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Research Article

Fabrication of Affordable and Sustainable Solar Cells Using NiO/TiO_2 *P-N* Heterojunction

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The need for affordable, clean, efficient, and sustainable solar cells informed this study. Metal oxide TiO_2/NiO heterojunction solar cells were fabricated using the spray pyrolysis technique. The optoelectronic properties of the heterojunction were determined. The fabricated solar cells exhibit a short-circuit current of 16.8 mA, open-circuit voltage of 350 mV, fill factor of 0.39, and conversion efficiency of 2.30% under 100 mW/cm^2 illumination. This study will help advance the course for the development of low-cost, environmentally friendly, and sustainable solar cell materials from metal oxides.

1. Introduction

The need for affordable and sustainable electricity in developing nations has been an issue of concern to all stakeholders. Renewable energy has been identified as a viable solution to ending global electricity problems as its availability exceeds world energy demand [1]. Solar energy is a good source of renewable energy [2]. The hourly solar influx on the surface of the earth surpasses annual human energy needs [3]. Photovoltaic energy has received increasing interest caused by a decrease in module prices in countries like China [4]. Interest in these devices is due to improved reliability, efficiency, and costs in generating electricity [5]. Solar cells of high efficiency have been achieved with inorganic materials [6], but they require expensive materials of high purity and a technique that is energy intensive. There is, therefore, a need to explore ways of manufacturing solar cells that can scale-up to large volumes at low cost.

Metal oxide solar cells offer a good replacement for conventional silicon solar cells. This is because metal oxides are low-cost materials, have flexible optical properties, can be deposited using low-cost techniques, and are simple to scale-up to large volume production. They also display quantum confinement effects in two dimensions [7]. Nanostructured metal oxides are used in a wide range of device applications because of their broad composition and band structures [8–14]. The widely used oxides are ZnO [15], CuO [16], In_2O_3 [17], and TiO_2 [18], to mention but a few. They are widely applied in optoelectronic devices such as humidity sensors [19], photodiodes [20], solar cells [21], and photocatalysts [22].

NiO is a *P*-type semiconductor with a wide bandgap between 3.5 eV and 4.0 eV [23]. The excellent properties of NiO make it a promising material for solar cells [24]. Similarly, TiO_2 is a desirable material for harvesting solar energy because of its optoelectronic properties, high resistance to photocorrosion, affordability, stability in a wide range of pH, and nonpoisonous nature [25]. Various techniques are available for depositing metal oxides [26–31]. Low cost of equipment, ease of control of deposited film structure, and the ability to coat large areas in thin layers with uniform thickness [32–35] influenced the choice of the technique used in this study.

Heterojunctions are known to be the most competitive method of solar cell fabrication on account of being the simplest [36]. A *P-N* junction is created when *P*-type (NiO) and *N*-type (TiO_2) semiconductor materials are placed in contact with one another. A solar cell is basically a *P-N* junction with

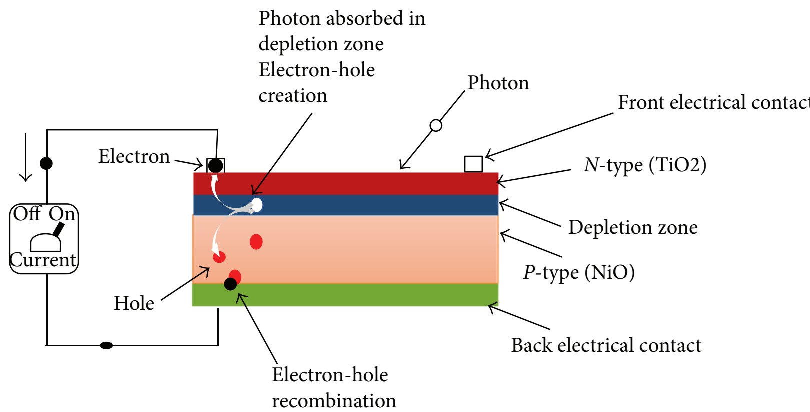

Figure 1: Solar cell generation of electricity using a *P-N* junction.

a large surface area. Figure 1 depicts generation of electricity by a solar cell using a *P-N* junction.

The overall aim of this research is the provision of affordable and sustainable solar panels for developing and low-income countries. This was achieved by fabricating nanostructured TiO_2/NiO heterojunction thin-film solar cells using the spray pyrolysis technique.

2. Methodology

2.1. Deposition. The chemicals used are of analytical reagent grade and were used without further purification. Distilled and deionized pure water were used during the course of the experiment.

