Low-Intensity UV light sensor based on p-NiO/n-Si heterojunction

Naif H Al-Hardan, Naser M Ahmed, Munirah A Almessiere and Azlan Abdul Aziz

1 School of Physics, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia
2 Department of Physics, College of Science, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia
3 Department of Nano-Medicine Research, Institute for Research & Medical Consultations (IRMC), Imam Abdulrahman Bin Faisal University, PO Box 1982, 31441 Dammam, Saudi Arabia

E-mail: n.h.alhardan@gmail.com

Keywords: NiO thin film, oxidation process, p-n junction, UV photodetectors

Abstract
We studied the performance of a photodiode UV sensor based on a p-NiO/n-Si heterojunction. NiO thin film was prepared via a two-step process. In the first step, a thin film of Ni metal was evaporated on an n-Si substrate. Subsequently, the sample was thermally oxidized at 500 °C for 3 h in an ambient atmosphere. The phases and surface morphology of the prepared sample was determined by using x-ray diffraction analysis and scanning electron microscopy, respectively. The rectifying ratio of the prepared device was approximately 7 at a bias voltage of ±10 V, with a barrier height and ideality factor of 0.77 ± 0.03 eV and 16, respectively. The prepared device was tested for potential applications as a UV sensor. The prepared device exhibits high repeatability and fast response times of 1.5 s and 0.7 s for the rise and full time, respectively. The prepared photodiode responds to low-intensity UV light in the range from 30 μW·cm⁻² to 430 μW·cm⁻².

1. Introduction

Metal oxide semiconductors are considered multifunction materials that have been tested and studied in detail for many applications [1–3]. Among these metal oxides, nickel oxide (NiO) has drawn the attention of several research groups. With an energy bandgap 3.6–4.0 eV at room temperature [1] and p-type conductivity, which is due to the non-stoichiometric defects [5], NiO shows promising features in several applications, such as electrochromic devices [6], gas sensors [7], and UV sensors [8]. NiO thin films have been prepared via several methods over different substrates. These methods include spin coating [9], chemical bath deposition [10], RF sputtering [5], thermal evaporation [11], and the oxidation process of Ni thin films [12].

UV light makes up part of the light spectrum. It is characterized by three bands, UV-C (100–280 nm), UV-B (280–320 nm), and UV-A (320–400 nm). UV-A radiation makes up the highest portion (~90%) of UV radiation received by the Earth [13]. The UV light has been used for medical treatment [14], astronomy [15], and other applications [13, 16]. Exposure to UV radiation can cause various diseases, such as skin cancer [17]. Consequently, detecting UV light at different wavelengths and intensities has become a crucial task.

Several groups have studied UV sensors. The p-n junction photodiode UV sensor shows promising features for UV detection [18]. P-n junctions, based on NiO, can be grown on an n-type semiconductor, such as n-GaN (gallium nitride) [10], ZnO [4], and n-type silicon (n-Si) [12]. The latter is a well-known semiconductor because it is considered the backbone of the semiconductor industry [19]. The p-NiO/n-ZnO junction, studied intensively as NiO, can replace the unstable p-type ZnO [4, 20, 21].

UV photodiode sensors, based on the NiO semiconductor, were studied by several groups. Tsai et al [4] reported on the application of the p-n junction based on the NiO/ZnO heterojunction for UV detection. Both materials were prepared via RF sputtering process over a glass substrate, and the leakage current of the prepared device was $6.64 \times 10^{-8}$ A cm⁻². Parida et al [9] fabricated p-NiO/p-Si heterojunction photodetectors by a sol-gel spin coating process. The prepared device shows clear rectifying behavior, with an ideality factor of 3.2 and a barrier height of 0.76 eV. Furthermore, the photoreponsivity value in the UV (385 nm) was calculated to be 156.3 μA W⁻¹. Yu et al [10] reported the fabrication of NiO nanosheets over an n-GaN substrate by the chemical
bath deposition method. The prepared device shows a photoresponsivity of \( \sim 0.5 \text{ mA W}^{-1} \) (at a UV wavelength of 365 nm) without applying a bias voltage. This implies that the prepared \( p-n \) junction is considered to be a self-powering device. A heterojunction diode for UV detection, based on \( p\)-NiO/\( n\)-Si, was prepared by Zhang et al [12]. The NiO was prepared via low-temperature thermal oxidation of Ni thin film, with the backup of UV radiation. A photoresponsivity of 0.815 A W\(^{-1}\) at \(-2\) V was calculated with the illumination of UV light.

