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Electrical and Photo-Electrical Characteristics of a GaInNAs based p-i-n Diode with 10-undoped Quantum Wells

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An electrical and photo-electrical characteristics of a dilute nitride GaInNAs p-i-n diode with 10-undoped quantum wells (10-QWs) were investigated at room temperature. The QWs consists of 10-nm thick and separated by 10 nm GaAs barriers. The dilute nitride-based p-i-n diode exhibits a good rectifying behavior and discloses that the fabricated devices has a Schottky property. The current-voltage (I-V) characteristics showed the forward-biased region of I-V curves exhibited an exponential dependence of current on applied bias, whereas the reversed-biased region shows the saturation current with negative reverse current value (leakage currents) under dark condition. As the device was exposed to photo-illumination, the electrical characteristic exhibited an increase of dark-current by four orders of magnitude to that of device under dark condition. Upon photo-illumination, there was also a shift in the threshold voltage from 0.58 V to 0.73 V. Ideality factor, n and barrier height, Φ_B are main electrical parameters were extracted using conventional forward bias I-V characteristics. The values of barrier height, which were obtained were in good agreement with other reported values. The value of n was found to be 1.95 and 28.56. Ideality factor approaches 2 indicated that fully trap-assisted recombination in quantum wells. While, high ideality factor at photo-illumination indicated that the charge transport mechanism is controlled by tunnelling emission.

Keywords: dilute nitride, GaAsNAs, p-i-n diode, current-voltage, ideality factor, barrier height

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I. INTRODUCTION

Various material system with different structure design have been investigated to improve opto-electrical conversion capability including group III-V dilute nitride materials. Interest in the dilute nitride material started from the discovery that small fractions of nitrogen, typically 3-5% composition into the host of group III-V lattice led to a large red-shift (Bank *et. al.,* 2007; Mascarenhas et al., 2002).

GaInNAs provides an independent band-gap tunability and lattice constant due to the addition of a few percent of nitrogen and indium to the group III-V semiconductor to allows a wide range up-to 2500 nm in near-infrared (NIR) spectrum (Jackrel *et. al.,* 2007; Nordin *et. al.,* 2018; Browne *et al.,* 2015). Thus, GaInNAs is considerable importance nowadays for a variety of applications including wavelength tunable photodetectors, lasers, light emitting diodes, and photovoltaics.

Recently, intrinsic region of GaInNAs/GaAs or GaInNAs/GaNAs based p-i-n diode consists of quantum wells (QWs) using hot electron light emitting and lasing semiconductor heterostructure can be enhanced the functionality of the optoelectronics devices (Balkan et al., 2000; Chaqmaqchee et al., 2011). In this work, a comparative analysis of current-voltage (I-V) characteristics under dark and photo-illumination conditions will be performed in a GaInNAs/GaAs p-i-n diode with quantum wells (MQWs).

II. MATERIALS AND METHODS

A. *Device Structure*

The cross-section structure of dilute nitride-based p-i-n diode is shown in Figure 1. The diode was grown on an n-type GaAs (100) substrate using molecular beam epitaxy (MBE) system with a radio frequency (RF) plasma source to supply nitrogen (Nordin *et. al.,* 2018). Initially, two 10 nm undoped GaAs graded layers were grown at the top and bottom of intrinsic region, sandwiched between GaAs and AlGaAs layers. These layers consists of a 600 nm emitter p-doped GaAs barrier with Be = 2 × 10^{18} cm^{-3}, and then followed by 40 nm a p-doped AlGaAs with Be = 2 × 10^{18} cm^{-3}, a GaAs top layer with Be = 4 × 10^{18} cm^{-3}, a base contact consisting of 1900 nm n-doped GaAs with Si = 2 × 10^{17} cm^{-3}, 20 nm n^+-doped GaAs with Si = 2 × 10^{18} cm^{-3} and n^+-GaAs as a substrate. The dilute nitride devices were fabricated in the shape of a mesa with a top circular aperture of 200-µm in a diameter window using photolithography technique. Finally, Au (gold) as top (p-type) and bottom (n-type) metal contacts was deposited using thermal evaporation technique.

