Analysis on Electrical Characteristics of Gallium Nitride (GaN) Material for Schottky Barrier Based Photodetectors

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Abstract—**This paper presents the design of a self-powered photodetector based on metal-GaN (Schottky barrier). The Schottky structure is a common structure used in wide bandgap semiconductor UV detectors. The design of Schottky barrier photodetector consists of a semitransparent Schottky contact and an Ohmic contact. Solar blind ultraviolet photodetector is mainly focoused in this research. In reality, AlGaN is suitable for solar blind ultraviolet photodetector. However, GaN is tested with various metals in this paper. Semiconductor materials are an important part of modern electronics devices for detectors, diodes, LEDs, solar cells, digital and analog ICs. GaN is the most desirable candidates for UV light detection. The simulation results of the varying energy band-gap, the electron and hole concentration and the height of Schottky barrier have been completed with the help of MATLAB.**

Keywords— **UV photodetectors, metal-semiconductor junction, GaN, doping concentration, band-gap.**

I. INTRODUCTION

Photodetectors work by converting optical signals into electrical signals. UV detectors can be applied for missile launching, flame detection, light safety satellite communications, chemical and biological analysis. Various solutions of metal-semiconductor (M-S) interfaces have been used to improve the performance of UV photodetectors. Metal oxide, group III- Nitrides, SiC materials for UV detectors [Bouzida,b, et.al. 2017].

There is a lot of interest in research on wide band-gap materials. The wide band gap (WBG) of semiconductor materials have various advantages. Due to the large band gap, WBG semiconductor devices can operate at higher voltages, currents, temperatures, and frequencies than conventional semiconductor devices.

Compared to other wide band-gap materials, III-Nitrides (GaN, AlN, InN) have unique advantages in UV light detection. A community of researchers with excellent improvements in Gallium Nitride (GaN) based light-emitting diodes (LEDs), laser diodes, and other GaN-based devices such as UV photodetectors (PD), [Yanan Zou, et.al. 2018]. The material of interest in this study is Gallium Nitride (GaN) with a band gap of 3.4 eV, much higher than silicon (with a band gap of 1.2 eV) [Bouzida,b, et.al. 2017]. GaN is a direct and wide band-gap semiconductor. GaN is an excellent material platform to make UV photodetectors because of its wide and direct band-gap. The most preferred type of GaN is the Wurtzite structure. GaN is a promising material for transistors, blue LEDs, high power high electron mobility transistors and UV photodetectors. GaN is a direct band-gap that absorbs more photons than other indirect forbidden bands [Xiaojuan Sun, et. al.2015].

To construct an ultraviolet photodetector, it is necessary first to clarify the electrical characteristics of gallium nitride (GaN) material that is used in metal-GaN interface for photodetector.

The rest of this paper is organised as follows. Section II mentions the background theory of GaN material and the band diagram of Schottky barrier (metal-semiconductor contact) between metal-GaN. Section III discusses the simulation results for energy dispersion, temperature dependent band-gap variation and Schottky barrier heights with different work functions. Section IV concludes the story of work.

II. BACKGROUND THEORY

A. Ultraviolet (UV) Photodetectors

UV detectors can be divided into two categories: vacuum and solid. Vacuum UV detectors are based on various types of photomultiplier tubes (PMT). Solid -state UV detectors are mainly based on semiconductor materials. According to various basic operating principles, wide band-gap UV semiconductor detectors can be divided into photoconductive UV detectors and photovoltaic UV detectors. Photovoltaic UV detectors can also be classified into the Schottky barrier type, metal-semiconductor-metal (MSM) type, p-n junction type, and p-i-n junction type [Yanan Zou, et.al. 2018].

