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Bias current optimization of Wurtzite-GaN DDR IMPATT diode for high power operation at THz frequencies

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Abstract

The properties and performance of DDR p^+pnn^+ Wurtzite Gallium Nitride (Wz-GaN) Impatt diodes at Terahertz (THz) frequencies has been investigated for optimum bias current density through modeling and simulation technique. A double iterative computer method based on drift-diffusion model has been used to study the DC and small signal admittance properties of the device. The bias current density is optimized with respect to maximum conversion efficiency and device negative resistance at both 0.3 and 0.5 THz frequencies. The simulation studies show that these devices are potential sources for generating high RF power. The DC-to-RF conversion efficiency of the device is found to be 12.3% and 11.4% at 0.3 THz and 0.5 THz at the optimum bias current density of 2×10^7 A/m^2 and 1.8×10^8 A/m^2 respectively. The design results presented in this paper will be useful to realize experimentally Wz-GaN IMPATTs for Terahertz frequencies.

Keywords: *Wurtzite GaN, Double drift Impatt diode, Optimum bias current density.*

1. Introduction

IMPact **A**valanche **T**ransit **T**ime (IMPATT) diodes have emerged as very important solid state sources capable of generating high frequency RF power at microwave, millimeter wave and sub-millimeter wave frequency bands. In view of the simple arrangement, low cost, tuning capability, frequency coverage, output power and reliability, Impatt devices have found a variety of applications as solid state transmitters in tracking Radars, Missile seekers, Radiometers and Millimeter wave communication systems.

The Terahertz domain is enriched with the emerging possibilities in the fields of Remote sensing, Imaging, Spectroscopy and Communication with unique application for detecting hidden biological weapons and explosives. The development of reliable solid state semiconductor devices operating in the Terahertz frequency region has therefore attracted the attention of researchers worldwide. During last decade, significant efforts were made to realize solid-state sources that may generate THz power. Among all the available solid state sources, IMPATT diodes have already emerged as the most efficient source for its ability to deliver high RF power even at 300 GHz or more. It is well known that the RF power depends on various factors like critical field for avalanche breakdown, saturation drift velocity for charge carriers, etc which varies for different semiconductor materials and play vital role in limiting the output power of an IMPATT diode at a particular operating frequency. Silicon and Gallium Arsenide Impatt diodes have been established as reliable sources; however owing to some fundamental limitations in material parameters, these Impatt diodes possess limitation in power and operating frequencies. The search is on to find new materials for Impatt diode fabrication such that they overcome these limitations and produce high power at higher frequencies.

Fortunately, wide band gap semiconductors like GaN having excellent material properties are recently been used as base material for electronic and optoelectronic devices [1]. GaN with band gap energy of 3.4 eV at room temperature enables devices based on this material to support peak internal electric field (E_C) about five times higher than those using Si and GaAs. Higher E_C results in higher breakdown voltage which is extremely important for devices handling high-power. Hence GaN based Impatts can operate at higher voltage at the same operating frequency. With a high E_C, much higher doping level can be achieved. GaN is less noisy and is chemically very stable at high temperatures. The inherent material properties of GaN result in width reduction of the devices thereby enabling GaN Impatts for high-frequency (THz range) operation unlike the conventional Si, GaAs and InP based IMPATT diodes.

Despite all these high frequency (THz) operating advantages, GaN is yet to hit the mainstream owing to the difficulties in growth and device fabrication. Considerable progress in the growth of nitrides during the last five years makes this material suitable for fabrication of various electronic devices. Recent experimental study [2] reveals the growth of high quality GaN films on Si substrate by MOCVD technique by using a Si_xN_y inserting layer. Hence, in the light of the maturity of the fabrication technology and the unique material properties, GaN appears to be one of the best choices for development of semiconductor devices, especially in THz region, in the coming decade.

To the best of the authors' knowledge, no experimental results on fabrication of GaN based IMPATT diodes are available in the literature. However some studies on GaN Impatts have been reported lately [3-10]. In the sub millimeter / Terahertz region high power IMPATT oscillators are extremely useful solid state sources. To satisfy the quest of increasing demand for high power THz sources in various strategic, civilian and defence applications, the authors have designed Wz-GaN DDR IMPATT diodes at terahertz domain for their optimum performance. A flat profile p^+pnn^+ device structure has been taken for operation at 0.3 and 0.5 THz and its high frequency performance has been investigated in the depletion layer at high bias current densities by incorporating the effect of mobile space charge. The entire paper is aimed to explore the potentiality of Wz-GaN DDR Impatt as a probable solid state source at Terahertz frequencies.

