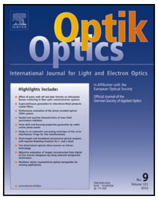
Optik 127 (2016) 5226–5229

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Coulomb blockade and plasmonic nanoantenna effect in back gated ZnO nanorod FET

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ARTICLE INFO

Article history:
Received 29 January 2016
Accepted 7 March 2016

Keywords:
ZnO nanorod
Solution synthesis
Nanorod FET
Plasmonic nanoantenna
Lithography
Ti/Au metal contacts
Coulomb bloackade

ABSTRACT

Fabrication and characterization of ZnO nanorod field effect transistor (FET) is reported. Back-gated ZnO nanowire FETs were fabricated on SiO_2 covered p-type Si substrate using lithographically patterned Ti/Au contacts. The ZnO nanorods were synthesized by chemical bath deposition method using the precursors zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$) and hexamethylenetetramine (HMT) ($C_6H_{12}N_4$). Fabricated FET has shown clear gate response. *I–V* characterization done on the fabricated FET has shown Coulomb blockade and plasmonic nanoantenna like effects. The observation of Coulomb blockade and plasmonic effect of the fabricated FET structure have been explained.

1. Introduction

Nanostructures of Zinc oxide (ZnO) such as nanorods (NR), nanowires (NW) and nanotubes (NT) have received extensive interest in the fabrication of electronic devices. Particularly the nanowire based devices are highly attractive in order to fabricate high density devices. They have demonstrated exciting role as the building blocks in nanoscale electronics. Among the various semiconductors ZnO nanowire has attracted tremendous interest due to its remarkable physical properties and versatile applications in electronics [1]. Fabrication of field effect transistors (FETs) using ZnO NR has also recently attracted interest considering the uniqueness of the nanorods [2–4].

Nanorod-based FETs are significantly attractive to overcome the problems encountered in conventional thin-film transistors [5]. The fabrication of such novel electronic devices is not only important to explore their novel electronic functionalities but also for the study of electronic properties at the nanolevel, because such nanolevel configuration is entirely different from bulk structures in terms of interfacial transport properties. In this work, we have fabricated FET devices using the solution synthesized ZnO NR as channel and thermally evaporated Ti/Au fingers as source and drain metal contacts. Synthesis of ZnO nanostructures by solution method is easy and inexpensive method [6], by which we can produce device quality ZnO with different morphologies. To the best of our knowledge no report is available on the fabrication FET using solution synthesized ZnO nanorods. Though the fabricated device has shown good modulation of drain current due to gate bias, some of the devices annealed using rapid thermal process have shown Coulomb blockade and plasmonic resonance effects.

The plasmonic nanoantenna is also a recent attraction, which helps to fabricate new and innovative photonic devices, it has promising applications in photonics [7,8]. In plasmonic nanoantenna a simple metallic nanoparticle acts as a tiny antenna capable of capturing and concentrating light waves by the use of localized surface plasmons (SPs). It can enhance the optical activity of the material by the way of using localized surface plasmon resonances (LSPRs) [9,10]. These plasmonic nanoanttenna structures can be used for light harvesting; it can also able to harvest the infrared radiation existing beyond the visible range [11,12].

Transparent conductive oxides (TCO) can act as a plasmonic nanoantenna when coupled with gold. Among the various oxides the ZnO nanostructures are attractive for the plasmonic structures. Here, we present the observation of Coulomb blockade and plasmonic nanoantenna effect in the fabricated ZnO nanorod FET.

2. Experimental method

ZnO nanorods used in this work were synthesized hydrothermally using the precursors zinc nitrate hexahydrate

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http://dx.doi.org/10.1016/j.ijleo.2016.03.026
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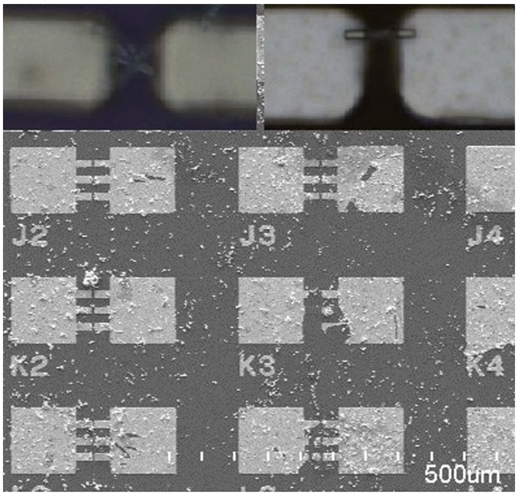

Fig. 1. SEM image of the fabricated metal pattern, insets show the optical image of the ZnO nanorods aligned with metal contacts.