In this study, we prepared NiO thin films through a two-step process. Initially, Ni metal thin films were thermally evaporated on an \( n\)-type Si as a substrate, and then, thermal oxidation was employed to convert the Ni thin film to NiO thin film. The performance of the prepared \( p-n \) junction for low-intensity UV light was also explored. The prepared device demonstrate good detection for low power UV lights down to 30 \( \mu \text{W cm}^{-2}\).

### 2. Experimental details

The manufacturing NiO thin films were prepared through a two-step process. Prior to the process, an \( n\)-type silicon wafer (\( n\)-Si with resistivity \( 1-10 \Omega \text{ cm} \) and orientation (1 0 0)) was used as a substrate. The wafer was cut into pieces of dimension 1.5 \( \times \) 1 cm\(^2\) and underwent a cleaning process. The Si samples were ultrasonically cleaned with acetone, ethanol, and deionized water. Then, the substrates were dipped into a buffered oxide etchant (HF: \( \text{H}_2\text{O}_2 = 1:5\) for 15 s, to etch any native oxide layer on the Si. Ni metal was thermally evaporated in a high-vacuum Edwards 306 unit. The ultimate vacuum of the system reached 1 \( \times \) \( 10^{-2} \) mbar, after which, the evaporation process of the Ni metal chunks began, using a tungsten boat. The prepared samples were thermally oxidized in a cylinder controllable furnace at 500 \( ^\circ\text{C} \) and at ambient atmosphere. The duration of the oxidation process was 3 h, and the samples were converted from a metallic looking thin film to a transparent thin film.

Silver was coated by thermal evaporation for electrical contacts on both sides of the device. Subsequently, the prepared device was heat-treated at 300 \( ^\circ\text{C} \) for 10 min in a high-purity nitrogen atmosphere. The area of the front contact was approximately 4 mm\(^2\). The prepared samples of NiO over \( n\)-type Si substrates underwent a structure identification phase by employing the Panalytical X’pert-Pro x-ray diffractometer (Malvern Panalytical technologies), while the morphology of the NiO surface was examined by employing the ZEISS SUPRA 50 VP (Carl Zeiss AG) field emission scanning electron microscope (FE-SEM).

The prepared \( p-n \) junction based on NiO over the Si substrate was electrically characterized by current-voltage measurements (\( I-V \)), employing the Keithley 2400 source meter unit (Tektronix, Inc.). The measurements were performed under dark and ambient light conditions, and UV illumination, by sweeping the bias voltage in the range of \( \pm 10 \) V. Furthermore, the capacitance-voltage (\( C-V \)) characteristics of the prepared diode were determined using the Agilent 4294 A Precision Impedance Analyzer (Keysight Technologies Inc.). The UV sensing performance of the prepared device was obtained by using the Nichia UV light-emitting diode (LED) at a wavelength of 365 nm and a power of 5.4 mW (Nichia Corporation- Japan).

### 3. Results and discussion

#### 3.1. The phase structure

The \( p-n \) junction device based on \( p\)-NiO/\( n\)-Si was prepared via a two-step process. In the first step, metal Ni was evaporated under high vacuum conditions. Subsequently, the Ni thin film underwent thermal oxidation at 500 \( ^\circ\text{C} \) for 3 h. The produced thin film of the NiO was converted from a metallic appearance to a transparent light brownish appearance, with a thickness of approximately 180 nm, as measured by the Filmetrics F20 optical reflectometer.

