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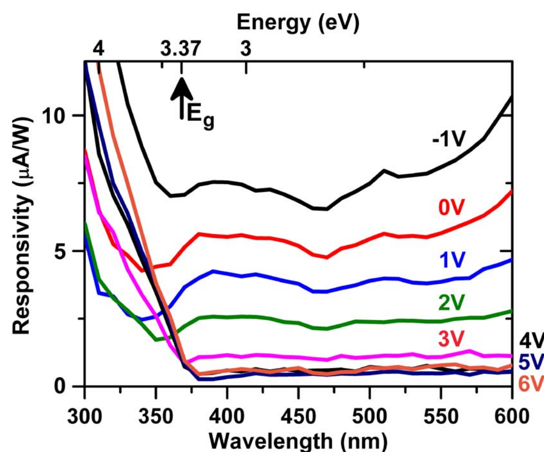

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Dynamic Control of Photoresponse in ZnO-Based Thin-Film Transistors in the Visible Spectrum

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Abstract: We present ZnO-channel thin-film transistors with actively tunable photocurrent in the visible spectrum, although ZnO band edge is in the ultraviolet. ZnO channel is deposited by atomic layer deposition technique at a low temperature (80 °C), which is known to introduce deep level traps within the forbidden band of ZnO. The gate bias dynamically modifies the occupancy probability of these trap states by controlling the depletion region in the ZnO channel. Unoccupied trap states enable the absorption of the photons with lower energies than the bandgap of ZnO. Photoresponse to visible light is controlled by the applied voltage bias at the gate terminal.

Index Terms: Metal oxide, tunable, transparent oxide, visible, defects, traps, phototransistor, TFT, optoelectronic materials, oxide materials.

1. Introduction

Metal oxide (MOx) semiconductors are attracting a great deal of interest as alternatives to amorphous Si (a-Si) in thin-film transistors (TFTs) especially in modern display applications [1]. ZnO is among the most popular MOx semiconductors, and there has been a surge of reports on ZnO-based devices. ZnO-based TFTs have higher reported carrier mobilities than a-Si-based TFTs [2]. Due to its large bandgap of 3.37 eV, ZnO is becoming the leading material of choice in transparent TFTs (TTFTs) [3]–[9]. Recently, TTFTs have emerging applications such as active-matrix organic light-emitting diodes (AMOLEDs) [1], [9]–[11] and active-matrix liquid crystal displays (AM-LCDs) [1], [12]. ZnO channel layer is obtained using a wide range of deposition techniques such as pulsed laser deposition [3], ion beam sputtering [4], RF magnetron sputtering [5], metal-organic chemical vapor deposition [6], and atomic layer deposition (ALD) [7], [9]. Among these techniques, ALD is preferred owing to precise thickness control over large areas and low process temperature.

ZnO grown at low temperature has crystallographic defects such as zinc interstitials and oxygen vacancies. Such crystal defects behave as electron donors yielding an effective n-type doping in ZnO [13]. These defects also create trap states in the forbidden energy band that enable the emission [14], [15] and absorption [16] of photons with energies lower than the bandgap energy. It was shown that the concentration of the defects could be controlled by ALD growth temperature in order to tune electrical properties of ZnO film [13]. However, there are no reports on the dynamic control of the density and occupancy of such trap states, which would offer the ability to actively

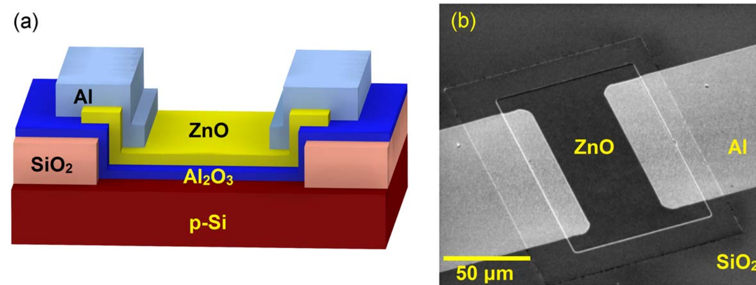

Fig. 1. (a) Device schematic of our ZnO TFT, where Si substrate is used as a back-gate electrode and top Al contacts are source and drain terminals. (b) Top view SEM image of a fabricated device.

