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Fabrication and Characterization of 2D ZnO nanosheets-based UV Sensor

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Abstract

2D-ZnO nanosheet structure has a height surface area and integrated structure where all sheets have good connectivity with each other. The ZnO nanosheets adsorb oxygen which increases its sheet resistance. The adsorbed oxygen can be photo-desorbed by UV light. In this paper, we have reported the fabrication and characterization of UV sensors using 2D-ZnO nanosheets. This sensor is characterized by an ON and OFF response. The ON state of the sensor is achieved when it flows photocurrent and the OFF state when it is kept in dark. This sensor has a response time of 1 s where it reaches 90% of current efficiency on UV illumination while the OFF-response time is 2 s where its current decreases by 90%. This sensor's on-and-off response is 62.6 and 15 times better than the previously reported ZnO-based UV sensor [1]. The quick response of the sensor is due to the larger surface area of 2D-ZnO nanosheets which adsorb a large amount of oxygen quickly as UV is OFF. The ON/OFF current ratio is 1x10⁴ without applying any gate voltage. The gate voltage increases the drain current but reduces the ON/OFF current ratio. At 200V V_{GS} the I_{DS} of 22 μA was achieved. This sensor has good UV detection properties with a simple design and low-cost fabrication.

Keywords: UV sensor; 2D-ZnO nanosheets; Anodic aluminium oxide; Aluminium, ON/OFF response, Filed effect transistor (FET).

INTRODUCTION:

ZnO is an important inorganic material consisting of Zn and O belonging to the second and sixth group of the periodic table respectively, and has a diverse range of applications, as it is low cost and promising in different fields [2]. ZnO is an N-Type material having a direct bandgap (3.37 eV) and high excitation binding energy (60 eV) [3]. It exhibits both semiconducting and piezoelectric properties due to which it has novel applications in different fields [4]. Using the solid vapour phase method (SVP) various nanostructures can be synthesized, showing that ZnO is the richest family of

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nanostructures, and gives a wide range of applications, such as nanosensors and Nano cantilevers, etc. [5]. The morphological transformation of ZnO Nanorods to pencil needle trees and spheres is reported by controlling ZnO's growth and polarity conditions [6]. Due to low toxicity economic and good biocompatibility, ZnO has good potential in biomedical, especially in anti-cancer and anti-bacterial fields [7]. ZnO is used in different industries, especially silicon rubber composite formation [8]. Multiple studies show that a combination of ZnO and TiO_2 gives a whitening formula cream in the cosmetic industry and UV-blocking properties in the textile industry [9]. It has a wide range of applications in photo electronics, solar cells, UV lasers, and varistors [10]. Ultraviolet photodetectors are of great interest in many fields and their applications in photodetectors' biological and chemical processes gain the attention of researchers [11]. New methods have been adopted to synthesise 1D Nano-Structures such as (SnO_2, ZnO, CdS), etc. [12]. Different researchers have synthesized UV sensors of different materials such as (ZnO, GaN, SnO2, SiC, and Diamond). Different Nanostructures of ZnO like Nano Wires, Nano Rods, and Nano Spheres have been synthesized by different methods for UV detection is reported. ZnO is a good candidate for UV sensors. The UV sensing in ZnO is based on photo generation of current (photocurrent). The hydrothermally grown ZnO is N-type in nature, which has a large number of oxygen vacancies. The oxygen is easily adsorbed on the ZnO, which increases the resistance of ZnO. This adsorbed oxygen can be removed from the ZnO surface by UV illumination, which is called photodesorption. Due to photo desorption the ZnO resistance decreases [13]. By applying the bias voltage, the increases and decreases in resistance can be reflected in the decrease and increase in current respectively. By comparing with bulk ZnO the UV response is much better in micro and nan-structured ZnO which is due to its large surface area and ability to adsorb oxygen [1].

In this paper, we have reported the fabrication and characterization of UV sensors using 2D-ZnO nanosheets. This sensor is characterized by an ON and OFF response. The ON state of the sensor is achieved when it flows photocurrent and the off state when it is kept in dark. This sensor has a response time of 1 s where it reaches 90% of current efficiency on UV illumination while the off-response time is 2 s where its current decreases by 90%. This sensor's on-and-off response is 62.6 and 15 times better than the previously reported ZnO-based UV sensor [1]. The quick response of the sensor is due to the large surface area of 2D-ZnO nanosheets which adsorb a large amount of oxygen. The ON/OFF current ratio is 2.6 x 10^5 without applying any gate voltage. The gate voltage increases the drain current but reduces the ON/OFF current ratio. This sensor has good UV detection properties with a simple design and low-cost fabrication. The fabricated sensor can also be used for the detection of oxygen in the ambient atmosphere.

