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ABSTRACT

In order to demonstrate tunable absorption characteristics of ZnO, photodetection properties of ZnO based thin-film-transistors are investigated. By controlling the occupancy of the trap states, the optical absorption coefficient of ZnO in the visible light spectrum is actively tuned with gate bias. An order of magnitude change of absorption coefficient is achieved. An optical modulator is proposed exploiting such tunable absorption mechanism.
Keywords: ZnO, tunable absorber, metal oxides, thin film transistor, optical modulator, atomic layer deposition

1. INTRODUCTION

ZnO based transparent thin film transistors are extensively investigated recently due to their potential of replacing amorphous Si thin film transistors [1-5]. Also, UV (ultra-violet) detecting properties of ZnO photodiodes are attracting increasing attention [6-8]. Phototransistors with ZnO channel layer deposited by high temperature RF magnetron sputtering systems are demonstrated in the literature [9]. However, such a high temperature process is not suitable for flexible low cost substrates. Atomic layer deposition (ALD) technique can be used to deposit highly conformal ZnO films at low temperatures with unmatched large-area uniformity.

ZnO based optical modulator in ultra-violet regime is proposed by Wraback et al [10]. In this work, the optical absorption coefficient of ZnO channel layer in the visible spectrum actively tuned by controlling gate bias. By exploiting this absorption tuning mechanism, ALD based ZnO thin-film optical modulator design is proposed.

2. METHODOLOGY

2.1 Fabrication and electrical characterization of ZnO based TFTs

ZnO TFTs fabricated on p-type doped Si substrate with 10-18 mΩ-cm resistivity. Si substrate is also used as a back gate electrode. A thick SiO_2 layer is deposited by PECVD to electrically isolate devices. SiO_2 layer is patterned and etched to define an active channel region. As a gate oxide, 20-nm-thick Al_2O_3 is deposited using ALD at 250°C (precursors: trimethylaluminum and water). 10-nm-thick ZnO is deposited as the channel layer at 80°C with ALD technique which uses diethylzinc and water as precursors. The ZnO channel layer is patterned and etched using dilute H_2SO_4:H_2O (2:98) solution. 100 nm thick Al source and drain contacts are deposited using a thermal evaporator and patterned with a lift-off technique. 3D schematic of ZnO TFTs and top SEM view of fabricated device are given in Figure 1.

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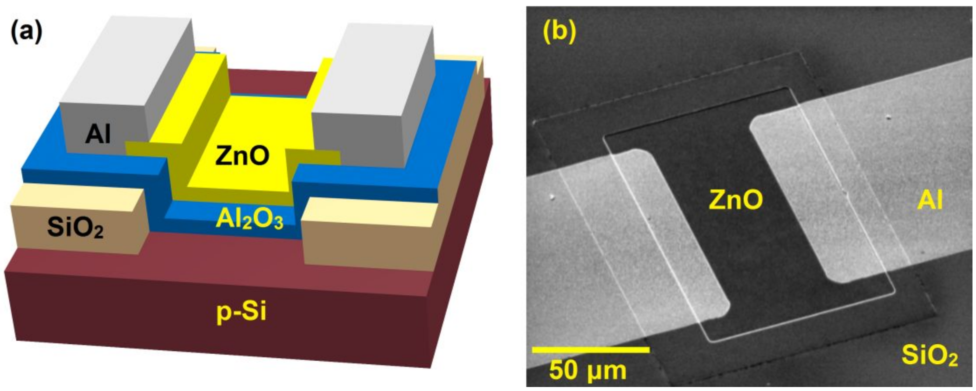

Figure 1. (a) The device schematic of ZnO TFT. (b) Tilted top view of the fabricated device.

Drain current of ZnO TFT measured for various gate voltage biases under constant source to drain voltage bias of 0.5 V are shown in Figure 2. Fabricated TFT operated as n-channel enhancement mode TFT with an on/off ratio of 10^9. The threshold voltage of 4.3 V and the subthreshold slope of 116 mV/dec are extracted from $\sqrt{I_D} - V_G$ and $\log(I_D) - V_G$ characteristics, respectively.

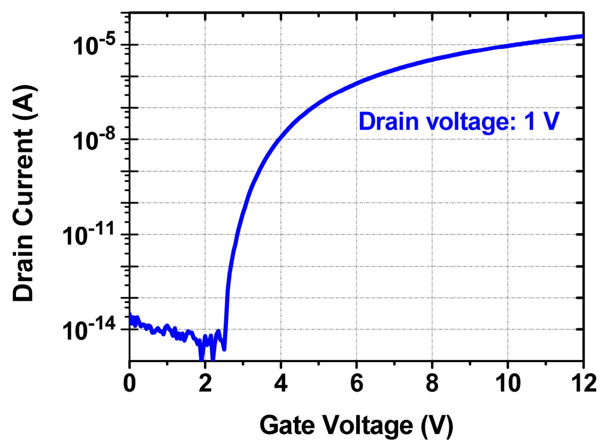

Figure 2. Drain current – gate voltage characteristics of fabricated devices.

