CHAPTER 8: STUDIES OF ATT PHASE DELAY DUE TO PHOTO-ILLUMINATION ON THz-IMPATTs

SIMULATION OF THE SHIFT OF AVALANCHE TRANSIT TIME (ATT) PHASE DELAY DUE TO PHOTO-GENERATED CARRIERS IN WBG SEMICONDUCTOR-BASED IMPATTs IN THE TERAHERTZ REGION.

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8.1 Introduction:

It has been discussed in Chapter 2 that control of high-frequency properties of an IMPATT oscillator by optical means has become a field of major research interest [1.27-1.29] [2.213]. It is earlier discussed that both switching [1.31] as well as injection locking of microwave power [2.212] of IMPATT oscillators are possible by external optical illumination. In the earlier Chapters, the author has discussed that optically generated carriers increase the leakage current flowing in the reverse-biased p-n junction of an IMPATT diode which, in turn, controls the dynamic properties such as frequency of oscillation, power density, quality factor and negative resistance of the oscillator. In the case of a WBG semiconductor diode a UV-laser beam is required for photo-generation.

Several researchers have analyzed the performances of optically-controlled microwave or MM-Wave IMPATT devices, mostly based on Si and GaAs. For the first time, author has systematically studied the effects of external illumination on MM-Wave and Terahertz IMPATT devices based on SiC and GaN. Detailed discussions in this regard are presented in Chapter 4, Chapter 5 and Chapter 6 of the dissertation. The composition of leakage current as regards the hole and electron components plays an important role in the optical modulation of IMPATT diodes. Vyas et al. [1.30] demonstrated that the output power and frequency of Si X-band IMPATT oscillator vary more appreciably with electron-dominated photo-current than with hole-dominated photo-current. However, in the earlier Chapters, author has shown that the situation is just the reverse in case of SiC and GaN IMPATTs in the MM-wave and THz-region, i.e. the hole-dominated photo-current is more effective than electron dominant current in modulating the device properties appreciably under photo-illumination.

As discussed earlier, optical control is fundamentally due to a strong interaction between the incident optical beam and the MM-wave or Terahertz output of the devices. Avalanche Transit Time (ATT) phase-delay is a vital parameter that governs the MM-wave and the Terahertz-frequency properties of the IMPATT devices. ‘Avalanche phase delay’ results due to the time delay inherent in the build-up of the avalanche current in the avalanche zone and the ‘transit time delay’ is produced as the generated carrier drift the drift region of the depletion layer. It is described in Chapter 3 that as soon as the IMPATT diode is reverse biased to avalanche breakdown, the current builds up from the thermally generated saturation current by the process of ‘Impact Ionization’. Optical illumination by suitable wavelength of radiation on the IMPATT device, considerably increase the magnitude of reverse saturation current due to the generation of enormous number of electron-hole pairs in the active region of the device, as a result of photon-absorption.
In 1970, Misawa [2.110] studied the influence of reverse saturation current or leakage current on the dynamics of avalanche process in a Read type diode. He also showed that the avalanche phase delay critically depends on the magnitude of reverse saturation current. In the review of fundamental physics related to IMPATT operation, presented in Chapter 2, it is mentioned that a premature build-up of the avalanche current results when the initial reverse saturation current is quite high. In case of the illuminated IMPATT, initial leakage current increases to a high value. Consequently the phase delay associated with the avalanche process is reduced as a result of the premature build-up of avalanche current, mentioned above. IMPATTs display negative resistance when the AC current lags behind applied RF voltage by a phase angle between 90° and 270°. The negative resistance in an avalanche diode occurs as a result of an 180° phase difference between the AC current and voltage when the diode is reversed biased to avalanche breakdown. In the photo-illuminated IMPATTs, a decrease of avalanche phase delay from the desired value of 90° is accompanied by a decrease of negative resistance and output power density of the device. This is because the decrease in avalanche phase delay would decrease the combined avalanche and transit time phase delay from the ideal value of 180° corresponding to maximum negative resistance. The decrease of ATT phase delay from 180° to some lower value as a result of optical illumination would lead to a decrease of device negative resistance (-ZR). Thus the negative resistance is a sensitive function of ATT phase delay in IMPATTs. It is observed in previous Chapters that the negative resistivity peaks decrease with increasing reverse saturation current. The total negative resistance, i.e. the area under the negative resistivity profile is an indicator of MM-wave and THz-region power delivery, which is found to decrease with increasing optical illumination.

