Supporting Information

Zero-Dimensional PbS Quantum Dot-InGaZnO Film Heterostructure for Short-Wave Infrared (SWIR) Flat-Panel Imager

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Figure S1. (a) FTIR of PbS-OA, PbS-TBAI, and PbS-EDT films. (b) and (c) Vis-NIR absorption spectra of pristine PbS-OA and PbS-TBAI and pristine PbS-OA and PbS-EDT, respectively after the ligand exchange process.
Figure S2. (a) and (b) Noise power spectral densities as a function of frequency and gate voltage of the PbS-TBAI/IGZO device. (c) Gate-dependent responsivity and square root of noise power spectral density as a function of gate voltage, and (d) resultant gate dependent specific detectivity ($D^*$) with different optical power density (1310 nm SWIR).
Figure S3. (a)–(j) Superimposed dark and photo-induced transfer curves of five different batches under 1310 nm LD illumination.
Figure S4. (a) The secondary and (b) valence spectra for IGZO/ITO (bottom, violet), PbS-TBAI/IGZO/ITO (middle, red) and PbS-EDT/IGZO/ITO (top, green) measured by ultra-violet photoelectron experiment, respectively. The energy band diagram for (c) PbS-TBAI/IGZO and (d) PbS-EDT/IGZO. All the values are given in electron volts (eV).

In order to clarify similar performance of PbS-EDT and PbS-TBAI ligand devices, we have conducted ultraviolet photoemission spectroscopy (UPS) experiment to investigate the interfacial energy level alignment of PbS/IGZO heterostructure. In this study, a very thin PbS QD (6 – 7 nm) was used in heterostructure devices, and it showed the best performance. In addition, energy level alignment is also affected by thickness of that, just like devices performance. In this reason, UPS experiment were carried out using a PbS QD on IGZO with same thickness. Due to the very thin PbS QD layers (6–7 nm), all phenomena we observe are an interface phenomenon, not a bulk alignment. According to UPS measurements combined with optical bandgap (obtained from absorption spectra in Figure S1b and S1c), the interfacial energy level alignment of PbS/IGZO heterostructure was extracted, which is a critical factor in determining the charge transport and photo response in devices. The work functions of IGZO, PbS-TBAI and PbS-EDT were 3.81 eV, 4.22 eV and 4.23 eV, respectively. Likewise, the onsets of valence band maximum (VBM), for Fermi levels, have been found to be 3.62 eV for IGZO,
0.62 eV for PbS-TBAI, 0.60 eV for PbS-EDT. In the energy diagram, the conduction band minimum (CBM) of both ligands QD is very close to the Fermi level representing the $n$-type characteristics. This observation is referred to as Fermi level pinning in previous reports, which suggested that a defect involving charge transfer (CT) between the substrate and QD resulted in an $n$-type characteristic via an electrostatic effect. As shown in Figure S4, the work function change of 0.4 eV (potential change) between IGZO and QDs were observed, which can also support the interfacial charge transfer (CT) to achieve electronic equilibrium at the interface. In summary, the presented energy diagram indicates that charge accumulation of QD and depletion of the IGZO surface occur at the interface; consequently, it can explain the similar performance regardless of the ligand molecules.

Figure S5. Photo-induced (and dark) transfer characteristics of (a) PbS-EDT/IGZO and (b) PbS-TBAI/IGZO devices. Thicker PbS QD layers were created by increasing the concentration of the solution (to 10–20 mg/ml).
Figure S6. Superimposed transfer characteristic of PbS-TBAI/IGZO devices after air exposure for (up to) 21 days. The four measured devices were fabricated on the same substrate.

Figure S7. Superimposed transfer characteristics of PbS-EDT/IGZO devices after air exposure for (up to) 21 days. The four measured devices were fabricated on the same substrate.
Figure S8. The ratio of S species (PbS, EDT, and SO$_x$) as a function of air exposure time.

<table>
<thead>
<tr>
<th>Days</th>
<th>S-PbS</th>
<th>S-EDT</th>
<th>S-O$_x$</th>
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<tbody>
<tr>
<td>0</td>
<td>75.56%</td>
<td>24.44%</td>
<td>0.00%</td>
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<td>3</td>
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<td>2.00%</td>
<td>21.22%</td>
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<td>7</td>
<td>74.81%</td>
<td>0.00%</td>
<td>25.19%</td>
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<tr>
<td>15</td>
<td>74.41%</td>
<td>0.00%</td>
<td>25.59%</td>
</tr>
</tbody>
</table>

Figure S9. XPS core level spectra of (a)–(d) PbS-EDT/IGZO and (e)–(i) PbS-TBAI/IGZO as a function of air exposure time.
Figure S10. (a) OM image and (b) photo-induced (and dark) transfer curves of the PbS-TBAI/IGZO device under 1310 nm LD illumination. Deep-ultraviolet (DUV) photo-annealed IGZO TFTs were used.

Figure S11. (a) OM image and (b) photo-induced (and dark) transfer curves of the flexible PbS-TBAI/IGZO device on a PI substrate under 1310 nm LD illumination.
Figure S12. (a) OM image and (b) photo-induced (and dark) transfer curves of the fully patterned PbS-TBAI/IGZO device under 1310 nm LD illumination.

Figure S13. (a)–(c) Photo-induced (and dark) transfer curves of three fully patterned PbS-TBAI/IGZO devices on a PI substrate under 1310 nm LD illumination with different optical power densities.
**Figure S14.** (a) Photo-induced (and dark) voltage transfer characteristics of the resistive-load photo-inverter, which is constructed by connecting a unit phototransistor to an external load resistor ($R_L = 10 \, \text{M}\Omega$). Photo-switching voltage dynamics at fixed input voltage ($V_{in} = -0.5 \, \text{V}$) at operating frequencies of (b) 1, and (c) 60 Hz, respectively. Positive gate voltage pulse (7 V for 100 µs) was applied soon after the LD was switched off.
Figure S15. (a)-(j) Photo-induced (and dark) voltage transfer characteristics and (f)-(j) photo-switching voltage dynamics at operating frequencies of 1 Hz of five resistive-load photo-inverters.
**Figure S16.** Schematic of a read-out circuit for a 1×6 flat-panel image pixel array.

Because the semiconductor parameter analyzer has only one input port, it cannot read signals from multiple image pixels simultaneously. Therefore, the relay module was used to switch between pixels one by one. The relay module was programmed and controlled by computer, and the switching speed of the relay module was fast enough to obtain an image from the 1×6 image pixel array.