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Bias Current Optimization Studies on Avalanche Transit Time Diode Based on Wurtzite and Zinc-Blende Phase of GaN at Terahertz Frequency

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Abstract

The Terahertz performances of Wurtzite (α-phase) and Zinc-Blende (β-phase) of GaN based p^+pnn^+ *DDR IMPATTs has been investigated at optimum bias current density. The modeling and simulation based on drift diffusion model has been carried out to study the DC and small signal properties of the device. The bias current optimization is based on maximum conversion efficiency and device negative resistance at 0.3 THz. The simulation results obtained reveals the strong potentiality of DDR IMPATTs based on α- and β-GaN as a powerful solid state source for generating high power in Terahertz domain. The conversion efficiency of the device is found to be 12.3% at an optimum bias current density of* 0.2×10^8 A/m^2 *for α-GaN IMPATTs while the same result for β-GaN IMPATTs is 11.5% at* 3.1×10^9 A/m^2*. The design results presented in the paper are very promising and immensely useful to realize experimentally α- and β-GaN IMPATTs at THz frequency.*

Keywords: *Wurtzite (α-phase) GaN, Zinc-Blende (β-phase) GaN, Double Drift IMPATT diode, Terahertz frequency, Optimum bias current density.*

1. Introduction

Terahertz regime roughly corresponding to the frequencies from 0.1-10 THz (3 mm-30 μm) has attracted lots of attention in the last decade owing to its promising applications in fields of medical science, biological and industrial imaging, broadband and safety communication, Radar, Space science, Remote Sensing, Spectroscopy etc [1]. The Terahertz gap throws a big challenge as it marks the margin of electronics-photonics technology. In the lower Terahertz domain, the electronics based devices viz., Gunn Diode, Impatt Diode, Resonant Tunneling Diode and Nanometer Field Effect Transistor (based on plasma wave) are widely investigated and on the upper Terahertz domain research is focused on photonics based devices such as Quantum Cascade Laser. The radiation power and the detection sensitivity of Terahertz devices are extremely low as compared to millimeter wave and optoelectronic based devices [2]. The ongoing research and development in this domain have brought up the possibility of opening up an extraordinary range of new markets in present decade [3]. The wide popularity of Terahertz technology has not only confined its applications in the field of medical science, food and security sectors but also spanned its web to the studies of fundamental physics and cultural heritage [4]. Presently the applications of Terahertz Technology are very widespread viz., in airport screening of passengers for hidden weapons, explosives, drugs, biological and medical sciences, fields of semiconductors, monitoring industrial plants etc. Apart from technological developments, commercial products are also available to satisfy the needs of high profile markets. In spite of already existing CW and pulse sources, scientists worldwide are working upon the development of solid state sources capable enough of delivering high power at Terahertz frequencies.

Among all the solid state sources presently available, Impact Avalanche Transit Time Diodes (IMPATTs) have been found to deliver high RF power with high efficiency even at Terahertz domain. IMPATTs covering a wide frequency spectrum find greatest applications as solid state source in tracking Radars, radiometers, missile seekers and in various civilian, military and space communication systems.

The popular base materials for IMPATTs viz. Silicon (Si), Germanium (Ge) and Gallium Arsenide (GaAs) are not suitable to operate at THz domain owing to some fundamental limitations in their material properties. However Si-based IMPATTs at THz domain have recently been reported [5]. The other base materials for IMPATTs viz. Indium Phosphide (InP), Silicon Carbide (SiC) and Gallium Nitride (GaN) are found to give satisfactory performance with high efficiency and power at THz domain [6-17].

