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Ultrafast photoresponse and enhanced photoresponsivity of Indium Nitride based broad band photodetector

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ABSTRACT

InN direct band gap semiconductor is a promising material in the nitride family for high power and high frequency optoelectronic devices. However, the reports on photo-sensing ability of the material are limited with photoresponsivity < 1 A/W only. Here, we report fast photoresponse from high quality molecular beam epitaxy grown InN islands delivering photoresponsivity of 13.5 A/W, about 30 times higher than the recently reported InN based photodetector operating in the near infrared spectral range. The ultra-broadband response with high photoresponsivity from visible to near infrared spectral range is experimentally demonstrated. To the best of our knowledge, this study presents the working of a photodetector having fast response (38 µs) and high photo detectivity (5.5×10^{10} W^{-1} $Hz^{1/2}$ cm) operating at room temperature. The device yields a quiet prompt saturation and decay under periodic illumination which demonstrate excellent stability and reliability of the device with switching time. The sub-linear dependent photocurrent on the bias voltage and incident power offers good tunability for multipurpose applications. This is the first report on ultra-broadband spectral range of InN based photodetectors that open up opportunities for developing the next generation high efficiency photodetectors.

1. Introduction

The ability to detect light over a broad spectral range in ultrafast detection time is vital to numerous technological applications such as imaging, sensing and communication [1,2]. III-Nitride semiconductors have become potential materials for fabrication of Photodetectors (PDs) since they have the asset of covering a wide range of spectrum varying from 0.7 to 6.2 eV (InN to AlN) along with the ability to tune the cut-off frequency of photodetectors. Moreover, these semiconducting materials hold better essential parameters required for an efficient ultra-violet (UV) photodetector such as high thermal stability, high electron saturation velocity, small dielectric constant & high breakdown field compared to the existing Si based technology for photodetectors [3]. Among III- nitride direct band gap semiconductors, Indium nitride (InN) has attracted much attention due to its unique potential characteristics such as high electron mobility, relatively high absorption coefficient, narrow band gap energy and peak drift velocity at room temperature, etc [4,5]. Up to now, most research efforts on development of III-Nitride based photodetector has been focused on UV operation [6,7]. Though, the developments in telecommunication demand for the extension of the photodetection range towards the infrared (IR) spectral region apart from UV detection. To date, nano-materials including metallic nano-particles [8] and colloidal quantum dots have been used in IR photodetection [9]. IR photodetection generally relies on small band gap semiconductor compounds such as HgCdTe, PbS etc [10]. However during earlier portion of 2000s, preliminary interest was on InGaAs, InGaP and InP materials. The performance of these devices was generally not promising and often requires operating temperature below liquid nitrogen levels. Moreover, these device performances were still lackluster, with responsivity regularly below 1 A/W [10]. In contrast to these materials, graphene is also believed to have great potential in broadband photodetection [11], due to its unique gapless electronic structure [12]. However, its atomic thickness induced limited optical absorption (~ 2.3%) of a monolayer of carbon atoms along with the ultrafast recombination of photo-generated carriers results in suffering the poor responsivity (photo-generated current per incident optical power) [13–16]. Konstantatos et. al. demonstrates integration of colloidal quantum dots in the light absorption layer to improve the responsivity of graphene photodetectors to 10^7 A/W [17].

Owing to an interesting nature of InN semiconductor, low effective mass of electron ($m^*0.06m_e$) [18] enables it to be a reliable candidate for high-speed electronics and its high internal gain which can lead to

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high photoresponsivity. Chen et al. [19] have presented temperature sensitive photosensitivity and long carrier life time induced high photocurrent gain ($\sim 10^7$) in the InN nanowires. Although, having the superior properties for photodetection [20], the reported InN based photodetectors are very few [21–23]. Winden et al. reported a vertical nano-pyramid InN photodetector with spectral responsivity of 0.2 A/W [21]. So far, the highest photoresponsivity reported on InN based photodetector is 0.44 A/W [22]. It is because of challenges in synthesizing high-quality InN due to its low dissociation energy and the lack of appropriate substrates [24]. Moreover, the growth of high quality epitaxial InN on GaN, sapphire and silicon leads to the generation of high dislocation density which further guide to higher leakage current at the interface [25,26]. The main challenge is to develop and assess photodetectors having high photoresponsivity and simultaneously possesses a large active area, high internal efficiency and fast response time. In the present work, we demonstrated InN based ultra-broadband visible- near infrared (VIS-NIR) photodetector fabricated on Si (111) substrate using plasma assisted – molecular beam epitaxy (PAMBE) delivering the enhanced photo responsivity of 13.5 A/W and 2 A/W in the NIR and visible region respectively. In addition, the investigated switching time reveals a sharp response time in the range of microsecond for NIR detection. Moreover, the photoresponse characteristics observed from the fabricated InN based PD are comparable with the potential graphene based broadband PDs. This is the first report on ultra-broadband (VIS-NIR) and high responsive photodetector based on InN semiconductor operating at room temperature. Therefore, the results open up new opportunities for developing the next generation high efficient photodetectors with broad spectral range.