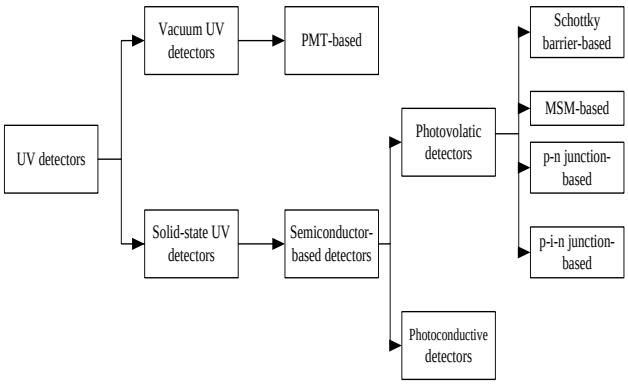

Fig. 1Classification of ultraviolet photodetectors

B. Calculation for the Characteristics of GaN Material

The electrical characteristics of Gallium Nitride (GaN) material has been calculated under the following equations.

1) Energy Dispersion: The energy difference between the conduction band and the valence band is known as energy dispersion. It is also called the band-gap energy. This energy can be calculated using the following equations:

$$E_C = \left[\frac{E_g q + \hbar^2 k^2}{2m_e^*}\right] \quad (1)$$

$$E_V = -\frac{\hbar^2 k^2}{2m_h^*} \quad (2)$$

$$k = \sqrt{\frac{2E}{(\frac{1}{m_e^*}+\frac{1}{m_h^*})\times \hbar^2}} \quad (3)$$

2) Temperature Dependence of the Energy Band-gap for Gallium Nitride (GaN) Material: The energy band-gap of semiconductor tends to decrease when the temperature is increased. Table 1 shows parameters for GaN material [I.Vurgaftman,2003]. The relationship between band gap energy and temperature can be described by the Varshni expression [Varshni Y.P, 1976],

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta} \quad (4)$$

Where, E_g= band-gap at Temperature

$E_g(0)$= band-gap at 0K

T = temperature (K)

α & β = fitting parameters of material

TABLE I
PARAMETERS FOR GALLIUM NITRIDE MATERIALS
[I.Vurgaftman, 2003]

Materials	Gallium Nitride (GaN)
Eg(0)	3.51
α (meV/K)	0.909
β (K)	830

3) Theoretical Calculation of Electron and Hole Concentrations via Doping Concentration for GaN Material: The electron concentration for n type semiconductor material could be calculated based on the following equation. In n type semiconductor, the electron is majority carrier and hole is minority carrier.

$$n = N_d \quad (5)$$

Where, n = electron concentration

To obtain the performance of materials, the hole concentration could be used under the specific equations.

$$N_c = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{\frac{3}{2}} \quad (6)$$

$$N_v = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{\frac{3}{2}} \quad (7)$$

$$n_i = \sqrt{N_c N_v}\, e^{\frac{-Eg}{2kT}} \quad (8)$$

$$p = \frac{n_i^2}{N_d} \quad (9)$$

Where, n_i = intrinsic carrier concentration (1.9×10^{-10} cm^{-3})

p = hole concentration

Nc=2.3×10^{18} cm^{-3}

Nv = 1.8×10^{19} cm^{-3}

C. Metal-Semiconductor Contact

Metal-semiconductor contacts (MS) are an important part of the performance of most semiconductor devices. Adhering metal and semiconductor materials are called MS junctions, [Qiming He et.al. 2017]. Two types of MS contacts that are widely used in semiconductor devices are:

1. Rectifying Schottky contact
2. Non-rectifying Ohmic contact

Schottky contact can form when a metal-semiconductor contact has a large barrier height and low doping concentration. An ohmic contact has a negligible contact resistance relative to the bulk of semiconductor. It has a low barrier height and high doping concentration. A satisfactory ohmic contact should not significantly degrade device performance and can pass the required current with a voltage drop [T.Ayalew, 2004].

The energy band diagram under zero bias of metal-GaN structure is shown in Fig 2 [B.L.Sharma, 2013].

