Analysis on Physical Characteristics of β-Ga_2O_3 for Schottky Barrier Diode Based Metal-Semiconductor

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Abstract - **The paper presents the analysis on physical characteristics of potential metal-semiconductor belta-gallium oxide (β-Ga_2O_3) material for Schottky barrier diode based on physical parameters. The β-Ga_2O_3 is one of the candidates to fabricate the Schottky barrier diode for obtaining the high performance characteristics in nature. The electron and hole concentrations, energy band-gap via temperature, breakdown electric field relationship with bandgap, J-V characteristic and breakdown voltage via doping concentration are very important physical parameters for device design. In this paper, the physical characteristics for electrical parameters for fabricating β-Ga_2O_3 metal-semiconductor devices are confirmed. The research finding shows that β-Ga_2O_3 is more suitable for power electronic devices than the other materials because it has wide bandgap, high breakdown electric field and high breakdown voltage.**

Keywords **- physical parameters, physical characteristics, β-Ga_2O_3, schottky barrier diode, breakdown electric field**

I. Introduction

Ga_2O_3 has been intensively investigated as a wideband-gap semiconductor for high-power electronics [Masataka,et.al. (2012)]-[G. Jessen, et.al. (2017)] and UV solar-blind phtodetectors [Xuejian Du, 2015]. It is available as large single crystals suitable for high-quality epitaxial thin-film growth by metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) [Encarnación G, et.al (2006)]; it displays high breakdown electric field [Masataka,et.al. (2012)], and the Baliga figure of merit exceeds that of SiC and GaN; it can be easily doped n-type, and bandgap engineering can be accomplished by incorporating In and Al, adding great flexibility to device design. As for gallium oxide, the monoclinic gallium oxide (β-Ga_2O_3) is chemically and thermally stable compound with a wide-band gap of 4.9 eV. It exhibits conductive and photoluminescence properties, therefore, it is a promising candidate for application as a transparent conducting material in next generation optoelectronic devices. Ga_2O_3 has recently attracted interest due to its applications ranging from gas sensors [Tippins, H.H., (1965)] and nano-structured materials to important materials in catalysis [Binet, L, 1998].

In the near future, stabilizing energy supplies and reducing global greenhouse gas emissions will require new energy solutions and innovative technologies to achieve production and use of fossil fuels. Power devices based on broadband semiconductors such as SiC and GaN can provide higher breakdown voltage (Vbr) and lower loss than Si devices, and are widely studied as follows. Oxide semiconductors are ideal for power devices for very high voltage switching applications. The superior material properties of oxide materials like Ga_2O_3, including a bandgap much larger than those of SiC and GaN, promise power devices with even higher V_{br} and efficiency than their SiC and GaN counterparts. Gallium oxide material is a promising candidate for the next generation high power devices including Schottky Barrier Diode (SBD) and Field Effect Transistor (FET).

Recently semiconductor device like schottky barrier diode based on non-compound material have been utilized for many applications. But there had been many disadvantages upon non-semiconductor compound but the oxide-based semiconductor devices more effective than non-semiconductor compound. And β-Ga_2O_3 is a candidate material for making the metal-semiconductor junction to get the effective structure for schottky barrier diode.

The paper organizes four sections with background theory, implementation, results and discussion.

II. Background Theory

A. Schottky Barrier Diode

A Schottky diodes are also called hot current diodes. The direct voltage drop is low and the switching operation is very fast. The voltage drop is usually 0.15-0.45 volts. This voltage drop increases switching speed and system efficiency. In a Schottky diode, a metal-semiconductor junction is formed between the semiconductor and the metal. An N-type semiconductor is used as the cathode and the metal side is used as the anode of the diode. There is no charge storage area for high-speed operation. The electron of N-side has lower energy level than that of metal. So electrons can't cross the junction barrier called Schottky barrier. In metal-semiconductor junction, Schottky Barrier is formed the potential energy barrier. Schottky Barrier diode is a unidirectional device conducting current flows only in one direction. It is operated at high frequencies from few MHz to GHz range. Widely used in various applications such as mixers, RF applications and power applications. The four most important functions of Schottky are direct voltage drop, reverse leakage current, reverse blocking voltage, and maximum junction temperature. Fig. 1 shows the physical structure of Schottky Barrier Diode (SBD).

