Photodetectors for weak signal conditions from Au/Cu co-doped ZnO

Imen Ben Elkamel1 · Nejeh Hamdaoui2 · Amine Mezni3 · Ridha Ajjel1 · Lotfi Beji4

Received: 15 March 2021 / Accepted: 6 June 2021 / Published online: 10 July 2021
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract
Here, we have used a simple method for polyol synthesis, analysis, and testing of Au/Cu-doped ZnO Ultraviolet (UV) photodetectors (PD). Our results are reported and discussed by X-ray diffraction (XRD) to ensure that the manufactured samples show a hexagonal wurtzite ZnO structure. Transmission electron microscopy (TEM) confirmed the nanoparticle growth in the hexagonal sample on the surface, which is the key to improving the light response. Our prepared UV PD Au/Cu codoped ZnO showed a rapid time at a power density of 7.6 mW. the highest responsivity of $R = 575$ mA/W and sensitivity $10^3$ obtained at 7.6 mW with an applied voltage of 1 V. Our results demonstrate the obvious substitution of Au and Cu in ZnO, thereby improving the UV-sensing light response.

Keywords Photodetectors · Au nanoparticles · Fast response · Polyol process

1 Introduction

Photodetectors are important for a range of applications such as smart sensors, biological sensors, satellite communication, and pharmaceutical analyses (Rosenbaum 2020; Chu et al. 2017; Liu et al. 2014). ZnO is considered to be an important material for future UV PD due to its interesting characteristics, such as optical transparency, a wide band gap of 3.37 eV, and a large exciton binding energy of 60 meV (Dib et al. 2020; Zhang et al. 2019). For photodetector applications, pure ZnO nanoparticles are n-type semiconductors, and their optical and electrical properties are inferior and more unstable without doping elements (Elkamel et al. 2020). There are many techniques to
to improve the physical properties of ZnO-based UV PD materials, such as doping/co-doping, sol–gel co-precipitation, etc. (Hamdaoui et al. 2019; Elkamel et al. 2018; He et al. 2017; Duta et al. 2015). Generally, doping is commonly used to improve the electrical and optical properties of ZnO. Despite the use of single-doped ZnO, electrical and optical properties cannot be improved simultaneously (Sharma and Jha 2017a; Ali et al. 2018). Therefore, co-doping is considered to be an effective method to improve both electrical and optical properties. In recent years, noble metals (Pt, Au, Ag, and Cu) and other nanoparticles have distinctive properties in terms of light, electricity, heat, and catalysis (Ben Elkamel et al. 2020; Elkamel et al. 2019). They have very good application prospects in the fields of micro-nano photoelectric devices and biosensors, which have attracted great attention and extensive research by research groups all over the world. Moreover, nanoparticles generate surface plasmon resonance (SPR) effects due to the quasi-free electrons in the conduction band under the excitation light of a certain wavelength, thus generating surface plasmon absorption peaks in the visible to near-infrared region. So, light is trapped and enhanced close to the Au NPs, resulting in an increase in the amount of photocurrent in the ZnO (Duta et al. 2015; Hsu et al. 2018a). In other words, the enhanced light absorption of the ZnO Nps by the SPR of the Au NPs results in an improvement in photoresponsivity.

Nowadays, UV PDs based ZnO may be ameliorated by doping of noble metals such as Ag, Au, and Pt (Elemike et al. 2019; Mahanti and Basak 2012; Kumar et al. 2017). The noble metal Au is very used as a doping element because of its larger ionic radii, high solubility, and minimal orbital energy (Lupan et al. 2019). Consequently, Cu and Au are considered as the most suitable doping elements as compared to other researchers used co-doping only with a transition metal. So, Au/Cu codoping ZnO may improve the UV photoresponse and responsivity also the presence of Au improved the response time which is recently a key parameter for UV PD. Our work reports a high photoreponsne UV PD-based Au/Cu codoped ZnO which is elaborated by polyol process. Up to our knowledge, Au/Cu codoped ZnO UV PD has not been reported.