Figure 1 depicts the x-ray pattern of the thermally oxidized NiO over the Si substrate. The pattern shows the polycrystalline nature of the prepared NiO film. The Bragg angles of the diffraction pattern appear at 37.44\(^\circ\) and 43.34\(^\circ\), which can be indexed to the (111) and (200) phase of the rhombohedral NiO (ICDD PDF 022-1189). The pattern also reveals that the produced NiO was fully converted through the oxidation process, as no other diffraction peaks are observed, except those belonging to the NiO structure and Si substrate.

The SEM micrograph image is as shown in figure 2. The image reveals a homogeneous distribution of nano-sized structures.

#### 3.2. \( p-n \) junction performance

The \( I-V \) characterization of the prepared \( p-n \) junction under dark conditions and ambient light can be seen in figure 3. The graph clearly shows the rectifying behavior of the prepared junction, and the graph also shows the effect of the light for dark, ambient, and UV conditions (365 nm) (graph 2(a) and 2(b) are linear and semi-log, respectively).
The I-V behavior under ambient light with a reverse bias shows an increase in the photocurrent at the reverse bias voltage range from $-3$ to $-8$ V. A significant increase in the photocurrent is notable under the exposure of UV light at the same reverse bias voltage.

From the graph, the barrier height and ideality factor can be estimated by applying the Schottky-Mott formula [22]:

$$I = I_s(e^{\frac{\phi}{kT}} - 1)$$

where $I_s$ is the saturation current, $T$ is the absolute temperature, $k$ is the Boltzmann’s constant and $q$ is the electron charge. $I_s$ is estimated at the bias value $V = 0$ V.

$$I_s = A A^* T^* e^{\frac{\phi}{kT}}$$

where $\phi$ is the Schottky barrier height, $A$ is the surface area of the contact (1.3 cm$^2$), and $A^*$ is the effective Richardson constant, equal to 112 A·cm$^{-2}$·K$^{-2}$ for the $n$-type Si [5]. The ideality factor $n$ can be found by applying the formula

$$n = \frac{q}{kT} \frac{dV}{d(Ln(I))}$$

The results of the diode parameters extracted from the current measurements show that $\phi$, $I_s$, and $n$ are $0.77 \pm 0.03$ eV, 40 nA, and 16, respectively. The results in this study is comparable with the results published before [5, 9, 23–27]. The high ideality factor implies that an ideal junction was not formed [9], which might be

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{x-ray_pattern.png}
\caption{The X-ray pattern of the prepared NiO thin film over n-type Si substrate.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{sem_image.png}
\caption{The SEM image of the prepared NiO thin film over n-type Si substrate with magnification of 100,000x.}
\end{figure}
due to various effects, such as high-series resistance, barrier inhomogeneity, tunneling processes, or non-uniform carrier distribution in the interfaces \[25\]. Furthermore, the \(C-V\) characteristics of the prepared device was studied, and the results are depicted in figure 4. The measurements were conducted at a bias voltage of \(-0.5\) to \(2\) V, with \(100\)-kHz signal frequency and amplitude of \(50\) mV. The constant values of the \(p-n\) junction capacitance at the reverse bias suggest that the NiO film is fully depleted \[28\]. Furthermore, the linear behavior of the capacitance implies that the carriers are homogeneously distributed within the depletion layer \[29\].

The graph also reveals the \(C^2-V\) relationship where the build-in voltage (diffusion voltage) can be estimated with the carrier concentration by applying the formula \[30\]

\[
\frac{1}{C^2} = \frac{2(N_D\varepsilon_1 + N_A\varepsilon_2)(V_b - V)}{A^2qN_DN_A\varepsilon_1\varepsilon_2}
\]

where \(N_D\) and \(N_A\) are the donor densities in the \(n\)-Si and the acceptor density in the \(p\)-NiO, respectively, and \(\varepsilon_1\) and \(\varepsilon_2\) are the dielectric constants of the Si and NiO, respectively. The applied bias voltage is denoted by \(V\), where \(V_b\) is the built-in potential.

