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The Use of a Patterned NiO Capping Layer to Improve Photoresponsivity of Ultraviolet Photodetectors Based on IGZO Field Effect Diodes

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Abstract

The fabrication and optoelectrical characteristics of ultraviolet photodetectors based on diode-connected bottom-gate-structured IGZO TFTs (called field-effect diodes, FEDs) are presented for the first time. To enhance sensing performance, a patterned NiO capping layer (CL) was deposited on the top surface of the IGZO channel to form a NiO(p)/IGZO(n) heterojunction (HJ) herein. Experimental results reveal that the proposed IGZO FED with a 5-µm-wide and 60-nm-thick NiO CL shows a photoresponsivity (R_{ph}) and a photosensitivity (S_{ph}) as high as 525.87 A/W and 1.28×10^7 at 275 nm under $V_D = -1.5$ V, which are about 133 and 356 times increase in R_{ph} and S_{ph}, respectively, as compared with the case without NiO CL. Such improvements are due to the NiO/IGZO HJ reduces the effective channel thickness to lower dark current and provides an additional amount of optically excited electrons to promote photocurrent.

1. Introduction

For having a wide energy bandgap and an open channel region for light illumination, bottom-gate IGZO TFTs have gained widespread interest in ultraviolet (UV) photodetection for the applications of flame sensing, combustion control, optical communication, solar UV monitoring, etc. [1–3] To enhance gate controllability, reduce leakage current and operation voltage, various high-κ dielectrics were used. Nevertheless, since the minimum currents at turn on voltage (V_{on}), I_{dark}, were commonly employed in $R_{ph}(\equiv (I_D - I_{dark})/P_{in}$ and $S_{ph}(\equiv (I_D - I_{dark})/I_{dark}$ evaluation, an extra bias voltage is required, in addition, the threshold voltage shift (ΔV_{th}) caused by reliability issues in IGZO TFTs would significantly increases the complexities of detection circuit design to anchor V_{on} for currents measurements.

In this work, IGZO field-effect diodes (FEDs), diode-connected IGZO TFTs with $Hf_{0.82}Si_{0.18}O$ gate dielectric, was used for UV light detection to release the problems mentioned above. With gate short-circuited to drain (or source), [4, 5] FEDs exhibit an excellent rectifying behaviors which are insensitive to ΔV_{th} especially in off state operation. Comparisons of UV sensing performances between TFT and FED types photodetectors are made. To improve UV sensing performance, deposition of a patterned NiO capping layer (CL) on the top surface of the IGZO channel to from a pn heterojunction (HJ) is demonstrated. The effectiveness of the NiO CL in enhancing photoresponse is clarified. While the influence of the thicknesses and widths of the NiO layer on the performance of FED based UV detectors are investigated and discussed.

2. Experimental

Fig. 1(a) depicts the schematic cross section view of the bottom gate IGZO TFTs and FEDs with the proposed NiO CL prepared in this study. All TFTs and FEDs are with the same width/length ratio of 200 µm/20 µm. First, Titanium (Ti) was deposited on SiO_2 (500 nm)/p-Si substrate by e-beam evaporation to serve as the bottom gate. Then $Hf_{0.82}Si_{0.18}O$ gate dielectric layer with an equivalent oxide thickness (EOT) of 10±1 nm was deposited by RF co-sputtering with HfO_2 and Si targets in Ar ambient at RT. It was subjected to a post-deposition annealing (PDA) at 600 ℃ for 10 min in O_2 ambient. Based on XRD and AFM analysis, it indicates that $Hf_{0.82}Si_{0.18}O$ layers which has a κ value of around 21.4 remains amorphous structure after 600 ℃ PDA and has a lower RMS surface roughness (0.158 nm) than that of HfO_2 (0.848 nm). Then a 30-nm-thick α-IGZO channel layer was deposited by RF sputtering using an IGZO (In_2O_3: Ga_2O_3: ZnO= 1:1:1) target, and followed by a PDA at 300℃ for 10 min in N_2 ambient. Note that the thickness of the channel (t_{IGZO}) is crucial in receiving a full depletion channel at $V_G = 0$ to minimize the dark current.

