A Near-Infrared Range Photodetector Based on Indium Nitride Nanocrystals Obtained Through Laser Ablation

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***Abstract*— We present a proof-of-concept photodetector that is sensitive in the near-infrared (NIR) range based on InN nanocrystals. Indium nitride nanocrystals (InN-NCs) are obtained through laser ablation of a high pressure chemical vapor deposition grown indium nitride thin film and are used as optically active absorption region. InN-NCs are sandwiched between thin insulating films to reduce the electrical leakage current. Under −1 V applied bias, the recorded photoresponsivity values within 600–1100-nm wavelength range are as high as 3.05×10^{-2} mA/W. An ultrathin layer of nanocrystalline InN thin film is, therefore, a promising candidate for NIR detection in large area schemes.**

***Index Terms*— Photodetector, near-infrared (NIR), indium nitride, nanocrystals.**

I. Introduction

Nanomaterials which possess plasmonic resonance features enabling the optical tuning of plasmonic devices that operate in near-infrared (NIR) range are under close scrutiny for critical nanophotonics and telecommunication applications [1]. The fact that a non-negligible portion of solar spectrum consists of NIR wavelength components strengthens the importance of the fabrication of plasmonic enhanced devices that operate in this wavelength range [2]. Up to date, various nanomaterials including metallic nanoparticles and colloidal quantum dots have been used in NIR plasmonic applications and significant enhancements in photo-generated currents have been observed [2]–[5]. Among the nanostructures which have NIR plasmonic resonance features are indium nitride nanocrystals (InN-NCs) [1], [6]–[8]. Not only having a low bandgap value of 0.7–0.9 eV, but also its high electron mobility make this material applicable in high speed and high frequency electronic device applications [9], [10]. It is possible to obtain InN-NCs through complex chemical procedures and tune their optical properties through electrochemical oxidation and reduction [1], [7], [8]. However, these procedures limit the use of InN-NCs in biological and environmentally friendly optoelectronics applications [6]. On the other hand, our group has successfully synthesized 3.24–36 nm sized InN-NCs using laser ablation of a high pressure chemical vapor deposition (HPCVD) grown InN thin film and reported the optical characteristics of InN-NCs [6]. Furthermore, a recent work of Intartaglia et al. also proves the efficiency of laser ablation technique in the synthesis of gram scale semiconductor nanoparticles that paves the way for large-scale optoelectronic applications of semiconductor nanoparticles [11]. Despite various experimental efforts to synthesize InN-NCs, their use in NIR photodetector applications have hardly been studied [12]–[14]. NIR photodetectors based on metal organic chemical vapor deposition (MOCVD) grown InN nanostructures have successfully been built and their performances have been reported in the literature [12] and [13]. However, these works involve the use of vacuum techniques and require high temperatures that limits the throughput and scalability of InN-NCs in large area photonics applications. In this letter, we present a proof-of-concept NIR range photodetector based on InN-NCs obtained through laser ablation of a HPCVD grown InN thin film. A schematic representation of the fabricated InN-NCs photodetector is given along with a scanning electron microscopy (SEM) image and electrical measurements of the fabricated photodetector.

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II. Device Fabrication and Nanocrystal Synthesis

The growth of InN thin film through HPCVD method is described in literature [15]. The generation of InN-NCs was carried out using a commercial nanosecond pulsed ND:YLF laser (Empower Q-Switched Laser, Spectra Physics) operated at 527 nm with pulse duration of 100 ns and a pulse repetition rate of 1 kHz. The laser output power was 16 W with a pulse energy of 16 mJ. The laser beam was focused on

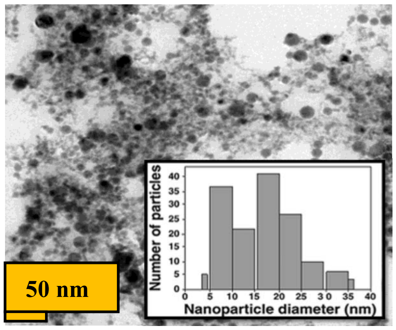

Fig. 1. Transmission electron microscopy (TEM) image of laser synthesized InN-NCs, size distribution given in the inset.