control electrical and optical properties of ZnO. Without dynamic photoresponse control, several groups reported ZnO-based metal–semiconductor–metal photodetectors for ultraviolet and visible light detection [17]–[19]. UV light detection properties of ZnO-based TFTs were also reported in the literature [20], [21]. In this work, we present a ZnO-channel TFT with actively tunable photoresponse to visible light using an external stimulus. The photocurrent is controlled by the application of a dc voltage bias at the gate terminal that modifies the local depletion layer profile in the metal–oxide–semiconductor (MOS) structure and the occupancy of deep level traps in the ZnO channel.

2. Experimental Details

ZnO TFTs are fabricated on highly doped (10–18 mΩ-cm) p-type (111) Si wafer, in a back-gate configuration, as depicted in Fig. 1. A thick SiO_2 layer is deposited and patterned for device isolation. A 20-nm-thick Al_2O_3 gate oxide layer is deposited at 250 °C (precursors: trimethylaluminum and water vapor) followed by 10-nm-thick ZnO channel deposited at 80 °C (precursors: diethylzinc and water vapor) using a Cambridge Savannah 100 ALD system. ZnO layer is patterned and etched in dilute sulfuric acid solution $(H_2SO_4 : H_2O_2\ 2 : 98)$, forming a channel region with 100 μm/150 μm width/length ratio. A 100-nm-thick Al layer is thermally evaporated and patterned by liftoff technique to form source and drain contacts on ZnO channel.

The drain current–gate voltage (I_{DS}–V_{GS}) measurements at 0.5-V drain-to-source bias, plotted in Fig. 2, indicate n-channel enhancement type TFT. The threshold voltage of the MOS device is found to be 4.3 V, which is extracted from experimental $\sqrt{I_{DS}}-V_{GS}$ characteristics using extrapolation method in the saturation region [22]. The turn-on gate voltage, V_{ON}, which is the gate bias at the onset of drain current, is 2.5 V (see Fig. 2). For ZnO TFTs, on/off ratio values from 10^2 to 10^8 are reported in the literature [3], [23]–[25]. Our device exhibits a very high 10^9 on/off ratio, which is attributed to low ALD growth temperature (80 °C). Earlier reports show that the transistor on/off ratio increases at lower ALD growth temperatures [23]. This is explained by the reduced electron concentration due to less number of defects in the crystal [26]. The device exhibits decent subthreshold slope of 116 mV/dec and electron mobility of 3.96 $cm^2/V \cdot s$, which are extracted from $\log(I_{DS})-V_{GS}$ characteristics of the device. Previously reported subthreshold slope values range from 24.1 to 0.25 V/dec and mobility values range from 0.03 to 70 $cm^2/V \cdot s$ [23]–[25].

3. Optical Characteristics

Photoluminescence (PL) measurement is performed on samples prepared by growing ZnO on quartz substrates (double side polished) using the same recipe described above. Room temperature PL characteristics of ZnO film at $\lambda = 350$-nm excitation is shown in Fig. 3. Luminescence in the 450- to 750-nm range corresponds to below-bandgap emission, which reveals the presence of deep level traps within the forbidden band of ZnO. The energy distribution of the trap states in the forbidden band cause a broad emission centered around $\lambda = 600$ nm (2.07 eV). Two possible trap-assisted routes that would result in the emission of a photon with $\lambda = 600$ nm (2.07 eV) are illustrated in Fig. 4(a). The first scenario is the capture of a free electron from the conduction band

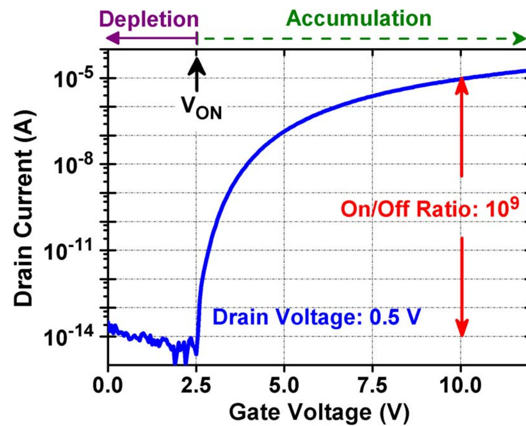

Fig. 2. Drain current–gate voltage (I_{DS}–V_{GS}) characteristics of the fabricated devices under a drain voltage of 0.5 V. The device exhibits 10^9 on/off ratio, a threshold voltage of 4.3 V, and turn-on voltage of 2.5 V.