The III Nitride family of Semiconductors fulfills the emerging market for semiconductor-optoelectronic devices. The wide bandgap III-V semiconductor like GaN possessing excellent material properties have recently been reported as a useful base material for electronic & optoelectronic devices [2].The expected excellent performances of wide bandgap devices are assessed by considering Keyes' FOM and Johnson's FOM. Assuming Keyes' and Johnson's FOM for Si as unity, the same for GaN are 1.6 and 756 respectively [18]. At THz domain GaN IMPATTs offer higher output power resulting from increased critical electric field, higher bandgap energy, higher saturation velocity and much better thermal conductivity. Higher critical electric field results in higher Breakdown Voltage which is very important for devices handling high power. GaN is found to exist in two polytypic forms viz., Wz-phase (α-phase) and ZnB-phase (β-phase). The bandgap energy of α-GaN is 3.39 eV and that of β-GaN is 3.2 eV. Even though Gallium Nitride does not possess a high thermal conductivity as compared to Silicon Carbide, its other properties viz. breakdown field, saturation drift velocity, dielectric constant and carrier mobility makes it an attractive candidate for high power, high frequency devices. Moreover Gallium Nitride has the ability to form heterojunction. The Wurtzite phase has received most of the attention because of the relative ease of growth when compared to Zinc-Blende Gallium Nitride. Cubic-phase-wide bandgap materials tend to be overshadowed by their Wurtzite-phase counterparts owing to their difficulty in obtaining experimental data.

Despite all the high frequency operating advantages, GaN is yet to hit the mainstream owing to the technological immaturity in fabrication; however advances have been made in the Wurtzite phase versions. Considerable progress in the growth of nitrides in past few years has made GaN suitable enough for fabricating several electronic devices. Recent experimental study reveals that high quality GaN films can be grown on Si substrate by MOCVD technique by the use of Si_xN_y inserting layer [19]. Thus in the light of maturity of fabrication technological process and suitable material properties, GaN appears to be one of the best choices for the development of THz based semiconductor devices in the coming decade.

Some theoretical studies are depicted in this paper for the Zinc-Blende Gallium Nitride phase, thus focusing the research on improving the models used for simulation. The authors have considered a flat profile $p^{+}pnn^{+}$ Double Drift GaN (both α-and β-phase) IMPATT structures to operate at 0.3 THz and have studied the high frequency performance of both devices in the depletion region at optimized bias current density by incorporating the effect of mobile space charge. The results presented in this paper are very helpful to realize THz IMPATT Diodes based on α-and β-GaN.

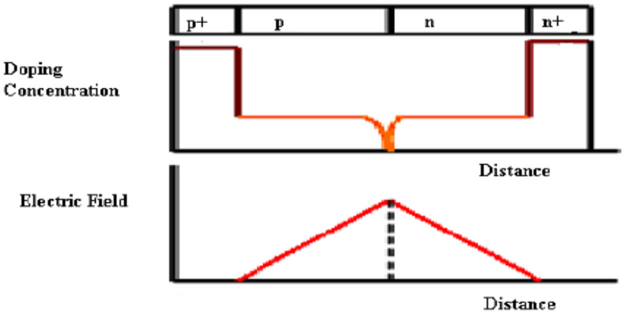

Figure 1. Doping Profile and Electric Field Profile of $p^{+}pnn^{+}$ DDR GaN Impatt Diode.

2. Simulation Methodologies

2.1. Doping Profile, Material & Design parameters of GaN based DDR Impatts

A double drift $p^{+}pnn^{+}$ structure of GaN (Wz- and ZnB-phase) Impatt have been considered and computer simulation has been carried out at 0.3 THz. The frequency of operation of an Impatt diode essentially depends on the transit time of charge carriers to cross the depletion layer of the diode. The transit time formula of Sze and Ryder [20] is considered here for the design of doping profile. The n^{+} and p^{+} regions considered here are highly doped substrates while n and p are epilayers. The simulation scheme incorporates the material parameters from the recent published papers [6-12, 15-17, 21-23] and Electronic Archive [24]. The material parameters of Wurtzite and Zinc Blende phase of Gallium Nitride are enlisted in Table-1 and design parameters of the Impatt diodes based on α- and β-GaN are shown in Table-2.