2 Experimental details

Undoped ZnO, Cu doped ZnO, and Au/Cu codoped ZnO were fabricated using the polyol medium. To prepare our samples, zinc acetate dihydrate (Zn (CH₃COO)₂.2H₂O), hydrogen tetrachloroaurate (III): trihydrate (HAuCl₄.3H₂O), copper acetate tetrahydrate (Cu (CH₃COO)₂.4H₂O) and polyol (1,2-propanediol (PEG), diethylene glycol (DEG)) are used in their appropriate stoichiometric ratio. The obtained solution is mixed at 50 °C for 30 min. The concentration of Cu and Au is 5at% and 3at%, respectively. The total amount of metal (Zn and dopant metal Cu) was fixed at 0.5 M.

The structural and morphological characterization of our samples was performed by X-ray diffraction (XRD) (diffractometer using cobalt radiation at 1.7890 Å) and transmission electron microscope (TEM) (JEOL 2011 microscope operating at 100 kV). The optical properties were analyzed by diffuse reflection spectroscopy (DRS). FTIR spectra in the range of 4000–400 cm⁻¹ were obtained by infrared spectrophotometer (two spectroscopic FTIR spectrometers of Perkin Elmer). Then, the 200 SCS Keithley instrument was used to study the optical response of the device under ultraviolet light with a wavelength of 375 nm under different bias voltages.
3 Results and discussion

3.1 Structural and morphological analysis

Figure 1 shows TEM images of the pure ZnO nanoparticles and Au/Cu co-doped ZnO. The images display that pure ZnO nanoparticles are nearly spherical having regular smooth surfaces. After codoping, the smooth surface is still retained with little aggregation. It is also very obvious that the nanoparticles have very clear and well-defined grain boundaries with a prominent effect on the physical properties of the samples (Rana et al. 2020). Moreover, particle size distribution is also calculated. For the undoped ZnO nanoparticles, the average particle size ranges from 4 to 16 nm. The average particle size distribution is from 12 to 20 nm for the codoping sample.

Figure 2 presents the XRD profiles of undoped ZnO and Au/Cu codoped ZnO. The diffraction peaks corresponded to (100) (002) (101) (102) (110) (103) (200) and (112). These peaks can be indexed to the ZnO hexagonal Wurtzite structure and it is demonstrated that the doping Cu and Au did not change the structure of ZnO. We can observe that there aren’t secondary phase related to Cu and Au. So, Cu$^{2+}$ and Au$^{3+}$ are successfully substituted in the ZnO lattice.
The interplanar spacing (d_{hkl}) value was determined by the following relation (Ben Elkamel et al. 2020)

\[
\frac{1}{d^2} = \frac{4}{3} \left( \frac{h^2 + hk + k^2}{a^2} + \frac{l^2}{c^2} \right)
\]

where h, k, and l are Miller’s indices.

The volume unit cell was calculated using the relation (Elkamel et al. 2020)

\[V = 0.866 \times a^2 \times c\]

The values of various structural parameters such as a, c, c/a ratio, degree of distortion R, and internal parameter u were estimated following ozgin and Morkoç (Sharma and Jha 2017a). These obtained values have been shown in Table 1. It is indicated that the different structural parameters increase after doping.

The average crystallite size D of the nanoparticles was calculated using Debye Scherrer’s relation (Elkamel et al. 2020)

\[D = \frac{0.9 \lambda}{\beta \cos \theta}\]

where k, λ, Θ and β are constant, the wavelength of XRD radiation, Bragg angle and full width at half maximum, respectively. The obtained value of pure ZnO and codoped ZnO are 22 and 26 nm, respectively. This increase of crystallite size is associated with the mismatched ionic radius of Cu^{2+}, Au^{3+} and Zn^{2+}.