The electron affinity (χ) for GaN material is 4.2eV. The relationship between the effective Schottky barrier height ϕ_{Bn} and built-in potential V_{bi} are expressed as

$$\emptyset_{Bn} = \emptyset_m - \chi \quad (10)$$

$$\phi_{Bp} = E_g - (\emptyset_m - \chi) \quad (11)$$

$$V_{bi} = \phi_{Bn} - (E_C - E_F) \quad (12)$$

$$E_C - E_F = -k_B T \ln\frac{N_d}{N_c} \quad (13)$$

Where, ϕ_{Bn} = Schottky barrier height for electron

ϕ_{Bp} = Schottky barrier height for hole

E_C-E_F = doping function

Φ_m = metal work function

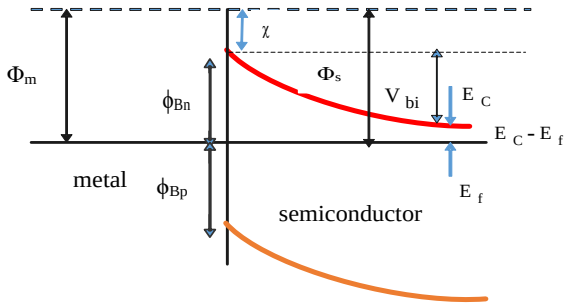

Fig. 2Energy band diagram under zero bias of metal/ GaN structure [B.L.Sharma, 2013]

D. Schottky Barrier Height via Metal Work Function

The height of Schottky barrier depend on metal work function. In this case, many kinds of metals are used to compare the Schottky barrier height. The different work function of metals are obtained from [B.Van Zeghbroeck, 2011]. In table II, the Schottky barrier height of metal-semiconductor is calculated using equation (10). And then the built-in potential is calculated using equation (12).

TABLE II
PARAMETERS FOR SCHOTTKY BARRIER HEIGHT (SBH) AND BUILD IN POTENTIAL (VBI) CALCULATION

Metal	Work Function(ϕ_m)	SBH (ϕ_{Bn})	Built-in Potential (V_{bi})
Ag	4.26	0.06	0.04
Al	4.28	0.08	0.06
Au	5.1	0.9	0.88
Cr	4.5	0.3	0.28
Mo	4.6	0.4	0.38
Ni	5.15	0.95	0.93
Pd	5.12	0.92	0.9

Pt	5.65	1.45	1.43
Ti	4.33	0.13	0.11

III. Results and Discussions

In this paper, the electrical characteristics of GaN material and the structure of metal-GaN have been observed based on the physical parameters of metals and GaN material. Fig.3, 4, 5 and 6 describe the electrical characteristics of GaN material. Fig. 7, 8 and 9 mention the metal-GaN for Schottky barrier photodetectors.

Fig. 3, 4, 5and 6 present the electrical characteristic of GaN material such as the energy dispersion for GaN material, energy band-gap variation of GaN material that depends on temperature, the variation of electron and hole concentrations depend on doping concentrations.

Fig. 7, 8 and 9 describe the changing of Schottky barrier heights base on metals work functions. These would be analyzed by using MATLAB tools.

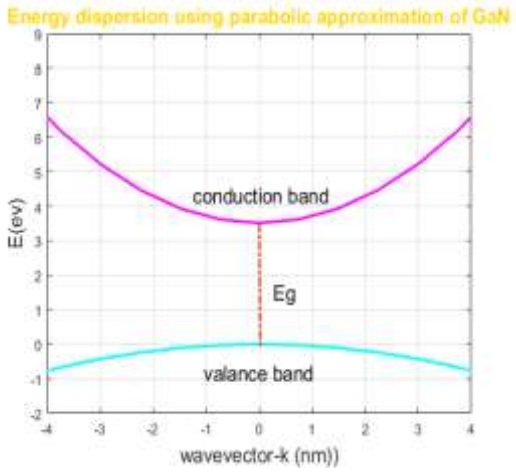

Fig. 3 Energy dispersion for GaN material

Fig. 3 shows the energy dispersion for GaN material. The band-gap energy of GaN material is 3.4eV at room temperature.