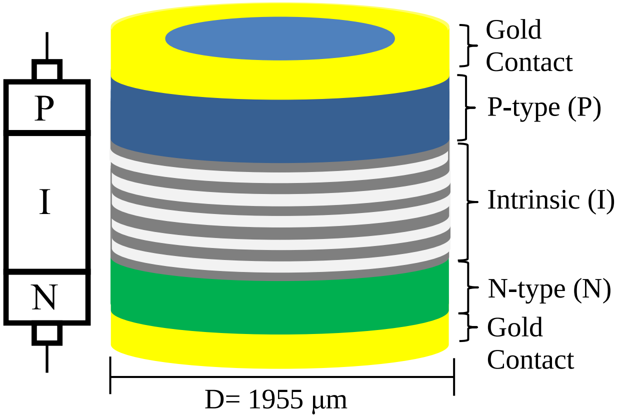

Figure 1. Structure of a GaInNAs/GaAs p-i-n diode.

B. *Measurement and Analysis*

For electrical measurement, the device was adhered with silver paste onto a copper heat sink. Samples for electrical and photo-electrical characterization were carried-out using current-voltage (I-V) measurement, which performed by using a Keithley 2400 source measurement unit (SMU) with two-point probe in ambient condition from a range of +1.0 to -1.0 V for forward-bias and reverse-bias voltages. The photo-illumination was carried out using portable solar simulator (PECCELL Technology) under dark and light (1.077 kW/m^2 light irradiance) conditions.

III. RESULTS AND DISCUSSION

A. *Diode Characteristics*

Figure 2 shows a set of I-V curves taken under dark condition and at photo-illumination, plotted both on forward- and reverse-biased region. The forward-biased region of I-V curves exhibited an exponential dependence of current on applied bias, whereas the reversed-biased region shows the saturation current with a negative reverse current value. This indicated that the dilute nitride-based p-i-n diode exhibits a good rectifying behaviour and discloses that the fabricated devices has Schottky properties. Under dark condition, the junction behaviour is suitable depicted by thermionic emission (TE) theory. However, the diode current produces at forward-bias region at photo-illumination is five times higher than that of under dark condition at 1.0 V bias. This indicated that charge transported across junction is no longer associated with thermionic emission mechanism (Gullu, et al., 2008). This finding is supported by the slightly difference in threshold voltages under dark and photo-illumination conditions which are 0.58 V and 0.73 V, respectively. Thus, the I-V characteristics of dilute nitride diode is further investigated using logarithmic scale to understand the junction behaviour. Moreover, the reverse current at photo-illumination (dark-current) exhibited an increment by a factor of about 10000 (four orders of magnitude) from dark condition at -1.0 V bias.

