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GaN/AlGaN Hetero-junction Terahertz

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Abstract:*A simulation study is carried out on the hetero-structure complementary (p^+-p^--p-n^+) IMPATT oscillator for Terahertz power generation. It is observed that hetero-structure GaN/AlGaN IMPATT may generate a pulsed power density of ~$8x10^{10}$ Wm^{-2} with an efficiency of 11%, whereas it's flatly doped counterpart is capable of delivering a pulsed power density of only $3x10^{10}$ Wm^{-2} with 7% efficiency. The total parasitic series resistance, R_S, including that due to the un-depleted region in device and also the effects of ohmic contact resistances, has been found to be a major problem that reduces the negative resistance significantly and thus it has a affects the THz performance and oscillation of the device. The study reveals that the value of R_S decreases by ~50% as the structure, semiconductor material pair as well as doping profile of the diode changes suitably from conventional to the proposed hetero-structure p^+-p^--p-n^+ type , by incorporating a $300A^0$ $Al_{0.4}Ga_{0.6}N$ layer in the p-drift region. This first study will be a useful guide in the THz-sector to meet the ever-increasing demand of semiconductor THz-sources for application in Imaging or in improvised explosive device (IED) detection.*

Keywords: *$Al_{0.4}Ga_{0.6}N$ hetero-structure; complementary IMPATT; Parasitic-resistance; THz-source.*

I. Introduction

Avalanche Transit Time (ATT) diodes are very powerful solid-state sources capable of generating high-frequency RF power at micro-waves and MM-waves, thereby covering a wide range of frequency spectrum. Over the past several years, significant progress in output power and efficiency has been achieved with IMPATT diodes and oscillators at frequencies from 30 to 300 GHz or even more. The Terahertz (THz) frequency range (0.1 – 10 THz) is sandwiched between the micro-waves and the infrared, bridging the gap between electronics and optics. Due to this exposed position in the electro-magnetic spectrum, a plethora of metrological applications with high impact on industries exist. The THz science is developing rapidly all over the world. Recent advances in THz-system technology suggest that its market introduction is rapidly approaching. The THz regime is rich with emerging possibilities in remote sensing, imaging, spectroscopy, and communication, with unique application for detecting hidden biological weapons and explosives. The THz domain has drawn immense interest from military and secure field also. There is tremendous urge observed among scientists worldwide to develop solid-state sources that may be employed as high-power THz-source.

In spite of its superiority among all the solid state sources, the THz region is still unapproachable by conventional Si, Ge and GaAs based IMPATT devices as because some fundamental limitations in the material parameters of these semiconductors impose restriction on THz frequency operation. The search is on to find new materials or material pairs for the development of IMPATT diodes such that they overcome these limitations and can act as an efficient solid-state, room-temperature THz generator.

GaN (band gap energy = 3.4 eV at 300K) supports peak internal electric field about 5 times higher than those of Si and GaAs, resulting in higher breakdown voltage, which is extremely important for devices handling high power. Another consequence of higher electric field and higher doping density is the width reduction in the drift region. Thus, not only high power but also the high frequency (THz) operation capability is expected from this wide band gap semiconductor based devices. Hence GaN based IMPATT is expected to operate at higher voltage at the same operating frequency. GaN is less noisy and is chemically very stable at high temperature [1]. Till date, most of the reported sub-mm/THz III-N IMPATTs are of GaN based p^+-n^-n^+ type. The performance of its complimentary structure (p^+-p-n^+) has not yet been reported due to the poor doping of p-GaN or AlGaN layers. However, the realization of this approach requires a high quality AlGaN-GaN hetero-structure with large band gap offset. A new strain energy band engineering (SEBE) approach can be employed to grow high Al-content thick AlGaN layers over c-plane sapphire substrates [2]. Insertion of a set of buffer-AlN/AlGaN super-lattices is expected to significantly reduce the biaxial tensile strain, thereby resulting in thick, crack-free $Al_{0.4}$ $Ga_{0.6}$ N layer. The simulated device structure is shown in Figure 1.

