Influences of series resistance and epitaxial doping densities on the terahertz performance of gallium nitride avalanche transit time source: A high-power 1.0 THz radiator

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Abstract: Two-dimensional large-signal and noise simulations are used to study the terahertz (THz) performance of Gallium Nitride (GaN) avalanche transit time source (ATT) source. A comprehensive model of parasitic series resistance has been developed by which the effect of series resistance on the large-signal and noise performance of the 1.0 THz GaN ATT source has been investigated; the proposed model is based on time varying depletion width modulation under large-signal oscillating condition. Significant amount of deterioration in power output and efficiency have been observed due to the existence of series resistance of the device. On the other hand, the realization of the optimized structure and doping profile as per the theoretical design is a tricky job by considering the state-of-the-art GaN fabrication technology. Especially, achieving the absolute values of epitaxial doping densities is almost an unrealistic task. Therefore, it is very important to acquire the knowledge about how much extent the power output, series resistance and noise measure of the source are affected due to the change in doping level of both n- and p-layers. In the present study, the sensitivities of the above-mentioned parameters with respect to the change in the doping densities of n- and p-layers have been investigated.

1. INTRODUCTION

Some exclusive material properties of wurtzite phase gallium nitride (Wz-GaN) like high breakdown field, high carrier mobility, high thermal conductivity, etc., make it a potential candidate for realizing terahertz (0.3 – 10 THz) sources based on it [1-3]. Impact avalanche transit time (IMPATT) diodes are the most suitable two-terminal devices for implementing terahertz (THz) sources [4] and GaN is one of the most promising materials for fabricating THz IMPATTs up to 5 THz [1]. In this paper, two-dimensional (2-D) large-signal and noise simulation [5, 6] are used to study the THz performance of double-drift region (DDR) IMPATT source based on GaN operating at 1.0 THz. A comprehensive model of parasitic series resistance has been developed by the authors in order to study the effect of series resistance on the large-signal and noise performance of the 1.0 THz GaN IMPATT source; the proposed model is based on time varying depletion width modulation under large-signal oscillating condition [7, 8]. Significant amount of deterioration in power output and efficiency have been
observed due to the existence of series resistance of the device. On the other hand, the realization of the optimized structure and doping profile as per the theoretical design is a tricky job by considering the state-of-the-art GaN fabrication technology. Especially, achieving the absolute values of epitaxial doping densities is almost an unrealistic task. Therefore, it is very important to acquire the knowledge about how much extent the power output, series resistance and noise measure of the source are affected due to the change in doping level of both $n$- and $p$-layers. In this paper, the sensitivities of the above-mentioned parameters with respect to the change in the doping densities of $n$- and $p$-layers have also been investigated.

2. STRUCTURE AND FABRICATION ISSUES

The realization of wide bandgap semiconductor material based avalanche transit time sources is a very attractive area of research to the researchers working since last two decades in order to find a high power, low noise solid-state source at terahertz frequency regime (0.30 – 10.0 THz). Among different wide bandgap materials like SiC, GaN, diamond, etc., GaN is the most potential material for realizing high frequency, high power, low noise semiconductor devices. The proposed structure of the DDR GaN IMPATT diode is shown in Figure 1. It is well known fact that the realization of the optimized structure is a tricky job by considering the state-of-the-art GaN fabrication technology. Especially, achieving the absolute value of doping density of $n$- and $p$-layers is almost unrealistic task. Therefore, it is very important to acquire the knowledge about how much extent the power output, series resistance and noise measure of the source are affected due to the change in doping level of both $n$- and $p$-layers.

![Figure 1. GaN IMPATT structure for 1.0 THz operation.](image-url)
3. SERIES RESISTANCE MODELLING

The series resistance of the device is modelled by considering the skin effect which must play a significant role at such high frequencies like 1.0 THz. A long conductor having square-shaped cross-section should have the AC resistance give by

\[
R_{ac} = \left\{ \begin{array}{ll}
\left( \frac{1}{\sigma} \right) \left[ \frac{W}{4\delta(d-\delta)} \right], & d > 2\delta \\
\left( \frac{1}{\sigma} \right) \left[ \frac{W}{d^2} \right], & d \leq 2\delta 
\end{array} \right. 
\]

where \( \delta = \sqrt{\frac{f\mu\sigma}{2}} \) is the skin depth, \( f \), \( \mu \) and \( \sigma \) are the frequency, magnetic permeability and conductivity respectively. The magnetic permeability of a material can be obtained from the knowledge of magnetic mass susceptibility \( \chi \) and density \( \rho \) from the relation \( \mu = \mu_0(1 + \rho \chi) \), where \( \mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1} \) is the permeability of the vacuum. The experimentally measured values of \( \chi, \rho \) and \( \sigma \) of the semiconductor and metal layers corresponding to the proposed DDR structure are taken from published literatures \([9-11]\) available in an organized tabular form in ref. [1].