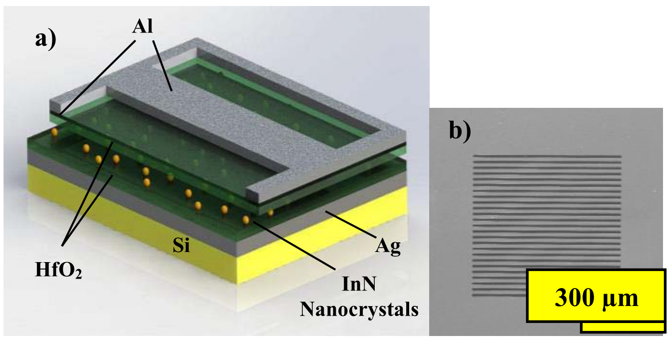

Fig. 2. a) InN-NCs photodetector, b) SEM image of InN-NCs photodetector, finger size = 10 μm, width = 10 μm.

InN sample target containing 20 ml pure ethanol using a plano-convex lens with a focal length of 50 mm. The height of liquid layer over the InN target was 5 mm. The laser ablation was carried out for 5 mins [6]. Fig. 1. shows a transmission electron microscopy (TEM) image of the laser synthesized InN-NCs in ethanol solution. InN-NCs are spherical and are within 3.24–36 nm size range with an average size of 16 nm. The optical and spectroscopic properties of InN-NCs along with their crystalline qualities are reported in detail by our group elsewhere [6]. Although InN-NCs are prepared from HPCVD grown thin film, it is possible to obtain InN-NCs directly from bulk InN pieces with laser ablation technique.

III. Device Fabrication

InN-NC photodetector [Fig. 2(a)] fabrication was performed on highly p-type ($0.1-0.9$ Ω cm boron doped) Silicon substrate. The substrate was cleaned through standard cleaning procedures involving acetone, isopropanol and water. 30 nm of Ag thin film was thermally evaporated on the Si substrate. This was followed by deposition of 4 nm thick HfO_2 on Ag/p-Si structure using atomic layer deposition. InN-NCs were then drop-casted on the HfO_2/Ag/p-Si structure. This was followed by deposition of 4 nm thick HfO_2 to sandwich InN-NCs between two HfO_2 dielectric layers. A thin 10 nm of Al layer was evaporated on top of the sandwich structure for charge collection followed by active area patterning by photolithography. Finally, 150 nm of Al was evaporated to form the front and back contacts. A scanning electron microscopy (SEM) image of the fabricated InN-NCs photodetector is given in Fig. 2(b).

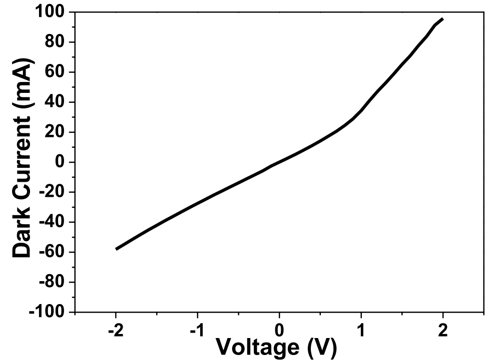

Fig. 3. Dark I-V characteristics.

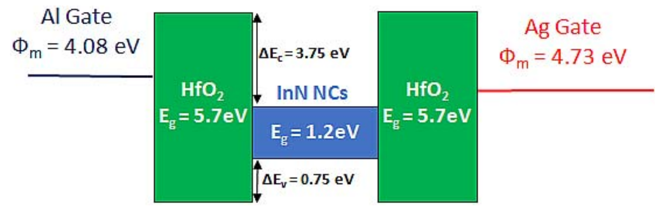

Fig. 4. Electronic band structure diagram of the fabricated InN-NCs based photodetector device.