MATERIALS AND METHODS

a. Formation of AAO

For the fabrication of AAO 2.5 by 2.5 cm pure Al (99.99 Good fellows) was ultrasonically cleaned in DI water and acetone. The electropolishing of the Al sample was carried out in 1:4 of phosphoric acid (H_3PO_4) and ethanol (C_2H_6O) at 0°C for 6 minutes at a constant voltage of 12V. To fabricate AAO on the Al sample two-step of anodization were carried out. Both anodization steps were performed in 0.3M oxalic acid ($C_2H_2O_4$) at a constant voltage of 40V and temperature of 0°C. The first step was performed for 6 hours, and the second step of anodization was carried out for 30 to 60 minutes.

b. Fabrication of 2D-ZnO Nanosheets

The schematic of the fabrication steps is shown in Figure 1. For the fabrication of 2D-ZnO NSs on an AAO membrane, the hydrothermal growth method was used. The sol-gel method was adopted for the seed layer of ZnO on AAO. The sol-gel solution was prepared by the combination of two chemical solutions. The first solution is the mixture of 0.11gm of zinc acetate dehydrate ($C_4H_{12}O_6Zn$) and 50ml of methanol (C_2H_6O) at 60 °C. The second solution is the mixture of 0.03gm of sodium hydroxide (NaOH) and 25ml of methanol (CH_3OH) at 60 °C. To get a transparent solution the second solution was added to the first solution drop by drop at 60 °C for two hours. The dip-coating method was used for the deposition of sol-gel on an AAO membrane. After deposition of the seed layer, the sample was annealed for 4 minutes at 140°C. The samples containing seed layer were fitted face-down in a floating chamber into a nutrient solution for hydrothermal growth for a period of 1,3, and 6 hours at 85°C. The nutrient solution was prepared by mixing 0.02M HMTA and 0.02M of zin nitrate ($Zn(NO_3)_2.6H_2O$) in 1000 ml of DI water.

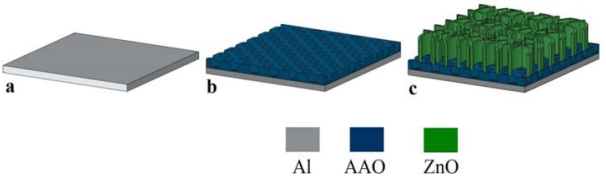

Figure 1. Schematic of 2D-ZnO NS fabrication steps

c. Sensor Fabrication

For sensor fabrication, the Au metallic layer was deposited on the top surface of 2D-ZnO nanosheets using. The gold electrodes were patterned using UV lithography to make source and drain electrodes for the device as shown in Figure. The source, drain and Al substrate were then connected with copper connectors using silver past. The Al substrate was utilized as the gate, AAO as the dielectric layer, and the 2D-ZnO nanosheet layer as the channel to form a FET type of UV sensor as shown in Figure 2.

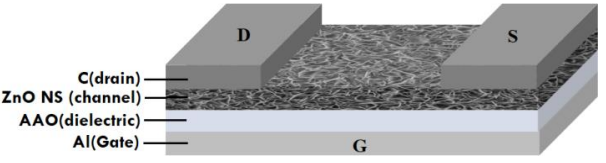

Figure 2. Schematic of ZnO NS-based FET type UV sensor.

RESULTS AND DISCUSSION:

Figure 3 is the FE-SEM image of the top surface of the AAO membrane that clearly shows the hexagonal and periodic arrangement of pores which possess the average values of pore diameter and inter-pore distance of 30 nm and 100 nm respectively. Fig. 1(b) shows the FE-SEM image of the top surface of 3D-ZnO NSSs which reveals that these nanosheets are interwoven to make a network. The sheet-like morphology of 2D-ZnO nanosheets may be due to Al doing in ZnO.

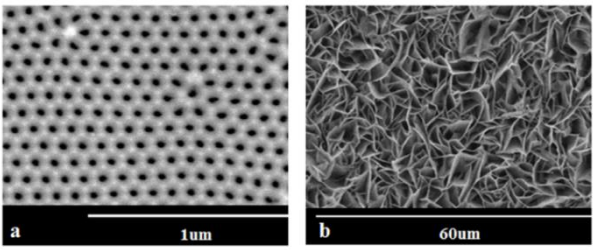

Figure 3. FE-SEM images of the a) top surface of AAO, b) top surface of ZnO NSs

In the fabricated device the Al substrate act as gate, AAO as dielectric layer, and 2D-ZnO nano sheet layer as channel to form FET type UV sensor as shown in schematic of Figure 4. Drain and source are fabricated by gold sputtering on the 2D-ZnO NSs as shown in Figure 2. The channel width is 200 µm and thickness 1-3 µm depending on the growth time of ZnO.