The solar cell was fabricated using a modified spray pyrolysis technique (SPT) as reported by Ukoba et al. [37] and represented pictorially in Figure 2. Prior to sample preparation, the indium tin oxide- (ITO-) coated glass and soda lime glass used as substrate were clean ultrasonically as reported by Adeoye Abiodun and Salau [38]. The precursor for the window layer titanium oxide (TiO_2) nanostructure thin film was prepared by mixing 3 ml of titanium ethoxide with 30 ml of distilled water and ethanol mixture, and three droplets of acetic acid. This was stirred for one hour before spraying on cleaned indium tin oxide- (ITO-) coated glass substrates and soda lime glass substrates maintained at about 350°C. Also, deposition parameters such as substrate temperature, carrier gas flow rate, and pressure were optimized to obtain quality films.

The nanostructured nickel oxide (NiO) absorber layer was deposited on the prepared ITO/TiO_2 layers and empty soda lime glass using SPT, as shown in Figure 3. The precursor for NiO was obtained by preparing 0.05 M nickel acetate tetrahydrate in double distilled water.

The precursors were thoroughly stirred for several minutes prior to spraying onto preheated substrates maintained at about 350°C. Other deposition parameters were maintained to obtain good quality thin films. The optimized parameters used in the deposition of the NiO films are tabulated in Table 1. To complete the TiO_2/NiO heterojunction solar cell illustrated in Figure 4, gold (Au) metal contact was deposited as a back contact using DC magnetron sputtering.

Figure 2: Pictorial representation of the experimental set-up of the spray pyrolysis technique.

2.2. Testing. The TiO_2 and NiO prepared on soda lime glass were used to study the elemental, morphological, and structural characteristics of TiO_2 and NiO using energy dispersive X-ray spectrometer (EDS or EDX: "AZtec Oxford Detector"), a ZEISS Ultra Plus field emission gun scanning electron microscope (FEGSEM), and Bruker AXS D8 Advance X-ray diffractometer (XRD) with Cu-Kα radiation, respectively. The *J-V* characteristics of the fabricated TiO_2/NiO heterojunction cell in dark and under illumination were done using the Keithley SourceMeter 2400, coupled with a two-point probe. Newport solar simulator of intensity (100 mW/cm^2) was used as the source of illumination.

3. Results and Discussion

3.1. Morphological Studies. Figures 5(a) and 5(b) show the scanning electron micrograph of the NiO thin film at lower and higher magnification, respectively. The micrograph reveals scattered distribution of the NiO particles across the surface of the film. The film has even distribution, is adherent to the film surface, and has no cracks. This represents a better surface morphology compared to that of NiO films reported by Sriram and Thayumanavan

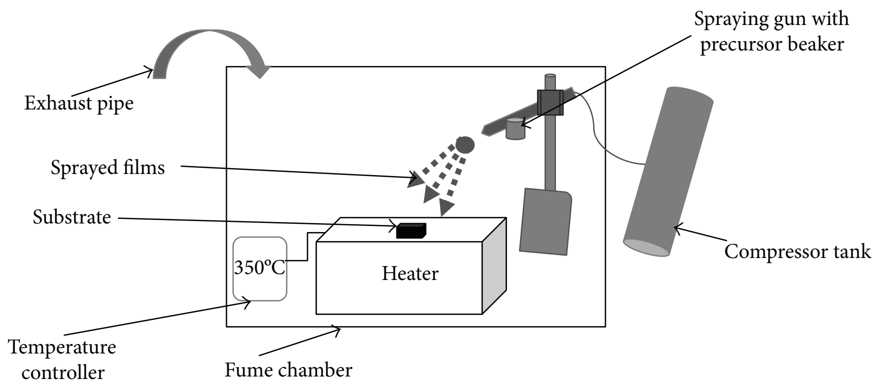

Figure 3: Experimental set-up of spray pyrolysis technique.

Table 1: Optimum deposition parameters of SPT NiO film.

Deposition parameter	Value
Substrate to nozzle height	20 cm
Rate of spray	1 ml/min
Spray time	1 min
Sprays interval	30 sec
Carrier gas	1 bar of filled compressed air

[39]. The SEM shows the potential of NiO as an absorber layer in solar cell fabrication. Figures 5(c) and 5(d) show the scanning electron micrograph of the heterojunction of NiO/TiO_2. This micrograph was obtained by the SEM at the junction or point of interaction between the TiO_2 and NiO. It shows a polycrystalline structure. The micrograph shows the *P*-type NiO and *N*-type TiO_2 of the thin film with their polycrystalline structures. It shows complete penetration at the heterojunction.

