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# β-GaN Avalanche Transit Time Diode as a Potential Source at Millimeter Wave Window Frequency

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## *Abstract*

*A computer simulation study based on Drift-Diffusion model has been carried out to explore and analyze the DC and high frequency properties of Zinc-Blende (β-phase) Gallium Nitride based $p^+pnn^+$ DDR IMPATT. The simulation study based on bias current optimization is performed at Ka-band window frequency of 35 GHz. The results portray the strong potentiality of β-GaN IMPATT as a powerful millimetre wave source with maximum conversion efficiency of 15% at an optimum bias current density of $3.2\times 10^9 A/m^2$. The design results presented in the paper will be very helpful in realization of these diodes for millimetre wave communication systems.*

**Keywords:** *Bias current density, Double-Drift IMPATT diode, Gallium Nitride (GaN), Ka-band, Zinc-Blende (β-phase) GaN*

## 1. Introduction

The present day research activity for Millimeter wave systems are centered on and around 35 GHz and 94 GHz window frequencies exhibiting relatively low atmospheric attenuation [1]. The Ka-band (26.5-40 GHz) window frequency of 35 GHz is an abode of innumerous applications mainly in the fields of communication satellites, Radars in military aircrafts, space telescopes, vehicles etc. The millimeter wave systems offer many advantages such as smaller size, lighter weight, small antenna size, high accuracy and resolution and better signal penetration through clouds, dust, smoke etc. Rain attenuation of radio wave is significant in satellite communication using frequencies higher than 10 GHz such as Ku-band and Ka-band [2-6]. Atmospheric effect plays a major role in design of satellite-to-earth links operating at frequencies above 10 GHz [7]. Most effective satellite communications are observed in very high frequency bands like Ka-band or millimeter wave bands where ionospheric propagation plays a major role [8]. As the electromagnetic spectrum becomes extremely congested, the need for higher frequency bands is in rise [9]. The Ka-band IMPATT proposed by the authors is a perfect solution to the challenging needs of development of solid state high power millimeter wave source.

Conventional IMPATTS based on Silicon, Indium-Phosphide and Gallium Arsenide is extremely powerful sources exhibiting good conversion efficiency and output power. The solution to develop IMPATTs generating high power at extra high frequency and even higher leads to wide band-gap semiconductors as obvious choice for consideration as base materials for IMPATT. The authors have picked up Zinc Blende (ZnB) phase or β-phase of Gallium Nitride (GaN) as a wide band-gap material for designing IMPATTs. The wide band-gap semiconductors based opto-electronic devices and various other electronic devices find extensive uses in market [10]. Keyes' and Jhonson's FOM [11] are assessed to exhibit superior performances of wide band-gap based devices over conventional semiconductor based devices. The Keyes' FOM and Jhonson's FOM values for silicon are unity and for GaAs are 0.45 and 7.1 respectively. The same parameters for GaN are 1.6 and 756 respectively thereby indicating its superior performance as compared to traditional silicon and GaAs in terms of high frequency and high temperature performance.

GaN in the ZnB form has a band-gap of 3.28 eV at zero Kelvin and 3.2 eV at 300K. The wide band-gap, the hetero junction capability and the strong atomic bonding of this material makes them good candidate for RF, microwave and millimetre wave devices. Other pertinent device related parameters like good terminal conductivity, large breakdown voltage, average saturation drift velocity at high fields, dielectric constant and carrier mobility makes it an obvious choice for designing IMPATTs using GaN. These novel features enrich GaN as a very lucrative material for development of semiconductor devices. Moreover GaN is less noisy and chemically very stable at high temperatures. Despite the high frequency operating advantages, GaN is yet to hit the main stream 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 many electronic devices. High quality GaN film can be grown on SiC substrate by MOCVD technique by using a $Si_xN_y$ inserting layer [12]. To the best of authors' knowledge no experimental results on GaN IMPATT are available in literature. However some studies on it have been reported lately [13-23].

