Photosensitivity enhancement in hydrogenated amorphous silicon thin-film phototransistors with gate underlap

Junyeon Kwon, Seongin Hong, Young Ki Hong, Sungho Lee, Geonwook Yoo, Youngki Yoon, and Sunkook Kim

Citation: Applied Physics Letters 107, 201103 (2015); doi: 10.1063/1.4935979

View online: http://dx.doi.org/10.1063/1.4935979

View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/107/20?ver=pdfcov

Published by the AIP Publishing

Articles you may be interested in

High-performance n-type organic thin-film phototransistors based on a core-expanded naphthalene diimide

Phototransistor with nanocrystalline Si/amorphous Si bilayer channel
Appl. Phys. Lett. 96, 173507 (2010); 10.1063/1.3422479

Photoresponses in polycrystalline silicon phototransistors incorporating germanium quantum dots in the gate dielectrics
Appl. Phys. Lett. 93, 191112 (2008); 10.1063/1.3028023

Photovoltaic and photoconductivity effect in thin-film phototransistors based on a heterocyclic spiro-type molecule
J. Appl. Phys. 102, 046104 (2007); 10.1063/1.2770828

Solution-processed organic thin-film phototransistors based on donor/acceptor dyad
Photosensitivity enhancement in hydrogenated amorphous silicon thin-film phototransistors with gate underlap

Junyeon Kwon,1,a) Seongin Hong,1,a) Young Ki Hong,1 Sungho Lee,2 Geonwook Yoo,2,b) Youngki Yoon,3,b) and Sunkook Kim1,b)

1Multi-Functional Nano/Bio Electronics Lab, Kyung Hee University, Yongin 446-701, South Korea
2Display Convergence Research Center, Korea Electronics Technology Institute, Seongnam 463-816, South Korea
3Department of Electrical and Computer Engineering, Waterloo Institute for Nanotechnology (WIN), University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

(Received 26 August 2015; accepted 3 November 2015; published online 16 November 2015)

Conventional α-Si:H phototransistors exhibit poor photosensitivity due to low photo-conversion efficiency. To overcome this intrinsic limit, we introduce gate underlap in α-Si:H phototransistors and demonstrate photosensitivity enhancement. We show that photocurrent can be significantly larger than dark current by 4 orders of magnitude, using 1-μm gate underlap at incident optical power density (Pinc) of 3.2 W/cm². Our 1-μm gate-underlap phototransistor exhibits higher photosensitivity than the device without gate underlap by 64 times with Pinc = 0.2 W/cm² and a wavelength of 785 nm. Our gate-underlapped phototransistors also show excellent time-resolved photoswitching behaviors, demonstrating the great potential for highly sensitive photodetectors.

Since the concept of ubiquitous computing was outlined by Mark Weiser, interactive display technologies have been widely explored.1 The interactive display plays a great role in the ubiquitous computing system that can carry out real-time interaction between humans and digital devices by sensing user’s motion or touch.2 An infrared (IR) photosensor composed of photodiode or phototransistor array might be most suitable for actual applications because it can easily detect user’s motion with or without physical contact and map into images from the input signals.3–5 Some important properties required for photosensors are low cost, high sensitivity, and the integration of sensors into active matrix display backplane. In this regard, hydrogenated amorphous silicon (α-Si:H) based devices have been considered and adopted as a strong candidate for various photosensor applications due to the favorable properties for the requirements mentioned above.6–8 However, the α-Si:H leads to low photo-conversion (photon to excess carriers) efficiency, which intrinsically limits its use for high-sensitivity photodetectors having a large signal-to-noise ratio.9 In this work, we demonstrate significant enhancement of photosensitivity in α-Si:H phototransistors based on the novel gate-underlapped structure that we have previously developed for the layer- semiconductor thin-film transistors (TFTs) where the photoresponsivity of indirect-bandgap multilayer MoS2 phototransistor was significantly enhanced by 3 orders of magnitude as compared to a device without gate underlap.10,11 The geometrical effects on electrical and optical properties with different lengths of ungated region (gate underlap) will be discussed in detail. By introducing gate underlap, electrical properties such as mobility and on/off current ratio (Ion/Ioff) are degraded accordingly, but it can significantly enhance the photosensitivity of α-Si:H device. Finally, time-resolved photosresponse measurement is performed to evaluate photoswitching capability of our gate-underlapped α-Si:H TFT.

