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Electrical Properties of a $Ga_{0.952}In_{0.048}N_{0.016}As_{0.984}$ p-i-n Schottky Barrier Diode

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The electrical characteristic of a $Ga_{0.952}In_{0.048}N_{0.016}As_{0.984}$ p-i-n diode with quantum wells was characterized by current-voltage (I-V) measurement at room temperature. The electrical parameters of the diode such as a leakage current (I_o), the threshold voltage (V_T) and dynamic resistance (R_d) were extracted from the I-V characteristics. The p-i-n diode has a leakage current of 0.010 μA, threshold voltage of 0.22 V and dynamic resistance of 262 kΩ. Moreover, the Schottky parameters of the Ti-Au/n-GaAs p-i-n diode such as an ideality factor (η), a Schottky barrier height (Φ_b) and series resistance (R_s) were determined using thermionic emission (TE) analysis of the forward-bias I-V characteristic as well as Norde and Cheung functions. The Schottky diode parameters showed an ideality factor of 4.79 with a barrier height of 0.79 eV were obtained using forward-bias I-V characteristics. On the other hand, barrier heights determined from the Norde and Cheung functions were calculated at 0.87 eV and 0.71 eV, respectively. As there is an inconsistency between the current-voltage characteristics and the models, the necessity to investigate the temperature dependence diode parameters for accurate determination of the mechanism responsible for the charge transfer and Schottky barrier height of GaInNAs p-i-n diode.

Keywords: GaInNAs; p-i-n diode; current-voltage; barrier height; thermionic emission theory

I. INTRODUCTION

Recently, dilute nitride semiconductors have been comprehensively developed for optoelectronic devices, especially in photovoltaic and photodetector applications. The incorporation of nitrogen (N) into the conventional III-V compound results in the dilute nitride material being able to tune its operational wavelength into an infrared range of 1.1 to 1.6 μm by tailoring its fundamental bandgap (Balkan *et al.*, 2015). Nitrogen has a small atomic radius and large electronegativity results in a large miscibility gap between the arsenides and nitrides (Mazzucato & Potter, 2008). Hence the nitrogen is likely acts as an impurity than a true alloy constituent, and thus these atomic differences give rise to interesting physical properties. The dilute nitrides, for example, GaInNAs-based devices have several interesting properties such as a long wavelength of p-i-n infrared photodiode, large redshift bandgap tunability, made of highly refractive material. The GaInNAs-based devices become a potential candidate to replace indium-phosphide (InP)-based devices in the development of Bragg's reflector (DBRs) on resonant-cavity-enhanced photodetector (RCEPD) devices (Balkan *et al.*, 2015). High-cost fabrication with a drawback of a non-monolithic growth process and low refractive index

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Table 1. Schottky diode parameters using the I-V characteristic and C-V measurement for a metal/n-type GaAs

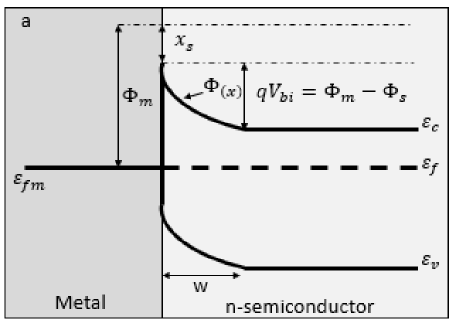
Analysis Method	MS contact	Ideality Factor, η	Barrier Height, Φ_b [eV]	Reference
I-V characteristic	Ti-Au/n-GaAs	2.70	0.51	Filali *et al.*, 2017
	Ti-Au/n-GaAs	5.59	0.48	Güçlü, Faruk and Özdemir, 2016
	Au/n-GaAs	1.05	0.60	Faruk *et al.*, 2008
C-V measurement	Au/n-GaAs	3.06	0.45	Kacha *et al.*, 2015
	Au/n-GaAs	1.95	0.53	Mamor *et al.*, 2014
	Ni/n-GaAs	1.10	0.70	Aldemir, Kökce and Özdemir, 2012

