CHAPTER 6: III-V NITRIDE BASED MM-WAVE & THZ IMPATTs

SIMULATION INVESTIGATIONS OF III-V GALLIUM-NITRIDE BASED IMPATT DIODES IN THE MM-WAVE AND TERAHERTZ REGIME AND PHOTOSENSITIVITY ANALYSIS OF THE DIODES.

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The purpose of the present Chapter is to thoroughly investigate the MM-wave and Terahertz frequency performances of the un-illuminated and illuminated IMPATT diodes based on another emerging semiconductor Gallium Nitride (GaN). The relevance of this study comes from the increasing demand of high-frequency, high-power device applications.

6.1 Introduction:

The last few decades have been characterized by efforts to extend communication and RADAR systems in the MM-wave frequency range. These frequencies provide many advantages over the microwave frequencies, such as broader bandwidth, increased resolution, reduced component size, decreased system weight, smaller antenna size, and lower voltage power supplies. The capacity of penetration of MM-wave signals through cloud, dust and fog is an added advantage in modern communication systems which use the low-attenuation atmospheric window frequencies. Recent development advances have allowed Si semiconductor technology to approach the theoretical limits of the Si material; however electronic device requirements for many applications are at a point that the present Si - IMPATT devices can not handle. The requirements include high-power, high-efficiency, high-temperature as well as high-frequency operation. The ever-increasing demand of using IMPATT devices in high-power and high-frequency system applications have given impetus for further work on short MM-wave operation of the devices based on new class of WBG semiconductors.

Recently, WBG semiconductor III-V Nitride (GaN) has expanded the scope of device application beyond those of Si and GaAs [6.1]. Exploitation of the material properties of GaN, holds promise for revolutionary improvements in high-temperature and high-frequency performances of a broad range of military and commercial devices. The most attractive material property of GaN is its wide bandgap energy. WZ-GaN has direct room temperature bandgap of 3.4 eV, much higher than conventional Si (1.12 eV) and GaAs (1.42 eV). Owing to its wide bandgap, GaN is promising for high-temperature application as it goes intrinsic at much higher ambient temperature than materials like Si and GaAs. It means that GaN based devices can operate with less cooling and with less high cost processing steps associated with complicated structures designed to maximize heat extraction. The second attractive property of III-V GaN is that it has a high value of critical breakdown field, $E_c$ ($50 \times 10^7$ V.m$^{-1}$), which is much higher than conventional Si ($3 \times 10^7$ V. m$^{-1}$) and GaAs ($4 \times 10^7$ V. m$^{-1}$). GaN also has excellent electron transport properties, including good mobility ($0.125$ m$^2$ V$^{-1}$ s$^{-1}$) and high saturation velocity ($2.5 \times 10^7$ m s$^{-1}$) of charge carriers. Based on these material parameters of GaN, one can expect that GaN based IMPATT may yield ~400 times more power than conventional IMPATTs, since power output from an IMPATT is proportional to $E_c^2 v_s^2$. This possibility has been studied through a simulation experiment on GaN based
SDR (p++ n n++) IMPATT diode in the D-band. The results are compared with those of a Si IMPATT at the same operating frequency. In the present Chapter, the author will report the results of systematic analysis of GaN and Si based SDR IMPATT diodes at 140 GHz window frequency.

Higher value of $E_C$ results in high breakdown voltage in GaN-based devices. For example, the breakdown voltage ($V_B$) of a diode is expressed as follows:

$$V_B = \frac{kT}{2q} N_d,$$

where, $q$ is the charge of electron and $N_d$ is the doping concentration.

Using the above equation and assuming a same doping concentration, the value of $V_B$ in GaN-based diode is expected to be $> 30$ times of a Si diode. This high breakdown voltage along with high saturation velocity, results in high-power operation in GaN based devices. Moreover, with a high value of $E_C$, much higher doping level can be achieved. Another consequence of higher $E_C$ and the higher doping density is the width reduction in the drift region of the devices. Thus, not only high-power but also high-frequency (THz) operation capability is expected from this WBG semiconductor based devices. The expected superior performances of GaN-based IMPATTs can also be established in terms of some commonly known Figure of Merits (FOM), as shown in Table 1.2. Taking Keyes' and Johnson's Figure of Merits for Si as unity, the Keyes' and Johnson's Figure of Merits for GaAs are 0.45 and 7.1, respectively, while those for GaN are 1.6 and 756, respectively. A very recent study predicts that the thermal conductivity $K$ of GaN is 225 Wm$^{-1}$K$^{-1}$ [6.2], higher than Si ($K = 150$ Wm$^{-1}$K$^{-1}$) and GaAs ($K = 46$ Wm$^{-1}$K$^{-1}$) but lower than that of SiC ($K = 490$ Wm$^{-1}$K$^{-1}$) (Table 1.1). However, growing GaN on SiC substrates, one can take advantage of the higher thermal conductivity of SiC. Thus, considering all the material parameters of GaN, it is evident that besides its ability to operate at extremely high temperature, the superior transport properties of GaN will make possible the operation of these devices in the high-frequency THz-region also.

It is discussed in Chapter 5 that much of the recent interest in THz region stems from its ability to penetrate deep into many organic materials without the damage associated with ionizing radiation such as X-Rays. The THz spectral range contains a unique fingerprint of crystalline substances, including explosives and illicit drugs as well as most other chemicals in powder form. Since many packing materials are transparent to THz radiation this fundamental property of crystalline compounds, in principle, allows remote sensing and recognition of the chemicals. THz imaging offers the opportunity to image in un-favorable weather condition. Moreover, the ability to penetrate dielectric has given rise to new applications in security scanning where weapons can be detected under clothing. It is mentioned earlier that THz applications and technologies are attracting increased attention from military and security fields. These have lead to new applications, such as space-based communication and atmospheric sensing. Non-availability of solid-state sources with reasonable power levels is well recognized as one of the
major obstacles for systems applications in this frequency range. Considerable progress in the growth of nitrides during the last five years has yielded GaN, suitable base material for good quality high-power electronic devices. Some of the advantages of nitrides as compared to other semiconductors are their large optical phonon energies (92.0 meV) and much higher optical phonon emission rate, which are favorable for THz generation. This Chapter is focused on simulation studies on the prospects of GaN-IMPATTs as a high-power, solid-state THz-source.

The fundamental material properties of GaN are found to be superior to those of the conventional Si and GaAs. In spite of its promising material properties, significant additional efforts are required in the areas of material growth and characterization, as well as doping and processing technologies before the full potential of GaN can be utilized. GaN occurs in two phases, Wurtzite (WZ) and Zincblende (ZB) with the former being stable and latter meta-stable. Again, as with the SiC family, the WZ phase material has received most attention because of the relative ease of growth when compared to ZB-GaN. WZ-GaN is grown on Sapphire or 6H/4H-SiC, whereas ZB-GaN is grown on polar cubic materials such as GaAs. The growth of GaN is challenging due to lack of suitable substrate material with a reasonably close lattice match. Until recently, GaN has been mostly grown on Sapphire and SiC substrates. Both of these substrates have significant disadvantages for commercial applications. Even though Sapphire has a long history as a substrate for GaN and is a relatively medium cost substrate, it is a poor thermal conductor and results in thermally limited devices. SiC substrates are excellent thermal conductors and offer a very close lattice mismatch to GaN, but it is relatively expensive. Both of these non-nitride substrates create high concentration of defects that are believed to significantly diminish device performances. Si can meet the requirement for a low cost and conducting substrate and this will enable integration of high power devices with Si based electronics. But the main problem that hinders the rapid development of GaN based devices on Si, is the thermal mismatch of GaN and Si, which generates cracks.

Recently, high quality GaN epilayers have been grown on Si (111) substrate by MOCVD by using a Si₃N₄ insertion layer [6.5]. These Si₃N₄ insertion layers can efficiently counteract the propagation of misfit dislocation usually observed in GaN epilayers grown on Si substrates and also improve the crystalline quality. This has helped GaN to emerge as relatively mature WBG semiconductor for developing high-power devices. Effective etching techniques are also essential to device fabrication. GaN has very high bond energies (8.9eV/atom) and wide bandgap energy, which makes it almost chemically inert at room temperature to bases and acids, which are low-cost and highly available as wet etchants used in Si processing. There are various methods of dry etching involving sources of external energy to initiate and sustain the break-up of the high energy bonds in GaN. A few of the dry etching technologies used for GaN include, Ion milling and Reactive Ion Etching (RIE). Ion milling relies upon
physical sputtering and is not very practical for GaN, because of low etch rate and extreme damage to the material caused by the purely physical process. The RIE method is a better technique of dry etching. Wet etching method provides low damage etching, low-cost and complexity. Photo-electrochemical wet etching (PEC) was found to etch GaN with significantly high etch rates [6.6].

A few other issues in the processing of GaN based devices include ohmic contact to the nitride material and also the consideration of power dissipation. For n-type GaN, ohmic contact with relatively low contact resistance ~ $10^{12} \, \Omega \, \text{m}^2$ was achieved using alloy composition such as Ti/Al/Ni/Au [6.7]. On the other hand, for p-type GaN, because of the difficulty in achieving high carrier density and the absence of suitable metals with high work function, a high quality ohmic contact with very low contact resistivity (~$10^7 \, \Omega \, \text{cm}^2$) has still not been achieved. For p-type GaN, however, the best result (4.5$x10^{-10} \, \Omega \, \text{m}^2$) is obtained from Be-doped (conc. 8.1$x10^{23} \, \text{m}^{-3}$) sample with Ni/Pd/Au contacts [6.8]. GaN devices are high power devices and consequently, the large amount of current flowing in the devices causes significant self-heating effects. GaN film grown on SiC substrate can increase the effective thermal conductivity and in this way a large amount of heat can be dissipated from the high power devices. One other option is that the GaN films grown on Sapphire substrate can be lifted off using a LASER lift-off technique and can successfully bonded to a Si substrate [6.9]. Thus in the light of maturity of the fabrication technology and the unique material parameters, GaN appear to be the best choice, overall, for the next decade of device development both in MM-wave as well as at THz region.

Though GaN is a promising material for developing high-power IMPATT devices, theoretical and experimental research activities on GaN-IMPATTs are very limited [1.11] [2.186]. To the best of author’s knowledge, only one simulation result on GaN THz (0.7 THz) IMPATT is available in recent literature [1.23], while, there are no corresponding experimental results. Identifying the emergent need for developing high-power IMPATT oscillators in the THz region (>1 THz), the author has designed and simulated the DC and small-signal behavior of SDR (p++ n n++ type) GaN (both WZ and ZB) IMPATT diodes suitable for operation in the THz frequency range. These results are further compared with those of a 4H-SiC-based SDR IMPATT at around 1.0 THz. This useful comparison will help device engineers to select the most promising semiconductor for developing efficient and powerful device for application in future THz space-communication systems.

It has been reported earlier that the effect of space-charge due to high current density in a flat profile IMPATT diode can be minimized by introducing charge-spikes (bumps) at appropriate positions in the depletion layer [2.87-2.92]. The resulting diodes with modified doping profile, known as the 'quasi-Read' (lo-hi-lo type) IMPATT diodes can be operated at higher current densities and also show better efficiency and higher power output. Hence the author has made an attempt to assess the performance of the Single Low-High-Low (SLHL) type GaN IMPATT diodes in the THz frequency
region. The simulation results have been compared with those of a GaN flat-profile diode under similar operating conditions.

This Chapter will throw light on the DC and high-frequency characteristics i.e. (1) breakdown voltage, (2) voltage drop across avalanche layer width, (3) maximum electric field, (4) conversion efficiency, (5) negative conductance, (6) admittance characteristics, (7) negative resistivity profiles, (8) maximum output-power density, (9) device quality factor (10) negative resistance (11) avalanche frequency, (12) peak operating frequency of the GaN diodes (flat & SLHL types) in the MM-wave (D-band) region, as well as in the THz frequency region (0.5 THz and 1.45 THz frequencies). It has already been shown that the admittance profiles and quality factors provide information about the overall high-frequency performances of the designed diodes, while the negative resistivity profiles provide information about the spatial variation of the resistivity of the diodes in the depletion layer. This in turn provides physical insight regarding the contribution of oscillatory power by different regions in the depletion layer. In order to investigate the above-mentioned characteristics, a generalized modified computer method for DC and high-frequency ac characteristics, as detailed in Chapter 3, has been used. The simulation technique has also incorporated the effect of mobile space-charge.

To the best of author’s knowledge, this is the first study on GaN based IMPATTs in the THz regime. During the simulation experiments, the author has considered certain aspects of study which may seriously affect the performance of GaN based devices, particularly if it is being operated in THz region. Those aspects are (i) thermal effects and (ii) effects of parasitic series resistances. Parasitic series resistance ($R_S$) is a crucial parameter that limits output-power and causes burn-out problem in THz IMPATTs. The author has determined the value of $R_{\text{total}}$ of the THz GaN-IMPATTs considering contribution from the substrates, the un-depleted epitaxial layer as well as ohmic contacts. Subsequently, the effect of $R_{\text{total}}$ on the THz performance of GaN IMPATT diode is also studied.

The importance of studying optical illumination effects on the MM-wave and THz IMPATT devices are described in previous Chapters. Optically generated carriers enhance the reverse saturation current or leakage current flowing in the reversed biased p-n junction of an IMPATT diode, and the enhanced reverse saturation current, in turn, controls the MM-wave properties such as (i) admittance characteristics, ii) frequency of oscillation, (iii) device quality factor, (iv) output power density, (v) negative resistivity profiles. The leakage current ($I_L$), which is normally due to thermally generated electrons and holes ($I_L = I_{ns} + I_{ps}$), is so small that the current multiplication factor, $M_{np} = \frac{I_o}{I_{ns}I_{ps}}$ (where, $I_o$ = bias current density), can be considered to be infinitely large. However, the saturation current in IMPATT diodes can be enhanced in a several ways such as (a) irradiation by high-energy electrons, (b) photo-excitations by optical-illumination. But in general, the previous experimental works have shown...
that increasing intensity of external radiation on the devices causes decrease of output-power along with an increase of tuning range [2.210]. To the best of author's knowledge, no published reports are available on studies of optically-modulated GaN-based MM-wave and THz devices. So, in order to get a clear insight into the photo-illumination effects on GaN based TM and FC diodes, detailed computer studies have been carried out on the effects of electron and hole current multiplication factors $M_e$ and $M_h$ on (i) admittance characteristics, (2) negative resistivity profiles, (3) power output,(4) diode negative resistance and (5) device quality factor of GaN-IMPATTs having flat and Quasi Read type doping profiles. The detailed analysis of the modified simulation scheme for studying the effects of external radiation on GaN based IMPATTs are described in Chapter 3.

6.1.1 Material Parameters of Hexagonal (WZ) and Cubic (ZB) GaN.

It is already discussed that GaN crystallizes in a wurtzite structure having hexagonal symmetry and zinc-blende structure with cubic symmetry. These two polytypes have different material parameters such as different impact ionization rates, different mobility of charge carriers and different velocity field characteristics. Experimentally observed electric field dependent ionization rates, mobilities and drift velocities of charge carriers in WZ-GaN and ZB-GaN are used to make a realistic modeling of the GaN based MM-wave and THz devices. The material parameters of GaN are shown in Table 6.1 and will be described now.

There are several models to describe electron high-field mobility $\mu (E)$ as a function of the electric field $E$ in different semiconductors. It is conventional to express this functional dependence in terms of the electron drift velocity $v(E)$ dependence on the electric field through the relationship $v (E) = \mu (E) E$. In 1993, Gelmont et al. [6.10] carried out a Monte Carlo simulation on the high-field velocity overshoot behavior in GaN. Mnatsakanov et al. [6.11] reported an electron mobility model which is based on experimental mobility data collected from technical literature published in between 1973 – 1996. This model allows calculating low field mobility depending on carrier concentration and temperature. The model is quite good to determine low-field mobility below room temperature. But above room temperature, this shows deviation from measured data. Also high-field transport was not considered in their model. A well established existing model is Canali model [6.12]:

$$v_C (E) = \frac{\mu_{low} E}{(1 + \left(\frac{\mu_{low} E}{v_{sat}}\right)^{\beta'})^{1/\beta'}}$$

(6.1)

where, $v_{sat}$ (electron saturation velocity) and $\beta'$ are fitting parameters. This formula is applicable for Si and other semiconductors, such as SiC-family, with a similar band structure. The Canali model features a monotonic increase of the carrier drift velocity and indicates a soft saturation behavior of carrier velocity.
It was recommended elsewhere [6.13] to choose parameter $\beta' = 1.7$ for GaN. At 300K, low-field mobility, $\mu_{\text{low}}$, can be taken as 0.1 $\text{m}^2/\text{Vs}$ [6.11]. Monte Carlo simulated value of $v_{\text{sat}}$ can be taken as 1.91x$10^5$ $\text{m.s}^{-1}$ [6.14]. However, Schwierz [6.15] recently remarked that the above expression is not suitable for modeling field dependent electron velocity in GaN. This is because, like GaAs and other III-V compounds, $v(E)$ characteristics of GaN has a peak in the low-field region and also a region of negative differential mobility (NDM) due to transferred-electron effect. Mansour et al. [6.16] explained that the origin of the peak is due to the change of dominant scattering mechanism in GaN as the applied electric field increases.