### 3.2 Optical properties

Figure 3 indicates the FTIR spectra of undoped ZnO and Au/Cu codoped ZnO Nps. The position and number of absorption bonds depend on the crystal structure, the particle morphology, and the chemical composition (Zhang et al. 2019). A broad absorption peak at 3451 cm\(^{-1}\) is associated to hydroxyl(–OH) group indicating the presence of water molecules. Then, the peak at 1385 cm\(^{-1}\) is due to the asymmetric stretching vibrations of the C=O group owing to lewis acidity (Fang et al. 2014). While the peak at 1616 cm\(^{-1}\) is associated to the symmetric stretching modes of acetate (COO–) group owing to Brosted acidity (Fang et al. 2014). The band at 2346 cm\(^{-1}\) confirmed the presence of CO\(_2\) molecules. It is observed a strong IR band at 434 cm\(^{-1}\) which corresponded to the vibration of Zn–O ( Gowrishankar et al. 2013), the peaks observed at 671 cm\(^{-1}\) could be related to the stretching vibrations of Zn–O bonds octahedral arrangements. The ZnO bonds on

| Sample                  | Average crystallite diameter D (nm) | Lattice parameter (nm) | Unit cell volume V (Å\(^3\)) | Zn–O bond length (Å) | Dislocation density (Å\(^{-2}\)) |
|-------------------------|------------------------------------|------------------------|-----------------------------|----------------------|---------------------------------|
|                         |                                    | a                      | c                           |                      |                                 |
| ZnO                     | 22                                 | 3.249                  | 5.208                       | 47.60                | 1.978                           | 8.16                            |
| Au/Cu codoped ZnO       | 26                                 | 3.241                  | 5.193                       | 47.23                | 1.972                           | 9.18                            |
octahedral arrangements are much lower than the tetrahedral coordination. The peaks at 671 cm\(^{-1}\) highlight that codoping do not influence band associated to octahedral coordination (Kumar et al. 2020). So, Au/Cu ions are substituted only at tetrahedral coordination in the ZnO lattice structure.

Figure 4 indicates the UV–Vis-DRS of pure and Au/Cu codoped ZnO. The absorption edges of Au/Cu codoped ZnO are slightly red-shifted than the pure ZnO. This shifting is associated to the doping of Au and Cu into ZnO. The data obtained from the diffuse reflectance spectra were fitted with the Kubelka–Munk function (Sharma and Jha 2017b) and are presented in Fig. 4. The optical band gaps are determined to be 3.24 eV and 3.26 eV for undoped ZnO and Au/Cu codoped ZnO, respectively. With doping, new occupied electronic states near the conduction band that are considered as donor levels are responsible for the widening of the optical band gap according to the Burstein–Moss theory (Kumar et al. 2017).

For the diffuse reflectance spectra, the other significant features in the visible region are shown in Fig. 4a. the absorption bonds at 566, 611 and 660 nm are associated to the d-d crystal field transitions \(4A_2(F)\rightarrow2A_1(G)\), \(4A_2(F)\rightarrow4T_1(P)\) and \(4A_2(F)\rightarrow2E_1(G)\), respectively.

### 3.3 I-V characteristics

Figure 5 shows the I-V characteristics of pure ZnO and Au/Cu co-doped ZnO Nps. The electrical characteristics were determined under two conditions: by scanning the voltage from \(-5\) V to 5 V. Under dark and UV illumination, the device exhibited non-linear behavior, showing Schottky contact (schema 5b). When 1 V is applied across this device, interestingly, both the dark \((6\times10^{-8}\) A) and photocurrent \((4\times10^{-7}\) A) increased significantly from the codoped device. Further increment of photocurrent in Au Nps based device is believed to be due to the localized surface plasmon resonance (LSPR) effects such as near-field enhancement, transfer of plasmon resonance energy and strong absorption light from plasmonic NPs to ZnO (Chang and Hsueh 2020; Hsu et al. 2018a; Young and Chu 2021). Under UV illumination, the electrons in Au NPs get excited to its surface and are easily transferred to the ZnO. Also, the photogenerated holes move towards the NPs and reduce...
the recombination rate, which results in enhanced photoresponse (Hu et al. 2017; Djamil et al. 2017; Agarwal et al. 2015; Hsu et al. 2018b).