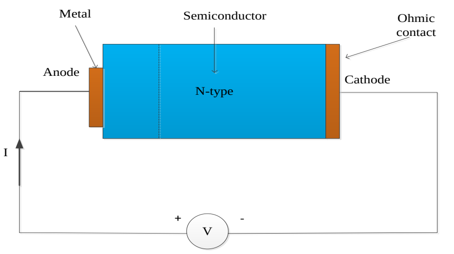

Fig. 1Physical structure of SBD

B. Gallium Oxide Material

Ga_2O_3 crystals exhibit polytypism with five confirmed polytypes (α, β, γ, δ, ε). The β-polytype shown in Fig. 2 is believed to be the most stable, while the other polytypes are metastable. β-Ga_2O_3 crystallizes into the β-gallium structure belonging to the monoclinic system. The bandgap of β-Ga_2O_3 is 4.7–4.9 eV.

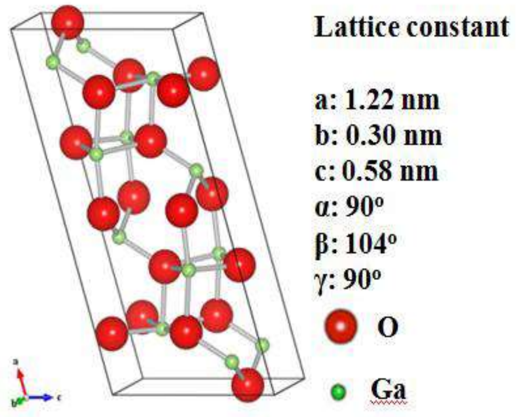

Fig. 2Atomic unit cell of β-Ga_2O_3

β-Ga_2O_3 is the only stable polymorph through the whole temperature range till the melting point, whilst all other polymorphs are metastable and transform into the β-Ga_2O_3 at temperatures above 750-900°C. Fig. 3 shows the transformation relationships among the crystalline phases of Ga_2O_3.

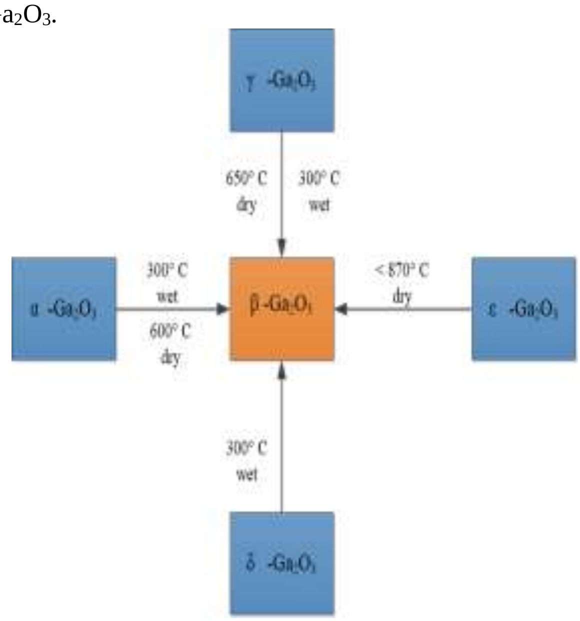

Fig. 3Transformation relationships among the crystalline phases of Ga_2O_3

III. Physical Parameters

The physical values for consideration of characteristics on β-Ga_2O_3 materials are based on the following parameters. The Hole Concentration, Electron Concentration, Energy band-gap, Breakdown Electric Field and Breakdown Voltage are fundamental parameters for analyzing the physical characteristics. The fundamental parameters of β-Ga_2O_3 materials have been carried out compare with other groups of materials in this paper.