One commonly used model for expressing field dependent carrier velocity in GaAs and other semiconductors with similar characteristic NDM region is the Transferred Electron (TE) model [6.17]:

$$v_{\text{TE}}(E) = \frac{\mu_{\text{low}} E + E_{\text{sat}}}{1 + (\frac{E}{E_{\text{sat}}})^{\beta_T}},$$

where, $E_T = 41x10^2 \text{kV.m}^{-1}$ can be chosen for GaN in order to reach the peak velocity $v_{\text{peak}} \sim 3x10^5 \text{m.s}^{-1}$. The value of $v_{\text{peak}}$ is at $T=300K$ and for the doping concentration equal to $10^{23} \text{m}^{-3}$ [6.14]. Several research groups [6.14] [6.18] carried out Monte Carlo simulation of carrier transport in GaN. From their study, a clear indication of typical drift velocity dependence on the electric field in GaN is found. It is mentioned that unlike Si, GaN has a peak in the drift velocity curves and unlike GaAs, GaN has a well-pronounced kink in the low-field region. Thus, the $v(E)$ dependence in GaN does not fit well with either Canali or TE models. It is very hard to adjust parameters for Canali or TE models to replicate simultaneously the kink and velocity field as there are in GaN. Farahmand et al. [6.14] developed a mobility model based on the results of Monte Carlo transport simulations. Schwierz also [6.15] proposed an expression, very similar to Farahmand et al., suitable for modeling $v(E)$ characteristics in WZ-GaN:

$$v(E) = \frac{\mu_{\text{low}} E + v_{\text{sat}} (\frac{E}{E_{\text{sat}}})^{n_1}}{1 + (\frac{E}{E_{\text{sat}}})^{n_2} + n_2 (\frac{E}{E_{\text{sat}}})^{n_3}},$$

where, $\mu_{\text{low}}$ is low-field mobility depends on carrier concentration and temperature according to the following two equations (6.4) and (6.5):

$$\mu_{\text{low}} = \mu_{\text{min}} + \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + (\frac{n}{n_{\text{ref}}})^{\alpha}},$$

where, $\mu_{\text{min}}, \mu_{\text{max}}, n_{\text{ref}}$ and $\alpha$ are fitting parameters. The parameter $\alpha$ is a measure of how quickly the mobility changes from $\mu_{\text{min}}$ to $\mu_{\text{max}}$. $n_{\text{ref}}$ is the carrier concentration at which mobility is half way between $\mu_{\text{min}}$ and $\mu_{\text{max}}$. The temperature dependence of $\mu_{\text{low}}$ can be obtained by incorporating the temperature dependent fitting parameters i.e. $\mu_{\text{min}}(T)$, $\mu_{\text{max}}(T)$, $n_{\text{ref}}(T)$ and $\alpha(T)$ in equation (6.4) [6.15], as considered by Schwierz. The temperature dependency of the abovementioned fitting parameters can be obtained from the following equation [6.15]:

$$\text{Fitting par}(T) = \text{Fitting par}(T = 300K) \times \left(\frac{T}{300K}\right)^{\text{Fitting par}}.$$
The necessary parameters for calculating $\mu_{\text{low}} (T = 300K)$ using equation (6.4) are discussed by Schwierz in details in reference [6.15]. Schwierz made a comparison between their temperature dependent mobility data and the measured data by other workers [6.19] and the validity of their model was well established. Schwierz's analysis reveals that $\mu_{\text{low}}$ at 300K is ~0.1 m$^2$.V$^{-1}$.s$^{-1}$, and similar result was obtained earlier by Albrecht et al. through Monte Carlo simulation of transport characteristics of GaN for high temperature device modeling [6.20].

In equation (6.3), $v_{\text{sat}}$, $E_C$, $n_1$, $n_2$ and $n_3$ are fitting parameters. The temperature dependence of these four fitting parameters can be expressed by [6.15]:

$$F_{\text{fitting par}}(T) = F_{\text{fitting par}}(T=300K) \times (a + bT + cT^2) \quad (6.6)$$

where, 'Fitting par' is the parameter of interest, i.e. $v_{\text{sat}}$, $E_C$, $n_1$, $n_2$ or $n_3$ and a, b, c are constants that have been determined by Schwierz [6.15]. Following Schwierz, the author in the present thesis included equation (6.3) for expressing $v(E)$ in WZ-GaN. Albrecht et al. proposed an analytical expression for peak value of electron drift velocity characteristics as a function of temperature as follows [6.20]:

$$v_{\text{peak}} = [3.7 - 0.65 \left(\frac{T}{300K}\right)] (10^5 \text{ m. s}^{-1}) \quad (6.7)$$

At T=300K, they obtained $v_{\text{peak}} \sim 3 \times 10^5$ ms$^{-1}$. Also Mansour et al. [6.16] and Farahmand et al. [6.14] obtained similar value of $v_{\text{peak}}$ in GaN from their analysis. Recently, Khurgin et al. [6.21] calculated saturation velocity in GaN from Rule-of-thumb consideration and obtained the saturation velocity in GaN of the order of $3 \times 10^5$ ms$^{-1}$. However, Khurgin et al. [6.21] identified the phonon-decay bottleneck to be the main factor that reduces high-field saturation velocity in GaN. They have considered the important factor of the increase of electron temperature, i.e. "hot-electron" effect due to the application of high electric field. Such hot electrons lose energy by transfer it to LO phonon, which however cannot easily decay into acoustic phonons in GaN, resulting in a large non-equilibrium LO phonon population. This phonon decay bottleneck is the main factor for reducing the high field carrier saturation velocity in GaN [6.21]. Khurgin et al. made an conclusion that the ensuing reduction in the carrier saturation velocity in GaN is mostly (~2/3 of the total) caused by heating due to phonon-bottleneck and significantly less (~1/3 of the total) by actual 'hot phonon' scattering. Khurgin et al. [6.21] have shown a possible way to remove the bottleneck by introducing local disorder in the lattice. The effect may be explained as disorder induced localization of LO phonons, with localized phonons occupying larger fraction of the Brillouin zone and thus providing more channels for transferring the heat from electrons to lattice. This is a promising approach for increasing the electron velocity in GaN and the power and modulation speed of GaN-IMPATTs and other devices. The author has taken into account the effects of hot phonon dynamics in considering the value of $v_{\text{sat}}$ for modeling WZ-GaN IMPATT diodes. While calculating $v_{\text{peak}}$ and $v_{\text{sat}}$ in GaN through a Monte-Carlo study, Yamakawa et al. [6.22] considered the effect of electron-phonon...
interaction. They obtained \( v_{\text{peak}} = 2.5 \times 10^2 \text{ ms}^{-1} \) and high field saturation velocity, \( v_{\text{sat}} \) within 1.5x10^5 - 2x10^5 ms\(^{-1}\). Schwierz [6.15] also shows \( v_{\text{sat}} (T = 300\text{K}) \approx 1.8 \times 10^5 \text{ ms}^{-1} \) from their analysis, which is within the range predicted by Yamakawa et al. and close to the value predicted by Khurgin et al. [6.21]. Farahmand et al. however estimated slightly greater value of \( v_{\text{sat}} \) in WZ-GaN, they have shown \( v_{\text{sat}} = 1.91 \times 10^5 \text{ ms}^{-1} (T = 300\text{K}) \) from their analysis. Meng et al. [2.186] studied the performance of WZ- and ZB-GaN based Read-type SDR flat-profile diodes at 300 GHz. They have also considered the value of electron saturation velocity in WZ-GaN as 1.9x10^5 ms\(^{-1}\), at 300K. Taking into consideration all the previous analysis, the author has taken \( v_{\text{sat}} (T = 300\text{K}) = 1.9 \times 10^5 \text{ ms}^{-1} \), in the present analysis. The author has also estimated the value of \( v_{\text{sat}} \) within 300K < T < 600K from equation (6.6). At T = 600K, \( v_{\text{sat}} \) is estimated as \( \sim 1.7 \times 10^5 \text{ ms}^{-1} \). Albrecht et al. [6.20] and Schwierz et al. [6.15] estimated temperature dependence of electron mobility in WZ-GaN. Following their calculations, author has taken electron mobility in WZ-GaN as 0.02 m^2 V\(^{-1}\).s\(^{-1}\) at T = 600K.

Lu and Cao designed and studied Terahertz generation and chaotic dynamics in NDR diode based on ZB-GaN [6.23]. They have considered an analytical expression for mobility-field characteristics in ZB-GaN, which is very similar to GaAs. In this dissertation, author has incorporated the following equation of \( v_n (E) \) for the modeling of ZB-GaN IMPATT [6.23]:

\[
\begin{align*}
v_n (E) &= \frac{\mu_{\text{low}} E + v_{\text{sat}} (p, E)}{1 + \left(\frac{E}{E_{\text{th}}}\right)^4} \\
\end{align*}
\]

where, \( E_{\text{th}} \) is threshold field at which electron velocity reaches its peak and its value is 8x10^6 Vm\(^{-1}\) [6.22]. In the above equation, electron saturation velocity, \( v_{\text{sat}} \) in ZB-GaN is taken as 1.75x10^5 m.s\(^{-1}\) (300K) and \( \sim 1.45 \times 10^5 \text{ m.s}^{-1} \) at 600K [2.186] [6.24]. Ando et al. [6.24] showed that in ZB-GaN increase of temperature from 300K to 600K causes \( \mu_{\text{low}} \) to decrease by 74%, i.e. from 0.055 m^2 V\(^{-1}\).s\(^{-1}\) to 0.0143 m^2 V\(^{-1}\).s\(^{-1}\). In the analysis author has incorporated equation (6.8) and the above mentioned values.

A velocity field characteristic for hole in both of the WZ- and ZB-GaN is considered as follows:

\[
\begin{align*}
v_p (E) &= v_s (1 - \exp\left(-\frac{-\mu_p E}{v_{\text{sat}} (p)}\right)),
\end{align*}
\]

where, \( E \) is electric field, \( \mu_p \) is hole mobility, \( v_{\text{sat}} (p) \) is saturated drift velocity of holes. To the best of author's knowledge, there are no experimental results available for these parameters, and simulation results are also very limited. Meng et al. [2.186] considered the room temperature values of hole saturation velocity in WZ-GaN and ZB-GaN as 4.8x10^4 ms\(^{-1}\) and 9.2x10^4 ms\(^{-1}\), respectively. In selecting these values, they have taken into consideration the Monte Carlo analysis by Oguzman et al. [6.25]. However, during the modeling of GaN-based near-THz IMPATTs, Reklaitis et al. [1.23] considered the hole saturation velocity in WZ-GaN as 7.7x10^4 m s\(^{-1}\) (T = 300K) and \( \sim 5 \times 10^4 \text{ ms}^{-1} \) (T= 600K).
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SECTION 6: III-V NITRIDE BASED MM-WAVE & THz IMPATTs

degradation of \( v_{\text{sat}}(P) \) at elevated temperature (600K) is almost 35%. Like Reklaitis et al., the author, in the present analysis considered hole saturation velocity in WZ-GaN as \( 5 \times 10^4 \text{ ms}^{-1} \) \((T = 600\text{K})\). Due to lack of temperature dependent value of hole saturation velocity in ZB-GaN, the author in the present analysis, has assumed that similar to WZ-phase GaN, \( v_{\text{sat}}(P) \) \((T = 600\text{K})\) in ZB-phase GaN also reduces by 35% than its room temperature value. Thus, in this thesis, \( v_{\text{sat}}(P) \) \((T = 600\text{K})\) in ZB-GaN is assumed as \( 5.98 \times 10^4 \text{ ms}^{-1} \). Room temperature hole mobility in WZ-GaN is taken as \( 28 \times 10^{-4} \text{ m}^2.\text{V}^{-1}.\text{s}^{-1} \) \([1.23]\) and the same in ZB-GaN is taken as \( 23.5 \times 10^{-4} \text{ m}^2.\text{V}^{-1}.\text{s}^{-1} \) \([6.26]\). In this analysis, author has assumed that temperature dependence of hole-mobility in GaN is \( \mu_p(T) = \mu_p(300\text{K})(T/300\text{K})^\alpha \), with parameter \( \alpha = 1.68 \) extracted from the Monte Carlo simulations \([1.23]\).

Electron (\( \alpha \)) and hole (\( \beta \)) ionization rates in WZ- and ZB-GaN are strongly dependent upon electric field. To accurately simulate the breakdown voltage and high-frequency characteristics of IMPATT diodes, it is necessary to use the correct model for impact ionization. Some of the most popular impact ionization models are the Selberherr model \([6.17]\), the Grant model \([2.57]\) and the Crowell-Sze model \([2.44]\). Among them, the simplest model, in terms of required number of fitting parameters, is the Grant model. Thus, following the Grant model, Electron (\( \alpha \)) and hole (\( \beta \)) ionization rates in WZ- and ZB-GaN can be expressed by the following empirical equation:

\[
\alpha(E) = A_{n,p} \exp \left( \frac{-B_{n,p}}{E} \right)^{m,n} \tag{6.10}
\]

where, \( A_{n,p} \) and \( B_{n,p} \) are respectively pre-exponential constant and electric field constant for electrons (n), and holes (p). In equation (6.10) \( \text{m}' \) and \( \text{n}' \) are exponential co-efficient in \( \alpha \) and \( \beta \) respectively. In 1997, Kolnik et al. \([6.27]\) presented the first calculation of electron initiated impact ionization in ZB and WZ-phase GaN. Their Monte Carlo model includes realistic band structures based on pseudo-potential calculations and numerically evaluated impact ionization transition rates. They performed calculations for electric field up to \( 3 \times 10^8 \text{ Vm}^{-1} \). They have found that an electron ionization rate in ZB-phase is higher than electron ionization rates in WZ-phase. Kolnik et al. predicted that an onset of electron initiated impact ionization in ZB-phase would take place at an electric field of \( 10^8 \text{ Vm}^{-1} \). At around \( 3 \times 10^8 \text{ Vm}^{-1} \), \( \alpha \) in ZB-GaN reaches \( 5 \times 10^6 \text{ m}^{-1} \). They have also reported that \( \alpha \) in WZ-GaN is more than one order of magnitude lower than those for ZB-phase at corresponding electric fields \([6.27]\). From their study it was revealed that in WZ-phase GaN, no impact ionization events occurred below \( 2 \times 10^8 \text{ Vm}^{-1} \). Kolnik et al. explained that the combined effects of a higher phonon scattering rate as well as greater density of states below 3 eV and a comparatively lower ionization transition rate results in a lower value of \( \alpha \) in WZ-GaN as compared to ZB-GaN. Later, Kunihito et al. \([6.28]\) experimentally evaluated electron initiated impact ionization co-efficient in WZ-GaN. They have performed gate-current analysis in the pre-breakdown regime of AlGaN/GaN heterojunction field effect transistor (HJFET). They have

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experimentally confirmed that breakdown field in GaN is eight times higher than that of GaAs. In the electric field region higher than $1 \times 10^8$ V.m$^{-1}$, $\alpha$ in WZ-GaN can be fitted as \[6.28\]:

$$\alpha (E) (m^{-1}) = 2.9 \times 10^{10} \exp (-3.4 \times 10^9 / E) \ (6.11)$$

where, the values of $A_{\alpha}$, $B_{\alpha}$ and $m$ are taken as $2.9 \times 10^{10}$ m$^{-1}$, $3.4 \times 10^9$ V.m$^{-1}$ and 1.0. No experimental value exists for the impact ionization coefficients of holes in WZ-phase GaN.

Electron and hole ionization rates in ZB and WZ-phase GaN as a function of inverse electric field are shown in Appendix 3. For the ZB-phase, little anisotropy in the ionization rates is observed for both carrier types. While, $\alpha$ is isotropic in the WZ-phase and ratio of the hole ionization coefficient, $\beta$ along the $<100>$ and $<001>$ is roughly about a factor of two. In the figure, only the ionization coefficients along the $<100>$ direction is shown for both type of carriers in ZB-and WZ-phase GaN [6.29]. At a lower electric field strength $\sim 2 \times 10^8$ V.m$^{-1}$, $\alpha \ll \beta$ in WZ-phase than that for the ZB-phase. However, at higher field strength $\sim 4 \times 10^8$ V.m$^{-1}$, difference in the values of $\alpha$ and $\beta$ between the two phases is very much less. From a curve fitting technique, the author has obtained the following empirical equation for $\beta$ in WZ-GaN:

$$\beta (E) (m^{-1}) = 5.0 \times 10^8 \exp (-1.97 \times 10^9 / E) \ (6.12)$$

where, the values of $A_{\beta}$, $B_{\beta}$ and $n$ are taken as respectively, $5.0 \times 10^8$ m$^{-1}$, $1.97 \times 10^9$ V.m$^{-1}$ and 1.0. These values are very similar with the data considered by Piprek et al. [6.30] for GaN-based device simulation. Within the wide electric field range of $2 \times 10^8$ V.m$^{-1}$ - $5 \times 10^8$ V.m$^{-1}$, $\alpha \approx \beta$ in ZB-phase GaN. Through curve fitting technique, the author has calculated the coefficients of electron and hole ionization rates in ZB-GaN:

$$\alpha (E) or \beta (E) (m^{-1}) = 1.1 \times 10^8 \exp (-8.0 \times 10^8 / E)^{1.0} \ (6.13)$$

where, the values of $A_{\alpha or \beta}$, $B_{\alpha or \beta}$, $m$ and $n$ are taken as respectively, $1.1 \times 10^8$ m$^{-1}$, $8.0 \times 10^8$ V.m$^{-1}$, 1.0 and 1.0.

Tirino et al. [6.31] studied the temperature dependence of the impact ionization coefficients in GaAs, 3C-SiC and ZB-GaN. They have found that the magnitude of the phonon energy in the semiconductors is principally responsible for changes in impact ionization coefficients as a result of temperature change. From their study it is revealed that in the materials with relatively small phonon energy, phonon scattering rates change considerably with temperature and therefore impact ionization rates also change significantly with changes in temperature. In GaAs, optical phonon energy is $\sim 34$ meV, whereas in ZB- and WZ-phase GaN it is $\sim 92.0$ meV. Due to this large difference in phonon energies, impact ionization coefficients are found to vary greatest with temperature in GaAs as compared to ZB-phase GaN [6.31]. Owing to its higher phonon energy ($92$ meV), temperature dependence of $\alpha$ and $\beta$ in WZ-GaN is assumed to be less significant particularly in the higher electric field region ($>3.0 \times 10^8$ V.m$^{-1}$). Thus the above mentioned impact ionization coefficients are considered for the temperature range $300K < T < 600K$. 
It is important to note that, since the ratio $a : b$ in ZB-phase is significantly small within the field range $2 \times 10^5 \text{ Vm}^{-1} - 5 \times 10^5 \text{ Vm}^{-1}$, ZB GaN based IMPATT may have less avalanche noise compared to their WZ-phase counterpart, according to the noise theory discussed in Chapter 2. Moreover, Chen et al. [6.32] has shown that the ratio $a : b$ in WZ-phase GaN is less than that in InP. Thus it may be predicted that WZ-GaN based IMPATT will be less noisy than InP-based IMPATTs according to the noise theories.

