UV Photodetector Based on p-NiO film/n-Si Heterojunction Prepared by Thermal Oxidation

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Abstract. In this work, p-type NiO film was grown on n-type Si substrate as UV photodetector. NiO film was prepared over n-type Si (100) through two-step method. First, metallic Ni film was deposited on Si wafer using thermal evaporator; then the film was thermally oxidized in a tube furnace at 500 \(^\circ\)C for 3 h to get NiO film. The film revealed polycrystalline structure of cubic NiO phase as confirmed from XRD characterization. The diffraction peaks ascribed to metallic Ni film were not detected in the XRD pattern which implies that Ni film was completely converted into NiO. For photoelectric measurements of NiO/Si heterojunction, Ag metal was deposited on both Si substrate and NiO film as a contact. The current-voltage curves exhibited rectifying behaviour with ideality factor and barrier height of 25 and 0.96 eV, respectively. NiO/Si heterojunction showed appreciable photoresponse towards UV light at wavelength of 365 nm. The responsivity, rise time and fall time of the photodiode were measured as 0.16 A/W, 1.7 s and 0.85 s, respectively at bias voltage of -5 V.

1. Introduction
Nickel oxide is a transition metal oxide semiconductor with p-type electrical conductivity. It has drawn researchers’ attention owing to its attractive properties which include high optical transparency in the visible light, wide energy band gap and desirable electrical properties [1]. Due to its potential properties, it has been utilized in solar cells, and different kind of sensors and photodetectors [2-4]. Recently, UV photodetectors are of a great interest in the research field owing to their potential applications in, military, solar UV radiation monitoring, and environmental observation [5-8]. The survey of the literature reported that NiO film was combined with other n-type semiconductors for UV light detection. Long and co-workers [9] designed UV photodiode by depositing p-NiO over n-ZnO thin film. The photodiode was tested towards UV light having wavelength of 365 nm. The applied voltage was fixed at -5 V. The photoresponsivity, rise time and decay time were measured as 2.2mA/W, 20 s and 30 s, respectively. Choi et al. [10] prepared p-NiO/n-Si photodiode using thermal evaporation. The photodiode showed photoresponsivity of ~ 0. 17 A/W at -5 V upon exposure to 350 nm light. Zhang et al. [11] studied the photoelectric characteristics of p-NiO/n-Si heterojunction prepared using hydrothermal method. The photodiode unveiled appreciable sensitivity and it was calculated as 938%. The response time was recorded as 30 ms under 350 nm light illumination. In this work, we investigate the UV photodetection performance of p-NiO/n-Si heterojunction prepared using two-step method. First, metallic Ni film was thermally evaporated over Si substrate, then it was thermally oxidized into
NiO film through annealing in atmospheric air. The photoelectric characteristics which are responsivity, rise time and fall time were investigated and reported.

2. Experimental Procedure
To fabricate p-NiO film/n-Si heterojunction, n-type Si (100) was used as a substrate. Prior to deposition, the substrate was cleaned according to the well-known RCA cleaning method. After that, the sample was fixed on the substrate holder and uploaded into thermal evaporator (Edwards 306 unit). NiO film was deposited in two-step method. First, nickel (Ni) granules were thermally evaporated over Si substrate in vacuum chamber at low pressure of $1 \times 10^{-5}$ mbar. Thereafter, the metallic Ni film was thermally oxidized in a tube furnace at 500 °C in ambient atmosphere for 3 h. The phase identification of the grown film was investigated through X-ray diffractometer (Panalytical X'pert pro unit equipped with Cu Kα radiation tube ($\lambda=1.5406$)). The surface morphology of the film was characterized via field emission scanning electron microscopy (ZEISS SUPRA 50 VP (Carl Zeiss AG)).

Figure 1 shows the schematic illustration of the photodiode under light exposure. Ag metal was deposited on NiO film and Si as a contact to investigate the photodetection characteristics. The current-voltage (I-V) characteristics of the p-n junction was recorded under bias voltage changing from -10 to 10 V using Keithley 2400 source meter apparatus. Light emitting-diode (LED) with light intensity and wavelength of 5.4 mW/cm² and 365 nm, respectively, was used as source of UV light.

