Fabrication of Silicon Dioxide by Photo-Chemical Vapor Deposition to Decrease Detector Current of ZnO Ultraviolet Photodetectors

Sheng-Joue Young,* Yi-Hsing Liu,* Shouou-Jinn Chang, and Chieh-Fei Chiu

ABSTRACT: Zinc oxide (ZnO)-based semiconductor is a promising application for ultraviolet photodetectors (UV PDs). The performance of ZnO UV PDs can be improved in two orientations: by reduction of the dark current and by increasing the photocurrent. In the study, we used two processes to prepare ZnO UV PDs: photochemical vapor deposition to fabricate silicon dioxide as an insulator layer and a radio frequency sputter system to prepare the ZnO film as an active layer. The results show that the silicon dioxide layer can reduce the dark current. Moreover, a large photo−dark current ratio of the metal−insulator−semiconductor (MIS) structured PD is 200 times than the metal−semiconductor−metal (MSM) structured PD. When the silicon dioxide thickness is 98 nm, we can significantly enhance the rejection ratio. The silicon dioxide layer can reduce the noise effect and enhance the device detectivity. These results indicate that the insertion of a silicon dioxide layer into ZnO PDs is potentially useful for practical applications.

INTRODUCTION

Ultraviolet (UV) light-related applications are widely used in daily life, medical equipment, and electronic materials. Common applications of UV include disinfection, banknote recognition, a curing material, frame detection, radiation detection, and optical communications.1−4 The right amount of radiation can increase the body’s vitamin D. However, excessive exposure easily causes harm to the human body. Therefore, high-performance UV detectors are important. In the last decade, the most commonly used semiconductor materials in the field of UV detectors include SiC, TiO2, GaN, Ga2O3, ZnO, and other wide band gap materials. These wide band gap materials have received considerable attention from researchers in different countries.

ZnO films based on UV photodetectors (PDs) have attracted attention because of their advantages, such as a simple fabrication step, non-toxicity, high gain, and low-cost synthesis.5−7 Fabrication techniques for a high-quality ZnO film include sol−gel, sputtering, pulsed laser deposition, and thermal evaporation.8−13 Radio frequency (RF) sputtering is the most reliable and a common method for a ZnO film. Most research groups have studied the metal−insulator−semiconductor (MIS) structure of UV PDs. To improve the performance of the MSM structure to increase the photocurrent and decrease the dark current efficiency, many groups inserted an insulating layer between the electrode and the active layer.14−18 Numerous studies focused on the fabrication of PDs with a metal−insulator−semiconductor (MIS) structure with SiO2, Si3N4, and Ga2O3 as the insulating materials.17−20 Among these materials, the silicon oxide layer is the easiest to be prepared by methods such as plasma-enhanced chemical vapor deposition (CVD) and liquid-phase deposition.17,18 Photo-CVD can also be used to deposit high quality and lower interface trap density SiO2 layers than other traditional methods, like PECVD, the sputter method, etc.21−24 However, no study applied this technology to ZnO-based UV PDs. Thus, in the study, we investigated the fabrication of UV PDs with the ZnO film MIS structure on a sapphire substrate through RF sputtering and the photo-CVD system. The optoelectronic and noise properties of the fabricated ZnO-based MIS PD were discussed.

RESULTS AND DISCUSSION

Figure 1 shows the measured XRD pattern for the ZnO film grown on a sapphire substrate. The results showed three diffraction peaks at the (002), (006), and (004) planes. Two diffraction peaks (002; 2θ = 32.24°) and (004; 2θ = 71.92°) denoted the hexagonal wurtzite structure of the ZnO crystal (JCPDS no. 36-1451). Another peak (006; 2θ = 41.8°) represented the sapphire substrate signal (Al2O3 crystal). The

Received: August 27, 2020
Accepted: October 1, 2020
Published: October 13, 2020
ZnO-based MSM and MIS structure samples were based on sapphire substrate. Light illumination (370 nm), the photocurrents (PD, respectively. It was found that a sharp cut-off occurred at around 370 nm. The smaller responsivity observed from the UV-to-visible rejection ratio as the responsivity measured at 370 nm divided by the responsivity measured at 460 nm. It shows that the SiO2 98 nm-thick MIS PD UV-to-visible rejection ratio was 400 with a 1 V applied bias. The result is 13.157 times higher than the MSM structured PD (30.4). These values indicate that we can significantly enhance the UV-to-visible rejection ratio by inserting SiO2 into our ZnO photodetectors.