Table 1. Material parameters of Wz-GaN and ZnB-GaN

	α-GaN	**β-GaN**
Ionization coefficient of electrons at low fields, An (m^{-1})	2.90×10^{8}	1.023×10^{9}
Ionization coefficient of electrons at low fields, bn (V/m)	3.4×10^{8}	0.602×10^{9}
Ionization coefficient of holes at low fields, Ap (m^{-1})	2.96×10^{8}	1.276×10^{8}
Ionization coefficient of holes at low fields, bp (V/m)	4.01×10^{8}	0.376×10^{9}
Ionization coefficient of electrons at high fields, Ahn (m^{-1})	2.90×10^{8}	5.284×10^{8}
Ionization coefficient of electrons at high fields, bhn (V/m)	3.4×10^{8}	0.547×10^{9}
Ionization coefficient of holes at high fields, Ahp (m^{-1})	2.96×10^{8}	8.328×10^{7}
Ionization coefficient of holes at high fields, bhp (V/m)	0.795×10^{9}	0.323×10^{9}
Bandgap Energy (eV)	3.39	3.2

Table 2. Design parameters of α- and β-GaN DDR Impatt at 0.3 THz

	α-GaN	β-GaN
Width of n-epilayer (Wn) (nm)	308.0	172
Width of p-epilayer (W_p) (nm)	306.0	163
Background doping concentration (10^{23} m^{-3})	4.0	27.5
Substrate doping concentration (10^{26})	5.0	5.0
Current density (Am^{-2})	0.2×10^{8}	3.1×10^{9}

2.2. Computer Simulation Techniques

The computer analysis of DC and small signal behavior of α-and β-GaN Impatt takes into account the following assumptions: (a) One dimensional model of the p-n junction is treated; (b) The electron and hole velocities are taken to be saturated and independent of the electric field throughout the space charge layer. The simulation method starts with DC analysis described in details elsewhere [25-27]. In this method the computation starts from the field maximum near the metallurgical junction. The distribution of DC electric field and carrier currents in the depletion layer is obtained by the double - iterative computer method, which involves iteration over the magnitude of field maximum (E_m) and its location in the depletion layer. A computer algorithm has been developed for simultaneous numerical solution of Poisson's equation, carrier continuity equations and the space charge equation taking into account the effect of mobile space charge and carrier diffusion in order to obtain the electric field profiles and carrier current profiles. The boundary conditions for the electric field at the depletion layer edges are given by

$$E(-x_1) = 0 \quad \text{and} \quad E(+x_2) = 0 \tag{1}$$

where $-x_1$ and x_2 define the p^+ and n^+ edges of the depletion layer.

The boundary conditions for normalized current density $P(x) = (J_P - J_n)/J_0$ (where J_p =hole current density, J_n = electron current density) at the two edges are given by

$$P(-x_1) = (2/M_p - 1) \text{ and } P(x_2) = (1 - 2/M_n) \tag{2}$$

The necessary device equations have been simultaneously solved [25-27] satisfying the appropriate boundary conditions mentioned in equations (1-2). The field dependence of electron and hole ionization rates and saturated drift velocities of electron ($v_{s,n}$) and holes ($v_{s,p}$) at 300K are made use of in the computation for the profiles of electric field and carrier currents.

The conversion efficiency is calculated from the approximate formula [28]

$$\eta(\%) = (1 x V_d) / (\pi \text{ x } V_B) \tag{3}$$

where V_d = Voltage drop across the drift region and V_B = Breakdown voltage.

Avalanche breakdown occurs in the junction when the electric field is large enough such that the charge multiplication factors (M_n, M_p) become infinite. Again, the breakdown voltage is calculated by integrating the spatial field profile over the total depletion layer width, i.e.,

$$V_B = \int_{x_1}^{x_2} E(x)dx \tag{4}$$

where $-x_1$ = n-side depletion layer width and $+x_2$ = p-side depletion layer width.

The high-frequency analysis of α- and β-GaN DDR IMPATT diode provides insight into its high frequency performance. The range of frequencies exhibiting negative conductance of the diode can easily be computed by Gummel-Blue method [29]. From the dc field and current profiles, the spatially dependent ionization rates that appear in the Gummel-Blue equations are evaluated, and fed as input data for the small signal analysis. The edges of the depletion layer of the diode, which are fixed by the dc analysis, are taken as the starting and end points for the small signal analysis. On splitting the diode impedance Z (x,ω) obtained from Gummel–Blue method, into its real part R (x,ω) and imaginary part X (x,ω), two differential equations are framed [29]. A double-iterative simulation scheme incorporating modified Runge-Kutta method is used to solve these two equations simultaneously. The diode negative resistance ($-Z_R$) and reactance ($-Z_x$) are computed through numerical integration of the -R (x) and -X (x) profiles over the active space-charge layer.