2. Materials and methods

The InN photosensing film was grown by PAMBE system (Riber Compact 21) equipped with a radio frequency plasma source (Addon) for supplying active nitrogen species and effusion cells to evaporate Indium and Aluminum on the substrate. The Si (111) (Boron doped (p type), 5–15 Ω-cm, 325 ± 25 µm) has been used as substrate for the growth of InN film, which was chemically pre-cleaned by employing the standard RCA cleaning process and immediately loaded into MBE system to avoid re-oxidation followed by out-gassing in the buffer chamber at 600 °C. The nitrogen flow of 1.5 sccm and RF plasma power of 500 W was kept constant throughout the growth process. Initially, an AlN buffer layer was grown on an atomically clean Si (111) 7×7 reconstructed surface at 850 °C, followed by the epitaxial InN film which was grown at 540 °C with In beam equivalent flux of 2×10^{-7} Torr. The epitaxial growth of InN film was analyzed in-situ by Reflection High Energy Electron Diffraction (RHEED) using STAIB electron gun operating at 12 keV. The structural quality of InN film was examined by High Resolution X-Ray Diffraction (HRXRD, Panalytical X'Pert PRO MRD System) instrument. Field Emission Secondary Electron Microscopy (FESEM, ZEISS AURIGA) was employed to analyze the morphology of the grown InN film. Crystallinity and orientation of the as-grown InN film was further explored by using High Resolution Transmission Electron Microscopy (HRTEM, FEI, Tecnai F30 G2 STWIN). A schematic diagram of the fabricated device is illustrated in the result part. Two electrodes of Ag metal contact were deposited on the InN film to collect the photo-generated current. Optoelectrical measurements were carried out using probe station setup (Cascade Microtech EPS150TRIAX) which has shield enclosure (EPS-ACC-SE750) for low signal measurements. The spectrometer is equipped with halogen source (power density, $P_d = 22\ \mathrm{mW/cm^2}$) for VIS detection and focused laser ($\lambda = 1064$ nm, $P_d = 6–29\ \mathrm{mW/cm^2}$) for NIR detection.

3. Results and discussion

The structural quality of the grown InN islands was inspected using HRXRD measurement (Fig. 1(a)). The HRXRD result shows a pronounced diffraction peak from InN (10 − 11) plane and AlN (0002) plane at 32.85° and 36° respectively, suggesting that the sample crystallizes in the wurtzite hexagonal structure. The visible presence of sharp and narrow x-ray diffractions of InN in the 2 theta-omega scan illustrates the highly crystalline InN film grown epitaxially along (10 − 11) direction (s-plane) on Si (111) substrate. The physical explanation could be the high growth temperature (540 °C) leads to the formation of InN islands epitaxially growing along (10 − 11) orientation [25]. Moreover, 2theta-omega scan shows a tiny peak at 39° (not visible in the spectra) which shows the presence of metallic In on the film. Anyebe et al. [25] also proven that metallic In adlayers will be present along with InN when the film are grown at extremely high growth temperature. This is due to increased InN dissociation rate due to high growth temperature which leads to an In rich condition, thereby a preferential adsorption of In metal on the surface (Influence of metallic In on the photoresponse behavior has included in the Supplementary information, S1). The d-spacing in the growth direction (along (10 − 11) plane) for InN is calculated directly by using Bragg's law,

$$2d_{hkl} sin\ \theta_{hkl} = n.\ \lambda \tag{1}$$

where, d is the lattice spacing, which is given by $d_{hkl} = 1/\sqrt{\{4/3(h^2 + k^2 + l^2)/a^2 + l^2/c^2\}}$ for hexagonal symmetry system, θ is the measured angle of diffraction, hkl are the miller indices, λ is the wavelength of x-ray source ($\mathrm{CuK}_{\alpha 1} = 1.5406$ Å) and 'a', 'c' are the lattice parameters of the grown InN. The value of d-spacing along InN (10 − 11) plane of diffraction was calculated to be 0.2725 nm. Further, HRXRD analysis has been employed to procure the information of crystalline quality as well as dislocation density of InN epitaxial layer. Inset of Fig. 1(a) shows the ω-scan in the symmetric plane of diffraction of InN film having full width half maximum (fwhm) of 373″. The fwhm value has been used to calculate threading dislocation (TD) density by using the following equations,

$$\mathrm{TD} = \frac{\beta^2}{9b^2} \tag{2}$$

where β is the fwhm value measured for (10 − 11) by HRXRD ω-scan and b is the Burgers vector length. The direction of burger vector is along $1/6 < 20\text{–}23 >$ [27] where the magnitude of b taken here for TD calculation is $a_{\mathrm{InN}} = 3.533$ Å. The calculated TD (screw) density was found to be $2.8 \times 10^8\ \mathrm{cm^{-2}}$ which is one order magnitude lower than the conventional InN epilayer. Recently, Wang et al. [28] reported N-polar InN with significantly reduced TD density (screw TD of $6 \times 10^8\ \mathrm{cm^{-2}}$) grown on sapphire substrate. The detailed structural characterization of the InN islands grown on Si (111) was performed by HRTEM. The cross sectional TEM image (Fig. 1(b)) shows the confirmation of the InN islands grown on AlN buffer layer on Si (111) substrate. The thickness of the AlN buffer layer was found to be 70 nm whereas InN islands are between 150 and 200 nm. The lattice spacing of 0.27 nm (inset Fig. 1(b)) corresponds to d-spacing of InN (10 − 11) crystal plane indicating the growth of crystalline islands along s-plane direction. The observed d-spacing value from HRTEM image is in good accordance with the calculated d-spacing value from HRXRD by Bragg's law.

Furthermore, morphological analysis by FESEM reveals that InN growth on Si (111) surface at 540 °C possesses a continuous surface morphology in large scale with uniformly distributed InN island like structure on the surface (Fig. 1(c)). The growth kinetic plays a dominant role in the observed island formation where surface energy anisotropy has been considered as the main reason to form nano sized structures. It can be explained using Wulff construction [29] where the surface Gibbs free energy is minimized by assuming a shape of low surface energy. Therefore, a nanostructure/island like structure growth will be preferable at high temperature. Anyebe et al. [25] studied the evolution of InN nanorods to microstructures on Si (111) by MBE where they have observed the similar structure of InN islands grown epitaxially along (10 − 11) direction at varied substrate temperature of