Figures 1(a) and 1(b) show a 2D cross-section view and an optical micrograph of the fabricated α-Si:H TFT with gate underlap on a glass substrate. The gate length is shorter than the channel length due to the ungated channel (gate underlap) region. A 200-nm-thick Cr gate electrode was deposited on the substrate by sputtering and it forms a bottom-gate geometry. A tri-layer comprising SiNx gate insulator (400 nm), α-Si:H active layer (170 nm, the doping concentration of 1016 cm⁻³), and n⁺-α-Si:H layer (70 nm, the doping concentration of 10¹⁹–10²⁰ cm⁻³) was deposited without vacuum break by plasma-enhanced chemical vapor deposition (PECVD).12 An electron-beam evaporated Ti/Au (20/200 nm) was used as source/drain (S/D) electrodes. After patterning the S/D electrodes, back channel etch (BCE) technique was conducted to remove the n⁺-α-Si:H in the back channel region. All patterning process was performed by standard photolithography, dry and wet etching. To investigate the effect of the different device geometry, the gate underlap lengths (L') of 0 μm, 1 μm and 2 μm were used without changing the channel length (L = 10 μm) and the width (W = 15 μm). Electrical measurements of the α-Si:H TFTs were performed using a semiconductor characterization system (Keithley 4200 SCS) at room temperature in atmospheric environments.

Figure 2(a), which is transfer characteristics of α-Si:H TFTs with and without gate underlap at drain voltage (Vd) of 1 V, exhibits the significant suppression of on current as L’ increases. The field-effect mobilities (μeff) of the 0-μm, 1-μm, and 2-μm gate-underlap TFTs were extracted to be 0.29, 0.05, and 0.02 cm²/V s, respectively. This can be understood from the fact that the gate modulation is inefficient in the ungated region of the bottom-gate TFTs and the gate underlap behaves like a series resistor both at the source and

---

a)J. Kwon and S. Hong contributed equally to this work.
b)Electronic addresses: gwyoo@keti.re.kr; youngki.yoon@uwaterloo.ca; and kimskcmt@gmail.com.
the drain sides. Other performance metrics of transistors such as on-off current ratio ($I_{on}/I_{off}$) and subthreshold swing (SS) are also gradually degraded with the gate underlap. Figure 2(b) compares the output characteristics ($I_{ds}$–$V_{ds}$) of the α-Si:H TFTs. For the sake of discussion, we adjusted the current level of two gate-underlapped TFTs in Fig. 2(b) to compare the device characteristics properly. It clearly shows that, as the gate underlap increases, non-linear behavior becomes more significant as usually observed in Schottky-barrier field-effect transistors, which indicates the weak interconnection of channel with the source/drain contacts through the large gate underlap.

Next, we investigated optoelectronic properties of the bottom-gate α-Si:H TFTs with gate underlap and compared against the device without gate underlap. We measured the transfer characteristics repeatedly at various incident optical power densities of 0.2, 0.4, 0.8, 1.6, and 3.2 W/cm² with a fixed wavelength of 785 nm (near IR) as well as under a dark condition. Figures 3(a)–3(c) show the transfer characteristics of the α-Si:H TFTs without gate underlap and with 1-μm and 2-μm gate underlap, respectively. In all cases, under the incident light, electron-hole pairs are generated in the channel region, and the excess carriers increase the total current of the device. The increase in the current by comparison with the dark current is photocurrent ($I_{ph}$) induced by photo illumination, which is directly affected by the optical power density of the incident light as shown in Fig. 3. In the presence of gate underlap, holes can be accumulated in the bottom-gate region, which reduces the potential barrier for electrons, boosting thermionic current further. Consequently, as the length of gate underlap increases, the difference between the total current under illumination ($I_{total}$) and the dark current ($I_{dark}$) increases, particularly at the on state, as presented in Figs. 3(b) and 3(c).

To understand the role of gate underlap, we have measured $I_{ds}$–$V_{ds}$ characteristics of a floating gate α-Si:H TFT (using the structure without gate underlap), which can be regarded as a two-terminal resistor, under illumination with various incident optical power densities. First, Fig. 4(a) shows symmetry with respect to the origin at $V_{ds} = 0$ V, which clearly indicates that the quality of contacts in our device is controlled perfectly during the fabrication process and the source and the drain have the same level of contact quality. Second, as we can see in Fig. 4(a), the total current increases dramatically under illumination. We have also plotted resistance as a function of incident optical power density.