contrast, are among the main issues in the development of InP-based devices (Mamor *et al.*, 2014). Furthermore, the GaInNAs-based devices have been introduced due to their ability to have lattice-matched on the structure of GaAs (Erol *et al.*, 2017) and monolithic growth process in developing DBRs stacks on RCEPD devices (Balkan *et al.*, 2015) with low-cost fabrication. Besides that, the Schottky barrier diode (SBDs) parameters of GaInNAs multiple quantum wells (MQWs) p-i-n devices often require perfect metallization. Thus, the study of the interface between metal and n-type GaAs diode is important for the current conduction mechanism on the metal-semiconductor (MS) interface (Kacha *et al.*, 2015). In a previous study, the SBDs parameters of a metal/n-type GaAs such as ideality factor (η), Schottky barrier height ($\emptyset_b$) and series resistance have been determined by using the forward-bias current-voltage (I-V) characteristic and temperature dependence capacitance-voltage (C-V) measurement (Filali *et al.*, 2017). There are inconsistency in finding Schottky diode parameters between the I-V characteristic and C-V measurement due to the presence of inhomogeneous barrier at the semiconductor/metal interface. Table 1 summarizes the comparison of Schottky diode parameters extracted using the I-V characteristic and C-V measurement for a metal/n-type GaAs.

In this work, an investigation on I-V characteristics for a GaInNAs p-i-n diode with MQWs was presented. The forward- and reverse-bias of the I-V characteristics allows the extraction of electrical diode parameters such as leakage current, threshold voltage and dynamic resistance. Later, the forward-bias I-V characteristics for SBD parameters of the Ti-Au/n- GaAs were analyzed through the thermionic emission theory (TE). Moreover, the SBD parameters obtained from Norde and Cheung functions were compared with those of the forward-bias I-V characteristics.

II. BACKGROUND STUDY

Figure 1 shows a schematic diagram of the Schottky barrier diode in the (a) equilibrium and under the (b) forward-bias. Fundamentally, the value of η can be reflected in the domination current flow across a diode, while the $\emptyset_b$ is defined as the potential barrier (V_D) difference between the Fermi level of metal (ε_{fm}) and covalent level band edge semiconductor material as shown in Figure 1, where x_s is an electron affinity, V_{bi} is a built-in potential and w is a barrier width of semiconductor. Based on the schematic diagram in Figure 1 (a), the work function of a metal, $\emptyset_m$ is higher than the work function of a semiconductor, $\emptyset_s$. This causes more electrons to be transferred from the semiconductor to the metal in equilibrium. Under the forward-bias condition, the reduction of the potential barrier enhanced the electron flow from semiconductor to metal (Kacha *et al.*, 2015). However, the electron flow from the metal to the semiconductor remains unchanged. Basically, the current conduction mechanism on the MS interface was investigated using a TE analysis method, in which the Schottky parameter on MS contacts can be determined in a wide temperature range (Mamor *et al.*, 2014).



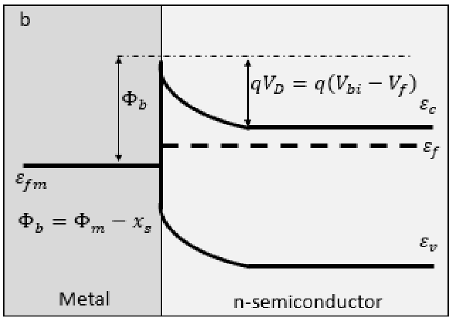


Figure 1. Schematic diagram of the Schottky barrier diode in the (a) equilibrium and (b) under the forward-bias conditions

The TE theory is utilized to explain the current conduction mechanism (CCM) in the MS Schottky barrier diode with insulator interface layer in the wide temperature through I-V analysis (Kim *et al.*, 2012). Moreover, the SBD parameters at low temperature were able to be verified using the Cheung and Norde analysis methods and were compared that there was inconsistency with I-V characteristics. Meanwhile, numerical simulation of CCM was also used to explain the inhomogeneous Schottky barrier of a diode and account for the Richardson constant via the Gaussian distribution of the barrier height (Güçlü, Faruk & Özdemir, 2016).