### 3.4 UV Photoresponse measurements

Figure 6 shows five cycles of the UV photoresponse of Au/Cu codoped ZnO Nps, which were performed to demonstrate the stability of UV PD. It is noted that the photoresponse values are the same as the UV illumination in all repetition cycles and recovery well at the baseline. Moreover, the responsivity (R) and sensitivity (S) are the important parameters for UV PD which was determined by using the following equation (Rana et al. 2020)

\[
R = \frac{I_{ph}}{P_{opt}} \cdot (A/W) \tag{4}
\]

\[
S = \frac{I_{light} - I_{dark}}{I_{dark}} \times 100 \tag{5}
\]

where \(I_{ph}\), \(I_{dark}\) and \(P_{opt}\) are the photocurrent, the dark current and the incident optical power.

Figure 7 shows a graph of sensitivity and responsivity as a function of power density. For our device, the observed sensitivity is up to level \(10^3\). As the value of power increase, the sensitivity of our fabricated device decrease since there is domination of drain current.
in the on-state by photogenerated charge carrier, but under illumination drain current is just associated by photogenerated charge carrier in the off state. Moreover, the responsivity decreased with the increase of power and it has a maximum of 575 mA/W at 1 V. As the nature of the metal/semiconductor interface and the incident light strongly affect the surface plasmon effect of the nanoparticles, changes in the wavelength of the incident light can improve the photoelectric detection performance (Ning et al. 2018).

The detectivity, which indicates the smallest detectable signal, is also calculated by $D^* = \frac{(\Delta f)^1}{2}/\text{NEP}$, where $\Delta f$ is the electrical bandwidth of the signal and NEP indicates
the noise equivalent power. By hypothesizing that the dark current is the major source of short noise, we get \( D^* = \frac{R S^{1/2}}{(2q I_{\text{dark}})^{1/2}} \) (Yuan et al. 2019) and then \( D^* \) of the detector is estimated to be \( 3.66 \times 10^{12} \) Jones.

Upon UV illumination, our device shows an improved photoresponse as compared to the results found in the literature (Pascariu et al. 2018; Jin et al. 2008; Gozeh et al. 2018). This enhancement of photoresponse is attributed to the LSPR effects of Au Nps. After incorporation of Au Nps in ZnO, local Schottky barriers at the interface of Au and ZnO rise the width of the depletion region. As result, these Schottky barriers lead to a smaller dark current and an effective separation of photogenerated holes from electrons.

The linear dynamic range (LDR, quoted in dB) is calculated as the following relation:
It is defined to describe the signal-to-noise ratio. The LDR of our device is 50 dB. A high LDR indicates that the ratio of photocurrent to dark current is quite large, and the signal-to-noise ratio is also large. At 1 V bias voltage, the output current of our device drops 3 orders of magnitude and increases almost 4 orders of magnitude with off/on UV light, respectively, within 0.5 s, demonstrating the quick response time of this device.

The impulse response of Au/Cu co-doped ZnO PD has six cycles, as shown in Fig. 6a, which also proves the stability and repeatability of our device. The single cycle of the impulse response in Fig. 6b indicates a rise time of 1.82 s and a decay time of 1.02 s. This is much faster than a pure ZnO film with a rise and decay times of 18 s and 56 s, respectively (Gozeh et al. 2018). Since the rise and fall times depend largely on the light intensity, the response time can be shortened by increasing the light intensity (Yakout 2018). The performance of our device is compared with other co-doped ZnO-based PD UVs in the literature. Importantly, response times as short as 1.82 s are better than most other material-based PDs. The high detectivity of $3.66 \times 10^{12}$ Jones is higher than that $(1.07 \times 10^{11})$ of ZnO based device, demonstrates the high performance of photodetection under a weak light condition (Han et al. 2020; Li et al. 2013; Ababii et al. 2019; Neena et al. 2019). Notably, our photodetector proves as superior as detectivity and responsivity of traditional UV detectors and excellent external quantum efficiency exceed 60%.

Table 2 shows the collected data of our Au/Cu codoped ZnO sample as compared to results found in the literature. The performances of our devices indicate the possibility of using Au/Cu codoped ZnO nanoparticles to develop photodetectors that demonstrate improved performance using a simple, and low cost elaboration method.