TABLE I

DESIGN PARAMETERS OF GAN AND p^{++}- p^{-} - n –n^{+} GAN/ALGAN IMPATTS AT BIAS CURRENT DENSITY: $2X10^{10}Am^{-2}$

Type of the diode	Low (p^-) epi-layer doping conc. (GaN) (10^{24} m^{-3})	$Al_{0.4}Ga_{0.6}N$ Doping conc. (10^{24} m^{-3})	$Al_{0.4}Ga_{0.6}N$ Layer width (nm)	Low epi-layer width (nm)
GaN flat-profile device	1.0	--	---	80.0
GaN/AlGaN p^+- p^- - p –n^+ device	0.8	1.4	30.0	50.0

Parasitic series resistance seriously degrades the THz-performances of the devices. Series resistance (R_S) is a crucial parameter that limits power dissipation and causes burn out problem in IMPATTs. Apart from the contribution from substrate and circuit, the p-n junction diode parameters, especially, the width of the depletion layer, doping density, etc., also contribute to R_S [3]. The reduction of R_S is therefore extremely important for negative resistance generation in THz IMPATT, since the positive parasitic tries to reduce it. In fabrication of IMPATT devices, the reduction in the value of R_S is usually ensured by thinning the substrate. A modification of doping profile may also reduce the value of R_S. In order to reduce series resistance of the GaN SDR diode, the author has thus investigated the modified complimentary device structure, incorporating a AlGaN thin layer in p-drift region of the diode and to the best of authors' knowledge, this is the first report in this aspect.

The AlGaN/GaN hetero-structure employed in this study can be grown by metalorganic chemical vapor deposition technique on a basal plane of sapphire substrate. The layer structure is schematically shown in the Fig. 1. It consists of a 1µ thick n^+ $Al_{0.4}$ $Ga_{0.6}$ N layer grown over sapphire. It can be doped with Si approximately to $5x10^{25}$ m^{-3} . Following it, a 300-Å-thick p- $Al_{0.4}$ $Ga_{0.6}$ N using bis-Mg as a dopant and then a 500-A^0 thick GaN layer can be grown successively one after another. Finally, a 800-Å-thick Mg-doped p-GaN layer ($1x10^{25}$ m^{-3}) is modeled to serve as the p^+ -contact layer. The n-contact consisted of Ti(100 Å)/Al(600 Å)/ Ti(200 Å)/Au(2000 Å) and the top p-ohmic contact is modeled using Pd(50 Å)/Au(50 Å). Finally, the presence of p-probe contacts consisting of Ti(200 Å)/Au(2000 Å) over the p-ohmic contact are also included in the model to make the analysis realistic.

II. SIMULATION EXPERIMENT TECHNIQUE

Diodes are first designed and optimized through a generalized double iterative simulation technique used for analysis of IMPATT action [4]. The method involves iteration over the magnitude of field maximum (E_m) and its location in the depletion layer. The electric-field and carrier current profiles are obtained through simultaneous solution of Poisson and current continuity equations. The experimental values of material parameters, viz., realistic field dependence of carrier ionization rates, saturated drift velocities of charge carriers, and carrier mobility in GaN and AlGaN/GaN [5 and references therein] are incorporated in the present analysis. The junction temperature is taken as 300K. Current multiplication factors ($M_{n,p}$) for electrons and holes are considered to be high enough (10^6) to initiate avalanche breakdown process.

The small signal analysis of the IMPATT diode is carried out through a double iterative simulation technique [4], used to solve two second order differential equations involving diode total integrated negative resistance (Z_R) and reactance (Z_X). The small signal admittance characteristics (negative conductance (-G) vs. susceptance (B) plots), negative resistance and quality factor (-Q =B/-G) of the optimized GaN SDR diodes are determined by Gummel-Blue approach after satisfying the appropriate boundary conditions [4]. The diode total negative conductance (-G) and susceptance (B) is calculated from the following expressions:

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

-G and B are functions of RF voltage (V_{RF}) and frequency (ω) such that the steady state condition for oscillation is given by [4]:

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

where, g is load conductance. -G, B, g are normalized to the area of the diode. The relation provides minimum uncertainty in g at low power oscillation threshold. The authors have evaluated R_S from the admittance characteristics using the realistic analysis of *Gummel-Blue* and *Adlerstein* et al [4] without any drastic assumption. Under the small signal condition, V_{RF} (amplitude of the RF swing) is taken as $V_B/2$, assuming a 50% modulation of the breakdown voltage V_B. For such a small value of V_{RF}, R_S can be calculated by considering the value of g nearly equal to the diode conductance (G) at resonance.