![Schematic diagram of p-NiO/n-Si photodiode under UV light exposure.](image)

3. Results and Discussion
3.1. Phase Identification and Surface Morphology Analysis
Figure 2a displays XRD pattern of NiO film grown on silicon using thermal oxidation of Ni metal film. As shown from the figure, the film revealed polycrystalline nature with face centered cubic structure of NiO phase according to Joint Committee of Powder Diffraction Standard (JCPDS) card no 047-1049. The diffraction peaks of the film are located at 37.35° and 43.33° which are assigned to (111) and (200) growth direction of NiO film, respectively. The diffraction peaks are found to be slightly higher as compared to that of unstrained NiO whose 20 angle values are 37.24° and 43.27°, respectively. The shift towards higher angle implies that the prepared film experiences compressive strain [12]. In addition, it is noteworthy to notice that there are no diffraction peaks of metallic Ni detected in the XRD pattern, indicating that as deposited Ni film was completely oxidized into NiO. Figure 2b represents the surface
morphism of the film at magnification of 50 kx. The FESEM image shows that the surface consists of compact and agglomerated grains that are uniformly distributed over silicon wafer.

![XRD pattern of NiO film grown on Si substrate](image1)

![Surface morphology of NiO film on Si substrate](image2)

**Figure 2.** (a) XRD pattern of NiO film grown on Si substrate (b) Surface morphology of NiO film on Si substrate.

3.2. *I-V Characteristic of p-NiO Film/n-Si Heterojunction*

The current-voltage (I-V) characteristic of p-NiO/n-Si photodiode under dark condition is displayed in Figure 3. As can be noticed from the figure, the I-V curves exhibit rectifying behaviour. Thermionic emission model theory can be utilized to describe the I-V curves of the p-NiO/n-Si heterojunction [13]. The current as a function of the applied voltage can be expressed as:

\[
I = I_0 (e^{\frac{qV}{nkT}} - 1)
\]

here, \(I_0\) is the saturation current, \(q\) is the charge of electron, \(V\) is the applied voltage, \(n\) is the ideality factor, \(k\) is the Boltzmann constant and \(T\) is the absolute temperature. The saturation current and the ideality factor were calculated by taking the logarithm of equation (1) which yields

\[
\ln I = \ln I_0 + \frac{qV}{nkT}
\]

The intercept of \(\ln I\) with y-axis at \(V=0\) gives the saturation current, whereas the slope gives the ideality factor of the heterojunction. The saturation current and the ideality factor of the p-NiO/n-Si heterojunction was calculated as 4.63 nA and 25, respectively. The high value of the ideality factor indicates that the p-n junction was not ideally formed which can be attributed to non-uniformity at metal-semiconductor interface, high series resistance and interface states [13, 14]. In addition, the barrier height ‘\(\phi_b\)’ was estimated by substituting \(I_0\) value in equation (3).

\[
\phi_b = \frac{kT}{q} \ln \left( \frac{AA^*T^2}{I_0} \right)
\]
where, $A$ and $A^*$ are the contact area and the effective Richardson constant of n-type silicon, whose values are $1.3 \text{ cm}^2$ and $112 \text{ A/(cm}^2 \cdot \text{K}^2)$, respectively [15]. The barrier height of the diode was calculated as $0.96 \text{ eV}$.

![Figure 3. I-V characteristic of p-NiO/n-Si photodiode under dark condition.](image)

3.3. Photoelectric Performance of p-NiO/n-Si Heterojunction

Figure 4 shows I-V characteristics of p-NiO/n-Si heterojunction in the dark and under UV light irradiation with wavelength of 365 nm at light intensity of $5.4 \text{ mW/cm}^2$. As can be seen from the figure, the current of the photodiode when the light is switched off is identical to the dark current in the forward bias; this suggests that in the forward bias the depletion region is very small and it decreases further with the increase of the applied voltage giving rise to neglected contribution of photocurrent as compared to the dark current (current of majority carriers). However, when the diode is reversely biased, the dark current in this case is a current of minority carriers (holes in Si substrate and electrons in NiO films). Therefore, with increasing the reverse bias voltage, the depletion layer extends, leading to a noticeable increase in the current when the photodetector is illuminated with UV light.
The repeatability and photoresponse speed are two important factors that must be investigated for any photodiode. These two factors were evaluated through recording the current of the photodiode over time while it was illuminated with 365 nm UV light in form of pluses as shown in Figure 5a. The photodetection measurements were carried out at bias of -5 V. It is clearly seen that the current of photodiode showed excellent repeatability over time upon exposure to the dark and UV light alternately. Moreover, the photodiode revealed rapid increase (decrease) in the current once the UV light was switched ON (OFF), implying that the photodiode exhibits appreciable rise and fall time. The rise time ($\tau_r$) and fall time ($\tau_f$) of the photodiode were estimated by magnifying the rise and decay edges of the current as depicted in Figure 5b-c. The rise time and fall time were evaluated by measuring the time required for the current to rise/drop from 10%/90% to 90/10% from its peak value when the UV light was turned ON/OFF, respectively. The rise time and fall time were estimated to be 1.7 s and 0.85 s, respectively. Furthermore, the photoresponsivity is another key parameter of photodiodes. The photoresponsivity is given by [16];

