Large-Signal and Noise Properties of Heterojunction DDR IMPATTs Based on AlxGa1−xN~GaN Material System at 1.0 THz

Soranjana Banerjee, Aritra Acharyya, J. P. Banerjee, Monojit Mitra

1Academy of Tech., West Bengal Univ. of Technology, Adisaptagram, Hooghly, West Bengal, India
2Supreme Knowledge Foundation Group of Institutions, Mankundu, Hooghly, West Bengal, India
3Institute of Radio Physics and Electronics, University of Calcutta, 92, APC Road, Kolkata, India
4Indian Institute of Engineering Science and Technology, Shibpur, Howrah, West Bengal, India

Abstract

In this paper, the authors have made an attempt to study the large-signal as well as avalanche noise properties of heterojunction double-drift region (DDR) impact avalanche transit time (IMPATT) diodes based on AlxGa1−xN~GaN material system designed to operate at 1.0 THz. The mole fraction of Al in AlxGa1−xN alloy is taken to be x = 0.4 in the simulation. Two different heterojunction structures such as N-AlxGa0.4N~p-GaN and n-GaN~P-AlxGa0.6N are considered and their large-signal and noise properties are compared with GaN and AlxGa0.6N~GaN homojunction DDR IMPATTs. The results show that N-AlxGa0.4N~p-GaN heterojunction DDR IMPATT device not only excels its complementary counterpart (i.e. n-GaN~P-AlxGa0.6N DDR IMPATT) but also its homojunction counterparts (i.e. GaN and AlxGa0.6N DDR IMPATTs) with respect to large-signal conversion efficiency and power output as well as avalanche noise performance at 1.0 THz.

Keywords

AlGaN, Avalanche Noise, DDR IMPATTs, GaN, Heterojunction, Large-Signal Simulation, Terahertz

I. Introduction

The terahertz (THz) frequency band popularly called “Terahertz-Gap” which lies between the millimeter-wave and infrared regions of the electromagnetic spectrum, is defined as the frequency range of 0.1 – 10 THz, i.e. between the wavelengths 3.0 and 0.03 mm. This particular frequency band is in great demand for various applications such as THz imaging [1], spectroscopy [2], bio-sensing [3], quality inspection in various industrial branches [4-6], medical and pharmaceutical applications [7, 8], THz astronomy [9], etc. The wide bandwidth of THz spectrum can be useful for broadband wireless communication providing data rate of tens of GBps (gigabits per second). Notwithstanding the tremendous application potential of THz frequency band, this field has yet not been fully exploited since it is difficult to develop reliable solid-state sources capable of generating, detecting and processing the terahertz signal with sufficient power required for system application. GaN is an excellent material as compared to conventional Si and GaAs for high power and high frequency applications owing to its favorable material parameters like wide bandgap (Eg = 3.40 eV at 300 K), high breakdown voltage, high carrier saturation velocity and high carrier mobility. Recently Acharyya et al. reported the potentiality of GaN as the base material of IMPATT diodes and explored its capability to deliver sufficiently high RF power with high conversion efficiency at THz frequency bands [10, 11].

Further, heterojunction IMPATTs have some advantages over their homojunction counterparts as regards lower noise figure and reduced tunnel component of current [12]. The heterojunction between GaN and AlxGa1−xN have been successfully used in different high frequency semiconductor devices such as high electron mobility transistors (HEMTs), heterojunction bipolar transistors (HBTs), etc. [13, 14]. This has prompted the authors to study the large-signal and noise properties of anisotype heterojunction DDR IMPATTs based on AlxGa1−xN~GaN material system designed to operate at 1.0 THz. A full scale large-signal simulation software based on non-sinusoidal voltage excitation model [15] and a small-signal noise simulation package [16] based on Gummel-Blue approach [17] have been used for the said purpose. The mole fraction of Al in AlxGa1−xN alloy is taken to be x = 0.4 in the simulation. Two types of DDR heterojunction structures i.e. N-AlxGa1−xN~n-GaN and n-GaN~p-AlxGa1−xN are considered for the present study. The results show that the THz performance of N-AlxGa1−xN~p-GaN heterojunction DDR structure not only excels its complementary counterpart (i.e. n-GaN~P-AlxGa1−xN) but also those based on bulk GaN and AlxGa0.6N.

II. Large-Signal Simulation Technique

One-dimensional model of reverse biased n+n+p+ structure of homojunction and heterojunction DDR IMPATTs, shown in figs. 1 (a) – (d) are used for large-signal simulation since the physical phenomena take place in the semiconductor bulk along the symmetry axis of the mesa structure of the device. The fundamental time and space dependent device equations i.e., Poisson’s equation, continuity equations, current density equations involving mobile space charge are simultaneously solved subject to appropriate boundary conditions [15] under large-signal condition to obtain the snap-shots of electric field (ξ(x,t)) and normalized current density (P(x,t) = Jp(x,t))/J0p(x,t)) for different bias current densities (J0) for different bias current densities (J0) for different bias current densities (J0) at several instants of time of one complete cycle of steady-state oscillation. The large-signal simulation is carried out by considering 500 space steps and 150 time steps. In the present simulation method, the IMPATT device is considered as a non-sinusoidal voltage driven source as shown in fig. 2. The input AC voltage is taken as

\[ V_{RF}(t) = V_0 \sum_{p=1}^{n} (m_x) \sin(p \omega t). \]  

The bias voltage is applied across the device through a coupling capacitor (C) to study the performance of the device at a given fundamental frequency (f = ω/2π) with its (n – 1) harmonics. The large-signal program is run till the limit of one complete cycle (i.e. 0 ≤ t ≤ 2π) is reached. The bias current density, RF voltage amplitude and frequency are J0, VRF and f respectively. The terminal current (J(t)) and voltage (VRF(t)) waveforms for a complete cycle of oscillation are Fourier analyzed to study the RF performance of the device at different phase angles of one complete cycle of oscillation i.e., ωt = 0, π/2, π, 3π/2, 2π.
point and the procedure is repeated until the entire depletion region is covered and the other edge of the depletion layer is reached. Numerical integration of noise electric field $e(x,x')$ over the entire depletion layer provides the terminal voltage $V_T(x')$ produced by noise source, i.e.

$$V_T(x') = \int_0^w e(x,x') \, dx.$$  

(2)

The transfer impedance of the device is defined as

$$Z_T(x') = \frac{V_T(x')}{I_n(x')}.$$  

(3)

where $I_n(x')$ is the average current generated in the interval $dx'$ due to $\gamma(x')$ located at $x'$. The mean-square noise voltage is obtained from

$$\langle v_n^2 \rangle = 2q^2 \cdot A \int Z_T(x')^2 \gamma(x') \, dx'.$$  

(4)

Mean-square noise voltage per bandwidth is called noise spectral density ($\langle v_n^2 \rangle / df$ V$^2$ sec). The noise performance of the device can be known from a parameter called the noise measure (NM) defined as

$$NM = \frac{\langle v_n^2 \rangle}{4K_B T} \left( Z_R - R_S \right)$$  

(5)

where $K_B$ is the Boltzmann constant ($K_B = 1.38 \times 10^{-23}$ J K$^{-1}$), $T$ is the absolute temperature, $Z_R$ is the device negative resistance and $R_S$ is the positive parasitic series resistance associated with the device. The value of $R_S$ is assumed to be zero in all the DDR IMPATT structures under consideration.

**IV. Results and Discussion**

The structural and doping parameters such as $n$- and $p$-layer widths ($W_n$, $W_p$), donor and acceptor concentrations ($N_d$, $N_a$) of the respective layers, doping concentrations of highly doped $n^0$- and $p^0$-layers, effective diameter of the p-n junction of the homojunction and heterojunction DDR IMPATT devices under consideration designed to operate at $f = 1.0$ THz are given in Table I. Initial design parameters ($W_n$, $W_p$, $N_d$, $N_a$) are chosen by using the transit time formula of Sze and Ryder [18] and finally those along with the bias current density ($J_b$) parameters are optimized subject to the maximum DC to RF conversion efficiency at 1.0 THz by using the large-signal simulation technique based on non-sinusoidal voltage excitation (NSVE) model [15]. The material parameters such as realistic field variations of ionization rates ($\alpha_n$, $\alpha_p$) and drift velocities ($v_{n\alpha}$, $v_{p\beta}$), appropriate experimental values of ionization coefficients ($A_{n\alpha}$, $B_{p\beta}$) and saturated drift velocities ($v_{n\alpha}$, $v_{p\beta}$) of charge carriers and other material parameters such as bandgap ($E_g$), intrinsic carrier concentration ($n_i$), effective density of states of conduction and valance bands ($N_c$, $N_v$), effective masses ($m_{n\alpha}$, $m_{p\beta}$), diffusion coefficients ($D_g$, $D_c$), mobilities ($\mu_n$, $\mu_p$) and diffusion lengths ($L_n$, $L_p$) of the both GaN and $\text{Al}_x\text{Ga}_{1-x}\text{N}$ are taken from the recently published experimental reports [19-23].

The large-signal simulation of homojunction and heterojunction DDR IMPATTs under consideration have been carried out for the bias current density ranges from $25 \times 10^8$ to $45 \times 10^8$ Am$^{-2}$ within the frequency range of 0.45 – 1.3 THz. The admittance characteristics of the DDR IMPATTs for $J_b = 45 \times 10^8$ Am$^{-2}$ obtained from the large-signal simulation are shown in fig. 3. It observed from fig. 3 that the magnitude of the large-signal peak negative conductance ($|G_{jn}|$) corresponding to the optimum frequency ($f_n^*$) of $\text{Al}_x\text{Ga}_{1-x}\text{N}$-p-GaN DDR IMPATT excels all other devices which indicates

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**III. Noise Simulation Technique**

The random nature of the impact ionization process is the main source of noise in Avalanche Transit Time (ATT) devices. This random impact ionization process gives rise to fluctuations in the DC current and DC electric field which appear as small-signal components to their DC values even in the absence of voltage variation across the device. Open circuit condition without any variation of applied voltage is considered for the noise analysis of IMPATT/MITATT device. Starting from the small-signal AC field due to noise $e(x,x') = e(x,x') + j e(x,x')$, two second order differential equations are framed corresponding to the real ($e(x,x')$) and imaginary ($e(x,x')$) parts of the noise electric field $e(x,x')$. This field is assumed to be due to a noise source $\gamma(x')$ located at space point $x'$ within the depletion region of the device [16]. The numerical solution of two simultaneous differential equations involving the real and imaginary parts of noise electric field $e(x,x')$ is carried out by using a double-iterative technique and Runge-Kutta method subject to the satisfaction of appropriate boundary conditions at the depletion layer edges [16]. The noise source $\gamma(x')$ is first considered to be located at one edge of the depletion region. The noise source is then shifted to the next space point and the procedure is repeated until the entire depletion region is covered and the other edge of the depletion layer is reached.

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**Fig. 1:** 1-D Models of (a) n-GaN-p-GaN, (b) N-Al$_x$Ga$_{1-x}$N-p-GaN, (c) n-GaN–p-Al$_x$Ga$_{1-x}$N and (d) n-Al$_x$Ga$_{1-x}$N–p-Al$_x$Ga$_{1-x}$N Structured DDR IMPATT Diodes.

**Fig. 2:** Voltage Driven IMPATT Diode Oscillator and Associated Circuit.

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that the said device is capable of delivering maximum RF power (PRF) with highest DC to RF conversion efficiency ($\eta_L$) since $P_{RF} = (1/2)\times(V_{FF}^2)/G_{DC}$ and $\eta_L = P_{RF}/P_{DC}$, where $P_{DC} = VDD\times J_{D}\times A$, and $A = \pi(D/2)^2$. Moreover the Q-factor ($Q_p = -B_p/G_p$) is found to be minimum in HTDD1 ($Q_p = 5.10$ for $J_0 = 45\times10^8$ Am$^{-2}$) which indicates the better oscillation growth rate and stability of the IMPATT oscillator based on the said device as compared to the other devices under consideration ($Q_p = 6.47$, $5.42$ and $8.58$ in HMDD1, HTDD2 and HMDD2 respectively for $J_0 = 45\times10^8$ Am$^{-2}$).

Variations of RF power output and DC to RF conversion efficiency of different homojunction and heterojunction DDR IMPATTs with bias current density are shown in Figs. 4 (a) and (b) for 60% voltage modulation. Both the RF power output and DC to RF conversion efficiency of HTDD1 are found to maximum among all the devices under consideration for all the current densities. Optimum bias current density for which the conversion efficiency of the device is maximum is found to be $45\times10^8$ Am$^{-2}$ for HTDD1 ($\eta_{L_{opt}} = 22.94\%$) and HMDD2 ($\eta_{L_{opt}} = 16.19\%$) while the same is found to $35\times10^8$ Am$^{-2}$ and $30\times10^8$ Am$^{-2}$ for HTDD2 ($\eta_{L_{opt}} = 21.38\%$) and HMDD1 ($\eta_{L_{opt}} = 19.97\%$) respectively. Thus N- Al$_{0.4}$Ga$_{0.6}$N- p-GaN heterojunction DDR IMPATT (HTDD1) not only excels its homojunction counterparts (i.e. n-GaN– p-GaN HMDD1 and HMDD2)) with respect to large-signal conversion efficiency and RF power output at 1.0 THz.

Now the avalanche noise performance of the homojunction and heterojunction device structures under consideration have been investigated by using the Gummel-Blue [16-17] technique as mentioned in section III. Noise spectral densities and noise measures of the DDR IMPATTs have been obtained as functions of frequency from the simulation. Variations of (a) RF power output and (b) DC to RF conversion efficiency of different homojunction and heterojunction DDR IMPATTs with bias current density for 60% voltage modulation. Figs. 5 (a) and (b) show the variations of noise spectral density and noise measure of different homojunction and heterojunction DDR IMPATTs with frequency for the bias current density of $40\times10^8$ A m$^{-2}$. It is observed from Figs. 5 (a) and (b) that both the noise spectral density and noise measure of heterojunction DDR IMPATTs are much smaller as compared to their homojunction counterparts. The smaller noise level in the heterojunction devices are due to suppression of noisy impact ionization phenomena in the narrower avalanche zones.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Symbol</th>
<th>$W_f$ (nm)</th>
<th>$W_r$ (nm)</th>
<th>$N_{n^+}$ ($\times10^{12}$ m$^{-2}$)</th>
<th>$N_{p^+}$ ($\times10^{15}$ m$^{-3}$)</th>
<th>$N_{n^+}$ ($\times10^{13}$ m$^{-3}$)</th>
<th>$N_{p^+}$ ($\times10^{15}$ m$^{-3}$)</th>
<th>$D$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-GaN– p-GaN HMDD</td>
<td>HMDD1</td>
<td>185.00</td>
<td>185.00</td>
<td>6.84</td>
<td>7.20</td>
<td>5.00</td>
<td>2.70</td>
<td>5.00</td>
</tr>
<tr>
<td>n-Al$<em>{0.4}$Ga$</em>{0.6}$N– p-GaN HTDD</td>
<td>HTDD1</td>
<td>174.00</td>
<td>185.00</td>
<td>6.97</td>
<td>7.15</td>
<td>5.00</td>
<td>2.70</td>
<td>5.00</td>
</tr>
<tr>
<td>n-GaN– p-Al$<em>{0.4}$Ga$</em>{0.6}$N HTDD</td>
<td>HTDD2</td>
<td>185.00</td>
<td>172.00</td>
<td>6.98</td>
<td>7.25</td>
<td>5.00</td>
<td>2.70</td>
<td>5.00</td>
</tr>
<tr>
<td>n-Al$<em>{0.4}$Ga$</em>{0.6}$N– p-Al$<em>{0.4}$Ga$</em>{0.6}$N HMDD</td>
<td>HMDD2</td>
<td>176.00</td>
<td>173.00</td>
<td>6.96</td>
<td>7.30</td>
<td>5.00</td>
<td>2.70</td>
<td>5.00</td>
</tr>
</tbody>
</table>

Variations of noise measure of different homojunction and heterojunction DDR IMPATTs with bias current density are shown in Fig. 6. It is observed that the noise measure of the devices decrease with the increase of bias current density. Also the noise measure of the heterojunction devices (HTDD1 and HTDD2) are found to be much smaller (around 7.9 – 7.2 dB within bias current density range of $25\times10^8 - 45\times10^8$ Am$^{-2}$) as compared to the same of their homojunction counterparts (around 10.2 – 9.1 dB within the bias current density range of $25\times10^8 - 45\times10^8$ Am$^{-2}$). Suppression of the noisy impact avalanche phenomena due to narrower avalanche region widths in heterojunction devices are the primary cause of lower noise levels in those.

![Fig. 3: Admittance Characteristics of Different Homojunction and Heterojunction DDR IMPATTs at the Bias Current Density of 45.00 $\times10^8$ Am$^{-2}$ for 60% Voltage Modulation](image-url)

![Fig. 4: Variations of (a) RF Power Output and (b) DC to RF Conversion Efficiency of Different Homojunction and Heterojunction DDR IMPATTs With Bias Current Density for 60% Voltage Modulation](image-url)
Fig. 5: Variations of (a) Noise Spectral Density and (b) Noise Measure of Different Homojunction and Heterojunction DDR IMPATTs With Frequency for the Bias Current Density of $40 \times 10^8$ A m$^{-2}$.

Fig. 6: Variations of Noise Measure of Different Homojunction and Heterojunction DDR IMPATTs With Bias Current Density $J_0$.

V. Conclusion

The authors have studied the large-signal and noise properties of heterojunction DDR IMPATT diodes based on $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N} - \text{GaN}$ material system designed to operate at 1.0 THz. Two different heterojunction structures such as N- $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$-p-GaN and n-GaN-P- $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ are considered and their large-signal and noise properties are compared with GaN and $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ homojunction DDR IMPATTs. The results show that N-$\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$-p-GaN heterojunction DDR IMPATT device not only excels its complementary counterpart (i.e. n-GaN-P- $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ DDR IMPATT) but also its homojunction counterparts (i.e. GaN and $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ DDR IMPATTs) with respect to large-signal conversion efficiency and power output as well as small-signal noise performance at 1.0 THz.

References