The authors have considered a flat profile $p^+pnn^+$ DDR β-GaN based IMPATT at an operating frequency of 35 GHz and carried out some theoretical and simulation studies on its DC and high frequency properties in the depletion region at optimised bias current density by taking into consideration the effect of mobile space charge. The simulated results obtained and presented in this paper are very encouraging and will be helpful for fabrication and designing of β-GaN IMPATT at 35 GHz.

## 2. Simulation Methodologies

Computer simulation at Ka-band window frequency of 35 GHz has been carried out on a double drift $p^+pnn^+$ structure of β-GaN (ZnB phase) based IMPATT diode. The authors have used the transit time formula of Sze and Ryder [24] for the design of doping profile. Both the $p^+$ and $n^+$ regions are the highly doped substrates while n and p are epi-layers. The material parameters are extracted from recent published papers [13-23] and Electronic Archive [25]. The doping profile and electric field profile of $p^+pnn^+$ DDR GaN Impatt Diode are depicted in Figure 1. The material parameters for β-GaN are enlisted in Table-I and the design parameters of β-GaN IMPATT are enlisted in Table-II.

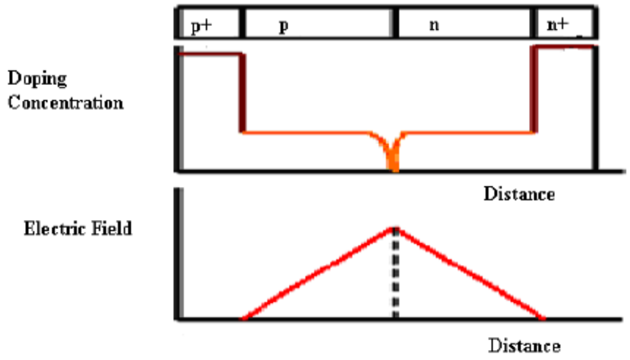

**Figure 1. Doping Profile and Electric Field Profile of $p^+pnn^+$ DDR GaN IMPATT Diode**

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. 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 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 [26]

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

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.*,

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

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 [27]. 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 [27]. 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:

$$-G = -Z_R / [(Z_R)^2 + (Z_X)^2]$$

$$B = Z_X / [(Z_R)^2 + (Z_X)^2]$$

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

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 1. Material Parameters of β-GaN**

| | |
|---|---|
| Ionization coefficient of electrons at low fields, $A_n$ ( $m^{-1}$) | $1.023 \times 10^9$ |
| Ionization coefficient of electrons at low fields, $b_n$ (V/m) | $0.602 \times 10^9$ |
| Ionization coefficient of holes at low fields, $A_p$ ($m^{-1}$) | $1.276 \times 10^8$ |
| Ionization coefficient of holes at low fields, $b_p$ (V/m) | $0.376 \times 10^9$ |
| Ionization coefficient of electrons at high fields, $Ah_n$ ($m^{-1}$) | $5.284 \times 10^8$ |
| Ionization coefficient of electrons at high fields, $bh_n$ (V/m) | $0.547 \times 10^9$ |
| Ionization coefficient of holes at high fields, $Ah_p$ ($m^{-1}$) | $8.328 \times 10^7$ |
| Ionization coefficient of holes at high fields, $bh_p$ (V/m) | $0.323 \times 10^9$ |
| Mobility of electrons ($cm^2/Vs$) at 300K | 1000 |
| Mobility of holes ($cm^2/Vs$) at 300K | 350 |
| Bandgap Energy (eV) | 3.2 |

**Table 2. Design Parameters of β-GaN DDR IMPATT at 35 GHz**

| | |
|---|---|
| Width of n-epilayer ($W_n$) (μm) | 0.3 |
| Width of p-epilayer ($W_p$) (μm) | 0.3 |
| Background doping concentration ($10^{23}$ $m^{-3}$) | 2 |
| Current density ($Am^{-2}$) | $3.2 \times 10^9$ |

**Table 3. DC and Small Signal Properties of β-GaN IMPATTS at 35 GHz at Optimum Bias Current Density of $3.2 \times 10^9$ A/$m^2$**

| | |
|---|---|
| Breakdown Voltage $V_B$ (V) | 84.1 |
| Peak Frequency (GHz) | 36 |
| Efficiency | 15 % |
| Quality Factor | 0.84 |
| Estimated output Power (W) | 2.83 |
| Peak Negative Conductance (S/$m^2$) | $-32 \times 10^6$ |