From the slope of the graph, it can be concluded that the carrier concentration was approximately \(5 \times 10^{18} \text{ cm}^{-3}\), and the build-in voltage was \(0.5\) eV.

Figure 3. The I-V characterization of the prepared \(p-n\) junction under the conditions of dark, ambient, and \(365\)-nm UV light, (a) linear presentation and (b) semi-log graph.
3.3. UV detection performance

The prepared p-n junction based on p-NiO/n-Si was tested for UV sensing application. The photo-transient current of the UV response to the 365-nm light is revealed in figure 5. The graph reveals the highly repeatability of the photocurrent under the influence of the UV light at reverse bias of −5 V. The frequency of the UV light was controlled through a function generator. Furthermore, the photocurrent rapidly increased once the device was exposed to the UV light and stabilized with almost constant values during the UV exposure. The decay of the photocurrent was very fast once the UV light was turned off.

To compare sensors, several characteristics need to be addressed such as the responsivity (R) and the response time of the sensor. The responsivity is calculated from

\[ R \left( \frac{A}{W} \right) = \frac{I_{ph}}{P_{\lambda}} \]  

where \( I_{ph} \) is the photocurrent (I_{illuminated}−I_{dark}), and \( P_{\lambda} \) is the incident UV light power at 365 nm, as measured by an optical power meter. The responsivity of the prepared photodiode was 160 mA·W⁻¹, and the rise time and the full time was approximately 1.5 s and 0.7 s (See figure 6), respectively.

The result of the responsivity of the prepared device is comparable with most published studies. Furthermore, the results obtained in this study are close to those of the commercially available UV sensors, with a responsivity of 0.1–0.2 A W⁻¹ [31, 32]. The photocurrent output of the prepared device shows a linear
dependence on the reverse bias voltage from 3 V to 7 V, as can be seen in figure 7. The photocurrent originates from the carriers generated in the depletion region. As the reverse bias voltage increases, the width of the depletion region increases, and consequently, the photocurrent under the effect of UV light will be enhanced [12].

The effect of different UV light intensities was also studied. The UV light intensity was controlled by changing the distance between the UV source and the prepared device, and the intensity of the UV light was measured via an optical power meter. Figure 8 reveals the repeatability of the measured photocurrent with different UV light intensity. The figure implies that the prepared p-n junction can be used to detect different UV intensities with high repeatability.

A straight line can be observed in figure 9, which reveals the dependence of the logarithm of the photocurrent versus the logarithm of the UV light intensity, which can be modeled by the formula [33].

\[ I_{ph} = bP^m \]  

(6)

where \( I_{ph} \) is the photocurrent, \( b \) is a constant, and \( m \) is the linearity ratio between intensity \( P \) and \( I_{ph} \).

The power value \( m \), with a non-unity exponent, is a result of the complex process of electron-hole generation, trapping, and recombination within the semiconductor [34].
From figure 9, a linear relation can be seen with $b = 7.1$ and $m = 0.3$. The obtained value of $m$ was lower than that published for most of the semiconductor-based UV sensors. However, according to Luo et al [35] and Zhang et al [36], the lower values of $m$ are attributed to the carrier traps within the energy gap. We believe that the origin of these traps might be due to the Ni diffusion in the Si substrate during the oxidation process of Ni [12].

The results obtained in this study reveal that the prepared UV photodiode has the ability to detect low UV intensity in the range $30 \mu W \cdot cm^{-2}$ to $431 \mu W \cdot cm^{-2}$. Choi and Im [37] reported on the UV-visible photodiode based on p-NiO/n-Si junction, using a UV light source of wavelength 290 nm and power density of 1 mW cm$^{-2}$, their results revealed that the responsivity at 290 nm was 0.15 A W$^{-1}$ and 0.17 A W$^{-1}$ at bias voltage of 0 and 30 V, respectively. A higher responsivity of 0.815 A W$^{-1}$ was reported by Zhang et al [12] for p-NiO/n-Si junction for an incident UV wavelength of 436 nm and power of 0.13 mW cm$^{-2}$.