Table 6.1
Material parameters (input data) of Si and GaN (WZ- & ZB-) IMPATT diodes, Considered in the analysis (300K < T < 600K)

<table>
<thead>
<tr>
<th>Description of the parameter</th>
<th>Si</th>
<th>WZ-GaN</th>
<th>ZB-GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron mobility ($\mu_e$) ($\text{m}^2\text{V}^{-1}\text{s}^{-1}$)</td>
<td>0.06</td>
<td>0.02</td>
<td>0.0143</td>
</tr>
<tr>
<td>Hole mobility ($\mu_h$) ($\text{m}^2\text{V}^{-1}\text{s}^{-1}$)</td>
<td>0.02</td>
<td>8.8x10^{-4}</td>
<td>7.4x10^{-4}</td>
</tr>
<tr>
<td>Electron saturation velocity ($v_{se}$) ($\text{m. s}^{-1}$)</td>
<td>0.643x10^5</td>
<td>1.70x10^5</td>
<td>1.45x10^5</td>
</tr>
<tr>
<td>Hole saturation velocity ($v_{sh}$) ($\text{m. s}^{-1}$)</td>
<td>0.634x10^5</td>
<td>0.47x10^5</td>
<td>0.59x10^5</td>
</tr>
<tr>
<td>Pre-exponential constant in electron ionization rate ($A_n$) ($\text{m}^{-1}$)</td>
<td>0.50x10^8</td>
<td>2.9x10^10</td>
<td>1.1x10^8</td>
</tr>
<tr>
<td>Pre-exponential constant in hole ionization rate ($A_n$) ($\text{m}^{-1}$)</td>
<td>0.56x10^8</td>
<td>5.0x10^8</td>
<td>1.1x10^8</td>
</tr>
<tr>
<td>Electric field constant in electron ionization rate ($B_n$) ($\text{V. m}^{-1}$)</td>
<td>1.38x10^8</td>
<td>3.4x10^9</td>
<td>8.0x10^8</td>
</tr>
<tr>
<td>Electric field constant in hole ionization rate ($B_n$) ($\text{V. m}^{-1}$)</td>
<td>1.65x10^8</td>
<td>1.97x10^9</td>
<td>8.0x10^8</td>
</tr>
<tr>
<td>Exponential co-efficient in electron ionization rate ($\alpha$)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Exponential co-efficient in hole ionization rate ($\beta$)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Dielectric constant ($\varepsilon_r$)</td>
<td>11.7</td>
<td>8.9</td>
<td>9.7</td>
</tr>
</tbody>
</table>
6.1.2 COMPUTER MODELING AND SIMULATION TECHNIQUE.

6.1.2.1 Simulation scheme for modeling of flat-profile and Lo-Hi-Lo devices.

The schematic diagram and doping profile of a Single Drift Region (SDR, p\textsuperscript{++} n\textsuperscript{++}) IMPATT diode are shown in Figure 2.3. The schematic diagram of flat-profile SDR diode reversed biased to avalanche breakdown is shown in Figure 2.2 (a). The direction of electric field (E), carrier currents (J\textsubscript{niP}) and total current density (J) of the diodes are also shown in the figure. The edge of the depletion layers of p and n sides are denoted by W\textsubscript{p} and -W\textsubscript{n}, respectively. The p\textsuperscript{++} n interface of the SDR diode is taken to be the origin of the x-coordinate system in the computation. The variation of doping concentration around the junction and at the interface of epitaxy and substrate (x > -W\textsubscript{n}) are described by suitable exponential and complementary error functions, respectively. The doping profile near the junction of the p\textsuperscript{++} n n\textsuperscript{++} diode is given by:

\[ N(x) = N\textsubscript{D} [1 - \exp (x/s)] \]  

where, s is the parameter which determines the exponential rise of doping concentration near the junction. The constant “s” involved in the above expression has been taken to be 5.0 nm for MM-wave frequency diode and 1.0 nm for THz-frequency diodes.

and, \[ N(x') = N\textsubscript{h} \exp (-1.08\lambda - 0.78\lambda^2) \]  

for the n\textsuperscript{++} n interface of epitaxy and substrate (6.15)

where, \[ \lambda = \frac{x'}{2\sqrt{D\tau}} \]  

where D is the diffusion constant for the impurity atoms, x' is the distance from the surface and t is the time of diffusion. The value of \[ 2\sqrt{D\tau} \] has been taken as 4.0 \textmu m for the diodes. The surface doping concentration, N\textsubscript{h} is usually very high and are kept fixed at \[ 5 \times 10^{25} \text{ m}^{-3} \] for the MM-wave diode and \[ 10^{26} \text{ m}^{-3} \] for the THz frequency diodes. In the above expressions N\textsubscript{D} is the donor impurity concentration.

The impurity bump (Read spike) of opposite polarity is incorporated into the n-region of the p\textsuperscript{++} n\textsuperscript{+} IMPATT diode, to give rise to a Lo-Hi-Lo SDR (p\textsuperscript{++} n\textsuperscript{+} n\textsuperscript{++}) structure. The schematic diode structure and doping profile are shown in Figure 2.8 (a). The doping concentrations in different regions of the SLHL SDR diode are expressed in the following way:

\[ N(x) = N\textsubscript{1} [1 - \exp (x/s)] \]  

for the region, 0 < x < | -W\textsubscript{1} |

\[ N(x) = N\textsubscript{2} \]  

for the region, | -W\textsubscript{1} | < x < | -W\textsubscript{2} |

\[ N(x) = N\textsubscript{3} \]  

for the region, | -W\textsubscript{2} | < x < | -W\textsubscript{n} |

\[ N(x') = N\textsubscript{h} \text{erfc} \lambda \]  

for the n\textsuperscript{++} n interface of epitaxy and substrate. (6.16)
\[ \lambda = \frac{x}{2\sqrt{D}t} \], where \( D \) is the diffusion constant for the impurity atoms, \( x \) is the distance from the surface and \( t \) is the time of diffusion. The value of \( 2\sqrt{D}t \) is \( 4\mu m \). \( N_h \) (substrate doping concentration) is usually very high and has been taken to be \( 10^{26} m^{-3} \) for the present analysis. And \( \text{erfc} \lambda \) is of the following form:

\[
\text{erfc} \lambda = 1 - \text{erf} \lambda = 1 - \frac{2}{\sqrt{\pi}} \int_0^\infty e^{-\lambda^2} d\lambda
\]  

(6.17)

In the above equation, complimentary error function is approximated by the following equation:

\[
N(x') = N_h \exp (-1.081 - 0.78A.2) \quad (6.18)
\]

The bump width on n-side is \( \delta_n = |W_2 - W_1| \). The simulation is made accurate and less time-consuming through incorporation of fast converging logic, explained in Chapter 3.

### 6.1.2.2 Simulation scheme for DC and small-signal analysis.

GaN SDR diodes are first designed and optimized through a generalized double iterative simulation technique used for analysis of IMPATT action, described in detail in Chapter 3. The process of simulation is initiated by accurately fixing the edges of the active zone of the diode through solving Poisson’s equation and the combined current continuity equations. Computation involve simultaneous numerical solution of the fundamental device equations by starting the computation from the location of field maximum \( (x_0) \) in the depletion layer and then terminating the computation at the right edge of the SDR diode. Very small space steps \( (10^{-9} \ m \ for \ MM-wave \ diode \ and \ 10^{-10} \ m \ for \ THz \ diodes) \) have been used to increase the accuracy of the simulation analysis. Double iteration over the value and location of field maximum \( (E_0 \ and \ x_0) \) are carried out until the boundary conditions of \( E(x) \) and \( P(x) = (J_P(x) - J_A(x))/J \), reported in Chapter 3, are satisfied at the edges of the device active layer. Maximum oscillation frequency of IMPATT diode limited by tunneling breakdown can be written as:

\[ f_{\text{max}} \sim v_s E_g^{1/2} \]  

(5.15). Elta and Haddad [2.96] showed that the performances of Si IMPATTs degrades beyond the tunneling frequency limit of \( 400 \ GHz - 500 \ GHz \), whereas, in GaAs IMPATT, this limit is only up to \( 150 \ GHz \). GaN has 2.3 times higher value of \( v_s \) and \( \sim 3 \) times higher value of \( E_g \), compared to Si. Thus, \( f_{\text{max}} \) in GaN-IMPATT is expected to increase by at least 4 times than that of its Si counterpart. So, tunneling effect may not be prominent in GaN-based IMPATTs at least up to 2.0 THz frequencies, provided background doping concentration in the devices are not very high. Maximum frequency limited by diffusion \( (v_s^2/2D_e) \) in GaN-IMPATT is \( \sim 7 \) times higher than that of Si IMPATTs. It is expected that in the modeling of GaN IMPATTs within the frequency range of \( 140 \ GHz < f_p < 1.4 \ THz \), the “quantum size-effect” may not arise since De-Broglie wavelength, \( \lambda_0 \), in GaN is \( \sim 18 \ nm \), much smaller than the device dimensions in the abovementioned frequency range. The mean free path in GaN is \( \sim 28 \ nm \), much smaller.
than the device dimensions of the simulated diodes. Hence, the possibility of any ballistic transport will not arise and hence it has not been taken into account in the present analysis.

Summarily, the DC analysis provides $E(x)$ and $P(x)$ profiles and also the values of maximum electric field, breakdown voltage, drift voltage drop, device efficiency etc. For IMPATT mode operation, avalanche breakdown occurs at the junction when the electric field is large enough such that the charge multiplication factors ($M_n$, $M_p$) become infinite. The breakdown voltage ($V_B$) is calculated by integrating the spatial field profile over the total depletion layer width, i.e,

$$V_B = \int_{-x_1}^{x_2} E(x) dx$$  \hspace{1cm} (6.19)

where, the limits $-x_1$ and $+x_2$ represents n side and p-side depletion layer widths. The boundary conditions for current density profiles are fixed by assuming a high multiplication factor, $M_{n,p} \approx 10^6$. The effect of mobile space-charge in the depletion region of the diode has also been taken into account. The efficiency ($\eta$) is calculated from the semi-quantitative formula: $\eta (%) = \frac{V_D}{V_B}$, where, $V_D =$ voltage drop across the drift region, $V_B =$ $V_{B} - V_A$, $V_A =$ voltage drop across the avalanche region.

The small-signal analysis of the IMPATT diode provides insight into the high-frequency performance of the diode. The range of frequencies exhibiting negative conductance of the diode has been computed by Gummel-Blue technique, as described in Chapter 3. From 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. The spatial variation of high frequency negative resistivity and reactivity in the depletion layer of the diode are obtained under small-signal conditions by solving two second order differential equations in $R(x, \omega)$ and $X(x, \omega)$, as described in Chapter 3. $R(x, \omega)$ and $X(x, \omega)$ are the real and imaginary part of diode impedance $Z(x,\omega)$, such that, $Z(x,\omega) = R(x, \omega) + j X(x, \omega)$. The high-frequency admittance characteristics, negative resistivity profiles and device quality factor ($Q$) of the optimized GaN SDR diodes are determined by this small-signal analysis after satisfying the appropriate boundary conditions, written in Chapter 3. The total integrated diode negative resistance ($Z_R$) and reactance ($Z_x$) at a particular frequency ($\omega$) and current density $J_{DC}$ are computed from numerical integration of the $R(x)$ and $X(x)$ profiles over the active space-charge layer.

The total diode impedance $Z_{\text{total}}(\omega)$ is obtained from the following equation,

$$Z_{\text{total}}(\omega) = \int_{-x_1}^{x_2} Z(x,\omega) dx = Z_R + j Z_X$$  \hspace{1cm} (6.20)

Negative conductance $G$ and susceptance $B$ are calculated from the following expressions, as described in Chapter 3:
G and B are functions of frequency.

The serious power degradation effect of positive series resistance $R_s$, in the THz region, is discussed earlier. In the THz region, $1 - Z_R I$ decreases significantly. However, the sustained oscillation condition requires that, $1 - Z_R I > R_s$. This vital aspect of study is also addressed in this chapter by estimating the values of $R_s$ in GaN-based THz diodes. Earlier, Adlerstein et al. [3.9] developed a method for determining positive series resistance, $R_s$ from the threshold condition of IMPATT oscillation. However, author has discussed in Chapter 3 that Adlerstein's approach involves several simplifying assumptions like equal ionization rates, equal drift velocities of charge carriers. In the thesis, the author has determined the realistic value of positive series resistance ($R_s$) of the THz GaN-based IMPATTs from the admittance characteristics using a realistic analysis of Gummel-Blue [2.63] and Adlerstein et al [3.9]. In order to get a realistic value of $R_s$, author has incorporated the values of p-GaN & n-GaN contact resistances in the calculation of total positive series resistance, $R_{s,\text{total}}$. The role of $R_{s,\text{total}}$ is considered for calculating realistic values of $P_{\text{max}}$ in case of THz devices.

The small-signal quality factor at peak frequency, $Q_P$ is obtained from the equation: $-Q_P = (B_p / -G_p)$. At peak optimum frequency, the semi-quantitative values of maximum output power density, $P_{\text{max}}$ from the devices is estimated from the expression: $P_{\text{max}} = (V_{RF}^2 \cdot |-G_P|)/2$, described in previous Chapters. The value of $|-G_P|$ is normalized to the area of the diode.

### 6.1.2.3 Simulation scheme for photo-sensitivity analysis.

It is described in earlier Chapters of the thesis that control of small-signal characteristics of the IMPATT oscillators by optical-means has become the field of major research, since such optical control of IMPATTs can have important application in advanced RADAR and communication systems. GaN based high-power IMPATT diodes, used as THz source in spacecraft, may be subjected to interstellar radiation that can produce appreciable changes in the performance of the oscillators. It is discussed in earlier Chapters that when optical or other radiation with a photon energy $h\nu > E_g$ is absorbed at the edges of the reversed biased p-n junction of an IMPATT diode, photo-excitation of electron-hole pairs occurs within the active region of the diode. These photo-generated carriers give rise to a photocurrent and thereby enhance the existing thermal leakage current in the IMPATT diode. The enhanced leakage current alters the avalanche phase delay which, in turn, modifies the phase and magnitude of terminal current in the device oscillator circuit. In order to get a clear insight into the optical-illumination effects on the GaN based MM-wave and THz devices, computer studies have been carried out on the effects of electron ($M_e$) and hole current multiplication factors ($M_p$) on (i) the admittance profile, (ii) negative resistivity profile, (iii) $Q_p$, (iv)
P\textsubscript{max}, and (v) | -Z\textsubscript{RP} | of the MM-wave and THz devices. Earlier, it was experimentally shown by Vyas [2.210], that the composition of leakage current plays vital role in controlling the high frequency behavior of the devices. Hence, in this Chapter, computer studies have been carried out on the photo-illuminated Top Mounted (TM) and Flip Chip (FC) devices for different values of M\textsubscript{n} (M\textsubscript{p} = 10^6) or M\textsubscript{p} (M\textsubscript{n} = 10^6).

A double iterative computer method, as described in Chapter 3, has been employed to study the effects of photo-illumination on GaN-based SDR diodes. Summarily, with the increase of either J\textsubscript{n} or J\textsubscript{p}, M\textsubscript{n} or M\textsubscript{p} is decreased, respectively. Hole dominated photo-current is produced in an illuminated FC structure, where the light is incident on the n\textsuperscript{++} substrate (Figure 2.10 (a)). Similarly electron-dominated photo-current is produced in an illuminated TM diode structure, where the light is incident on the p\textsuperscript{++} side (Figure 2.10 (b)). The boundary conditions of E(x) and P(x) for enhanced electron leakage current in the TM IMPATTs and enhanced hole leakage current in the FC IMPATTs are discussed in Chapter 3. It is shown in Chapter 3 that the hole or electron dominated photo-current increases with the increasing intensity of optical-radiation falling on the devices, which consequently reduce the values of M\textsubscript{p} or M\textsubscript{n} in the FC or TM IMPATTs, respectively.

Computer simulation of the DC and small-signal properties of un-illuminated GaN based p\textsuperscript{++} a n\textsuperscript{++} IMPATTs (both in the MM-wave and THz region), for which M\textsubscript{n} and M\textsubscript{p} are both large (~ 10^6), will be carried out first then the following two cases will be simulated:

1. Effects of illumination on TM diode whose junction is at the top and substrate is at the bottom, so that M\textsubscript{n} can have different values < 10^6 and M\textsubscript{p} = 10^6.
2. Effects of illumination on FC diode whose substrate is at the top and junction is at the bottom, so that M\textsubscript{p} can have different values < 10^6 and M\textsubscript{n} = 10^6.

\textit{Poisson's} equation, combined current continuity equations and space-charge equation have been simultaneously solved for the TM and FC diodes, subject to appropriate boundary conditions as given in Chapter 3. The present analysis takes into account of the mobile space-charge in the depletion region and involves double iteration over E\textsubscript{0} and x\textsubscript{0} for proper electric field and carrier current density corresponding to different values of M\textsubscript{n} or M\textsubscript{p}. The DC data thus obtained are fed as input for small-signal analysis of TM and FC IMPATTs. Following \textit{Gummel-Blue} approach [2.63] and using modified \textit{Runge-Kutta} method for numerical analysis, the small-signal properties of the diodes have been simulated for the above two illumination configurations. The iterative small-signal computer simulation method, described in Chapter 3, is adopted to obtain the effects of illumination on small-signal (i) admittance profile, (ii) negative resistivity profiles, (iii) device Q-factor and (iv) P\textsubscript{max} of the TM and FC diodes.
6.2 Simulation Studies of GaN-Based Flat-Type SDR IMPATTs in the MM-Wave and Terahertz Region

6.2.1 Modeling and Analysis of WZ-GaN Based Un-Illuminated Diodes at MM-Wave Frequency.

GaN and Si-based SDR IMPATTs have been simulated at around 140 GHz following the simulation methodology, outlined in previous section. GaN-IMPATT design parameters are shown in Table 6.2. In order to make a comparison, Si based IMPATT diode has been studied. The corresponding design parameters are also shown in the same table. The material parameters of Si and GaN, incorporated in the analysis, are shown in Table 6.1 and the related discussions are made in Sub-section, 6.1.1.

6.2.1.1 Small-signal properties of un-illuminated diode at 140 GHz (D-band) [6.33].

The DC and small-signal properties of GaN and Si based diodes are summarized in Table 6.3 and now will be discussed. Table 6.3 shows that the peak electric field \( (E_m) \) in GaN based diode is \( 3.25 \times 10^3 \) Vm\(^{-1} \), which is about 5 times higher than that \( (0.65 \times 10^3 \) Vm\(^{-1} \) in Si SDR. It is found that GaN based SDR diode breaks down at 102.0 V, which is 12.3 times higher than the Si SDR IMPATT in the D-band. The band gap energy, \( E_g \) in WZ-GaN is \( \sim 3 \) times higher than in Si. The high value of \( E_g \) in GaN decreases the tunneling current in this material compared to Si. Due to tunneling current in Si, ionization of charge carriers occurs over a wider range and this in turn increase the avalanche zone width, \( x_a \) and consequently avalanche zone voltage, \( V_A \). With the increase of \( x_a \) and \( V_A \), the values of \( x_d \) (drift region width) and \( V_D \) (drift zone voltage, \( V_D = V_B - V_A \) decrease. This is reflected in the values of normalized voltage drop, which is the ratio of \( V_D \) and \( V_B \), in Si and GaN IMPATTs, as seen from Table 6.3. It is very interesting to note that the normalized voltage drop in Si IMPATT is 18.84%, which is much lower than that in WZ-GaN based IMPATT (73.79%). Thus efficiency of GaN based devices enhances to 23.5% compared to its Si counterpart (6.0%). The electric field \( E(x) \), and normalized current density \( P(x) \) profiles of the GaN and Si IMPATT diodes are compared in Figure 6.1 and 6.2, respectively. \( P(x) \) profiles also indicate that \( x_a \) in Si-IMPATT is higher than that in WZ-GaN based IMPATT.

