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Study of photoconduction properties of CVD grown β-Ga_2O_3 nanowires

Sudheer Kumar [a,*], Sajal Dhara [b], Ritesh Agarwal [b], R. Singh [a,**]

[a] Department of Physics, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
[b] Department of Materials Science and Engineering, University of Pennsylvania, Philadelphia, PA 19104, United States

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ABSTRACT

We have investigated photoconductive properties and photoconduction mechanism in single crystalline β-Ga_2O_3 nanowires. To investigate photoconduction, metal-semiconductor-metal (MSM) based photodetectors were fabricated using single crystalline β-Ga_2O_3 nanowires grown by CVD technique. The current-voltage characteristics of these photodetectors were measured with varying incident laser powers. It was observed that the photocurrent was almost linear with the incident power. Under illumination, the photocurrent increased by three orders of magnitude. The photoconduction mechanism in β-Ga_2O_3 nanowires has also been discussed. The photoconduction properties of nanowires demonstrate the possibility of future applications of these nanowires in sensors and photodetectors.

1. Introduction

In the last decade, low dimensional wide-bandgap semiconductors such as ZnO, GaN, SnO_2, and β-Ga_2O_3 have allured most of research community due to their applications in optoelectronic devices [1–8]. The most important phenomenon is sensitivity of nanowires towards light (photons) which is known as photoconductivity. There are emerging applications of nanowires in photodetectors, optical switches and photovoltaics [6–11]. The photoconductivity is a well-known property of semiconductors where electric conductivity changes with incident light [12]. Recently, the achievement of very high photoresponsivity and photoconduction mechanism in low dimensional structures like nanowires with high surface states density has attracted the researchers for the potential applications of nanowires in photodetectors.

Wang et al. [2] demonstrated UV-photodetector using ZnO nanowires and observed very high internal gain. The authors mentioned that high sensitivity of nanowires was mainly due to (i) the large surface-to-volume ratio and deep trap states in the nanowires which enhances the photocarrier lifetime; (ii) the reduced dimensionality of the active area in nanowires which makes the carrier transit time shorter. For the first time, Feng et al. [13] reported single β-Ga_2O_3 nanowires based solar-blind photodetectors. The conductivity of photodetectors increased about three orders of magnitude under incident wavelength of 254 nm. Hsieh et al. [11] fabricated β-Ga_2O_3 nanowire based optical switches. The authors found enhancement in photoresponse via Au particle surface plasmon resonance photoresponse (SPR) when the photoresponse of fabricated device was measured using a double frequency Nd:YAG laser light (wavelength of 532 nm) and thus resulted into a high on/off ratio. Despite a number of research reports on nanowire based photoconductive measurements, there are only a few studies related to photoconduction in β-Ga_2O_3 nanowires.

In the present work, we report about photoconduction behavior of β-Ga_2O_3 nanowires. To investigate photoconduction in β-Ga_2O_3 nanowires, a single nanowire based metal-semiconductor-metal (MSM) photodetector has been fabricated utilizing electron beam lithography (EBL) and lift off process. The structural, morphological and optical properties were measured using field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM), X-ray diffraction (XRD) and Raman spectroscopy. These results showed good structural as well as optical properties of β-Ga_2O_3 nanowires. The current-voltage (I-V) characteristics of

* Corresponding author.
** Corresponding author.
E-mail addresses: sudheer83.iitr@gmail.com (S. Kumar), rsingh@physics.iitd.ac.in (R. Singh).

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single nanowires were measured under dark and illumination. The photoconduction mechanism in β-Ga_2O_3 nanowires has been elucidated.

2. Experimental section

2.1. Synthesis of β-Ga_2O_3 nanowires

Initially, an ultra thin film of Au (~5 nm) was deposited on the sapphire (0001) substrates under a vacuum of 10^{-5} Torr by thermal evaporation technique. Then these Au coated samples were annealed at 600 °C for 1 h in order to form Au nanoparticles through the dewetting mechanism [14,15]. Then β-Ga_2O_3 nanowires were grown on Au nanoparticles coated sapphire substrates via chemical vapor deposition. The precursor for Ga source was metal (99.99999% from Sigma Aldrich). The Au coated samples were kept inside the mini CVD Tube Furnace (OTF-1200X-S50-2F from MTI Corporation, USA) at 900 °C for 15 min. The Ar gas flow was maintained in quartz tube at a constant rate of 40 ml/min during growth whereas the oxygen gas was flowing during constant temperature (900 °C for 15 min) at the rate of 20 ml/min. The ramp rate was 10 °C/min. Then the furnace was cooled down naturally up to room temperature. After the growth process, a layer of β-Ga_2O_3 was observed over the surface of sapphire. These grown samples were used for device fabrication.

2.2. Characterization of β-Ga_2O_3 nanowires

The as-synthesized β-Ga_2O_3 nanowires were characterized utilizing dual beam field-emission scanning electron microscopy (Model No Quanta 3D FEG, FEI), X-ray diffraction ($\lambda = 1.5406$ Å, Philips Xpert Pro) and high resolution electron microscopy (FEI-Technai-G20 with a LaB_6 filament, operated at 200 keV along with selected area electron diffraction (SAED) pattern) to study the size and structural properties.