Some of the samples were subjected to deposition of a patterned NiO CL with different thicknesses (20 and 60 nm) and widths (5 and 10 µm) on the top surface of the IGZO channel by RF sputtering using a NiO target. A patterned 25-nm-thick Al-doped ZnO contact buffer layer and a 200-nm-thick Ti metal were deposited as the source/drain electrodes by RF sputtering and e-beam evaporation, respectively. For FEDs fabrication, an additional metallization process to connect the drain and bottom gate metal was made (not shown). Finally, a 150-nm-thick SiO_2 was deposited as a passivation layer by RF sputtering (not shown).

Note that the NiO CL forms a NiO(p)/IGZO(n) HJ coupled with the IGZO channel region. Fig. 1(b) illustrates the possible energy band diagram of the NiO/IGZO HJ under thermal equilibrium. According to transmittance spectra and the corresponding Tauc plots (not shown), the optical band gap of α-IGZO and NiO films were estimated to be 3.33 and 3.71 eV, respectively. Based on $n_{IGZO} = 6.02\times10^{19}$ and $p_{NiO} = 1.50\times10^{17}$ cm^{-3} obtained from Hall measurement, W_1 and W_2 were estimated to be of about 1.54 and 61.79 nm, respectively. It is noted that, since the IGZO channel is fully depleted, both the TFTs and FEDs should have a much large W_1 (e.g., $n'_{IGZO} = n_{IGZO}/10$, $W'_1 = 15.88$ nm).

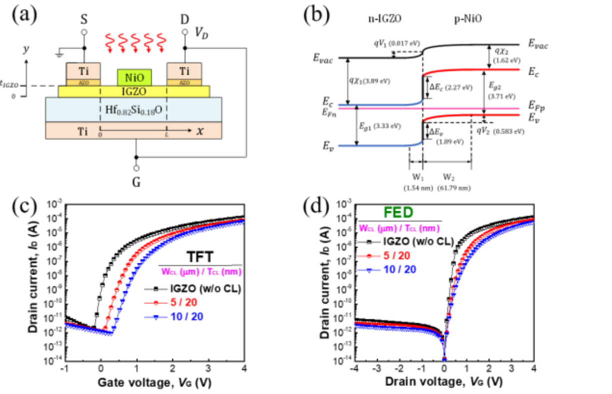

Fig. 1 (a) Schematic cross section view of the proposed IGZO FED with a patterned NiO CL. (b) The possible energy band diagram of NiO/IGZO HJ under thermal equilibrium. (c) Typical transfer characteristics of the fabricated IGZO TFTs and (d) I–V curves of FEDs without and with NiO CL on the IGZO channel in the dark.

3. Results and Discussion

The typical transfer characteristics of the fabricated IGZO TFTs and FEDs (w/o and w NiO CL) are shown in Figs. 1(c) and 1(d). The typical threshold voltage (V_{th}), on/off current ratio (I_{on}/I_{off}), electron mobility (μ_n), subthreshold swing (SS) of the fabricated TFTs are 0.11 V, 17.8 cm^2/Vs, 6.34×10^7, and 112 mV/dec, respectively. While FEDs show a typical rectification ratio at ± 4 V of 1.61×10^7 and 2.06×10^7 without and with NiO CL. Note that FEDs with the gate shorted to source exhibit backward rectifying I-V characteristics (not shown) which are nearly symmetrical to the forward rectifying I-V curves shown in Fig.1(d). It is seen that the off-state ($V_D < 0$) current of FEDs has a relatively weaker voltage dependence than that of TFT in $V_G < V_{on}$ region. Because the peak potential drop (V_p) between the gate and channel in off state of the FED is $V_G(= V_D)$ at the source end of channel is less than that of $|V_G| + V_D$ at drain end of the channel in TFT, consequently, gate leakage current which strongly depends on V_p is much released in FED. The use of NiO CL in TFTs causes V_{th} right shift, and in turn, reduced both I_{off} and I_{on}. The same situation is also found in FEDs, which is attributed to the formation of NiO/IGZO HJ on the back channel reduces the effective channel thickness, as evident in Fig. 1(b).