III. MATERIALS AND METHOD

A. Sample fabrication and preparation

Figure 2 shows a $Ga_{0.952}In_{0.048}N_{0.016}As_{0.984}$ p-i-n diode with a Ti-Au contact on the p-type and n-type. The diode was grown on a lightly doped n+-type (100) GaAs substrate using an RF plasma source-based molecular beam epitaxy (MBE) system. The RF plasma source was used for nitrogen incorporation. Two 10-nm undoped GaAs layers were grown at a top and one layer at the bottom of an intrinsic region of 20 undoped GaInNAs/GaAs quantum wells. The top contact layer of a 600-nm emitter followed by a 40-nm AlGaAs and a 200-nm GaAs layers above the top graded layers were p-doped with Be = 2×10^{18} cm^{-3}. A base contact of 1900-nm and 20-nm GaAs was n-doped with Si = 2×10^{18} cm^{-3} between bottom graded layer and a substrate. The intrinsic region was embedded within the compositional graded p-type and n-type of Be and Si, respectively. Table 2 summarizes the doped layer of the heterogeneous structure of $Ga_{0.952}In_{0.048}N_{0.016}As_{0.984}$ MQWs p-i-n diode.

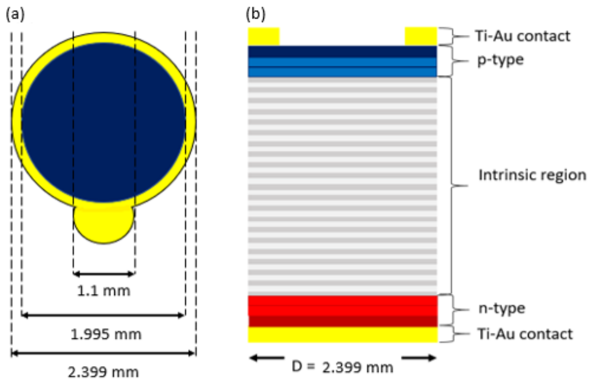


Figure 2. Schematic diagram of a dilute nitride $Ga_{0.952}In_{0.048}N_{0.016}As_{0.984}$ 20-MQWs p-i-n diode with a Ti-Au contact on the p-type and n-type: (a) the top view of mesa circular Ti-Au contact with 1.995 mm inner diameter and 2.399 mm outer diameter and (b) the cross-section of a diode

B. Electrical Characterise diode

The electrical characteristics of the GaInNAs p-i-n diode were characterized using a Keithley 2400 source measurement unit (SMU) in the dark condition at room temperature. The forward- and the reverse-bias voltage was swept from a range of -1.0 to +1.0 V in order to determine the electrical parameters such as leakage current, threshold voltage and dynamic resistance.

C. Current-Voltage Analysis

The analysis of the forward-bias I-V characteristics was used to determine the SDBs parameters using TE numerical analysis. The TE numerical analysis was used for the lightly-doped semiconductor on the metal-n-type contact to thermally excite the electron to cross the barrier. Therefore, the ideality factor and barrier height values of an SDBs diode were used to describe the charge conduction mechanism in a Schottky junction. In this study, Norde and Cheung function was used to reevaluate the value of Schottky diode parameters for comparison with the values obtained by I-V characteristic method.

Table 2. The semiconductor layers of GaInNAs heterogeneous structure

Material	Doped	Repeat	Layer Thickness (nm)
GaAs	Be doped ($p^+ = 4\times10^{18}$ cm^{-3})	1	200
AlGaAs	Be doped ($p = 2\times10^{18}$ cm^{-3})	1	40
GaAs	Be doped ($p = 2\times10^{18}$ cm^{-3})	1	600
GaAs	Undoped	1	10
GaAs	Undoped (barrier)	1	10
$Ga_{0.952}In_{0.048}N_{0.016}As_{0.984}$	Intrinsic	20	10
GaAs	Undoped (barrier)	20	10
GaAs	Undoped	1	10
GaAs	Si doped ($n = 5\times10^{17}$ cm^{-3})	1	1900
GaAs	Si doped ($n^+ = 2\times10^{18}$ cm^{-3})	1	20
n+-GaAs Substrate			