Given the results obtained in this study, it was demonstrated that the prepared p-n junction can be employed as a UV light sensor at low UV light intensities. The mechanism of UV light detection can be proposed for this purpose. The UV sensing behavior of the prepared p-NiO/n-Si heterojunctions can be explained using the Anderson model [38]. It was reported that the bandgap for NiO and Si is 3.5 eV and 1.1 eV, respectively, and the electron affinities of NiO and n-type Si were reported to be 1.4 eV and 4.29 eV, respectively [16, 39–42]. The discontinuity in the valance band ($\Delta E_{v} = (\chi_{Si} + E_{gSi}) - (\chi_{NiO} + E_{gNiO}) = (4.05 + 1.1 eV) - (3.5 eV - 1.47 eV) = 0.18 eV$) [10] was smaller than the discontinuity of the conduction band ($\Delta E_{c} = \chi_{Si} - \chi_{NiO} = 2.58 eV$). This lower value will result in easy
movement of the holes to the n-Si under forward bias. As a result, a forward current will flow. The barrier from the conduction offset to the flow of electrons from the n-Si to the p-NiO was high (2.58 eV). Therefore, the current was small under the reverse bias.

Under ambient conditions, the oxygen from the environment will adsorb onto the surface of NiO and capture the electrons from its surface. As a consequence, a depleted layer will be formed near the NiO/Si interface [30, 43];

\[ \text{O}_2(\text{g}) + e^- \rightarrow \text{O}_2^- \]  

(7)

in the presence of UV illumination, with higher energy than the bandgap of the sensing layer where the photons are absorbed in the NiO layer, consequently, a pair of electron-holes are generated (\( h\nu \rightarrow e^- + h^+ \)). The photogenerated pairs are diffused into the built-in electric field, where the electron–holes will be drifted to the positive and negative electrodes of NiO and Si. The holes will migrate to the surface of the Si along the potential gradient. As a result, it will discharge the negatively charged adsorbed oxygen ions

\[ \text{O}_2^- + h^+ \rightarrow \text{O}_2(\text{g}) \]  

(8)

Consequently, the negatively charged oxygen ions are desorbed from the surface, resulting in an increase in the free carrier concentration and a decrease in the width of the depletion layer. This leads to an increase in the carrier injection and the flow of the producing photocurrent [30, 43]. Furthermore, an increase in the UV light intensity will cause an increase in the carrier concentration, which will increase the photocurrent.

Furthermore, the effect of the blinking time of the UV LED on the response of the photodiode based on NiO/Si was studied. The frequency was changed so that the UV LED cycles through ON-OFF in 60 s, 13 s, and 3 s. The photocurrent response is depicted in figure 10. The figure reveals the high response of the prepared sensors to the timing duration of the UV LED, and a clear response can be noticed, even for a low ON-OFF cycle duration of 3 s. The timing behaviour of UV depends on several parameters; one of the most important parameters is the distance between the electrodes as can been seen in several published works [44, 45]. For the present case, we can probably improve the UV sensing behaviour of the present junction by using an interdigital electrode type.

4. Conclusions

In summary, we report on the fabrication of UV photodiode based on the p-NiO/n-Si heterojunction. The NiO thin film was prepared via a two-step process. The XRD pattern reveals the polycrystalline nature of the prepared thin film. Furthermore, the I-V and the C-V characterization of the prepared device reveals the formation of the p-n junction, and the device under different UV intensities proves that the device can be applied for UV detection.
Acknowledgments

The authors would like to thank the School of Physics at USM for supporting this research and providing the appropriate research environment. Our gratitude also goes to the RCMO-USM, for supporting us with the bridging grant (304.PFIZIK.6316276).

