Optically Controlled III-V GaN Based Avalanche Transit Time Diode for Application in Terahertz Communication

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***Abstract* — The prospects of single drift region (SDR), flat profile GaN IMPATT diode as terahertz source are studied through a simulation experiment. The study indicates that GaN IMPATT device is capable of generating high RF power (P_{RF}) of 14.4 W at around 0.7 THz with an efficiency of 20.0 %. The effects of photo-illumination on the GaN device is also investigated using a modified double iterative simulation scheme. Under photo-illumination, the negative conductance and the negative resistance of the device is found to decrease, while, the frequency of operation and the device quality factor shifts upward.**

Index Terms — IMPATT diode, Optical-illumination, parasitic series resistance, THz power source, Top Mounted device, Wz-GaN

I. INTRODUCTION

Terahertz (THz) technology is rapidly developing all over the world. Though the THz frequency regime offers many technical advantages (e.g., wider bandwidth, improved spatial resolution, compactness), the solid-state high-power active devices within the THz regime remains extremely limited. There has been a steadily growing interest, among the international Scientific and Technical communities, in developing high power semiconductor devices for application in THz communication. Among all two-terminal semiconductor devices (Gunn, IMPATT, TRAPATT, BARITT etc.), **IMP**act **A**valanche **T**ransit **T**ime (IMPATT) devices have already emerged as the most efficient solid state sources that can deliver highest RF power (P_{RF}) even at 300 GHz [1]. Moreover, in recent years the possibility of using IMPATT diode as a THz source has also been predicted [2]. For realizing higher RF power (P_{RF}) from an IMPATT device, one should choose a semiconductor material that has higher values of critical electric field (E_c) and saturated carrier drift velocity (v_s), since the P_{RF} of an IMPATT device is proportional to $E_c^2 . v_s^2$. Although the conventional IMPATT diodes fabricated on GaAs (Gallium Arsenide) and Si (Silicon) are found to be reliable, these are limited by power and operating frequencies due to the fundamental limitations of the material parameters. On the other hand, wide band gap semiconductor like GaN (Gallium Nitride) has excellent material properties, such as (i) 10 times higher E_c, and (ii) 2 times higher v_s in comparison to those of Si and GaAs. These material properties can be explored to develop high power and high frequency IMPATT devices. A recent review work on wide band gap semiconductor establishes the superiority of GaN as a high power and high frequency device [3]. Moreover, a recent experimental study has shown that high quality GaN films can be grown on SiC substrates by MOCVD [4]. So, in the light of maturity of the fabrication technology and the unique material properties, GaN appears to be the best choice, overall, for the next decade of device development especially in THz regime.

To the best of our knowledge, the experimental results on GaN IMPATT diodes are still unavailable. However, there is an emergent need for developing solid state high power IMPATT oscillators in the THz region. The authors were therefore simulated the DC and small signal behavior of SDR ($p^+ n n^+$ type) GaN IMPATT diode suitable for operation at THz frequency range. Among the two polytypes of GaN (Wurtzite and Zinc-Blende), Wurtzite phase (Wz) GaN based IMPATT was found to better than its Zinc-Blende (ZnB) counterparts in terms of diode break down voltage, efficiency and power output at around 140 GHz [5]. This led the authors to choose Wz phase GaN as a base material for IMPATT diode operating in THz region. Again, at THz region, the parasitic series resistance (R_S) is a crucial parameter that restricts power dissipation in IMPATTs. The authors were also addressed this aspect of study in the present analysis.

IMPATT oscillators used as THz sources in spacecrafts may be subjected to interstellar radiation that can produce appreciable changes in the performance of the oscillators. Basic process involved is that, the additional carriers generated through optical illumination enhance the reverse saturation current or leakage current flowing in the reverse biased p-n junction of an IMPATT diode, and the enhanced reverse saturation current, in turn, modifies the microwave properties, such as the frequency of oscillation and the power output of the oscillator. The leakage current which is normally due to thermally generated electrons and holes ($J_n = J_{ns}+J_{ps}$) is so small that the current multiplication factor,

$M_{n,p}= J_0/(J_{ns} \text{ or } J_{ps})$, J_0= bias current density can be considered to be infinitely large. The enhancement of leakage current thus lowers the current multiplication factor and subsequently modifies the avalanche phase delay in the diode. In the present study, the authors also

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simulated the changes in the THz IMPATT performance due to photo illumination.