2.2 Trap states of ZnO

Polycrystalline ZnO has natural crystallographic defects such as Zinc interstitials and Oxygen vacancies which make ZnO a naturally n-type doped material [11]. Optical absorption spectrum of 30-nm-thick ZnO, coated on a double side polished quartz substrate, exhibits band to band absorption mechanism and its absorption decreases significantly after the band gap energy (Figure 3). Photoluminescence measurement of this ZnO film shows broadband emission characteristic around 600 nm as shown in Figure 3. The distribution of trap states in the band gap is responsible for this broad emission, and the traps in the forbidden band gap are located around 2.07 eV below the conduction band of ZnO.

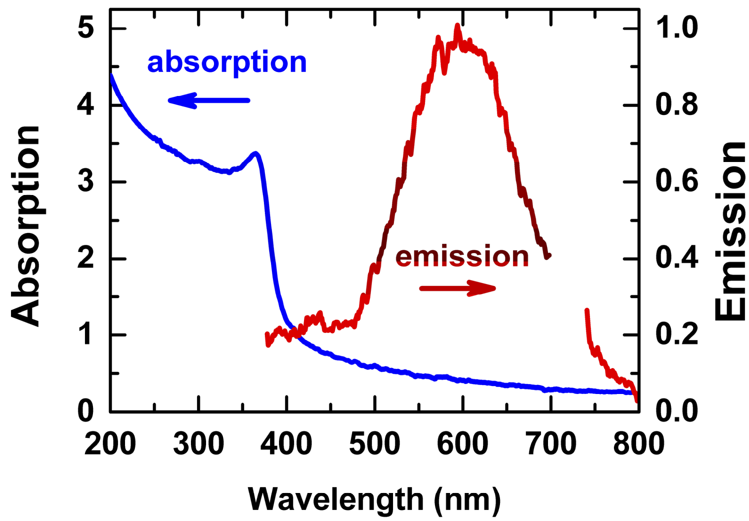

Figure 3. Spectral absorption and emission characteristics of ZnO deposited on double side polished quartz substrate. ZnO is optically pumped at λ = 350 nm for the emission measurement.

3. RESULTS AND DISCUSSION

3.1 Tunable absorption of ZnO channel region

Optical absorption mechanisms of ZnO film are shown in Figure 4. Interband mechanism (1) is the absorption of a photon with energy higher than the band gap (hv > 3.37 eV) which results in a transition of an electron from the valence band to the conduction band. For trap-assisted absorption, electron either moves from the valence band to the trap state (2) or from the trap state to the conduction band (3). A photon with energy higher than the energy difference between the trap state and the edge of the valence band (hv > 1.3 eV) excites an electron from the valence band to the trap state energy level, E_T. For this trap-assisted absorption mechanism an unoccupied trap state is required. The third possible absorption mechanism is from the trap state energy level to the conduction band, but spatially localized nature of trap states significantly reduces the probability of such a mechanism.

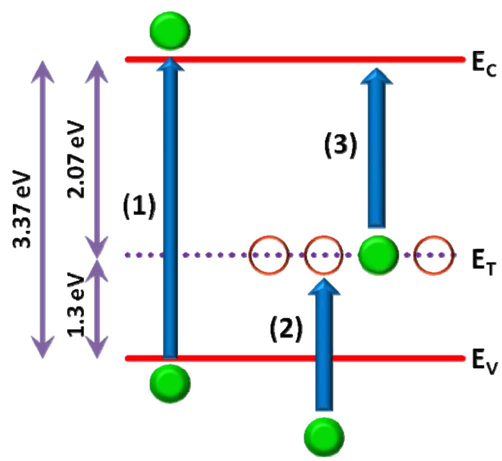

Figure 4. Absorption mechanisms of ZnO. Interband absorption (1). Sub-band gap absorption mechanisms: from valence band to trap state (2), from trap state to conduction band (3).

Responsivity measurements of fabricated ZnO TFTs are taken with the experimental setup shown in Figure 5. The wideband light source is monochromated with Oriel 1/8m Cornerstone monochromator. The monochrome light is mechanically chopped at 400 Hz and optically focused on fabricated devices from top-side at normal incidence. Source and gate terminals of our TFTs are directly connected to Keithley 2400 sourcemeter whereas drain terminal is connected to the sourcemeter by passing through a lock-in amplifier which measures dynamic photocurrent.