A computer method has been suggested by the author to obtain the shift of the ATT phase delay due to the optical illumination. For this purpose the author has studied the negative resistivity profiles of the THz-diodes. In Chapter 6, author has shown that the hole dominated photo-current component of leakage current is more pronounced in modulating the THz-frequency performances of the p⁺ n n⁺ SDR diodes based on GaN and SiC. A comparative study of the effects of hole versus electron photo-current on the shift of ATT phase-delay, avalanche zone width and related high-frequency properties of the THz-devices will be presented in this Chapter.

An accurate knowledge of the ATT phase delay is a pre-requisite to understand the interaction between the optical beam and THz-frequency output of the IMPATT devices. The simulation results of the optically-modulated THz-devices can be understood from a study of the ATT phase delay in the illuminated devices. Hence these studies should be useful to explain the difference of electron and hole
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initiated avalanches in controlling the THz-characteristics of GaN and SiC-based Top Mounted and Flip Chip IMPATTs.

8.1.1 COMPUTER ANALYSIS:

8.1.1.1 Method of calculation of the negative resistivity profiles:

The shift of ATT phase delay in an illuminated p++ n n++ IMPATT diode in THz-regime is calculated from the computer simulation of the respective negative resistivity profiles ($R(x)$) in the depletion region of the device. The simulation technique for obtaining $R(x)$ profiles of the illuminated and un-illuminated devices is discussed in detail in Chapter 3. A brief description of the computer program is described below:

Under small-signal conditions two second order differential equation involving diode negative resistivity $R(x)$ and reactivity $X(x)$ are obtained, shown in Chapter 3. The equations are obtained from Gummel-Blue [2.63] analysis of the device impedance $Z(x, \omega)$ under small-signal condition [3.5] where $Z(x, \omega) = R(x, \omega) + j X(x, \omega)$. A double iterative computer method [3.5] as discussed in Chapter 3 has been used to numerically solve the above-mentioned equations subjected to the boundary conditions given in Chapter 3. The small-signal computation is initiated at the nn++ interface and terminated at the np+ junction of the SDR diodes. The exact locations of the interface and the junction are obtained from a simultaneous numerical solution of Poisson’s equation, combined current continuity equation and space-charge equation under static conditions subject to the following boundary conditions for electric field and normalized current density. The static and dynamic characteristics of the diodes are studied for three different configurations: (a) Un-illuminated diode, (b) Top Mounted illuminated diode and (iii) Flip Chip illuminated diode. The corresponding modified boundary conditions for these three configurations are as follows:

(a) Un-illuminated SDR diodes in THz-region:

$$E(-x_1) = 0, \quad E(x_2) = 0$$

$$\left[ \frac{J_{diff}(x)}{J_0} \right]_{x = x_1} = \left( 2 M_p \right)^{-1} = -1, \quad \left[ \frac{J_{diff}(x)}{J_0} \right]_{x = x_2} = \left( 1 - \frac{2}{M_n} \right)^{-1} = 1$$

(b) Illuminated Top-Mounted SDR diode in THz-region:

$$E(-x_1) = 0, \quad E(x_2) = 0$$

$$\left[ \frac{J_{diff}(x)}{J_0} \right]_{x = x_1} = \left( 2 M_p \right)^{-1} = -1, \quad \left[ \frac{J_{diff}(x)}{J_0} \right]_{x = x_2} = \left( 1 - \frac{2}{M_n} \right)^{-1} = 1$$
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\[
\left[ \frac{J_{\text{diff}}(x)}{J_0} \right] x = -x_1 = -1, \quad \left[ \frac{J_{\text{diff}}(x)}{J_0} \right] x = x_2 = \left(1 - \frac{2}{M_n} \right)
\]