The admittance characteristics of the designed diodes are shown in Figure 6.3. It is observed that the negative conductance of GaN and Si IMPATTs are respectively, \( 43 \times 10^6 \) S.m\(^{-2} \) and \( 27 \times 10^6 \) S.m\(^{-2} \). The peak frequencies of the designed diodes are found to be very close to the design frequency of 140.0 GHz (Table 6.3). The higher value of breakdown voltage as well as negative conductance in GaN IMPATT, results in higher power density which is \( 5.6 \times 10^{10} \) Wm\(^{-2} \). On the other hand, Si SDR IMPATT is capable of generating a power density of \( 0.023 \times 10^{10} \) W.m\(^{-2} \), which is significantly lower than its GaN counterpart.
Negative resistance in the WZ-GaN-based device is found to be ~5 x 10^9 Ω m^2, higher than that (4.4 x 10^9 Ω m^2) in Si IMPATT in the D-band. The negative resistivity profiles of the diodes at peak-frequencies are shown in Figure 6.4. Like 4H-SiC SDR diodes, the R(x) profiles in GaN-SDR diodes are characterized by negative resistivity peak in the middle of the drift layer with negative resistivity minima near the metallurgical junction. It is observed that the magnitude of negative resistivity peak in GaN IMPATT is higher than that in its Si counterpart. The impedance profile of the WZ-GaN-IMPATT at 140 GHz is shown in Figure 6.5.

To the best of author’s knowledge no experimental results of GaN based IMPATTs are available in published literature. Only one theoretical work [1.11] by Panda et al., on GaN-IMPATT in the D-band is available. A comparison reveals that, although the breakdown voltage of the designed WZ-GaN based SDR is slightly lower than that was published by Panda et al., the diode designed by the author is much more efficient (23.5%) compared to the diode published earlier [1.11]. Moreover, compared to the diode designed by Panda et al. [1.11], the designed diode, reported here, may yield more power at 140 GHz window frequency. The earlier reported diode [1.11] is capable of delivering an output power density of 3.775x10^10 Wm^2, compared to 5.6x10^10 Wm^2 as predicted by the author. The better output power density can be explained on the basis of their negative resistance values. Simulation investigation by author reveals that the negative resistance in WZ-GaN-based p++ n n++ diode at 140 GHz is ~5x10^9 Ω m^2, but the value is only 10^9 Ω m^2 for the diode simulated by Panda et al. Thus, the present analysis definitely establishes the superiority of WZ-GaN based material systems over conventional Si, particularly in terms of power density and efficiency. It is evident that if GaN-based SDR IMPATT can be realized in practice, it will outperform Si IMPATT. Panda et al. also studied the performance of ZB-GaN based p' n n' IMPATT. They have shown that at 140 GHz, WZ-GaN based IMPATT is capable of delivering more power with better efficiency compared to its ZB-GaN counterpart (3.775x10^10 Wm^2 (η =12.5%) vs. 1.854x10^10 Wm^2 (η =11.4%)). On the basis of their simulation investigation, Panda et al. [1.11] have shown that the values of V_b and maximum electric field in WZ-GaN is also higher than in ZB-GaN based p' n n' SDR IMPATT. So, from their analysis the prospects of WZ-GaN for developing high-power IMPATT diodes are well established. This led the author to choose WZ-GaN to design high-power MM-wave IMPATT. Also the above comparison reveals that the diode simulated by the author is expected to perform better than the diode simulated by Panda et al. at 140 GHz.
### Table 6.2
Design data of Si and GaN based SDR IMPATTs at D-band

<table>
<thead>
<tr>
<th>Type of the diode</th>
<th>Si SDR (Flat profile)</th>
<th>GaN SDR (Flat profile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low epilayer doping conc. (n) (10^{22} \text{m}^{-3})</td>
<td>18.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Low epilayer (n) width ((\mu\text{m}))</td>
<td>0.25</td>
<td>0.45</td>
</tr>
<tr>
<td>Current density (10^8 \text{Am}^{-2})</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

### Table 6.3
DC and Small-Signal properties of Si and GaN based SDR IMPATTs at D-band

<table>
<thead>
<tr>
<th>Diode parameters</th>
<th>Si (SDR)</th>
<th>GaN (SDR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_m (10^8 \text{Vm}^{-1}))</td>
<td>0.65</td>
<td>3.25</td>
</tr>
<tr>
<td>(V_a (V))</td>
<td>8.3</td>
<td>102.0</td>
</tr>
<tr>
<td>(V_c/V_a (%))</td>
<td>18.84</td>
<td>73.79</td>
</tr>
<tr>
<td>(\eta (%))</td>
<td>6.00</td>
<td>23.50</td>
</tr>
<tr>
<td>(f_s (GHz))</td>
<td>55.00</td>
<td>48.00</td>
</tr>
<tr>
<td>(f_p (GHz))</td>
<td>143.0</td>
<td>145.00</td>
</tr>
<tr>
<td>(-G_p (10^6 \Omega \text{m}^{-2}))</td>
<td>27.0</td>
<td>43.00</td>
</tr>
<tr>
<td>(-Q_p)</td>
<td>2.70</td>
<td>1.90</td>
</tr>
<tr>
<td>(-Z_{ap} (10^3 \Omega \text{m}^{-2}))</td>
<td>4.4</td>
<td>5.04</td>
</tr>
<tr>
<td>(P_{HF} (10^{10} \text{Wm}^{-2}))</td>
<td>0.023</td>
<td>5.6</td>
</tr>
</tbody>
</table>
CHAPTER 6: III-V NITRIDE BASED MM-WAVE & THz IMPATTs

Figure 6.1: Electric field profiles of Si and GaN IMPATTs at D-band.

Figure 6.2: Normalised current density profiles of Si and GaN based SDR IMPATT diodes at D-band.
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Figure 6.3: Admittance plots of (a) Si and (b) GaN SDR IMPATT diodes at D-band.

Figure 6.4: Negative resistivity plots of (a) GaN and (b) Si SDR IMPATT diodes at D-band.
Current density = $4 \times 10^5 \text{Am}^{-2}$

$n$-epilayer thickness = 450 nm

Figure 6.5: Impedance plot of $W_z$-GaN based SDR IMPATT at D-band.
6.2.2 Modeling and Analysis of WZ-GaN Based Un-illuminated Diodes at THz-Frequencies.

In the earlier sub-section, it is established that GaN is a potential candidate for replacing Si in fabricating high-power IMPATTs. The superior material properties of GaN, especially the higher values of \(E_c\) and \(v_{\text{smax}}\), are very much conducive for choosing it as a semiconductor material for fabrication of potential THz IMPATT devices. This possibility has been studied through a simulation technique as described in Chapter 3 and also briefly stated earlier in this Chapter. Electric field and temperature dependent ionization rate, mobility and saturated velocities of charge carriers (Table 6.1) in WZ-GaN are incorporated in the analysis. The author has studied the performance of WZ-GaN based diodes first at 0.5 THz and then at much higher frequency, ~ 1.40 THz. The design data of the diodes at 0.5 THz and at around 1.4 THz are shown in Table 6.4.

6.2.2.1 Small-signal properties of un-illuminated diode at 0.5 THz.

The DC and small-signal properties of the designed diode at 0.5 THz is shown in Table 6.5. The \(E(x)\) and \(P(x)\) profiles of the diode are shown in Figures 6.6 and 6.7. The efficiency of GaN based device is found to be 20.0% at 0.505 THz. It is interesting to note that at such a high-frequency region, GaN IMPATT can deliver a power density of \(17.66 \times 10^{10}\) W.m\(^{-2}\). However, the presence of parasitic resistance may degrade the performance of the THz device. The author has estimated the value of \(R_s\) (without ohmic contact resistance) through a simulation technique as described earlier. The estimated value of \(R_s\) is shown in Table 6.6. It is found that the value of \(R_s\) is \(1.7 \times 10^{11}\) \(\Omega\) m\(^2\). In order to realistically estimate the value of series resistance, the author has further considered the effects of ohmic contact resistance in this analysis. In order to realize appreciable power from an IMPATT device at THz region, one should achieve low specific contact resistance since at THz region; intrinsic diode negative resistance is usually very small. It is discussed earlier that ohmic contact resistance for n-type GaN is ~ \(10^{12}\) \(\Omega\) m\(^2\) [6.7]. But, for p-GaN, ohmic resistance of \(4.5 \times 10^{10}\) \(\Omega\) m\(^2\) has been experimentally obtained, till now [6.8]. So, the total positive resistance (\(R_{\text{S,total}}\)) becomes \(46.8 \times 10^{11}\) \(\Omega\) m\(^2\). It is interesting to note that this value is still much lower than the device negative resistance (Table 6.6), which is an essential criterion to ensure good device performance. The effect of \(R_{\text{S,total}}\) on \(|-G_{p}|\) is shown in Figure 6.8. Due to the presence of \(R_{\text{S,total}}\), \(|-G_{p}|\) reduces by ~20.0%. The impedance plot of the diode is shown in Figure 6.9. The nature of the impedance profile is same as that was obtained for SiC IMPATTs in the THz-region. From Figure 6.9 it is observed that at a particular frequency \(|-Z_{x}| < |-Z_{x}|\), as expected from the basic IMPATT theory. Thus the above study reflects that GaN IMPATT is a potential candidate for THz operation. The spatial
distribution of high frequency negative resistivity $R(x)$ in the depletion region of the designed diode is shown in Figure 6.10. The $R(x)$ profile is characterized by one peak ($R_{\text{max}}$) in the middle of the drift layer and a minimum ($R_{\text{min}}$) near the metallurgical junction. It is found that $R_{\text{min}}$ has appreciable negative value.

<table>
<thead>
<tr>
<th>Table 6.4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design data of GaN based flat profile SDR IMPATT diodes in the THz Region</strong></td>
</tr>
<tr>
<td>4H-SiC DDR IMPATT Diode</td>
</tr>
<tr>
<td>Design frequency = 0.5 THz</td>
</tr>
<tr>
<td>Design frequency = 1.40 THz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DC and Small-Signal properties of GaN SDR IMPATTs in the THz region</strong></td>
</tr>
<tr>
<td>DDR diode type</td>
</tr>
<tr>
<td>Peak electric field $(E_m) (10^8 \text{ Vm}^{-1})$</td>
</tr>
<tr>
<td>Breakdown voltage $(V_B) (\text{V})$</td>
</tr>
<tr>
<td>Avalanche layer voltage $(V_A) (\text{V})$</td>
</tr>
<tr>
<td>$V_A/V_B$</td>
</tr>
<tr>
<td>Efficiency (in %)</td>
</tr>
<tr>
<td>Peak negative conductance $(-G_P) (10^8 \text{ Sm}^{-2})$</td>
</tr>
<tr>
<td>Diode negative resistance at peak frequency $(-Z_{RP}) (10^{-11} \Omega \text{ m}^2)$</td>
</tr>
<tr>
<td>Output power density $(R_S = 0.00)(10^{10} \text{ Wm}^{-2})$</td>
</tr>
<tr>
<td>Output power density $(R_S = R_{S,\text{total}})(10^{10} \text{ Wm}^{-2})$</td>
</tr>
<tr>
<td>Quality factor $(-Q_p)$</td>
</tr>
<tr>
<td>Avalanche frequency $(f_A) (\text{THz})$</td>
</tr>
<tr>
<td>Peak operating frequency $(f_p) (\text{THz})$</td>
</tr>
</tbody>
</table>
### Table 6.6.
Values of series resistance ($R_s$) and load conductance ($G_L$) at oscillation threshold (resonance) of GaN SDR IMPATT.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Diode conductance ($-G \times 10^8$) (Sm$^{-2}$)</th>
<th>Diode Susceptance ($B \times 10^8$) (Sm$^{-2}$)</th>
<th>$-Z_R$ ($10^{-11}$ $\Omega$m$^2$)</th>
<th>$R_s$ ($10^{-11}$ $\Omega$m$^2$)</th>
<th>$R_s$, total ($10^{-11}$ $\Omega$m$^2$)</th>
<th>Expected load conductance ($G_L \times 10^8$) (Sm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat SDR at 0.5 THz</td>
<td>7.25</td>
<td>4.2</td>
<td>103.27</td>
<td>1.70</td>
<td>46.8</td>
<td>7.22</td>
</tr>
<tr>
<td>Flat SDR at 1.11 THz</td>
<td>19.00</td>
<td>58.00</td>
<td>5.10</td>
<td>2.82</td>
<td>3.92</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Figure 6.6: Electric field profile of GaN flat profile SDR IMPATT at 0.5 THz.
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7.5

6.0

5.5

5.0

4.5

4.0

3.5

3.0

2.5

2.0

1.5

1.0

Frequency (f) (THz)

WZ-GaN SDR IMPATT at 0.5 Terahertz

Conductance (G) (10^6 Sm^-1)

a: R_s=0.0Ω

b: R_\text{equiv}=4.68 \times 10^{-10} \, \Omega \, m^2

Figure 6.8 Effect of series resistance of negative conductance of GaN SDR IMPATT diode at 0.5 THz.

Figure 6.7: Normalised current density profile of GaN SDR IMPATT diode at 0.5 THz.

Figure 6.8 E f f e c t o f s e r i e s r e s i s t a n c e o f n e g a t i v e c o n d u c t a n c e o f G a N S D R I M P A T T d i o d e a t 0 . 5 T H z .

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Figure 6.9: Impedance plot of GaN SDR IMPATT diode at 0.5 THz.

Figure 6.10: Negative resistivity profile of GaN SDR IMPATT diode at 0.5 THz.
6.2.2.2 Small-signal properties of un-illuminated diode at 1.4 THz [6.34].

The encouraging performance of GaN at 0.5 THz region, prompted the author to study the prospects of this device at much higher THz frequency (~ 1.4 THz). The design data is shown in Table 6.4. For the first time, the performances of GaN-based THz diode at > 1.0 THz region are studied and will be described in detail now. The DC and small-signal results of the THz IMPATT device are shown in Table 6.5. It is found that the designed diode has an efficiency of 17.0%. This efficiency is calculated from the semi-quantitative formula, given in Chapter 3. The electric field profile and normalized current density profile of the diode are shown in Figures 6.11 and 6.12. It is found that at the higher THz regime, negative resistance of the device falls quite sharply. It is depicted from Table 6.5 that the magnitude of $-Z_{dp}$ is only $3.0 \times 10^{11} \, \Omega \cdot m^2$ at 1.4170 THz. The admittance characteristic of the device is shown in Figure 6.13. The higher value of negative conductance ($74.21 \times 10^8 \, S \cdot m^{-2}$) and breakdown voltage (22.7 V) enhances the output power level from the device. It is depicted from Table 6.5 that $P_{\text{max}}$ from the device is $47.8 \times 10^{-10} \, W \cdot m^{-2}$.

The effects of parasitic series resistance becomes much serious in the THz region, since for such a high-frequency application (~1.4 THz), negative resistance of the device decreases significantly. Thus the author has included the effect of $R_s$, while calculating the value of $P_{\text{max}}$. The small-signal values of negative conductance, susceptance ($B$) and expected values of load conductance ($G_L$), at low power oscillation threshold are reported in Table 6.6. The value of $R_s$ (barring the contribution of ohmic contact resistance) is found to be $2.82 \times 10^{11} \, \Omega \cdot m^2$, for GaN IMPATT at 1.11 THz. Ohmic contact resistance may put a severe restriction on the high frequency (THz level) performance of the WBG IMPATTs and thus the presence of contact resistances have been included in the realistic estimation of $R_{s,\text{total}}$. For n-type GaN, ohmic contact resistance of $10^{12} \, \Omega \cdot m^2$ [6.7] is taken into account. However, for p-GaN, because of the difficulty in achieving high carrier density and the absence of suitable metals with high work function a high quality ohmic contact with very low contact resistivity ($< 10^{11} \, \Omega \cdot m^2$) has still not been achieved. Till now, contact resistance of $4.5 \times 10^{10} \, \Omega \cdot m^2$ for p-GaN has been achieved experimentally [6.8]. But, in order to get sustained oscillation, p-GaN contact resistance should be decreased to ~ $10^{11} \, \Omega \cdot m^2$, since $-Z_{dl}$ reduces significantly. Increasing the carrier concentration, a desired p-type contact resistance ~ $10^{11} \, \Omega \cdot m^2$ may be achieved in reality. Measurement of such a low-contact resistance may be possible with Transmission Line Measurement (TLM) technology. The effect of $R_{s,\text{total}}$ on $-G$ and $P_{\text{max}}$ are shown in Figures 6.14 and 6.15, respectively. It is observed that due to the presence of $R_s$ ($2.82 \times 10^{11} \, \Omega \cdot m^2$), the values of $-G_p$ as well as $P_{\text{max}}$ of the flat profile diode reduces approximately by 25%. However, due to the presence of total parasitic resistance ($R_{s,\text{total}} = 3.92 \times 10^{11} \, \Omega \cdot m^2$), $-G_p$ as well as $P_{\text{max}}$ are reduced by ~ 35% (Figures 6.14 and 6.15). It is interesting to note that even in the presence of aforesaid $R_{s,\text{total}}$, considerably
high power density of 31.07 $\times 10^{10}$ W.m$^{-2}$ may be obtained from the designed THz device. It is further interesting to observe that the value of $R_{\text{total}}$ is still lower than the negative resistance of the device (Table 6.6) and this supports the possibilities of device oscillation in the THz region.

For the practical realization of THz IMPATT, self-heating of the device is a major problem that should be considered. For THz operation, the devices are operated at a large current density. It is found from the present simulation experiment, that at least 31.07 $\times 10^{10}$ W.m$^{-2}$ power density may be achieved from the THz diodes. Since the conversion efficiency of the device is only 17%, a major fraction of power is dissipated as heat raising the temperature of the device. As a result the junction temperature of the device increases over the ambient (300K). The junction temperature ($T_j$) may be estimated from the following equation [6.34], as described in Chapter 3:

$$T_j (°C) = 25 + R_{\text{th}} (1 - \eta) V_{\text{DC}} J_{\text{DC}} A$$  (6.22)

where, $V_{\text{DC}}$ is DC bias voltage (assumed as DC breakdown voltage, $V_B$ in the present analysis), $R_{\text{th}}$ is the total thermal resistance of the device and the heat sink. The size, shape and thermal conductivity of the diode and metal heat sink determine the value of $R_{\text{th}} (°C/W)$. Assuming the diode (diameter 8.0 μm) with contact metallization is mounted on a semi-infinite diamond heat sink of radius 4-5 times than the diode, $R_{\text{th}}$ may be approximately determined from the abovementioned formula. Putting the approximate value of $R_{\text{th}}$ in the above equation, it is estimated that the junction temperature varies within 500K to 600K. Moreover, it can be mentioned that the safe operating temperature for Si IMPATT device is 573K. The corresponding value of thermal-conductivity for GaN (225 W.m$^{-1}$K$^{-1}$) is higher than that of Si (150 W.m$^{-1}$K$^{-1}$) (Table 1.1). Hence, GaN-IMPATT devices are most unlikely to suffer thermal runaway even these are operated at a higher temperature [6.34]. The best way to resolve the self-heating problem is to operate the device under pulsed mode conditions with a small duty cycle so that the device does not heat up and degrade in performance.