II COMPUTER METHODOLOGY

GaN SDR diodes were designed and optimized through a simulation technique used for analysis of IMPATT action [6]. The fundamental device equations, i.e. the one dimensional Poisson's equation and carrier continuity equation under steady state conditions, have been numerically solved subject to appropriate boundary conditions, by using a generalized double iterative computer algorithm [6] for simulation of electric field and normalized carrier current density profiles. The electron-hole pair generation rate (g) from impact ionization was estimated from the following equation [7]: $g = (\alpha_n v_n n + \alpha_p v_p p)$ ($m^{-3}.s^{-1}$), where, α_n and α_p are electron and hole ionization rate respectively. v_n and v_p are electron and hole velocities respectively. n and p are electron and hole density respectively. For the IMPATT mode operation, the avalanche breakdown condition is satisfied when the multiplication factor ($M_{n,p}$) tends to infinite [7]. So the boundary conditions for current density profiles are fixed by assuming a multiplication factor ~ 10^6. Even for a lower value of $M_{n,p}$, the IMPATT characteristics didn't show any significant change. During its operation at THz region, IMPATT diode generates a substantial amount of heat, which results in an increase of the diode junction temperature that plays a significant role in deciding the performance of the IMPATT diode. The authors had therefore considered the Monte Carlo simulated values of saturated drift velocity and mobility of electrons and holes in GaN within the range 300 K < T < 600 K [8] in this analysis. Ionization rate data of charge carriers [9] [10] were extrapolated to the high temperature (mentioned earlier) ionization rate data, and were used in the present analysis. The effect of mobile space charge in the depletion region of the diode was taken into account. The effect of tunneling in wide band gap GaN devices was reported to be negligible [5] and hence, this effect was not considered in the present analysis. The diode design parameters were as follows: epilayer doping (n region) = $1x10^{24}$ m^{-3}, epilayer width = 100 nm, current density = $1.6x10^9$ Am^{-2}. The space step for the present simulation was ~ 10^{-10} m.

The small signal analysis of the IMPATT diodes was carried out through a double iterative simulation technique [6], used to solve two second order differential equations involving diode negative resistance ($-Z_R$) and reactance ($-Z_x$). The THz frequency admittance characteristics (negative conductance (– G) vs. susceptance (B) plots), negative resistivity profiles and device quality factor (– Q= B/ – G) of the optimized GaN SDR diodes were determined by this technique after satisfying the appropriate boundary conditions [11]. The diode total negative conductance (G) and Susceptance (B) were calculated from the following expressions:

$$G = -Z_R / ((Z_R)^2 + (Z_X)^2)$$
$$\text{and } B = Z_X / ((Z_R)^2 + (Z_X)^2) \quad (1)$$

G and B are function of RF voltage (V_{RF}) and frequency such that the steady state condition for oscillation is given by [12]

$$g(\omega) = -G(\omega) - \{B(\omega)\}^2 R_S(\omega) \quad (2)$$

where, g is load conductance. G, B, g were normalized to the area of the diode. The relation provides minimum uncertainty in g at low power oscillation threshold. The authors had evaluated R_S from the admittance characteristics following the analysis of Gummel and Blue [13] and Alderstein et al [12]. In this analysis low power oscillation threshold data (avalanche frequency) were taken for calculation of R_S. At the avalanche frequency (or at resonance) oscillation starts to build up in the external circuit. At f_P, the maximum RF power output (P_{RF}) from the device was obtained from the expression:

$$P_{RF} = (V_{RF}{}^2 . G_P . A)/2, \quad (3)$$

The area of the diode A was considered to be $5x10^{11}$ m^2 in the present analysis. The diode negative conductance at the optimum frequency ($-G_p$) is normalized to the area of the diode. At a given bias current density, the peak frequency (f_P) is the frequency at which the negative conductance of the diode is a maximum, and the quality factor is a minimum. Under the small signal condition V_{RF} (amplitude of the RF swing) was taken as $V_B/2$, assuming a small signal (50%) modulation of the breakdown voltage V_B. The role of parasitic positive series resistance (R_S) was also considered for calculating realistic values of P_{RF}.

In order to assess the role of leakage current in controlling the dynamic properties of IMPATT oscillators at THz frequencies, simulation studies were carried out by the authors on the effect of M_n (keeping M_p very high ~ 10^6) on (i) the small signal admittance characteristics, (ii) the negative resistivity profile, and (iii) the device quality factor (Q) of SDR GaN IMPATT for flat structure. The details of mathematical calculations based on modified boundary conditions due to enhancement of leakage current were described elsewhere [11].