Comparison of UV sensing performances of TFT and FED without NiO CL under UV light illumination at different wavelengths is shown in Fig. 2. Note that both devices exhibit visible light (~ 400 − 630 nm) blind behavior because IGZO (3.33 eV) and NiO (3.71 eV) are hard to absorb visible light. It is seen that I_D increases significantly as decreasing the wavelength, which is mainly attributed to the band-tail and interband transition light absorption. Table I listed the calculated R_{ph} and S_{ph}. Note that the bias condition of $V_D = -4$ V for FED and $V_D = 4$ V and $V_G = -0.28$ V for TFT were used. It indicates that the FED has a better UV sensing performance. With no need of an extra bias for the gate to pinpoint V_{on} for the minimum current, I_{dark}, measurement and ΔV_{th}-independent off state behavior, UV photodetectors based FEDs should be easier and more cost effective in detecting circuit design and more reliable than conventional UV photodetectors based on TFTs.

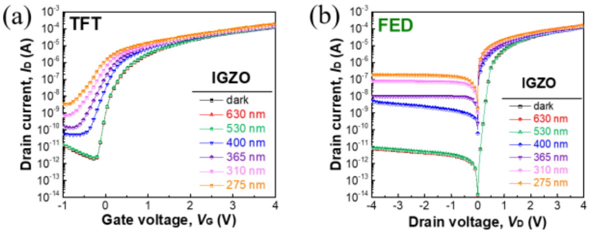

Fig. 2 UV sensing performances of the fabricated (a) TFTs and (b) FEDs.

Figs 3(a) and 3(b) show the $I-V$ curves of IGZO FEDs with NiO CL in dark and under UV light illumination at different wavelengths of the incident light. Our FEDs exhibit superior UV photo responses, especially for the cases with NiO CL. The quantitative results of the corresponding R_{ph} are also listed in Table I. To reduce power consumption, note that the bias voltage was set to be –1.5 V for all R_{ph} measurements. Fig. 3(c) shows the relationship between R_{ph} and wavelength of the irradiated light. FEDs with 5-μm-wide and 20-nm-thick NiO CL shows the highest rejection ratio at 275 and 630 nm of about 8.79×10^9. As compared with the case without NiO CL, it is noted that the photoresponsivity at 275 nm of FED with a 5-μm-width and 20-nm-thick NiO CL increases from 3.95 to 307.79 A/W, i.e., an increase in R_{ph} by about 78 times is achieved. Such improvements is due to the NiO/IGZO HJ not only reduces the effective channel thickness to decrease I_{dark} but also contribute considerable additional photo currents during UV light irradiation. However, the increase in the CL width (W_{CL}) from 5 to 10 μm shows an adverse effect on R_{ph}. Though further studies is still needed, it might be attributed to the portion of IGZO channel covered by NiO CL increases with increasing W_{CL}, hence the effect of the increase in channel series resistance which reduces channel current overrides the increase in photocurrent from the widen HJ.

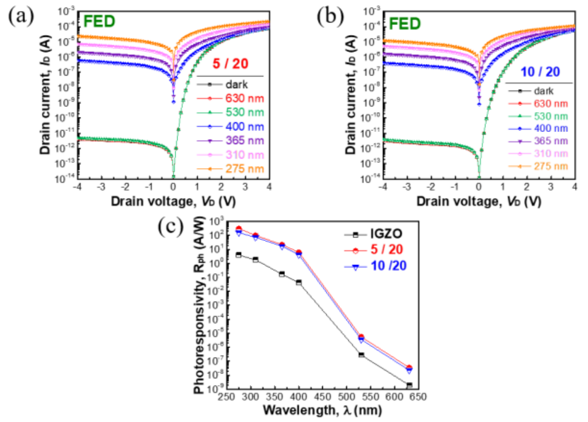

Fig. 3 Experimental $I-V$ curves of IGZO FEDs. (a) Without NiO CL, (b) with 5-μm-wide and 20-nm-thick NiO CL, (c) with 10-μm-wide and 20-nm-thick NiO CL, and (d) the corresponding $R_{ph}-\lambda$ curves.

Fig. 4 depicts the details of the mechanism to create photocurrents in the proposed FEDs, where $0 < x < L$. The dashed lines shown in the figure denote the case without NiO CL. Under UV light irradiation, essentially, the NiO/IGZO HJ operates in photovoltaic mode with the NiO CL being floating. Electron-hole pairs are generated mainly through interband transition. They are separated by the built-in electric field in the depletion region of the NiO/IGZO HJ along the *y*-direction and the electric field in the channel created the drain voltage along *x*-direction. The energy difference between the Fermi levels in IGZO and NiO layer indicates qV_{oc}, where V_{oc} is the open-circuit voltage of the HJ, which arises from the accumulation of photo generated carriers outside of the depletion region of NiO/IGZO HJ. Note that the accumulation of photo-generated carriers within the front and back channel regions is responsible for the considerably enhanced currents in FEDs.

