

A comparative study on optimized bias current density performance of β -GaN Avalanche Transit Time diode at Ka-band and Terahertz frequency

Soumen Banerjee, Oishee Mandal, Saswati Halder, Arinima Saha, Debashree Bhowmik

Abstract— The Terahertz (THz) and Ka-band performance of Zinc-Blende (β -phase) of GaN based p^+pnn^+ DDR IMPATT has been studied at optimum bias current density. The study based on drift diffusion model has been carried out to explore the DC and small signal properties of the device. The bias current optimization based on maximum conversion efficiency and device negative resistance reveals the strong potentiality of β -GaN DDR IMPATT as a powerful solid state source for generating high power at Ka-band and THz frequency. At Ka-band (35 GHz) the conversion efficiency obtained is 15% at an optimized current density of 3.2×10^9 A/m² while the same at the THz frequency (0.3 THz) is 11.5% at 3.1×10^9 A/m².

Index Terms— Double Drift IMPATT diode, Ka-band, Optimum bias current density, THz frequency, Zinc-Blende (β -phase) GaN.

1 INTRODUCTION

THE Terahertz domain (0.1 - 10 THz) 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, Remote sensing, Space science, Spectroscopy etc [1]. The terahertz domain throws a big challenge as it marks the margin of electronics-photonics technology. The electronic based devices viz., Gunn diode, IMPATT diode, Resonant Tunneling Diode (RTD) and Nanometer Field Effect Transistor based on plasma wave have been widely investigated at lower THz domain while photonics based devices such as Quantum Cascade Laser has been investigated at upper THz domain. As compared to millimeter wave and opto-electronic based devices, the radiation power and the detection sensitivity of THz devices are extremely low [2]. The ongoing research and development in THz domain have brought up the possibility of opening up an extraordinary range of new markets in present decade [3]. The wide popularity of THz technology has spanned its wave to the studies of fundamental physics and cultural heritage [4]. The Ka-band (26.5 - 40 GHz), on the other hand, is of relative importance especially at 35 GHz window frequency where atmospheric attenuation is relatively low. It also opens application windows in field of communication satellites, high resolution close range targeting radar abode military aircrafts, vehicle speed detection by law enforcement, scientific data collection b),[y space telescope etc [5]. IMPATTs being a powerful],[solid state source of microwave, millimeter & sub-millimeter wave are found to deliver high power with high efficiency. The search is on to find new materials acting as base materials for IMPATT diodes fabrications. Fortunately,

Gallium Nitride (GaN) exhibits excellent material properties to satisfy the needs and recent reports on its applications as base materials for electronic and opto-electronic devices are reported in literature [6]. GaN supports peak internal electric fields about five times higher than those using Silicon (Si) and Gallium Arsenide (GaAs) results in higher breakdown voltage which is extremely important for devices handling high power.

Gallium Nitride is found to exist in two polytypic forms viz., Wurtzite and Zinc-Blende phase. The band gap energy of β -GaN is 3.2eV and other notable properties like saturation drift velocity, breakdown field dielectric constant and carrier mobility makes it an attractive candidate for high power and high frequency devices. Recent experimental studies reveal that high quality GaN films can be grown on silicon substrate by MOCVD technique by the use of Si_xN_y inserting layer [7]. Thus in the light of maturity of fabrication technology process and suitable material properties GaN appears to be one of the best choice for the development of IMPATTs. The expected superior performance of wide band gap semiconductors like GaN based devices are assessed by taking into consideration Keyes' FOM and Jhonson's FOM [6] where the values for GaN are 1.6 and 756 respectively, thereby exhibiting superiority in comparison to traditional Si and GaN with respect to high frequency and high temperature performance of wide gap semiconductor.

To satisfy the quest of increasing demand for high solid state sources, the authors have designed a flat profile p^+pnn^+ β -GaN DDR (Double Drift Region) IMPATT at 35 GHz and its dc and high frequency properties has been investigated and compared with the same at 0.3 THz [8] to explore the potentiality of the device.

The structure & doping parameter of the device are first optimized for highest efficiency and optimum punch through factor at the optimum bias current density by taking into consideration the effect of mobile space charge. The high frequency

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admittance properties and negative resistance profile has also been simulated following an iterative method. The simulation scheme incorporates material parameters from recent published papers and electronic archive. The results obtained are very encouraging and reveals the strong potentiality of the device as a powerful high power solid state source at Ka-band and THz frequency.