### 3.5 UV Detection mechanism

Figure 8 shows the mechanism of UV photodetection and charge transfer process for ZnO nanoparticles based UV PD without and with Au/Cu codoped ions. In the absence of UV illumination, the large surface area of ZnO nanoparticles adsorbs the oxygen molecules in the atmosphere and kept at grains and their grains boundaries (Fig. 8). these oxygen molecules capture free electrons from $n$-type ZnO Nps.

So, oxygen ions ($O^{-2}$, $O^{-}$ and $O^{2-}$) are produced on the surface by the following chemical reactions

$$O_2(g) + e^- \rightarrow O^{-2}(ads)$$

(7)

$$O_2(g) + e^- \rightarrow 2O^{-}(ads)$$

(8)

$$O^{-}(g) + e^- \rightarrow O^{-2}(ads)$$

(9)

From these reactions, we can conclude that the free charge carrier concentration is minimized by removing electrons from the ZnO surface, thus, there is a creation of low conductivity depletion near the surface of ZnO Nps (Fig. 8a).

Upon UV illumination, electrons- holes were migrated to the surface of ZnO to interact which the adsorbed oxygen ions, with leads to the desorption of oxygen by the surface. This phenomenon can be explained by the following chemical reaction

$$LDR = 20 \log \left( \frac{I_{ph}}{I_d} \right)$$

(6)
| Materials                     | Wavelength (nm) | Dark current (µA) | Rise time (s) | Recovery time (s) | Responsivity (A/W) | Sensitivity | References                  |
|------------------------------|-----------------|-------------------|---------------|-------------------|---------------------|-------------|------------------------------|
| N-Al codoped ZnO             | 365             | 5.5               | 4             | 5                 | 0.1                 | 127.2       | Rana et al. (2020)           |
| Cd-La codoped ZnO            | 365             | –                 | 2.5           | 3                 | –                   | 75          | Gozeh et al. (2018)          |
| Cd/Mg doped ZnO              | 325             | 0.18              | 5             | 15                | –                   | 23          | Vettumperumal et al. (2014)  |
| Doped ZnO thin films         | 315–400         | 194               | –             | –                 | –                   | 15.7        | Tsay and Yu (2014)           |
| Fe₂O₃:ZnO–Au                 | 350             | –                 | 7             | 17                | –                   | –           | Kaneti et al. (2015)         |
| Au/Cu codoped ZnO            | 375             | 400               | 1.82          | 1.02              | 0.57                | 10³         | Our work                    |
Fig. 8 The schematic energy band diagram of pure ZnO (a) and (b) Energy band diagram of ZnO UV PD decorated with Au NPs illustrating the charge transfer process under UV light illumination.
Consequently, the free electrons concentration increase and the depletion layer width decrease.

To understand, the mechanism of improved photoresponse in ZnO nanoparticles UV PD codoped with Au/Cu ions, an energy band diagram for the device was also presented (Fig. 8b). Under the illumination, the electrons are excited from the valence band to the conduction band of ZnO, leaving the identical quantity of holes in the valence band. The newly shaped Fermi energy of the Au/ZnO is lower than the energy level of the bottom of the conduction band of ZnO, so the photoexcited electrons would be transferred from ZnO to Au, driven by the energy difference to reduce carrier recombination. The mechanism of photoresponses for Au/ZnO is noble metal as a medium for storing and releasing electrons through a Fermi level between semiconductor and metal nanoparticle, the quantum rate of the photogenerated electron transfer process can be enhanced by promoting the interfacial charge transfer in these conforming systems. At a similar time, attributable to the change of the metal particles, that causes the surface plasmon oscillation to be improved, causes the local electric field change just about it. This local field successfully causes the interaction between the electrical field and also the metal cluster. In the meantime, because of SPR excitation, Au nanoparticles absorb the resonant photons to get hot electrons, and hot electrons were transferred to the conduction band of ZnO. Owing to the presence of an applied electric field, the recombination rate of photogenerated electrons and holes is greatly reduced. So, Au can affect as an electron sink, reducing the recombination rate of the electron–hole pairs, thereby increasing the directional separation efficiency of the photogenerated charge.

