Structure—Property Relation in Organic–Metal Oxide Hybrid Phototransistors

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ABSTRACT: We report an optoelectronic device consisting of a solution-processed indium gallium zinc oxide (IGZO) thin-film transistor and vacuum-deposited small organic molecules. Depending on the configurations of the organic materials, either bulk heterojunction or planar heterojunction (PHJ), the device assumes the functionality of either a photosensor or a photoinduced memory, respectively. Under $\lambda = 625$ nm light illumination, the photosensor shows response and recovery time of $\sim 50$ ms, responsivity of $\sim 5$ mA/W, sensitivity above $10^4$, and a linear response. The mechanism of the photoinduced memory is studied experimentally and verified using a device simulation. We find that the memory is due to long charge retention time at the organic PHJ interface which is stable for over 9 days. It is correlated with the low leakage current found in ordered organic junctions having low subgap tail states. The presented integration of the PHJ with the transistor constitutes a new design of write-once-read-many-times memory device that is likely to be attractive for low-cost applications.

KEYWORDS: organic, IGZO, phototransistor, memory, heterojunction, subgap states

1. INTRODUCTION

In recent decades, there has been a rapid development of organic and metal oxide semiconductor materials. On the one hand, organic materials, because of their diverse compositions, have attractive optical properties over traditional semiconductor materials.1–3 On the other hand, thin-film transistors (TFTs) composed of a metal oxide semiconductor,4,5 especially amorphous indium gallium zinc oxide (IGZO),6–9 are believed to be a good substitute for amorphous Si TFTs in the backplane technology.10–12 Integration of organic and metal oxides, making use of the advantages of both materials, is a promising route for a range of optoelectronic applications, including photodetection.13–16

We show that depending on the configuration of the organic layers in the phototransistor, one can achieve phototransistors acting either as a photosensor or as a photoinduced memory device. The device was based on solution-processed IGZO TFTs, and the photoactive medium was an organic donor/acceptor small molecule combination. Having established a process for reproducible IGZO transistors, on 4 in. wafers, we compared the response to light excitation of various configurations of the organic layers. Specifically, we first demonstrate a photosensor by using an organic bulk heterojunction (BHJ) structure on top of IGZO.17 The fabricated device showed typical photosensing characteristics, with $\sim 50$ ms response and recovery time, decent responsivity, and a linear response at a gate voltage ($V_g$) of $-0.8$ V. Second, changing the BHJ structure to a planar heterojunction (PHJ) structure, a photoinduced write-once-read-many (WORM) memory was successfully demonstrated. We consider this change of functionality to be the main result of this paper. The memory cell showed excellent charge retention capability, with $\sim 75\%$ preserved up to 9 days. Compared to diode structure WORM,18–20 the programming process here consumes almost no electrical power (only gate bias), and the device is inherently immune to the “read times” test because of the floating nature of the retained charges. Finally, the long charge retention was investigated using several device configurations, surface potential microscopy, and semiconductor device simulation. We have found that the charges were retained in the top organic layer and correlated the charge retention/leak mechanism with subgap states in organic PHJ.
2. METHODS

2.1. Device Fabrication. The IGZO solution was synthesized by first dissolving indium nitrate hydrate (In(NO$_3$)$_3$·xH$_2$O, Aldrich, 99.999%), gallium nitrate hydrate (Ga(NO$_3$)$_3$·xH$_2$O, Aldrich, 99.999%), and zinc nitrate hydrate (Zn(NO$_3$)$_2$·xH$_2$O, Aldrich, 99.999%) in 2-methoxyethanol solvent separately, with a same molar concentration of 0.1 M. Then, the three precursor solutions were stirred at room temperature overnight and mixed in a volume ratio of 70:15:15 to reach to the final IGZO solution. The mixed IGZO solution was also stirred overnight before use.

To prepare the TFT, a bottom gate top contact structure was used in this work. The process was established on a 4 in. wafer, where the heavily doped Si and thermally grown 100 nm SiO$_2$ were used as gate and dielectric, respectively. First, the wafer surface was cleaned by acetone, methanol, isopropanol, and deionized water sequentially and fully dried at 120 °C for 30 min. The cleaned wafer was then treated in ozone for 15 min to increase the surface wettability to the IGZO solution. Next, the prepared IGZO solution was spin-coated on the wafer at 3000 rpm for 30 s. The coated wafer was quickly transferred onto a hotplate for annealing, at 100 °C for 3 min first and followed by annealing at 450 °C for 3 h. The annealing was done under a clean-room ambient condition with humidity around 42% RH and temperature of about 22.5 °C. The same spin-coating and annealing process was repeated for an additional time to achieve a uniform active layer with a final thickness of ~8 nm.