It has already been explained by the authors in their earlier report that the primary components of series resistance in a DDR IMPATT structure are (i) fixed parasitic series resistance \( R_{s0} \) arising due to the metal layers at both electrodes, anode-\( p^+ \) metal-semiconductor contact, cathode-\( n^- \) metal-semiconductor contact and un-depleted semiconductor layers like \( n^- \), \( p^+ \) and \( n^+ \)-buffer layers, and (ii) time-varying un-depleted portions of \( p^- \) and \( n^- \)-epitaxial layers \( R_{n,p}(t) \) arising due to the depletion width modulation under large-signal oscillating condition \([7, 8]\). Thus, the series resistance of DDR IMPATT oscillator is essentially a time-varying quantity which can be written as

\[
R_s(t) = R_{s0} + R_{n,p}(t) + R_n(t). 
\]

The time-varying components can be expressed as

\[
R_{n,p}(t) = \left[ \frac{1}{qN_{D,A} \mu_n \mu_p} \left[ W_{n,p} - y_{D_n,p}(t) \right] \right] \frac{d_0^2}{d_0^2}, 
\]

where \( \mu_n \) and \( \mu_p \) are the mobility of electrons and holes, \( y_{D_n}(t) \) and \( y_{D_p}(t) \) are the time-varying depletion layer widths associated with \( n^- \) and \( p^+ \)-layers respectively under large-signal oscillating condition. Finally, the frequency domain of the time-varying series resistance can be obtained by using Fourier transformation and it is given by

\[
R_s(\omega) = \int_{-\infty}^{+\infty} R_s(t) e^{-j\omega t} dt. 
\]

4. SIMULATION METHOD

The use of most convenient Cartesian coordinate system for analysing the proposed device structure has been ensured by considering square-shaped cross-section of the device instead of circular cross-section. However, this assumption will not affect the general conclusions taken in this work. Therefore, the radius values like \( r_0 = 2.5 \text{ μm}, r_{S,1} = 10.0 \text{ μm}, r_{EE} = 40.0 \text{ μm}, r_{ES} = 70.0 \text{ μm} \) and \( r_{buffer} = 100.0 \text{ μm} \) (see Figure 1) are transformed to corresponding square edge dimensions by using the
equation $d_k = r_k(\pi)^{1/2}$ (assuming the area of each layer fixed, although the shape is changed from circular to square), where the suffix ‘$k$’ stands for the layer-type. By using the said transformation, the square edge dimensions are obtained as $d_0 = 4.43 \mu m$, $d_{5:1} = 17.72 \mu m$, $d_{11} = 70.89 \mu m$, $d_{2} = 124.07 \mu m$ and $d_{buff} = 177.25 \mu m$. Absence of any variation of doping density along $z$-direction (doping is uniform along $z$-direction) leads to no $z$-variation of the electrical parameters of the device structure under its operating condition. Therefore, the device structure can be analysed by using a 2-D model (omitting the $z$-coordinate) as shown in Figure 2. The position of the origin $(x,y) = (0,0)$ and coordinates of all other edges have been defined in Figure 2, which is used for 2-D large-signal and noise analysis of the device.

![Figure 2. Simplified 2-D model considering rectangular cross-section of the diode.](image)

![Figure 3. Diode voltage and current waveforms at different bias currents.](image)

Under large-signal condition, the time and space dependent fundamental drift-diffusion equations are simultaneously solved subject to appropriate boundary conditions imposed at the depletion layers.
edges in order to obtain the time-varying diode voltage \( (V_d(t)) \) and current \( (I_d(t)) \). The time-varying \( V_d(t) \) and \( I_d(t) \) obtained from the simulation shown in Figure 3 are observed to be periodic but non-sinusoidal in nature under steady-state oscillating condition. The frequency domains of the \( V_d(t) \) and \( I_d(t) \) are obtained by using Fourier transformation \( (V_d(\omega) \) and \( I_d(\omega)) \). After that the device impedance is obtained by dividing the frequency domain diode voltage by current, i.e. \( Z_D(\omega) = \frac{V_D(\omega)}{I_D(\omega)} = (-R_D(\omega) + R_s(\omega)) + j X_D(\omega) \), where \(-R_D(\omega)\) is the negative resistance of the device and \(X_D(\omega)\) is the capacitive reactance of it under oscillating condition. The simplified diode equivalent circuit is shown in Figure 4. The reciprocal of \( Z_D(\omega) \) provides the diode admittance \( Y_D(\omega) = \frac{1}{Z_D(\omega)} = -G_D(\omega) + j B_D(\omega) \), where \(-G_D(\omega)\) is the negative conductance and \(B_D(\omega)\) is the capacitive susceptance of the device under large-signal oscillating condition. Finally the power output and efficiency of the source are obtained as

\[
P_{RF} = \frac{1}{2} (m_i V_B)^2 |G_D(\omega)|_{\text{peak}},
\]

\[
\eta_L = \left( \frac{P_{RF}}{P_{DC}} \right) \times 100 \%.
\]

where \( m_i \) is the voltage modulation factor, \( V_B \) is the breakdown voltage (time average of \( V_d(t) \)), \(|G_D(\omega)|_{\text{peak}}\) is the peak magnitude of conductance of the diode corresponding to the optimum frequency \( f_p = 1.0 \text{THz} \), \( P_{DC} = V_B I_0 \) is the input DC power and \( I_0 \) is the bias current.