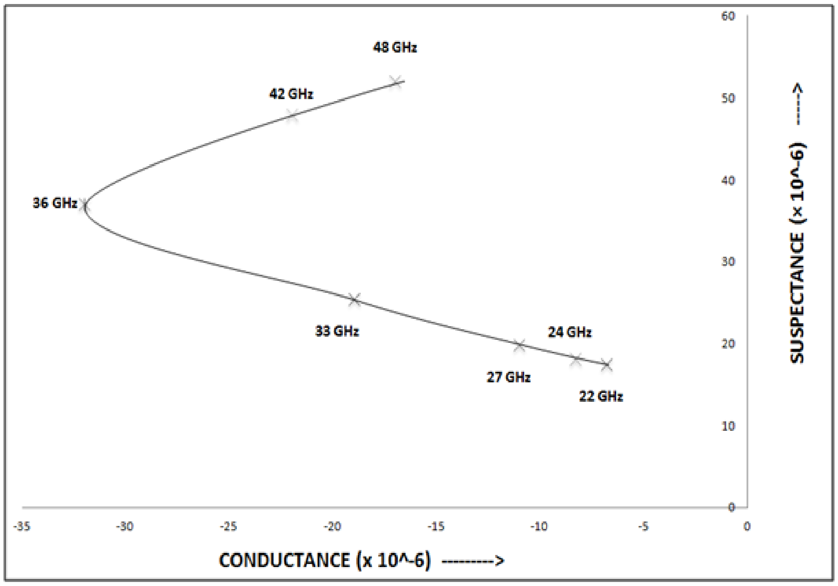

Figure 2. Conductance – Susceptance plot of ZnB-GaN DDR IMPATT at 35 GHz

## 3. Results and Discussions

Table-I depicts the material parameters of β-GaN. The material parameters includes ionization coefficient of electrons and holes at low fields and high fields, mobility of electrons and holes and band gap energy. The structural or design parameters for β-GaN IMPATT diode at Ka-band window frequency of 35 GHz are enlisted in Table-II. The width of both the n-epilayer and p-epilayer are taken to be 0.3 micron. The background doping concentration is taken to be $2\times10^{23}$ $m^{-3}$. Simulation studies have been done for proper understanding of the DC and high frequency properties of the IMPATT diode as analytical methods do not provide accurate information. Computer simulation has been carried out at various bias current densities and the optimum bias current density of $3.2\times10^{9} A/m^{2}$ is considered in this paper with respect to maximization of efficiency and output power. The simulated DC and high frequency parameters of β-GaN IMPATT at an optimum bias current density of $3.2\times10^{9}$ $A/m^{2}$ is depicted in Table-III. The simulated DC properties for β-GaN IMPATT reveal a high value breakdown voltage of 84.1 V at an optimum bias current density of $3.2\times10^{9} A/m^{2}$. The calculated conversion efficiency for β-GaN IMPATT is 15% with an output power of 2.83 W. The simulated DC results which include DC field, current profiles and space dependent quantities are used for obtaining the high frequency properties of β-GaN DDR IMPATT. Small signal analysis of IMPATT diode provides insight into the millimeter wave. The peak negative conductance of β-GaN IMPATT at a bias current density of $3.2 \times 10^{9}$ $A/m^{2}$ is $-32 \times 10^{6}$ $S/m^{2}$ . The real and imaginary parts of the diode admittance are computed for various DC current densities and for different frequencies to obtain G-B plots. The plot of Conductance (G) vs. Susceptance (B) at 35 GHz window frequency for β-GaN IMPATT is depicted in Fig. 2. The optimum frequencies for peak negative conductance and the avalanche frequency at which G becomes negative is obtained from G-B plots. The small signal G-B plots also give the frequency range of operation of the device as well as the optimum values for the current density and the structural parameters for maximum output. From the G-B plot it is evident that the peak negative conductance occurs at 36 GHz which is very close to the design frequency of 35 GHz. The small signal analysis indicates that the magnitude of maximum negative conductance initially increases with DC current but begins to decrease when the DC current exceeds the threshold value for sharp expansion of the central avalanche zone. The Q-factor determines the growth rate and the stability of oscillation. Less Q-factor means better device performance. The Q-factor of β-GaN IMPATT has been calculated to be 0.84. The simulated DC and Small Signal parameters of β-GaN IMPATT as enlisted in Table-III are very encouraging and portray a strong potentiality of β-GaN IMPATT as a powerful oscillator for millimeter wave communication.