To understand the effect of the SiO2 layer thickness on the photodetector, we have tried different thicknesses of silicon films on our devices, including 0, 22, 45, 98, 132, and 198 nm. Obviously, it can be seen that dark currents decrease with the thicker SiO2 layers more critically than photocurrents. Because the dark current is supposed to tunnel through two insulator layers, and the photocurrent is supposed to tunnel only one insulator layer. The photocurrent to dark current contrast ratios for these photodetectors can be determined from the measured dark currents and photocurrents, which are shown in Figure 4. It was found that the photocurrent to dark current contrast ratios of the ZnO MIS photodetectors were 1.46, 5.84, 7.95, 7.95, 200, 10.5, and 4.59 with 0, 22, 45, 98, 132, and 198 nm SiO2 thicknesses at a 1 V applied bias. This shows that we can achieve a much larger photocurrent to dark current contrast ratio from the ZnO MIS photodetector. Furthermore, the ratio increases with the thicker SiO2 layer, the optimum performance occurs with 98 nm SiO2, and then the ratio decreases with the thicker SiO2 layer. Some significant topics related to ZnO-based photodetectors have been reported recently, which are summarized in Table 1. Among the results, the photodetection characteristics of the MIS structure are better than the MSM structure. It can be expected that such a device will be well used for UV detection.

The working principle of the device is as follows. In dark conditions, oxygen molecules are attached to the ZnO film surface. This process formed a depletion layer on the ZnO surface, which reduced the carrier concentration of the film. In our case, the ZnO-based MSM structure sample achieved a high current in darkness. This phenomenon is not conducive to the detection capability of sensors. When the silicon film is sandwiched between the ZnO film and electrode, an electronic flow must pass through the insulation layer twice. It can suppress an excessive electron flow. Under UV light illumination, electron–hole pairs were generated after the sample absorbed UV light. The photogenerated holes are combined with the adsorbed negatively charged oxygen ions on the surface. Moreover, the depletion layer near the surface of the ZnO film was reduced. The remaining negative charges in the conduction band increased conductivity. When the silicon film was sandwiched between the ZnO film and electrode, the photocurrent was also suppressed by the insulation layer. However, the photo–dark current ratio was increased compared with that of the silicon film sample. The results indicate that the insulation layer can effectively suppress excessive current and enhance the detection ratio of PDs.

To confirm the trap distribution between the electrode and active layer, we measured the noise power spectra from 1 to 100 Hz in the ZnO-based PDs with MSM and MIS structures (Figure 5). The measurement parameters included the varied bias voltages from 2 to 4 V in the dark environment. The noise spectral density was analyzed by Hooge-type equations, including frequency against noise power.
where $S_0$ is a constant, $S_n(f)$ is the spectral density of noise power, $f$ is the frequency from the noise current preamplifier, $I_d$ is the detection current for a sample, and $\alpha$ and $\beta$ are the fitting parameters from frequency against noise power. In general, flicker noise was the main analysis target for our device because it is caused by ionized defect and acoustic phonons, which produce mobility fluctuation through impurity and lattice scatterings. In other words, the defects presented in our sample affected the $1/f$ noise spectrum. The noise equivalent power (NEP) and normalized detectivity ($D^*$) are important analysis indexes for PDs. These indicators can be used to determine the device performance. The total noise current power of PDs can be estimated by integrating $S_n(f)$ for a given bandwidth $B$.

Figure 3. Photoresponse performance of ZnO-based MSM and MIS structures under various applied biases. (a, b) $I$–$V$ characteristics of the MSM and MIS PDs under darkness and UV light (370 nm) irradiation environment conditions. (c, d) Responsivity characteristics of MSM and MIS PDs at irradiation wavelengths from 310 to 460 nm.

Figure 4. Photocurrent to dark current contrast ratios of MIS photodetectors with different silicon oxide film thicknesses under an applied voltage.