2. Simulation Methodologies

2.1. Design of Doping Profile

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. A double drift p^+pnn^+ structure of Wz-GaN Impatt have been designed by using computer simulation technique for operation at 0.3 and 0.5 THz frequencies by using the transit time formula of Sze and Ryder [11] which is $W = 0.35\, v_{sn} / f$; where W, v_{sn} and f are the total depletion layer width, saturation velocity of electrons and operating frequency respectively. Here n^+ and p^+ are highly doped substrates and n and p are epilayer.

2.2. Material & Design Parameters

The simulation scheme incorporates the material parameters from the recent published papers and Electronic Archive [12]. The material parameters of Wz-GaN are enlisted in Table-1 and design parameters of the same are shown in Table-2.

Table 1. Material parameters of Wz-GaN

Ionization coefficient of electrons at low fields, A_n (10^8 m^{-1})	2.90
Ionization coefficient of electrons at low fields, b_n (10^8 V/m)	3.4
Ionization coefficient of holes at low fields, A_p (10^8 m^{-1})	2.96
Ionization coefficient of holes at low fields, b_p (10^8 V/m)	4.01
Ionization coefficient of electrons at high fields, Ah_n (10^8 m^{-1})	2.90
Ionization coefficient of electrons at high fields, bh_n (10^8 V/m)	3.4
Ionization coefficient of holes at high fields, Ah_p (10^8 m^{-1})	2.96
Ionization coefficient of holes at high fields, bh_p (10^8 V/m)	4.01
Saturation drift velocity of holes, v_{sp} (10^6 m/s)	0.25
Mobility of electrons, μ_n (m^{2}V/s)	0.10
Mobility of holes, μ_p x 10^{-3} (m^{2}V/s)	3
Permittivity, ε (10^{-10} F/m)	0.79

Table 2. Design parameters of Wz-GaN DDR Impatt

	f = 0.3 THz	f = 0.5 THz
Width of n-epilayer (W_n) (nm)	308.0	183.0
Width of p-epilayer (W_P) (nm)	306.0	184.0
Background doping concentration (both n and p region) (10^{23} m^{-3})	4.0	3.0
Current density (10^7 Am^{-2})	0.8 – 10.0	18.0 – 50.0
Substrate doping concentration (10^{26} m^{-3})	5.0	5.0

2.3. Computer Simulation Techniques

In the computer simulation of DC and small-signal behavior of the GaN DDR IMPATT diodes, the following assumptions are made, viz., (i) one dimensional model of the p-n junction is treated; (ii) 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 [13]. 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

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

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

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

The necessary device equations have been simultaneously solved [13] 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 [12].
The conversion efficiency is calculated from the approximate formula [14]

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

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.,

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

where $-x_1$ = n – side depletion layer width
$+x_2$ = p – side depletion layer width
The high-frequency analysis of Wz-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 [15]. 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 [15]. 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,

$$-Z_R = \int_{x_1}^{x_2} -Rdx \qquad \text{and} \qquad -Z_X = \int_{x_1}^{x_2} -Xdx$$

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.

3. Results and Discussions

The various design parameters used to study the DC and high frequency properties of GaN DDR Impatt diode at 0.3 and 0.5 THz are given in Table 1 & Table 2 respectively. It is observed from Table 3 that the peak electric field E_m at the p-n junction decreases with the increase in current density. The E(x) profiles at high bias current levels are found to be punch through type. The avalanche zone width is obtained from the region of the depletion layer near the junction where the current grows through avalanche multiplication to 95% of its dc value (J_0). These values are given in Table 3 & Table 4 for Wz-GaN DDR Impatts at 0.3 & 0.5 THz. Table 3 reveals that with the increase of current density, the field maximum increases gradually, but owing to the increasing space charge effect, efficiency degrades from 11.998 % to 11.596 %. The optimum bias current density has been found to be 2 x 10^7 A/m^2 where the DC-to-RF conversion efficiency is of maximum value 12.3% as is evident from Figure 1. Similarly it is observed from Table 4 that in the case of 0.5 THz Impatt, with the increase in current density, the field maximum increases first and then it reduces slightly. Also the efficiency reduces from 11.396 % to 10.43 % due to the space charge effect. In this case, the optimum bias current density for the maximum efficiency of 11.4% is found to be 1.8 x 10^8 A/m^2 as obtained from Figure 2. The breakdown voltage in case of 0.3 THz Impatt is 35.6 V at a current density of 0.8 x 10^7 A/m^2. It is found from Table 4 that breakdown voltage reduces to 23.172 V in case of 0.5 THz Impatt at a bias current density of 1.8 x 10^8 A/m^2. The conversion efficiency η increases very slowly at lower range of current density and attains a maximum value of η = 12.3% at bias current density of 2.0 x 10^7 A/m^2 for 0.3 THz and a maximum value of η = 11.4% at bias current density of 1.8 x 10^8 A/m^2 for 0.5 THz as revealed in Figure 1 & 2 respectively. Thus the optimum bias current density for the device operation at different frequencies is obtained. As we further increase the bias current density, the efficiency falls owing to the mobile space charge effect. The small signal results of the device at optimized bias current density are shown in Table 5. The admittance plot (G-B) of Flat profile Wz-GaN DDR Impatt diode is shown in Figure 3 & Figure 4. The Q-factor determines the growth rate and stability of oscillation. Less Q-factor means better device performance.