## 4. Proposed Methodology for Fabrication of GaN Impatt Diode

MOCVD technique and to some extent molecular beam epitaxy can be used to fabricate p-n junction GaN [20]. The most advanced results may be obtained by the MOCVD technique, which includes the growth of GaN epitaxial layer from the vapor phase. GaN may be grown from the vapor phase using metal–organic gases as sources of gallium and nitrogen using this method. For example, trimethylgallium (TMG) can be used as a gallium source, and ammonia can be used as a nitrogen source. Growth of a GaN semiconductor on a substrate may take place in a reactor chamber. The substrate may be grown at growth temperature ranging from 800 ℃ to 1100℃. Single crystal wafers of sapphire or SiC may serve as substrates for GaN deposition by the MOCVD method. Thin layers (usually not thicker than 5 $\mu$m) of GaN can be grown on sapphire or SiC substrates using MOCVD technique. Electrically active impurities can be introduced in the reaction chamber during the growth in order to control the type of electrical conductivity in the grown material. Undoped GaN layers usually exhibit n-type conductivity. The value of n-type conductivity can be controlled by introducing Si impurity (in a form of $SiH_4$ gas) in the reaction chamber during the growth. In order to obtain the p-type GaN material by the MOCVD method, Mg impurity can be introduced in the reactor chamber during the growth.

Windows can be opened on the $p^{++}$ GaN layer for subsequent metal deposition through the photolithographic process. Using photolithography and liftoff techniques, low-resistance contact metals, an alloy of Ni (20 nm)/Pd (20 nm)/Au (100 nm), can be deposited inside the windows by an electron beam evaporator. The metal contacts should then be annealed in air, nitrogen and oxygen ambient conditions at different annealing temperatures ranging from 350 ℃ to 650 ℃. Circular TLM (CTLM) system may be used for the measurement of specific contact resistance.

Effective etching techniques are useful for diode fabrication. GaN has very high bond energy (8.9 eV/atom) and a WBG, making it almost inert to bases and acids, which are low cost, and highly available wet etchants, used in Si technology. A few of the dry etching techniques used for GaN include ion milling and reactive ion etching (RIE). Wet etching is an important complement to dry etching methods by providing low damage etching, low cost, and complexity. Due to the inability of etching of nitrides using conventional acids and bases, a recently developed technique called photoelectrochemical (PEC) wet etching is found to etch GaN with significantly high etch rates.

After finishing the fabrication process, on-wafer dc testing should be performed before the diodes are packaged. DC testing will serve as the initial screening step of the device, and the test results will be used for process evaluation.

The packaging should provide a low thermal resistance between the GaN diode chip and waveguide mount and should be mechanically rugged and hermetically sealed. The device can be bonded to a pill-type package. In pill-type configuration, the diode is bonded to a heat sink, which is usually gold plated. A ceramic or quartz ring encloses the diode and separates the heat sink from the package cap.

## 5. Conclusion

The extensive simulation studies on the DC and high frequency properties gives an insight into the prospect of β-GaN avalanche transit time diode as a potential source at millimeter wave window frequency of 35 GHz. The results at 35 GHz window reveal that β-GaN DDR IMPATT diode provides a maximum conversion efficiency of 15% at a bias current density of $3.2\times10^9$ A/m$^2$ and the device delivers a high peak output power of 2.83W. Moreover, from the G-B plot it is quite evident that negative resistance can be generated in the millimeter wave frequency band. Thus the simulation results are very encouraging, promising and indicate clearly the possibility of designing and fabricating IMPATT diodes based on β-phase of GaN as the base material, suitable for operation at millimeter wave domain.

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