The variations of impedance with frequency of the WZ- and ZB-GaN THz diodes are shown in Figure 6.16(a-b). Figure 6.16 (b) will be discussed in the next Sub-section. Figure 6.16 (a) shows that the THz-device posses negative resistance for all frequencies above the avalanche frequency ($f_a$), where its reactance is capacitive. This is due to the fact that, in the oscillating frequency range, the magnitude of $-Z_R$ is found to be small compared to $-Z_X$. This is also evident from Figure 6.16(a), that the values of $|Z_R|$ and $|Z_X|$ decrease as the operating frequency increases. The impedance level of the THz device can further be increased in a Double Drift region (DDR) device. Figure 6.17 show the R(x) profile at the peak frequency of the THz diode. Negative resistivity profile gives physical insight into the region of the depletion layer that contributes to output power. This figure shows that the profile exhibits negative resistivity peak in the middle of the drift layer with dip in the avalanche layer close to the junction. The
nature of the graph is found to be similar at all the designed frequencies: 140 GHz, 0.5 THz and 1.45 THz, however, the dissimilarity exists in the magnitudes of the peaks and their locations in the drift layers.

The above analysis thus establishes the potential of GaN IMPATT devices at higher THz region (> 1.0 THz) also.

Figure 6.11: Plots of electric field profile for (a) WZ phase and (b) ZB phase GaN (flat-profile) SDR IMPATT diodes in the THz region. The distance of the n-side from the metallurgical junction has been shown as negative.
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Figure 6.12: Normalized current density $P(x)$ profiles of (a) WZ-GaN and (b) ZB-GaN based SDR IMPATT diodes in the Terahertz region. The distance of the n-side from the metallurgical junction has been shown as negative.

Figure 6.13: Conductance (G) - Susceptance (B) plots of (a) WZ-GaN and (b) ZB GaN based IMPATT diodes in the Terahertz region.
Figure 6.14: Effect of series resistance on the negative conductance of un-illuminated WZ-GaN (flat type) SDR IMPATT diode.

- a: Flat Profile IMPATT ($R_s = 0.0 \Omega$)
- b: Flat Profile IMPATT ($R_s = 2.82 \times 10^{12} \, \Omega \cdot \text{cm}^2$)
- c: Flat Profile IMPATT ($R_{ss0} = 3.92 \times 10^{13} \, \Omega \cdot \text{cm}^2$)
Figure 6.15: Effect of series resistance on $P_{\text{max}}$ of un-illuminated WZ-GaN (flat-type) SDR IMPATT diode.

- a: Flat Profile IMPATT ($R_s = 0.0 \, \Omega$)
- b: Flat Profile IMPATT ($R_s = 2.82 \times 10^{10} \, \Omega \text{cm}^2$)
- c: Flat Profile IMPATT ($R_{\text{sum}} = 3.92 \times 10^{11} \, \Omega \text{cm}^2$)
Figure 6.16(a): Diode impedance vs. frequency plots of WZ-GaN flat profile SDR THz IMPATT diode.

WZ GaN flat profile SDR IMPATT diode
(Current density = 3.52 x 10^5 Am^-1)
Figure 6.16 (b): Diode impedance vs. frequency plot of ZB-GaN flat profile SDR THz IMPATT diode.

ZB-GaN flat profile SDR IMPATT diode
(Current density = 4.5 x 10^6 Am⁻²)

Figure 6.16 (b): Diode impedance vs. frequency plot of ZB-GaN flat profile SDR THz IMPATT diode.
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Figure 6.17: Negative resistivity profiles of (a) WZ-GaN and (b) ZB-GaN based flat profile SDR IMPATT diodes in the Terahertz region.

6.2.3 MODELING AND ANALYSIS OF ZB-GaN BASED UN-ILLUMINATED DIODE AT THz-FREQUENCY [6.35].

The prospects of WZ-GaN based SDR IMPATT diodes in the MM-wave and THz frequency region are thoroughly studied and the results are presented in the last two sub-sections of this Chapter. It is also shown that the overall performance of WZ-GaN IMPATT is better than their ZB-GaN counter in the MM-wave region. Meng et al. [2.186] studied the performances of MM-wave ZB-GaN based Read diode at 300 GHz. They have obtained an efficiency of ~10% and an RF power density of ~ 0.5x10^13 W.m^2 from their designed diode. In the Terahertz-frequency region (> 300 GHz), no reports are available on the modeling and analysis of ZB-GaN. Thus to make a comparison with WZ-GaN IMPATTs at around 1.4 THz, the author has designed and studied the performances of the ZB-GaN IMPATT in the Terahertz region and the results will be discussed in this sub-section. The device is designed following an IMPATT mode DC and small-signal scheme, as described earlier in Chapter 3. The maximum power generated from the devices is also estimated from the simulation analysis incorporating the effects of
parasitic positive series resistances. The optimized background doping concentration of the diode is taken as: $2.5 \times 10^{24}$ m$^3$, similar with WZ-GaN IMPATT. The depletion layer width of the device is taken as 70 nm and the bias current density is $4.5 \times 10^9$ A.m$^2$. The material parameters of ZB-GaN in the temperature range $300 K < T < 600 K$ is discussed in Section 6.1.

The $E(x)$ and $P(x)$ profiles of the diode are shown in Figure 6.11 and Figure 6.12, respectively. In the same Figures, $E(x)$ and $P(x)$ profiles of WZ-GaN IMPATT are also shown in order to make a comparison. It is found that field maximum in case of ZB-GaN IMPATT is $3.5 \times 10^6$ V.m$^{-1}$, which is almost 12.5% less than that of WZ-GaN IMPATT. $P(x)$ profiles reveal that avalanche zone in WZ-GaN based diode is more localized compared to its ZB-GaN counterpart. This in turn increases the avalanche layer voltage in ZB-GaN IMPATT and thereby reduces the efficiency. The study reveals that ZB-GaN diode is only 5% efficient, whereas the efficiency is significantly high (17%) in case of WZ-GaN IMPATT. Breakdown voltages in both the diodes are found to be almost same (22.7 V (WZ-GaN IMPATT) vs. 21.0 V (ZB-GaN IMPATT)). The author has further studied the high-frequency characteristics of the ZB-GaN diode. The admittance plot of the device is shown in Figure 6.13. Compared to admittance characteristics of the WZ-GaN IMPATT, as shown in Figure 6.13, admittance plots of ZB-GaN IMPATT are less favorable for generating high-power from the devices. The magnitude of negative conductance in case of ZB-GaN is $41.5 \times 10^8$ S.m$^{-2}$, which is $-44\%$ less than the value of $|\text{-}G_p|$ in WZ-GaN IMPATT. The estimated power density from ZB-GaN IMPATT is found to be $22.8 \times 10^{10}$ Wm$^{-2}$ at 2.3 THz, whereas WZ-GaN is capable of delivering a power density of $31.07 \times 10^{10}$ Wm$^{-2}$ at 1.4170 THz. It is interesting to observe that positive series resistance, without considering contact resistances, in ZB-GaN diode is only $1.24 \times 10^{-2}$ Q m$^{-2}$, which is almost 2.3 times smaller than that in WZ-GaN. The impedance plot of ZB-GaN IMPATT is shown in Figure 6.16 (b). It is evident from the graph that above the avalanche frequency both the diode resistance ($Z_R$) and the reactance ($Z_X$) are negative and also $|\text{-}Z_R| < |\text{-}Z_X|$ within the oscillating frequency range, these are the essential criterion for sustained oscillation. The author has compared the $R(x)$ profiles of both types of GaN diodes at THz-frequency. $R(x)$ profiles, as shown in Figure 6.17, reveal that the nature of the profiles are same, however, the magnitude of negative resistivity peak, $R_{n, max}$ in the middle of the n-drift region in ZB-GaN IMPATT is $7 \times 10^4$ Q m, which is quite lower than the magnitude of $R_{n, max}$ ($10.2 \times 10^4$ Q m) in WZ-GaN based diode.

These comparative analyses establish that although WZ-GaN based IMPATT can deliver high power density with better efficiency compared to its ZB-GaN counterpart, positive series resistance in ZB-GaN IMPATT is much lower than in WZ-GaN IMPATT operating in the Terahertz region.
6.3 Simulation Studies of GaN-Based Lo-Hi-Lo SDR IMPATT in the Terahertz Region [6.34].

Computer studies on the prospects of III-V Nitride based flat profile SDR IMPATT diodes in the MM-wave and THz region are presented in the previous section. The results indicate that GaN is an ideal semiconductor material for IMPATT device development, both in the MM-wave and THz region. It is discussed in details in Chapter 2 of this dissertation that the efficiency and power density of the IMPATT diodes can be greatly improved through the suitable modification of the doping profile by introducing a charge bump selectively in the flat-doped region of the diodes. The superiority of these ‘quasi-Read’ type SLHL IMPATT diodes and their fabrication techniques have been reviewed in Chapter 2. SLHL SDR IMPATT’s, available in the literature, are mostly concerned with Si and GaAs as base semiconductor materials. For the first time, the author has studied the performances of SiC-based SLHL diodes in the MM-wave and THz-region and these are discussed in detail in Chapter 4 and Chapter 5. It is observed that the overall performances of SiC-based SLHL diodes are much better than their flat-profile counterpart. This leads the author to study the characteristics of the SLHL IMPATT device based or GaN.

The doping densities in the different regions of the SLHL diode are shown in Section 6.1. The bump width $\delta_n$, bump doping, and the location of the bump are adjusted to obtain appropriate punch-through factor (PTF) corresponding to maximum efficiency. The background doping concentration, epilayer width, substrate doping, bump width, bump doping, bias current density of the SLHL diode are shown in Table 6.7. The accurate computer method, as described in Chapter 3, and briefly discussed in Section 6.1, has been adopted for studying DC and small-signal properties of the GaN based SLHL IMPATT. At first, the device is analyzed under static conditions by the simultaneous solution of the Poisson's equation, current continuity equations, and the space-charge equation, subject to boundary conditions, through the use of a double-iterative computer method, as described in Chapter 3. The $E(x)$ and $P(x)$ profiles, $E_m$, $V_B$, $\eta$ of the 'quasi-Read' diode are obtained from the DC analysis. Another iterative computer program that simultaneously solves two second order implicit differential equations or diode resistivity $R(x)$ and reactivity $X(x)$ is adopted from small-signal analysis of the SLHL IMPATT diode. The numerical method is described in Chapter 3 and briefly stated in Section 6.1 of this Chapter. The analysis gives the avalanche frequency, optimum frequency, admittance characteristics, spatial variation of negative resistivity, power density, negative resistance and quality factor of the 'quasi-Read' (SLHL) GaN device.
6.3.1 Results and Discussions [6.341].

DC and small-signal characteristics of the SLHL diode are shown in Table 6.8. To make a comparison with its flat profile counterpart, the corresponding results of flat type SDR IMPATT diode are re-written in the same table. The electric field profile \( E(x) \), normalized current density profiles \( P(x) \) of the SLHL diode are shown in Figures 6.18 and 6.19. In order to compare the profiles of SLHL diode with those of flat profile diode, the corresponding \( E(x) \) and \( P(x) \) profiles of the flat type SDR diode are re-drawn in Figures 6.18 and 6.19, respectively. It is observed from Figure 6.18, that the electric field falls much more rapidly within the highly doped n-region for the low-high-low GaN SDR diode as compared to that of the GaN flat SDR diode. The space-charge effect has been reduced due to the incorporation of the charge-spike (high bump) in the n-region of the flat-doped SDR structure. This in turn localizes the avalanche region in SLHL diode. Localization of the avalanche region decreases the avalanche layer voltage, provides higher drift layer voltage, and thereby increases the device efficiency. Figure 6.19 compares the normalized current density profiles of the simulated GaN SDR diodes. The profiles indicate that the avalanche region in the SLHL diode is more localized compared to its flat-profile counterpart, which in turn, provides a high value of drift region voltage drop \( V_D \) in SLHL diode. It is interesting to note that the normalized voltage drop is 53.7% in flat profile diode, while it is more (63%) in SLHL diode (Table 6.8). The increased value of \( V_D/V_B \) ratio in the SLHL diode provides higher efficiency than the flat-profile SDR IMPATT. This is also evident from Table 6.8, where it is depicted that the device conversion efficiency \( (\eta) \) is higher (20.0%) in SLHL structure compared to that of the flat profile diode (17.0%).

The admittance characteristic of the SLHL diode is shown in Figure 6.20. The corresponding admittance characteristic of the flat-profile diode is redrawn in the same figure in order to make a comparison. It is also found that the value of \( | -G_R \) for the SLHL structure \( (84.15 \times 10^8 \text{ Sm}^{-2}) \) is higher compared to that of the flat profile variety \( (74.21 \times 10^8 \text{ Sm}^{-2}) \). Consequently, the value of \( P_{\text{max}} \) of the SLHL device is found to be \( 62.62 \times 10^{10} \text{ Wm}^{-2} \), which is 31% higher than that of \( P_{\text{max}} \) of the flat-profile counterpart. The high-frequency performance of the SLHL device is expected to be better since the quality factor of the SLHL diode \( (-Q_B = 1.7) \) is found to be less than that of the flat profile device \( (-Q_B = 1.9) \). Thus the SLHL SDR diode evidently establishes its superiority over flat profile SDR device in terms of \( P_{\text{max}} \), efficiency and Q factor at around 1.4 THz frequency. These observations have a trend agreement with the earlier results of Si and GaAs based SLHL diodes [2.88-2.92].

The presence of parasitic series resistance \( R_s \) seriously degrades the power density. Thus the value of \( R_s \) in case of the quasi-Read SLHL diode is calculated and it is included while estimating realistically the maximum power density. Table 6.9 shows the value of \( R_s \) (excluding the contribution of
the ohmic contact resistance) of the THz SLHL IMPATT, calculated through a simulation technique, described earlier. The small-signal values of \(|-G|\), \(B\) and the expected value of \(G_L\) at the threshold (resonance) condition are also shown in Table 6.9. The value of \(R_s\) for SLHL diode is found to be \(2.21 \times 10^{11} \text{ \(\Omega\) m}^2\). It is evident that, due to the incorporation of charge bump in flatly doped device, the value of \(R_s\) reduces by 22\% (comparing Table 6.6 and Table 6.9). This again proves the advantage of using SLHL diode in the THz region. Furthermore, the author has incorporated the values of contact resistance in realistic estimation of series resistance. The p-type and n-type contact resistances in GaN are briefly described in Sub-section 6.2.2.2. A p-type contact resistance of \(\sim 10^{11} \text{ \(\Omega\) m}^2\) and an n-type contact resistance \(\sim 10^{12} \text{ \(\Omega\) m}^2\) have been taken in this analysis. Considering the contact resistance, total parasitic series resistance in case of SLHL IMPATT becomes \(3.31 \times 10^{11} \text{ \(\Omega\) m}^2\). The effect of series resistance on \(-G_p\) and \(P_{\text{max}}\) of the SLHL IMPATT are shown in Figures 6.21 and 6.22, respectively. It is observed that due to the presence of \(R_s\) \((2.21 \times 10^{11} \text{ \(\Omega\) m}^2)\), the values of \(-G_p\) as well as \(P_{\text{max}}\) of the SLHL diode reduces by \(\sim 22\%\). However, due to the presence of \(R_{s,\text{total}}\), \(-G_p\) as well as \(P_{\text{max}}\) are reduced by \(\sim 30\%\) for the SLHL diode. It is interesting to note that even in the presence of aforesaid \(R_{s,\text{total}}\), a considerably high power density of \(42.58 \times 10^{10} \text{ \(W\) m}^2\) may be obtained from the simulated 'quasi-Read' THz device.

The self-heating problem in case of high-frequency operation of the SLHL IMPATT may be solved by properly designing a heat-sink. The estimation of thermal resistance is shown in Sub-section 6.2.2.2. Compared to CW operation, pulsed mode operation of the high-power, high-frequency SLHL device is preferable to overcome the serious self-heating and consequently burn-out problems.

The plot of variation of impedance of the SLHL diode with frequency is shown in Figure 6.23. The graph shows that the device possesses negative resistance for all frequencies above the avalanche frequency \(f_a\), where its reactance is capacitive. This is because, in the oscillating frequency range, the magnitude of \(Z_R\) is found to be small compared to \(Z_X\). The values of \(|-Z_R|\) and \(|-Z_X|\) decrease as the operating frequency increases. Moreover, the impedance of the SLHL diode is found to be higher than that is in flat-profile diode. These results and consequent discussions definitely establish that the overall performance of SLHL diode is much better than that of flat profile GaN based SDR IMPATT at around 1.4 THz frequency.
### Table 6.7

<table>
<thead>
<tr>
<th>Diode Structure</th>
<th>Low epilayer doping conc. (N_1) (\times 10^{24}\ \text{m}^{-3})</th>
<th>High epilayer doping conc. (N_2) (\times 10^{24}\ \text{m}^{-3})</th>
<th>Width of low epilayer (W_1) (nm)</th>
<th>Width of high epilayer bump (W_2-W_1) (nm)</th>
<th>Position of the bump (charge spike) from metallurgical junction (W_j) (nm)</th>
<th>Current density (\times 10^5\ \text{A m}^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLHL</td>
<td>2.0</td>
<td>7.5</td>
<td>75.0</td>
<td>5.0</td>
<td>50.0</td>
<td>3.52</td>
</tr>
</tbody>
</table>

### Table 6.8

<table>
<thead>
<tr>
<th>DDR diode type</th>
<th>GaN flat-profile SDR designed at 1.4 THz frequency</th>
<th>GaN SLHL SDR designed at 1.4 THz frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak electric field (E_m) (\times 10^3\ \text{V m}^{-1})</td>
<td>4.0</td>
<td>4.17</td>
</tr>
<tr>
<td>Breakdown voltage (V_d) (V)</td>
<td>22.7</td>
<td>24.4</td>
</tr>
<tr>
<td>Avalanche layer voltage (V_A) (V)</td>
<td>10.5</td>
<td>9.0</td>
</tr>
<tr>
<td>(V_d/V_A)</td>
<td>0.537</td>
<td>0.63</td>
</tr>
<tr>
<td>Efficiency (in %)</td>
<td>17.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Peak negative conductance (-G_p) (\times 10^8\ \text{Sm}^{-2})</td>
<td>74.21</td>
<td>84.15</td>
</tr>
<tr>
<td>Diode negative resistance at peak frequency (-Z_{up}) (\times 10^{11}\ \Omega\ \text{m}^2)</td>
<td>3.0</td>
<td>3.10</td>
</tr>
<tr>
<td>Maximum output power density (R_g=0.00) (\times 10^{12}\ \text{W m}^{-2})</td>
<td>47.8</td>
<td>62.62</td>
</tr>
<tr>
<td>Maximum output power density (R_g=R_{\text{total}}) (\times 10^{13}\ \text{W m}^{-2})</td>
<td>31.07</td>
<td>42.58</td>
</tr>
<tr>
<td>Quality factor (-Q_o)</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Avalanche frequency (f_a) (THz)</td>
<td>1.0</td>
<td>1.02</td>
</tr>
<tr>
<td>Peak operating frequency (THz)</td>
<td>1.4170</td>
<td>1.434</td>
</tr>
</tbody>
</table>
Table 6.9.
Values of series resistance ($R_s$) and load conductance ($G_L$) at oscillation threshold (resonance) of GaN SDR SLHL IMPATT [frequency = 1.11 THz].

