Optical Switch of a-IGZO TFT and Triple Junction Photovoltaic Cell

Jei-Li Hou,a Sheng-Po Chang,b+ Chih-Hung Wu,a Hwen-Fen Hong,a and Ting-Jen Hsuehc

a Institute of Nuclear Energy Research, Taoyuan City 325, Taiwan
b Institute of Microelectronics and Department of Electrical Engineering, Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan 701, Taiwan
c National Nano Devices Laboratories, Tainan 741, Taiwan

This study presents an optical switch that integrates an indium gallium zinc oxide (IGZO) thin-film transistor (TFT) and a GaInP/GaAs/Ge triple junction (TJ) photovoltaic (PV) cell. The device is driven by a TJ PV cell, which has a steady output voltage and a voltage regulator, to induce current in it. It should be noted TJ solar cell is broadband sensitive and the open circuit voltages are close under different illumination levels and a voltage regulator can assist it has identical working voltages. Moreover, The switch off (dark) and on (illuminated) current values of the optical switch are around $10^{-8}$ and $10^{-5}$ A, under different simulated test lights, respectively. The test light source is from solar simulator. The stable characteristics and good on/off ratio levels of this device under different light make it practicable in outdoor and indoor environments.

Recently, self-powered devices that harvests power from the environment for sensing or electricity generation have attracted a lot of attention. Self-powered devices driven by solar, piezoelectric, thermal, acoustic energy and etc, have already been demonstrated. In the published reports, Yang and his group fabricated self-powered devices by connecting an nanowire CdSe photodetector and a GaN/ZnO cell in series. Similar design optical driven transistor was also demonstrated. However, those components in their design were easily effected by background light intensities.

To solve the problem, authors introduced a vertical integration design and presented a self-powered optical switch device in this study. Similar study integrated a crystalline-Si interdigitated back contact (IBC) PV cell and a-IGZO TFTs with a direct 3D stacking structure. However, it connected several Si-based PV and cost dimensions. Compared with that, our device integrated an IGZO TFT and a GaInP/GaAs/Ge triple junction TJ PV cell into a chip which saved chip dimensions and got better performance, as shown in Fig. 1. For the TFT, IGZOwas chosen due to its high mobility, superior uniformity, and good transparency to visible light. A high-k material, Ta$_2$O$_5$, was used as the gate dielectric underneath IGZO film to control the conduction channel in IGZO. The TJ PV cell was adopted because it has the highest and stable output voltage among PV cells. Moreover, TJ solar cell is broadband sensitive and the open circuit voltages (Voc) are close under different illumination levels and voltages. The TJ PV cell was measured using the semiconductor parameter analyzer under simulated solar light intensities of 100, 300, 600 and 1000 W/m$^2$. It should be noted that solar light is used as test light source. The I-V curve of the TJ PV cell was measured using a Keithley 2400 source meter. For real operations, the monitored current in IGZO is operated with repeatedly switching light on and off.

Results and Discussion

The external quantum efficiency (EQE) is defined as the number of photon-generated charge carriers contributing to the photocurrent per incident photon. Fig. 2 shows the EQE plots for the TJ PV cell from 300 to 1800 nm (UV–vis-near-infrared). From the EQE data, it can be seen the device is broadband sensitive, especially the EQE plots are about 80% in the range of 450 to 1500 nm.

Fig. 3 shows illuminated I-V characteristics of the independent TJ PV cell under various illumination levels. The short-current density (JSC) and open-circuit voltage (VOC) of the TJ PV cell under illumination of 1000, 600, 300, 100 W/m$^2$ were 13.75, 9.02, 4.75, 1.40 mA

Experimental

The TJ PV cell comprises subcells of GaInP (top cell, bandgap energy Eg = 1.9 eV), GaAs (middle cell, Eg = 1.42 eV), and Ge (bottom cells, Eg = 0.67 eV). The structure is grown on Ge substrates using a metal-organic chemical vapor deposition (MOCVD) system at 650 °C and a reactor pressure of 50 mbar. The metal of Ni/Ge/Au alloy was deposited on front side of PV cell by E-beam evaporation. To isolate the IGZO TFT on TJ PV cell, a 2-μm-thick SiO$_2$ layer was deposited on the rear side. The SiO$_2$ was patterned and removed. Al electrode was deposited the removed SiO$_2$ area and taken as electrode of gate of IGZO TFT. A 100-nm-thick Ta$_2$O$_5$ gate dielectric was subsequently deposited on the bottom gate by E-beam evaporation. A 50-nm-thick a-IGZO (target In:Ga:Zn = 1:1:1 in atomic ratio) active layer was then deposited via RF sputtering. Finally, in order to form ohmic contact, an Al layer was deposited onto the a-IGZO film to serve as the source and drain electrodes. The gate length and gate width of a-IGZO were 100 and 2000 μm, respectively. The negative electrodes of the TJ PV cell was connected to the source electrodes of the of the a-IGZO TFT. The I-V curves of the IGZO TFT on the TJ PV cell were measured using the semiconductor parameter analyzer under simulated solar light intensities of 100, 300, 600 and 1000 W/m$^2$. It should be noted simulated solar light is used as test light source. The I-V curve of the TJ PV cell were measured using a Keithley 2400 source meter. For real operations, the monitored current in IGZO is operated with repeatedly switching light on and off.

![Figure 1. Schematic diagram of the optical switch made of TJ PV and a-IGZO TFT.](image-url)
and 2.48 V, 2.41, 2.32 V, 2.28 V, respectively. It should noted Voc decreased from 2.48 to 2.28 V when the light intensity was decreased from 1000 to 100 W/m².