At a given bias current density and at the peak frequency (f_P), the maximum pulsed power output (P_{RF}) from the device is obtained from the expression:

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

The peak negative conductance at the optimum frequency ($-G_p$) is normalized to the area of the diode. The effect of series resistance (R_S) on P_{RF} is also considered.

III. RESULTS AND DISCUSSIONS

DC and high-frequency properties of GaN and GaN/AlGaN based complementary hetero-structure IMPATT diodes have been investigated employing the simulation method discussed in section II. The design parameters of the diodes are shown in Table I. The DC and high-frequency properties of diodes at peak operating frequencies are summarized in Table II and will be discussed in this section.

It is seen that the peak electric field in GaN/AlGaN SDR is about 1.04 times higher than that in flat type device. It is also evident from the table that the breakdown voltage (V_B) for the *modified* diode is higher than that in flat-type IMPATT. Again, the DC to RF conversion efficiency (η) of *GaN/AlGaN* SDR diode is found to be higher than that of its flat profile counterpart. It is also evident from the Table II that the ratio of drift region voltage (V_D) to the diode breakdown voltage (V_B) is the highest in the *hetero-structure* SDR. It is interesting to note that the normalized voltage drop is only 22 % in flat-type diode, while it is more than 35% in *hetero-structure* diode. The increased value of V_D/V_B ratio in *hetero-structure* SDR provides higher efficiency. The DC to RF conversion efficiency of 11% for *hetero-structure* SDR diode is much higher as compared to the efficiency of only 7% for flat-type diode. It is exciting to note that the values of P_{RF} of *hetero-structure* GaN SDR are almost 2.8 times higher than flat-type SDR operating at THz frequency. Moreover, it is evident from Table II that in terms of quality factor also, *hetero-structure* SDR IMPATT is better than its flat-profile counterpart. It is observed that avalanche frequency in both the diodes is nearly 1.0 THz. Fig. 2 shows the electric field profiles comparison for the diodes. It is observed from Fig. 2 that electric field falls much more sharply with in the highly doped region for the *hetero-structure* diode than flat SDR.

TABLE II

DDR diode type	GaN flat-profile device designed at 1 THz frequency	GaN/AlGaN hetero-structure device designed at 1THz frequency
Peak electric field (E_m) (10^8 Vm^{-1})	4.0	4.17
Breakdown voltage (V_B) (V)	22.7	24.4
V_D/V_B	0.22	0.35
Efficiency (in %)	7.0	11.0
Peak negative conductance ($-G_P$) (10^7 Sm^{-2})	50.0	112.0
Diode negative resistance at peak frequency ($-Z_{RP}$) (10^{-10} Ω m^2)	3.6 (estimated $R_S = 3.0\Omega$)	5.5 (estimated $R_S = 1.7\Omega$)
Maximum output power density (10^{10} Wm^{-2})	3.0 (including $R_S = 3.0\Omega$)	8.3(including $R_S = 1.7\Omega$)
Quality factor ($-Q_P$)	2.1	0.8
Peak operating frequency (THz)	1.0	1.0

THz - PROPERTIES OF GaN and GaN/AlGaN IMPATTs at 1 THz

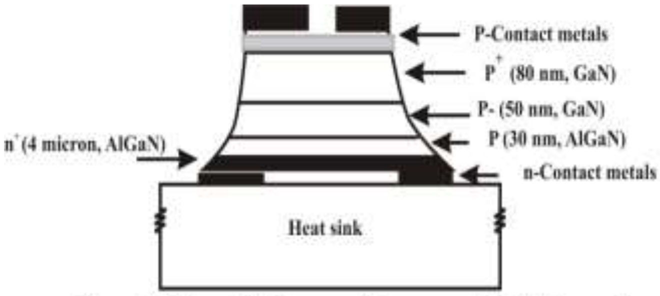

Figure 1. Schematic diagram of top - mounted (TM) complementary SDR IMPATT diode structure suitable for Thz-operation.