Table 1. Comparison of the Photoresponsivity Probed in the Literature

| device structure | bias (V) | light source | sensitivity ($I_{\text{photo}}/I_{\text{dark}}$) | responsivity (mA/W) | ref |
|------------------|---------|--------------|---------------------------------------------|----------------------|-----|
| Au-ZnO film@MSM | 3       | 365 nm       | ~100                                        |                      | 25  |
| BeCdZnO film@MSM| 5       | 330 nm @0.57 mW/cm² | 32.94                                      | 3.74                 | 26  |
| Cd-ZnO film@MSM | 5       | 365 nm       | 93.78                                       |                      | 27  |
| Mg-ZnO film@MSM | 5       | 365 nm       | 71.68                                       |                      | 28  |
| Al-ZnO film@MSM | 1       | 365 nm @34 μW/cm² | ~10                                        | 5630                 | 29  |
| Ga-ZnO nanorods @MSM | 1 | 365 nm       | 11.7                                        | <50                  | 30  |
| ZnO film@MSM    | 1       | 365 nm       | 1.46                                        | 16.416               | this work |
| ZnO film@MIS    | 1       | 365 nm       | 200                                         | 12.62                | this work |

https://dx.doi.org/10.1021/acsomega.0c04136
ACS Omega 2020, 5, 27566–27571
We assumed that \( S_n(f) = S_n(1 \text{ Hz}) \) when \( f < 1 \text{ Hz} \). Thus, NEP can be given by the following equation:

\[
\text{NEP} = \frac{\sqrt{\langle i_d \rangle^2}}{R}
\]

where \( R \) is the responsivity of the device. \( D^* \) can then be determined by the following equation:

\[
D^* = \frac{\sqrt{A \times B}}{\text{NEP}}
\]

where \( A \) is the area of the device and \( B \) is the bandwidth. In the part, we expect to obtain a lower value for NEP and a higher value for \( D^* \). When the bandwidth was at the maximum measurement frequency (100 Hz) with an applied bias of 2 V, the NEP and \( D^* \) values of the MSM structure were 4.082 \times 10^{-7} \text{ W} and 4.9 \times 10^6 \text{ cm}^2 \text{ Hz}^{-0.5} \text{ W}^{-1}, respectively. When a silicon oxide layer was inserted, the NEP and \( D^* \) of the device (MIS structure) reached 6.826 \times 10^{-9} \text{ W} and 2.93 \times 10^7 \text{ cm}^2 \text{ Hz}^{-0.5} \text{ W}^{-1}, respectively. These phenomena indicate the good performance of the insulating layer for PDs. The results show that inserting an insulating layer in ZnO PDs is potentially useful for practical applications.

### EXPERIMENTAL SECTION

Before the ZnO MIS PDs were fabricated, the sapphire substrates with a (0001) plane were cleaned with acetone, isopropanol, and deionized water for 5 min. Then, the substrates were dried in an oven.

The active layer of the ZnO film was fabricated by an RF sputtering system. Before the ZnO film was fabricated, a sapphire substrate was placed on a holder of an anode terminal. A ZnO (99.99%, pure) target of 3 in. in diameter was set at the cathode side. The distance was 50 mm between the sapphire and the ZnO target. After the sample was loaded, air was extracted in a chamber with a pressure of \( 5 \times 10^{-6} \text{ Torr} \). Then, the reaction with oxygen and argon was carried out in the chamber. The gas ratio was maintained at 1/10, and the working pressure was maintained at \( 5.0 \times 10^{-2} \text{ Torr} \), whereas the RF power was set at 200 W. The thickness of the ZnO film was 1 \( \mu \text{m} \). Sequentially, the sample was annealed by a quartz furnace tube system at 600 °C for 30 min in air.

Before the insulator layer and electrode were fabricated, we had defined a working area of the interdigitated contact pattern. Then, the sample was fabricated by standard photolithography and liftoff. Wet etching was also used to isolate the region that would be fabricated in the device.

A silicon dioxide insulator layer was deposited by the photo-CVD system. The system can provide extra photon

![Figure 5](https://dx.doi.org/10.1021/acsomega.0c04136)
energy to excite the reactant species or heat substrate in the gas phase. The excitation light source used a deuterium (D$_2$) lamp (150 W, wavelength at 110–170 nm) as a vacuum UV light reactor source. The strong vacuum UV radiation can effectively excite the gas source. Figure 6 shows the schematic of the ZnO-based MIS structure. Before silicon dioxide was fabricated on the ZnO film, the sample was loaded in a stainless-steel reaction chamber and evacuated below $8 \times 10^{-6}$ Torr via a diffusion pump. Subsequently, three reactive gases, including silane (SiH$_4$ 15%, N$_2$ 85%), oxygen (O$_2$), and high-purity N$_2$ gas, were introduced into the chamber through mass flow controllers. During deposition, the chamber pressure was fixed at 0.9 Torr, and the samples were continuously exposed to the D$_2$ lamp source. The thickness of the deposited silicon dioxide film was approximately 98 nm. Finally, we deposited a 30 nm-thick Ir film on the silicon dioxide layer as the contact electrode through an electron beam evaporation system.