IV. Results and Discussion

A. Dark I-V Characteristics

The electrical characterization of the fabricated devices was performed with a commercial Keithley 4200-SCS type semiconductor parameter analyzer. Current-voltage (I–V) characteristics were obtained under dark conditions as shown in Fig. 3. The dark current of the device is relatively high. Device parameters such as the thickness of the dielectric layers could be optimized to reduce the dark current and increase the signal-to-noise ratio. However, such an optimization is beyond the scope of this letter.

Different devices exhibit repeatable and scalable electrical characteristics that verify repeatable and robust device preparation process. The electronic band structure of InN-NCs based devices is shown in Fig. 4. With applied reverse bias voltage, generated electron-hole pairs are collected by metal/HfO_2 junctions. Since HfO_2 barriers are quite thin (4 nm each), electron hole pairs can tunnel through these barriers.

B. Photoresponsivity Characteristics

Photoresponsivity measurements were performed using a Fianium SC400-4 supercontinuum light source equipped with acousto-optical tunable filter in the 600–1100 nm range. Outcoming light is modulated using a mechanical chopper. The photocurrent is read using a lock-in amplifier which is connected in series to the fabricated device and voltage source. Photoresponsivity values are measured within the wavelength range of 600–1100 nm, under -0.25 V, -0.5 V, -0.75 V and -1 V biasing conditions. The results are shown in Fig. 5.

As seen in Fig. 5, photoresponsivity values increase as bias voltage increases from -0.25 V to -1 V, due to more

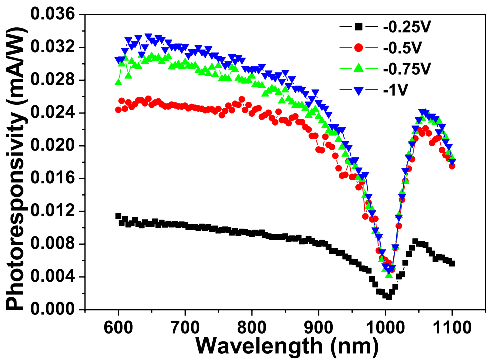

Fig. 5. Photoresponsivity spectrum obtained under bias voltages of −0.25 V, −0.5 V, −0.75 V and −1 V.

efficient charge collection. Responsivity decreases steadily from 600–1005 nm. There is a steep increase of responsivity from 1005–1050 nm where a clear peak is observed. Photoresponsivity characteristics agree well with the HPCVD grown InN film which confirms that photogenerated current is due to InN-NCs [15]. The steady decrease in responsivity from 600–1005 nm and the steep increase in responsivity from 1005–1050 nm are explained by deep level excitations confirmed in the UV/VIS spectrum of InN thin film [16]. The decrease in photoresponsivity from 900–1005 nm is explained by the band edge of InN as reported in [16]. The slight increase in photoresponsivity in NIR region is attributed to InN point defects. It is reported that such point defects (antisite N on an In site (N_{In}) and In on an N site (In_N)) can occur during crystal growth [17]. Such defects are shown to increase optical absorption at around 1200 nm, wich agrees with our experimental results. Compared to UV/VIS spectrum of InN thin film, the shift in photoresponsivity values to lower wavelengths occurs due to Mose-Burstein effect [1] and due to the larger dielectric constant of the surrounding Silicon substrate (compared to glass) and HfO_2 layers (compared to air) [18]. InN nanostructured layers based on MOCVD or MBE growth are significantly different than the InN-NCs obtained using laser ablation. The main drawback of conventional techniques such as MOCVD and MBE is the high growth temperature (ca 500 °C). On the other hand, laser ablated NCs are deposited at room temperature that paves the way for integration of photodetectors on low-cost substrates.

V. Conclusions

A scalable and agile near infrared range photodetector technology is demonstrated based on InN-NCs obtained through laser ablation of a HPCVD grown InN thin film. Under −1 V bias, photoresponsivity values vary between 3.05×10^{-2} mA/W and 1.81×10^{-2} mA/W. Such InN-NCs could find potential applications in low-cost optoelectronics applications such as flexible and disposable sensors and solar cells. Laser induced synthesis of InN-NCs has great potential in large-area optoelectronics applications by providing greater throughput and scalability.

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