The wafer with the IGZO film was then diced into dies of size 12 mm × 12 mm. Al source and drain electrodes (20 nm) were deposited on each individual die by e-beam deposition in a vacuum deposition system (Vinci Technologies), with a base pressure of 6 × 10$^{-7}$ mbar, at the rate of 1 Å/s through a shadow mask (with channel length 50 μm and width 2 mm). The dies, with the electrodes, were consequently patterned using diluted hydrochloric acid (HCl) to remove IGZO at the periphery of the die to reduce the unwanted gate leakage current. Finally, all the devices underwent a postannealing process at 170 °C for 3 h to stabilize the doping level in the IGZO film and bring the threshold voltage of the transistor close to zero volt. It is worth noting that the process can be easily further optimized by simply introducing a photolithography mask for device patterning and electrode deposition, resulting in up to 50 dies being fabricated in parallel. More details regarding IGZO TFT fabrication can be found in the Supporting Information.

After the IGZO TFT structure was completed, small organic molecules were deposited on top of the IGZO channel. The materials that have been used in this work were copper phthalocyanine (CuPc, Creaphys, Ultra-High-Purity), fullerene (C$_{70}$, SES Research, purity 99.95%), and tetraphenyldibenzoperi$$^2$$ anthene (DBP, Lumtec, purity 99%). Specifically, for those devices containing single material in each layer ($C_{70}$ and DBP single layer, $C_{70}$/DBP, and C$_{70}$/CuPc bilayer), organic materials were thermally evaporated in the Vinci evaporator with a base pressure of 6 × 10$^{-7}$ mbar, at a rate around 0.35 Å/s. $C_{70}$/DBP mixed layers were obtained by co-deposition from two independent organic sources at the same rate of 0.35 Å/s and with a total thickness of 50 nm. The film thickness and deposition rate are monitored by quartz-crystal microbalances inside the vacuum chamber. After fabrication, all the devices were kept in a nitrogen-filled glove box where they were also characterized.

2.2. Device Characterizations. The absorption spectra of different organic films were measured in a UV–vis–NIR spectrophotometer (Cary 5000, Agilent), using films grown on a glass substrate. The electrical properties of TFTs were characterized by a semiconductor parameter analyzer (SPA B1500A, Agilent Technologies) inside the glove box. The transfer curves of TFTs were recorded with a gate voltage interval of 0.2 V and a delay time of 0.2 s between two points. For light response measurements, devices were illuminated by a light-emitting diode (LED) with a center wavelength of 625 nm. The light intensity was controlled by a function generator (KEITHLEY 3390 Arbitrary Waveform Generator). Before measurement, the actual light intensity was calibrated using a standard Si photodetector (model 2031, New Focus). Kelvin probe force...
microscopy (KPFM) was performed using a MFP-3D Infinity atomic force microscope operated in the KPFM mode. All measurements were done in a nitrogen-rich environment.

2.3. Simulation Settings. Here, we have used a Sentaurus 2D numerical simulator in order to understand how different aspects and layers of the TFT play a role in the device performance. The device structure and layers were set to replicate the fabricated devices. Regarding light excitation, within this simulation program, we found that the closest to exciton dissociation and charge generation at the donor/acceptor junction would be electron and hole generation at the donor (DBP) and only at 10 nm adjacent to the DBP/C70 interface. This ensures that holes are generated only at the DBP and that electrons generated at the DBP cross C70 through diffusion. The charge generation rate was set at 10^18 cm\(^{-2}\)s\(^{-1}\) to match the estimated light absorbed at the LED intensity used (∼30 μW/cm\(^2\)). Recombination processes were bimolecular (radiative) in the layers and trap-assisted surface recombination at the interfaces. Other relevant parameters are summarized in Table S1.

3. RESULTS AND DISCUSSION

In this article, we study different structures of organic capping layers deposited on top of IGZO TFTs and their different functionalities as well as the physical mechanisms that govern the device characteristics. The IGZO TFT basic structure is schematically shown in Figure 1a. Figure 1b shows the chemical structures of the three organic materials used in this work, as well as the relevant energy levels.\(^2\)\(^2\)\(^2\)\(^2\)\(^2\)\(^2\)\(^2\)\(^2\) The absorption spectra of the organic films (single layer, double layer, and mixed layer) are shown in Figure 1c.

