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Electrical transport properties and impedance analysis of Au/ZnO nanorods/ITO heterojunction device

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Abstract

Our work involves the growth of well aligned vertical nanorods of ZnO on transparent indium doped tin oxide (ITO) conductive substrate and fabrication of Au/ZnO Nanorods/ITO Heterojunction device. The observation of non-ideal diode current density-voltage (J-V) characteristics of the device has been evaluated with various conduction mechanisms [Ohmic, space-charge limited conduction (SCLC)]. The charge carrier mobility is estimated to be ~0.05 cm²/Vs. The presence of deep level defects in the ZnO nanorods is accountable for these two different transport mechanisms and it is backed by photoluminescence, distinctly. The estimated density of deep trap states is ntrap ∼ 5.76 × 10¹³ cm⁻³. The charge carrier density and built-in potential of this device are obtained from electrochemical impedance spectroscopy (EIS). The average work function of vertical ZnO nanorods is found out to be ~4.93 eV. Henceforth, our results explain the charge transport mechanism which plays a key role in optoelectronic based devices for various applications.

1. Introduction

ZnO belongs to II–VI group having a wide bandgap with a direct energy gap of nearly 3.37 eV and possess large exciton binding energy of 60 meV [1–4]. ZnO falls under the class of hexagonal wurtzite structure with good chemical, mechanical as well as thermal stability [5–7]. Also, it is featured by high breakdown electric field, high electron saturation velocity and radiation tolerance [8]. These characteristic features make it an appropriate material for high temperature and high-power devices [9]. Formation of heterojunction and Schottky contacts on ZnO nanostructures can aid in the fabrication of these electronic devices. Realization of heterojunction of ZnO is far easier than homojunction as reproducible p-type with expected hole concentration is still under research [10, 11].

Also, ZnO has the ability to form a Schottky contact with noble metals having higher work function i.e., platinum (Pt), gold (Au) and palladium (Pd) [4]. Nevill and Mead et al reported the first Schottky contact with ZnO. Yadav et al studied the Schottky contact of ZnO with Pd which was fabricated via sol-gel method. Aydogan et al demonstrated the Au Schottky contact on ZnO by electrodeposition technique on the n-type silicon substrate [16]. Earlier, Au/ZnO nanorod/ n-SiC based Schottky diodes had been studied by Willander’s group [17]. They briefly investigated the interface traps and electrical characteristics by current-voltage (I-V), capacitance-voltage (C-V), Capacitance- frequency (C-ω) and conductance-frequency (Gp/ω-ω) measurements.
Faraz et al. fabricated Ag/ZnO/Silver (Ag) Schottky diode using aqueous chemical growth (ACG) and evaporation technique [18]. Periyasamy et al. deposited Pt on ZnO thin film using vacuum evaporation and thermal evaporation technique [19, 20]. A proper interpretation and detailed analysis of the electrical parameters of ZnO based Schottky contact and heterojunction is very much in need to carve a path for their extensive usage in optoelectronic based applications.

Various optoelectronics applications based on ZnO has been extensively studied for different purposes. Applications such as light emitting diodes, photodetectors, Dye sensitized solar cells and many more involves ZnO nanostructures [21–24]. Due to such wide usage, studying the electrical parameters, i.e., ideality factor, barrier height, charge carrier density, deep trap states, interface resistance, capacitance, and so on can play a key role in the fabrication of efficient devices. As previously reported, studies on defect and trapped charges is used in identifying the affected interfacial energy band alignment [25, 26].

Herein, we have grown vertical ZnO nanorods with diameter from 40–90 nm on ITO substrate using the hydrothermal method and deposited Au on top on ZnO nanorods using e-beam evaporation for fabrication of Au/ZnO/ITO heterojunction device. The structural, morphological and optical characterizations of as-grown ZnO nanorods were carried out by XRD, FESEM and PL spectra. Ideality factor, barrier height, density of deep trap states, conductivity and effective charge carrier mobility of the device are obtained from I–V characterization. The charge carrier density and built-in potential of this device are obtained from electrochemical impedance spectroscopy (EIS). Finally, the work function of vertical ZnO nanorods and Au/ZnO nanorods interface were measured by scanning kelvin probe system (SKP).