After the completion of large-signal simulation, the small-signal noise simulation has to be carried out in order to obtain the comprehensive performance evaluation of the source. The 2-D noise analysis procedure has already been described elsewhere [6]. The material parameters of GaN have been taken from recently published literature [11-15] for constructing the material parameter data set which is used for both the large-signal and noise simulations.

5. EFFECT OF SERIES RESISTANCE

The time varying un-depleted portions of \( n\)- and \( p\)-sides of the epitaxial layers and corresponding series resistance contributions are shown in Figure 5. It is observed that the significant portions of the epitaxial layers remain un-depleted during negative half-cycles of \( V_d(t) \), i.e. when the device becomes significantly non-punch-through in nature. Due to the higher value of electron mobility as compared to hole mobility in GaN [13, 14], the peak magnitude of \( R_n(t) \) is found to be much smaller than that of \( R_p(t) \). Therefore, the series resistance contribution of \( p\)-side is significantly higher than that of \( n\)-side in a DDR GaN IMPATT diode. Finally the variation of \( R_D(\omega) \) at 1.0 THz with \( I_0 \) has been shown in Figure 6. Due to the increase in the reverse bias current \( (I_0) \), the mean value of the depletion layer width increases, which leads to decrease in the un-depleted portions of the \( n\)- and \( p\)-epitaxial layers
during the negative half-cycles of $V_d(t)$; this fact increases the value of $R_s$.

**Figure 5.** Waveforms associated with Un-depleted $n$ and $p$-layers and corresponding series resistances at different bias currents under large-signal oscillating condition.

The effect of series resistance on both power output and efficiency of the source are very much prominent at 1.0 THz, which is evident from Figures 7 (a) and (b). Significant amount of decrease in both $P_{RF}$ and $\eta_L$ is obtained when the series resistance is taken into account in the calculations. Mean square noise voltage per unit bandwidth (or noise spectral density ($NSD$)) and noise measure ($NM$) of the source for $R_s = 0$ $\Omega$ for different bias current have been shown in Figures 8 (a) and (b) respectively. Suppression of small-signal voltage and current fluctuations (arising due to the random impact ionization phenomena) occurs for higher bias currents. Therefore, the source becomes less noise at higher bias current levels. Next, the effect of series resistance on the noise performance of the source has been depicted in Figure 9 in the $NM$ versus $I_0$ plots for different $R_s$ values. The $NM$ value increases with the increase of $R_s$, which is a significant observation from Figure 9.

**Figure 6.** Series resistance versus bias current plot.
Figure 7. (a) Power output and (b) efficiency versus bias current plots with and without considering the effect of series resistance.

Figure 8. (a) Mean-square noise voltage per unit bandwidth and (b) noise measure (assuming $R_S = 0$) versus frequency plots.
Figure 9. Noise measure versus bias current plots for different values of series resistance.

Figure 10. Variations of percentages of change in power output, series resistance and noise measure with the percentage of change in doping density of \(n\)- and \(p\)-layers.

6. EFFECT OF EPITAXIAL DOPING DENSITIES

The doping concentrations of both \(n\)- and \(p\)-layers are assumed to be varied between \(\Delta N = \pm 10\%\) of the optimized values, i.e. \(\pm 10\%\) of \(6.8 \times 10^{23}\) and \(7.0 \times 10^{23}\) \(\text{m}^{-3}\) respectively, and the structure is re-simulated in order to study the aforementioned effect. The Figure 10 illustrates the sensitivity analysis results. Maximum 21.9\% of change in power output is observed. It is observed that the power output is increased with the decrease of doping levels. Sharp increase in power output is observed just after the device enters to the punch-through region. Sharp decrease in series resistance is observed after the device become punch-through for lower doping density of \(n\)- and \(p\)-layers. Noise measure is slightly increased with the decrease of doping density of \(n\)- and \(p\)-layers.

7. CONCLUSION

The 2-D large-signal and noise simulations are have been carried out to study the THz performance of GaN IMPATT source at 1.0 THz. A inclusive model of parasitic series resistance has been presented in this paper, by using which the effect of series resistance on the large-signal and noise performance of the 1.0 THz GaN IMPATT source has been investigated; the proposed model is based on time varying depletion width modulation under large-signal oscillating condition. Significant amount of
deterioration in power output and efficiency have been observed due to the existence of series resistance of the device. On the other hand, the realization of the optimized structure and doping profile as per the theoretical design is a tricky job by considering the state-of-the-art GaN fabrication technology. Especially, achieving the absolute values of epitaxial doping densities is almost an unrealistic task. Therefore, it is very important to acquire the knowledge about how much extent the power output, series resistance and noise measure of the source are affected due to the change in doping level of both $n$- and $p$-layers. In the present study, the sensitivities of the above-mentioned parameters with respect to the change in the doping densities of $n$- and $p$-layers have also been investigated. Significant variations in power output, series resistance and noise measure have been observed due to slight variation in epitaxial doping levels.

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