First, IGZO TFTs capped with a mixed C70/DBP layer were studied. This structure demonstrates the performance baseline of the device under dark and light conditions. We use this part to show that there is nothing in the IGZO or the organic materials to promote long-term persistent characteristics. Next, we report the study of the PHJ-capped devices and report long-term charge retention and WORM-type operation as well as the underlying mechanism.

3.1. Phototransistor as a Photosensor. The inset of Figure 2b shows the device structure schematics of the fabricated phototransistor. To demonstrate the functionality of the photosensing in this section, C70 and DBP BHJ structure were used as a donor layer, while the IGZO TFT channel serves as the acceptor. We chose C70/DBP as their energy levels (Figure 1b) support exciton dissociation and subsequent charge generation at the BHJ between them. The relative

direction band minimum (CBM) energy of IGZO ensures that photoelectrons would be transferred to it. To be consistent with the following device structures, we used a 50 nm thick BHJ layer which absorbs about 50% of the light around 600 nm (Figure 1c).

Figure 2a,b shows the dark transfer curves of the transistor before and after the deposition of organic materials, respectively. The gate bias sweep speed dependence of transfer characteristics and the off current are discussed in the Supporting Information (Figure S1). Besides the slight hysteresis, there is a negligible change in transistor characteristics in terms of field-effect mobility, threshold voltage, and subthreshold swing (see Table S2, Supporting Information), which indicates that the BHJ forms a good interface with the IGZO TFT. It should be noted that we sometimes observed some V\(_{th}\) shift upon deposition of organic layers (Figure S7), and we attribute that to fine details of the top surface structure of the IGZO channel. The mobility extracted from Figure 2 (0.3 cm\(^2\)V\(^{-1}\)s\(^{-1}\)) is lower than the value usually reported in the literature.\(^3\) This lower extracted mobility does not reflect on the material quality as it is due to the series resistance imposed by choice of 20 nm ultrathin Al electrodes. This thin electrode was used to maintain compatibility with the other structures reported below. Higher mobility (∼2.5 cm\(^2\)V\(^{-1}\)s\(^{-1}\)) is observed for TFTs, with a thicker electrode and longer channel that underwent the same IGZO TFT process (Table S3 and Figure S2).

Next, the photoresponse of the fabricated phototransistor was characterized. Figure 3 shows the transistor transfer curves in the dark, under a light intensity of 4.5 mW/cm\(^2\), and back to dark immediately after the light is turned off. It was also confirmed that the transfer curves were stable during continuous sweeps under dark and light, exhibiting no bias stress effect (not shown). Figure 3 shows that light excitation causes an increase in the off-current together with a leftward shift of the turn-on voltage (V\(_{on}\)). As the largest effect is the increase in the off current, the subthreshold slope degrades. Once the light is turned off, the curve goes back to its original dark position without any noticeable delay. This observation is consistent with the idea of using BHJ as a light absorber layer;\(^7\)\(^,\)\(^7\)\(^,\)\(^7\)\(^,\)\(^7\)\(^,\)\(^7\) that is, excitons under light quickly dissociate into electron and hole inside the BHJ layer, and they further diffuse and separate at the BHJ and IGZO interface with the electron being transferred to the IGZO. Eventually, photoelectrons flow

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**Figure 2.** Transfer curves of the IGZO TFT-based organic BHJ phototransistor (a) before and (b) after deposition of the organic BHJ (mixed) layer. Inset of (b) shows the device structure.
primarily in the IGZO as part of the photocurrent. Once the light is removed, residual electrons and holes recombine in the BHJ structure, leading to the recovery of the curve.

