Thin Film Transistors p-type Depletion Mode based on Nickel-doped Zinc Oxide

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Abstract. In this work, Nickel-doped Zinc oxide (Ni:ZnO) thin film transistors (TFTs) p-type depletion mode were fabricated with different channel lengths. Channel lengths for TFTs were 50 μm, 70 μm and 100 μm. Ni:ZnO thin films deposited by hydrothermal technique. The X-ray Diffraction (XRD) was used to examine the structural analytic of the prepared thin films. The diffraction peaks of prepared Ni:ZnO thin films are fairly matching with the hexagonal wurtzite ZnO structure with the preferred orientation (002) plane. The Scanning Electron Microscopy (SEM) with Atomic Force Microscopy (AFM) were used to characterize the surface morphologies of the fabricated thin films and study them. The SEM images confirm nanorods nanostructures. Hall Effect measurements reveal that the fabricated thin film is p-type. The characterization of Ni:ZnO TFTs p-type depletion mode was investigated by transfer (IDS–VGS) characteristics. The threshold voltage (VTh), subthreshold-swing (S.S), the on-off current ratio (ION/OFF) and the mobility carrier (saturation regime) were calculated. The 50μm Ni:ZnO TFT shows better performance based on device carrier mobility and highest ION/OFF ratio.

1. Introduction
Zinc Oxide (ZnO) is a very important metal oxide compound that widely deployed in many solid state electronics, due to its electronic and optical properties. It is used for a variety of electronic devices, including, light emitting diode [1], solar cell [2], gas sensor [3], piezoelectric nanogenerator [4], quantum dots [5], and thin film transistors [6–10].

Nanostructure ZnO deployed in TFT because its exhibiting semiconductive characteristic with thermal stability, large exciton binding energy (60 m eV), excellent chemical and wide band gap (3.3 eV) [11–13]. ZnO is intrinsically n-type material because electrons are naturally produced due to the deficiencies such as oxygen vacancies (VO) and zinc interstitials (Zni). Tailoring of the physical and chemical properties can be achieved for nanostructured ZnO based on the demand of the device fabrication. One technique to tailor properties is doping [14]. However, fabrications of good quality p-type ZnO is still a challenge due to self-donor deficiencies VO and Zni [15]. Many research teams have attempted to achieve p-type ZnO material. He et al. [16], have observed p-type behavior for a Nickel-doped ZnO (ZnO:Ni) nanostructures. Attributed p-type property to a Ni3+ cation which contribute as a positive charge carrier.
In Nickel-doped Zinc Oxide system have been observed diverse magnetic properties [17]. Both undoped and Ni-doped ZnO thin films are ferromagnetic at room temperature [18].

Many chemical and physical deposition technologies are utilized to make ZnO film, such as pulsed laser deposition [19], sol-gel [20], spray pyrolysis [21], chemical vapor deposition [22] and hydrothermal method [23][24] etc. The hydrothermal solvents deposition technique is easy to use, not expensive and not toxic for the production of crystalline materials [25]. By using hydrothermal method we are able to fabricate specific characteristics of the crystal such as shape, size, composition, and doping to use for particular applications.

ZnO nanostructured thin film transistors exhibit high channel mobility for electrons with wide range of electrical characteristic due to the deviation in contact quality of the dielectric/nanowire, the metal/nanowire and the nanowire/nanowire interfaces [26].

In this work here, fabrication and characterization of 10% Nickel-doped Zinc Oxide thin film-field effect transistors (TFT). Nickel-doped Zinc Oxide layers were prepared by hydrothermal method. The ZnO nanostructured thin film examined by XRD system and SEM. The transfer characteristics were studied for fabricated thin film transistors.

## 2. EXPERIMENTAL WORK

The commercially analytical grade chemicals were used without any purification. Thin field effect transistors (TFTs) were fabricated in a bottom contact configuration on silicon/silicon oxide (Si/SiO₂) substrate. The thickness of commercial Si/SiO₂ substrate is a round 400 μm. The utilized substrate consisting of a p-type silicon, with a resistivity of 2–7 Ω.cm, and 50 nm thick SiO₂ thermally grown layer. The step by step process of fabrication and characterization of Zinc Oxide and Nickel-doped Zinc Oxide nanorods based TFTs is shown in Figure 1. Before the seed layer deposition the Si/SiO₂ substrates were cut with an area (1.5x1.5) cm² and cleaned. Cleaning is an important step to remove the impurities and contaminants of Si/SiO₂ substrates. The cleaning process done by number of steps. Firstly, the substrates were immersed by isopropyalkohol (C₃H₈O) to remove the organic remains, and then kept in acetone. Finally, the substrates rinsed in deionized water.

The seed solution was produced by dissolving 0.005M zinc acetate dehydrate (Zn (CH₃COO)₂.2H₂O) in 20ml isopropanol (C₃H₈O) and 0.005M diethanolamine (DEA: [CH₂(OH)•CH₂]₂NH). The solution was stirred at 50°C to 3h by stirrer device to get clear and homogeneous solution. The resultant sol-gel was used for coating. The ZnO seed layer were coated onto substrates by spin coater. The spinning time is 1600 rpm for 10 s and then 3000 rpm for 40s at room temperature. Then the substrates were pre-heated to 10 min. at 100°C and then cooled at room temperature. After that, the substrates were annealed at 300°C for 1 h.