2. Experimental details

ZnO nanorods were grown vertically on indium tin oxide (ITO) via the wet chemical method [27, 28]. Initially, seed layer was prepared by dissolving 0.005 M Zinc acetate dihydrate in 50 ml ethanol, which is later irradiated with UV light for 20 min to enhance the wetting on ITO substrate. Seed layer formation on ITO substrate was done by drop casting and subjected to annealing in air at 400 °C for 30 min. Annealed ITO substrate with seed layer was then vertically inserted into the precursor solution of Zinc Acetate dihydrate [Zn(AC)2.H2O, Sigma-Aldrich, 99%] and hexamethylenetetramine (HMTA, Sigma-Aldrich, 99%) dissolved in 200 ml of deionized (DI) water at 90 °C for 4 h. Finally, the substrate was removed and rinsed with DI water, followed by drying in air.

Crystallinity studies of ZnO nanorods were carried out by XRD (Rigaku, Japan) with Co-Kα as the radiation source. Morphology of prepared ZnO nanorods were characterized by FESEM (Field Emission Scanning Electron Microscopy). Steady state room-temperature photoluminescence (PL) spectroscopical studies helped to understand the optical properties of the ZnO nanorods. The PL measurement setup was elaborately discussed in our previous article [29].

To form a heterojunction device, well aligned ZnO nanorods has been grown on the n-type ITO substrates by using the hydrothermal method. The gold electrode was deposited on the top of the well-aligned, vertical ZnO nanorod surfaces by using e-beam evaporation technique to make Schottky contacts. Current-voltage (I–V) measurements were conducted using a semiconductor parameter analyser (Keithley 4200A-SCS, Tektronix, USA) with table top vacuum probe station (Lakeshore PS100) setup. AC Impedance measurements were performed with frequency range of 0.8 KHz to 1 MHz with applied voltage of 10 mV using a potentiostat (Autolab, PGSTAT30 and FRA2 module).

Fabricated Au/ZnO nanorods on conducting ITO substrate was used for the SKP. The contact potential difference measurements of vertically aligned ZnO nanorods in ambient condition at room temperature was characterized by SKP system which consists of vibrating gold tip with 2 mm diameter at the frequency of 78.3 Hz (SKP5050, KP Technologies Ltd, UK).

3. Results and discussion

The XRD spectrum of as-grown ZnO nanorods sample is shown in figure 1. The main peak in the x-ray diffraction pattern of ZnO nanorods (figure 1(a)) occurred at 2θ = 40.5° which is attributed to the ZnO (002) plane. The observed x-ray diffraction pattern and rocking curve (figure 1(b)) has confirmed the well aligned c-axis oriented growth. The FESEM image of the as-grown ZnO nanorods is depicted in figure 2. The nanorods has grown vertically and they possess wurtzite structure thereby confirming the growth along the c-axis direction. From the FESEM images, diameter of nanorods is found to be about ~40–90 nm and an average length is estimated to be ~1.76 µm from length distribution plot.

Figure 3 shows the room temperature PL spectra of ZnO nanorods. The broad emission centered at 585 nm is mainly due to the deep level emission (DLE) aroused from intrinsic defects and/or the presence of impurity
states [30]. The absence of near-band-edge (NBE) in the PL spectra indicates that wet chemistry route induced a large number of defects so as to completely quench the band to band emission. The observed defects and presence of impurity states play a major role in the device performance.

The schematic illustration of the Au/ZnO/ITO heterojunction device is shown in figure 4(a). The typical current density-voltage (J-V) characteristics of the Au/ZnO/ITO device is shown in figure 4(b). It shows a rectifier behaviour with a fast growing forward current ($I_F$) and slightly increased reverse current density ($I_R$) in the reverse bias region from $-0.5$ V onwards. Au/ZnO junction dominates the electric characteristics and the observed forward current is compatible with a thermionic emission from ZnO towards Au. The large inverse current is likely contributed by holes diffusion from ZnO bulk to the interface. The magnitude of the current also
reveals a low concentration of electrons. The barrier parameters can be estimated from the linear part of the forward bias curve in the semi logarithmic scale (figure 4(c)). For that, I–V characterization can be written as

\[
I = I_0 \exp \left( \frac{qV}{nkT} \right) \left[ 1 - \exp \left( -\frac{qV}{kT} \right) \right]
\]