Table 3. DC properties of Wz-GaN DDR Impatt at 0.3 THz

	$J = 0.8X10^{7}$ A/m^{2}	$J = 2X10^{7}$ A/m^{2}	$J = 8X10^{7}$ A/m^{2}	$J = 10X10^{7}$ A/m^{2}
E_m (10^8 V/m)	0.99	0.99	0.9825	0.98
X_0 (10^{-11} m)	4.1875	10.438	40.75	50.50
W_{an} (m)	1.5396	1.499	1.489	1.4849
W_{ap} (m)	1.215	1.215	1.3841	1.4451
W_n (m)	3.0796	3.079	3.0759	3.074
W_p (m)	3.0604	3.061	3.0641	3.065
V_B (V)	35.603	35.827	36.467	36.677
V_A (V)	22.19	22.0036	22.985	23.322
η (%)	11.998	12.30	11.774	11.596

Table 4. DC properties of Wz-GaN DDR Impatt at 0.5 THz

	$J = 1.8X10^{8}$ A/m^{2}	$J = 2.5X10^{8}$ A/m^{2}	$J = 3X10^{8}$ A/m^{2}	$J = 4X10^{8}$ A/m^{2}	$J = 5X10^{8}$ A/m^{2}
E_m (10^8 V/m)	1.1275	1.1225	1.11875	1.11	1.10125
X_0 (10^{-11} m)	39.25	54.00	64.00	83.00	100.50
W_{an} (m)	0.816	0.821	0.8	0.791	0.75995
W_{ap} (m)	0.8039	0.837	0.878	0.9683	1.0601
W_n (m)	1.8361	1.8346	1.8336	1.8317	1.8499
W_p (m)	1.8439	1.8454	1.8464	1.8483	1.8300
V_B (V)	23.172	23.445	23.633	23.945	24.167
V_A (V)	14.88	15.15	15.32	15.8315	16.2534
η (%)	11.396	11.267	11.202	10.79	10.428

Table 5. Small signal properties of Wz-GaN DDR Impatt at the optimized bias current density

Designed frequency (GHz)	Current Density ($10^{7}Am^{-2}$)	$-Q_P$	G_P (10^{6} Sm^{-2})	P_{RF} (W)	f_P (THz)
0.3	2.0	4.78	28.0	4.54	0.305
0.5	1.8	5.38	11.0	3.18	0.53

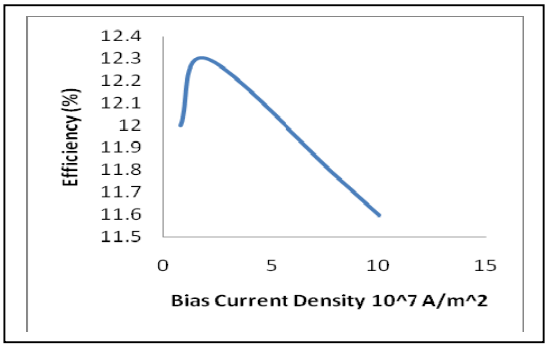

Figure 1. Efficiency vs Bias current density plot of Wz GaN DDR Impatt at 0.3 THz