Zinc Oxide nanorods (NR) solution were made by dissolving 0.05M HMTA (C₆H₁₂N₄), 0.05M zinc nitrate hexahydrate (Zn (NO₃)₂.6H₂O) and 0.005M (10%) nickel acetate (Ni (CH₃COO)₂) at room temperature in 40 ml DI (deionized) water by stirrer device for 5 to 10 minutes. By hydrothermal method, the Si/SiO₂/Ni:ZnO seed layer were immersed vertically in the solution, and the sealed autoclave with screw cap were heated at 90°C inside a laboratory oven for 6 h.

The molybdenum metal shadow mask was fabricated to have TFTs channel Lengths (0.05 mm, 0.07 mm and 0.1mm) and channel width 4mm. The metal mask was fabricated by wire cutting machine (W-A430, ACRA). The schematic diagram of experimental procedures shown in Figure 2. The metallization via mask technique was adopted to fabricate TFT devices. Aluminum (Al) metal was deposited by thermal vacuum evaporation system (VSAMA VAC) on the Si/SiO₂/Ni:ZnO NRs structures to obtain the pattern of Al source-drain. Finally a blanket of Al was deposited on the back side of the wafer for bottom gate contact configuration. The thickness of Al was deposited about 200nm. The process sequences of Ni:ZnO NRs TFTs are shown in Figure 3.
Yes

No

Figure 1. Block diagram of the experimental procedures.
Figure 2. The schematic diagram of the metal mask.

Figure 3. The process sequences of TFT with channel length (0.05mm).

3. RESULTS AND DISCUSSIONS

The XRD patterns were analyzed for ZnO NRs and Ni:ZnO NRs thin films deposited by hydrothermal technique. Figure 4 shows XRD patterns for undoped ZnO and Ni:ZnO NRs were measured in the range of 2θ from 10° to 65°. The patterns for undoped ZnO NR and Ni:ZnO NR show hexagonal wurtzite structure ZnO peaks. The peaks appeared that correspond to the (100), (002), (101), (102), (110) and (103) orientations. The undoped ZnO NR and Ni:ZnO NR patterns show the strongest diffraction peaks associated with (100), (101) and (002) orientations. The additional diffraction peak was shown at 17.78° might be attributed to silicon crystal. The diffraction peak of Ni:ZnO (10% Nickel) samples were extremely oriented along the peak at 2θ=34.4° corresponding to (002) reflection plane with the crystals nature as shown in Figure.
Figure 4. The XRD patterns of (a) pure ZnO (b) 10% Ni:ZnO.
4(b). The successfully incorporation of Ni in ZnO structure, where the impurity peak was not found in Ni phase, it is due comparable ionic radii of Zn$^{2+}$ (0.074 nm) and Ni$^{2+}$ (0.069 nm) [27]. The (002) indicates c-
orienation of the crystalline structure. The diffraction peak intensity for (002) increases when ZnO doped by Ni as seen from Figure 4(b). The significantly increases of the intensity of the peak (002) for Ni:ZnO indicating an improvement in the crystallization of Ni:ZnO layer [28]. The grain size of the synthesized films for the peaks is estimated from Scherer equation [29]:

\[ D = \frac{K \lambda}{\beta \cos \Theta} \]  

where D is the grain size of the thin films in (nm), K is a constant and equal to 0.9, \( \lambda \) is the wavelength of Cu K\( \alpha \) radiation (1.5406 Å), \( \Theta \) is the peak position and \( \beta \) is the full width half maximum (FWHM).

The XRD parameters of undoped ZnO and Ni:ZnO were listed in the table 1. The results were shown when Ni doped ZnO the grain size decreases from 53.2nm for undoped ZnO to 51.1 nm for Ni-doped ZnO. In the Nickel-doping concentration, the grain size decreases and the diffracted intensity increases due to increasing the crystallity of ZnO particles [30].

| Samples       | d spacing (Å) | Lattice parameters (Å) | Volume (Å³) | Grain size (nm) |
|---------------|----------------|------------------------|-------------|----------------|
| Undoped ZnO   | 2.62926        | 3.036 5.259            | 41.979      | 53.2           |
| Ni:ZnO        | 2.62820        | 3.035 5.257            | 41.935      | 51.1           |

SEM (Scanning electron microscope) images of the surface morphology and the cross-section of Ni:ZnO sample is shown in Figs 5 and 6 respectively. Figure 5 shows different micro sizes of hexagonal rods with length range from 1 to 4 μm and diameter range from 2 to 4 μm. Theses micro rods laterally aligned on uniformly grown vertically aligned hexagonal smaller nanorods. These smaller nanorod structures with a diameter around 100 nm. Fig 6 shows the cross section of Ni:ZnO sample where the thickness of Ni:ZnO thin film were about 3.7 μm.