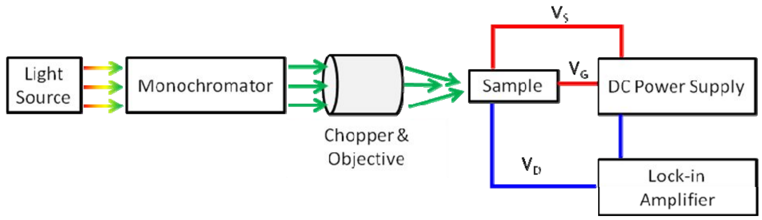

Figure 5. Responsivity measurement setup. Monochromated and mechanically chopped light is focused on fabricated device from top with normal incidence. The photocurrent between drain and source terminals is measured with lock-in amplifier.

In Figure 6, spectral responsivity measurements of our ZnO TFT are given for various gate to source biases and the constant drain to source bias of 3 V. The photoresponse of ZnO channel layer in the visible spectrum can be actively tuned by controlling gate bias. As it is aforementioned, the sub-band gap absorption mechanism of ZnO films requires unoccupied trap states. When the ZnO TFT is biased in the depletion region, its traps loose electrons and the number of unoccupied trap states increases. Due to the increasing number of empty trap states, the probability of sub-band gap photon absorption mechanism increases. As ZnO channel is accumulated with electrons, both its Fermi level and the number of occupied trap states increases.

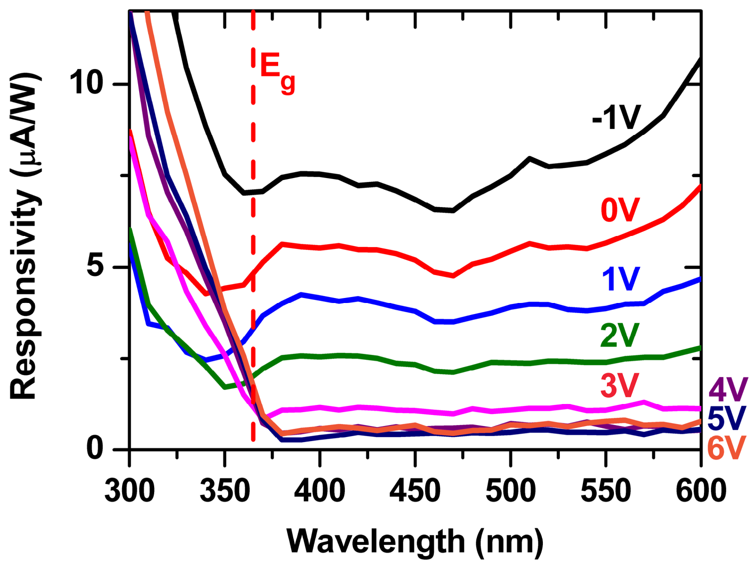

Figure 6. Spectral responsivity measurements of our ZnO TFT for various gates to source (V_{GS}) biases under the constant drain to source voltage of 3V. The dashed red line shows cutoff wavelength (365 nm) of ZnO band-to-band absorption.

3.2 Theoretical analysis of absorption coefficient change

Our ZnO TFT is illuminated from the top-side, and the incident light intensity at the top surface is denoted as I_0 (after surface reflection). The light intensity at a distance of 'x' decreases to I_x which is calculated by Eq. 1 where α is the absorption coefficient of ZnO.

$$I_x = I_0 \cdot e^{-\alpha x} \tag{1}$$

$$\text{Absorption}: I_0 - I_x = I_0 \cdot (1 - e^{-\alpha x}) \tag{2}$$

The absorption coefficient of ZnO films at visible wavelengths can be controlled by applying gate bias as it is shown in Figure 6. By assuming the carrier collection efficiency is independent of gate bias, the absorption coefficient ratio is linearly proportional to the responsivity ratio as it is given in Eq. 3. For the wavelength of 550 nm, our ZnO TFT has responsivity values 8.09 μA/W and 0.79 μA/W respectively for depleted (V_{GS} = -1 V) and accumulated (V_{GS} = 6 V) ZnO TFT, respectively. The absorption ratio given in Eq. 3 can be simplified to ratios of absorption coefficients (Eq. 4) by using Taylor series expansion of exponential term and assuming the product $\begin{bmatrix} Absorption \\ Coefficient \end{bmatrix} \times [Depth]$ (αx) is small for both depletion and accumulation cases.