$$R = \frac{I_{ph}}{AP_{\lambda}}$$

(4)

here, $I_{ph}$ is the photocurrent and defined as the difference between the current under light irradiation and the current under dark condition (dark current). ‘A’ is the irradiated area with UV and ‘$P_{\lambda}$’ is the UV light intensity of the LED. The photoresponsivity of the photodiode was calculated as 0.16 A/W.
4. Conclusion

p-NiO film was successfully deposited over n-type silicon (100) using two-step method. In the first step, Ni metal film was thermally evaporated on Si substrate using thermal evaporator. In the second step, Ni film was thermally oxidized into NiO film through annealing process at 500 °C in atmospheric air for 3h. UV photodiode based on p-NiO film/n-Si was prepared by depositing Ag metal contact on Si substrate and on NiO film by thermal evaporator. The photodetection performance of the photodiode was measured under UV light illumination with wavelength of 365 nm. The photoresponsivity, rise time and fall time were calculated as 0.160 A/W, 1.7 s and 0.85 s, respectively. The photodetection measurements revealed that p-NiO film/n-Si heterojunction is a promising candidate to be utilized in UV light detection application.
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References
[1] Wang N, Liu C Q, Wen B, Wang H L, Liu S M and Chai W P 2014 Enhanced optical and electrical properties of NiO thin films prepared by rapid radiation pyrolysis method based on the sol–gel technique Mater. Lett 122 269-72
[2] Kim H S, Jeong E P, Malkeshkumar P, Hyunki K, Dae S K, Sung K B, Donggun L and Joondong K 2016 Optically transparent and electrically conductive NiO window layer for Si solar cells Mater. Lett. 174 10-3
[3] Hotovy I, Huran J, Spiess L, Hascik S and Rehacek V 1999 Preparation of nickel oxide thin films for gas sensors applications Sensor Actuat. B-Chem. 57 147-52
[4] Ahmed A A, Mutharasu D and Naveed A 2017 Fabrication and characterization of high performance MSM UV photodetector based on NiO film Sensor Actuat. A-Phys 262 78-86
[5] Soei C, Zhang A, Xiang B, Dayeh S A, Aplin D P R, Park J, Bao X Y, Lo Y H and Wang D 2007 ZnO nanowire UV photodetectors with high internal gain Nano. Lett. 7 1003-9
[6] Aga Jr R S., Jawhar D, Ueda A, Pan Z, Collins W E, Mu R, Singer K D and Shen J 2007 Enhanced photoresponse in ZnO nanowires decorated with CdTe quantum dot Appl. Phys. Lett. 91 232108
[7] Mendoza F, Vladimír M, Brad R W and Gerardo M 2015 Solar-blind field-emission diamond ultraviolet detector Appl. Phys. Lett. 107 201605
[8] Razeghi M and Antoni R 1996 Semiconductor ultraviolet detectors J. Appl. Phys 79 7433-7473
[9] Long H, Lei A, Songzhan L, Huihui H, Xiaoming M, Haoning W, Zhao C, Yuping L and Guojia F 2014 Photosensitive and temperature-dependent I–V characteristics of p-NiO film/n-ZnO nanorod array heterojunction diode Mater. Sci. Eng. B 184 44-8
[10] Choi J and Seongil I 2005 Ultraviolet enhanced Si-photodetector using p-NiO films Appl. Surf. Sci. 24 435-8
[11] Zhang Y, Tao J, Wenlong Z, Guoqiang G, Qilong R, Kaibing X, Xiaojuan H, Rujia Z and Junqing H 2017 A self-powered broadband photodetector based on an n-Si (111)/p-NiO heterojunction with high photosensitivity and enhanced external quantum efficiency J. Mater. Chem. C 5 12520-8
[12] Gupta V and Abhai M 1996 Influence of postdeposition annealing on the structural and optical properties of sputtered zinc oxide film J. Appl. Phys 80 1063-73
[13] Mahato S, Debalene B, Luis G G, Cristobal V and Joaquim P 2017 Analysis of temperature dependent current-voltage and capacitance-voltage characteristics of an Au/V2O5/n-Si Schottky diode AIP Adv 7 085313
[14] Yıldırım M and Adem K 2018 Characterization of Al/In: ZnO/p-Si photodiodes for various In doped level to ZnO interfacial layers J. Alloys Compd. 768 1064-1075
[15] Luisa G M, 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
[16] Al-Hardan N H, Abdul Hamid M A, Naser M A, Roslinda S and Norinsan K O 2016 Ag/ZnO/p-Si/Ag heterojunction and their optoelectronic characteristics under different UV wavelength illumination Sensor Actuat. A-Phys 242 50-7