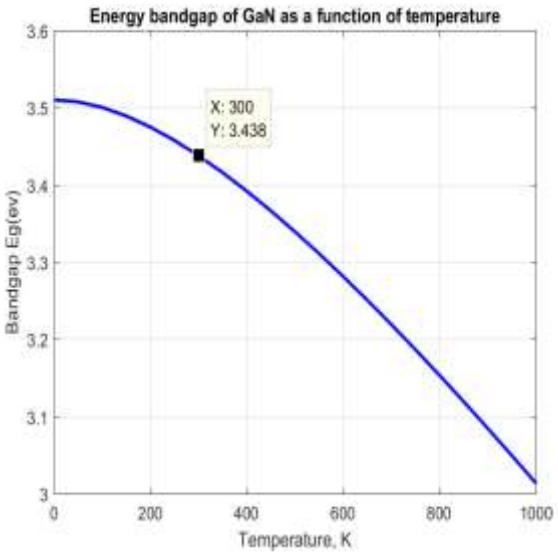

Fig. 4Energy band-gap variation for GaN material depend on temperatures

Fig. 4 demonstrates the band-gap variation for GaN material that depend on temperature. Lower temperature sensitivity is the key point to ensure the stable operation of an intended device. The band-gap energy of GaN material decreases non-uniformly with the uniform increase of temperature.

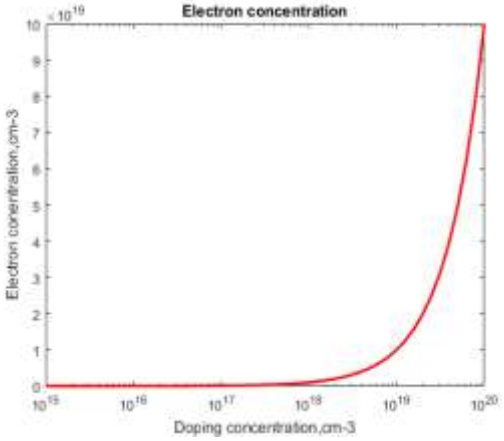

Fig 5.Electron concentration with doping concentration

Electron concentration with doping concentration is shown in Fig. 5. Electron concentration can be calculated by using equation (5). Theoretically, when the donor concentration is increased, the electron concentration will also increase in n type semiconductor material. Electron is a majority carrier for n type material. This simulation result shows that the doping concentration is increased, the electron concentration will increase. This simulation result is consistent with theoretical prediction.

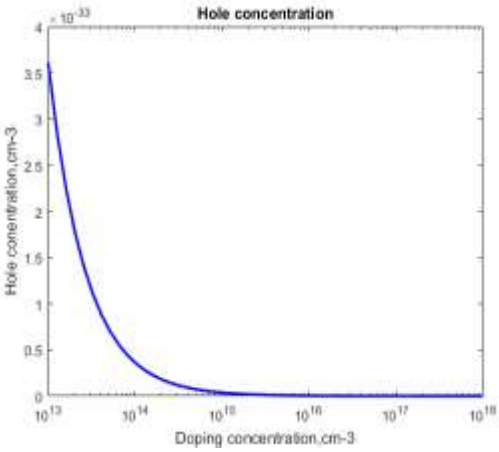

Fig. 6Hole concentration with doping concentration

Fig. 6 illustrates hole concentration with doping concentration. In theoretical, the hole concentration is inversely proportional to the donor concentration. The hole concentration in n type semiconductor material can be obtained by using equation (9). When the doping concentration increases, the hole concentration will decrease.