Where \( q \) is the elementary charge, \( k \) is the Boltzmann’s constant, \( T \) is the absolute temperature, \( V \) is the applied bias voltage and \( I_0 \) is the reverse saturation current. The ideality factor \( \eta \) can be calculated from the slope of the \( \ln(I/(1-\exp(-qV/kT))) \) versus \( V \) plot. On the other hand, the reverse saturation current \( I_0 \) can be expressed as
$I_0 = A A^* T^2 \exp \left( - \frac{q \phi_B}{kT} \right)$ \hspace{1cm} (2)

where $A^*$ is the effective Richardson constant, $A$ is the Au electrode area and $\phi_B$ is the barrier height. From equation (1), the ideality factor is calculated from the slope of the ln($I/(1-\exp(-qV/kT))$) versus $V$ plot and found to be 4.54. At the same time, the barrier height of the ZnO nanorods obtained from equation (2) is calculated from intercept as 0.44 eV. This highest ideality factor and slightly low barrier height confirms the formed Au/ZnO heterojunction is far from ideal Schottky contact and also confirms the existence of an interfacial layer or surface states \cite{31, 32}.

Also, the limited concentration of electrons in ZnO is suggested by the superposition of linear, exponential and power law J-V dependences of the J-V curve in forward bias as shown in figure 4(c). This is compatible with a space charge limited current (SCLC) occurs in low-carrier density semiconductor materials where the injected charges alter the overall charge density inducing additive electric field respect to the bias voltage. As observed in PL spectra, the lack of NBE emission suggests an excess of defects in the material and thus a low charge carrier density.

The J-V characteristic of the SCLC theory can be expressed as $J \propto V^n$. The presence of deep trap states can alter both the exponent and the magnitude of the space-charge limited current. Thus, it was suggested that the particular shape of the J-V characteristic curve can be used to determine the energy distribution of traps \cite{31, 33, 34}.

For instance, $n = 2$ indicates an ideal trap-free state material. The SCLC behaviour can be inferred from the log-log current density-voltage plot as shown in figure 5. The plot shows a short Ohmic region followed by a steeply increased current density indicates the presence of trap-filling state region from trap-filling level voltage ($V_{TFL} = 0.2$ V). Low-voltage tunnelling through the deep-level trap states explains the conduction in the ohmic region. From the results, we have calculated the density of deep trap states, $n_{trap} \sim 5.76 \times 10^{13}$ cm$^{-3}$ which is estimated by using the following formula.

$$n_{trap} = \frac{2 \varepsilon \varepsilon_0 V_{TFL}}{qL^2}$$ \hspace{1cm} (3)

where $\varepsilon$ is the relative permittivity of ZnO, $\varepsilon_0$ is the permittivity of free space, $q$ is the elemental charge and $L$ is the distance between the contacts corresponding to the length of the ZnO nanorods. Analysis of the ohmic region provides an estimate of the conductivity $\sigma \sim 5.42 \times 10^{-6}$ (Ω cm)$^{-1}$.

The charge trap states can be found out through proper analysis of J-V characteristics with SCLC mechanism \cite{31}. According to Mott-Gurney’s law, solid materials is expected to follow $J \propto V^2$. Following equation has been used to fit the experimental data and to estimate effective charge carrier mobility ($\mu$) in the ideal condition where the charge trap states of ZnO are absent.

$$J = \left( \frac{9}{8} \right) \frac{\mu \varepsilon \varepsilon_0}{L^3} V^2$$ \hspace{1cm} (4)

Where $L$ represents the length of nanorod, $\varepsilon$ is the relative permittivity of ZnO and $\varepsilon_0$ represents permittivity of a vacuum. From equation (4), the value of the effective charge carrier mobility is found out to be ~0.05 cm$^2$/Vs which is near to the value of the reported literature \cite{35}. 