1. *Foward-Bias I-V Characteristic*

In this numerical analysis, the value of the forward bias current (I), series resistance current (I_s) and the saturation current (I_o) are expressed by Shockley equation as follows (Faruk *et al.*, 2008):

$$I = I_0[\exp\left(\frac{q(V-I_sR_s)}{\eta kT}\right) \quad (1)$$

where V is a bias voltage, where V is greater than or equal to 3kT/q, T is the room temperature 300 Kelvin, q is the charge and k is the Boltzmann's constant. The value of the saturation current (I_o) is expressed as

$$I_o = AA^*T^2 \exp(-\frac{q\,\Phi_b}{kT}) \quad (2)$$

where the Richardson constant, A^* is 8.16 A/cm² for n-type GaAs and A is the effective contact area, where the value is 6.16 μm² for the GaInNAs diode. Therefore, to obtain the ideality factor and barrier height of Ti-Au/n-GaAs, the following equations are used, where

$$\Phi_b = -\frac{kT}{q}\ln\left(\frac{I_0}{AA^*T^2}\right) \quad (3)$$

$$n = \frac{q}{kT}\left(\frac{dV}{d(\ln I)}\right) \quad (4)$$

Accordingly, the ideality factor and series resistance values are determined from the linear equation as,

$$G(I) = \frac{dV}{d\ln(I)} = IR_s + n\left(\frac{kT}{q}\right) \quad (5)$$

where the slope of $dV/d\ ln\ (I)$ as a function of I exhibits the series resistance value while its intercept of the y-axis corresponding to nkT/q can also be used to obtain the ideality factor value.

2. *Cheung Function*

The Cheung function is one of the numerical methods to determine the barrier height and series resistance values through a change of forward current to the applied bias. The barrier height is extracted using the following equation (Mamor *et al.*, 2014),

$$H(I) = V - \left(\frac{nkT}{q}\right)\ln\left(\frac{I}{AA^*T^2}\right)IR_s + n\Phi_b \quad (6)$$

Using the ideality factor value which obtained the equation, a plot of *H(I)* as a function of *I* exhibited a straight line where the slope is used to determine the series resistance while its intercept is used to calculate the barrier height of MS contacts.

3. *Norde Function*

In addition, Norde function also one of thermionic emission method to determine the barrier height and series resistance values based on a change of current flow using the following equation (Kacha *et al.*, 2015),

$$F(V) = \frac{V}{\gamma} - \frac{q}{kT}\ln\left(\frac{I}{AA^*T^2}\right) \quad (7)$$

where the value of γ is defining the greatest integer value that the ideality factor. The *F(V)* is plotted as a function of the voltage (V), the minimum value of $F(V_{min})$ and the minimum value of voltage (V_{min}), where its used to determine the barrier height value as the following equation:

$$\Phi_b = F(V_{min}) + \frac{V_{min}}{\gamma} - \frac{kT}{q} \quad (8)$$

Additionally, the series resistance from Norde function is calculated using the following equation:

$$R_s = \frac{kT\,(\gamma-\eta)}{qI_{min}} \quad (9)$$

where I_{min} is the minimum value of current at the minimum value of the voltage.

IV. RESULTS AND DISCUSSION

Figure 3 shows the I-V characteristic of a GaInNAs 20-MQWs p-i-n diode, which can be classified into two regions according to applied reverse- and forward-bias voltages. The plot represented a typical rectification in a diode characteristic such as the leakage current, threshold voltage and dynamic resistance. The threshold voltage of the diode was 0.22±0.03 V and the dynamic resistance was 262±3.81 kΩ. The effect of series resistance and interface layer on the Ti-Au/n-GaAs structure caused the forward current to deviate from the linearity in the forward-bias region at higher than 0.22 V. Thus, the I-V characteristics of the GaInNAs 20-MQWs p-i-n diode can be analyzed using a Schottky diode model. Meanwhile, the value of the leakage current was 0.010 μA at zero bias.

