. 3) layer; followed by a 220nm SiNx deposition atop to form a top gate dielectric through PECVD at 200°C; a 130nm ITO was then sputtered and patterned to form the top gate electrodes (Mask No. 4); in the end, a 200nm SiNx was deposited by PECVD to passivate the entire device and was patterned for via opening on the source, drain, and gate electrodes through dry etching of multiple layers (Mask No. 5).

The resulted device was examined under an optical microscope and layer thickness and interface information were obtained using scanning electron microscopy (SEM) and a cross-sectional interface was obtained through focused ion beam milling. Fig. 2 is a cross-sectional image, clearly demonstrating each layer and interfaces there between.

![Cross-sectional Image](image)

**Fig. 2** The cross-sectional image of the dual-gate photo TFT by FIB-SEM

### 3.2. Device Characterization

![Transfer Characteristics](image)

**Fig. 3** The transfer characteristics of the bottom TFT in the presence and absence of light exposure.

White light source: 3.8 Lux.

Upon light exposure, the transfer characteristics were modulated as shown in Fig. 3. The IV curve shifted towards negative gate voltage, indicating that the device could be easily turned ON under illumination. In another word, the threshold voltage was lowered as a result of light illumination. This served as experimental evidence of amplification effect. The photo-induced threshold voltage decrease conferred the device a signal gain when it was operated in the subthreshold voltage region. For instance, at a dark gate bias of ~2V, the output photocurrent $I_{DS}$ can be enhanced by four orders of magnitude from $\sim10^{-12}$A to $\sim10^{-8}$A. Such signal gain mainly stems from the decrease in threshold voltage which is a function of the light intensity, the $V_{PG}$, and the top transistor capacitance.
To explore its potential application in low-dose light detection, the device was studied particularly under low-level light exposure. Fig. 4 illustrates the dependence of threshold voltage on light intensity. At a lower $V_{PG}$ and lower light intensity, the threshold voltage change was not distinguishable. However, as the $V_{PG}$ increased, the device became more sensitive since the threshold voltage also increased and accordingly, the threshold voltage change became more distinguishable (Fig. 4). The essential role that the $V_{PG}$ played was to enhance the low-dose light sensitivity through increasing the original threshold voltage. The preliminary result showed a ~ 80dB dynamic range at low light levels. The device is therefore promising to work in the low-dose light exposure for low-dose indirect X-ray imaging.

4. Conclusion

We have successfully designed and fabricated a dual-gate photo TFT based on amorphous silicon TFT-LCD processes. With the sensor, storage, and readout functions combing in one device, the dual-gate photo TFT have demonstrated desirable features such as high resolution, high sensitivity, and simplicity. The device was sensitive to low-level light exposure as well and therefore could potentially work as a single transistor active pixel sensor for low-dose X-ray imaging especially for pediatric patients.

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