The phototransistor was further characterized under different light intensities, as shown in Figures S3 and S4. Specifically, Figure S3 plots the photo responsivity and photosensitivity as a function of gate bias under different light intensities. Figure S4 shows the photocurrent as a function of light intensity for three gate voltages of −2.4, −0.8, and 4 V, which represent off-state, close to V_{out} and on-state, respectively. Interestingly, at V_g close to V_{out}, the fabricated device exhibits a linear response (∼5 mA/W) and high photosensitivity (>10^6 for P > 1.85 mW/cm^2). The linearity is demonstrated through the almost perfect linear fit in Figure S4b and the crossing of the curves, at the same bias, in Figure S3b. The highest photosensitivity obtained at this gate bias is associated with the transfer curve shifting leftward under light due to the photo gating effect.30 The high value obtained for V_g close to V_{on} is enabled by the low off-current and the steep subthreshold swing of the IGZO TFT. For both off-and on-state, the photo responsivity is sublinear due to increasing recombination loss at high light intensity. However, at V_g close to V_{out}, this loss is compensated by the shift of the curve from off-state to on-state.31

Figure 4a shows the photoswitching behavior under different light intensity at V_g = −0.8 V and V_g = 10 V. At this gate bias, the device shows a fast response and recovery time of around 50 ms, which is limited by the SPA response/settle time. Figure 4b shows the response in the photovoltaic regime (V_g = 4 V) where the transistor is at the on state and the current response is mainly governed by the V_{on} shift. The decay here is composed of a fast component and a long tail with a characteristic decay time of 6.6 s. This implies that the charges causing the V_{on} shift either recombine or are swept-out in a few seconds. The mechanism governing the V_{on} shift will be discussed below in the context of the memory device.

3.2. Phototransistor as a Memory Device. The inset of Figure 5a illustrates the device structure of the C_{70}/DBP bilayer (PHJ) device, and its absorption spectra can be found in Figure 1c. We used a 20 nm Al source/drain contact, in order to form a well-defined structure where the 40 nm thick C_{70} layer fully covers the electrodes so that the DBP layer would have no direct contact with the Al electrode. The importance of this design will be further addressed below. At first, we characterized the PHJ device in the same way as its BHJ counterpart. However, under light, the transfer curve kept shifting toward negative gate values with the V_{on} approaching the negative gate bias at which the sweep starts (see Figure S5a in Supporting Information). Moreover, once the light was removed, the curve does not recover to its original position. On the other hand, if we limit the sweep to gate bias range where the device is always on (positive gate bias), we did not observe light-induced shift of the curves (Figure S5b).

Because the transistor capped with PHJ is very different from the BHJ one and is mainly exhibiting memory effect, we changed the measurement protocol to better characterize this memory effect. As will be shown later, we also employed modified device structures to better identify the origin of the memory effect, and the following was found to be reliable and allow comparison between structures. The baseline performance is measured under dark conditions. The light excitation is done with V_{ds} = 0 V and the gate bias at V_g = V_{on} − 8 V (8 V below the transistor V_{on} in the dark baseline). The light intensity is fixed at 30 μW/cm^2 and is kept on for 30 s. Once the light is off, we measure the transfer curve to characterize the induced V_{on} shift and repeat this measurement at time intervals to characterize the retention time of the shift.

To verify the observation that positive gate bias does not promote the V_{on} shift, we performed the above protocol but with V_g = V_{on} + 5 V and V_g = V_{on} + 8 V. Indeed, no shift in V_{on} was observed in this case. Because the as-fabricated turn-on voltage, V_{on} (t = 0), may vary due to processing conditions, we eliminate its effect in Figures 5 and 6 by plotting the curves as...
a function of $V_g - V_{on}$ ($t = 0$). The original transfer curves can be found in the Supporting Information. We first verify that stressing the device at $V_g = V_{on} - 8$ V under dark does not cause transfer curve shift (Figure S6). Next, Figure 5a shows the C$_{70}$/DBP PHJ device characterized as described in the above protocol ($V_g = V_{on} - 8$ V with light on). For this negative gate bias, the light induces a shift of 4–5 V in the transfer characteristics toward negative values. The curve measured immediately after the light was turned off is marked as $t = 0^+$ in Figure 5a. Surprisingly, the curve shows very little recovery even after 9 days (see the dashed curve in Figure 5a). The IGZO TFT subthreshold slope, together with the low off-current, enables 10$^4$ current modulation induced by light-writing with a 4–5 V shift in the transfer curve. Therefore, by merely changing the organic capping layer from BHJ to PHJ, the functionality of the device has been changed accordingly, from a photosensor to a photoinduced memory cell.