4 Conclusion

In summary, we have successfully prepared Au/Cu co-doped ZnO UV PD using a polyol process. Our samples were analyzed by various methods and investigated in detail. Structural analysis shows that our sample has a polycrystalline wurtzite ZnO structure oriented along the c-axis (002). The morphological analysis shows that Au Nps has been dispersed on the surface of ZnO Nps particles with medium uniform size. In addition, with the co-doping of Au and Cu, the optical band decreased from 3.24 eV (ZnO) to 3.26 eV (Au/Cu co-doped ZnO). Compared with the literature attributed to the LSPR mechanism, we obtain a fast response time. The highest responsivity and sensitivity (R = 575 mA/W and S = 10^3) are obtained at 7.6 mW for bias voltage at 1 V. Our results showed Au/Cu codoped ZnO has a good crystalline structure, rapid response, highest responsivity, and gain. This new structure is suitable for UV photodetectors.

Acknowledgements Taif University Researchers Supporting Project number (TURSP-2020/28), Taif University, Taif, Saudi Arabia.

References

Ababii, N., Hoppe, M., Shree, S., Vahl, A., Ulfa, M., Pauporté, T., Sontea, V.: Effect of noble metal functionalization and film thickness on sensing properties of sprayed TiO2 ultra-thin films. Sens. Actuators, A 293, 242–258 (2019)
Agarwal, H., Khandelwal, S., Dey, S., Hu, C., Chauhan, Y.S.: Analytical modeling of flicker noise in halo implanted MOSFETs. IEEE J. Electron Devices Soc. 3(4), 355–360 (2015)

Ali, R.N., Naz, H., Li, J., Zhu, X., Liu, P., Xiang, B.: Band gap engineering of transition metal (Ni/Co) codoped in zinc oxide (ZnO) nanoparticles. J. Alloy. Compd. 744, 90–95 (2018)

Ben Elkamel, I., Hamdaoui, N., Mezni, A., Ajjel, R.: Photoconduction, dielectric and photoluminescence properties of Cu2+: ZnO nanoparticles elaborated by a polyol method. Phase Transit. 93(4), 388–406 (2020)

Chang, T.J., Hsueh, T.J.: A NO2 gas sensor with a TiO2 nanoparticles/ZnO/MESS-structure that is produced using ultrasonic wave grinding technology. J. Electrochem. Soc. 167(2), 027521 (2020)

Chu, J., Wang, F., Yin, L., Lei, L., Yan, C., Wang, F., Xiong, J.: High-performance ultraviolet photodetector based on a few-layered 2D NiP3S3 nanosheet. Adv. Funct. Mater. 27(32), 1701342 (2017)

Dib, K., Trari, M., Bessekhouad, Y.: (S, C) co-doped ZnO properties and enhanced photocatalytic activity. Appl. Surf. Sci. 505, 144541 (2020)

Djamil, R., Aicha, K., Souifi, A., Fayçal, D.: Effect of annealing time on the performance of tin oxide thin films ultraviolet photodetectors. Thin Solid Films 623, 1–7 (2017)

Duta, M., Mihaiu, S., Munteanu, C., Anastasescu, M., Osiceanu, P., Marin, A., Gartner, M.: Properties of In–N codoped p-type ZnO nanorods grown through a two-step chemical route. Appl. Surf. Sci. 344, 196–204 (2015)

Elemike, E.E., Onwudiwe, D.C., Wei, L., Chaogang, L., Zhiwei, Z.: Noble metal–semiconductor nanocomposites for optical, energy and electronics applications. Sol. Energy Mater. Sol. Cells 201, 110106 (2019)

Elkamel, I.B., Hamdaoui, N., Mezni, A., Ajjel, R., Beji, L.: High responsivity and 1/f noise of an ultraviolet photodetector based on Ni doped ZnO nanoparticles. RSC Adv. 8(56), 32333–32343 (2018)

Elkamel, I.B., Hamdaoui, N., Mezni, A., Ajjel, R., Beji, L.: Synthesis and characterization of Cu doped ZnO nanoparticles for stable and fast response UV photodetector at low noise current. J. Mater. Sci.: Mater. Electron. 30(10), 9444–9454 (2019)

