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# Fabrication and characterization of RF sputtered ZnO thin film based phototransistors for UV detection applications

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This article reports the fabrication and electrical properties of RF sputtered Zinc oxide (ZnO) thin film based staggered bottom gate phototransistors. XRD, AFM, SEM and optical measurements are carried out for the studying the surface morphological, optical as well as structural quality of the deposited thin films. The RF sputtered ZnO thin films are normal to the substrate oriented along the c-axis and exhibit high absorption in the ultraviolet (UV) region. The Thin-Film Transistor (TFT) presented in this work employs sputtered ZnO film as the active channel layer. The proposed enhancement mode device exhibits threshold voltage, channel mobility, and on-off ratio of 4.8V, 5.2 $cm^2$/V.s, and $10^6$ respectively. The potential of the device in UV detection application was tested subsequently using an optical power source of 2.3 W/$cm^2$. The device output current (drain to source current: $I_{DS}$) increased dramatically with UV illumination and the illumination-to-dark current ratio evaluated to be greater than 4 proving the possibility of the device to stand as a potential candidate in UV photodetection applications.

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*Keywords:* ZnO thin films, RF Sputtering, Thin-film Transistors, Phototransistor, Electrical Properties, UV sensor

## 1. Introduction

Development of ultraviolet (UV) photodiode and thin film phototransistor has received huge research attention in the recent years because of the wide range of application domains that it covers in the modern society. They find wide applicability in ground and space-based application domains that require UV detection, such as space to space communication, internet-of-things sensors, environmental monitoring, fire alarms, biological and chemical analysis etc., [1-5]. Many of these applications require UV instrumentation capable of operating in high-temperature harsh environments. While most sensors and electronics today are Silicon (Si) based due to well-established manufacturing processes, easy circuit integration, and low cost, Silicon has shown limited usefulness as a high-temperature UV detecting material platform.

**Properties of ZnO Thin Films:** Recent literature demonstrates wide band gap oxides like ZnO and $TiO_2$ used in UV sensing applications. Particularly, nanocrystalline ZnO thin film has been considered as a promising one of wide band gap material for ultraviolet (UV) detectors owing to its inherent properties that include a binding energy and large energy band gap of 60 meV and 3.37eV respectively. [6-8] ZnO crystallizes in three main forms such as zinc blende, cubic rock salt and hexagonal wurtzite. The predominant form is hexagonal wurtzite structure [1-8].

**Why ZnO and FET is Used for UV Detection:** Silicon and other narrow bandgap semiconductor materials are not good candidates for absorb UV detector applications due to their band gaps corresponding to near infrared or visible wavelengths. Since UV light is higher energy than the bandgap of Si and other narrow bandgap materials, part of the energy will be lost to heating, resulting in low quantum efficiency. On the other hand, in the optoelectronic domain direct bandgap materials like GaN and GaAs are widely used in the synthesis of lasers, light emitting diodes (LEDs), solar cells and multi domain sensors for application in physical, chemical and bio-detections [2]. Their direct band gaps, linearity as well as electroluminescence make them overpower the existing indirect band gap materials. These compound semiconducting materials are facing challenges due to its high production cost and difficult to grow [1, 2]. Therefore, new thin film materials need to be explored for the fabrication of UV detector potentially with lower cost and higher efficiency. ZnO based two-terminal UV photo-detectors with varies technologies such as Metal Semiconductor metal (MSM), Metal Semiconductor Insulator Material (MISM), Schottky diode, p-n heterojunction diode have already been reported in the literature [1-5]. All these two terminal detectors in literature faces the limitation of degraded recovery time due to persistent photoconductivity (PPC). PPC enhances the response times of conventional two terminal based detectors [4, 5]. This limitation can be overcome using phototransistors as detectors. ZnO-TFTs have more importance because of its potential leading to recent applications in photonic applications such as realising modern devices. Compared with other TFTs ZnO based TFT have enhanced properties as the UV detectors such as defect density control due to oxygen vacancies and Zinc interstitials that tends to the good transfer characteristics of the device. The other reason is that ZnO thin film is biocompatible and its user free plays an important role in UV photodetectors, since they can be used in various fabrication techniques and low conductivity depletion layer.

**ZnO Based Thin Film Transistor (ZnO-TFTs):** A few of the several TFT architectures [6, 8, 9] that finds applicability in photodetection is shown in Fig. 1. Coplanar devices with top and bottom gates are depicted in Fig. 1 (b) and (e) respectively. Staggered configurations are presented in Fig. 1 (c) and (d). The configurations differ from each other and can be easily distinguished by the electrode placements. Electrodes on the same side of the insulator/semiconductor interface indicates coplanar configuration whereas electrodes are placed on opposite sides in staggered structures. Contact resistance is minimum in staggered configuration due to larger area of the contacts and significant charge accumulation underneath. The architecture of TFT device is important as the device performance largely depends on the device configurations and gate oxide interface charges. Further device configurations are to be chosen intelligently so that process integration complexities can be minimized. The staggered bottom-gate arrangement (Fig. 1(a)) is being selected as reference test structure for fabrication of ZnO TFTs in this research since its compatibility in fabrication with standard CMOS technology, controllability, stability and the cheapness of Si wafer [6].

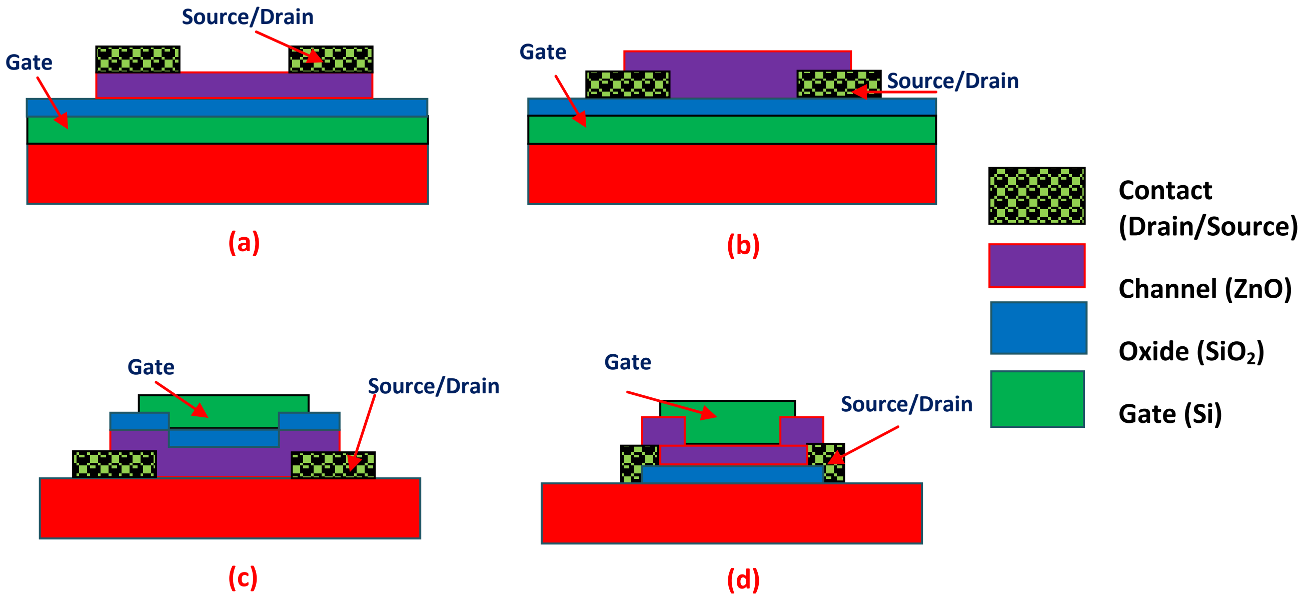


*Fig. 1. Schematic diagram of different TFT structure (color online)*

ZnO films grown on Si/$SiO_2$ compatible with standard Si based fabrication processes and potential candidates to replace two terminal based photodetectors. Proposed in this work, we present the development and characterisation of UV photodetectors based on Staggered ZnO TFT structure.

## 2. Fabrication and characterization of ZnO TFTs

Fig. 2 depicts a schematic cross-sectional view of the proposed bottom gate configured ZnO TFT. The device design comprises of a 200 nm $SiO_2$layer grown thermally over a p-type Si substrate. ZnO thin film layer with 300 nm has been grown using sputter deposition followed by source drain contact metallization where Al contacts of 150 nm have been deposited. The channel length (L) and width (W) of the proposed device are 100 µm and 500 µm, respectively.

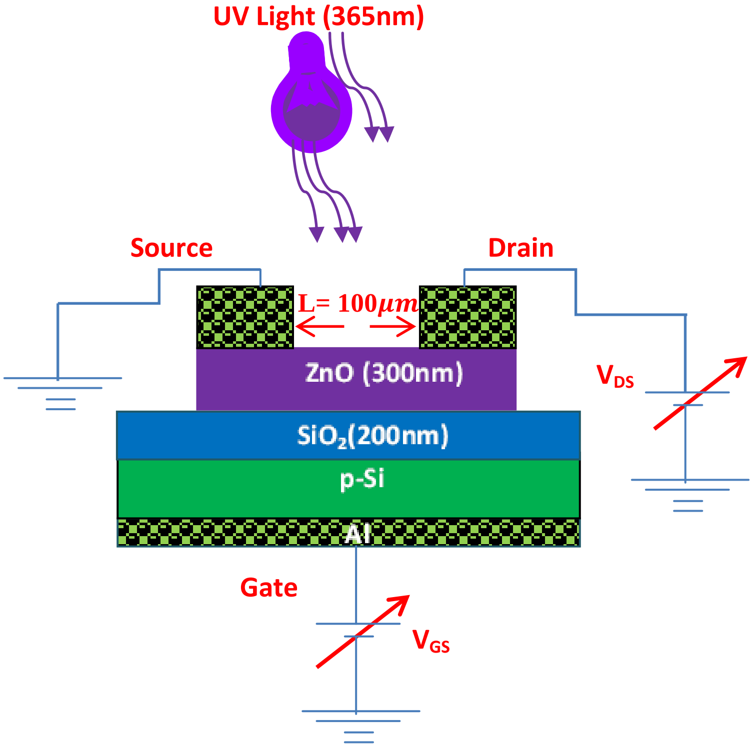


*Fig. 2. Schematic cross-sectional view of the proposed bottom gate configured ZnO TFT (Channel length (L) =100 μm and Width = 500 μm) (color online)*

**ZnO Thin Film Deposition Using RF Sputtering:** According to the literature, numerous methodologies are being used in ZnO deposition. Together with sol-gel, chemical vapour deposition, pulsed laser deposition, sprays pyrolysis, molecular beam epitaxy and RF sputtering [2-11]. Because of its flexible nature and its microstructure, RF sputtering is being selected in this work as the standard deposition methodology for ZnO thin films. Thermal dry oxidation technique has been used for growth of the $SiO_2$ layer on the wafer that is free of organic and inorganic contaminants. After growth of $SiO_2$ layer on Si, thin film of 300 nm, ZnO thin film was deposited using RF sputtering. ZnO thin film deposition was done using a ZnO target from Merck's Chemicals that is commercially available. The sputter deposition was carried out in Ar ambient (gas flow rate of 10sccm). The plan to substrate distance was sustained at 10cm and optimized sputtering parameters were used. The sputtering power of around 100 W is set to trigger the plasma and deposition pressure of $4–6\times10^{-3}$ mbar was maintained to ensure conformal deposition of quality film. The substrate maintained at room temperature. Subsequently the samples with deposited ZnO were annealed for one hour at 450 degrees in Ar ambient. It produces improved ZnO films with denser structure, higher resistivity, smoother surface, relieved stress, and stronger c-axis orientation.

After fabrication of active ZnO layer, suitable source drain electrodes need to be deposited. A variety of conductive source and drain contact layers of suitable thickness and area were deposited over active semiconductor layer. The aluminium source and drain contacts are set down by thermal evaporation and the thickness of 150 nm is to be considered. Back gate deposition involved deposition of a thin Al metal layer through shadow-mask based patterning and e-beam evaporation on the back side of the Si substrate. During the fabrication processes, source, drain and gate contacts were defined by standard photolithography and shadow-mask techniques.

Investigation of structural and optical characteristics of sputtered ZnO: Ellipsometry has been used in confirming the thickness of ZnO film and oxide layer. An atomic force microscope (AFM) scanning electron microscope (FESEM) was used in characterising the surface topographical characteristics of the ZnO film. The crystallographic analysis of the ZnO thin film has been investigated using X-ray diffraction (XRD) technique. The optical absorbance/transmittance characteristics were studied by UV-Vis spectrophotometry. The semiconductor parameter analyser was used to study the transfer and output characteristics of the fabricated ZnO TFTs.

## 3. Results and discussions

The XRD analysis of ZnO thin film on $Si/SiO_2$ substrate is depicted in Fig. 3. The RF sputtered ZnO thin film shows diffraction peak of 002 orientation at $2\theta=34.45$ and also the good crystalline nature as hexagonal wurtzite structure. From the Scherrer̓s formula the size of the grain was calculated to be 35 nm of (002) crystallographic plane [15, 16].

$$D = \frac{0.94\lambda}{\beta cos\Theta} \quad (1)$$

$$a = b = \frac{\lambda}{\sqrt{3} sin\Theta} \quad (2)$$

$$c = \frac{\lambda}{sin\Theta} \quad (3)$$

where, $\lambda$, $\beta$, and $\theta$ represents the X-ray wavelength, full width half maximum (FWHM) of diffraction peak (002) and diffraction angle respectively. Lattice parameters $(a, b, c)$ is being computed by Eq. (2 and 3) and value obtained for a=b, c was found to be 3.07Å and 5.14Å respectively which is same as results shown in [15, 16].

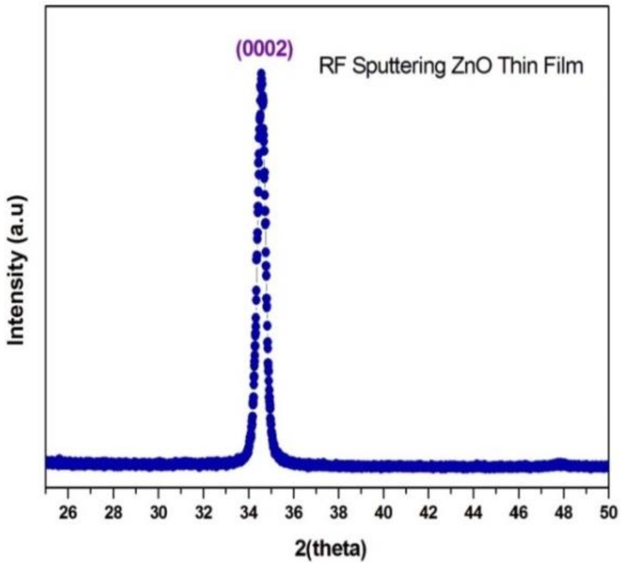


*Fig. 3. XRD spectra of the sputter deposited ZnO thin film over processed substrate (color online)*

The surface topographical analyses of the sputtered ZnO thin film were carried out subsequently through SEM and atomic force microscope (AFM) techniques. The AFM and SEM image (Fig. 4(a) and (b)) clearly demonstrates that uniform ZnO thin film with excellent surface morphology can be deposited through sputtering based deposition on p-Si substrate. The average diameter of the ZnO nanocrystalline was found to be in the range of 30-50 nm. Fig. 5 displays optical absorbance spectra of deposited ZnO thin film on glass substrate. The deposited ZnO showcases excellent adsorption characteristics in ultraviolent region (wavelength range: 300-390 nm) and high transmittance of 85 to 90%. This high transmittance of sputtered ZnO film proves its suitability in being used as transparent window layer for various optoelectronic applications. The absence of visible emission bands is the signature of very low concentration of faults in nanocrystalline ZnO thin film, making it is suitable for use in visible bind UV detectors.

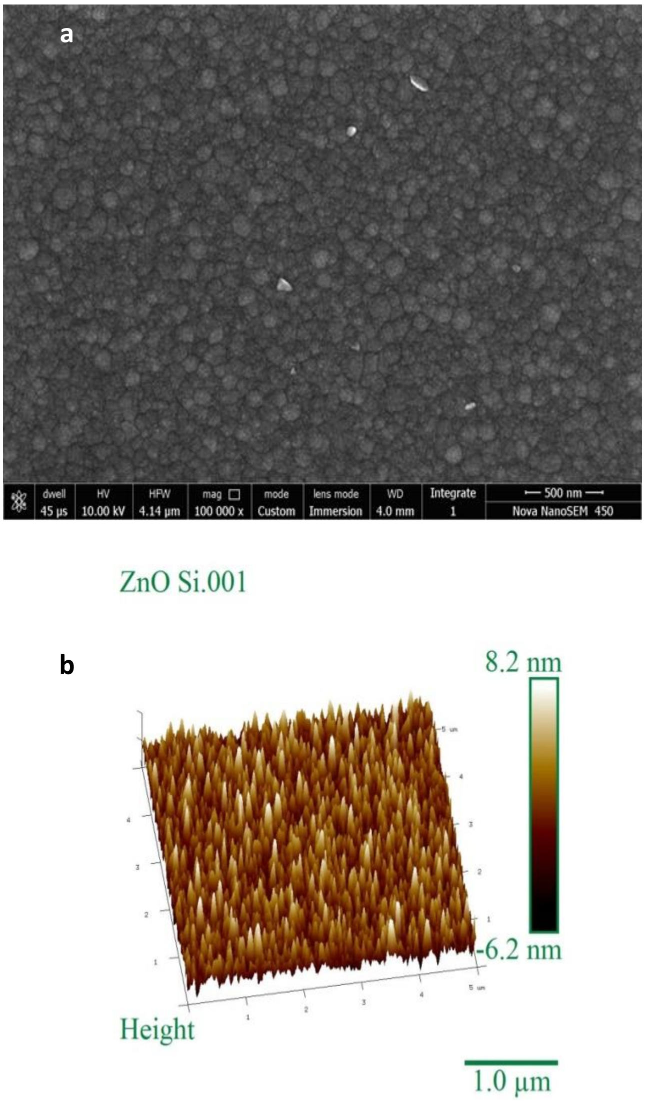


*Fig. 4. (a) Surface morphological (SEM) analysis, (b) 3-D AFM analysis of ZnO thin film on Si substrate (color online)*

The evaluation of optical band gap of the sputtered ZnO films has been done using the following equation [15, 16].

$$\alpha h\nu = B(h\nu - E_g)^{\frac{1}{2}} \quad (4)$$

$$\alpha = 2.303\left(\frac{A}{t}\right) \quad (5)$$

where α, A, $h\nu$, and $E_g$ represents the absorption coefficient, absorbance, photon energy, and optical band gap respectively. $B$ is a constant to represent direct transition and t is the thickness. Using $(\alpha h\nu)^2$ versus $(h\nu)$ relation (Inset Fig. 5), optical band gap was estimated. The obtained optical band gap value of ZnO is

3.41 eV and good agrees nearly with band gap of bulk ZnO (3.37 eV).

**Transfer and Output Characteristics of ZnO TFT**: The input/transfer characteristics of the fabricated device plotted at constant drain bias of 10V is depicted in Fig. 6(a). The electrical parametric quantity of the fabricated ZnO TFTs device is computed on basis of following equation [17-19].

Linear region: $0 \leq V_{DS} \leq V_{GS} - V_{th}$

$$I_{DS} = \frac{1}{2}(\mu C_g)\left(\frac{W}{L}\right)\left[2(V_{GS} - V_{th})V_{DS} - {V_{DS}}^2\right] \qquad (6)$$

Saturation region: $V_{DS} > V_{GS} - V_{th}$

$$I_{DS} = \frac{1}{2}(\mu C_g)\frac{W}{L}(V_{GS} - V_{th})^2 \qquad (7)$$

where, $L$ is termed to be channel length, $W$ as channel width, $V_{th}$ threshold voltage, $\mu$ termed to be field-effect mobility and $Cg$ as gate capacitance per unit area. The device characteristics and parameters such as threshold voltage, device saturation mobility, ON/OFF ratio etc. can be evaluated from the device transfer characteristics. Threshold voltage can be evaluated by the linear extrapolation of the transfer characteristics ($\sqrt{I_D}$ versus $V_{GS}$) and evaluating the point of intersection for a high drain bias applied. When a lower drain bias is applied, the same can be evaluated from the normal transfer characteristics [16, 17]. In this work, we have used later one to extracted threshold voltage from the transfer characteristics and it is found to be 4.8V. The positive threshold voltage of the device denotes an enhancement mode/normally off device. In enhancement mode operation, the channel conductance of the device enhances with positive gate bias. This makes the device suitable for application as switching device where low power dissipation has to be ensured. Enhancement devices are known for their inherent advantage of low power dissipation due to the normally off nature. Further the device ON/OFF ratio has been calculated and the device gives and enhanced switching ratio of $10^6$ as shown in Fig. 6(a).

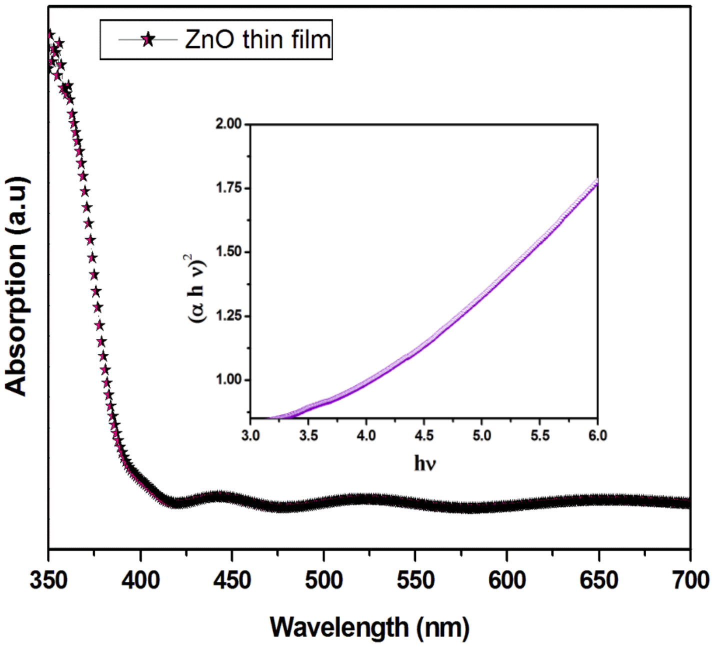


*Fig. 5. Optical absorption spectra of ZnO thin film and Inset shows* $(\alpha h\nu)^2$ *versus (* $h\nu$ *) plot*

Mobility is one of the major performance metric of a TFT device and it can be expressed as:

$$\mu_l = \frac{Lt}{W\varepsilon_0\varepsilon_r}\frac{dI_{DS}}{dV_{GS}} \qquad (8)$$

where, $t$ is the thickness of the channel, $\varepsilon_0$ and $\varepsilon_r$ represents the permittivity's of free space and ZnO (relative) respectively. Peak transconductance ($g_m$ = $dI_{ds}/dV_g$) has been extracted from the maximum slope of the device transfer characteristics. The fabricated device exhibits channel mobility of 5.2 $cm^2$/V.s. The output characteristics curves depicting the deviation of drain current with drain voltage for different gate voltage of the fabricated phototransitor is depicted in Fig. 6(b). For this characterization, the gate voltage has been increased from 5 to 20V in uniform steps of 5 V and the drain voltage has been swept from -30 to 30V. The $I_D$-$V_{DS}$ characteristics of the fabricated devices hows good gate modulated characteristics and showed typical n-type behavior. The drain current notably increased and showed saturation behavior from ~ 20 voltdrain voltage.

### UV Sensing Properties of ZnO TFTs

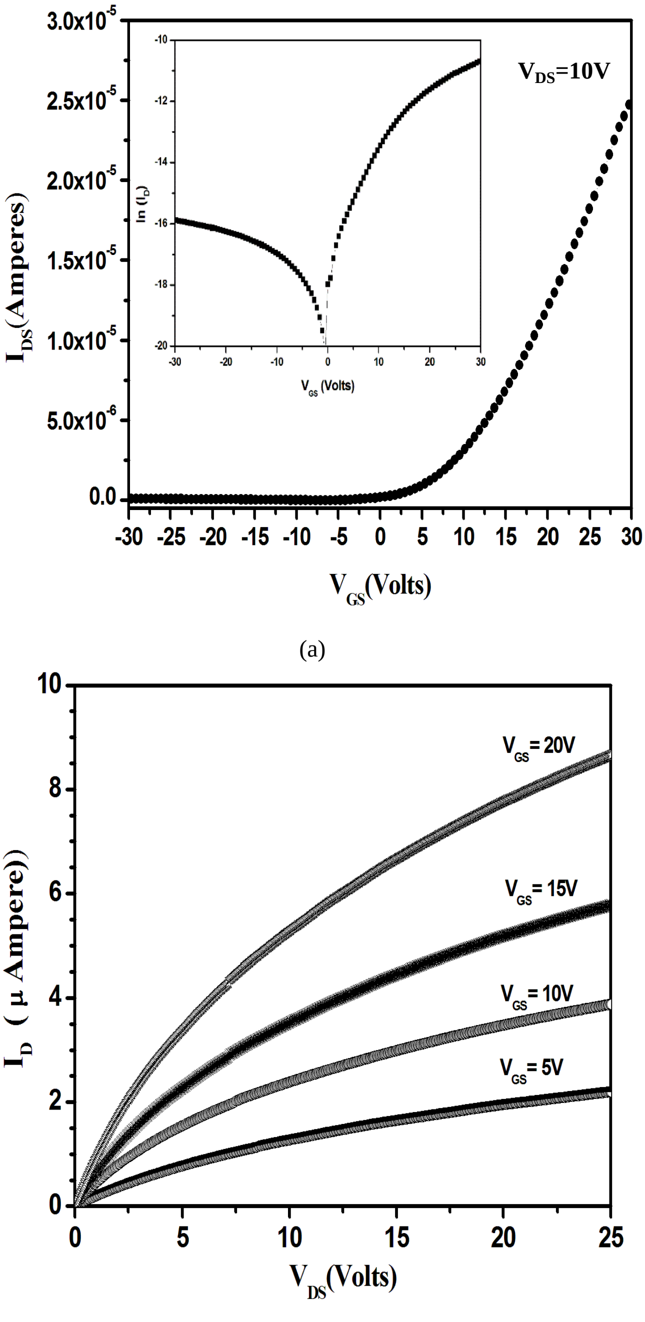
The fabricated ZnO based phototransistoris subsequently tested to the UV light with wavelength of 365 nm to analyse the UV-sensing ability. The responsivity of the phototransistor was tested by UV light source with an optical power level of 2.3 mW/cm$^2$ at room temperature (300 K). The set up for dark current measurement included the Semiconductor Device Analyzer which was covered with a black opaque cloth to prevent entry of natural light. The current-voltage characteristics of the fabricated device on application of a gate voltage sweep have been plotted. The gate voltage was varied from 0-15V and the drain voltage was ramped from 0V-30V in order to plot the device characteristics. Further an UV lamp was introduced into the set up and again keeping it well covered using the black cloth, and letting the UV light from the lamp fall directly on to the device. Fig. 7 shows the response of our ZnO based phototransistor to ultraviolet light and it is clearly seen from the output plot ($I_{DS}$ vs $V_{DS}$) that the presence of UV light results in a significant variation in output drain current. The enhancement in conductivity can be attributed to the photo-stimulation that leads to desorption of adsorbed oxygen molecules in the ZnO film. In the dark condition, oxygen molecules get adsorbed on the device surface and forms a negatively charged surface layer that keeps captured the free electrons of the n-type semiconductor. This creates a depletion layer with lower conductivity near the surface that is exposed. When the fabricated device gets exposed to UV light with photons having energy in the UV region, electron hole pairs are generated in the device which leads to an increase in the device conductivity. The wide variation in currents shows that the fabricated device is a promising candidate for optoelectronic applications. The UV sensing performance of the device can be studied in terms of responsivity (R) and detectivity (D). Responsivity is the produced photocurrent per unit incident UV light power, explained as [17]:

$$R = \frac{I_D' - I_{Dark}}{P_{inc}} \tag{9}$$

where, $P_{inc}$ as power of incident light and $I_{Dark}$ as dark current. The detectivity of the photodetector can be evaluated as [20-22]:

$$D = \frac{S^{1/2}}{e^{1/2} I_{Dark}^{1/2}} R \tag{10}$$

where, R is the responsivity, D is the detectivity, S is the effective area of the phototransistor, *e* is an elementary charge, and $I_d$ is the dark current. The fabricate ZnO based phototransistor showed very good response to UV light with a responsivity of 1.36 A/W and a directivity of 3.72 $\times 10^{10}$ Jones. The obtained values are comparable with values reported by others [17-19]. It is evident from the results that the device responsivity depends on the device configuration, wavelength of incident radiations, structural, composition and morphological properties of the material. Another factor that affects the responsivity is the applied external bias. The fabricated ZnO based TFT with long channel length of 100 μm exhibited promising responsivity at room temperature. The output drain current ($I_D$) measurements in UV illumination conditions has confirmed the potential for UV sensing of our fabricated ZnO based thin film transistor.



(a)

(b)

*Fig. 6. (a) Transfer plot ($I_D$ vs $V_{GS}$) of ZnO TFT, Inset shows corresponding ln (I) plot, and (b) $I_{DS}$ vs $V_{DS}$ characteristics of fabricated ZnO TFT*

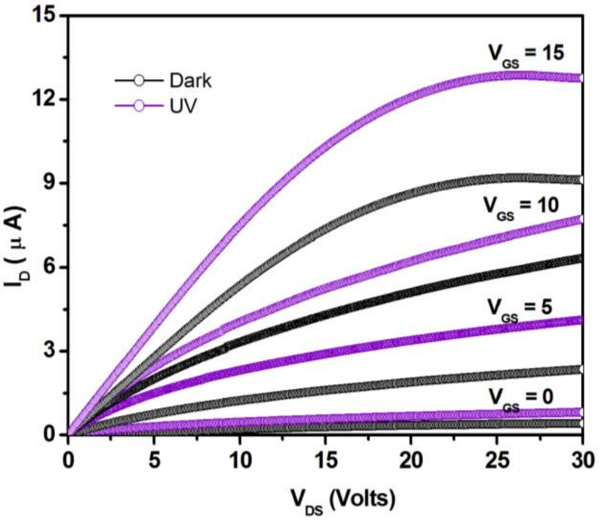


*Fig. 7. $I_{DS}$ vs $V_{DS}$ characteristics of fabricated ZnO based phototransistor under dark and UV illumination (365 nm wavelength) (color online)*

## 4. Conclusion

Bottom-gated phototransistor with sputter deposited ZnO based active channel region has been fabricated and characterized. VLSI compatible RF sputtering based deposition has been used for deposition of the thin ZnO film on Si substrate with thermally grown $SiO_2$ layer. XRD, AFM, SEM and UV-visible measurements techniques are carried out for quality and surface analysis where the surface morphological, structural and optical properties of the deposited thin films have been investigated. The fabricated ZnO based TFTs showcased excellent electrical as well as optical characteristics with high field effect mobility and ON/OFF ratio of 5.2 $cm^2/V·s$ and $\sim 10^6$ respectively. The fabricate ZnO based phototransistor showed very good response to UV light with a responsivity of 1.36 A/W and a directivity of 3.72 ×1010 Jones. The output drain current ($I_D$) measurements in dark and illumination conditions has confirmed the potential for UV sensing of our fabricated ZnO based thin film transistor. Thus, the proposed ultraviolet sensor finds tremendous utility in various fields such as ultrafast photo sensing, medical/monitoring and other optoelectronic processes.

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