A. Hole Concentration via Doping Concentration for β-Ga_2O_3

The hole concentration could be utilized to obtain the estimation of the performance of materials by using the specific equations.

$$N_c=2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{\frac{3}{2}} \quad (1)$$

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

$$n_i=\sqrt{N_c N_v} e^{\frac{-Eg}{2kT}} \quad (3)$$

$$p=\frac{n_i^2}{N_d} \quad (4)$$

From (1) to (4), those mathematical models have been applying to estimate the hole concentration of that material.

B. Electron Concentration via Doping Concentration for β-Ga_2O_3

The electron concentration could be observed based on (5).

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

C. Energy Band-gap via Temperature

The energy bandgap depending on the temperature is very essential for considering the characteristic of material. In this case, there are three kinds of materials for comparison of physical properties.

TABLE I
PARAMETERS FOR ENERGY BANDGAP CALCULATION

Materials	Ge	Si	β-Ga_2O_3
Eg(0) (eV)	0.7437	1.166	4.95
α (meV/K)	0.477	0.473	4.45
β (K)	235	636	2000

$$Eg = Eg(0) - \frac{\alpha T^2}{(\beta + T)} \quad (6)$$

Eg (0) = bandgap value at 0K
β and α = material constants or (Varshni parametrs)

D. Breakdown Electric Field of SiC, GaN and β-Ga_2O_3

The breakdown electric field is also important for estimating the physical characteristics of materials. The breakdown electric field could be evaluated based on the following mathematical equation.

$$E_{br}=a[E_g]^n \quad (7)$$

E_{br} = breakdown electric field
a= coefficient
n= index value

TABLE II
PARAMETERS FOR BREAKDOWN ELECTRIC FIELD CALCULATION BASED ON A AND N

Semiconductor	a	n
All	$1.75*10^5$	2.359
Indirect	$2.38*10^5$	1.995
Direct	$1.73*10^5$	2.506

TABLE III
PARAMETERS FOR BREAKDOWN ELECTRIC FIELD CALCULATION BASED ON EG

Semiconductor	Eg	E_{br}
SiC	3.03 eV	2.8 MV/cm
GaN	3.4 eV	3.7 MV/cm
β-Ga_2O_3	4.85 eV	9 MV/cm

E. Evaluation of J_0 For SBD on Si, GaAs, β-Ga_2O_3

The J-V Characteristics estimation is also significant for device performance. The specific equations for considering the characteristics of current density with voltage responses could be analyzed based on the following equations.

$$J=J_0\left(e^{\frac{v}{V_T}}-1\right) \tag{8}$$

$$V_T=\frac{kT}{q}=0.026 \tag{9}$$

$$J_0=A^*T^2e^{\frac{-\phi_{Bn}}{kT}} \tag{10}$$

$$A^*=\frac{4\pi m_0qk^2}{h^3}\times\frac{m_n^*}{m_0}=120\frac{m_n^*}{m_0} \tag{11}$$

$$V=V_T\ln\left(\frac{J}{J_0}\right) \tag{12}$$

$$\phi_{Bn}=\frac{2}{3}E_g \tag{13}$$

J = current density
J_0 = reverse saturation current density
V = forward bias voltage drop
Φ_{Bn} = Schottky barrier height
A^*= Richardson constant

TABLE IV
CALCULATION OF SCHOTTKY BARRIER HEIGHT, RICHARDSON CONSTANT, REVERSE SATURATION CURRENT DENSITY AND FORWARD BIAS VOLTAGE DROP FOR VARIOUS MATERIALS

Parameters	Si	GaAs	β-Ga_2O_3
ϕ_{Bn}	0.75	0.85	3.2
A^* $A/cm^2/K^2$	72	8.04	33.6
J_0 A/cm^2	$6*10^{-7}$	$1.24*10^{-9}$	$7.8*10^{-50}$
V at J=1 A/cm2	0.358	0.513	2.8

F. Breakdown Voltage Via Doping Concentration for Ge, Si and β-Ga_2O_3

The breakdown voltage with respect to doping concentration is also considered to observe the physical characteristics of specific materials for real applications.

$$V_{br}=k\left[\frac{N_d}{10^{16}}\right]^{-0.75} \tag{14}$$

V_{br} = breakdown voltage
k= material constant
N_d = doping concentration

IV. RESULTS AND DISCUSSION

In section III, the important parameters of β-Ga_2O_3 material have been calculated comparing to the other materials. In section IV, these parameters are analysed by using MATLAB and the main points are discussed. The physical characteristics of β-Ga_2O_3 materials could be observed based on the parameters which have been mentioned in the above section. The electron and hole concentrations, energy band-gap via temperature, breakdown electric field relationship with bandgap, breakdown voltage via doping concentration and J-V characteristic have been analysed by using computerized system design. According to the background theory of the parameter estimation, there have been analysed to obtain the electrical characteristics of β-Ga_2O_3 material for exact applications.