An X-ray diffraction (XRD) system was used to analyze the structure and crystal quality of the thin film. The target was irradiated with Cu K$_\alpha$ radiation at a scanning angle between 20 and 80°. Photoluminescence (PL) technology was employed to analyze the optical characteristics of the semiconductor material. The optical source of the system was excited by an He–Cd laser of 325 nm line with a 25 mW power. For the fabricated PDs, an HP 4155 semiconductor parameter analyzer was used to measure the current–voltage (I–V) characteristics. A spectral responsivity measurement system was operated with a xenon arc lamp as the light source (monochromator range: 310–170 nm) as a vacuum UV light source. A spectral responsivity measurement system was performed using a low-noise current preamplifier (frequency range of 1–100 Hz) and HP35670A fast Fourier transform spectrum analyzer.

**AUTHOR INFORMATION**

**Corresponding Authors**

Sheng-Joue Young — Department of Electronic Engineering, National United University, Miaoli 36063, Taiwan; orcid.org/0000-0003-3164-2949; Email: shengjoueyoung@gmail.com, youngsj@nuu.edu.tw

Yi-Hsing Liu — Institute of Microelectronics, Department of Electrical Engineering, National Cheng Kung University, Tainan 701, Taiwan; Email: yhliu0870@gmail.com

**Authors**

Shou-Jinn Chang — Institute of Microelectronics, Department of Electrical Engineering, National Cheng Kung University, Tainan 701, Taiwan

Chieh-Fei Chiu — Institute of Microelectronics, Department of Electrical Engineering, National Cheng Kung University, Tainan 701, Taiwan

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c04136

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

This work was supported by the Ministry of Science and Technology under contract numbers MOST 109-2221-E-239-031-MY2, 108-2622-E-239-010-CC3, 107-2622-E-150-002-CC2, 106-2221-E-239-037-MY3, 106-2622-E-150-005-CC3, and 106-2622-E-150-017-CC2. We also acknowledge the assistance of the Common Laboratory for Micro/Nano Science and Technology of National Formosa University for some of the measurement equipment used in this study and the Center for Micro/Nano Science and Technology of National Cheng Kung University for device characterization.

**REFERENCES**

(1) Sugumar, R.; Angappane, S. Influence of substrate heating and annealing on the properties and photosresponse of manganese doped zinc oxide thin films. *Superlattices Microstruct.* 2017, 110, 57–67.

(2) Shaikh, S. K.; Gabavle, V. V.; Mohite, S. V.; Rajpure, K. Y. Chemical synthesis of pinecone like ZnO films for UV photodetector applications. *Thin Solid Films* 2017, 642, 232–240.

(3) Kar, J. P.; Das, S. N.; Choi, J. H.; Lee, Y. A.; Lee, T. Y.; Myoung, J. M. Fabrication of UV detectors based on ZnO nanowires using silicon microchannel. *J. Cryst. Growth* 2009, 311, 3305–3309.

(4) Dhar, S.; Majumder, T.; Mondal, S. P. Phenomenal improvement of external quantum efficiency, detectivity and responsivity of nitrogen doped graphene quantum dot decorated zinc oxide nanorod/polymer schottky junction UV detector. *Mater. Res. Bull.* 2017, 95, 198–203.

(5) Mamat, M. H.; Khusaimi, Z.; Zahidi, M. M.; Mahmood, M. R. Performance of an Ultraviolet Photoconductive Sensor Using Well-Aligned Aluminium-Doped Zinc-Oxide Nanorod Arrays Annealed in an Air and Oxygen Environment. *Ipn. J. Appl. Phys.* 2011, 50, 4.

(6) Gahtar, A.; Rahal, A.; Benhaua, B.; Benramache, S. A comparative study on structural and optical properties of ZnO and Al-doped ZnO thin films obtained by ultrasonic spray method using different solvents. *Optik* 2014, 125, 3674–3678.

(7) Mondal, S.; Bhattacharyya, S. R.; Mitra, P. Effect of Al doping on microstructure and optical band gap of ZnO thin film synthesized by successive ion layer adsorption and reaction. *Pramana* 2013, 80, 315–326.