![FIG. 1. (a) 2D cross-sectional schematic of a bottom-gate α-Si:H TFT with gate underlap. The dashed lines indicate the length of gate underlap ($L'$. (b) Optical microscope image in top view of the fabricated α-Si:H TFT.](image1)

![FIG. 2. (a) Transfer characteristics of the bottom-gate α-Si:H TFTs at $V_{ds} = 1$ V with various gate underlap lengths. (b) Output characteristics of the same phototransistors. The current level was adjusted for 1-μm and 2-μm gate underlap devices for the sake of discussion and comparison.](image2)

![FIG. 3. Transfer curves under illumination at various incident optical power densities for α-Si:H phototransistors (a) without gate underlap ($L' = 0$ μm), and with gate underlap of (b) $L' = 1$ μm and (c) $L' = 2$ μm at $V_{ds} = 1$ V. Wavelength of the laser is 785 nm and incident optical power densities are 0, 0.2, 0.4, 0.8, 1.6, and 3.2 W/cm².](image3)

![FIG. 4. (a) Transfer characteristics of the floating gate α-Si:H TFT at $V_{ds} = 0$ V with various gate underlap lengths. (b) Output characteristics of the same phototransistors. The current level was adjusted for 1-μm and 2-μm gate underlap devices for the sake of discussion and comparison.](image4)
density in Fig. 4(b), which shows that the resistance reduces significantly even with very weak incident optical power density, i.e., by ~3 orders of magnitude at 0.2 W/cm² as compared to the dark state. This can be attributed to Schottky barrier thinning at the contact-channel interface as shown in Fig. 4(c). Carriers generated during the illumination are accumulated at the interface (electrons at the drain side, and holes at the source side when a positive \( V_{ds} \) is applied), which lower potential barrier height, resulting in thinner Schottky barrier and significantly larger carrier injection from the contact to the channel. As the incident optical power density increases, the resistance reduces even further, but it is saturated to a certain value as shown in Fig. 4(b), where the resistance does not decrease linearly with the increase in the incident optical power density since the increased number of electrons injected from the source due to the barrier thinning, in turn, increases the potential barrier by a certain amount, making the increase of power density (increasing the number of photons and electron-hole pairs) less effective in reducing the contact resistance, particularly at high optical power densities.

In order to quantify the effect of photo-illumination for various gate underlap lengths in the bottom-gate α-Si:H TFTs, we have plotted the sensitivity as a function of gate underlap length for different light power densities in Fig. 5(a). Consequently, the photocurrent can be larger than the dark current by 4 orders of magnitude with 1-μm gate underlap at 3.2 W/cm² of light power density. Sensitivity ratio of the device with 1-μm gate underlap to the device without gate underlap (\( S_{L'=1\mu m}/S_{L'=0\mu m} \)) at the incident optical power density of 0.2 W/cm² is shown in Fig. 5(b), which reaches its peak at \( V_{gs} \) of 1.5 V. At this point, the sensitivity of the 1-μm gate underlap phototransistor is larger than that of the device without gate underlap by 64-fold. In a real image application, the most valuable figure of merit for a phototransistor/photodetector is a linear dynamic range (LDR), defined as \( 20 \times \log_{10}(I_{ph}/I_{dark}) \), to identify the sensitivity of a photodetector. In this work, gate underlap leads to high photosensitivity (a large signal-to-noise ratio) as \( I_{dark} \) is significantly decreased while keeping the similar level of \( I_{ph} \), and our relatively simple modification of phototransistor structure can greatly enhance the photosensing performance of α-Si:H phototransistors.

Finally, in order to characterize the photoswitching behavior of our α-Si:H TFTs with gate underlap, we measured time-resolved photoresponse of the α-Si:H TFT with \( L'=1 \mu m \) as shown in Fig. 5(c). The measurement was conducted at \( V_{gs}=0 \) V and \( V_{ds}=10 \) V with a 785-nm laser at different incident optical power densities (0.2, 0.4, 0.8, 1.6, and 3.2 W/cm²). As the illuminating light was switched on and off with a period of 20 s, the photocurrent responded immediately. This excellent photoresponse near IR range demonstrates the practical potential application of α-Si:H phototransistors.

In general, the photosensitivity calculated based on the measurement data (Fig. 3) exhibits an increasing behavior with the length of gate underlap. Furthermore, the increase rate of sensitivity is drastically higher at larger incident optical power densities as shown in Fig. 5(a).
In summary, we fabricated α-Si:H thin-film phototransistors including gate-underlap region, and studied the electrical and optical characteristics by varying the length of gate underlap. Our gate-underlapped α-Si:H phototransistor exhibited high sensitivity, which can be enhanced by 64 times as compared to the device without gate underlap. This huge photosensitivity and its excellent photoswitching behavior suggest that our bottom-gate α-Si:H phototransistor with gate underlap can be a promising candidate of photodetectors for highly sensitive interactive displays as well as other large-area photosensor applications.

This work was supported in part by the National Research Foundation of Korea (2013M3C1A3059590, 2014M3A9D7070732, and 2013K1A3A1A32035549) and in part by NSERC Discovery Grant No. RGPIN-05920-2014.

5S. Y. Han, K. T. Park, H. S. Jeon, Y. W. Heo, and B. S. Bae, J. Disp. Technol. 8, 617 (2012).