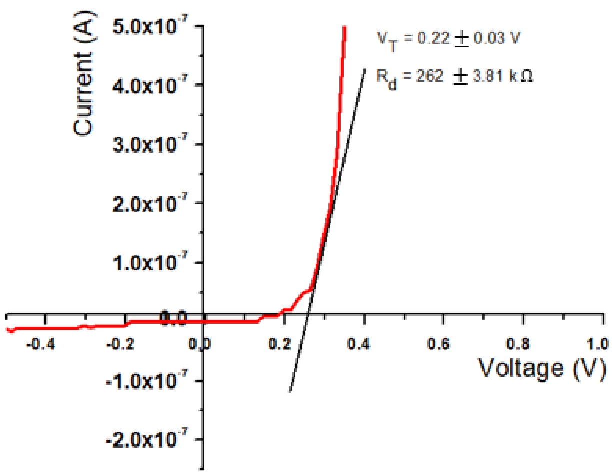
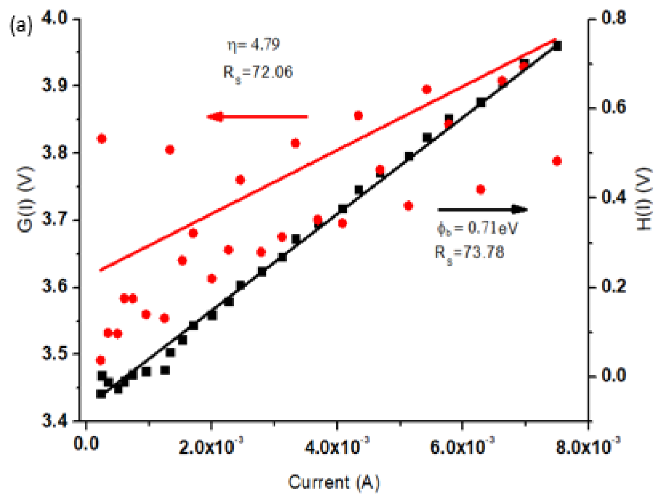


Figure 3. The I-V Characteristic of a GaInNAs 20-QWs p-i-n diode at room temperature

In the previous study, the electrical properties of $Ga_{0.952}In_{0.048}N_{0.016}As_{0.984}$ 20 MQWs p-i-n diodes have been evaluated using IV measurement for indicating the thermal escape carrier of a sample by contributing to leakage current (Khalil, *et al.*, 2014). Moreover, the dark current density of the 20-MQWs p-i-n diode was comparable with 10-MQWs GaInNAs p-i-n diode which indicated the effect of number QWs on the carrier flow through a diode with -22.6 nA/cm² and -472.8 nA/cm², respectively (Mohamad *et al.*, 2019). Therefore, the extending studies on the electrical properties of a diode on the forward bias is required to evaluate the electrical performance of MS contact of a diode in conducting a current across a diode.

Generally, the total current passing through a Schottky barrier device may be attributed by a conduction mechanism or a combination of several conduction mechanisms such as thermionic emission of carriers across a Schottky barrier, the drift and diffusion of carriers from the semiconductor into the metal and quantum-mechanical tunnelling through the barrier. Thus, the SDBs parameter of the Ti-Au/n-GaAs p-i-n Schottky diode was evaluated using three plots based on *G(I)*, *H(I)* and *F(V)* functions. The leakage current I_0 was used in calculating the Φ_b, and then η was determined using a slope of *G(I)* for the I-V characteristic analysis. Figure 4 shows a plot of *G(I)* and *H(I)* function and plot of the *F(V)* function. The SBDs parameters of the Ti-Au/n-GaAs p-i-n Schottky diode which extracted by using three different numerical analysis is summarized in Table 3

The barrier height of the sample from G(I) is approximately closer than H(I) with 0.79 eV and 0.71 eV, while the value of 0.87eV was extracted using F(I) function. The extracted barrier heights are almost identical to the three numerical analysis and in the similar range for most metals in the case of GaAs (Palmstrom, 2001).