Fig. 3 represents the negative conductance (-G) against operating frequency plots for the diode structures. It is found from Fig. 3 that $|-G_P|$ at peak frequency records a value of 112×10^7 Sm^{-2} for *hetero-structure* GaN SDR followed by 50 $\times 10^7$ Sm^{-2} for flat-profile SDR. The small-signal properties regarding – G, B and expected value of g at threshold (resonance) condition is estimated through a modified simulation technique reported elsewhere [4]. The introduction of AlGaN layer in the p-drift region increases the mobility of carrier in p-drift region and thus increases the drift region conductivity which in turn reduces the resistivity significantly. So, the parasitic resistance contribution due to un-depleted region in GaN/AlGaN device reduces considerably and this in turn improves negative resistance, RF power density in the proposed hetero-structure device. It is depicted from Figs. 4 (dashed curves) that the presence of R_S (i.e. including the effects of contact resistances) reduces RF power density of the flat profile and *hetero-structure* diodes by ~40% and only 8%, respectively. So the simulation results presented in Table II depicts that the value of - Z_R increases but the value of R_S decreases as doping profile changes from flat to complementary hetero-structure type.

I. CONCLUSION

For the first time, authors have studied the complementary SDR IMPATT diode performance in GaN material systems. Suitable ohmic contact metals are proposed for p- and n-contacts and their effects in estimating parasitic resistance of both the designed diodes.

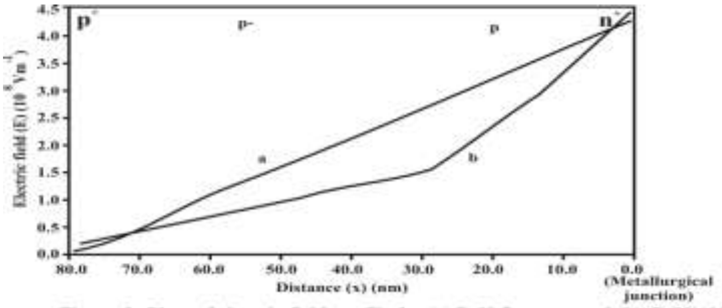

Figure 2: Plots of electric field profile for (a)GaN flat type and (b) GaN/AlGaN hetero-structure complementary SDR IMPATT diodes.

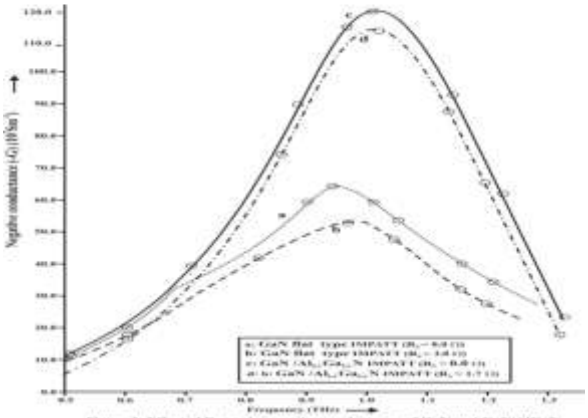

Figure 3: Effect of R_s on the negative conductance of GaN and GaN/AlGaN IMPATT diodes in the Terahertz region.

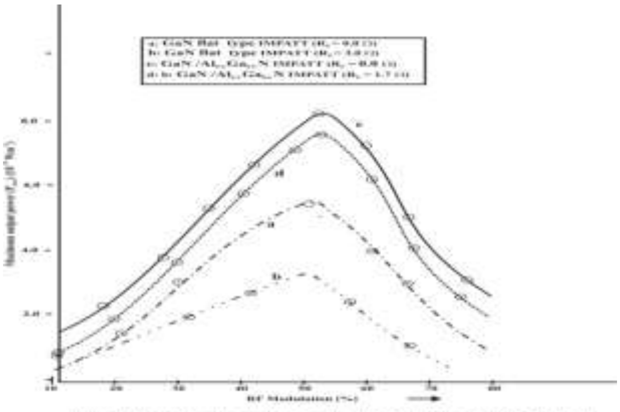

Figure 4: Effect of series resistance on P_{max} of GaN (flat-type) and GaN/AlGaN hetero-structure complimentary SDR IMPATT diode.

Fig. 3: The negative conductance (-G) against operating frequency plots for the diode structures

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