In Hall effect measurements, it is noticed that Ni:ZnO thin film was fabricated as p-type because of the existence of trivalent Ni\(^{3+}\) cations [16] [31]. The carrier concentration, mobility and resistivity were \(2.06 \times 10^{15}\) cm\(^{-3}\), 89.3 cm\(^2\)/V.s and \(33.91\) Ω/cm, respectively.

The transfer characteristics of fabricated devices were characterized at constant \(V_{DS}=-20\) V with different gate width (W) to length (L) aspects (W/L) of (80, 60 and 40) shown in Figures 7, 8 and 9, respectively. The transfer characteristics of all devices show typical p-type depletion mode MOSFET behavior. In depletion mode the channel permanently exists at the time of its fabrication, that's means, the MOSFET has a channel even for zero gate to source voltage (normally ON device).

The threshold voltage (\(V_{TH}\)) value was calculated from the plot of the square root of drain current versus gate voltage at fixed drain source voltage (\(V_{DS}\)) 20 V. The threshold voltage \(V_{TH}\) are calculated using conventional method the x-axis intercept of \(I_{DS}^{1/2} - V_{GS}\) curve. The field-effect mobility (\(\mu\)) extracted from the transconductance given by [32] :
Figure 7. The transfer curve of Ni:ZnO TFT with the channel length 50 µm.

Figure 8. The transfer curve of Ni:ZnO TFT with the channel length 70 µm.
Figure 9. The transfer curve of Ni:ZnO TFT with the channel length 100 µm.

Figure 10. Log scale of the Ni:ZnO with 50µm channel length.
Figure 11. Log scale of the Ni:ZnO with 70µm channel length.

Figure 12. Log scale of the Ni:ZnO with 100µm channel length.
where $C$ is the device capacitance per area and $\mu$ is field-effect mobility.

The subthreshold swing (S.S) and on-to-off current ratio ($I_{\text{ON/OFF}}$) were calculated from the curve Logarithm scale $I_{DS}$ versus gate voltage, using the equation $S.S = \frac{d}{d \log I_{DS}} (V_{GS})$. The log ($I_{DS}$)–$V_{GS}$ transfer curves for Ni:ZnO TFTs with W/L ratio of 80, 60 and 40 are shown in the Figs 10, 11 and 12, respectively.

The results of $V_{Th}$, $I_{\text{ON/OFF}}$, $\mu$ and S.S of Ni:ZnO were listed in Table 2. The device with Ni:ZnO with channel length 50 $\mu$m (W/L=80) was exhibit the highest $I_{\text{ON/OFF}}$ equal to $1.56\times10^4$ and the highest field-effect mobility equal to 0.284 cm$^2$/V.s. The highest ION/OFF and the highest field effect mobility of Ni:ZnO leading to an improvement in the on–off current ratio, carrier mobility and threshold voltage.

| Channel Length ($\mu$m) | W/L | $V_{Th}$ (V) | S.S (V/decade) | $I_{OFF}$ (A) | $I_{ON/OFF}$ | Mobility (cm$^2$/V.s) |
|-------------------------|-----|-------------|----------------|--------------|--------------|---------------------|
| 50                      | 80  | 11.5        | 3.14           | $4.31\times10^{-8}$ | $1.56\times10^4$ | 0.284               |
| 70                      | 60  | 3           | 1.95           | $1.21\times10^{-7}$ | $1.21\times10^4$ | 0.102               |
| 100                     | 40  | 3.8         | 3.1            | $8.6\times10^{-7}$ | $5.38\times10^2$ | 0.041               |

4. Conclusion
In this research, depletion mode p-type TFTs based on Ni:ZnO were successfully obtained. We studied the structural, morphological, and electrical characteristics of Ni:ZnO nanostructure layer, one doping concentrations 10% Ni-ZnO with channel lengths 50 $\mu$m, 70 $\mu$m and 100 $\mu$m regarding to W/L ratio of 80, 60, 40), respectively, in TFT devices. The active layer deposited by a hydrothermal method at 90°C for 6h. Nano and micro rods structures obtained for Ni:ZnO thin film. XRD results shows that grain size decreases when ZnO doped by Ni. SEM images show different micro sizes of hexagonal rods with diameter range from 2 to 4 $\mu$m and nano sizes less than 100nm. The electrical characteristics by Hall Effect system show decrease in the carrier concentration and the increase in resistivity due to imperfections are introduced Ni dopant. Hall measurements also reveal that the fabricated thin film is p-type. The characterization of Ni:ZnO TFTs p-type depletion mode was investigated by transfer ($I_{DS}$–$V_{GS}$) characteristics. The threshold voltage ($V_{Th}$), subthreshold-swing (S.S), the on-off current ratio ($I_{ON/OFF}$) and the field-effect mobility (saturation regime) were calculated. The device with Ni:ZnO with channel length 50 $\mu$m was exhibit the highest ION/OFF equal to $1.56\times10^4$ and the highest field-effect mobility equal to 0.284 cm$^2$/V.s, so it shows better performance based on device carrier mobility and highest $I_{ON/OFF}$ ratio.

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