We propose that the $V_{on}$ shift is caused by hole accumulation in the DBP layer, which effectively acts as a 2nd gate. We suggest that the process leading to the hole accumulation can be understood with the aid of the schematic picture shown in Figure 5b. Light absorption ($\lambda = 625$ nm) takes place in both organic layers, but exciton dissociation occurs at the C$_{70}$/DBP planar junction. The electrons in C$_{70}$ may transfer to the IGZO channel or are extracted at the Al contact. The holes generated at the DBP side of the junction are blocked by the C$_{70}$ layer and may decay only through charge-transfer (CT) recombination, via subgap (or CT) states at the junction, with electrons on the C$_{70}$ side. Apparently, the removal of electrons from C$_{70}$ plays a role in the hole accumulation by minimizing this recombination process. The accumulated holes act as a counter gate electrode, with C$_{70}$ as a dielectric layer, modulating the charge density in the IGZO TFT and thus shifting the transfer curve to negative gate voltages (leftward).

A first confirmation of the proposed mechanism is of the positive-charge retention. This was measured using KPFM of the top surface with and without the light-induced $V_{on}$ shift. It was found that the $V_{on}$ shift correlates with a decrease in the contact potential difference ($V_{CPD}$), see Figure S8 in the Supporting Information.

The physical picture we have depicted in the figure relies on the DBP layer accumulating holes and as C$_{70}$ isolates it from the Al contacts, it retains its charges. To further test this, we fabricated the devices with the same C$_{70}$/DBP PHJ but deposited the Al electrodes on top of the organic layer, as shown in the inset of Figure 6a. In this top contact structure, Al was deposited after the organic layers, and we used a higher deposition rate (3 Å/s) to make Al partially penetrate the
organic layer and reduce the series resistance of the IGZO channel. Figure 6a shows the transfer curves before and after light exposure using the same protocol as for the bottom contact PHJ reported in Figure 5a. The light exposure is taken to be \( t = 0 \), and each curve is marked by the time it was taken and the number of that sweep in the measurement sequence. The figure shows that the device transfer curve completes full recovery within 20 min, which happens to be the 7th measurement sweep. The same measurement sequence was repeated several times, and the results were the same. The clear and relatively fast recovery in this top contact structure supports the notion that holes reside in the DBP layer and that making physical contact with the Al electrode allows them to exit the structure. If this is the case, one would expect the source/drain bias to play a role too. To this end, we altered the measurement sequence, and especially, the first measurement after light exposure was taken only at \( t = 10 \) min. Figure 6b shows that in the absence of measurement sweep (drain/source bias), the recovery is significantly slower. In Figure 6a, after 10 min, the recovery is almost of the entire 5 V shift, while in Figure 6b, the 10 min recovery is of only \( \sim 1 \) V. Once the measurement sequence continues, the recovery process (Figure 6b) becomes faster and the transfer curve fully recovers after about 8 sweeps (35 min). Namely, the recovery process in this structure takes place through two mechanisms. First, when no bias is applied, the holes diffuse toward the contact where they would recombine. Second, when a bias is applied, the holes drift toward the contacts and recombine at the contact interface. This drift-related mechanism is responsible for the faster recovery once the sweep sequence commences.

The results reported above are all in favor of the holes being retained at the DBP and do not leak/recombine across the C70/DBP interface. If this is the case, the retention time should depend on the quality of the interface and its leakage performance. Hence, we followed ref 32 and replaced DBP with CuPc as the top layer in the phototransistor. The details of device performance at different stages of the fabrication can be found in Figure S7, and the absorption spectra are shown in Figure 1c. Figure 7 summarizes the \( V_{on} \) shift with respect to time for all the devices mentioned thus far as well as two devices capped by a single layer only (DBP or C70). We note that we have verified that unstressed transistors, from the same substrate, are stable and show no \( V_{on} \) shift over the time of the measurements (Figure S9a). This was possible due to the optimized process and the capping of IGZO by the organic layers (Figure S9).

As shown in Figure 7, both C70/DBP and C70/CuPc devices show long retention time. However, one can clearly see that the retention time of the disordered C70/CuPc interface is shorter than that of the better ordered C70/DBP interface. As was postulated, the retention time of the PHJ inversely correlates with the reverse leakage current measured for the same PHJ in a photodiode configuration.32 As reported in ref 32, the leakage across the PHJ is associated with the CT states at the organic PHJ. Specifically, the C70/CuPc photodiode
shows a stronger signal and longer sub-gap tail states compared to C70/DBP. The effect of varying C70 or DBP layer thickness can be found in the Supporting Information, Figure S10 and Table S4.

