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Reduction of persistent photoconductivity in ZnO thin film transistor-based UV photodetector
Highly selective and responsive ultra-violet detection using an improved phototransistor

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An ultra-violet (UV) phototransistor with \( 700 \times 200 \mu m^2 \) gate area decorated with vertically aligned Zinc Oxide (ZnO) nanorods to enhance UV responsivity is designed and manufactured. Spectral responsivity of the device was measured for wavelengths ranged from 200 to 1100 nm of the electromagnetic spectrum in different transistor working regions. The best responsivity was achieved at sub-threshold and very weak inversion region. In order to enhance UV range selectivity, oxygen plasma has been employed on the nanorods, and consequently, nearly 3-fold improvement in its relative sensitivity at 375 nm was achieved. The final manufactured phototransistor shows a highly selective response of 24 kA/W in the UV range.

Recent studies on ZnO’s different applications have been increasing significant due to its unique characteristics like being a semiconductor with wide direct band gap (3.3 eV).1 ZnO has been vastly used in many applications. Various growth methods of ZnO nanostructures has been developed and among them, aqueous methods like hydrothermal2–4 and microwave assisted5,6 growth of ZnO nanorods (NRs) are commonly used to synthesize fairly high quality ZnO nanorods.7 ZnO nanostructures are very interesting for sensing applications mainly because of their high surface to volume ratio.8

At present, plenty of ultra-violet (UV) detectors with different structures and types of performance have been developed. Among them, resistive UV detectors and schottky diodes are considered to be the simplest. In these detectors, photons create electron-hole pairs, and the generated current is linearly dependent on the intensity of light.9,10 Heterojunction diodes are considered to be the simplest. In these detectors, p-n junctions are formed resulting in the forward and reverse conduction.11 Transistor-based UV detectors were previously constructed by a ZnO NR bridging between two electrodes, but one of the major obstacles in fabrication of such devices is making an ohmic contact to the NR. Furthermore, the order of generated current and voltage in these devices are usually very low that restricts their applications in noisy environments.12 Here, we report a UV phototransistor which exploits integration of ZnO NRs on the gate of an nMOSFET as a highly selective and responsive UV detector.

P-type (100) silicon wafers with 5–10 Ω cm resistivity were utilized for the fabrication of the nMOS transistors. Afterwards, 90 nm silicon dioxide (SiO2) as the transistor’s gate dielectric was grown using dry oxidation at 1100 °C. The wafer was then introduced into Low Pressure Chemical Vapor Deposition (LPCVD) chamber to deposit a 200 nm layer of polysilicon at 650 °C using SiH4 at the total pressure of 10 Torr. The next step was to define the gate area (size: \( 700 \times 200 \mu m^2 \)) by patterning and then dry etching of the polysilicon and SiO2. Electrochemical CV profiler (WEP-CVP21) was exploited to measure the doping level. To define n-type source and drain areas, the surface was doped with phosphorous diffusion using POCl3, which was done at 830 °C for a total time of 14 min (including pre-deposition and drive-in). TiAu metallization was finally processed with 100 nm Ti followed by 350 nm Au using RF sputtering. Prior to the growth of ZnO nanorod array, as the UV absorber material on the gate polySi, a 200 nm thick layer of ZnO was sputtered acting as the seed layer. ZnO nanorods were grown using conventional hydrothermal method. At 85 °C, the samples were immersed into a solution containing 25 mM solution of zinc nitrate hexahydrate (Zn(NO3)2-6H2O) and 13 mM hexamethylenetetramine ((CH2)6N4). The growth resulted in an array of NRs with \( 6.5 \times 10^8 \) cm\(^{-2} \) density and

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**FIG. 1.** Schematic of the UV phototransistor and the measurement circuit. The MOSFET cross sectional view is shown in the bottom inset. The inset on the top shows the FESEM top image of ZnO nanorods (Scale bar in the inset is 500 nm).
1 μm in length. Fig. 1 illustrates the schematic of the fabricated device. Finally, 25 min oxygen plasma was utilized to treat the surface lattice defects and enhance the performance.

Different wavelength Light Emitting Diode (LED) light sources ranged from ultra-violet to infra-red were used for the initial examination of the device detection. 375 nm, 470 nm, 530 nm, 630 nm, and 940 nm light sources were chosen to evaluate the spectral response of these phototransistors. Optical power of the LEDs was measured using Coherent’s company power meter with LM2 UV and VIS sensor. At the end full wavelength responsivity of detector for the optimized bias was measured in the range of 200–1100 nm using a monochromator (Varian Cary 5E Spectrophotometer). Electrical characterizations were performed using KEITHLEY 2361, KEITHLEY 236, and KEITHLEY 213. Field emission scanning electron microscope (FESEM) and PL (Photoluminescence) were used to check the morphology, size of the ZnO nanostructures, and their crystallinity.

Fig. 2(a) shows the drain current (I_D) vs. drain-source voltage (V_DS) for our phototransistor in off and on state exposure of 120 μW/cm² UV light (375 nm). To evaluate the effect of the gate bias voltage, two different gate biases (V_GS) were applied. Fig. 2(b) illustrates the I_D-V_GS curves, in which threshold voltage (V_TH = 1.2 V) and its shift due to the carrier generation can be observed.