2.3. Device fabrication for photoconductive measurements

The single β-Ga_2O_3 nanowires were configured as nanoscale photodetectors using nano fabrication process in a Clean-room atmosphere. These nanowires were dispersed in ethanol and spread on a Si substrate having a 200 nm thick SiO_2 layer, which is schematically shown in Fig. 1. The Ti/Au (10/100 nm) contacts were patterned on the top of the nanowires using electron beam

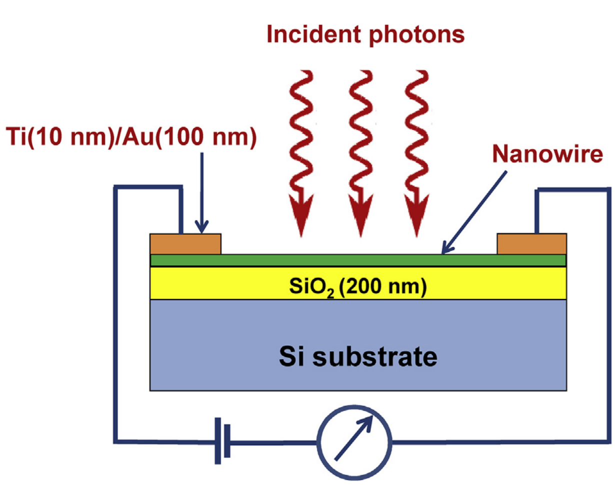

Fig. 1. A schematic diagram of the device constructed for the photoconduction measurements.

deposition (EBL) and lift-off process. In the patterning process, EBL system was used from Elionix. The two layer EBL resist was used. The first layer was spin coated at 4000 rpm (resist-PMMA-495) while the second layer was spin coated a 3000 rpm (resist PMMA 950). The baking temperature was 180 °C. Then metals such as Ti (10 nm) and Au (110 nm). were deposited by electron beam evaporation. Total nine devices have been tested. These devices were tested using Lakeshore TTPX cryogenic probe station and in an optical microscopy cryostat. The current-voltage (I-V) characteristics of nanowires based photodetector were measured with Keithley 2602 (I-V analyzer/source meter). For photoconductivity, the fabricated MSM photodetectors were excited at 450 nm using femto-second pulsed laser, having a spot size of 15–20 μm. All the photoresponse measurements were carried out at room temperature and the laser power varied from 1 mW to 20 mW.

3. Results and discussion

In the first part of this section, the fundamental properties such as structural and morphological of the CVD-grown β-Ga_2O_3 nanowires were studied. In the later part, the photoconductive properties of individual β-Ga_2O_3 nanowire based MSM photodetector have been described.

3.1. Properties of β-Ga_2O_3 nanowires

The morphology of the as-grown β-Ga_2O_3 nanowires was analyzed using field emission scanning electron microscopy (FESEM) and TEM. The surface of the CVD grown β-Ga_2O_3 nanowires, which are highly dense, is as shown in Fig. 2(a)-(b). The nanowires are uniform along the length as can be clearly seen in Fig. 2(b) and (c). The diameter of the as-grown nanowires is in the range of 100–200 nm whereas their lengths are in tens of micrometers. The high resolution TEM image is also shown in Fig. 2(d), indicating clear lattice spacing. The inset of Fig. 2(d) shows selected area electron diffraction (SAED) pattern exhibiting single crystalline nature of the nanowires. The growth direction of nanowires was along $[\bar{3}10]$. The detail explanation about SAED pattern has been reported in our previous studies [14,15].

In order to investigate the structural properties of β-Ga_2O_3 nanowires, XRD and Raman measurements were performed. In XRD, all diffraction peaks can be easily indexed according to JCPDS (Card no. 43–1012) of Ga_2O_3 with monoclinic crystal structure and the lattice parameters $a = 12.23$ Å, $b = 3.04$ Å, $c = 5.80$ Å, $\alpha = 90°$, $\gamma = 90°$ and $\beta = 103.7°$. Fig. 3(a) reveals that all the XRD diffraction peaks in the pattern matched well with monoclinic phase of Ga_2O_3 [15]. The Raman peak positions are also in good agreement with literature reports, which is shown in Fig. 3(b). The Raman spectra show twelve Raman peaks with positions at 113.6 (A_g), 144.3 (B_g), 169.3 (A_g), 199.8 (A_g), 319.4 (A_g), 346.4 (A_g), 416.2 (A_g), 474.8 (B_g), 629.3 (A_g), 652.0 (B_g), 657.5 (A_g) and 767 (A_g) cm^{-1}. These Raman peaks can be classified into three categories such as low (below 200 cm^{-1}), mid ($\leq$300 cm^{-1} and $\geq$500 cm^{-1}), and high ($\leq$500 cm^{-1}) frequency modes. In our present case the peaks such as 113.6 (A_g), 144.3 (B_g), 169.3 (A_g) and 199.8 (A_g) cm^{-1} are related to low frequency and assigned due to libration and translation of tetrahedra-octahedra chains. The peaks such as 319.4 (A_g), 346.4 (A_g), 416.2 (A_g) and 474.8 (B_g) cm^{-1} are related to mid frequency and produced due to deformation of Ga_2O_6 octahedra. The last four peaks such as 629.3 (A_g), 652.0 (B_g), 657.5 (A_g) and 767 (A_g) cm^{-1} are related to high frequency and designated to stretching and bending of GaO_4 tetrahedra. The more details of Raman spectra classification as well as modes related to β-Ga_2O_3 nanowires have been discussed in our previous reports [16,17]. Based on above results, we conclude that these nanowires have good crystalline