Thus,

$$-Z_R = \int_{x_1}^{x_2} -R dx \quad \text{and} \quad -Z_X = \int_{x_1}^{x_2} -X dx$$

The negative conductance (G), Susceptance (B) and the quality factor (Q) of the device can be calculated using the following relations:

$$-G = -Z_R /[(Z_R)^2 + (Z_X)^2] \text{ and } B = Z_X / [(Z_R)^2 + (Z_X)^2] \text{ and}$$

$$-Q_{peak} = (B /-G)_{\text{at peak frequency}}$$

It may be noted that both –G and B are normalized to the area of the diode. The avalanche frequency (f_a) is the frequency at which the imaginary part (B) of the admittance changes its nature from inductive to capacitive. Again it is the minimum frequency at which the real part (G) of admittance becomes negative and oscillation starts to build up in the circuit.

At a resonant frequency of oscillation, the maximum power output P_{RF} from the device can be obtained from the following expression,

$$P_{RF} = V^2_{RF} (G_p) A/2 \qquad (5)$$

where, V_{RF} is the amplitude of the RF swing and is taken as $V_B/2$, assuming 50% modulation of the breakdown voltage V_B. G_p is the diode negative conductance at the operating frequency and A is the area of the diode, taken as 10^{-10} m^2.

Table 3. DC and small signal properties of α- & β-GaN Impatts at 0.3 THz

	α-GaN	**β-GaN**
Peak Electric Field (V/m)	18.17×10^7	6.2×10^7
Breakdown Voltage V_B (V)	110.26	163
Peak Frequency (THz)	0.3	0.3
Efficiency	12.3%	11.5%
Quality Factor	3.5	2.85
Estimated output Power (W)	6.23	1.08
Peak Negative Conductance (S/m^2)	-0.41×10^8	-3.26×10^6