Elkamel, I.B., Hamdaoui, N., Mezni, A., Ajjel, R.: Enhancement of dielectric properties of Ni and Co doped ZnO due to the oxygen vacancies for UV photosensors application. Phys. E: Low-Dimensional Syst. Nanostructures 119, 114031 (2020)

Fang, D., Lin, K., Xue, T., Cui, X., Chen, X., Yao, P., Li, H.: Influence of Al doping on structural and optical properties of Mg–Al co-doped ZnO thin films prepared by sol–gel method. J. Alloy. Compd. 589, 346–352 (2014)

Gowrishankar, S., Balakrishnan, L., Balasubramanian, T., Gopalakrishnan, N.: Fabrication of n-Zn1–xGaxO/p-(ZnO) 1–x (GaP) x thin films and homojunction. Mater. Sci. Eng., B 178(1), 31–38 (2013)

Gozeh, B.A., Karabulut, A., Yildiz, A., Yakuphanoglu, F.: Solar light responsive ZnO nanoparticles adjusted using Cd and La Co-dopant photodetector. J. Alloy. Compd. 732, 16–24 (2018)

Hamdaoui, N., Elkamel, I.B., Mezni, A., Ajjel, R.: Highly efficient, low cost, and stable self-powered UV photodetector based on Co2+: ZnO/Sn diluted magnetic semiconductor nanoparticles. Ceram. Int. 45(14), 17729–17736 (2019)

Han, Y., Yao, C.B., Cai, Y., Bao, S.B., Jiang, G.Q.: Copper decorated ZnO nanowires material: Growth, optical and photoelectrochemical properties. J. Alloys Compd. 835, 155339 (2020)

He, G.H., Zhou, H., Shen, H., Lu, Y.J., Wang, H.Q., Zheng, J.C., Shen, D.Z.: Photodetectors for weak-signal detection fabricated from ZnO: (Li, N) films. Appl. Surf. Sci. 412, 554–558 (2017)

Hsu, C.L., Jhang, B.Y., Kao, C., Hsueh, T.J.: UV-illumination and Au-nanoparticles enhanced gas sensing of p-type Na-doped ZnO nanowires operating at room temperature. Sens. Actuators, B Chem. 274, 565–574 (2018a)

Hsu, C.L., Wu, H.Y., Fang, C.C., Chang, S.P.: Solution-processed UV and visible photodetectors based on Y-doped ZnO nanowires with TiO2 nanosheets and Au nanoparticles. ACS Appl. Energy Mater. 1(5), 2087–2095 (2018b)

Hu, K., Teng, F., Zheng, L., Yu, P., Zhang, Z., Chen, H., Fang, X.: Binary response Se/ZnO p-n heterojunction UV photodetector with high on/off ratio and fast speed. Laser Photonics Rev. 11(1), 1600257 (2017)

Jin, H.J., Oh, S.H., Park, C.B.: Unidirectional variation of lattice constants of Al–N-codoped ZnO films by RF magnetron sputtering. Appl. Surf. Sci. 254(7), 2207–2210 (2008)

Kaneti, Y.V., Moriceau, J., Liu, M., Yuan, Y., Zakaria, Q., Jiang, X., Yu, A.: Hydrothermal synthesis of ternary α-Fe2O3-ZnO-Au nanocomposites with high gas-sensing performance. Sens. Actuators B Chem. 209, 88–897 (2015)

Kumar, A., Dixit, T., Palani, I.A., Nakamura, D., Higashihata, M., Singh, V.: Utilization of surface plasmon resonance of Au/Pt nanoparticles for highly photosensitive ZnO nanorods network based plasmon field effect transistor. Phys. E 93, 97–104 (2017)
Kumar, A.G., Li, X., Du, Y., Geng, Y., Hong, X.: UV-photodetector based on heterostructured ZnO/(Ga, Ag)-co-doped ZnO nanorods by cost-effective two-step process. Appl. Surf. Sci. 509, 144770 (2020)