Regarding the single layer devices, they show a negligible $V_{on}$ shift despite the fact that they exhibit absorption comparable to the bilayer devices (see Figure 1c). This could be due to several reasons such as: (1) the organic/IGZO interface may be leaky and holes in the organic layer recombine with electrons in the n doped IGZO, (2) the interface with IGZO is not efficient at exciton dissociation, and (3) the direct contact between the organic layer and the electrodes allows the holes to be swept out.

The combined experimental results presented above indicate that, in the PHJ configuration, positive charge accumulates at the top layer and that this accumulation requires a negative gate bias (see Figure S5b). To support the suggested picture and better understand the charge accumulation mechanism of the PHJ device, we performed 2D numerical simulation using the Sentaurus tool. As detailed in the Simulation Settings Section, the light-induced generation rate of electrons and holes is taken to match the light absorbed in the experiments and is implemented only close to the DBP/C70 interface. The gate bias of $-1.3$ and $+3$ V was chosen to be below and above the simulated turn-on voltage and thus represent on and off states, respectively. Figure 8 shows the hole and electron density distribution across the device layers, at the middle point between the source/drain electrodes, under different gate biases and with or without light excitation. Figure 8a presents the hole density distribution, and it shows that in the absence of light illumination, the hole density is very low across the layers, regardless of the gate bias. Under illumination, there is an increase of the hole density at the DBP layer, and the accumulated hole density is only significant at negative gate bias (off state). The light-induced accumulation of holes at the DBP and in the off state only is in line with the conclusions drawn based on the experimental data. To offer an explanation for these phenomena, we examine the electron density distribution in Figure 8b. As shown in Figure 8b, light excitation has a very little effect on the electron density, and we mainly observe the electron accumulation at the IGZO under positive gate bias. However, the inset of Figure 8b shows that at positive gate bias, the channel extends into the C70 layer. The resulting electron density at the C70/DBP interface is above $10^{10}$ cm$^{-3}$. This is a result of the IGZO layer being only 8 nm thick and of the low mismatch between the IGZO/C70 CBM/lowest unoccupied molecular orbital levels. Namely, the enhanced electron density at the C70/DBP interface suppresses hole accumulation in the DBP layer. We suggest that in the real device, the mechanisms that suppress hole accumulation/generation could be electron–exciton annihilation, recombinaton across the interface, and possibly also partial state filling of C70 that mitigates exciton dissociation.

4. CONCLUSIONS

In conclusion, we demonstrate two optoelectronic devices based on solution-process IGZO and vacuum deposition of organic small molecules. Both devices adopt the same IGZO TFT-based structure. By choosing the structure of the organic capping layer to be either BHJ or PHJ, the phototransistor device functions as either a photosensor or WORM device, respectively. The photosensor shows relatively fast response, decent responsivity, and sensitivity, together with a linear response under a small negative gate bias of $V_g = -0.8$ V. Upon changing the BHJ structure to a PHJ one, the WORM device shows excellent charge retention behavior extending beyond 9 days. The novel WORM device structure reported here has a potential advantage compared to other structures. In many memory cell configurations, the charges are trapped inside a floating electrode that resides between the source/drain and the gate. In such a structure, the charges are subject to the gate field, promoting charge leakage during the read process. Here, the trapped charges are placed outside the transistor structure, suggesting better resilience to read tests.

We investigated the charge retention/leak mechanism and found that it is primarily governed by the quality of the PHJ interface or by the sub-gap tail states of the junction. Following the suggestion by the anonymous referee, we also studied the effect of changing the layer thickness (see Supporting Information Figure S10) and found that this can also be used to enhance the retention time. The surprising effect of the DBP layer thickness suggests that allowing the holes to spread away from the junction reduces the leakage through it and enhances the charge retention. We believe that further optimization could make this new device design attractive for low-cost applications.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsami.9b22165.

Simulation parameters, transistor characteristic before and after depositions of organic layer, transistor characteristic for thick electrodes and different channel lengths, phototransistor characteristic as a photosensor, memory effect of IGZO--C70/DBP PHJ devices, KPFM measurement of charge retention, device stability with and without organic capping layer, and additional details of the device fabrication process (PDF)

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Author Contributions

Z.C. prepared the devices and performed the measurements, G.S. performed the device simulation, H.S. performed KPFM studies, and H.S. and N.T. suggested the project and were involved in its progress. The manuscript was written through
contribute to the understanding of various authors. All authors have given approval to the final version of the manuscript.

**Notes**
The authors declare no competing financial interest.

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