($Zn(NO_3)_2{\cdot}6H_2O$) and hexamethylenetetramine (HMT) ($C_6H_{12}N_4$) following the procedure reported elsewhere [13]. For the fabrication of FET using ZnO NR, the nanorods are to be aligned with the metal contacts, it is rather a difficult process. In this work we deposited ZnO NRs onto a precleaned substrates, then metal contacts were formed by standard E-beam lithography and a lift-off technique. It is a simple and easy method to fabricate nanorod-based planer devices. The synthesized ZnO NRs were dispersed in ethanol, and this nanorod suspension was dropped onto the SiO_2 covered (300 nm) p-type silicon substrate. Then a finger type pattern was produced over the ZnO NRs deposited substrates using lithography and lift-off technique. Ti/Au (20 nm/100 nm) metal was thermally evaporated to form finger type electrodes. The electrodes were consisted of three10 μm wide fingers pointing head to head with a gap of 2–5 μm and these fingers were connected to $100 \times 100\,\mu m^2$ pads for probe contacts as shown in Fig. 1. For the fabrication of FET and its measurement, the nanorods aligned in the metal gaps were considered. After fabrication, the ZnO NR aligned devices were selected using optical microscope, and they were subjected for I–V characterization using the Keithly (4200SCS) electrical parameter analyzer at room temperature. The devices fabricated by coating Ti/Au metal on the already deposited ZnO NR were found to show weak response as back-gated FET. Therefore, in order to improve the metal contacts, we done rapid thermal annealing at 500 °C/2 min. However, in these devices also we could not get appreciable FET effect as there is no well ZnO aligned devices. Hence, in the next step we drop-casted ZnO nanorods over the RTP done metal contacts, then the devices were annealed at about 350 °C for 1 h.

3. Result and analysis

The nanorods synthesized are found as 5–10 μm long in length and 300–500 nm in diameters with smooth surfaces and perfect hexagonal shape. These nanorods were dispersed in ethanol and drop-casted onto the metal pattern. SEM image of the synthesized ZnO nanorods deposited on Ti/Au metal pattern is shown in Fig. 1; it presents the rods scattered randomly on the metal pattern. Two of the ZnO nanorods aligned with metal contacts are shown in the inset of Fig. 1. The schematic diagram of the fabricated FET is shown in the inset of Fig. 2(a). I–V characterization of the device is shown in Fig. 2. Fig. 2(a) shows the drain current vs drain-source voltage (I_d–V_{ds}) characteristics of ZnO NR FET at different gate voltages. As shown in the figure there is a current modulation due to gate bias, it confirms that the fabricated FET is working. Moreover the drain current varies as stair case like variation. We can see the stair case like variation more prominently in the curve of V_g −2 and −4 V, which denotes the Coulomb blockade effect of the fabricated FET. It is an interesting phenomenon usually obtained in tunnel junctions of nanolevel devices. In ZnO nanorods the tunnel junctions are produced due to the formation of electronic islands within the nanorod, which causes the appearance of Coulomb blockade effect in electronic transport [14].

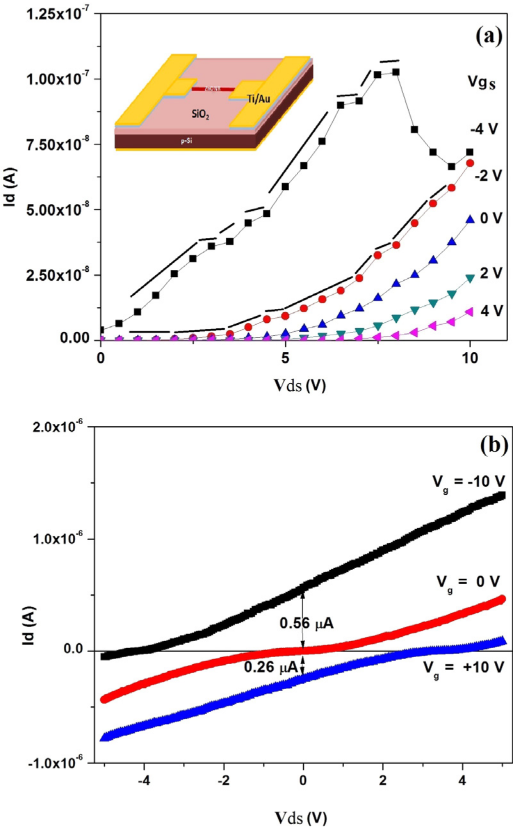

Fig. 2. Plot of I_d vs V_{ds} of the device 1(a) V_{ds} 0–10 V for different V_{gs} and (b) V_{ds} −4 to +4 for different V_{gs}; inset shows the schematic diagram of the fabricated FET.

Fig. 2(b) shows the variation of I_d for the change of V_{ds} from −4 V to 4 V of different V_{gs} −10 V, 0 V and 10 V. It shows symmetric and non-linear variation for both positive and negative bias of gate voltage. It shows opposite effects suggesting influence of gate on the channel current. Whereas, the curve of $V_g = 0$ V is not in non-linear (nearly flat) at minimum bias voltage. This is because, when zero voltage is applied to the gate and the source-drain bias, the current is zero as there is no enough energy for the electrons to enter into the island. The electrons can get through the island when the bias is increased to the Coulomb energy of the system. This again confirms the Coulomb blockade effect of the device [15]. When applying gate bias the drain current is not zero at zero V_{ds}, which may be due to the charging effect of tunneling barrier and the incomplete depletion of conducting channel due to back gate. Fig. 3 shows the I_d vs V_{gs} plot recorded for different V_{ds}. It shows spike like current changes with different heights at irregular gaps. The sharp peaks obtained in the I–V curve for the change of gate voltage attributes the occurrence of Coulomb-blockade in tunneling of electrons through the electronic islands formed in the ZnO nanorod of the fabricated device. As the charges pass through the island as quantized units, the spike like increase of current is produced. The irregular height and size of the peaks suggest that there are number of electronic islands of different size and shape along the nanowire [16]. Fig. 3(a) shows