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A study on non-stoichiometric *p-NiOx/n-Si* heterojunction diode fabricated by RF sputtering: Determination of diode parameters

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NiO_x thin films were grown on n-Si substrates by radio frequency sputtering technique for the fabrication of a heterojunction p-n diode. X-ray diffraction, scanning electron microscope and atomic force microscope results revealed that NiO_x films had nano sized polycrystalline nature. The X-ray energy dispersive analysis was used to determine elemental composition of the NiO_x films. High quality vacuum evaporated silver (Ag) (ohmic) layer and nickel (Ni) (measurement electrode) dots were used to make contacts to the *p-NiO$_x$/n-Si* heterojunction, in such a way that 8 *Ni/p-NiO$_x$/n-Si/Ag* devices were fabricated. Current-voltage (*I*–*V*) and capacitance-voltage (*C*–*V*) measurements of the *p-NiO$_x$/n-Si* heterojunctions showed good diode characteristics and the average barrier height has been calculated as 0.652 eV.

1. Introduction

Transparent conductive oxides (TCOs) attract great interest because of their high optical transparency in the visible region and their high electrical conductivity [1,2]. Nowadays, *n*-type semiconductors such as ZnO, indium doped tin oxide (ITO) and SnO_2 are used in many optoelectronic applications [3,4]. Nickel oxide is a p-type TCO, in which p-type conductivity is due to non-stoichiometric defects such as Ni vacancies and oxygen interstitials. Besides its optical and electrical characteristics, extraordinary properties of NiO such as excellent chemical stability, wide band gap energy (in the range of 3.5–4.0 eV), with weak absorption bands in the visible region due to *d-d* transition, and magnetic properties have drawn researchers' attention [5]. These above mentioned properties make NiO a very promising candidate for nanotechnological applications ranging from solar cells to electrochoromic coatings [6]. Also, NiO can be synthesized using various techniques [7]. Recently, the sensing properties of NiO have been widely investigated. *Hotovy* et al. [8] showed that hydrogen sensing response depends on the

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properties of 3–5 nm Pt overlayer on NiO film. *Purushothaman and Muralidharan* [9] have investigated the electrochromic properties of sol-gel NiO films and revealed that the film synthesized at 300 °C with a thickness of 306 nm shows maximum anodic/cathodic diffusion coefficient of 11×10^{12} $cm^2/s/6.44 \times 10^{12}$ cm^2/s. Morover, *Zhang* [10] studied Schottky properties of NiO nanowires synthesized by hydrothermal reaction technique and the *I–V* curves of nanomaterials' Schottky contacts (nano-M/SCs) exhibited good photoelectric switching effect at reverse bias. Many efforts have been devoted to investigate *p*-NiO/*n*-ZnO device parameters [11,12], but limited studies are reported on *p*-NiO/*n*-Si heterojunction devices [13,14]. Therefore, more studies are needed about *p*-NiO/*n*-Si heterojunction diodes to better understand their transport mechanism. NiO_x films with tailored optical and electrical properties are in fact interesting for their potential application as hole-selective contacts in Si-based heterojunction solar cells [15,16]. In this work, we deposited by radio frequency (RF) sputtering p-type NiO_x interface layers on n-Si wafers to fabricate Schottky diode, with the aim of giving further insights into the electric properties of these heterojunctions. The main goal of this study is to investigate microstructural and morphological features of non-stoichiometric r.f sputtered NiO_x film and the device performance of Ni/*p*-NiO_x/*n*-Si/Ag heterojunction. Our previous study indicated that NiO_x films prepared by RF sputtering at different growth parameters, showed *p*-type conductivity with band gap values in the range of 3.18–3.30 eV [1]. Eg value of the film reported in this study is 3.26 eV. In this work, the microstructural and morphological properties of the NiO_x film were evaluated respectively by X ray diffraction (XRD) and Atomic Force Microscopy (AFM) measurements, and the diode parameters were analyzed by using current-voltage (*I–V*) and capacitance-voltage (*C–V*) measurements.