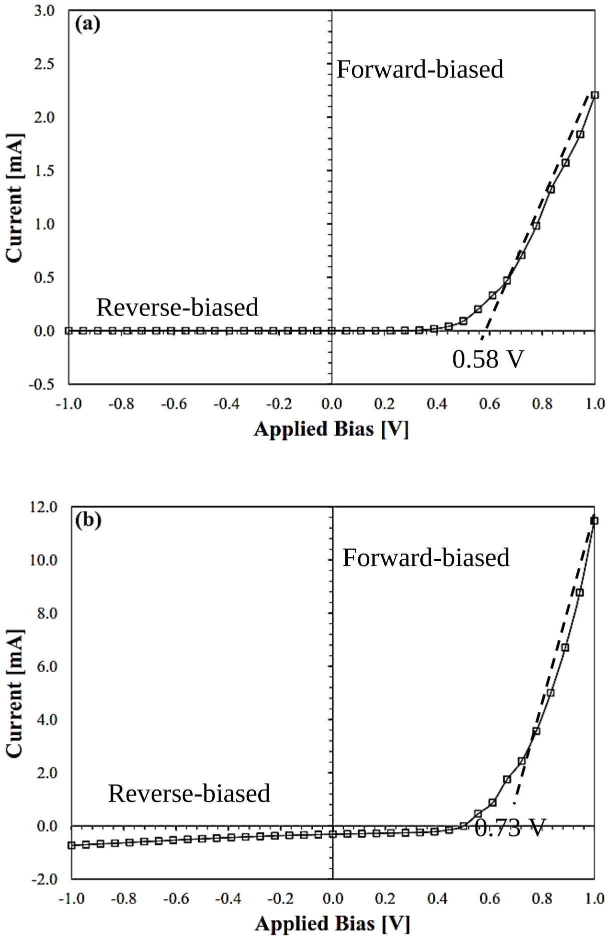

Figure 2. (a) Electrical characteristic under dark condition and (b) photo-electrical characteristic under photo-illumination condition for a dilute nitride device with 10-quantum wells (10-QWs).

B. Electrical Parameters

Figure 3 shows the linearity of electrical characteristics in the logarithmic current scale. The results indicate that the forward-bias region where an exponential dependence of current on bias. Note that there is a discontinuity at the origin in Figure 3(a) caused by having a change of scales from forward to reverse voltage during characteristic measurement.

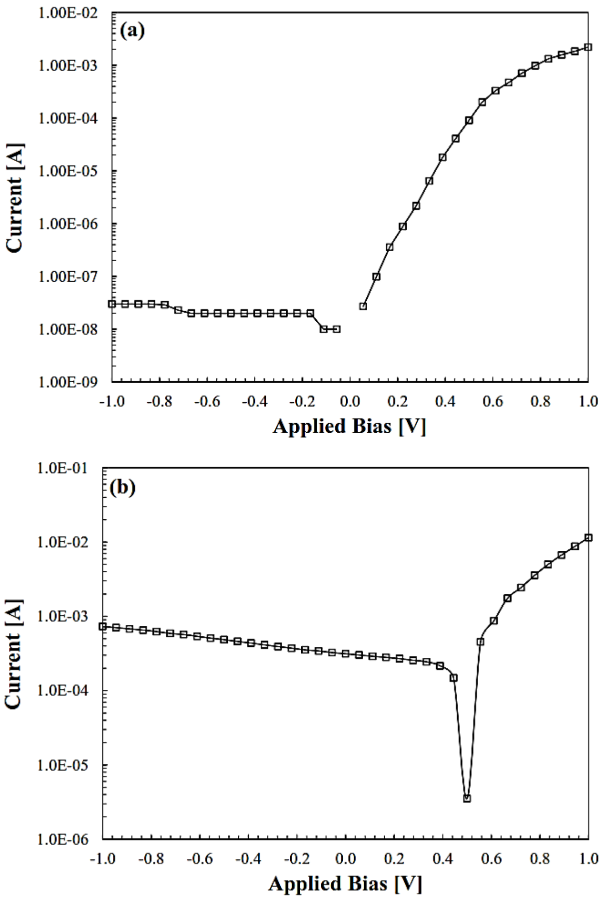

Figure 3. Logarithmic scale of (a) electrical characterization under dark and (b) photo-electrical characterization under photo-illumination.

The thermionic emission model is one of numerical models for heterojunction devices and commonly used to extract the electrical parameters and obtain the comparative characteristic of the photo-electrical properties. According to the theory of thermionic emission, the diode current can be expressed as (Sze & Ng, *et. al.,* 2006)

$$I_D = I_S\left(e^{V_D/nV_T} - 1\right) \qquad (1)$$

where I_S is a saturation current or reverse-biased constant current, V_D is the applied voltage across the diode, V_T is the thermal voltage, and n is the diode ideality factor (or emission coefficient). The diode ideality factor is used to describe the difference between ideal device and non-ideal devices. The value of ideality factor varies from 1 to 2 depending on various impacts such as semiconductor material, mechanism process, interface states between materials and fabrication process. For ideal diode, the value is assumed to be equal to 1 (unity). The thermionic emission is derived with the assumption that the only processes giving rise to current in the diode are drift current, diffusion current and Shockley-Read-Hall (SRH) or Auger recombination-generation.