(8) Claflin, B.; Leedy, K. D.; Look, D. C. Dopant profiles in heavily doped ZnO. *Opt. Eng.* 2013, 52, 4.
(9) Singh, S.; Chakraborti, P. Simulation, Fabrication and Characterization of Sol-Gel Deposited ZnO Based Thin Film Transistors. Sci. Adv. Mater. 2012, 4, 199–203.

(10) Karak, N.; Samanta, P. K.; Kundu, T. K. Green photoluminescence from highly oriented ZnO thin film for photovoltaic application. Optik 2013, 124, 6227–6230.

(11) Aoun, Y.; Benhassar, B.; Benramache, S.; Gasmì, B. Effect of annealing temperature on structural, optical and electrical properties of zinc oxide (ZnO) thin films deposited by spray pyrolysis technique. Optik 2015, 126, 5407–5411.

(12) Singh, S.; Chakraborti, P. Effect of Mesa Structure Formation on the Electrical Properties of Zinc Oxide Thin Film Transistors. J. Nanosci. Nanotechnol. 2014, 14, 3552–3556.

(13) Singh, S.; Chakraborti, P. Optical Characterization of ZnO Thin Films Grown by Thermal Oxidation of Metallic Zinc. Adv. Sci. Eng. Med. 2013, 5, 677–682.

(14) Young, S. J.; Ji, L. W.; Chang, S. J.; Liang, S. H.; Lam, K. T.; Fang, T. H.; Chen, K. J.; Du, X. L.; Xue, Q. Q. ZnO-based MIS photodetectors. Sens. Actuators, A 2007, 135, 529–533.

(15) Zhou, J.; Gu, Y.; Hu, Y.; Mai, W.-H.; Yeh, P.-H.; Bao, G.; Sood, A. K.; Polla, D. L.; Wang, Z. L. Giant enhancement in response and rise time of ZnO UV nanosensor by utilizing Schottky contact and surface functionalization. Appl. Phys. Lett. 2009, 94, 3.

(16) Ali, G. M.; Chakraborti, P. ZnO-based interdigitated MSM and MISIM ultraviolet photodetectors. J. Phys. D: Appl. Phys. 2010, 43, 8.

(17) Casey, H. C., Jr.; Fountain, G. G.; Alley, R. G.; Keller, B. P.; DenBaas, S. P. Low interface trap density for remote plasma deposited SiO$_2$ on n-type GaN. Appl. Phys. Lett. 1996, 68, 1850–1852.

(18) Arulkumaran, S.; Egawa, T.; Ishikawa, H.; Jimbo, T.; Umeno, M. Investigations of SiO$_2$/n-GaN and Si$_3$N$_4$/n-GaN insulator-semiconductor interfaces with low interface state density. Appl. Phys. Lett. 1998, 73, 809–811.

(19) Fu, D. J.; Kwon, Y. H.; Kang, T. W.; Park, C. J.; Baek, K. H.; Cho, H. Y.; Shin, D. H.; Lee, C. H.; Chung, K. S. Ga metal-oxide-semiconductor structures using Ga$_2$O$_3$ dielectrics formed by photoelectrochemical oxidation. Appl. Phys. Lett. 2002, 80, 446–448.

(20) Peng, L.-H.; Liao, C.-H.; Hsu, Y.-C.; Jong, C.-S.; Huang, C.-N.; Ho, J.-K.; Chiu, C.-C.; Chen, C.-Y. Photoenhanced wet oxidation of gallium nitride. Appl. Phys. Lett. 2000, 76, 511–513.

(21) Huang, C. J.; Su, Y. K. Effect of substrate temperature on the properties of SiO$_2$/InP structure prepared by photochemical vapor-deposition. J. Appl. Phys. 1990, 67, 3350–3353.

(22) Chang, S. J.; Su, Y. K.; Jiang, F. S.; Lin, C. T.; Der Chiang, C.; Cherng, Y.-T. Photo-enhanced native oxidation process for Hg$_{sub:0.8}$/Cd$_{sub:0.2}$/Te photoco nductors. IEEE J. Quantum Electron. 2000, 36, 583–589.

(23) Lin, C. T.; Su, Y. K.; Chang, S. J.; Huang, H. T.; Chang, S. M.; Sun, T. P. Effects of passivation and extraction surface trap density on the 1/f noise of HgCdTe photodetector. IEEE Photonics Technol. Lett. 1997, 9, 232–234.