<table>
<thead>
<tr>
<th>Structure</th>
<th>Diode conductance ($-G \times 10^8$) (Sm$^{-2}$)</th>
<th>Diode Susceptance ($B \times 10^9$) (Sm$^{-2}$)</th>
<th>$-Z_a$ ($10^{11}$ Om$^{-1}$)</th>
<th>$R_s$ ($10^{11}$ Om$^{-1}$)</th>
<th>$R_{s,\text{total}}$ ($10^{11}$ Om$^{-1}$)</th>
<th>Expected load conductance ($G_L \times 10^8$) (Sm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLHL SDR</td>
<td>21.00</td>
<td>52.1</td>
<td>6.65</td>
<td>2.21</td>
<td>3.31</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Figure 6.18: Plots of electric field profiles for (a) flat profile and (b) SLHL type GaN SDR IMPATT diodes. The distance of the n-side from the metallurgical junction has been shown as negative.
Figure 6.19: Normalised current density $P(x)$ profiles of WZ-GaN SDR IMPATT diode at THz region (a) Flat profile IMPATT, (b) SLHL IMPATT diode. The distance of the n-side from the metallurgical junction has been shown as negative.

Figure 6.20: Conductance ($G$) – Susceptance ($B$) plots of GaN (a) SLHL and (b) flat type SDR THz IMPATT diodes.
Figure 6.21: Effect of series resistance on the negative conductance of WZ-GaN (SLHL type) SDR IMPATT diode.

- a: SLHL IMPATT ($R_s = 0.0 \Omega$)
- b: SLHL IMPATT ($R_s = 2.21 \times 10^{12} \Omega \text{cm}^2$)
- c: SLHL IMPATT ($R_{total} = 3.31 \times 10^{12} \Omega \text{cm}^2$)

Figure 6.21: Effect of series resistance on the negative conductance of WZ-GaN (SLHL type) SDR IMPATT diode.
Figure 6.22: Effect of series resistance on $P_{\text{max}}$ of WZ-GaN (SLHL) SDR IMPATT diode in the Terahertz region.
6.4 Effects of Photo-Illumination on the Small-Signal Characteristics of GaN-Based SDR IMPATTs in the MM-Wave and THz-Region [6.36][6.34].

In the previous two sections (6.2 & 6.3), the author has established that un-illuminated GaN-IMPATT has great potential to generate high-power at MM-wave and THz-frequencies. Moreover, the author has established that like 4H-SiC SLHL IMPATT, GaN-based SLHL diode performs much better than their flat-profile counterpart. It is discussed in Chapter 2 and Section 6.1 of this Chapter that incident of optical radiation on the FC and TM diodes modulates the high-frequency characteristics of the devices. Optically-controlled high-power IMPATTs can have immense possibilities in communication systems.
Thus the author has studied the effects of optical illumination on the high-power GaN-based MM-wave and THz IMPATT devices. To the best of author’s knowledge, this is the first report on photo-irradiated GaN-based IMPATTs.

6.4.1 SMALL-SIGNAL PROPERTIES OF PHOTO-ILLUMINATED FLAT-PROFILE DIODE AT 140 GHz [6.36].

The computed values of $-Z_{RP}$, $-G_p$, $-Q_p$ and $f_p$ for different i) electron and ii) hole current multiplication factors are shown in Table 6.10. In this simulation $M_n$ and $M_p$ varies from $10^6$ to 25, i.e. by a factor of 4x10^4 (Table 6.10) due to photo-illumination, which indicates an increase of leakage current by the same factor. As discussed in Chapters 4 & 5, Vyas experimentally showed that the leakage current increases from 1 nA to 500 μA, i.e. by a factor of 5x10^5 by varying the incident optical power. The admittance characteristics of the un-illuminated and illuminated TM and FC diodes are plotted in Figures 6.24 (a) and (b), respectively. The figures show that the values of $|-G_p|$ of the diode decrease with the lowering of $M_n$ and $M_p$. At the same time, the frequency range over which the device exhibits negative conductance, shifts towards higher frequencies with the lowering of $M_n$ or $M_p$. The output data for illuminated IMPATT (Table 6.10) diode in MM-wave frequency-region indicate that the value of $|-G_p|$ and $P_{max}$ decrease by nearly 10.5% when $M_n$ reduces from $10^6$ to 25, corresponding to TM illumination configuration. On the other hand, in case of FC IMPATT diode, lowering of $M_p$ from $10^6$ to 25 causes more (14.6%) reduction in the value of $|-G_p|$. It is worthwhile mentioning that the frequency chirping is prominent (6.0 GHz) in case of the FC diode than that in case of the TM diode (4.0 GHz) for a similar variation of $M_p$ or $M_n$, respectively. The variation of negative resistance ($|-Z_{RP}|$) and Quality factors ($Q_p$) (at peak frequencies) with $M_n$ or $M_p$ for TM and FC diodes are shown in Table 6.10. The oscillator power output depends on the negative resistance but the high-frequency performance of the oscillator under illumination depends on the Q-factor. A smaller value of $Q_p$ indicates higher conversion efficiency and better stability of oscillation. It is observed from the present studies that the MM-wave power density delivered to the load as well as the conversion efficiency decrease with a shift of operating frequency when the active area of the device is illuminated. It is evident from Table 6.10 that the magnitude of $Q_p$ is lowest for the un-illuminated diode. It is also depicted from Table 6.10 that, as $M_n$ or $M_p$ decreases from the high value of $10^6$, the magnitude of Q-factor increases while $|-Z_{RP}|$ decreases. However, the increase of Q-factor and decrease of $|-Z_{RP}|$ are sharper in the FC configuration than in the TM configuration. The results further indicate that a lowering of $M_n$ from $10^6$ to 25 causes a decrease of $|-Z_{RP}|$ by 23 % and an increase of $1-Q_p$ by 25.26 %. However for a similar variation of $M_p$, the value of $|-Z_{RP}|$ decrease by 27 % and the magnitude of $-Q_p$ increase by 33.0 %.
Figures 6.25 (a) and (b) show the negative resistivity profiles in the space-charge layer of the illuminated TM and FC diodes for different values of \( M_n \) or \( M_p \). In both the figures, the negative resistivity profiles exhibit a peak in the middle of the drift region with dips in the avalanche layer, close to the metallurgical junction. It is observed from the figures that the magnitude of negative resistivity peak is maximum in case of the un-illuminated device. Under illumination, the negative resistivity peaks are depressed with a shift of their location from the middle of the drift layer to the n⁺ edge. The decrease of the negative resistivity peaks are more pronounced in case of the FC illumination configuration, corresponding to hole-dominated photo-current.

Thus the above results indicate that the hole-dominated photo-current (in FC diodes) has more pronounced effect in modulating the device characteristics than that of electron-dominated photo-current (in TM diode) in GaN-based MM-wave IMPATT device.

<table>
<thead>
<tr>
<th>Diode type</th>
<th>( M_n )</th>
<th>( M_p )</th>
<th>(-G_p) ((10^6) Sm(^2))</th>
<th>(-Z_{sp}) ((10^9) (\Omega)m(^2))</th>
<th>(f_p) (GHz)</th>
<th>(Q_p)</th>
<th>(P_{max}) ((10^{10}) W m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-illuminated</td>
<td>10(^6)</td>
<td>10(^6)</td>
<td>43.0</td>
<td>5.0</td>
<td>145.0</td>
<td>1.9</td>
<td>5.6</td>
</tr>
<tr>
<td>TM</td>
<td>50</td>
<td>10(^6)</td>
<td>41.2</td>
<td>4.36</td>
<td>147.0</td>
<td>2.13</td>
<td>5.36</td>
</tr>
<tr>
<td>TM</td>
<td>25</td>
<td>10(^6)</td>
<td>38.5</td>
<td>3.87</td>
<td>149.0</td>
<td>2.38</td>
<td>5.00</td>
</tr>
<tr>
<td>FC</td>
<td>10(^6)</td>
<td>50</td>
<td>40.0</td>
<td>4.12</td>
<td>149.0</td>
<td>2.25</td>
<td>5.20</td>
</tr>
<tr>
<td>FC</td>
<td>10(^6)</td>
<td>25</td>
<td>36.7</td>
<td>3.67</td>
<td>151.0</td>
<td>2.53</td>
<td>4.77</td>
</tr>
</tbody>
</table>
Figure 6.24 (a): Conductance (G) – Susceptance (B) plots of unilluminated GaN SDR IMPATT diode (a) and the illuminated diode (b-c) for different values of $M_n$ at D-band.

Figure 6.24 (b): Conductance (G) – Susceptance (B) plots of unilluminated GaN SDR IMPATT diode (a) and the illuminated diode (b-c) for different values of $M_p$ at D-band.
CHAPTER 6: III-V NITRIDE BASED MM-WAVE & THz IMPATTs

Figure 6.25 (a): Negative resistivity profiles of the unilluminated GaN flat profile SDR IMPATT diode (a) and the illuminated diode (b-c) for different values of $M_n$ and corresponding different values of optimum frequencies, $f_p$ in GHz: a: $M_n = 10^6$, $M_p = 10^6$, $f_p = 145$ GHz; b: $M_n = 50$, $M_p = 10^6$, $f_p = 147$ GHz, c: $M_n = 25$, $M_p = 10^6$, $f_p = 149$ GHz.
6.4.2 SMALL-SIGNAL PROPERTIES OF PHOTO-ILLUMINATED FLAT-PROFILE DIODE

At 1.4 THz [6.34].

The high-frequency properties of GaN-based THz IMPATT diodes, under optical modulation are shown in Table 6.11. Admittance plots of TM and FC diodes for different values of $M_n$ ($M_p = 10^6$) or $M_p$ ($M_n = 10^6$) are shown in Figures 6.26 (a) & 6.26 (b), respectively. The graphs show that the values of $|G_p|$ decrease and the optimum frequency shifts upward with the lowering of carrier multiplication factors, $M_n$ or $M_p$. The output data for illuminated TM and FC diodes (Table 6.11) indicate that the values of negative conductance at peak frequencies, $|G_p|$, decrease by 8.0% and 93.6%, as $M_n$ or $M_p$ reduce from $10^6$ to 25, at a particular current density ($J_{DC} = 3.52 \times 10^8\text{A.m}^{-2}$). The optimum frequency of oscillation ($f_p$) for an illuminated flat profile TM diode increases by 0.006 THz (1.4170 -1.4230 THz) as $M_n$ reduces from $10^6$ to 25. However, for the similar variation of $M_p$, the upward shift of $f_p$ is much higher (~0.153 THz) in case of FC illumination configuration.

Figures 6.27(a) and 6.27(b) show the profiles of negative resistivity at the peak frequencies corresponding to different values of $M_n$ ($M_p = 10^6$) or $M_p$ ($M_n = 10^6$) for TM and FC diodes, respectively.
Negative resistivity profiles give a physical insight into the region of the depletion layer that contributes to output power density. As observed previously, the profiles exhibit negative resistivity peaks in the middle of the drift layer with dips in the avalanche layer close to the metallurgical 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. It is also found that the decrease of negative resistivity peaks are more pronounced in the illuminated FC diode than that in the illuminated TM diode.

The output power densities \( P_{\text{max}} \) at optimum frequencies for the illuminated TM and FC diodes are shown in Table 6.11. It is found that \( P_{\text{max}} \) degrades by 7.8% and 93.6%, in case of TM and FC diodes, respectively. The quality factors \( Q_p \) of illuminated diodes are found to increase gradually with the decrease in the values of \( M_n \) and \( M_p \). It is evident from Table 6.11, that in case of the flat-profile TM diode, a lowering of \( M_n \) from \( 10^6 \) to 25 causes the diode negative resistance \( |-Z_{rp}| \) to decrease by 13.3%, while there is a corresponding lowering of \( |-Z_{rp}| \) by 79.0% in case of FC diode. All the results show a similar trend as observed previously for the MM-wave GaN based illuminated devices.

All the above mentioned results indicate that GaN devices are quite photo-sensitive and it further explores the possibilities of using this device as optically integrated THz module for application in interstellar explorers. It is however interesting to note that the photo-sensitivity of the GaN based IMPATTs increase with the increasing operating frequencies and the photo-illumination effect is found to be much prominent when the devices are operated in the THz regime.

The pronounced effect of hole dominated leakage current in modulating the MM-wave as well as THz characteristics of GaN based IMPATT diodes can be interpreted on the basis of the relative magnitudes of hole and electron ionization rates in WZ-GaN for different electric field ranges. The effects of predominant hole and electron photo-currents on the negative resistance profiles and the admittance characteristics of the FC and TM diodes can be explained from the ionization integral:

\[
\int_0^{x_a} (\beta - \alpha) \, dx
\]

where, \( \alpha \) and \( \beta \) are electron and hole ionization rates and \( x_a \) is the avalanche zone width.

As the magnitude of \( \beta > \alpha \) for the entire electric field in the avalanche zone of the WZ-GaN [6.32] IMPATT, the value of the integral will be larger for hole dominated photo-current corresponding to the FC diode structure than for electron dominated photo-current, corresponding to the TM diode structure. This explains why the high-frequency characteristics of illuminated GaN IMPATT diodes are more sensitive to photo-generated leakage current dominated by holes in FC configuration. On the other hand, in case of illuminated Si IMPATT, electron-dominated photo-current (corresponding to TM configuration) was found to play the dominant role in modulating the RF characteristics [2.210].
because the electron ionization rate is greater than the hole ionization rate in Si. Although GaN and Si IMPATTs show opposite behavior with respect to electron and hole-dominated photo-currents, the natures of optical modulation is similar in both the cases, as far as the decrease of $P_{\text{max}}$, increase of $f_p$, decrease of $|G_p|$ and $|Z_{R_\text{p}}|$ are concerned. To the best of author's knowledge no experimental results are available on photo-irradiated GaN IMPATTs. Although the simulated results could not be compared with experimental observations due to lack of experimental data, the results reported here, have an excellent trend agreement with those of the experimental observations for photo-illuminated Si-IMPATTs, as described in Chapter 2.

### Table 6.11

<table>
<thead>
<tr>
<th>Diode structure</th>
<th>$M_n$</th>
<th>$M_p$</th>
<th>$f_p$ (THz)</th>
<th>$-G_p$ ($10^8$ Sm$^{-2}$)</th>
<th>$-Z_{R_\text{p}}$ ($10^{11}$ $\Omega$ m$^{-2}$)</th>
<th>$P_{\text{max}}$ ($10^{10}$ Wm$^{-2}$)</th>
<th>$-Q_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDR flat doping profile</td>
<td>$10^6$</td>
<td>100</td>
<td>1.4170</td>
<td>74.21</td>
<td>3.00</td>
<td>47.79</td>
<td>1.90</td>
</tr>
<tr>
<td></td>
<td>$10^6$</td>
<td>100</td>
<td>1.4188</td>
<td>72.30</td>
<td>2.85</td>
<td>46.56</td>
<td>1.96</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.4197</td>
<td>69.50</td>
<td>2.76</td>
<td>44.76</td>
<td>2.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1.4230</td>
<td>68.40</td>
<td>2.60</td>
<td>44.05</td>
<td>2.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^5$</td>
<td>100</td>
<td>1.4520</td>
<td>23.0</td>
<td>1.00</td>
<td>14.81</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.4606</td>
<td>11.0</td>
<td>0.75</td>
<td>7.08</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1.5700</td>
<td>4.71</td>
<td>0.63</td>
<td>3.03</td>
<td>18.3</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.26 (a): Conductance ($G$) - Susceptance ($B$) plots of unilluminated WZ-GaN flat profile SDR THz IMPATT diode (a) and the illuminated diode (b-d) for different values of $M_n$.

Figure 6.26 (b): Conductance ($G$) - Susceptance ($B$) plots of unilluminated WZ-GaN flat profile SDR THz IMPATT diode (a) and the illuminated diode (b-d) for different values of $M_p$. 

$\text{Susceptance (}$B$) \text{ (}\times 10^8 \text{ Sm}^{-2}\text{)}$

$\text{Conductance (}$G$) \text{ (}\times 10^8 \text{ Sm}^{-2}\text{)}$

$\text{Current density } = 3.52 \times 10^7 \text{ A m}^{-2}$
Figure 6.27 (a): Negative resistivity profiles of the unilluminated WZ-GaN flat profile SDR IMPATT diode (a) and the illuminated diode (b-d) for different values of \( M_n \) and corresponding different values of optimum frequencies, \( f_p \) in THz: a: \( M_n = 10^6, M_p = 10^6, f_p = 1.4170 \text{ THz} \); b: \( M_n = 100, M_p = 10^6, f_p = 1.4188 \text{ THz} \); c: \( M_n = 50, M_p = 10^6, f_p = 1.4197 \text{ THz} \); d: \( M_n = 25, M_p = 10^6, f_p = 1.4230 \text{ THz} \).
6.4.3 Small-signal Properties of Photo-illuminated LO-HI-LO Diode at 1.4 THz [6.34].