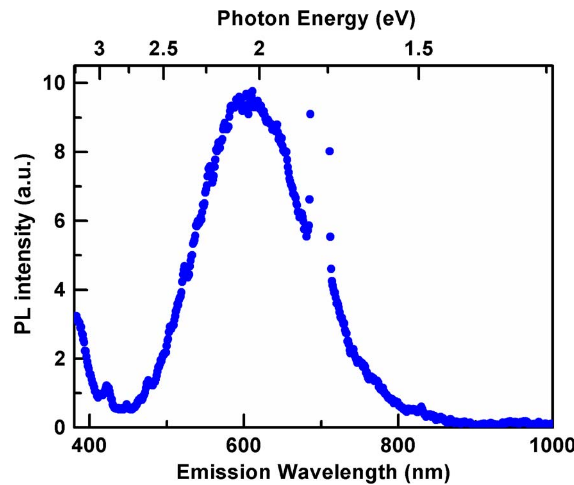

Fig. 3. Spectral photoluminescence of ZnO layer coated on quartz substrate. Absorption and emission are given in arbitrary units. Photoluminescence excitation wavelength is 350 nm.

by a trap state (unoccupied trap) (route I), and the second one is the recombination of an electron in a trap state (occupied trap) with a hole in the valence band (route II). The latter predicts trap energy states are located in the forbidden band of ZnO, closer to the conduction band. In such a scenario, incident photons with higher energy than 2.07 eV (but less than the bandgap energy) excite electrons from the valence band directly to trap states. This is followed by light emission (at 600 nm) through route II when excited electrons recombine with holes in the valence band. Fig. 4(b) plots PL intensity at a constant emission wavelength (600 nm) for different excitation wavelengths. The figure shows that excitation photons with lower energy than the bandgap of ZnO do not result in luminescence at 600 nm. This evidence supports trap-assisted luminescence through route I, which predicts trap energy states located closer to the valence band. This is in good agreement with earlier observations about the energy levels of point defects in the forbidden band of ZnO [14], [27], [28].

Optical absorption of ZnO film on quartz substrate is also characterized. Measured spectral optical absorption of ZnO (see Fig. 5) exhibits band-to-band absorption behavior with an excitonic absorption peak located at $\lambda = 365$ nm. Such room temperature excitonic peaks are attributed to large exciton binding energy and are observed in the literature [29]. The dominant photon absorption mechanisms in ALD-grown ZnO are (1) interband and (2) valence band-to-trap state