3.2. Elemental Composition. Figure 6 shows the elemental composition of the NiO/TiO_2 heterojunction solar cell deposited on the ITO-coated glass substrate. Figure 6 shows the presence of Ti, O, and Ni for the TiO_2 and NiO, respectively, and the indium (In) representing the ITO-coated glass substrate. This confirms the presence of the metal oxides in the heterojunction.

3.3. Structural Analysis. Figure 7 shows the X-ray diffraction patterns of the fabricated ITO/TiO_2/NiO heterojunction solar cell. The peaks corresponding to NiO and TiO_2 were determined with JCPDS patterns. The XRD spectrum indicates strong NiO peaks with (1 1 1), (2 0 0), and (2 2 0) preferential orientation. The patterns of the NiO thin film have peak diffractions at ($2\theta = 37^\circ$, 43°, and 64°) for the (1 1 1), (2 0 0), and (2 2 0) plane. The XRD analysis confirms Bunsenite, which corresponds to the JCPDS card: 04-0835 for nickel oxide [40] confirming it as a good absorber layer of solar cells [41]. The TiO_2 spectrum also shows strong spectrum and polycrystalline structures typical of *N*-type in heterojunction solar cells. The structure of the heterojunction indicates that the film is polycrystalline and chemically pure.

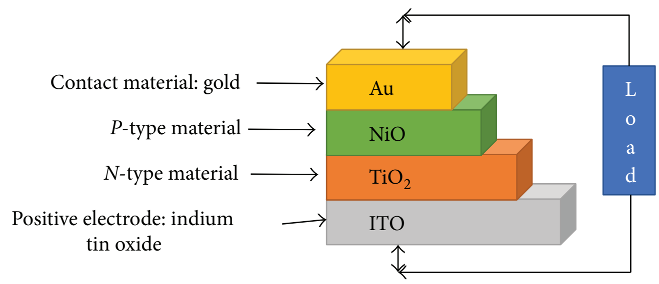

Figure 4: Schematic of the fabricated NiO/TiO_2 heterojunction solar cells.

3.4. Current Density-Voltage (J-V) Characterization. The *J-V* characteristic curve of the prepared TiO_2/NiO heterojunction thin-film solar cell under illumination and in the dark is depicted in Figure 8. The *J-V* characteristic at room temperature in the dark shows that the forward current of the cells increases slowly with increasing voltage. The solar cell has rectification properties since the dark *J-V* plots were similar to the Shockley diode characteristics, which can be expressed by the standard diode equation

$$J = J_O \left[\exp\left(\frac{qV}{AkT} \right) - 1 \right], \tag{1}$$

where q is the electronic charge, A is the diode quality factor (ideality factor), k is Boltzmann's constant, T is the absolute temperature, and J_o is the reverse saturation current.

The solar cell parameters evaluated from the *J-V* curve are presented in Table 2. The fabricated solar cell exhibits the short-circuit current (J_{sc}) of 16.8 mA, the open-circuit voltage (V_{oc}) of 350 mV, the fill factor (FF) of 0.39, and the conversion efficiency (η) of 2.30%. This is a marked improvement on the values of 0.33 V and 0.29 recorded by Georgieva and Tanusevski [42] for the open-circuit voltage and fill factor, respectively. It also showed improvement in the fill factor of 0.28 reported by Noda et al. [43].

4. Solar Cell Parameters

The primary parameters that describe the performance of a photovoltaic device are discussed below.