In the previous sub-section, it is clearly established that the incorporation of charge bump in the flatly doped structure, improves the overall performance of GaN-diodes. Moreover, it is most interesting to note that the value of parasitic resistance significantly decreases in the SLHL ($p^{++}n^+n^+n^++$) diode compared to the flat-profile ($p^+nn^+$) diode and this effectively increases the device negative resistance in the SLHL diode. Because the doping profile of the flat-type and the Quasi-Read type IMPATT diodes are quite different, it is predicted that the photo-sensitivity of these two types of devices would be different. In the previous two Chapters, the author has already shown that SiC-based photo-illuminated SLHL diodes are more photo-sensitive than their flat-profile
counterpart. In order to investigate the photo-sensitivity of the SLHL type GaN-IMPPATTs, computer studies will now be carried out on the photo-illumination effects on the GaN-based p\^{}++\ n\ n^{}+\ n\ n^{}++ IMPATT diode. The results will be compared with those of the p\^{}++\ n\ n^{}++ type illuminated IMPATT at around 1.4 THz. The details of the simulation technique and the modified boundary conditions are described in Chapter 3 and are outlined in Section 6.1.

It is discussed earlier that the photo-generated carriers increase the reverse saturation current or leakage current flowing in the reversed biased p-n junction of an IMPATT diode. This enhanced leakage current controls the high-frequency performances, such as \( f_p \), \( P_{\text{max}} \) etc, of the oscillator. It has also been discussed that the enhancement of leakage current in IMPATT oscillators are manifested as the lowering of the carrier multiplication factors, \( M_n \) or \( M_p \). The author will study the effect of photo-illumination on the ‘quasi-Read’ (SLHL) diode, for the following two cases:

1. Effects of illumination on the SLHL diode, whose junction is at the top and substrate is at the bottom (TM illumination configuration), so that \( M_n \) can have different values <10\^{}6 but \( M_p = 10^6 \).
2. Effects of illumination on the SLHL diode, whose substrate is at the top and junction is at the bottom (FC illumination configuration), so that \( M_p \) can have different values <10\^{}6 but \( M_n = 10^6 \).

Small-signal properties of the illuminated SLHL IMPATT diode, for the above two cases, are shown in Table 6.12. To make a comparison, results of flat profile illuminated IMPATT is re-written in the same Table. Admittance plots of the SLHL diode for different values of \( M_n \) (\( M_p = 10^6 \)) or \( M_p \) (\( M_n = 10^6 \)) are shown in Figures 6.28 (a) and 6.28(b), respectively. The graphs show that \( | -G_p | \) of the diode decrease with the lowering of \( M_n \) or \( M_p \). At the same time, the frequency range over which the device exhibits negative conductance, shifts towards higher frequencies with the lowering of carrier multiplication factors. The output data for illuminated TM SLHL IMPATT diode (Table 6.12) indicates that the value of negative conductance at peak frequency \( | -G_p | \) decreases by 37.7% when \( M_n \) reduces from 10\^{}5 to 25, while in case of the illuminated FC structure, the lowering of \( M_p \) from 10\^{}6 to 25 causes \( | -G_p | \) to decrease by 87.5% at a particular current density (\( J_{\text{dc}} = 3.52 \times 10^9 \text{A m}^{-2} \)). The optimum frequency of oscillation (\( f_p \)) for an illuminated SLHL diode increases by 0.016 THz (1.4340 - 1.4500 THz) as \( M_n \) reduces from 10\^{}6 to 25. However, at the same current density, the upward shift of \( f_p \) is much higher (~0.189 THz) in case of the illuminated FC device when the value of \( M_p \) reduces from 10\^{}6 to 25.

The variations of power output and device quality factors with optimum frequency for different values of \( M_n \) and \( M_p \) are shown in Table 6.12. It is found that \( P_{\text{max}} \) as well as \( Q_p \) gradually decreases with increasing intensity of optical radiation, which is demonstrated here by reducing current multiplication factors. It is also evident from Table 6.12, that in the case of SLHL diode, a lowering of \( M_n \) from 10\^{}6 to
25, corresponding to the TM illumination configuration (Case 1), causes the diode negative resistance (-\(Z_{RP}\)) to decrease by 38.7%. For the FC illumination configuration, there is a corresponding lowering of -\(Z_{RP}\) by 93.22 % for the similar variation of \(M_p\) from \(10^6\) to 25. These results provide qualitative agreement with the theoretical analysis carried out by the author in case of 4H-SiC SLHL IMPATT, described in previous two Chapters.

The effects of photo-irradiation on the small-signal properties of the flat-profile GaN IMPATT at 1.45 THz are described in Sub-section 6.4.2 and the corresponding results are re-written in Table 6.12. A simple comparison could be made between the degree of variation of high-frequency properties of the flat type and the SLHL type TM and FC diodes, under optical illumination. This reveals that under similar illumination condition the SLHL diode is more photo-sensitive than its flat profile counterpart, as far as degradation of \(|-Z_{RP}|\) as well as up-shift of \(f_p\) are concerned.

Figures 6.29 (a) and 6.29 (b) show the profiles of negative resistivity at the peak frequencies corresponding to different values of \(M_n\) (\(M_p = 10^6\)) or \(M_p\) (\(M_n = 10^6\)) for the SLHL diode. The profiles exhibit negative resistivity peaks in the middle of the drift layer with dips in the avalanche layer close to the junction. The figures depict that, due to the enhancement of saturation current, the magnitude of negative resistivity peaks decrease gradually. It is interesting to note that this variation of magnitudes of negative resistivity peaks in the SLHL IMPATTs is much more prominent than in the flat-profile THz diode (Figures 6.27 (a) and 6.27 (b)). Similar to illuminated flat-profile THz diode, in case of the illuminated SLHL diode, decrease in negative resistivity peaks are more pronounced for the FC illumination configuration.

Thus the study reveals that like 4H-SiC IMPATTs, GaN-based SLHL diodes are also more photosensitive than their flat-profile counterpart. The pre-dominance of hole-leakage current over electron-leakage current in modulating the THz-characteristics of the SLHL diode can be explained on the basis of their relative magnitudes of electron and hole ionization rates, as explained earlier in Sub-section 6.4.2.
### Table 6.12

Variations of small-signal properties of GaN SDR IMPATT diodes under photo-illumination (values are reported at peak operating frequencies).

<table>
<thead>
<tr>
<th>Diode structure</th>
<th>Mn</th>
<th>Mp</th>
<th>$f_P$ (THz)</th>
<th>$-G_p$ ($10^8$ Sm$^{-2}$)</th>
<th>$-Z_{sp}$ ($10^{-11}$ Ω-m$^2$)</th>
<th>Output Power density ($10^{10}$ W/m$^2$)</th>
<th>$-Q_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>$10^6$</td>
<td></td>
<td>1.4170</td>
<td>74.21</td>
<td>3.00</td>
<td>47.79</td>
<td>1.90</td>
</tr>
<tr>
<td>TM diode</td>
<td>100</td>
<td>$10^6$</td>
<td>1.4188</td>
<td>72.30</td>
<td>2.85</td>
<td>46.56</td>
<td>1.96</td>
</tr>
<tr>
<td></td>
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<td>69.50</td>
<td>2.76</td>
<td>44.76</td>
<td>2.05</td>
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<tr>
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<td>25</td>
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<td>68.40</td>
<td>2.60</td>
<td>44.05</td>
<td>2.15</td>
</tr>
<tr>
<td>FC diode</td>
<td>$10^6$</td>
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<td>1.4520</td>
<td>23.0</td>
<td>1.00</td>
<td>14.81</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>100</td>
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<td>23.0</td>
<td>1.00</td>
<td>14.81</td>
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<td>62.62</td>
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<td>58.94</td>
<td>1.90</td>
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<tr>
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<td>100</td>
<td></td>
<td>1.4370</td>
<td>79.20</td>
<td>2.74</td>
<td>58.94</td>
<td>1.90</td>
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<td>44.13</td>
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<td>52.40</td>
<td>1.90</td>
<td>38.99</td>
<td>3.10</td>
</tr>
<tr>
<td>FC diode</td>
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<td>1.5020</td>
<td>45.3</td>
<td>0.26</td>
<td>33.71</td>
<td>9.20</td>
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<tr>
<td></td>
<td>100</td>
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<td>45.3</td>
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<td>33.71</td>
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<td>1.6230</td>
<td>10.5</td>
<td>0.21</td>
<td>7.81</td>
<td>21.0</td>
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</table>
Figure 6.28 (a): Conductance (G) - Susceptance (B) plots of unilluminated WZ-GaN SLHL SDR THz IMPATT diode (a) and the illuminated diode (b-d) for different values of $M_n$. 

- a: $M_n = 10^6$, $M_p = 10^6$
- b: $M_n = 100$, $M_p = 10^6$
- c: $M_n = 50$, $M_p = 10^6$
- d: $M_n = 25$, $M_p = 10^6$

Current density = $3.52 \times 10^9$ A$m^{-2}$
Figure 6.28(b): Conductance (G) - Susceptance (B) plots of unilluminated WZ-GaN SLHL SDR THz IMPATT diode (a) and the illuminated diode (b-d) for different values of $M_p$.

- a: $M_p = 10^6$, $M_n = 10^6$
- b: $M_p = 100$, $M_n = 10^6$
- c: $M_p = 50$, $M_n = 10^6$
- d: $M_p = 25$, $M_n = 10^6$

Current density = $3.52 \times 10^9$ A/m$^2$
Figure 6.29 (a): Negative resistivity profiles of the unilluminated WZ-GaN SLHL SDR IMPATT diode (a) and the illuminated diode (b-d) for different values of $M_n$ and corresponding different values of optimum frequencies, $f_p$ in THz: a: $M_n = 10^6$, $M_p = 10^6$, $f_p = 1.4340$ THz; b: $M_n = 100$, $M_p = 10^6$, $f_p = 1.4370$ THz, c: $M_n = 50$, $M_p = 10^6$, $f_p = 1.4450$ THz; d: $M_n = 25$, $M_p = 10^6$, $f_p = 1.4500$ THz.
6.5 Comparative Analysis of WZ-GaN and 4H-SiC-Based IMPATTs at 1.0 THz Frequency [6.37].

The potential of 4H-SiC, as a suitable base semiconducting material for fabricating high-power THz IMPATT device has been established in Chapter 5. Earlier in this chapter the author has established that like SiC WBG GaN is another potential semiconductor that can be used for fabricating high-power THz IMPATT devices. The state-of-the-art technological developments of these promising WBG materials are also briefly discussed in this dissertation. Both the semiconductors have proven their superiority over conventional Si. In this endeavor, it will be interesting to compare the performances of SiC and GaN IMPATTs in the THz frequency region. This comparative analysis will be useful in the foreseeable future for fabricating WBG semiconductor (WZ-GaN and 4H-SiC) based high-power THz...
IMPATT devices. Moreover, control of the THz-characteristics of these high-power devices, possibly by optical illumination, will be a vital requirement in the near future. In this section, the author will first report the comparison of THz frequency performances of the WZ-GaN and 4H-SiC based un-illuminated SDR diodes. Thereafter the photo-sensitivity of the devices will also be compared, under similar operating conditions. To the best of author’s knowledge, comparative analysis between WBG GaN and SiC-based IMPATTs at around 1.0 THz frequency has not yet been reported in any literature.

6.5.1 Comparison of DC and Small-Signal Properties of the Un-illuminated SDR Diodes [6.37].

The doping profile and bias current density of Wz-GaN and 4H-SiC based SDR devices are varied to optimize the device design at around 1.0 THz frequency. A generalized double iterative simulation scheme, used for analysis of IMPATT action, is adopted for the purpose and the scheme is described in Chapter 3 and briefly mentioned in Section 6.1. For the present analysis, a flat profile SDR (n++ n p++) structure is considered, where, n++ and p++ are highly doped substrate and cap layer respectively and n is the epilayer. As before in the DC method, the computation starts from the field maximum near the metallurgical junction. The optimized design parameters of the un-illuminated SDR diodes are summarized in Table 6.13. Both the diodes are designed to be operated at around 1.0 THz frequency. It is observed from the table that compared to GaN device, 4H-SiC device is a high-current device at almost same operating frequency. The dynamic properties of the designed diodes are reported in Table 6.14. Figure 6.30 shows the electric field profiles of the optimized IMPATT diodes. It is evident from Table 6.14 and Figure 6.30, that the maximum value of electric field $E_m$ is higher in 4H-SiC IMPATT device. As a consequence, $V_B$ for GaN based device is slightly lower than that of 4H-SiC based device. But on the other hand, the normalized voltage drop ($V_d/V_B$) for GaN based device is much higher than that of SiC counterpart (Table 6.14). It is interesting to note that the normalized voltage drop is 28.26 % in 4H-SiC IMPATT, while it is ~ 57.0 % in case of the GaN IMPATT. This observation can be explained on the basis of Figure 6.31, which compares the normalized current density profiles of the simulated diodes. The profiles indicate that the avalanche region in GaN SDR diode is more localized compared to its SiC counterpart. This in turn, provides a higher value of drift region voltage drop ($V_D$) in the GaN SDR device. The increased value of $V_D/V_B$ ratio in the GaN diode provides higher efficiency (18.2%) in this device compared to that (9%) in SiC SDR device. It is seen from Table 6.14, that the value of the peak negative conductance ($-G_p$) for GaN device is $51.0 \times 10^8$ S m$^2$, much higher than that of the SiC based device ($16.0 \times 10^8$ S m$^2$). A similar trend is found in the admittance plots of the THz diodes, shown in Figure 6.32. A maximum power density ($P_{max}$) of $3.37 \times 10^{11}$ Wm$^2$ is expected from GaN diode at 1.126 THz frequency. On the other hand, the optimized SiC diode is capable of generating a maximum...
power density of $1.35 \times 10^{11}$ W/m$^2$ at 1.05 THz. Thus in terms of $\eta$ and $P_{\text{max}}$, GaN-based SDR IMPATT is superior to 4H-SiC based SDR diode in the THz regime ($>1$ THz).

Table 6.15 compares the values of $R_S$ at 1.0 THz for both the simulated diodes. The small-signal values of negative conductance, susceptance ($B$) and expected values of load conductance ($G_L$), at low power oscillation threshold, are also reported in the Table 6.15. The value of $R_S$ for 4H-SiC IMPATT is lower ($1.5 \times 10^{11}$ $\Omega$ m$^2$) than that of the GaN IMPATT ($4.44 \times 10^{11}$ $\Omega$ m$^2$). Ohmic contact resistance may put a severe restriction on the THz-frequency performances of the wide bandgap IMPATT devices and thus the presence of contact resistance should be included in the realistic analysis of parasitic positive series resistance. Suitable n-type and p-type contact resistances of GaN are mentioned in earlier section. N-type and p-type ohmic contact resistances in 4H-SiC are described in Chapter 5. Considering the contribution of contact resistances, more realistic values of effective parasitic series resistance ($R_{S,\text{total}}$ including the contribution of contact resistance) become approximately $5.54 \times 10^{11}$ $\Omega$ m$^2$ and $3.50 \times 10^{11}$ $\Omega$ m$^2$ respectively for GaN and 4H-SiC IMPATT. The effect of $R_{S,\text{total}}$ on $P_{\text{max}}$ of the diodes are shown in Fig. 6.33. It is reflected from the Figure 6.33, that even in the presence of aforesaid $R_{S,\text{total}}$, an appreciable output power density of $2.45 \times 10^{11}$ W/m$^2$ (Wz-GaN diode) and $1.04 \times 10^{11}$ W/m$^2$ (4H-SiC diode) may be obtained from these THz IMPATT devices. Figure 6.34 shows the small-signal impedance plots for both the diodes. The graphs show that the devices possess negative resistance for all frequencies above the avalanche frequency ($f_a$), where its reactance is capacitive. This is due to the fact that, in the oscillating frequency range, the magnitude of $Z_R$ is found to be small compared to $Z_X$. This is also evident from Figure 6.34, that the values of $|Z_R|$ and $|Z_X|$ decrease as the operating frequency increases. Moreover, it is interesting to note that in the THz region, total impedance level of the GaN based device is higher than of its SiC counterpart.

Thus the above comparison reveals that III-V nitride based IMPATT is more powerful and efficient than its 4H-SiC counterpart at around 1.0 THz frequency. This observation can be explained on the basis of Baliga's Figure of Merit (Table 1.2) which is important for evaluation of high-frequency and high-power application of devices. Baliga's Figure of Merit in GaN is 77.8, much higher than in SiC (29.0). Thus GaN IMPATT is much more favorable in THz-region, as also observed from the simulation investigations.
### Table 6.13
Design data of GaN and SiC based flat profile SDR IMPATT diode in the THz Region

<table>
<thead>
<tr>
<th>Diode type (SDR)</th>
<th>Epilayer (n) doping conc. ((10^{24} \text{ m}^{-3}))</th>
<th>Width of epilayer (n) ((\text{nm}))</th>
<th>Current density ((10^{9} \text{ A m}^{-2}))</th>
</tr>
</thead>
<tbody>
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<td>Wz-GaN</td>
<td>2.85</td>
<td>75.0</td>
<td>3.2</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>8.0</td>
<td>50.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>

### Table 6.14
DC and small-signal results of GaN and SiC based SDR IMPATT diode in the THz Region

<table>
<thead>
<tr>
<th>Diode type</th>
<th>Wz-GaN based SDR</th>
<th>4H-SiC based SDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak electric field (E_m) ((10^8 \text{ V m}^{-1}))</td>
<td>4.30</td>
<td>6.50</td>
</tr>
<tr>
<td>Breakdown voltage (V_B) ((\text{V}))</td>
<td>23.0</td>
<td>26.0</td>
</tr>
<tr>
<td>Normalized voltage drop ((V_D = V_B - V_A)/V_B) ((%)))</td>
<td>57.1</td>
<td>28.26</td>
</tr>
<tr>
<td>Efficiency ((\eta)) ((%))</td>
<td>18.2</td>
<td>9.0</td>
</tr>
<tr>
<td>Peak frequency ((\text{THz}))</td>
<td>1.126</td>
<td>1.050</td>
</tr>
<tr>
<td>Peak conductance (G_p) ((10^8 \text{ Sm}^{-1}))</td>
<td>51.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Output power density (P_{\text{output}}) without (R_s) ((10^{11} \text{ W m}^{-2}))</td>
<td>3.37</td>
<td>1.35</td>
</tr>
<tr>
<td>Output power density (P_{\text{output}}) with (R_s), total ((10^{11} \text{ W m}^{-2}))</td>
<td>2.45</td>
<td>1.04</td>
</tr>
</tbody>
</table>

### Table 6.15
Values of series resistance \(R_s\) and load conductance \(G_l\) at oscillation threshold (resonance) of GaN and SiC SDR IMPATT [bias current density = \(3.2 \times 10^9 \text{ A m}^{-2}\) and frequency = 1.0 THz].