(24) Lin, C. T.; Su, Y. K.; Huang, H. T.; Chang, S. J.; Chen, G. S.; Sun, T. P.; Luo, J. J. Electrical properties of the stacked ZnS/photo-enhanced native oxide passivation for long wavelength HgCdTe photodiodes. IEEE Photonics Technol. Lett. 1996, 8, 676–678.

(25) Jin, Y.; Jiao, S.; Lu, H.; Wang, D.; Gao, S.; Wang, J. Localized Surface Plasmon-Enhanced Ultraviolet and Visible Photoresponse Based on ZnO Films with Au Nanoparticles. J. Electron. Mater. 2020, 4491.

(26) Zhang, T.; Xu, Z.; Chen, J.; Li, M.; Lu, Y.; He, Y. Effects of oxygen pressure on PLD-grown Be and Cd co-substituted ZnO alloy films for ultraviolet photodetectors. J. Alloy. Compd. 2020, 833, 7.

(27) Kumar, N.; Srivastava, A. Faster photoresponse, enhanced photosensitivity and photoluminescence in nanocrystalline ZnO films suitably doped by Cd. J. Alloy. Compd. 2017, 706, 438–446.

(28) Kumar, N.; Srivastava, A. Green photoluminescence and photocconductivity from screen-printed Mg doped ZnO films. J. Alloy. Compd. 2018, 735, 312–318.

(29) Kumar, C.; Kushwaha, B. K.; Kumar, A.; Jarwal, D. K.; Upadhyay, R. K.; Singh, A. P.; Jit, S. Fibrous Al-Doped ZnO Thin Film Ultraviolet Photodetectors With Improved Responsivity and Speed. IEEE Photonics Technol. Lett. 2020, 32, 337–340.

(30) Hsiao, C. H.; Huang, C. S.; Young, S. J.; Chang, S. J.; Guo, J. J.; Liu, C. W.; Yang, T. Y. Field-Emission and Photoelectrical Characteristics of Ga-ZnO Nanorods Photodetector. IEEE Trans. Electron Devices 2013, 60, 1905–1910.

(31) Mhlongo, G. H.; Motaung, D. E.; Cummings, F. R.; Swart, H. C.; Ray, S. A. A highly responsive NH$_3$ sensor based on Pd-loaded ZnO nanoparticles prepared via a chemical precipitation approach. Sci. Rep. 2019, 9, 18.

(32) Wang, Y.; Meng, X.; Yao, M.; Sun, G.; Zhang, Z. Enhanced CH$_4$ sensing properties of Pd modified ZnO nanosheets. Ceram. Int. 2019, 45, 13150–13157.

(33) Chen, X.; Shen, Y.; Zhou, P.; Zhong, X.; Li, G.; Han, C.; Wei, D.; Li, S. Bimetallic Au/Pd nanoparticles decorated ZnO nanowires for NO$_2$ detection. Sens. Actuators, B 2019, 289, 160–168.

(34) Kim, J.-H.; Mirzaei, A.; Kim, H. W.; Kim, S. S. Combination of Pd loading and electron beam irradiation for superior hydrogen sensing of electrosyn ZnO nanofibers. Sens. Actuators, B 2019, 284, 628–635.

(35) Zhang, Y.-H.; Cai, X.-L.; Song, L.-Z.; Feng, F.-Y.; Ding, J.-Y.; Gong, F.-L. 2D nanosheet-assembled Pd-ZnO microflowers for acetone sensor with enhanced performances. J. Phys. Chem. Solids 2019, 124, 330–335.

(36) Joshi, R. K.; Hu, Q.; Alvi, F.; Joshi, N.; Kumar, A. Decorated Zinc Oxide Nanowires for CO Sensing. J. Phys. Chem. C 2009, 113, 16199–16202.

(37) Li, Q. H.; Gao, T.; Wang, Y. G.; Wang, T. H. Adsorption and desorption of oxygen probed from ZnO nanowire films by photocurrent measurements. Appl. Phys. Lett. 2005, 86, 3.

(38) Lai, W.-C.; Chen, J.-T.; Yang, Y.-Y. Optoelectrical and low-frequency noise characteristics of flexible ZnO-SiO$_2$ photodetectors with organosilicon buffer layer. Opt. Express 2013, 21, 9643–9651.

(39) Voss, R. F.; Clarke, J. flicker (1/f) noise-equilibrium temperature and resistance fluctuations. Phys. Rev. B 1976, 13, SS6–573.