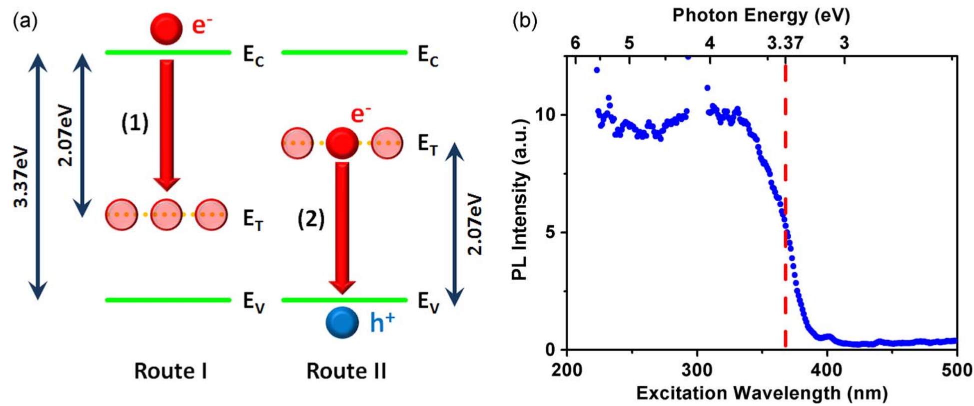

Fig. 4. Energy level of trap states. (a) Two possible trap-assisted emission routes: Route I: trap energy states are closer to the valence band. Conduction band electrons and localized holes of trap states (unoccupied trap) recombine and emit light (1). Route II: Trap energy states are closer to the conduction band. Localized electrons of trap states (occupied trap) and free holes of valence band recombine and emit light (2). (b) Measured photoluminescence intensity at 600 nm (2.07 eV) for various excitation wavelengths. The dashed line shows bandgap energy of ZnO.

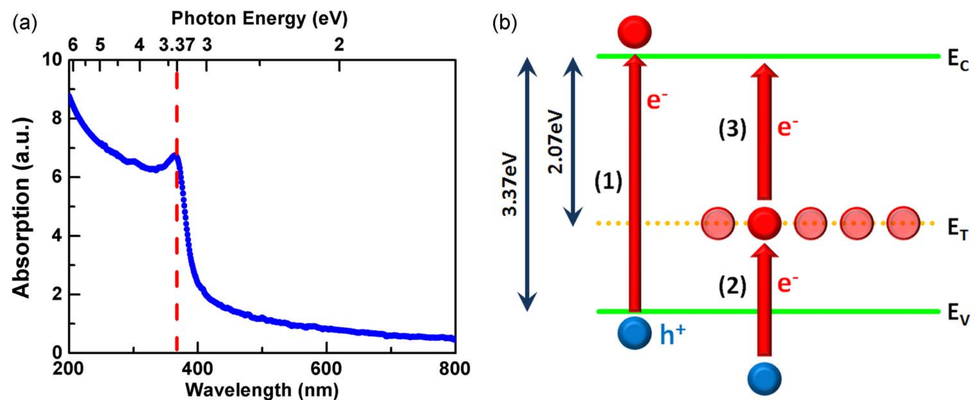

Fig. 5. Optical absorption characteristics. (a) Absorption spectrum of ZnO layer on a quartz substrate. Absorption is given in arbitrary units. The dashed line shows bandgap energy of ZnO. (b) Absorption types of ZnO: Interband (1), valence band to trap state (2), and trap state to conduction band (3).

transitions, as depicted in Fig. 5. Only photons with energies greater than the bandgap of ZnO (i.e., $h\nu > 3.37$ eV) are absorbed in an interband transition (1). Whereas photons with energies less than the bandgap can excite valence electrons to empty states at the trap energy level, E_T (2). This process is limited by the availability of unoccupied trap states because the density of states in the valence band is much larger compared to that of the defect states. Photons could also be absorbed exciting electrons from an occupied trap state to conduction band (3). However, the rate of this transition is very low since it involves an initially occupied trap state, which is spatially localized, to absorb an incident photon before the electron is emitted from the trap to the valence band.

Spectral responsivity measurements of the fabricated TFTs are performed with the experimental setup shown in Fig. 6. A 150-W Xenon lamp is used as a wideband illuminating source. Monochrome light (Oriel 1/8 m Cornerstone Monochromator, 1200 lines/mm grating) is obtained and mechanically chopped. The light is focused on the fabricated device from the top at normal incidence. The source and drain terminals of the device are biased with a Keithley 2400 sourcemeter. Gate terminal voltage bias is independently controlled with a separate voltage supply. A lock-in amplifier is connected in series to measure the electrical current through the source–drain terminals of the device. Incident optical power at each wavelength is recorded by a calibrated Si