<table>
<thead>
<tr>
<th>Diode type</th>
<th>Negative conductance ((-G)) (\times 10^8 \text{ Sm}^{-1})</th>
<th>Susceptance ((-B)) (\times 10^8 \text{ Sm}^{-1})</th>
<th>Load conductance ((-G_l)) (\times 10^8 \text{ Sm}^{-1})</th>
<th>Series resistance ((R_s)) (\times 10^{-11} \Omega \text{ m}^{-2})</th>
<th>Negative resistance ((Z_n)) (\times 10^{-12} \Omega \text{ m}^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wz-GaN SDR</td>
<td>37.0</td>
<td>60.0</td>
<td>21.0</td>
<td>4.44</td>
<td>7.45</td>
</tr>
<tr>
<td>4H-SiC SDR</td>
<td>14.6</td>
<td>58.6</td>
<td>9.5</td>
<td>1.50</td>
<td>4.00</td>
</tr>
</tbody>
</table>
Figure 6.30: Plots of electric field profiles for WZ-GaN and 4H-SiC SDR IMPATT diodes. The distance of the n-side from the metallurgical junction has been shown as negative.

Figure 6.31: Normalized current density $P(x)$ profiles of (a) WZ GaN and (b) 4H-SiC SDR IMPATT diodes at THz region. The distance of the n-side from the metallurgical junction has been shown as negative.
Figure 6.32: Admittance plots of IMPATT diodes: a. WZ-GaN, b. 4H-SiC.
Figure 6.33: Effect of series resistance on maximum power output of SiC and GaN IMPATT diodes in the THz region.

- a: GaN IMPATT, $R_s = 0.00 \Omega m^2$
- b: GaN IMPATT, $R_s = 4.44 \times 10^{-4} \Omega m^2$
- c: GeN IMPATT, $R_{s=1} = 5.54 \times 10^{-3} \Omega m^2$
- d: SiC IMPATT, $R_s = 0.00 \Omega m^2$
- e: SiC IMPATT, $R_s = 1.50 \times 10^{-4} \Omega m^2$
- f: SiC IMPATT, $R_{s=1} = 3.50 \times 10^{-4} \Omega m^2$
6.5.2 COMPARISON OF PHOTO-SENSITIVITY OF THE SDR DIODES [6.37].

Computer studies on the role of enhanced saturation current in controlling the THz properties of the flat profile SDR IMPATT diodes, based on WBG WZ-GaN and 4H-SiC have been compared through a modified simulation technique, as described in Chapter 3. This comparative study is very important to find the photo-sensitivity of the devices under similar operating conditions.
CHAPTER 6: III-V NITRIDE BASED MM-WAVE & THz IMPATTs

The effects of electron- and hole-dominated photocurrents on the THz performance of the WBG IMPATTs are presented in Table 6.16. Admittance plots of the TM and FC diodes for different values of $M_n (M_p = 10^6)$ or $M_p (M_n = 10^6)$ are shown respectively in Figures 6.35 and 6.36(a-b). The graphs show that the values of $|G_p|$ of the diodes decrease with the lowering of $M_n$ and $M_p$. At the same time, the frequency range over which the devices exhibit negative conductance shift towards higher frequencies with the lowering of $M_n$ and $M_p$. The output data for the TM flat profile GaN IMPATT diode (Table 6.16) indicates that the values of negative conductance at peak frequencies $|G_p|$ and $P_{\text{max}}$ decrease by 6.0\% when $M_n$ reduces from $10^6$ to 25, while in case of the illuminated TM SiC device, the lowering of $M_n$ from 10^6 to 25 causes $|G_p|$ and $P_{\text{max}}$ to decrease by 37.5\%. On the other hand, the degradation of $|G_p|$ and $P_{\text{max}}$ is much more prominent in case of the FC diodes, as shown in Table 6.16. It is found that, in case of the FC illumination configuration, as $M_p$ reduces from $10^6$ to 25, $|G_p|$ and $P_{\text{max}}$ degrade by ~88.0\%, in case of the GaN IMPATT and 47.0\%, in case of the 4H-SiC IMPATT. The optimum frequency of oscillation ($f_\text{p}$) for the illuminated TM GaN diode increases by 0.006 THz (1.126 - 1.132 THz) as $M_n$ reduces from $10^6$ to 25, while, under similar illumination condition, the up-shift of $f_\text{p}$ is much higher (~0.040 THz) in case of the TM SiC IMPATT. However, for the similar variation of $M_p$ from 10^6 to 25, corresponding to FC illumination configuration, the upward shift of $f_\text{p}$ is much higher (~0.174 THz) in case of GaN based IMPATT device than that (0.150 THz) in case of SiC based IMPATT. It is also evident from Table 6.16, that in case of GaN TM device, a lowering of $M_n$ from $10^6$ to 25 causes the diode negative resistance ($-Z_{\text{Rdp}}$) to decrease by 10.71\%, while there is a corresponding lowering of $-Z_{\text{Rdp}}$ by 45.7\% in case of SiC IMPATT diode. Similarly, in case of FC GaN and SiC IMPATTs, decrease of $-Z_{\text{Rdp}}$ are 78.5\% and 71.7\%, respectively. Figure 6.37(a-b) and Figure 38(a-b) show the profiles of negative resistivity at the peak frequencies corresponding to different values of $M_n (M_p = 10^6)$ or $M_p (M_n = 10^6)$ for GaN and SiC diodes, respectively. The figures show that for both types of diodes, the profiles exhibit negative resistivity peaks in the middle of the drift layer with dips in the avalanche layer close to the junction. It is seen that for both the diodes, decrease of negative resistivity peaks are more pronounced in the FC illumination configuration than in the TM illumination configuration.

The above analysis reveals the following facts:

(1) Both 4H-SiC and WZ-GaN-IMPATTs are more photo-sensitive when they are illuminated from substrate sides (FC illumination configuration).

(2) As the diodes are illuminated from the junction-side, photo-generated electron leakage current dominates the over-all performances of 4H-SiC IMPATT more seriously compared to WZ-GaN diode. Moreover, the optimum frequency of oscillation in the TM SiC-IMPATT
shifts upward by 40 GHz, which is much higher than the up-shift of $f_p$ (6 GHz) in TM GaN-IMPATT.

(3) As the diodes are illuminated from the substrate side, photo-generated hole leakage current dominates the overall performances of GaN-IMPATT diode more seriously compared to its 4H-SiC counterpart. Also the frequency up-chirp in case of the FC GaN-IMPATT is more (174 GHz) than in the FC SiC-IMPATT (150 GHz).

Table 6.16
Variations of small signal parameters of GaN and 4H-SiC SDR IMPATT diodes due to photo-illumination (values are reported at peak operating frequencies).

<table>
<thead>
<tr>
<th>SDR diode type</th>
<th>$M_p$</th>
<th>$M_n$</th>
<th>Peak frequency (THz)</th>
<th>Output power density ($P_{max}$) $(10^{11} \text{W/m}^2)$</th>
<th>Negative conductance (-$G_p$) $(10^8 \text{Sm}^2)$</th>
<th>Negative resistance (-$Z_{rp}$) $(10^{11} \Omega \text{m}^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-illuminated Wz-GaN</td>
<td>10^6</td>
<td>10^6</td>
<td>1.126</td>
<td>3.37</td>
<td>51.0</td>
<td>2.8</td>
</tr>
<tr>
<td>Top Mounted diode</td>
<td>100</td>
<td>1.126</td>
<td>3.36</td>
<td>50.8</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.128</td>
<td>3.31</td>
<td>50.0</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1.132</td>
<td>3.17</td>
<td>48.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Flip Chip diode</td>
<td>100</td>
<td>10^6</td>
<td>1.145</td>
<td>1.58</td>
<td>24.0</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.180</td>
<td>0.75</td>
<td>11.3</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1.300</td>
<td>0.40</td>
<td>6.0</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Un-illuminated 4H-SiC</td>
<td>10^6</td>
<td>10^6</td>
<td>1.050</td>
<td>1.35</td>
<td>16.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Top Mounted diode</td>
<td>100</td>
<td>1.065</td>
<td>1.28</td>
<td>15.2</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.085</td>
<td>1.18</td>
<td>14.0</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1.090</td>
<td>0.85</td>
<td>10.0</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Flip Chip diode</td>
<td>100</td>
<td>1.120</td>
<td>1.14</td>
<td>13.5</td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>1.180</td>
<td>0.93</td>
<td>11.0</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1.200</td>
<td>0.72</td>
<td>8.5</td>
<td>0.99</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.35: Admittance plots of WZ-GaN and 4H-SiC based photo-illuminated Top Mounted SDR THz IMPATTs.
Figure 6.36 (a): Admittance plots of WZ-GaN based photo-illuminated Flip Chip SDR THz IMPATTs.
Figure 6.36 (b): Admittance plots of 4H-SiC based photo-illuminated Flip Chip SDR THz IMPATTs.
Figure 6.37 (a): Negative resistivity profiles of the unilluminated WZ-GaN flat profile SDR IMPATT diode (a) and the illuminated diode (b-c) for different values of \( M_n \) and corresponding different values of optimum frequencies, \( f_p \) in THz: 

- a: \( M_n = 10^6, M_p = 10^6, f_p = 1.126 \) THz.
- b: \( M_n = 50, M_p = 10^6, f_p = 1.18 \) THz.
- c: \( M_n = 25, M_p = 10^6, f_p = 1.30 \) THz.

Figure 6.37 (b): Negative resistivity profiles of the un-illuminated GaN flat profile SDR IMPATT diode (a) and the illuminated diode (b-c) for different values of \( M_p \) and corresponding different values of optimum frequencies, \( f_p \) in THz: 

- a: \( M_n = 10^6, M_p = 10^6, f_p = 1.126 \) THz.
- b: \( M_n = 10^6, M_p = 50, f_p = 1.18 \) THz.
- c: \( M_n = 10^6, M_p = 25, f_p = 1.30 \) THz.
Figure 6.38 (a): Negative resistivity profiles of the unilluminated 4H-SiC flat profile SDR IMPATT diode (a) and the illuminated diode (b-c) for different values of $M_n$ and corresponding different values of optimum frequencies, $f_p$ in THz: a: $M_n = 10^6$, $M_p = 10^6$, $f_p = 1.050$ THz; b: $M_n = 50$, $M_p = 10^6$, $f_p = 1.085$ THz; c: $M_n = 25$, $M_p = 10^6$, $f_p = 1.090$ THz.

Figure 6.38 (b): Negative resistivity profiles of the unilluminated 4H-SiC flat profile SDR IMPATT diode (a) and the illuminated diode (b-c) for different values of $M_p$ and corresponding different values of optimum frequencies, $f_p$ in THz: a: $M_n = 10^6$, $M_p = 10^6$, $f_p = 1.050$ THz; b: $M_n = 10^6$, $M_p = 50$, $f_p = 1.18$ THz; c: $M_n = 10^6$, $M_p = 25$, $f_p = 1.20$ THz.
6.6 Summary:

Simulation investigations are carried out to study the prospects of GaN-based SDR IMPATTs (both flat and SLHL type) in the MM-wave and THz-frequency region. The author has compared the performances of WZ-(hexagonal) GaN based diodes with those of ZB-(cubic) GaN diodes. It is observed that WZ-phase GaN is superior to ZB-phase GaN for developing high-power IMPATTs with better efficiency in the MM-wave and Terahertz region. However, positive series resistance in ZB-GaN IMPATT is much less than that in WZ-GaN IMPATT. Moreover, almost equal values of carrier ionization rates ($\alpha \approx \beta$) in ZB-GaN are favorable for minimizing avalanche noise in these diodes, as may be predicted from the avalanche noise theory. The study has established that the SLHL diodes are performing better than their flat-profile counterparts as far as output power density efficiency and lower value of positive series resistances are concerned. Computer studies have been carried out to study the photo-sensitivity of WZ-GaN based diodes. Like SiC, GaN is also more photo-sensitive in the Flip Chip configuration than in the Top Mounted configuration. It is observed that optical illumination on the GaN-based devices increases the optimum frequencies, but decrease negative conductance, negative resistance as well as power density. Device quality factors also found to degrade with the increasing intensity of optical illumination. The diodes are more photo-sensitive in the Terahertz frequency region than in the MM-wave region. It is also found that SLHL type illuminated diodes are more photo-sensitive than their flat-profile counterparts. An upward frequency shift of $\sim$189 GHz may be achieved with the enhancement of reverse saturation current due to photo-illumination on the SLHL diode at THz frequency. In conclusion, it is established that GaN-based IMPATTs are potential candidate for replacing conventional IMPATTs in the high-frequency region. Also, author has carried out a comparative analysis of the THz-frequency performances of the hexagonal (4H-) SiC and hexagonal (WZ-phase) GaN based un-illuminated as well as illuminated IMPATTs at around 1.0 THz. The simulation study reveals that un-illuminated GaN-IMPATTs are potential candidate than un-illuminated 4H-SiC IMPATT at 1.0 THz, as far as output power density and efficiency are concerned. Photo-illumination study indicates that Top Mounted GaN-based IMPATT is less photo-sensitive than its SiC counterpart, but optical modulation is found to be more pronounced in GaN-based Flip Chip IMPATT than in SiC-based Flip Chip IMPATT.

To the best of author's knowledge this is the first report on the photo-sensitivity analysis of GaN-IMPATTs having both flat and SLHL doping profiles in the MM-wave and THz-frequency region. Due to lack of experimental data simulation results could not be compared. It may be mentioned, in conclusion, that the simulated results obtained from the small-signal model give useful information regarding the MM-wave and THz frequency tuning of such devices by optical means. These findings may further be used for realizing optically integrated high-power MM-wave and THz modules for applications in interstellar explorers.
CHAPTER 6: Replies to 2nd Examiner’s comments

Examiner’s 4th comment:
a. GaN grown on substrate Sapphire has typically $10^9 - 10^{10} \text{cm}^2$ dislocations/cm$^2$. How would these defects affect the working of the device since the author concludes that GaN may be the preferred material?

Reply:
To the best of author’s knowledge, GaN epilayers on Sapphire substrates were first grown with dislocation densities $\sim 10^9 - 10^{10} \text{cm}^2$. Even so, quantum well lasers and high-brightness LEDs could be fabricated as these dislocations were considered to be electrically inactive. The presence of dislocation in GaN has been discussed in the thesis (Chapter 6, page 4). The dislocations can act as scattering centres for carriers, thus reducing the mobility of electrons and holes, as well as the thermal conductivity. The latter may increase the junction temperature of IMPATTs under high-power operation. Thus the author has studied the performance of GaN IMPATTs at an elevated temperature $\sim 600 \text{K}$ (Chapter 6), incorporating the relevant material parameters.

GaN epitaxial layers with a dislocation density as low as $6 \times 10^7 \text{cm}^2$ have been grown on 2-inch-diameter sapphire wafers by hydride vapor phase epitaxy (HVPE) (Usui et al., Jpn. J. Appl. Phys. Vol. 36, pp. L899-L902, 1997). Recently, the dislocation density has been reduced to $\sim 10^7 \text{cm}^2$ using a cone-shaped patterned Sapphire substrate (H. Y. Shin et al. Journal of Crystal Growth, vol. 311, issue. 17, pp. 4167-4170, 2009). High quality (dislocation density $< 10^6 \text{cm}^2$) free standing GaN has been obtained using a modification of the epitaxial overgrowth technology (US patent, “Process for Growth of low dislocation density GaN”, Beaumont et. al, Pub No: US/2009/0278136 A1, Pub. Date: Nov. 12, 2009). It is well known that semiconductor epitaxy on native substrates lowers the dislocation density appreciably. More recently, Kyma Technologies (http://www.kymatech.com) has produced GaN epitaxy on GaN substrates with dislocation density as low as $\sim 10^4 \text{cm}^2 - 10^6 \text{cm}^2$. Thus, as evidenced in above discussion, dislocation densities should not pose any major problem for GaN IMPATT operation.

Examiner’s 5th comment:
b. GaN is known to be ferroelectric material and spontaneous polarization in the c-direction is fairly high. How will this affect the IMPATT device operation?

Reply:
To the best of author’s knowledge, GaN is a piezoelectric material but not ferroelectric. Ferroelectricity is defined as spontaneous reversible dielectric polarization which is not present in GaN. Thus it is like
ZnO and ZnS which also have wurzite-structure but are not ferroelectric. Moreover, ferroelectric materials usually have high value of dielectric constant, whereas in GaN the value is only 8.9, and this is one of the causes to choose GaN for modeling THz IMPATT devices. The polarization, present in GaN/AlGaN, GaN/AlN hetero-structures, has two contributions, spontaneous and piezoelectric. The spontaneous polarization, intrinsic to the material, has its origin in the non-centrosymmetric nature of the WZ-crystal, where the crystal possesses electric dipoles along the c-axis ([0001] direction). At the Ga-face of GaN, spontaneous polarization is opposite to the [0001] direction, i.e. in the downward direction, pointing towards the substrate. Piezoelectric polarization arises as a consequence of the strained state of the hetero-structure, also along the c-axis. The built-in electric field in electronic devices, due to this polarization effect, can be useful in transistors and sensor applications but detrimental for optoelectronic devices. One possible solution, as has been widely applied, is the growth of devices along non-polar directions perpendicular to the c-axis, such as the M-axis or A-axis (T. Paskova, "Nitride with non polar surfaces: Growth, Properties and Devices", Wiley, New York, 2008). Spontaneous polarization effects in IMPATTs thus depend on the orientation of the GaN crystal plane and also on its structure (WZ or ZB). This can be chosen to enhance IMPATT performance. These polarization effects are more effective in hetero-structures. The present thesis however deals entirely with homo-structure IMPATTs based on III-V GaN.

Examiner's 6th comment:

c. It is known that permissible p-type doping of GaN is limited to low concentration (10^{17} - 10^{18} \text{ cm}^{-3}). The author should comment on the limitation imposed by this in Chapter 6. The referee could not locate the doping assumed for the p''\text{layer} in this chapter.

Reply:

p-type doping in GaN is discussed in the thesis (Chapter 6, page: 5). Reference [6.8] is also included, where hole concentration of 8x10^{19} \text{ cm}^{-3} in highly doped p-GaN (p''\text{layer}) has been obtained. Another recent study reported that as-grown Mg doped GaN layer has p-type conductivity with concentration ~3x10^{19} \text{ cm}^{-3} (A. Usikov et al., Phys. Stat. Sol. (c), vol.5, page-1829, 2008). These are much higher than the values (10^{17} - 10^{18} \text{ cm}^{-3}) quoted by the examiner. The highly doped p''\text{cap layer} is used to lower the contact resistance which in turn improves the high-power performance of IMPATTs.
6.7 Bibliography:


