

Plasmonically Enhanced ZnO Thin-Film-Photo-Transistor with Dynamic Responsivity Control

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Abstract- We fabricated an ZnO based thin-film photo-transistor with electrically tunable photo-responsivity operating in the UV and visible spectra and designed plasmonic structures enhancing the device performance up to 6 folds below the band-gap of ZnO.

I. INTRODUCTION

Recently, Zinc-Oxide (ZnO) based thin film transistors (TFTs) attracted much attention due to their potential of replacing amorphous Silicon (a-Si) which is used widely for conventional TFTs [1]. Especially, higher mobility of ZnO compared to a-Si makes it more plausible for TFT applications [2]. Several techniques are used to deposit ZnO channel layer of transistors including RF magnetron sputtering [3], chemical vapor deposition [4], molecular beam epitaxy (MBE) [5], laser ablation [6] and atomic layer deposition (ALD) [7] techniques. Among these techniques, ALD comes forward with high quality film growth, high-precision thickness control and large area application advantages [7].

Along with its supreme electrical properties, ZnO has been started to use as an active layer for optoelectronic applications. ZnO has a strong absorption up to the wavelength of about 375nm [8] due to its band-gap of 3.31eV. However, ALD grown ZnO has considerable amount of traps that give rise absorption in the visible spectrum observed in the previous photoluminescence studies [8]. ZnO based light emitting diodes[9], photo-detectors [4], solar cells [10] and photo-transistors [11] have been realized in this spectrum. Yet, the performance of such devices has been limited to bulk absorption properties of ZnO layers.

In recent years, many methods have been developed to improve the performance of photodetectors and photo-voltaic devices. Surface plasmons, collective oscillations of electrons coupled with electromagnetic waves, have been proven to be very useful at ultra-violet and visible spectrum for increasing device absorption [12]. In order to maximize absorption, localized and propagating surface plasmons excited by nanoparticles or gratings are very useful due to their immense subwavelength scaling properties.

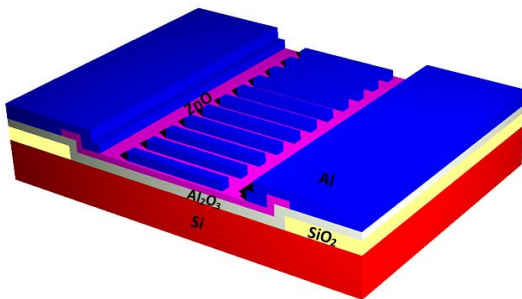


Figure 1 a) 3-dimensional depiction of the plasmonically enhanced ZnO based photo-transistor device structure

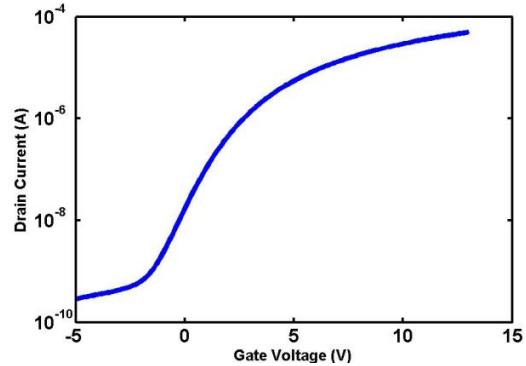


Figure 2 – At 0.5V of drain to source voltage (V_{DS}), contrast ratio of about 10^4 and turn on voltage of -2V is observed in drain-source current to gate voltage ($I_{DS}-V_{GS}$) relation of the fabricated device.

In this work, we demonstrate a plasmonically enhanced ZnO based thin film photo-transistor (TFPT). We fabricated and characterized an ALD grown ZnO based TFPT operating at ultraviolet and visible wavelengths. We electrically characterized transistor characteristics of the fabricated device and we performed optical responsivity measurements. We designed metallic gratings enhancing overall photo-response of the fabricated device up to 6 fold in the wavelength range of 400 - 600nm.

II. EXPERIMENT

The device fabrication by deposition of a SiO₂ contact isolation layer with plasma enhanced chemical vapor deposition on a p-type highly doped Si substrate. This layer is patterned with optical lithography and etched with buffered oxide etchant (BOE). Then, an Al₂O₃ gate oxide layer is deposited at 250°C for 200 cycles with Cambridge Savannah 100 ALD System using tri-methyl-aluminum and water precursor. A 100cycles of ZnO channel layer is deposited at 250°C using diethyl-zinc and water. The ZnO layer is patterned with optical lithography and etched with dilute H₂SO₄ solution. After an optical lithography process, a 100nm thick Al drain and source layer is deposited followed by lift-off. The finalized structure is depicted in Figure 1.

The fabricated transistors are electrically characterized by Keithley 4200-SCS semiconductor parameter analyzer system. The drain-source current to gate voltage ($I_{DS}-V_{GS}$) is plotted in Figure 2 for 0.5V drain to source (V_{DS}) bias. The turn on gate voltage, V_{ON} , and the ON/OFF ratio, I_{ON}/I_{OFF} are determined to be -2V and 10^4 , respectively. Threshold voltage of this device is extracted from the $\sqrt{I_{DS}-V_{GS}}$ relation as 1V. From the log $I_{DS}-V_{GS}$ curve, the sub-threshold slope of the device is determined to be 1.17 V/dec.

Under a modulated illumination with a mechanical chopper at a frequency of about 375Hz and a lock-in amplifier, we measured the responsivity, defined as ratio of the photocurrent

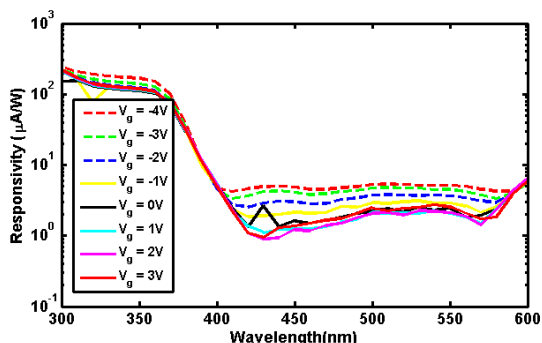


Figure 3 - The responsivity of the device is controlled by applying different gate bias voltages. The responsivity for the region below the band-gap is much lower than that of the region above band-gap.

(I_{DS}) to incident optical power. Figure 3 shows the responsivity of the photo-transistor under different gate bias voltages. Applying reverse bias from the gate depletes the trapped carriers and allows more absorption in the visible region. In this way, the photo-response from the photo-transistor can be controlled by applying different gate-bias. Yet, the responsivity in the spectral region below the band-gap remains low comparing to the region above band-gap.

III. SIMULATION RESULTS

In order to increase the responsivity of the device in the visible region, we integrate rectangular plasmonic structures on top of the active ZnO layer as shown in Figure 1. We performed 2-dimensional finite difference time domain simulations using FDTD solutions from Lumerical Inc. The rectangular gratings are assumed to be placed periodically. The height of the rectangular grating is kept constant at 100nm, whereas, width (w) and distance (d) parameters are swept for optimization. The refractive index of ZnO and Al₂O₃ layers are obtained using a spectroscopic ellipsometer (JaWoollam V-Vase). For Al and Si layers, optical constants from literature data [] are used. We compared the absorption inside the active ZnO layer for the case with and without plasmonic gratings assuming a light polarization suitable for plasmon excitation i.e. electric field vector is normal to the gratings. We also investigated the effect of metallic gratings, experimentally.

In Figure 4a, overall absorption enhancement integrated over 400-600nm spectrum is depicted. The optimum structure parameters are found to be w=90nm and d=125nm with an overall enhancement of about 7 times. Spectral absorption enhancement for the optimum structure is depicted in Figure 4b. The highest enhancement is observed at the wavelength where the plasmon resonance is much stronger near the

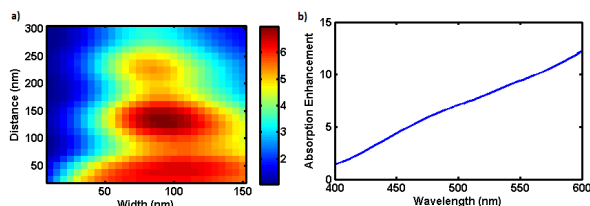


Figure 4 - a) Dependence of overall enhancement for 400-600nm spectrum on the structure parameters, distance (d) and width (w). b) For the optimum structure, spectral absorption enhancement is depicted

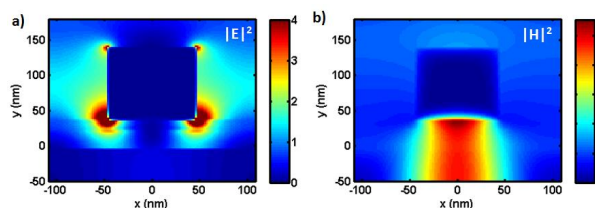


Figure 5 – Electric and magnetic field intensity profiles at the wavelength of highest absorption enhancement (600nm).

ZnO/Al interface as can be seen from the electric field intensity profile in Figure 5a. Absorption enhancement is attributed to localized surface plasmon (LSP) resonance excited at the ZnO/Al interface which is weakly coupled to the LSP mode excited at air/Al interface. H field intensity profile in Figure 5b indicates that the plasmonic structure acts like a strong forward scatterer.

IV. CONCLUSION

We fabricated an ALD grown ZnO based thin film photo-transistor (TFPT) and designed plasmonic grating structure exhibiting overall performance enhancements up to 6 fold in the overall spectrum of 400-600nm. We predicted that the responsivity in the spectral region below the band-gap can be increased up to the values of the responsivity in the region above band-gap. This study paves the way of realizing efficient photo-transistors operating in the UV and visible region.

ACKNOWLEDGEMENTS

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