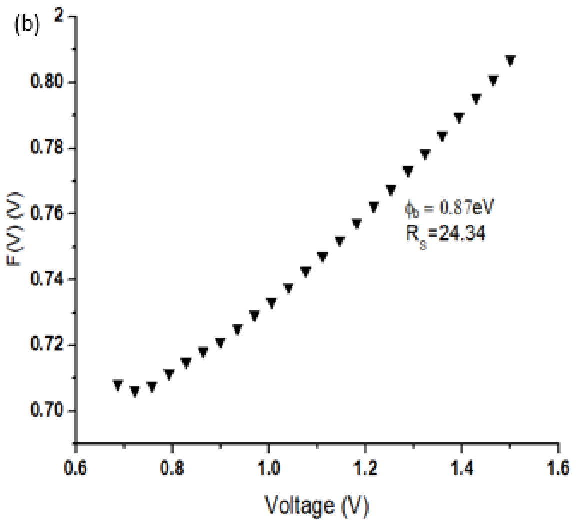


Figure 4. The SBDs parameters of Ti-Au/Si/n-GaAs p-i-n Schottky diode using (a) plot of the *G(I)* and *H(I)* function and (b) plot of the *F(V)* function

Table 3. SBDs parameters of Ti-Au/n-GaAs p-i-n Schottky diode

Sample	I-V Characteristic		Cheung Method		Norde Method	
	η	Φ_b (eV)	Φ_b (eV) *H(I)*	R_s (Ω) *H(I)*	Φ_b (eV) *F(V)*	R_s (Ω) *F(V)*
Ti-Au/n-GaAs	4.79	0.79	0.71	73.78	0.87	24.34

Meanwhile, the value of the idealiy factor of the diode which obtained through forward-bias I-V characteristics was 4.79. The ideality factor is greater than unity and in a similar range as reported by Güçlü, Faruk and Özdemir, 2016. Generally, the ideality factors of the Ti-Au/n-GaAs diodes have been found to be greater than unity as reported in the literature (Filali et al., 2017; Bouiadjra et al., 2014; Faruk et al., 2008). Moreover, the values of series resistance were obtained which was 73.78 Ω and 24.34 Ω for Cheung and Norde functions, respectively.

The effect of series resistance is significant, especially in the non-linear region as high series resistance resulted in decreasing the linear range of the forward-bias region. As the series resistance in the Schottky contact affected the evaluation of barrier height, Norde function evaluates the values even for high series resistance. Generally, the series resistance of the diode is lead on the curvature of the forward-bias I-V slope with a sum of contact resistance and semiconductor device's resistance (Bouiadjra et al., 2014). However, the series of resistance can be negligible by assuming that the diode has a high injection level of the p-n junction (Kacha et al., 2015).

The deviation of Schottky barrier diode parameters of the Ti-Au/n-GaAs device between the analysis is attributed by the presence of interface state between the metal and the semiconductor (Bachir et al., 2014) and inhomogeneous of composition of the layer or surface defects during the fabrication process, which produce electronic energy levels in the bandgap of GaAs semiconductor (Güçlü, Faruk and Özdemir, 2016). Besides, carrier generation-recombination current within the SRC affects the components current in addition to thermionic emission current and series resistance causes the actual voltage drop across the barrier region to be less than the applied forward-bias may also be contributed the inconsistency between the current-voltage characteristics and the models.

V. CONCLUSION

The electrical properties of the Ti-Au/n-GaAs Schottky diode were successfully investigated. The GaInNAs 20-MQWs p-i-n diode was determined to exhibit a threshold voltage of 0.22±0.13 V and 262±3.81 kΩ of dynamic resistance and leakage current of 0.010 μA. The SBDs parameters of the Ti-Au/n-GaAs p-i-n diode were analyzed using forward-bias I-V characteristics and the ideality factor of 4.79 with 0.79 eV barrier height was extracted. On the other hand, barrier heights determined from the Norde and Cheung functions were calculated at 0.87 eV and 0.71 eV, respectively. As there are multiple numbers of the operative transport mechanism, an investigation of the temperature dependence electrical parameters of the Ti-Au/n-type GaAs Schottky diode is required for the determination of dominant current conduction mechanism and nature of barrier formation at the metal-semiconductor interface

VI. ACKNOWLEDGMENT

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