Heterojunction IGZO Phototransistors for Next-generation Photodetectors and Image Sensors

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ABSTRACT

Heterogenous integration of oxide TFT with an organolead halide perovskite photoabsorbing layer is an attractive approach for developing low-noise high-sensitivity photodetectors. Here, the development of various perovskite/IGZO heterojunction phototransistors are reviewed. The proposed phototransistor architecture described here provides a viable route to realize low cost, high-resolution x-ray imaging or neuromorphic vision applications.

1 Introduction

Conventionally, the flat panel imager (FPI) is composed of arrays of amorphous silicon (a-Si) photodiodes (PD) and thin film transistors (TFTs) [1]. Although the a-Si FPI is commercially available, the large density of trap states in the a-Si leads to image lag and memory effects [2]. It is also quite challenging to meet high-resolution requirements as the leakage current of a-Si PD is usually increased when scaling down the pixel size [3]. Moreover, the fabrication of the a-Si PD requires combustible process gases and 4-5 additional photolithography masking steps, which makes the manufacturing process costly. Phototransistors (photo-TFTs), which have advantages such as low dark-current, low noise and high photoconductive gain[4-7], are emerging as a low-cost sensing alternative photosensor. Moreover, the fabrication process of photo-TFTs is compatible to the TFT production line, and can facilitate the design of pixels with channel length/width in the scale of several microns. The use of a-Si photo-TFT for photodetection can be dated back to early 1990s[8]. However, the application of a-Si photo-TFT has largely been hindered by its low responsivity. The IGZO TFT can also act as a photosensor as well, yet it is only sensitive to ultraviolet or deep blue illumination. Low-cost organolead halide perovskite materials, with their outstanding optoelectronic properties, provide new opportunities for developing highly sensitive photodetectors for various sensing scenarios. Heterogenous integration of oxide TFT with an organolead halide perovskite photoabsorbing layer is an attractive approach for developing low-noise high-sensitivity photodetectors.

Here, the development of heterojunction IGZO phototransistor by using quasi-two-dimensional (quasi-2D) perovskite is reported. The fabrication process of heterojunction phototransistor is compatible with conventional TFT manufacturing processes. Using photolithography and spin-on patterning techniques, photodetector size with 5 μm channel length is obtained. The patterned phototransistor achieves a suppressed off-state drain current of ~10 pA, a high responsivity of larger than 10³ A/W, and a detectivity of greater than 3×10¹³cm·Hz¹/₂W⁻¹. The perovskite-IGZO photo-TFT can be applied to low dose x-rays detection under a dose rate of ~10μGy/s. Moreover, by replacing perovskite thin films with perovskite quantum dots, the phototransistor demonstrates tunable photo-synaptic behavior. The phototransistor architecture reviewed here provides a viable route to realize low cost, high-resolution x-ray imaging or neuromorphic vision applications.

2 Experiment

2.1 Quasi-2D perovskite layer

A precursor of BA₂MA₃Pb₁₃ was optimized for heterojunction photo-TFT performance. The quasi-2D perovskite layer is deposited by hot-casting method. The BAI, MAI, and PbI₂ powders were mixed at a molar ratio of 2:3:4, and heated to 70 °C. The device substrate is heated to 150 °C. The spin coating speed is 5000 rpm for 20 seconds in a glove box in a nitrogen environment. Precursors with 0.3M Pb concentration gives a perovskite layer thickness of ~150 nm.

2.2 Device Fabrication

First, the n+ type doped silicon wafer substrate used in the device preparation is ultrasonically cleaned using acetone. The molybdenum source-drain electrodes were sputter-deposited and patterned by lift-off. Next, the IGZO film is deposited using a sputtering process, and annealed at 300 °C for one hour in an oxygen environment after the sputtering is completed. After annealing, wet etching proceeds to pattern the IGZO film. Finally, PECVD was used to deposit the passivation layer on the device at 80 degrees Celsius. The passivation layer and the quasi-2D perovskite film on the device were patterned by RIE, as shown in Fig.1. In experiment, different sizes of photo-TFTs were fabricated, with channel length varying from 5 μm to 100 μm. The smallest photo-TFT fabricated in this work has...
a W/L=20 μm/5 μm, and the biggest device has a W/L=6600 μm/100 μm with interdigitated electrode. Fig. 1c shows a SEM image of P/IGZO photo-TFTs with channel length of 15 μm, 10 μm and 5 μm as examples of patterned photo-TFT arrays.

Fig. 1. Schematic diagram of the fabrication process of perovskite-IGZO (P/IGZO) photo-TFT.

3 Results
The transfer characteristic curves of two P/IGZO photo-TFTs, with W/L=100/5 and W/L=20/5, are compared in Fig 2. The off-state dark current of the P/IGZO photo-TFT with W/L=100 μm /5 μm is less than ~2pA; whereas the off-state dark current of the W/L=20 μm/5 μm device is even lower, which is below measurement limit of our instruments (~0.1pA). Under 400 nm light (60 μW/cm²), both devices show significant photocurrent. At Vg=-0.8V, the photocurrents of the W/L=100/5 and the W/L=20/5 device reach 9x10⁻⁹A and 1.1x10⁻¹⁰A, which are around 3-4 orders of magnitudes higher than their off-state dark currents.

Fig 2. The transfer characteristic curves of two P/IGZO photo-TFTs, with W/L=100/5 and W/L=20/5

After characterizing the performance of the P/IGZO photo-TFT, the device is combined with scintillators for x-ray detection. GOS scintillators was chosen to convert the x-rays into visible light. The scintillator emits visible light in the range of 350-700 nm, which falls within the photosponse range of the P/IGZO photo-TFT. During the x-ray exposure, the positions of the x-ray source, the scintillator and the photo-TFT were fixed, and the photocurent of the photo-TFT under different x-ray doses is recorded. Fig. 3 shows the transfer curve of the x-ray indirect test when the photo-TFT is paired with the GOS scintillator. During the test, the drain-to-source voltage of the device was 4 V, and the gate voltage of each curve was swept from -20 V to 20 V. In Fig. 3, it is shown that the device maintains a dark current of ~10 pA. When the x-ray is turned on, it is found that the photo-TFT has a significant photocurrent in the negative gate voltage region (Vg < -10V). This current increases with the x-ray dose rate. Similarly, when the GOS scintillator is replaced with a quantum dot scintillator, a higher photocurrent at the negative gate biased region can be observed.

Fig 3. The transfer curve of the photo-TFT for indirect x-ray detection using GOS scintillator

4 Discussion
The photo-TFT is capable of distinguishing x-ray signals of different doses. The P/IGZO photo-TFTs possess high X-ray sensitivity due to their high photoresponsivity. We compared the photo-TFT with other X-ray detectors in Fig. 3E and Table S1. The X-ray detection sensitivity of the photo-TFT in this work outperforms most other types of indirect X-ray detectors, and is even comparable to the direct type X-ray detection. The lowest X-ray dose rate in the measurement is 10 μGy/s. It is worth to note that 10 μGy/s is not the ultimate limit of photo-TFT, there is still room for optimizing the light coupling efficiency between the photo-TFT and the scintillator in the future.

In commercial X-ray panels based on a-Si TFT backplane, a typical frame rate is 10Hz, resulting a 100ms per frame[28]. If a 100ms frame time and a dose rate of 10 μGy/s are adopted to evaluate potential image sensor based on our phototransistor pixel, a total dose as low as 1 μGy/frame can be obtained.

Compared with PDs, phototransistors (photo-TFTs) are emerging as a low-cost sensing alternative in view of their compatibility to the TFT production line, and can facilitate the design of pixels with channel length/width in the scale of several microns. These are important features for next generation image sensors, particularly
for biomedical x-ray imaging as low dose and high sensitivity helps reduce the risk in diagnostic medical exposures.

5 Conclusions

In summary, a highly photosensitive perovskite-IGZO heterojunction photo-TFT is demonstrated in this work by using quasi-2D perovskite as the light absorption layer. The photo-TFT achieves a high responsivity of above $10^5$ A/W, while maintaining a low dark current in the range of tens of picoamperes. As a result, a high specific detectivity of above $3 \times 10^{13}$ cm·Hz$^{1/2}$W$^{-1}$ is obtained. These highly-desirable attributes render the proposed photo-TFT a suitable alternative for low dose x-ray detection. Combined with scintillators, the photo-TFT shows reproducible photocurrent signals under low dose X-ray exposure with a detectable dose rate as low as 10 μGy/s. The fabrication processes introduced in this work enable top-illuminated, patternable photo-TFTs with 5 μm channel length. Its capability for image sensing is also demonstrated by integration of the photo-TFTs in an active-matrix array. This work demonstrates a promising sensor and pixel configuration for low dose, flat-panel x-ray imaging.

References