When the incident photons, with different energies or wavelengths, are exposing to the ZnO nanorods on the gate, only the ones with energy higher than ZnO bandgap can be absorbed by the semiconductor and create an electron-hole pair. A positive voltage bias on the gate can drain the electrons leaving more positive charges on the gate than in the dark condition. The increased charge on the gate affects the existing depletion or inversion in the p-substrate beneath the gate. This, in fact, leads to accumulating more charges in the channel of transistor and finally results in excess drain current. Here, we defined a variable called relative sensitivity (S_r) to study the effect of gate bias on the changes of I_D when the device is exposed to light

\[ S_r = \frac{I_{\text{Exposed}} - I_{\text{Dark}}}{I_{\text{Dark}}} \times \left( \text{Input optical power} \right)^{-1}. \]

As illustrated in Fig. 2, the drain saturation current is increased with the gate voltage in both dark and UV conditions. It is worth mentioning that the device concerning the applied V_GS is performing under different operational regions, i.e., strong, medium, and weak inversions. At all three cases, the saturation occurs due to a same phenomenon. By increasing the V_DS, the effective length of the channel becomes smaller than the nominal channel length, and the current becomes saturated. However, when the device is biased at higher gate voltages, S_r-UV is reduced (see Fig. 3). This happens especially when the gate voltage is above the transistor’s threshold voltage, which is 1.2 V.

The optimum working point is where maximum I_D changes can be obtained, i.e., maximum S_r. Due to the fact that in the sub-threshold region the drain current is exponentially dependent on the gate voltage, the experiment was repeated at gate biases below the transistor’s threshold voltage. In Fig. 3, the relative sensitivity of the phototransistor is depicted when 0 < V_GS < 1. It obviously demonstrates that S_r increases as V_GS decreases (see the inset in Fig. 3). At smaller gate voltages in the sub-threshold region and dark condition, the channel has higher resistance and any small charge induced on the gate can make a significant change in the final current. As it can be seen in Fig. 3, the relative sensitivity to UV (S_r-UV) hits a top of about 229/μW at V_GS = 0.16 V.

Therefore, the gate voltage was set to 160 mV as the lowest possible value at which the drain’s current was high enough to avoid the noise level of our measurement systems. Another important feature in Fig. 3 is that S_r is decreasing when V_DS increases. After entering saturation area at
drain-source voltages more than 1.2 V, the relative change in \( \text{I}_D \) is less affected by changes in \( V_{\text{GS}} \). Thus, the induced \( V_{\text{GS}} \) variations by the incident photons will not cause any significant change in \( \text{I}_D \).

To study the selectivity of the phototransistor to UV light, it was exposed to different wavelengths from UV to IR range and the measurements results are shown in Fig. 4.

It is implied from Fig. 4 that the \( S_\text{R} \) is maximum and fairly constant for \( V_{\text{DS}} \) lower than 1.2 V, thus an average value of \( S_\text{R} \) when \( 0.1 < V_{\text{DS}} < 1.2 \) is chosen as the device’s relative sensitivity. Fig. 5 illustrates the normalized relative sensitivities. Although the device (the dashed line) demonstrates a high sensitivity to UV, it also exhibits a fairly good sensitivity to 500–600 nm and also to 940 nm. Comparing this figure to the PL spectra shown in the inset, suggests that the response in 530–600 nm is definitely due to the absorption itself in this wavelength range.

In order to improve the UV selectivity of the phototransistor, those crystal defects must be annihilated. These defects which are mainly oxygen vacancies normally happen after the ZnO NR growth. These mid gap states absorb photons with lower energies than the ZnO band gap (3.36 eV or 375 nm), i.e., higher wavelengths and directly affect the spectral sensitivity of the device, as shown in Fig. 5. To solve this issue, oxygen plasma was applied as a treatment for the ZnO oxygen vacancies. Obviously, the device selectivity has improved dramatically after plasma treatment (see the solid line in Fig. 5).

The final spectral responsivity of the device (\( (\text{I}_{\text{Exposed}} - \text{I}_{\text{Dark}}) / \text{input optical power} \)) is shown in Fig. 6, which touches characteristics of highly selective and responsive UV phototransistors. The measurements were performed, while it was biased with \( V_{\text{GS}} = 160 \text{ mV} \) and \( V_{\text{DS}} = 1 \text{ V} \). The device exhibits a high responsivity of 24 kA/W in the wavelengths lower than 380 nm, which corresponds to ZnO bandgap. 24-fold increase in responsivity compared to the previously published results is a very good evidence that ZnO nanorods are superior compared to the ZnO films for photonic detection applications. This huge improvement can be explained by either NR’s high surface-to-volume ratio or higher absorption due to the light trapping in the NRs forest. In all other wavelengths, no notable response is seen and this indeed supports the fact that the proposed device is highly UV selective.

In summary, a UV phototransistor with a gate decorated with vertically aligned ZnO nanorods was manufactured and examined for optical spectrum at wavelengths ranged from 200 to 1100 nm. The relative sensitivity of the phototransistors has been measured at different gate reference voltages. At the sub-threshold region, and specifically 160 mV, the best relative sensitivity was achieved. Oxygen plasma has been exploited to create a 3-fold increase in the relative sensitivity at 375 nm exposure due to the treatment of the oxygen vacancies. Finally, a highly selective response of about 24 kA/W in the UV range was obtained.

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