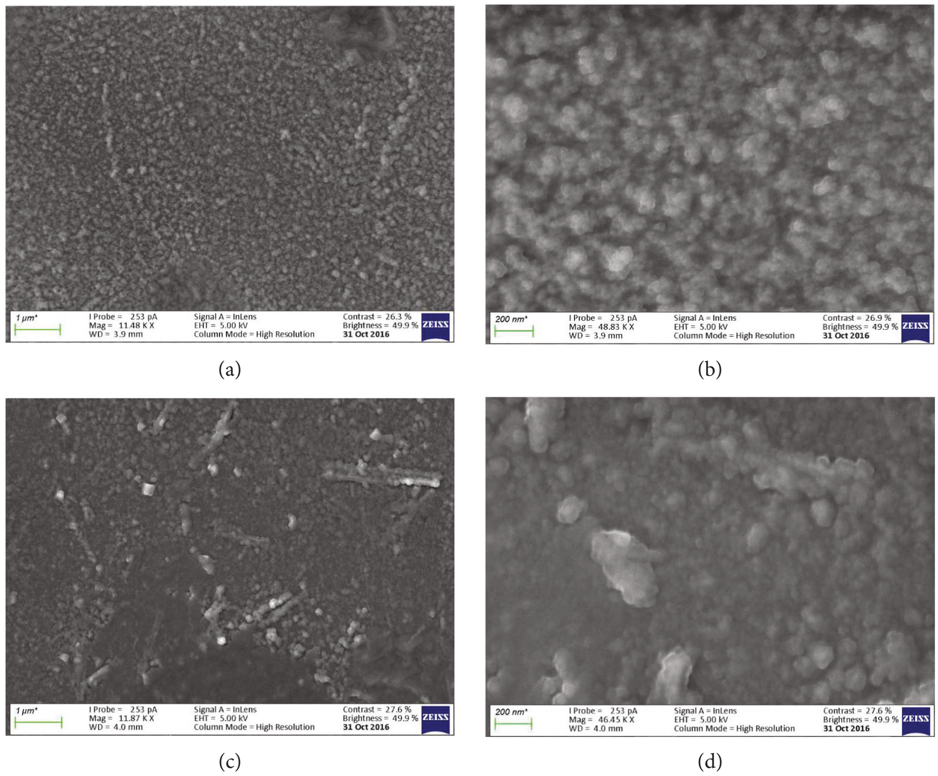

FIGURE 5: SEM of (a) NiO thin film at lower magnification, (b) NiO thin film at higher magnification, (c) fabricated NiO/TiO_2 heterojunction solar cell at lower magnification, and (d) fabricated NiO/TiO_2 heterojunction solar cell at higher magnification.

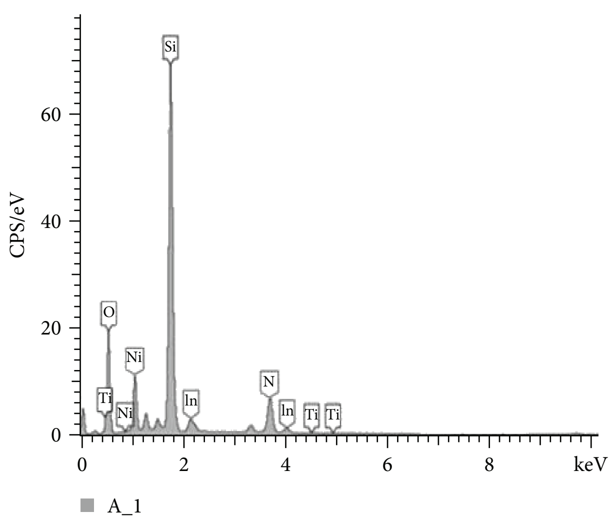

FIGURE 6: EDX of fabricated ITO/TiO_2/NiO heterojunction solar cell.

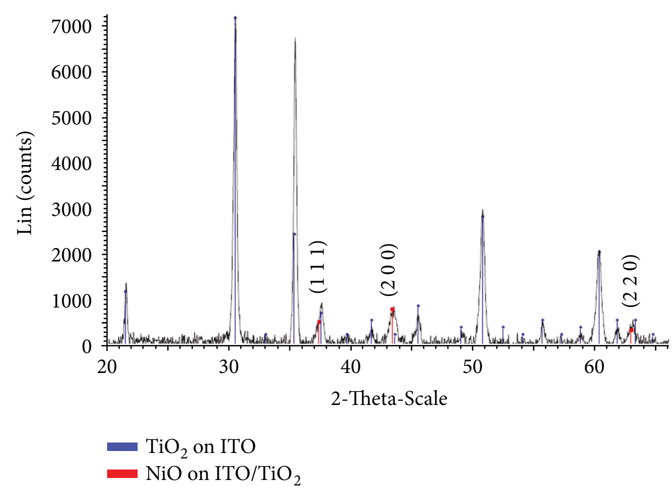

FIGURE 7: XRD of fabricated ITO/TiO_2/NiO heterojunction solar cell.

4.1. Open-Circuit Voltage (V_{oc}). Open-circuit voltage is the applied voltage relative to an open circuit where no current flows through the device (i.e., the voltage across the device at zero current). V_{oc} is obtained at the point of intersection of the *I*-*V* curve under illumination at the voltage axis. Under open-circuit conditions, the structure has to bias itself to some voltage V_{oc} in order to counter the light-beam-induced current. The open-circuit voltage V_{oc} arises as a result of the built-in electric field present in the materials system and can be expressed as

$$V_{OC} = \frac{AkT}{q} \ln\left(\frac{J_L}{J_o} + 1\right). \tag{2}$$

This quantity is left unaffected by series resistance losses in the cell but is sensitive to shunt losses.

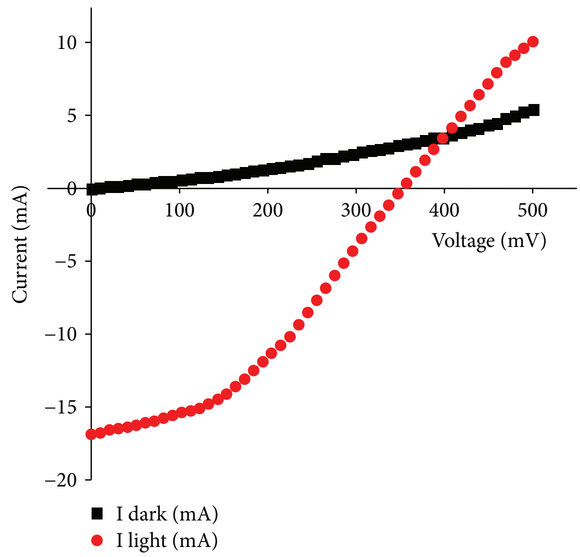

FIGURE 8: Typical *I-V* curve for the prepared TiO_2/NiO heterojunction thin-film solar cell under illumination and in the dark.

TABLE 2: Solar cell parameters of the fabricated solar cell.

Sample	J_{sc} (mA)	V_{oc} (mV)	J_{max} (mV)	V_{max} (mV)	FF (%)	η (%)
TiO_2/NiO	16.8	350.0	13.10	173.57	39	2.30

4.2. Short-Circuit Current Density (J_{sc}). J_{sc} is the current that flows through the junction under illumination at zero applied voltage, that is, $J_{sc} = J(V = 0)$. In the ideal case, it equals the photogenerated current density (J_L) and is proportional to the incident number of photons or alternatively the intensity of illumination.

J_{sc} is represented as the intersection of the *J-V* curve under illumination at the current axis. For an ideal solar cell ($R_S = 0$ and $R_{SH} = \infty$), the short-circuit current is given by

$$J_{sc} = J_o\left[\exp\left(\frac{q(0)}{AkT}\right) - 1\right] - J_L, \qquad V = 0. \tag{3}$$

4.3. Fill Factor (FF). The fill factor is defined as the inverse of the ratio of the ideal power to the maximum power in operating conditions. It can be defined also as the area of the maximum power rectangle to the product of the short-circuit current and the open-circuit voltage. This is shown as

$$\mathrm{FF} = \frac{V_{max} J_{max}}{V_{oc} J_{sc}}. \tag{4}$$

4.4. Efficiency (η). The most important parameter of a solar cell in terms of its ultimate function is the photovoltaic conversion efficiency. This is defined as the ratio of the output power (electricity) to the input power (light) and can be calculated as

$$\eta = \frac{P_{max}}{P_{in}} = \frac{\mathrm{FF}\left(V_{oc} J_{sc}\right)}{P_{in}}. \tag{5}$$

5. Conclusion

In this study, TiO_2 and NiO thin films were used to fabricate ITO/TiO_2/NiO heterojunction solar cells. It shows that NiO can be used in thin-film solar cells. The conversion efficiency, open-circuit voltage, short-circuit current, and fill factor were 2.30%, 350 mV, 16.8 mA, and 0.39 under 100 mW/cm^2 illumination, respectively. This is an improvement on existing values. This will open up frontiers in affordable and sustainable solar cell fabrication in developing and low-income countries.

Nomenclature

NiO:	Nickel oxide
Ni:	Nickel
Ti:	Titanium
O:	Oxygen
TiO_2:	Titanium oxide
ZnO:	Zinc oxide
CuO:	Copper oxide
In_2O_3:	Indium oxide
ITO:	Indium tin oxide
Au:	Gold
SPT:	Spray pyrolysis technique
FEGSEM:	Field emission gun scanning electron microscope
EDX:	Energy dispersive X-ray spectrometer
XRD:	X-ray diffractometer
J-V:	Current density-voltage
I-V:	Current-voltage
V_{oc}:	Open-circuit voltage
J_{sc}:	Short-circuit current density
FF:	Fill factor
P_{in}:	Power in
P_{max}:	Maximum power.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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