$$\text{Absorption ratio}: \frac{I_0 \cdot (1 - e^{-\alpha_1 x})}{I_0 \cdot (1 - e^{-\alpha_2 x})} = \frac{8.09 \mu A/W}{0.78 \mu A/W} = 10.37 \tag{3}$$

$$\frac{1 - e^{-\alpha_1 x}}{1 - e^{-\alpha_2 x}} \approx \frac{1 - (1 - \alpha_1 x)}{1 - (1 - \alpha_2 x)} = \frac{\alpha_1}{\alpha_2} = 10.37 \tag{4}$$

3.3 Optical modulator design

The tunable absorption coefficient mechanism shown in the ZnO TFT device can be applied as an optical modulator in the visible wavelengths by using the proposed modulator design shown in Figure 7. A thin ZnO film is deposited on a bottom metal contact which is grounded. A thin oxide layer is used to block current flow between contacts and to create an electric field which will deplete or accumulate ZnO film depending on the applied active modulation bias. The proposed design also improves modulation contrast ratio of thin ZnO film, by extending the optical path length of incident light in a waveguide configuration.

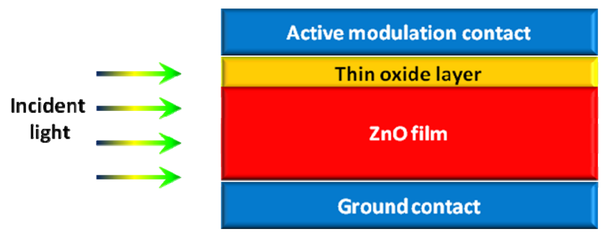

Figure 7. Proposed optical modulator design. The absorption coefficient of ZnO in the visible spectrum, controlled by applied bias to active modulation contact.

4. CONCLUSION

ZnO channel TFTs are fabricated at 80°C by atomic layer deposition technique to demonstrate tunable absorption characteristics of ZnO layer. The fabricated TFTs exhibited tunable absorption characteristics in the visible light spectrum. As we deplete ZnO channel an order of magnitude absorption coefficient change is achieved. An optical modulator design which exploits this tunable absorption mechanism is proposed.

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REFERENCES

[1] Wager, J. F., "Transparent Electronics," Science, 300, pp. 1245-1246 (2003).
[2] Fortunato, E., Barquinha, P., and Martins, R., "Oxide Semiconductor Thin-Film Transistors: A Review of Recent Advances," Advanced Materials, 24, pp. 2945-2986 (2012).

[3] Masuda, S., Kitamura, K., Okumura, Y., Miyatake, S., Tabata, H., and Kawai, T., "Transparent thin film transistors using ZnO as an active channel layer and their electrical properties," Journal of Applied Physics, 93, pp. 1624-1630 (2003).
[4] Hoffman, R. L., Norris, B. J., and Wager, J. F., "ZnO-based transparent thin-film transistors," Appl. Phys. Lett., 82, pp. 733-735 (2003).
[5] Carcia, P. F., McLean, R. S., Reilly, M. H., and Nunes, G., "Transparent ZnO thin-film transistor fabricated by rf magnetron sputtering," Appl. Phys. Lett., 82, pp. 1117-1119 (2003).
[6] Liang, S., Sheng, H., Liu, Y., Huo, Z., Lu, Y., and Shen, H., "ZnO Schottky ultraviolet photodetectors," Journal of Crystal Growth, 225, pp. 110-113 (2001).
[7] Kind, H., Yan, H., Messer, B., Law, M., and Yang, P., "Nanowire Ultraviolet Photodetectors and Optical Switches," Advanced Materials, 14, pp. 158-160 (2002).
[8] Soci, C., Zhang, A., Xiang, B., Dayeh, S. A., Aplin, D. P. R., Park, J., Bao, X. Y., Lo, Y. H, and Wang, D., "ZnO Nanowire UV Photodetectors with High Internal Gain," Nano Letters, 7, pp. 1003-1009 (2007).
[9] Bae, H. S., Yoon, M. H., Kim, J. H., and Im, S., "Photodetecting properties of ZnO-based thin-film transistors," Appl. Phys. Lett., 83, 5313 (2003).
[10] Wraback, M., Shen, H., Liang, S., Gorla, C. R., and Lu, Y., "High contrast, ultrafast optically addressed ultraviolet light modulator based upon optical anisotropy in ZnO films grown on R-plane sapphire," Appl. Phys. Lett., 74, 507 (1999).
[11] Guziewicz, E., Godlewski, M., Wachnicki, L., Krajewski, T. A., Luka, G., Gieraltowska, S., Jakiela, R., Stonert, A., Lisowski, W., Krawczyk, M., Sobczak, J. W., and Jablonski, A., "ALD grown zinc oxide with controllable electrical properties," Semiconductor Science and Technology, 27, p. 074011 (2012).