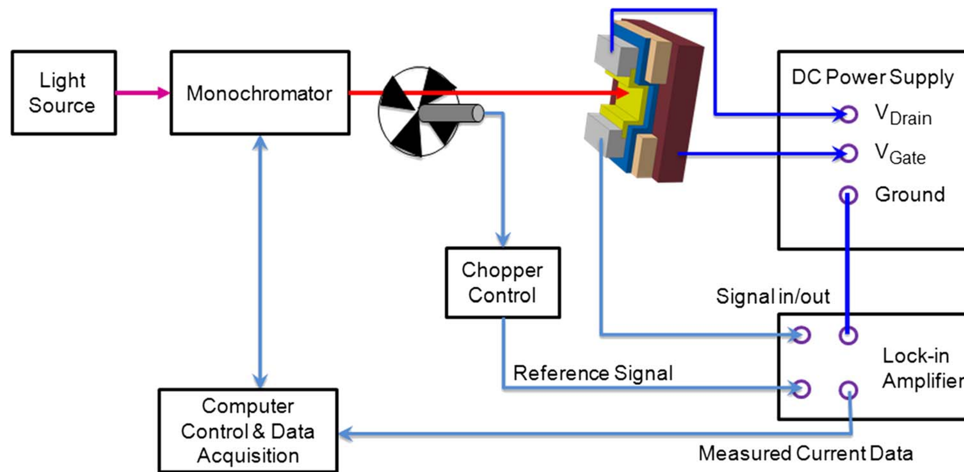

Fig. 6. Responsivity measurement setup. Monochrome light is focused on the fabricated device from the top at normal incidence. The photocurrent between drain and source terminals is measured with a lock-in amplifier.

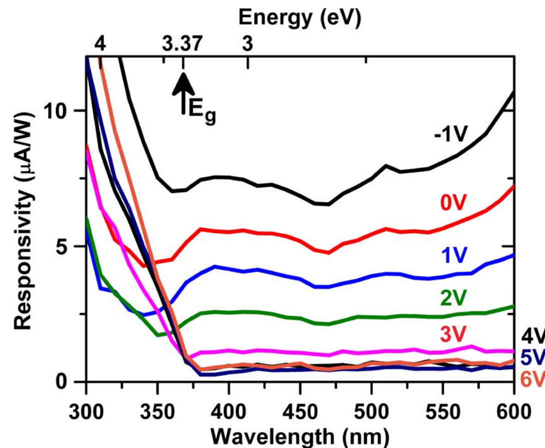

Fig. 7. Spectral responsivity measurements of our ZnO TFT for various gate-to-source voltage bias values under the constant drain-to-source voltage of 3V. Black arrow shows the cutoff wavelength (3.37 eV) of the ZnO band-to-band absorption.

photodetector. Responsivity is defined as the ratio of photogenerated current I_{DS} to incident optical power.

ZnO band edge is at 3.37 eV; however, lower energy photons can be absorbed through trap-assisted routes, as described above. The magnitude of photocurrent generated by below-bandgap photons depends on the density and availability of proper trap states. Therefore, the photo-generated current in the ZnO channel can be dynamically controlled via changing the occupancy of deep level traps by applied gate voltage bias, as shown in Fig. 7. The gate voltage bias modifies the depletion region in the ZnO channel and preferentially accumulates or depletes the channel. The transition from accumulation to depletion state begins at V_{ON} (2.5 V) gate bias, as shown in Fig. 2. When the channel is depleted, the deep level states are unoccupied; therefore, strong absorption of subbandgap photons is possible. In the accumulation mode, electrons from the source and drain contacts are attracted to the ZnO channel layer with the applied gate bias, and an accumulated region with a higher electron density, higher conductivity, and higher quasi-Fermi level is formed. As the quasi-Fermi level increases, the trap states are also filled with these extra electrons. Due to the

decreasing number of empty trap states, the subbandgap photon absorption mechanism is prevented. On the other hand, in the depletion mode, applied gate bias repels electrons from the channel region, and the quasi-Fermi level is shifted down. Therefore, the probability of subbandgap photon absorption is boosted by the increase in the number of empty trap states.

4. Conclusion

We have experimentally demonstrated the electrical tuning of the optical response of ZnO-based TFTs to visible light. The dynamic control of light absorption is achieved by modifying the occupancy of deep level traps in ZnO channel. The applied gate voltage biases the channel to an accumulation or a depletion state. The deep traps are filled in the accumulation state and are unoccupied in the depletion state. Subbandgap photons with $\lambda = 400-600$ nm (visible light) are absorbed when there are available empty trap states in the forbidden energy band. Therefore, we can dynamically control the visible light absorption property of the ZnO channel layer by controlling the electron occupancy of trap states.

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