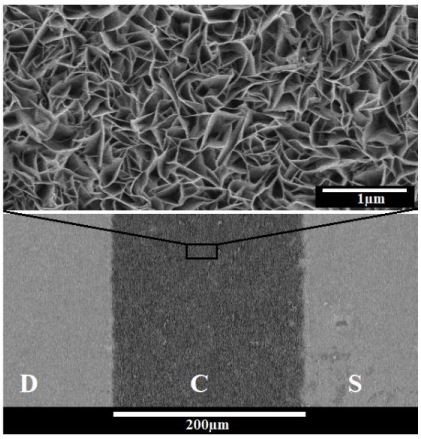

Figure 4. FE-SEM images of the Top surface of the fabricated UV sensor

The working principle of the device can be understood from the schematic of Figure 5. Oxygen molecules are adsorbed onto ZnO surfaces by capturing free electrons from the n-type ZnO which creates a low-conductivity depletion layer near the surface. In the dark environment, the adsorbed O^2 will consume one electron to form O^{2-} that will induce a depleted region as shown in Figure. Upon UV illumination, electron-hole pairs are generated. The holes that migrate to the surface along the potential gradient produced by band-bending discharge the negatively charged adsorbed oxygen ions to photo-desorb oxygen from the surface resulting in an increase in the free carrier concentration and a decrease in the width of the depletion layer.

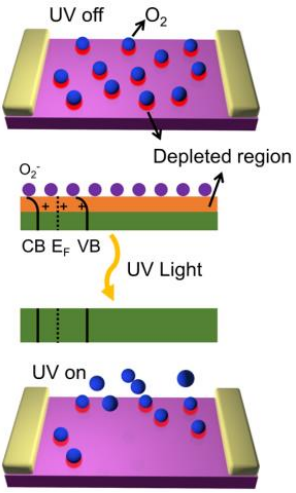

Figure 5. The Schematic of the sensing mechanism of UV sensor based on ZnO NSs [1].

For electrical analysis, the source, drain and gate were connected with Keithley's (6701) electrometer and variable DC power supply. The plot in Figure 6 shows the basic working of a fabricated UV sensor. At V_{DS}=2V and V_{GS}=0V the I_{DS} is almost 0A when the device is placed in the dark, and I_{DS} suddenly increases when it is illuminated by UV. Here in dark, the sheet resistance of the ZnO channel increases due to oxygen adsorption which tends to reduce the source to drain current I_{DS}. When the device is illuminated by UV light, the photo desorption phenomena accrues where the adsorbed oxygen atoms are ejected from the surfaces which tend to decrease the sheet's resistance of the ZnO channel resulting in an increase of I_{DS} [1]. The UV with 0.1m W/cm^2 produced 3.2 nA current within 1 s. Here the device in dark is considered to be OFF and ON in UV illumination. By precise measurement of ON and OFF state currents the ON/OFF current ratio was calculated. With V_{GS}=0V and V_{DS}=2V the ON/OFF current ratio was 2.6 x 10^5 which is very promising for such types of sensors. However, the low ON current was a major hindrance in the practical application of the device.

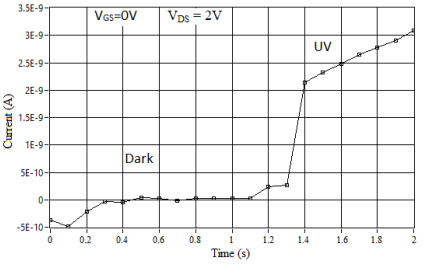

Figure 6: The ON and OFF current plot of the UV sensor with V_{GS}=0V, V_{DS}=2V, and UV intensity of 0.1 W/cm^2.

For increasing the I_{DS} the device was characterized with by applying varying values of V_{GS} as shown in Figure 7. Here the OFF current (I_{DS} in Dark) as a function of V_{GS} was measured. From the Plot, it is clear that increasing the V_{GS} induces charge carriers in

channel cussing to increase I_{DS} even in dark. Here at V_{GS}=50V the I_{DS} of 0.23 µA was achieved and it was further increased with an increase in V_{GS}. Though this behaviour of the device was very interesting, at the same time it was a question mark for the adsorbed oxygen and UV switching.

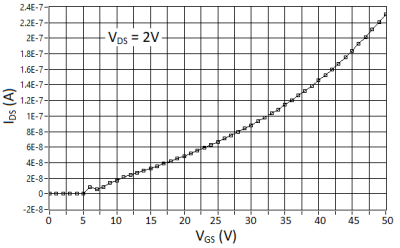

Figure 7. Transfer characteristics of FET type UV sensor (Plot between V_{GS} and I_{DS}).