ORCID iDs

Naif H Al-Hardan https://orcid.org/0000-0001-7309-9660

References

[1] Hosono H 2006 Ionic amorphous oxide semiconductors: Material design, carrier transport, and device application J. Non-Cryst. Solids 352 851–8
[2] Kamiya T and Hosono H 2010 Material characteristics and applications of transparent amorphous oxide semiconductors NPG Asia Mater. 2 15
[3] Rim S Y, Chen H, Zhu B, Bae S-H, Zhu S, Li P J, Wang I C and Yang Y 2017 Interface engineering of metal oxide semiconductors for biosensing applications Advanced Materials Interfaces 4 1700020
[4] Tsai S-Y, Hon M-H and Lu Y-M 2011 Fabrication of transparent p-NiO/n-ZnO heterojunction devices for ultraviolet photodetectors Solid-State Electronics 63 37–41
[5] Grilli M L, Aydogan S and Yilmaz M 2016 A study on non-stoichiometric p-NiOx/n-Si heterojunction diode fabricated by RF sputtering: Determination of diode parameters Superlattices Microstruct. 100 924–33
[6] Atak G and Coşkun O D 2017 Annealing effects of NiO thin films for all-solid-state electrochromic devices Solid State Ionics 305 43–51
[7] Strässler S and Reis A 1983 Simple models for N-type metal oxide gas sensors Sensors Actuators 4 465–72
[8] Ahmed A A, Devarajan M and Afzal N 2017 Fabrication and characterization of high performance MSM UV photodetector based on NiO film Sens. Actuators, A 262 78–86
[9] Parida B, Kim S, Oh M, Jung S, Baek M, Ryou J-H and Kim H 2017 Nanostructured-NiO/Si heterojunction photodetector Mater. Sci. Semicond. Process. 71 29–34
[10] Yu N, Li H and Qi Y 2019 NiO nanosheet/GaN heterojunction self-powered ultraviolet photodetector grown by a solution method Opt. Mater. Express 9 26–34
[11] Pereira S, Gonçalves A, Correia N, Pinto J, Pereira L, Martins R and Fortunato E 2014 Electrochromic behavior of NiO thin films deposited by e-beam evaporation at room temperature Sol. Energy Mater. Sol. Cells 120 109–15
[12] Zhang D, Nozaki S and Uchida K 2014 NiO/Si heterostructures formed by UV oxidation of nickel deposited on Si substrates Journal of Vacuum Science & Technology B 32 031202
[13] Sciuto A, Mazzillo M C, Franco S D, Mannino G, Badalà P, Renna L and Caruso C 2017 UV-A Sensor Based on 6H-SiC Schottky Photodiode IEEE Photonics J. 9 1–10
[14] Westerhof W and Nieuweboer-Krotoleva L 1997 Treatment of vitiligo with uv-b radiation vs topical psoralen plus uv-a Archives of Dermatology 133 1525–8
[15] Wilson R and Boksenberg A 1969 Ultraviolet astronomy Annu. Rev. Astron. Astrophys. 7 411–22
[16] Al-Hardan N H, Abdul Abdul Hamid M A, Ahmed N M, Shamsudin R and Othman N K 2016 Ag film Schottky diode and p-Si heterojunction prepared by DC magnetron sputtering Superlattices Microstruct. 37 68–76
[17] Kim S, Jang H, Lee J, Cho C W, Litton C W and Othman N K 2016 Activating effect of Ag deposited on p-Si heterojunction photodiode J. Alloys Compd. 660 8–14
[18] Jung S, Kim Y and Kim H 2017 Interface engineering of metal oxide semiconductors for biosensing applications Sensors Actuators B 267 42–47
[19] Gupta R K, Ghosh K and Kohal P K 2010 Temperature dependence of current–voltage characteristics of gold–stannite titanate thin film Schottky diode Physica E 42 1509–12