Fig. 4 shows the $I_{DS}$-$V_{DS}$ and $I_{DS}$-$V_{GS}$ characteristics, respectively. Fig. 4a plots its output $I_{DS}$-$V_{DS}$ characteristics in a dark environment without connection to the TJ PV cell. The device exhibits typical n-type TFT characteristics with a clear pinch-off and current saturation. With 1.5 V applied gate bias, it was found that the saturation drain current, $I_{DS}$, was approximately $10^{-5}$ A. Fig. 4b shows $I_{DS}$-$V_{GS}$ characteristics of the independent TFT device. The values of the field effect mobility ($\mu_{FE}$) and the threshold voltage ($V_T$) were determined from the linear $I_{DS}$-$V_{GS}$ plots. The values of field effect mobility, $\mu_{FE}$ and threshold voltage, $V_T$ were 51.5 cm²/V-s and 1.25 V, respectively. These values indicate that the performances of the fabricated TFT is good. Moreover, These results indicate that the TJ PV cell can afford to provide enough voltage to drive TFT even under weak illumination by referring to Fig. 3.

To realize the optical device, the conductive paths were connected from the TJ PV cell’s electrodes to the gate and source electrodes of the a-IGZO TFT as shown in Fig. 5a. It should be noted that a voltage regulator component was added to keep the $V_{GS}$ at a stable value. Two probes of B1500 analyzer were used to measure the drain and source electrodes. Fig. 5b shows the a-IGZO TFT output characteristics of the device under various illumination levels. The plots also show that the switch-on current values and working voltage ($V_{on}$) values were stable and kept at around $10^{-5}$ A and 1.5 V under 100, 300, 600 and 1000 W/m². These performances proved that the a-IGZO TFT which was driven by TJ PV cell with was reproducible in the condition of bright or low illumination. Fig. 5c shows the measured transient response of the fabricated a-IGZO TFT, obtained with the light switched on and off with the intervals of 20 seconds. The probes of B1500 with a constant $V_{DS} = 1.2$ V were applied to the source and drain electrodes. The current responses work stably for both turning on and off the light illumination. Under the illumination of 1000, 600, 300, and 100 W/m², the dynamic responses of the device overlap with an on/off current contrast ratio of around 3 orders and function identically in a bigger range of timeline. Moreover, we still can see a little difference when zooming in a specific range of rising time under different illumination, in Fig. 5d. The response is faster with bright light and slower with weak light. That means rising time depends on the velocity of accumulated carriers generated by the illumination. It should be noted the results are not optimized, and we will still work harder to make the responses identical and faster.

Conclusions

This study presents a device that integrates an IGZO TFT and a GaInP/GaAs/Ge TJ PV cell. From the EQE data, TJ PV cell is broadband sensitive and can provide enough voltage values under different illumination levels. The authors also add a voltage regulator to assist the device has identical working voltages and perform identically. The optical switch has a high current on/off ratio about 3 orders to eliminate background light disturbances because it is driven by TJ PV cell but light directly. Under the illumination of 1000, 600, 300, and 100 W/m², the dynamic responses of the device is identical and stable,
which means it can be used in outdoor and indoor environments. It is not optimized from rising time chart, but we will work harder to make the responses identical and faster in our next phase.

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References

1. H. Y. Wang, T. Luo, Z. J. Lu, H. J. Song, and J. B. Christen, *Opt. Lett.*, 39, 2618 (2014).
2. R. Dhakal and J. Kim, *Appl. Opt.*, 53, 5712 (2014).
3. T. Imai, S. Fujimoto, and M. Ichiki, *J. Phys.: Conf. Ser.*, 557, 012100 (2014).
4. M. Lallart and D. Guyomar, *Smart Mater Struct.*, 17, 035030 (2008).
5. A. F. Yu, M. Song, Y. Zhang, Y. Zhang, L. B. Chen, J. Y. Zhai, and Z. L. Wang, *Nano Res.*, 8, 765 (2015).
6. Z. Y. Zhan, L. X. Zheng, Y. Z. Pan, G. Z. Sun, and L. Li, *J. Mater. Chem.*, 22, 2589 (2012).
7. Y. Q. Bie, Z. M. Liao, H. Z. Zhang, G. R. Li, Y. Ye, Y. B. Zhou, J. Xu, Z. X. Qin, L. Dai, and D. P. Yu, *Adv. Mater.*, 23, 649 (2011).
8. L. S. Jin and L. J. Li, *Opt. Lett.*, 40, 1798 (2015).
9. Y. M. Jian, H. T. Hou, S. J. Chang, T. H. Chang, K. C. Lai, T. C. Cheng, Y. D. Lin, C. J. Chiu, and W. Y. Weng, *IEEE Electron Device Lett.*, 40, 1040 (2014).
10. P. Migliorato, M. D. H. Chowdhubry, J. G. Um, M. Seok, M. Martivenga, and J. Jang, *J. Display Technol.*, 11, 497 (2015).
11. X. D. Huang, Y. Ma, J. Q. Song, and P. T. Lai, *J. Display Technol.*, 12, 1522 (2016).
12. H. K. Li, T. P. Chen, S. G. Hu, X. D. Li, Y. Liu, P. S. Lee, X. P. Wang, H. Y. Li, and G. Q. Lo, *Opt. Express*, 23, 27683 (2015).
13. K. Nomura, H. Ohta, K. Ueda, T. Kamiya, M. Hirano, and H. Hosono, *Science*, 300, 1269 (2003).
14. T. H. Chang, C. J. Chiu, W. Y. Weng, S. J. Chang, T. Y. Tsai, and Z. D. Huang, *Appl. Phys. Lett.*, 101, 261112 (2012).
15. C. J. Chiu, S. P. Chang, and S. J. Chang, *IEEE Electron Device Lett.*, 31, 1245 (2010).
16. M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, *Prog. Photovoltaics*, 24, 905 (2016).