2 SIMULATION METHODOLOGIES

A double drift p^+pnn^+ structure of β -GaN IMPATT has been considered and simulation has been carried out at 35 GHz and 0.3 THz. The transit time formula of Sze and Ryder [23] is used here for the design of doping profile. The highly doped substrates are p^+ and n^+ regions while n and p are epi-layers. The material parameters are extracted from recent published papers[8],[9],[10],[11],[12],[13],[14],[15],[16],[17],[18],[19],[20],[21] and Electronic Archive [22]. Fig. 1 depicts the doping profile and electric field profile of p^+pnn^+ DDR GaN IMPATT diode. The parameters for β -GaN are enlisted in Table-1 and the design parameters of β -GaN IMPATT at the two frequencies are enlisted in Table-2.

The computer analysis of DC and small signal behavior of 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. In this simulation 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.

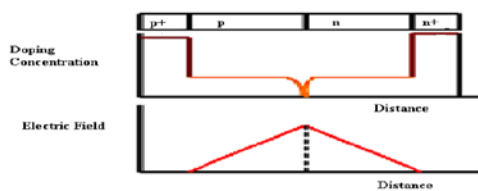


Fig. 1. Doping profile and Electric Field profile of p^+pnn^+ DDR GaN Impatt Diode.

The boundary conditions for the electric field at the depletion layer edges are given by

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

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

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

The necessary device equations have been simultaneously solved satisfying the appropriate boundary conditions mentioned in (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 [24]

$$\eta(\%) = (1 \times V_d) / (\pi \times V_B) \quad (3)$$

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.,

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

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

The high-frequency analysis of 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 [25]. 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 $Z(x, \omega)$ obtained from Gummel-Blue method, into its real part $R(x, \omega)$ and imaginary part $X(x, \omega)$, two differential equations are framed [25]. 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.

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

The negative Conductance (G), Susceptance (B) and the Quality Factor (Q) of the device can be calculated using the following relations:

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

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,

$$P_{\text{RF}} = V_{\text{RF}}^2 (G_p) A / 2 \quad (5)$$

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 .