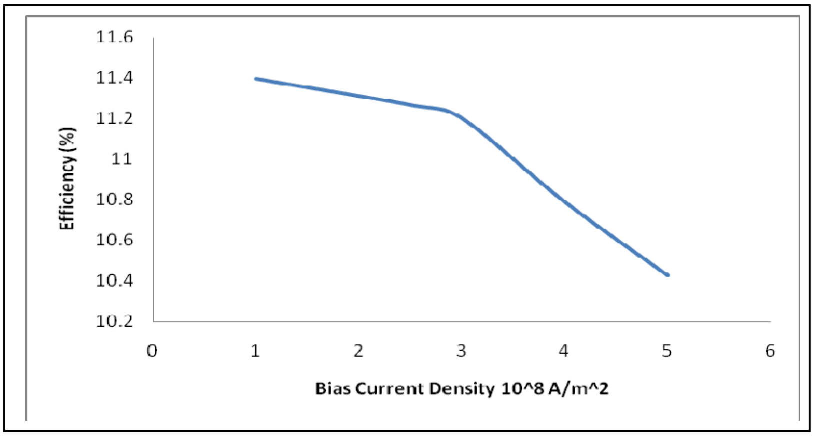

Figure 2. Efficiency vs Bias current density plot of Wz GaN DDR Impatt at 0.5 THz

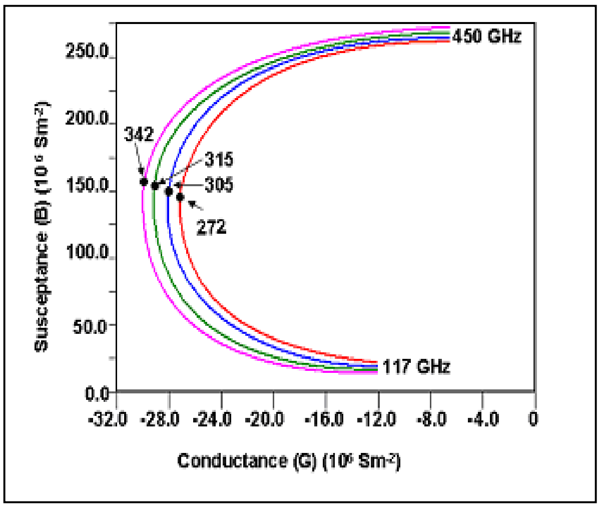

Figure 3. Conductance-Susceptance plot of Wz GaN DDR Impatt at 0.3 THz

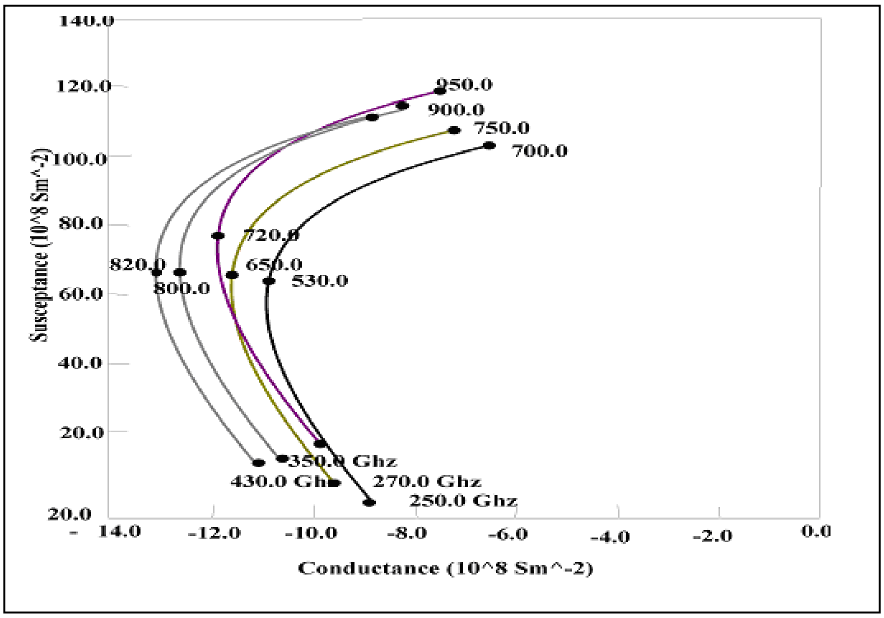

Figure 4. Conductance-Susceptance plot of Wz GaN DDR Impatt at 0.5 THz

4. Conclusion

The simulation results show that GaN DDR Impatt diode provides a maximum conversion efficiency of 12.3 % at 0.3 THz and 11.4 % at 0.5 THz and delivers large output power. It is also possible to generate negative resistance in the Terahertz frequency band. The results are encouraging and clearly indicate that it is possible to design and fabricate Impatt diodes using GaN as base material. Thus GaN based Impatts will be highly suitable for operation in Terahertz frequency region in near future.

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