Li, X., Gao, C., Duan, H., Lu, B., Wang, Y., Chen, L., Xie, E.: High-performance photovoltaic-type self-powered UV photodetector using epitaxial TiO2/SnO2 branched heterojunction nanostructure. Small 9(11), 2005–2011 (2013)

Liu, H., Zhang, Z., Hu, L., Gao, N., Sang, L., Liao, M., Fang, X.: New UV-A photodetector based on individual potassium niobate nanowires with high performance. Adv. Opt. Mater. 2(8), 771–778 (2014)

Lupan, O., Postica, V., Pauperté, T., Hoppe, M., Adelung, R.: UV Nanophotodetectors: a case study of individual Au-modified ZnO nanowires. Sens. Actuators, A 296, 400–408 (2019)

Mahanti, M., Basak, D.: Highly enhanced UV emission due to surface plasmon resonance in Ag–ZnO nanorods. Chem. Phys. Lett. 542, 110–116 (2012)

Neena, D., Kondamareddy, K.K., Humayun, M., Mohan, V.B., Lu, D., Fu, D., Gao, W.: Fabrication of ZnO/N-rGO composite as highly efficient visible-light photocatalyst for 2, 4-DCP degradation and H2 evolution. Appl. Surf. Sci. 488, 611–619 (2019)

Ning, Y., Zhang, Z., Teng, F., Fang, X.: Novel transparent and self-powered UV photodetector based on crossed ZnO nanofiber array homojunction. Small 14(13), 1703754 (2018)

Pascariu, P., Tudose, I.V., Suchea, M., Koudoumas, E., Fifere, N., Airinei, A.: Preparation and characterization of Ni, Co doped ZnO nanoparticles for photocatalytic applications. Appl. Surf. Sci. 448, 481–488 (2018)

Rana, V.S., Rajput, J.K., Pathak, T.K., Purohit, L.P.: Influence of N2 flow rate on UV photodetection properties of sputtered p-ZnO/n–Si heterojunctions. Coll. Surf. A: Physicochem. Eng. Asp. 586, 124103 (2020)

Rosenbaum, L.: Facing Covid-19 in Italy—ethics, logistics, and therapeutics on the epidemic’s front line. N. Engl. J. Med. 382(20), 1873–1875 (2020)

Sharma, D., Jha, R.: Transition metal (Co, Mn) co-doped ZnO nanoparticles: effect on structural and optical properties. J. Alloy. Compd. 698, 532–538 (2017a)

Sharma, D., Jha, R.: Analysis of structural, optical and magnetic properties of Fe/Co co-doped ZnO nanocrystals. Ceram. Int. 43(11), 8488–8496 (2017b)

Tsay, C.-Y., Yu, S.-H.: Optoelectronic characteristics of UV photodetectors based on sol–gel synthesized GZO semiconductor thin films. J. Alloy. Compd. 596, 145–150 (2014)

Vettumperumal, R., Kalyanaraman, S., Thangavel, R.: Photoconductive UV detectors based heterostructures of Cd and Mg doped ZnO sol gel thin films. Mater. Chem. Phys. 145, 237–242 (2014)

Yakout, S.M.: Pure and Gd-based Li, Na, Mn or Fe codoped ZnO nanoparticles: insights into the magnetic and photocatalytic properties. Solid State Sci. 83, 207–217 (2018)

Young, S.J., Chu, Y.L.: Hydrothermal synthesis and improved CH3OH-sensing performance of ZnO nanorods with adsorbed Au NPs. IEEE Trans. Electron Devices 68(4), 1886–1891 (2021)

Yuan, H., Xu, M., Dong, C., Ma, J., Wang, X.: Mechanistic insights into magnetic and gas sensing properties of (F, Na)-codoped ZnO nanocrystals by room-temperature photoluminescence. Appl. Surf. Sci. 496, 143511 (2019)

Zhang, H., Li, W., Qin, G., Ruan, H., Huang, Z., Wu, F., Fang, L.: Role of zinc interstitial defects in indium and magnesium codoped ZnO transparent conducting films. Appl. Surf. Sci. 492, 392–398 (2019)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.