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Electrical and photovoltaic properties of Ag/p-Si structure with GO doped NiO interlayer in dark and under light illumination

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In our work, graphene oxide (GO) doped nickel oxide (NiO) nanocomposite was used an interfacial layer to investigate electrical and photovoltaic properties of the Ag/*p*-Si metal semiconductor structures. GO doped NiO nanocomposite films were prepared by Hummers method. This nanocomposite films were characterized by EDX and SEM analyses. The electrical and photovoltaic characteristics of the Ag/GO-doped NiO/*p*-Si heterojunction were investigated using current-voltage (*I-V*) and capacitance-voltage (*C-V*) measurements under dark and 30 mW/cm^2 light illuminations conditions at room temperature. The values of ideality factor, reverse saturation current, and barrier height were obtained as 4.52, 1.66 × 10^{-10} A, and 0.903 eV; 4.38, 3.12 × 10^{-10} A and 0.887 eV in dark and under light illumination, respectively. At the same time, the interface state densities as a function of energy distributions was extracted from the forward-bias *I–V* measurements. Experimental investigations show an increase in a reverse current in photodiodes with increasing the illumination intensity.

1. Introduction

In the recent years, researchers have identified graphene-based semiconductor devices as a possible future alternative to metal-semiconductor technology. Thus, graphene nanocomposite materials are considered one of the most promising candidates for future semiconductor industry applications because of their successful applications in optical and electronic devices [1–4]. Because, graphene is a zero-gap semiconductor having a high intrinsic carrier mobility [1,2]. This situation makes it possible to control the conduction of graphene with the use of a gate [5]. There have been growing interest in the field of graphene oxide nanocomposite materials due to excellent in-plane mechanical, structural, thermal and electrical properties of graphite [1–4]. Graphene oxides are important materials and can be used instead of pure graphene for nanocomposite formation and graphene can be synthesized by different methods [6–22]. There are different methods developed to produce GO doped NiO nanocomposite films in the literature [7–22]. In this study, GO doped NiO nanocomposite films were prepared by Hummer's method [17]. Because, graphene oxide can be easily synthesized by Hummer's method. Also, Hummer's method has various advantages such as simplicity, homogeneity, layers of many compositions on various substrates and low production costs.

Metal oxide semiconductors (MOS) structures are future availability for electronic and optoelectronic applications. There are some studies about Schottky diodes based on GO-doped NiO. One of this structures is nickel oxide, NiO with a wide band gap of 3.6–4.0 eV [23]. Stengl et al. [24], show that doping TiO2 with GO reduces the nanocomposite optical band gap to below 2.50 eV. Thus NiO is interesting material due to its low material cost, optical properties, promising ion storage. Zhao et al. [25] fabricated the two-dimensional graphene/NiO composite material via self-assembly method. Hendi et al. [26] were investigated photoresponse properties of Al/p-Si/GO:TiO2/Au diodes using transient photocurrent and conductance spectroscopy techniques. Najla [27] was investigated electrical and photoconductivity properties of Al/graphene oxide doped NiO nanocomposite/p-Si/Al photodiodes with various graphene oxide contents. Çiçek et al. [28,29] were produced with and without interlayer to evaluate synthesis and characterization of pure and graphene (Gr)-doped organic/polymer nanocomposites on the electrical parameters of Au/n-GaAs devices.

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Kaya et al. [30] were investigated electrical characteristics of the Au/n-Si (MS)-type SBD with and without a 2% GC-doped Ca3Co4-Ga0.001Ox interfacial. Zhua et al. [31] have reported the effect of graphene oxide on the nanomechanical reinforcement, nano-scratch resistance, and thermal stability of PVA, which were studied from nanoscale to macroscale for the first time, and they demonstrated that the incorporation of 0.5 wt% GO in PVA gives the highest improvement in nano-mechanical properties. Chengpeng et al. [32] have presented PVA and PVA/graphene composites. Shao et al. [33] has been prepared graphite oxide was prepared from graphite using Hummers method [17]. Thus, due to the technological importance of electronic circuit components which are among the most simple of the graphene-Si contacts [5,34], a full understanding of the nature of their electrical and photovoltaic properties are of great interest.

In the previous study [34], we were investigated illumination impact on electrical properties of Ag/nGO-PVA/p-Si heterojunction. As different previous study [34], In this study, our purpose is to experimentally investigate the relationship among the electrical, photovoltaic and interface state densities of the Ag/GO-doped NiO/*p*-Si heterojunction using current-voltage (*I-V*) and capacitance-voltage (*C-V*) measurements under dark and 30 mW/cm^2 light illuminations conditions at room temperature. Therefore, this study can be divided into three categories: first, our aim is to investigate the SEM image of GO-NiO structure by means of scanning electron microscope (SEM-Zeiss EVO 10LS) with energy dispersive X-ray spectrometry (EDX). The second goal is to investigate the electrical and photovoltaic properties of the Ag/GO-NiO/*p*-Si heterojunction by means of *I-V* and *C-V* measurements under dark and illuminated conditions. The third goal is to investigate as a function of energy density distribution profiles of the interface state densities (N_{SS}) obtained from the forward-bias *I-V* measurements by taking into account the bias dependence of the effective barrier height under dark and illuminated conditions.