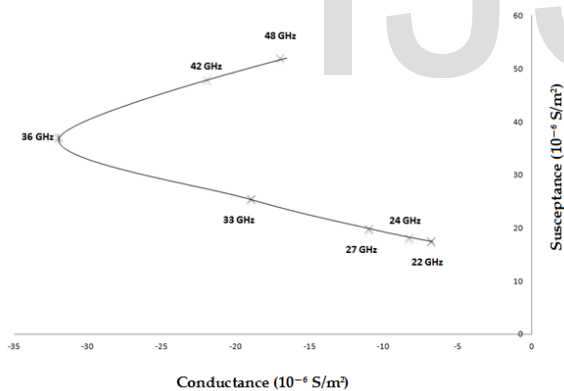


Fig. 2. Conductance-Susceptance plot of ZnB-GaN DDR Impatt Diode at 35 GHz

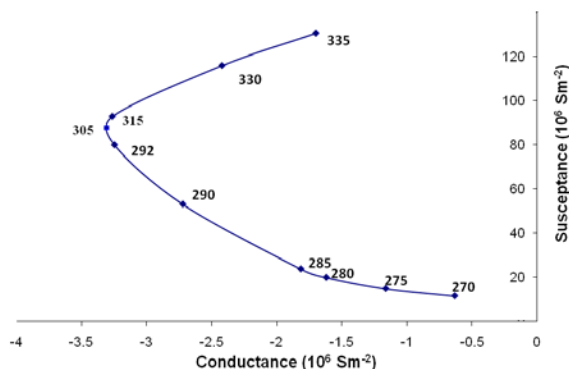


Fig. 3. Conductance-Susceptance plot of ZnB-GaN DDR Impatt Diode at 300 GHz

TABLE 1
MATERIAL PARAMETERS OF ZNB-GAN

Ionization coefficient of electrons at low fields, $A_n (\text{m}^{-1})$	1.023×10^9
Ionization coefficient of electrons at low fields, $b_n (\text{V/m})$	0.602×10^9
Ionization coefficient of holes at low fields, $A_p (\text{m}^{-1})$	1.276×10^8
Ionization coefficient of holes at low fields, $b_p (\text{V/m})$	0.376×10^9
Ionization coefficient of electrons at high fields, $A_{hn} (\text{m}^{-1})$	5.284×10^8
Ionization coefficient of electrons at high fields, $b_{hn} (\text{V/m})$	0.547×10^9
Ionization coefficient of holes at high fields, $A_{hp} (\text{m}^{-1})$	8.328×10^7
Ionization coefficient of holes at high fields, $b_{hp} (\text{V/m})$	0.323×10^9
Bandgap Energy (eV)	3.2

TABLE 2
DESIGN PARAMETERS OF ZNB-GAN DDR IMPATT AT 35 GHz AND 0.3 THz

Design Parameters	$f = 35\text{GHz}$	$f = 0.3\text{THz}$
Width of n-epilayer (W_n)	$0.3 \mu\text{m}$	172nm
Width of p-epilayer (W_p)	$0.3 \mu\text{m}$	163nm
Background doping concentration (m^{-3})	2×10^{23}	27.5×10^{23}
Current density (Am^{-2})	3.2×10^9	3.1×10^9

TABLE 3
DC AND SMALL SIGNAL PROPERTIES OF ZNB-GAN DDR IMPATT AT 35 GHz AND 0.3 THz

Parameters	$f = 35\text{GHz}$	$f = 0.3\text{THz}$
Breakdown Voltage V_B (V)	84.1	163
Peak Frequency (GHz)	36	305
Efficiency	15 %	11.5%
Quality Factor	0.84	2.85
Estimated output Power (W)	2.83	1.08
Peak Negative Conductance (S/m^2)	-32×10^6	-3.26×10^6

3 RESULTS AND DISCUSSIONS

The material parameters of ZnB-GaN are enlisted in Table-1. Table 2 depicts the design parameters of β -GaN DDR IMPATT at 35 GHz and 0.3 THz while the DC and small signal properties are enlisted in Table 3. The DC properties reveal that the breakdown voltage at an optimum bias current density of $3.2 \times 10^9 \text{ A/m}^2$ is 84.1 V at 35 GHz while the same at 0.3 THz is 162 V at an optimum bias current density of $3.1 \times 10^9 \text{ A/m}^2$. The conversion efficiency is 15% at 35 GHz with an output power of 2.83 W and the same at 0.3 THz is 11.5% with an estimated output power of 1.08 W. The peak negative conductance is $-3.2 \times 10^6 \text{ S/m}^2$ at $3.2 \times 10^9 \text{ A/m}^2$ for β -GaN DDR IMPATT at 35 GHz while the same at 0.3 THz is $-3.26 \times 10^6 \text{ S/m}^2$ at $3.1 \times 10^9 \text{ A/m}^2$. Fig.2 and Fig.3 depicts the conductance –susceptance

(G-B) plot for β -GaN DDR IMPATT at 35 GHz and 0.3 THz respectively. From the plots it is evident that the peak negative conductance occurs at 36 GHz and 305 GHz which are very close to the design frequency of 35 GHz and 300 GHz respectively. The Q-factor determines the growth rate and stability of oscillation. Less Q-factor means better device performance. The Q-factor of ZnB-GaN DDR IMPATT obtained at 35 GHz and 0.3 THz is 0.84 and 2.85 respectively. The results obtained are very encouraging & portrays a strong potentiality of β -GaN DDR IMPATT as a powerful oscillator for millimeter wave and THz communication.

4 CONCLUSION

The simulation results reveal that β -GaN DDR Impatt provides maximum conversion efficiency of 15% and 11.5% at 35 GHz and 0.3 THz respectively and delivers high peak output power of 2.83 W and 1.08 W at the corresponding frequencies. Simulation also reveals that generating negative resistance at Ka-band and THz frequency is possible. The results obtained are very encouraging and clearly indicates the possibility of materialization of Impatt diodes using Zinc Blende phase of GaN as the base material. Thus, Impatts based on β -GaN will be highly suitable for operation at millimeter wave and THz domain in near future.

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