III. RESULTS AND DISCUSSIONS

The optimized design parameters of the unilluminated GaN SDR IMPATT diode for which M_n and M_p are both large (=10^6) have mentioned earlier. The DC and high frequency properties of the simulated diode are reported in table I. It is shown that the THz IMPATT diode based on GaN breaks down at 32 V. The study also predicts that a maximum P_{RF} of 14.40 W with efficiency (η) of 20% can be obtained from the diode. It is interesting to note that due to the presence of R_S (2.2 Ω), the values of P_{RF} of the unilluminated diode reduce approximately by 25 %.

The effect of electron dominated photocurrent on the high frequency properties of GaN IMPATT diode are shown in table II. The output data for illuminated flat

profile SDR IMPATT diode (table II) indicate that the value of negative conductance at peak frequency $|-G_P|$ decreases by 8% when M_n reduces from 10^6 to 25. The optimum frequency of oscillation (f_P) for the diode increases by 0.005 THz (0.72 -0.725 THz) as M_n reduces from 10^6 to 25. The same trend is reflected in admittance plots for different values of M_n ($M_p = 10^6$), shown in figure 1. The graphs show that the values of $|-G_P|$ decrease with the lowering of M_n. At the same time, the frequency range over which the diode exhibit negative conductance shift towards higher frequencies with the lowering of M_n. Figure 2 shows the profile of negative resistivity at the peak frequencies corresponding to different values of M_n ($M_p = 10^6$) for the diode. The profiles exhibit negative resistivity peaks in the middle of the drift layer with dips in the avalanche layer close to the junction. Due to the enhancement of electron photocurrent, the negative resistivity peaks are lowered accompanied by a gradual shift in their locations from the middle of the drift layer towards the n^+ edge. The quality factors of illuminated SDR diode are found to increase gradually with the decrease in the values of M_n (table II). The variations of P_{RF} with optimum frequency for different values of M_n are also shown in table II. It is also evident from table II, that, a lowering of M_n from 10^6 to 25 causes the diode negative resistance ($-Z_{Rp}$) to decrease by 43.7%.

TABLE I

DC AND SMALL SIGNAL PROPERTIES OF THz IMPATT DIODE

Output parameters of the diode	p^+nn^+ Diode
Field Maximum (10^8 Vm^{-1})	1.3
Breakdown Voltage (V_B) (V)	32.0
Peak frequency (f_P) (THz)	0.72
Peak Conductance ($-G_p$) (10^8 S m^{-2})	22.5
Quality Factor (Q)	0.8
P_{RF} (W)	14.40
Efficiency (η) (%)	20.0

IV. CONCLUSION

It may be concluded that, the simulation results reported here, reveal the potential of GaN IMPATT as high-power THz source and the design may further be used for experimental realization of optically integrated THz module for application in space THz communication systems.

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TABLE II.

EFFECT OF M_n ON SMALL SIGNAL PROPERTIES OF GaN THz SDR IMPATT ($M_P = 10^6$)

M_n	f_p (THz)	$-G_p$ (10^8 Sm^{-2})	$-Z_{Rp}$ (10^{-10} Ω-m^2)	RF Power (P_{RF}) (W)	Quality Factor $-Q_P$
10^6	0.72	22.5	2.70	14.40	0.8
10^2	0.721	22.0	2.69	14.08	0.83
50	0.723	21.5	1.55	13.76	1.41
25	0.725	20.7	1.52	13.25	1.57

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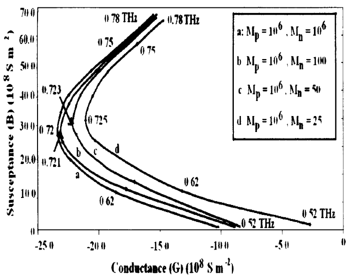

Fig 1.: Effect of electron current multiplication factor (M_n) on admittance (Conductance - Susceptance) plots of Wz GaN based IMPATT device at THz region.

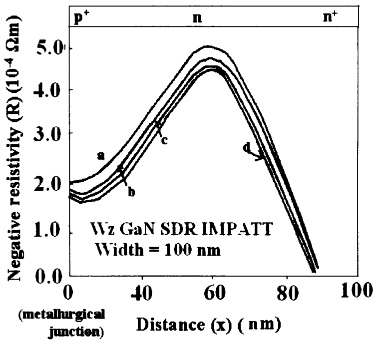

Fig 2. Negative resistivity profiles of Wz GaN IMPATT: a: $M_n = 10^6$, $M_p = 10^6$, f_p =0.72 THz, b: M_n = 100, $M_p = 10^6$, f_p = 0.721 THz, c: M_n = 50, $M_p = 10^6$, f_p = 0.723 THz, d: M_n = 25, $M_p = 10^6$, f_p = 0.725 THz.