2. Experimental process

In this section, first, the processes of chemical cleaning and ohmic contact formation on p-Si substrates are described, after, GO-NiO nanocomposites film on the p-Si was spin coated at 3000 rpm for 30 s, and finally, the electrical measurements on the Ag/GO doped NiO/*p*-Si structure are introduced.

2.1. Chemical cleaning and contact formation

For the fabrication of Ag/GO doped NiO/p-Si structure, *p*-type silicon (Si) wafer was used as substrate with (100) surface orientation, 400 μm thickness and 2–8 Ω-cm resistivity. The *p*-type Si wafer was chemically cleaned by using RCA cleaning procedure [35]. The cleaning processes leaved wafers with a thin oxide film which is known that an ohmic contact is required for realizing long-lifetime operation of optical and electrical devices. The native oxide on the front surface of the substrate was removed in HF:H_2O (1:10) solution and finally the wafer were rinsed in de-ionized water for 30 s. Then, low resistivity ohmic back contact to p-type Si (100) wafers was made by using Ag, followed by a temperature treatment at 570 °C for 3 min in N_2 atmosphere.

2.2. Preparation of GO doped NiO nanocomposites

The GO was prepared from extra pure graphite powder (Sigma Aldrich, 99.99%) according to improved Hummers. The GO was synthesized as powder, as we reported before in detail [36,37]. The GO doped NiO ($C_{64}O_{27}Ni$) material was characterized by the scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDX) techniques. The *p*-Si (100) substrates were exposed to oxygen plasma cleaner to make the surface hydrophilic and dried. After, in order to prepare GO-NiO nanocomposites film on the *p*-Si was spin coated (6800 Spin Coater Series) at 3000 rpm for 30 s. This is followed by annealing the film at 50 °C for 1 h in N_2 atmosphere. The thickness of the GO-NiO nanocomposites film was measured using image of the cross section Scanning Electron Microscopy (SEM). The Schottky contacts have been formed by thermal evaporating about 50 nm thick Ag as dots with diameter of about 1.0 mm on the front surface of the GO-NiO/*p*-Si. Thus, the GO-NiO nanocomposites based diode, Ag/GO-NiO/*p*-Si structures was obtained by a spin coating and thermal evaporation technique. As can be seen Fig. 1, it shows the schematic diagram of the Ag/GO-NiO/p-Si structures based diode structure used in this study.

2.3. Electrical measurements

The current–voltage measurements of Ag/GO-NiO/*p*-Si heterojunction were performed at room temperature using a Keithley 2400 source meter. The capacitance–voltage measurements were carried out with ST2826/A High Frequency LCR Meter. All measurements were carried out with the help of a microcomputer through an IEEE- 488 AC/DC converter card. In addition, the cross-sectional SEM image of GO-NiO nanocomposites was examined by means of scanning electron microscope (SEM-Zeiss EVO 10LS) with energy dispersive X-ray spectrometry (EDX). The photo-response measurements of Ag/GO-NiO/***p***-Si heterojunctions were measured using a halogen lamb. The intensity of the light was controlled by solar power-meter (Model TM 206).

3. Results and discussion

3.1. Structural properties of GO doped NiO nanocomposite

The structural and elemental analysis of the synthesized GO doped NiO layer were performed using scanning electron microscope (SEM) and energy dispersive X-ray spectrometry (EDX). The SEM image of the GO doped NiO layer is shown in Fig. 2. Accordingly, graphene layers are naturally wrinkled and flexible, in contrast to graphite. The graphene layers are substantially thin and irregular according to Fig. 2(a–b). This situation was approved by energy dispersive spectroscopy, where nickel oxide particles at high densities were observed at certain sites. As can be seen in Fig. 2, the NiO nanoparticles are covered by GO layers. The coverage of GO on NiO nanoparticles change the dispersion of particles in GO doped NiO nanocomposites. This distributions have significant effects on the photo-response properties of GO-NiO/p-Si structure. Also, the GO-NiO structure was analyzed by energy dispersive X-ray spectrometry (EDX). The EDX spectrum of the film is shown in Fig. 3. As seen in Fig. 3, the X-ray (EDX) spectrum indicates the presence of C (61.01 wt %), O (34.32 wt %) and Ni (4.67 wt %) elements in GO-NiO structure.

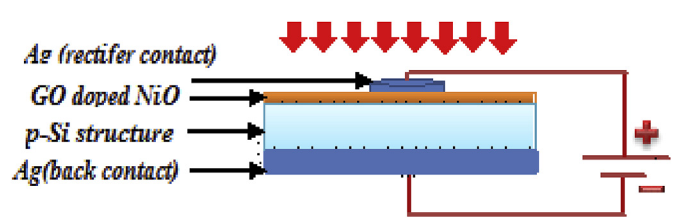

Fig. 1. Schematic representation of Ag/GO doped NiO/*p*-Si structure.