For further confirmation, the V_{GS} from -40 to 150V was applied as shown in Figure 8. This plot confirmed the typical transfer characteristics of a FET device. At V_{GS}=150V, 23 µA of I_{DS} was recorded. The requirement of very high V_{GS} is due to the larger thickness of the dielectric layer (alumina thickness). The dielectric layer thickness can be reduced and optimized for the device to work at lower gate voltage.

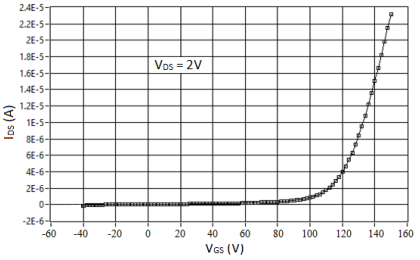

Figure 8. Transfer characteristics of FET type UV sensor at the greater value of V_{GS}.

The step response (ON/OFF) graph of the fabricated device at V_{GS} 60V is shown in Figure 9. Here on UV illumination of 0.1 W/cm2, 0.59 µA of I_{DS} was recorded. On exposing the sensor to the UV light, a sharp increase in current was observed and switching off the UV the current decreased to a minimum value. This sensor has a response time of 1 s where it reaches 90% of current efficiency on UV illumination while the off-response time is 2 s where its current decreases by 90%. The on-and-off response of this sensor is 62.6 and 15 times better than the previously reported ZnO-based UV sensor [1]. The quick response of the sensor is due to the larger surface area of 2D-ZnO nanosheets which adsorb a large amount of oxygen quickly as UV is OFF. It can be observed from this graph that the ON/OFF ratio decreases by increasing the gate voltage. The higher gate voltage produces a field which moves the charge carriers towards the surface making an induced channel to flow current from sources to drain even in dark. The UV however increases this current by photo desorption where the channel resistance decreases.

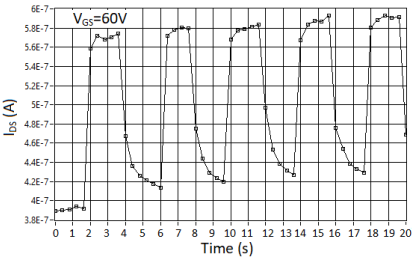

Figure 9. Step response of UV sensor

Figure 10 depicts typical I-V curves of the sensor in dark and under UV illumination. The V_{GS} was kept constant at 200V and the V_{DS} were varied from 0 to 2V whereas the I_{DS} were recorded in the dark and in UV. The graph clearly shows that I_{DS} increases linearly with V_{DS} and there is a significant increase in I_{DS} when UV is ON. Here the ON/OFF ratio is approximately 10 which is much less compared to the sensor response with V_{GS}=0. This is because of the charge carriers induced from the file provided by V_{GS} as explained above. The higher V_{GS} makes it useful for interfacing without using any amplifier or signal conditioner. However, in the presence of a good signal conditioner, the sensor without V_{GS} (V_{GS}=0) is recommended where it gives high sensitivity.

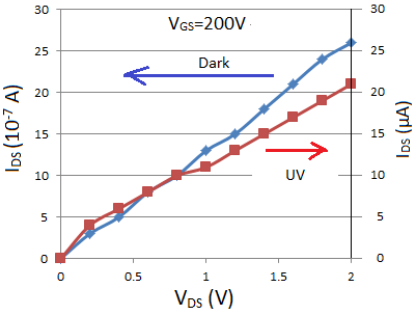

Figure 10. IV curve of a sensor in dark and in UV illumination

CONCLUSION:

In summary, we have fabricated an innovative 2D ZnO sheets-based UV sensor which has high sensitivity and quick response time. The ON state of the sensor is achieved when it flows photocurrent and the OFF state when it is kept in dark. This sensor has a response time of 1 s where it reaches 90% of current efficiency on UV illumination while the off-response time is 2 s where its current decreases by 90%. This sensor's on-and-off response is 62.6 and 15 times better than the previously reported ZnO-based UV sensor [1]. The quick response of the sensor is due to the larger surface area of 2D-ZnO nanosheets which adsorb a large amount of oxygen quickly as UV is OFF. The ON/OFF current ratio is $1x10^4$ without applying any gate voltage. The gate voltage increases the drain current but reduces the ON/OFF current ratio. At V_{GS} 200V the I_{DS} of 22 μA was achieved. The higher V_{GS} makes it useful for interfacing without using any amplifier or signal conditioner. However, in the presence of a good signal conditioner, the sensor without V_{GS} (V_{GS}=0) is recommended where it gives high sensitivity.

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