(c) Illuminated Flip-Chip SDR diode in THz-region:

\[
E(-x_1) = 0, \quad E(x_2) = 0
\]

and,

\[
\left[ \frac{J_{\text{diff}}(x)}{J_0} \right] x = -x_1 = \left(\frac{2}{M_p} - 1\right), \quad \left[ \frac{J_{\text{diff}}(x)}{J_0} \right] x = x_2 = 1,
\]

where, \(-x_1\) and \(x_2\) define the \(n^n\) and \(np^n\) boundaries of the depletion layer.

The fundamental device equations under static conditions are numerically solved subject to the above-mentioned boundary conditions by a double-iterative field-maximum computer method [2.79]. E(x) and P(x) profiles for all the above cases are obtained for different values of \(M_n\) and \(M_p\). Once the depletion layer widths are fixed by the corresponding E(x) profiles for different values of \(M_n\) and \(M_p\) and the DC parameters at the two edges are known for different situations as shown in the boundary conditions (8.1 - 8.6), small-signal simulation is carried out. The small-signal analysis is described in detail in Chapter 3. The admittance profiles and \(R(x)\) profiles of the un-illuminated and illuminated diodes are thus simulated for the three different illumination configurations, as mentioned above.

8.1.1.2 Method for calculating the shift of ATT phase-delay:

The ATT phase delays in the WBG-semiconductor based THz IMPATT diodes, due to optical illumination, can be calculated from the corresponding R(x) profiles for the following three cases:

(i) Unilluminated diode \((M_n = 10^6, M_p = 10^6)\);
(ii) Illuminated TM diode \((M_n = 10^6, M_p = 50, 25)\) and
(iii) Illuminated FC diode \((M_n = 10^6, M_p = 50, 25)\).

The \(R(x)\) profiles of the diode for all the above three cases exhibit negative resistivity peaks in the middle of the drift layer, but the magnitudes and the locations of the peaks change due to optical illumination. The spatial shift of the negative resistivity maxima determines the shift of ATT phase delay due to illumination. If the distances of the peaks from the junctions are \(x_1\) | unilluminated case, \(x_{21}\) illuminated TM diode \((M_n = 25)\) and \(x_{32}\) illuminated FC diode \((M_p = 25)\) and corresponding optimum frequencies are \(f_1\), \(f_{22}\) and \(f_{32}\), then the phase delays at \(x_1\), \(x_{22}\) and \(x_{32}\) for cases (i), (ii) and (iii), respectively, are obtained from the following relations:

\[
\Phi_1 = 2\pi x_1 f_1 / v_n, \quad \Phi_2 = 2\pi x_{22} f_{22} / v_n, \quad \Phi_3 = 2\pi x_{32} f_{32} / v_n
\]

The relation \(\Phi_{a1} + \Phi_{a2} = \Phi_{a3} + \Phi_{b3} = \pi\) is satisfied at \(x_1\), \(x_{22}\) and \(x_{32}\) where \(\Phi_{a1}\), \(\Phi_{a2}\), and \(\Phi_{b3}\) are the avalanche phase delays and \(\Phi_{a1}\), \(\Phi_{a2}\), and \(\Phi_{b3}\) are the transit time delays for the three cases.
The shifts of ATT phase delays due to the effect of illumination on the TM and FC diodes are calculated from the following equations:

\[
\delta_{TM} |_{(Mn=25)} = (\phi_2 - \phi_1) = \left(\frac{2\pi v_m}{V_{ns}}\right)(x_{22} f_{22} - x_1 f_1)
\]

\[
\delta_{FC} |_{(Mn=25)} = (\phi_3 - \phi_1) = \left(\frac{2\pi v_m}{V_{ns}}\right)(x_{32} f_{32} - x_1 f_1)
\]