[20] Bo H et al 2009 Characterization of AZO/p-Si/Al heterojunction photodetector based by DC magnetron sputtering Mater. Sci. Semicond. Process. 12 248–52
[21] Jin J, Zhang J, Shaw A, Kudina V N, Mitrovic I Z, Wrench J S, Chalker P R, Balocco C, Song A and Hall S 2018 A high speed PE-ALD ZnO Schottky diode rectifier with low interface-stable density J. Phys.: D: Appl. Phys. 51 065102
[22] Rhoderick E H 1972 Comments on the conduction mechanism in Schottky diodes J. Phys.: D: Appl. Phys. 5 1920–9
[23] Al-Hardan N H, Jalar A, Abdul Hamid M A, Keng I K, Ahmed N M and Shamsudin R 2014 A wide-band UV photodiode based on n-ZnO/p-Si heterojunctions Sensors Actuators, A 207 61–6
[24] Zahedi F, Dariani R S and Rozati S M 2013 Ultraviolet photoreponse properties of ZnO:N/p-Si and ZnO/p-Si heterojunctions Sensors Actuators, A 199 123–8
[25] Olha H, Kamiya M, Kamiya T, Hirano M and Hosono H 2003 UV-detector based on pn-heterojunction diode composed of transparent oxide semiconductors, p-NiO/n-ZnO Thin Solid Films 445 317–21
[33] Khusayfan N M 2016 Electrical and photoresponse properties of Al/graphene oxide doped NiO nanocomposite/p-Si/Al photodiodes J. Alloys Compd. 666 501–6
[34] Kind H, Yan H Q, Messer B, Law M and Yang P D 2002 Nanowire ultraviolet photodetectors and optical switches Adv. Mater. 14 158–60
[35] Luo L B, Jie J S, Chen Z H, Zhang X J, Fan X, Yuan G D, He Z B, Zhang W F, Zhang W J and Lee S T 2009 Photoconductive properties of selenium nanowire photodetectors J. Nanosci. Nanotechnol. 9 6292–8
[36] Zhang X, Jie J, Zhang W, Zhang C, Luo L, He Z, Zhang X, Zhang W, Lee C and Lee S 2008 Photoconductivity of a single small-molecule organic nanowire Adv. Mater. 20 2427–32
[37] Choi J-M and Im S 2005 Ultraviolet enhanced Si-photodetector using p-NiO films Appl. Surf. Sci. 244 435–8
[38] Sze S M and Ng K K 2006 Physics of Semiconductor Devices (New York: Wiley Inc.)
[39] Koffyberg F P and Benko F A 1981 P-type NiO as a photoelectrolysis cathode J. Electrochem. Soc. 128 2476–9
[40] Ho J-K, Jong C-S, Chiu C C, Huang C-N, Shih K-K, Chen L-C, Chen F-R and Kai J-J 1999 Low-resistance ohmic contacts to p-type GaN achieved by the oxidation of Ni/Au films J. Appl. Phys. 86 4491–7
[41] Tao M, Agarwal S, Udeshi D, Basit N, Maldonado E and Kirk W P 2003 Low Schottky barriers on n-type silicon (001) Appl. Phys. Lett. 83 2593–5
[42] Abbasi M A, Ibpupoto Z H, Khan A, Nur O and Willander M 2013 Fabrication of UV photo-detector based on coral reeflike p-NiO/n-ZnO nanocomposite structures Mater. Lett. 108 149–52
[43] Echresh A, Chey C O, Zargar Shoushtari M, Khranovskyy V, Nur O and Willander M 2015 UV photo-detector based on p-NiO thin film/n-ZnO nanorods heterojunction prepared by a simple process J. Alloys Compd. 632 165–71
[44] Gu X, Zhang M, Meng F, Zhang X, Chen Y and Ruan S 2014 Influences of different interdigital spacing on the performance of UV photodetectors based on ZnO nanofibers Appl. Surf. Sci. 307 20–3
[45] Hullavarad S S, Hullavarad N V, Karulkar P C, Luykx A and Valdivia P 2007 Ultra violet sensors based on nanostructured ZnO spheres in network of nanowires: a novel approach Nanoscale Res. Lett. 2 161–7