Figure 5. J-V log-log scale, showing two distinct slopes.
Charge carrier density of ZnO and the built-in potential of Au/ZnO/ITO junction can be obtained through AC impedance analysis. The AC impedance measurement setup is shown in figure 6(a). The complex impedance spectra of Au/ZnO/ITO interface were measured at various reverse bias voltages (0.2 V–0.8 V) in the frequency range of 0.8 kHz–1 MHz at room temperature. The reverse bias voltage range is fixed from the J-V characterization which is shown in figure 4(b). The impedance of ZnO nanorods can be expressed by the following relationship:

\[ \frac{1}{Z^*} = \frac{1}{Z' + jZ''} = \frac{1}{R} + j\omega C \quad (5) \]

where

\[ Z' = \frac{1}{\left(\frac{1}{R}\right) + \omega^2 C^2} \quad (6) \]

\[ Z'' = \frac{-\omega C}{\left(\frac{1}{R}\right) + \omega^2 C^2} \quad (7) \]

The complex impedance plots at different reverse-bias voltages (0.2–0.8 V) are shown in figure 6(b). The complex impedance plot exhibits single semi-circle at all the voltages indicating that the ZnO nanorods array contributes to the total conductivity. Depressed semi-circles with their centres lay below the real axis (Z’) at all the voltages indicates the deviation from the ideal Debye behaviour of the interface. Electrode (Au)—semiconductor (ZnO nanorods) interface contribution to the charge transport of ZnO nanorods seems irrelevant. There are no inclined straight lines at low frequencies as observed.

Figure 6(c)(i) and (ii) shows the frequency variation of real (Z’) and imaginary part (−Z'') of Au/ZnO/ITO device at different reverse-bias voltages. Figure 6(c)(i) indicates that the real part of the impedance decreases with increasing frequency due to increasing conductivity of the Au/ZnO/ITO interface at all the reverse bias voltages. It can be explained that the increasing voltage and frequency, hopping of charge carriers (electron) increases, leading to enhancement of conductivity. The imaginary part of impedance (−Z'') as a function of frequency at various voltages is depicted in figure 6(b)(ii). −Z'' shows the broader asymmetric peak, indicating the presence of relaxation processes and their spreading in Au/ZnO/ITO interface. Frequency at which the asymmetric Debye peak appears in the complex impedance spectra indicate that the hopping frequency of conducting electron in
Au/ZnO/ITO interface matches with the frequency of the externally applied AC field. It has been observed that the asymmetric Debye peaks shift towards the higher frequencies with increasing voltage from 0.2 V to 0.8 V due to the increasing hopping rate of conduction electrons in Au/ZnO/ITO interface. In addition to that, $Z''$ is seen to decrease with increasing voltage due to the decrease of loss in the resistive part.

Figure 7. (a) Fitting results (solid line) of impedance data using the equivalent circuit model. (b) Proposed equivalent circuit consisting of Au/ZnO nanorods heterojunction. (c) Relaxation time versus reverse-biased voltage. (d) Plot between inverse junction capacitance squared versus the reverse-bias voltage.

**Table 1.** Estimated interface resistance and interface capacitance of Au/ZnO interface and ZnO/ITO interface through the equivalent circuit model.

| $V_r$ (V) | $R_s$ (kΩ) | $R_{Au-ZnO}$ (kΩ) | CPE$_{Au-ZnO}$ (nF) | CPE-Q | CPE-n | $R_{ZnO-ITO}$ (kΩ) | CPE-Q | CPE-n | $\chi^2$ |
|------|-------|-----------------|------------------|-------|-------|-----------------|-------|-------|-------|
| 0.2  | 0.06  | 0.85            | 4.48             | 0.99  |       | 94.05           | 0.59  | 0.75  | 0.0011 |
| 0.3  | 0.27  | 0.80            | 4.22             | 0.99  |       | 90.76           | 0.69  | 0.76  | 0.0014 |
| 0.4  | 0.47  | 0.76            | 4.01             | 0.99  |       | 85.63           | 0.76  | 0.76  | 0.0014 |
| 0.5  | 0.50  | 0.70            | 3.82             | 0.99  |       | 80.19           | 0.78  | 0.77  | 0.0014 |
| 0.6  | 0.61  | 0.65            | 3.66             | 0.99  |       | 75.24           | 0.82  | 0.77  | 0.0016 |
| 0.7  | 0.48  | 0.60            | 3.51             | 0.99  |       | 70.08           | 0.86  | 0.77  | 0.0017 |
| 0.8  | 0.38  | 0.55            | 3.38             | 0.99  |       | 62.44           | 0.76  | 0.76  | 0.0015 |