Furthermore, the value of I_S can be obtained by extrapolating the linear portion of the logarithmic scale of I-V characteristics at unbiased voltage (0 V) and can be expressed as (Tuan, et al., 2015; Imer, *et. al.,* 2016; Sertel, *et. al.,* 2017)

$$I_S = AA^*T^2 \cdot e^{q\emptyset_B/kT} \qquad (2)$$

where A is the contact area, A^* is the Richardson constant and Φ_B os the barrier height between contact-semiconductor interface. The barrier height (Φ_B) and ideality factor (n) are obtained by using the following expressions (Tuan, et al., 2015; Imer, et al., 2016; Sertel, et al., 2017),

$$n = \frac{q}{kT}\frac{\mathrm{d}V}{\mathrm{d}\ln(I)} \qquad (3)$$

$$\emptyset_B = \frac{kT}{q}\ln\frac{AA^*T^2}{I_S} \qquad (4)$$

Table 1. Electrical parameters of a GaInNAs/GaAs p-i-n diode with 10-undoped MQWs determined by I-V characteristic.

Dark		**Photo-illumination**	
n	Φ_B [eV]	n	Φ_B [eV]
1.95	0.67	28.56	0.39

The electrical diode parameters of the dilute nitride GaInNAs/GaAs p-i-n diode with 10-QWs is summarized in Table I. The barrier height values, especially under dark condition, which were obtained is in good agreement with other reported values (Chitnis, *et. al.,* 2000). The calculated the ideality factor values of the p-i-n diode are 1.95 and 28.56 under dark and photo-illumination conditions, respectively. The ideality factor value under dark condition is approximately equal to 2, which indicates that the carrier recombination in the depletion region or space charge region is a dominant factor in current transport mechanism (Sertel, *et. al.,* 2017; Chitnis, *et. al.,* 2000; Shah, *et. al.,* 2003). Meanwhile, high ideality factor was reported in Schottky diode such as gold-strontium titanate (Au-STO) (Gupta, *et. al.,* 2010; Gupta, et al., 2009). As the value of ideality factor was increase under photo-illumination condition may attributes to recombination-generation currents during light absorption, the existence of interface states between metal contact and semiconductor interface in a heterojunction device, the existence of series resistance, a broad intrinsic distribution of low-Schottky barrier height (low-SBH) or shallow patches and charge carrier tunnelling (Chitnis, *et. al.,* 2000; Mamor, *et. al.,* 2014; Alialy, *et. al.,* 2014; Elgazzar, *et. al.,* 2014). In addition, the ideality factor also a strong temperature dependent non-physical parameter of a diode (Gupta, *et. al.,* 2010).

Furthermore, the numerical model may not suitable method to describe the high value of ideality factor in photo-illumination condition, which non-agree with thermionic emission theory. There is high possibility that mechanism such as tunnelling emission starts to control the current flow because the dilute nitride-based p-i-n diode consist of a few thin interfacial layers (Gullu, *et. al.,* 2008).

IV. SUMMARY

The electrical and photo-electrical characteristics of an III-V dilute nitride p-i-n diode with quantum wells (10-undoped quantum wells) were characterized by current-voltage (I-V) measurement under dark and photo-illumination conditions at room temperature. The I-V characteristics of the p-i-n diode were analysed using thermionic emission theory based on a numerical model. The ideality factors were found to be 1.95 and 28.56 under dark and photo-illumination, respectively. The ideality factor under dark condition was good agreement with other reported values, thus indicated that by the trap-assisted recombination by both carriers in space-charge region is dominant factor in contributing to the current transport mechanism in dilute nitride p-i-n diode. Meanwhile, the main reason contribute to the high ideality factor for photo-illumination condition can be referred to various impacts which is the possibility of tunnelling emission process controlling the charge transport mechanism is high.

V. ACKNOWLEDGEMENT

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