Fig. 4 shows the hole concentration relationship with doping concentration. According to the equation (4), the hole concentration decrease as the doping concentration is increased because the hole is the minority carrier in n-type semiconductor.

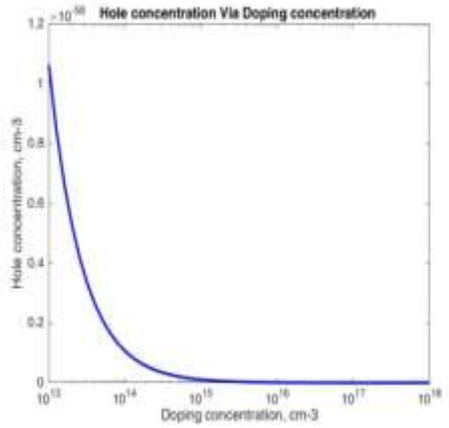

Fig. 4Hole concentration relationship with doping concentration of β-Ga_2O_3

Fig. 5 demonstrates the electron concentration relationship with doping concentration. According to the equation (5), the electron concentration increase as the doping concentration is increased because the electron is the majority carrier in n-type semiconductor.

Fig. 6 illustrates the energy band gaps of materials with temperature. The energy band gaps decrease as the temperature is increased. Germanium has the lowest energy band gap. At absolute zero temperature, the value of energy band gap for β-Ga_2O_3 is 4.9eV. With the increase of the temperature, it is found that the energy band gap decreases.