Since the work function of ZnO and ITO are similar, the strong Schottky junction is expected in the Au/ZnO nanorods interface. This is confirmed by the extracted resistance and capacitance values from complex impedance data. The capacitance values of ZnO/ITO interface are in the range of picofarad, which is three orders smaller than the Au/ZnO interface. At the same time the junction resistance is higher in the ZnO/ITO interface. As a result, the ZnO/ITO interface is dominated by resistance, which is close to ohmic behaviour. So, we consider the Au/ZnO nanorods interface for the further discussion. The bulk resistance $R_{Au-ZnO}$ at different reverse bias voltages have been calculated from fitting the impedance spectra. The constant phase element...
(CPE$_{\text{Au–ZnO}}$) presented in the equivalent circuit is the responsible for the depression of the semicircle in Nyquist plot. The bulk capacitance $C_{\text{CPEAu–ZnO}}$ values are calculated using the relation $\omega R_{\text{Au–ZnO}} C_{\text{Au–ZnO}} = 1$, at maximum $Z''$ point in the depressed semicircle. The junction capacitance $C_{\text{PCEAu–ZnO}}$ values at all the voltage lie in the order of $10^{-9}$ F. The relaxation time can be expressed using the following relations.

$$\tau = \frac{1}{\omega} = R_{\text{Au–ZnO}} C_{\text{PCEAu–ZnO}}$$  \hspace{1cm} (8)

The calculated values of the relaxation time ($\tau$) at various voltages lie in the order of $10^{-6}$ s. Relaxation time decreases linearly with increasing reverse bias voltage as shown in figure 7(c).

This Schottky junction is determined in terms of junction capacitance and resistance. The inverse capacitance squared is directly proportional to the applied reverse-biased voltage ($V_{B}$). Figure 7(d) shows the plots of $1/(C_{\text{PCEAu–ZnO}})^2$ versus applied $V_{B}$. The observed linear plots suggest that the electron concentration of the ZnO nanorods ($N_{dn}$) and the built-in potential ($V_{bi}$) can be estimated from the slopes and intercepts, respectively. The $N_{dn}$ and $V_{bi}$ are estimated to be $7.12 \times 10^{22}$ m$^{-3}$ and 0.59 V, respectively. The calculated total space-charge region width $W$ is approximately about 100 nm under reverse-bias from electron concentration $N_{dn}$ and built-in potential $V_{bi}$ through equation (9).

$$W = \left[ \frac{2 \varepsilon_{s} (V_{bi} + V_{F})}{\varepsilon N_{dn}} \right]^{1/2}$$ \hspace{1cm} (9)

The SKP system has been used for work function measurement of ZnO nanorods coated ITO substrate and to provide the scientific evidence for the presence of Au on the ZnO nanorods. Here, the contact potential difference (CPD) between the sample and the conductive gold tip is measured. The SKP system working principle is discussed elaborately in our previously published papers [36–40].

Figure 8 shows the raster scan image of Au/ZnO nanorods heterojunction device on ITO substrate. The measured average work function of ZnO nanorods and Au are $\sim$4.93 eV and $\sim$5.18 eV, respectively. Noteworthy, the obtained scan image shows that in spite of the nanorods structure, at the length scale of the Kelvin probe tip, the surface is rather homogeneous. Inhomogeneities are more likely due to a surface roughness due to non-uniform nanorods height. Noteworthy, this characterization is the scientific evidence for the Au/ZnO nanorods heterojunction formation.

4. Conclusions

We have demonstrated the fabrication of Au/ZnO/ITO heterojunction device, successfully and carried out its J-V characterization, electrochemical impedance analysis and finally work function studies by measuring CPD of Au/ZnO nanorods heterojunction. Vertically well aligned ZnO nanorods have been prepared by hydrothermal method and the crystallinity, morphology and optical properties were measured by XRD, SEM and PL spectra. We have obtained the ideality factor, barrier height, conductivity, density of deep trap states, charge carrier mobility, built-in potential, charge carrier density, width of the space charge region and work function using J-V characterization, electrochemical impedance analysis and SKP measurements. All these parameters are utilized to understand the interfacial properties of Au/ZnO nanorods heterojunction. These
studies will be helpful to develop novel Au/ZnO heterojunction based optoelectronic devices to be utilized in various applications.

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Author contributions

K G, G M and Y S have done the experiments. G V and K K have supported in the discussion of I–V characterization and impedance analysis data. K G, K K, S V J, C D and Y S have written the paper.

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References

[1] Neville R C and Mead C A 1970 Surface barriers on zinc oxide J. Appl. Phys. 41 3795–800
[2] Tsaiaras C, Girginoudi D and Georgoulas N 2014 Electrical characteristics of Pt Schottky contacts on ZnO films Mater. Sci. Semicond. Process. 17 199–206
[3] Yadav A B, Pandey A and Jit S 2014 Pt schottky contacts on sol-gel derived ZnO thin films with nearly ideal richardson constant IEEE Electron Device Lett. 35 729–31
[4] Rajan L, Periasamy C and Sahula V 2016 Electrical characterization of Au/ZnO thin film Schottky diode on silicon substrate Perspectives in Science 8 66–8
[5] Zhang Q, Zhao Y, Jia Z, Qin Z, Chu L, Yang J, Zhang J, Huang W and Li X 2016 High stable, transparent and conductive ZnO/Ag/ZnO nanofilm electodes on rigid/ flexible substrates Energies 9 443
[6] Liu Y, Li Y and Zeng H 2013 ZnO-based transparent conductive thin films: doping, performance, and processing J. Nanomater. 2013 1–9
[7] Lee S, Ahn S-E, Jeon Y, Ahn J-H, Song I, Jeon S, Yun D-J, Kim J, Choi H and Chung U 2013 Impact of transparent electrode on photoresponse of ZnO-based phototransistor Appl. Phys. Lett. 103 251111
[8] Von Wenckstern H, Brandt M, Schmidt H, Biehne G, Hochmuth H, Lorenz M and Grundmann M 2007 Donor-like defects in ZnO substrate materials and ZnO thin films Appl. Phys. A 88 135–9
[9] Faraz S M, Shah W, Alvi N U H, Nur O and Wahab Q U 2020 Electrical characterization of Si/ZnO nanorod PN heterojunction diode Adv. Condens. Matter Phys. 2020 1–9
[10] Rahman F 2019 Zinc oxide light–emitting diodes: a review Opt. Eng. 58 10901
[11] Janotti A and Van de Walle C G 2009 Fundamentals of zinc oxide as a semiconductor Reports Prog. Phys. 72 126501
[12] Alvi N H, Riaz M, Tzamalis G, Nur O and Willander M 2010 Junction temperature in n-ZnO nanorods/(p–4H–SiC, p–GaN, and p–Si) heterojunction light emitting diodes Solid. State. Electron. 54 536–40
[13] Djurišić A B, Chen X, Leung Y H and Ng A M C 2012 ZnO nanostructures: growth, properties and applications J. Mater. Chem. 22 6526–35
[14] Gaddam V, Kumar R R, Parmar M, Nayak M M and Rajanna K 2015 Synthesis of ZnO nanorods on a flexible Phynox alloy substrate: influence of growth temperature on their properties RSC Adv. 5 89985–92
[15] Fabbiyoda S and Kennedy L J 2019 Bandgap engineering in doped ZnO nanostructures for dye sensitized solar cell applications J. Nanosci. Nanotechnol. 19 2963–70
[16] Aydogan S, Cinar K, Asil H, Coskun C and Turut A Electrical characterization of Au/n–ZnO Schottky contacts on n-Si J. Alloys Compd. 1 913–8
[17] Hussain I, Soomro M Y, Bano N, Nur O and Willander M Interface trap characterization and electrical properties of Au–ZnO nanorod Schottky diodes by conductance and capacitance methods J. Appl. Phys. 6 064506
[18] Faraz S M, Willander M and Wahab Q 2006 Interface state density distribution in Au/n-ZnO nanorod Schottky diodes IOP Conf. Series: Materials Science and Engineering 34 01
[19] Periasamy C and Chakrabarti P 2009 Structural and electrical properties of metal contacts on n-type ZnO thin film deposited by vacuum coating technique J. Vac. Sci. Technol. B Microelectron. Nanom. Struct. Process. Mass. Phenom. 27 2124–7
[20] Periasamy C and Chakrabarti P 2011 Time–dependent degradation of Pt/ZnO nanoneedle rectifying contact based piezoelectric nanogenerator J. Appl. Phys. 109 54306
[21] Hsu Y F et al 2008 Adv. Funct. Mater. 18 1020–30
[22] Law M, Greene L E, Johnson J C, Saykally R and Yang P 2005 Nanowire dye-sensitized solar cells Nat. Mater. 4 455–9
[23] Je H J, Chang P H, Chen C Y and Tsai K T 2009 Electrical and optoelectronic characterization of a ZnO nanowire contacted by focused-ion-beam-deposited Pt Nanotechnology 20 135701
[24] Thompson D B, Richardson J J, DenBaars S P and Lange F F 2009 Light emitting diodes with ZnO current spreading layers deposited from a low temperature aqueous solution Appl. Phys. Express 2 42101
[25] Djurišić A B, Ng A M C and Chen X Y 2010 ZnO nanostructures for optoelectronics: material properties and device applications Prog. Quantum Electron. 34 191–259
[26] Nakayama T and Murayama M 2000 Electronic structures of hexagonal ZnO/GaN interfaces J. Cryst. Growth 214 299–303
Sivalingam Y, Martinelli E, Catini A, Magna G, Pomarico G, Basoli F, Paolesse R and Di Natale C 2012 Gas-sensitive photoconductivity of porphyrin-functionalized ZnO nanorods J. Phys. Chem. C 116 9151–7