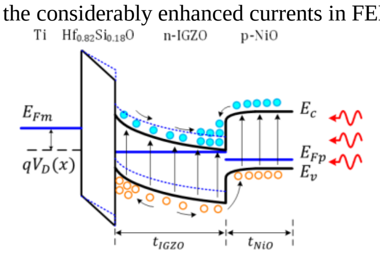

Fig. 4 Schematics to illustrate the operation mechanism of the proposed FED (a) in dark (b) and under UV light illumination. The dashed lines denotes the case without NiO CL.

Fig. 5 shows the influence of the thickness of NiO CL on photoelectrical performance of the FEDs. Keeping the same width of 5 μm, it is found that as the thickness of NiO CL, T_{CL}, was increased from 20 to 60 nm, the transfer curve of TFT shifts positively ($\Delta V_{th} = 0.6$ V), leading to a considerable decrease in the off current. It suggests that the degree of depletion could be effectively enhanced by increasing T_{CL}. The increase in T_{CL} might also expand the non-depleted region in NiO CL to accommodate enough minority carrier diffusion length to have photo generated charges to be collected, as a result, the amount of photo-generated electrons supplied by the HJ to IGZO channel increases. Upon UV light (at 275 nm) irradiation, it is quite encouraging to find that R_{ph} and S_{ph} as high as 525.87 A/W and 1.28×10^7 were obtained from the proposed FEDs. It is expected that much better sensing performance could be achieved from the proposed UV photodetectors based on FEDs after optimization in device structure and material have been made.

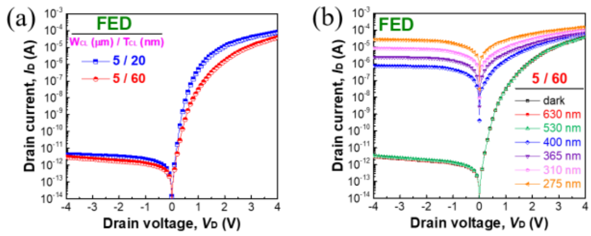

Fig. 5 The influence of the thickness of the NiO CL on photo response of FEDs.

Table I Photoresponsivity of IGZO FEDs with and without NiO CL.

Light source	w/o NiO CL (devices shown in Fig. 2)		FEDs w/o and with NiO CL at –1.5 V (devices shown in Fig. 3 and Fig. 5)			
	TFT	FED	IGZO	5 / 20	10 / 20	5/ 60
630 nm (0.058 mW)	1.5×10^{-8}	2.0×10^{-8}	1.9×10^{-8}	3.5×10^{-8}	2.3×10^{-8}	3.7×10^{-8}
530 nm (0.058 mW)	2.5×10^{-6}	2.8×10^{-6}	2.8×10^{-6}	5.5×10^{-6}	3.6×10^{-6}	5.6×10^{-6}
400 nm (0.058 mW)	0.013	0.091	0.041	6.15	4.11	11.20
365 nm (0.058 mW)	0.15	0.19	0.17	21.80	17.08	37.72
310 nm (0.042 mW)	1.17	1.84	1.79	100.27	72.65	171.64
275 nm (0.045 mW)	4.27	4.31	3.95	307.79	158.85	525.87

4. Conclusions

UV photodectors based on IGZO FEDs with NiO CL having superior UV sensing performance has been demonstrated. Through formation of NiO(p)/IGZO(n) heterojunction to further deplete the channel and supply photo generated carriers to enhance photocurrent, the proposed FED with a 60-nm-thck and 5-μm-wide NiO CL has been found exhibiting an excellent UV light sensing performance with R_{ph} as high as 525.87 A/W and S_{ph} as high as 1.28×10^7 at 275 nm under $V_D = -1.5$ V. It is believed that, after optimization in both device structure and materials have been made, the proposed FED type photodetectors could be very potential in promoting applications of UV and non-UV light sensing.

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