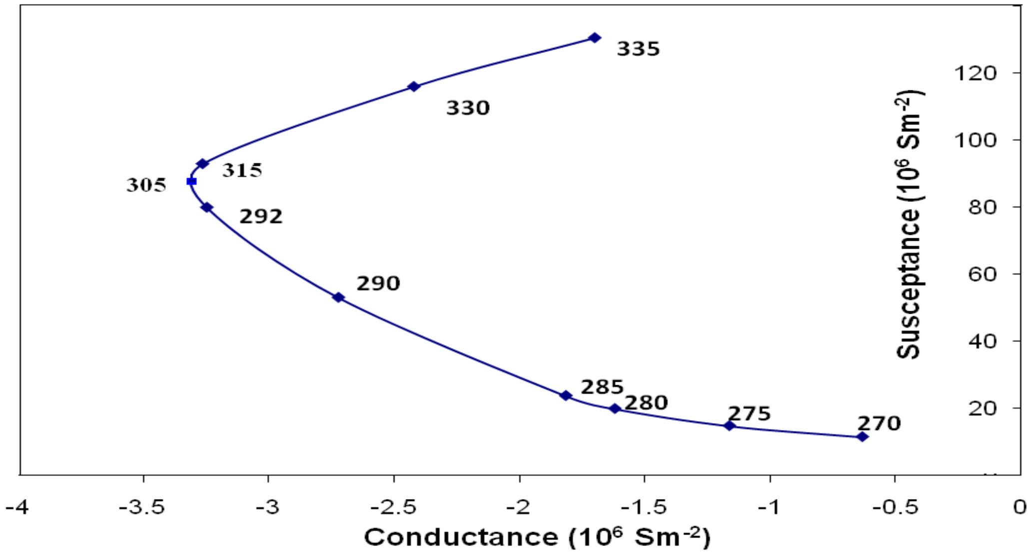

Figure 2. Conductance – Susceptance plot of ZnB-GaN DDR Impatt at 0.3 THz

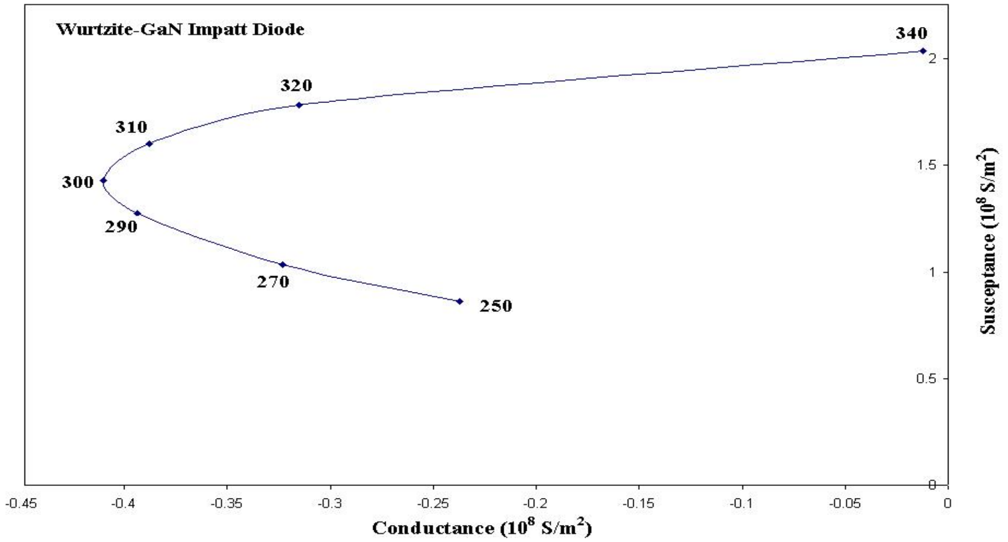

Figure 3. Conductance – Susceptance plot of Wz-GaN DDR Impatt at 0.3 THz

3. Results and Discussions

The material parameters of α- and β-GaN are enlisted in Table-1 and its structural or design parameters for Impatt diodes at 0.3 THz are enlisted in Table-2. The DC properties of the devices, obtained after simulation, reveal that β-GaN based Impatts has a high breakdown voltage of 163 V at an optimum bias current density of 3.1 × 10^9 A/m^2. The Breakdown Voltage for α-GaN Impatt is found to be 110.26 V at an optimum bias current density of 0.2 × 10^8 A/m^2. The peak electric field value obtained is 18.17 × 10^7 V/m and 6.2 × 10^7 V/m for α- and β-GaN Impatt diodes respectively. The conversion efficiency for α-GaN Impatt is calculated to be 12.3% with an output power of 6.23 W while that for β-GaN Impatt is 11.5% with an output power of 1.08 W. The peak negative conductance of α-GaN Impatt at a bias current density of 0.2 × 10^8 A/m^2

is -0.41 × 10^8 S/m^2. The peak negative conductance of β-GaN Impatt diode at a bias current density of 3.1 × 10^9 A/m^2 is found to be -3.26 x 10^6 S/m^2. Fig. 2 and 3 depicts the plots of Conductance vs. Susceptance at 0.3 THz frequency for α- and β-GaN based DDR Impatt diode respectively. From the plots it is evident that the peak negative conductance occurs at 300 GHz for α- GaN Impatt and 305 GHz for β-GaN; both the frequencies being very close to the design frequency of 300 GHz. The Q-factor determines the growth rate and stability of oscillation. Less Q-factor means better device performance. The Q-factor of α- and β-GaN Impatt has been found to be 3.5 and 2.85 respectively. The results obtained are very encouraging and portrays the strong potentiality of both α- and β-GaN Impatt diode as a powerful oscillator for Terahertz communication.

4. Conclusion

The simulation results show that α- and β-GaN DDR Impatt diode provides a maximum conversion efficiency of 12.3 % and 11.5 % at 0.3 THz and both devices delivers high peak output power of 6.23 W and 1.08 W respectively. It is also possible to generate negative resistance in the Terahertz frequency band. The encouraging simulated results clearly indicate the possibility of designing and fabricating Impatt diodes using Wurtzite and Zinc-Blende phase of GaN as the base material. Thus in near future, GaN based Impatts will be highly suitable for operation in the Terahertz domain.

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