Vayssieres L 2003 Growth of arrayed nanorods and nanowires of ZnO from aqueous solutions Adv. Mater. 5 464–6

Sivalingam Y, Pizzoferrato R, Paoloni S, Medaglia P G, Basoli F and Di Natale C 2015 Structural and optical correlation of Ni doped ZnO nanorods 2015 IEEE 15th Int. Conf. on Nanotechnology (IEEE-NANO) pp 319–22

Khranovskyy V, Lazorenko V, Lashkarev G and Yakimova R 2012 Luminescence anisotropy of ZnO microrods J. Lumin. 132 2643–7

Klasson P, Nur O and Willander M 2008 Nanotechnology 19 475202

Venugopal G, Sivalingam Y, Krishnamoorthy K, Surya V J Y, Devaraju M K and Kim S -J 2018 Observation of anomalous transport characteristics in graphene-oxide thin film Mater. Chem. Phys. 213 89–94

Amin G, Hussain I, Zaman S, Bano N, Nur O and Willander M 2010 Phys. Status Solidi A 207 748

Dacuña J, Xie W and Salleo A 2012 Estimation of the spatial distribution of traps using space-charge-limited current measurements in an organic single crystal Phys. Rev. B 86 115202

Walther S, Polster S, Jank M P M, Thiem H, Ryssel H and Frey L 2011 Tuning of charge carrier density of ZnO nanoparticle films by oxygen plasma treatment Adv. Powder Technol. 22 253–6

Dutta G K, Kasthuri S, Marappan G, Jayaraman S V, Sivalingam Y, Natale C D and Nutralapati V 2019 Aggregation behavior in naphthalene- appended diketopyrrolopyrrole derivatives and its gas adsorption impact on surface potential J. Mater. Chem. C 7 9954–65

Kalidoss R, Umapathy S, Anandan R, Ganesh V and Sivalingam Y 2019 Comparative study on the preparation and gas sensing properties of reduced graphene oxide/SnO2 binary nanocomposite for detection of acetone in exhaled breath Anal. Chem. 91 5116–24

Chidambaram D, Vattikondala G, Marappan G and Sivalingam Y 2019 Indium content dependent VOCs interactions in monolithic InGaN/GaN multi quantum well structures grown by MOCVD Mater. Sci. Semicond. Process. 104 104694

Elakia M, Gobinath M, Sivalingam Y, Palani E, Ghosh S, Nutralapati V and Surya V J 2020 Investigation on visible light assisted gas sensing ability of multi-walled carbon nanotubes coated with pyrene based organic molecules Physica E 124 114232

Davis D, Marappan G, Sivalingam Y, Panigrahi B B and Singh S 2020 Tribological behavior of NiMoAl-based self-lubricating composites ACS Omega 5 14669–78