2. Experimental

NiO_x film were grown on *n-Si (100) (resistivity of 1 Ωcm)* substrate by RF sputtering in Ar + O_2 atmosphere (66% oxygen partial pressure) using a 6.5 inch diameter Ni target of 99.99% purity. The distance between the target and the substrate was fixed at 70 mm. The base pressure in the deposition chamber was about 2×10^{-4} Pa. The power of RF source and the substrate temperature were fixed at 250 W and 300 K, respectively. The thickness of the obtained sample has been calculated by surface profilometer KLA-Tencor P-10 with an error of about 5% and measured about 100 nm. Eight circular metallic (Ni) dots, each of 7.85×10^{-3} cm^2 area and 70 nm thickness, were evaporated on NiO_x film using DC magnetron sputtering, at 10^{-6} torr. A thin Ag layer of 80 nm thickness, was evaporated on the back side of the Si substrate as ohmic contact. In this way, *8 Ni/p-NiOx/n-Si/Ag* heterostructure devices were fabricated by exploiting all the surface area occupied by NiO_x film on the Si substrate. Fig. 1(a) and (b) shows the schematic cross section of the obtained devices and the energy band diagram of *p-NiOx/n-Si* heterojunction, respectively. In Fig. 1 ΔEc is the difference in the electron affinities of NiO and Si semiconductors, where eV_{d1} is the barrier to hole injection from NiO_x side to Si side and eV_{d2} is the barrier to electron injection from Si side to NiO side. The electrical characteristics of *8 Ni/p-NiOx/n-Si/Ag* devices have been obtained by the current-voltage (*I–V*) measurements, and the capacitance-voltage (*C–V*) measurements of the devices have also been performed at 500 kHz frequency. The *I–V* and *C–V* measurements were carried out with Keithley 487 Picoammeter/Voltage Source and HP 4192A (50 Hz–13 MHz) LF Impedance Analyzer, respectively, and all measurements have been performed at room temperature.

3. Results and discussion

The XRD pattern of the NiO_x film on n-type Si is shown in Fig. 2. As can be seen in Fig. 2, each pattern exhibits strong *CuKα* peaks at 36.50°, 42.69°,61.70°,75.43° which correspond to (111), (200), (220) and (311) reflections, respectively. From this result, it can be said that the NiO_x film grown on n-type Si shows cubic crystal structure features. Similar results have been observed by Dhanya and Sasi in an earlier study [17]. To calculate the interplanar distance (*d*) values for NiO_x film, Bragg's Law ($n\lambda = 2d\sin\theta$) has been used. The '*d*' values of (111), (200), (220) and (311) are 0.24631 nm, 0.21117 nm, 0.14955 nm, 0.12591 nm, respectively, and they are in harmony with the standard ones obtained from JCPDS card no: 78-0643. Grain size of the film is measured from highly textured (111) peak by means of X-ray line-broadening method by using the Scherrer's

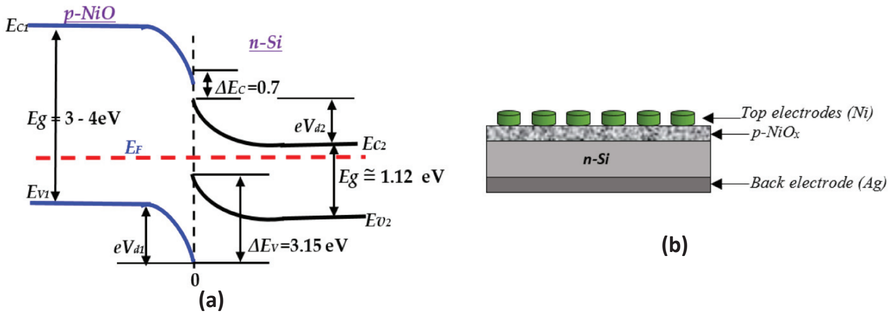

Fig. 1. (a) The energy band diagram of *p*-NiO_x/*n*-Si heterojunction, (b) the schematic cross section of the Ni/*p*-NiO_x/*n*-Si/Ag device.