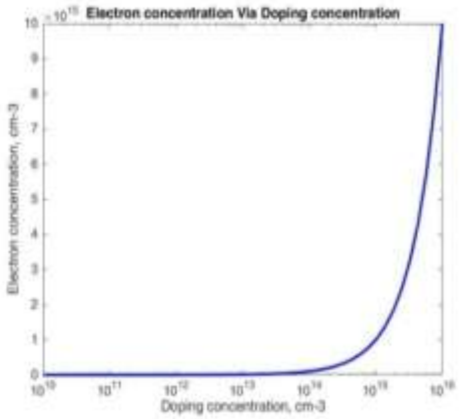

Fig. 5Electron concentration relationship with doping concentration of β-Ga_2O_3

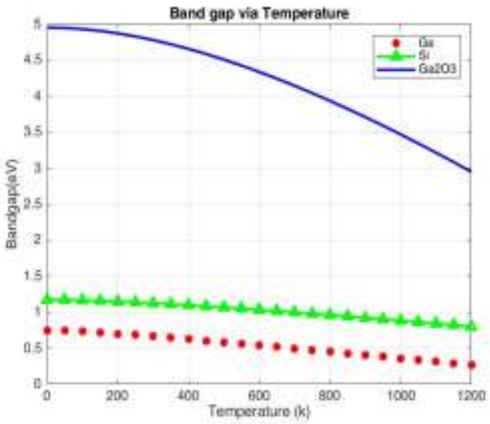

Fig. 6Energy bandgap values varied with temperature

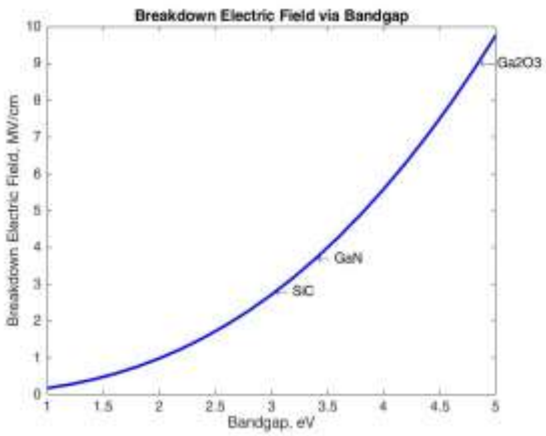

Fig. 7Breakdown electric field relationship with bandgap

Fig. 7 mentions the breakdown electric field relationship with band gap. β -gallium oxide has breakdown electric field nearly three times larger than SiC and GaN. β -Gallium oxide has large breakdown voltage because large breakdown electric field. According to equation (14), the more the doping concentration, the less the breakdown voltage is. Lightly doping concentration is required to get the large breakdown voltage as shown in Fig.9. The changes of breakdown voltage depend on the device structure. The reduced self-heating allows devices to be driven at higher reverse breakdown voltages, improving overall performance.

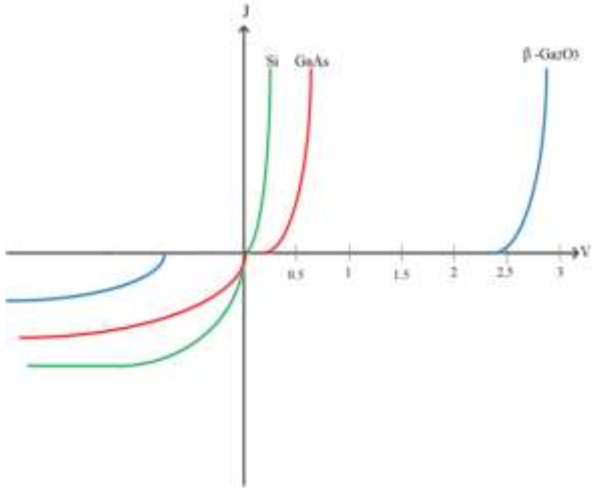

Fig. 8J-V characteristic for various materials

Fig. 8 shows the J-V characteristic for various materials. To achieve the high reverse breakdown voltage, the high forward voltage drop is needed. Moreover, according to the equations (8) to (13), in order to increase the current density, the applied voltage must be increased.

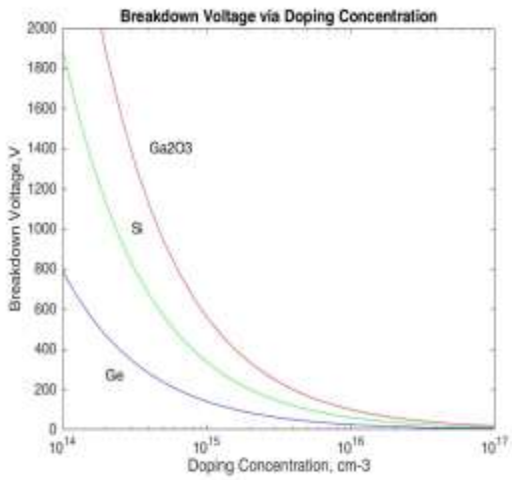

Fig. 9Breakdown voltage relationship with doping concentration for various materials (Si, Ge, β-Ga_2O_3)

Fig. 9 expresses the breakdown voltage relationship with doping concentration for various materials. Breakdown voltage increase as the doping concentration is decreased. β-Ga_2O_3 is larger breakdown voltage than silicon and germanium because it has large breakdown electric field. So, β-Ga_2O_3 is more suitable for the high breakdown voltage applications such as high power devices.

V. CONCLUSIONS

The schottky barrier diodes based on compound material have been utilized for many applications. And β-Ga_2O_3 is a candidate material for making the metal-semiconductor junction to get the effective structure for schottky barrier diode. It can be concluded that the analysis on physical characteristics of β-Ga_2O_3 material has been done by using MATLAB. It is found that β-Ga_2O_3 material has ultra wide bandgap (4.9eV at 0K), large breakdown electric field (8MV/cm) and large breakdown voltage (>1000V) comparing to other materials. Therefore, the outcome from the research on β-Ga_2O_3 based schottky barrier diode would be appropriated for high power electronic devices.

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