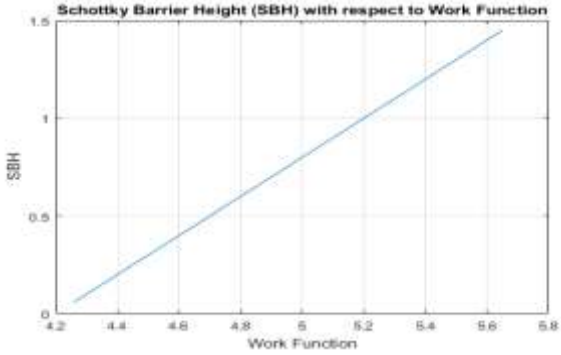

Fig. 7Schottky barrier height (SBH) with metal work function

Fig. 7 presents the Schottky barrier height with respect to metal work functions. The Schottky barrier height can be calculated from equation (10) and that depends on metal work function. According to this equation, the higher Schottky barrier height the greater metal work function. This simulation result shows that when the metal work functions increase, the Schottky barrier height will increase. Therefore, this result is in line with theoretical prediction.

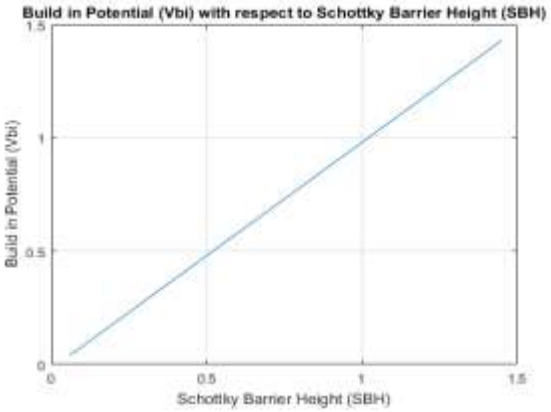

Fig. 8Built-in potential (v_{bi}) relationship with schottky barrier height (SBH)

Fig 8 illustrates the Built-in Potential (V_{bi}) with Schottky Barrier Height (SBH). In equation (12), the built-in potential is directly proportional to the Schottky barrier height. In this simulation result, the Schottky barrier height increases, the built-in potential will increase. This result is the same with theoretical prediction [T.Ayalew, 2004].

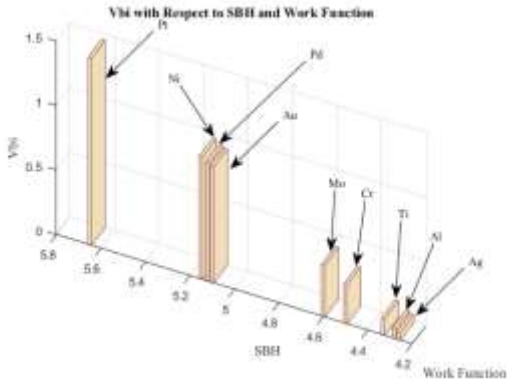

Fig. 9Built-in potential (v_{bi}) with respect to SBH and work function

Fig. 9 mentions the built-in potential (V_{bi}) with Schottky barrier height (SBH) depending on the electron affinity of Gallium Nitride (GaN) material and different metal work function. The status of Schottky barrier height depends on selected metal work function and the changing of built-in potential based on Schottky barrier height. According to this result, the larger the metal work function, the higher the barrier height. Inversely, the smaller the metal work function, the lower the barrier height. The changes of built-in potential depend on Schottky barrier heights. As Schottky barrier height is increased, V_{bi} will increase. This simulation result is consistent with theoretical prediction.

IV. Conclusions

This paper analysed the electrical characteristics of GaN material because this material was used to form metal-semiconductor structure to get high performance of Schottky barrier based photodetectors. The temperature dependence of direct band-gap energy of metal-semiconductor GaN by using Varshni's expression in the temperature range between 0K and 1000K. Result shows that the band- gap energy at 300 K is 3.4 eV. To enhance the performance of metal-semiconductor GaN photodetector, the electron and hole concentration, the height of Schottky barrier) are analysed by utilizing MATLAB programme.

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