8.2 Shift of ATT Phase Delay Due to Photo-generated Carriers in III-V GaN Based THz IMPATT Diode [8.1].

Design parameters of GaN-based Single Drift Region \( p^+ n n^+ \) IMPATT diodes are optimized for an optimum punch-through factor (PTF). Bias current densities are so chosen that the mobile space-charge effect has not become prominent. The diode design data are as follows: background doping concentration = \( 2.85 \times 10^{24} \) m\(^{-3} \), bias current density = \( 3.2 \times 10^9 \) Am\(^{-2} \) and depletion layer width = 75 nm. The author has incorporated the Monte Carlo simulated values of saturated drift velocity and mobility of charge carrier and experimental ionization rate data of carrier in WZ-GaN within the temperature range \( 300 K < T < 600 K \) for the present analysis. The detailed discussions on the material parameters of WZ-GaN are presented in Chapter 6 and for the sake of brevity the details are excluded here. In order to consider realistic doping profile, exponential function and complementary error function at the junction and at \( n^+ n \) contact region have been incorporated in the analysis, as discussed in earlier Chapters. The accuracy of the device simulator is enhanced by considering very small space step ~ 0.1 nm.

8.2.1 Results and Discussions [8.1]:

The simulation experiments reveal that the optimized WZ-GaN based diode may generate an output power density of \( 3.37 \times 10^{11} \) Wm\(^{-2} \) with an efficiency of 18.2%. The effects of electron and hole dominated photocurrents on the THz performance of the WBG IMPATT is presented in Table 8.1. The plots of electric field profiles for the un-illuminated and illuminated TM and FC diodes are shown in Figure 8.1. It is interesting to note that there are small changes in the \( E(x) \) profiles due to the lowering of \( M_n \), corresponding to TM illumination configuration, while the change is comparatively more due to the lowering of \( M_p \), corresponding to FC illumination configuration. In Figure 8.2 plots of avalanche region width of the symmetrical GaN-diode are shown as functions of electron and hole current multiplication factors. It is found that due to optical-illumination, the avalanche region (\( x_a \)) becomes narrower in case of the TM diode than in case of the FC diode.
The output data for illuminated SDR IMPATTs (Table 8.1) indicate that the value of negative conductance at peak frequency $| -G_p |$ decreases by 6% when $M_n$ reduces from $10^6$ to 25, corresponding to TM illumination configuration. On the other hand, in case of the FC IMPATT diode, lowering of $M_p$ from $10^6$ to 25 causes more (88%) reduction in the value of $| -G_p |$. The frequency chirping is much more prominent (174.0 GHz) in case of the FC diode than in case of the TM diode (6.0 GHz) for a similar variation of $M_p$ or $M_n$, respectively. The above results thus indicate that the hole dominated photo-current (in FC diodes) has more pronounced effect in modulating the device admittance characteristics than that of electron dominated photo-current (in TM diode) in GaN based THz IMPATT devices.

The variation of negative resistance ($Z_{sp}$) and Quality factors ($Q_p$) at the peak frequencies with $M_n$ or $M_p$ for the TM and FC diodes are plotted in Figure 8.3. 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 efficiency and better stability of oscillation. It is observed that the THz power output delivered to the load and conversion efficiency decrease with an upward shift of the operating frequency when the active area of the device is illuminated. It is evident from Figure 8.3 that $Q_p$ is lowest for the un-illuminated diode. It is also shown in the same figure that, as $M_n$ or $M_p$ decreases from the high value of $10^6$, the magnitude of $Q$-factor increases while $Z_{sp}$ decrease. However, these changes are sharper for FC illumination configuration than for TM illumination configuration. The results further indicate that a lowering of $M_n$ from $10^6$ to 25 causes a decrease of $Z_{sp}$ by 10.7 % and an increase of $Q_p$ by 14.0 %. However for the similar variation of $M_p$, the value of $Z_{sp}$ decrease by 78.5 % and the magnitude of $Q_p$ increase by 85.0 %.
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Table 8.1
Effects of photo-illumination on small-signal properties of GaN based THz-IMPATT diode (Bias Current Density = 3.2 x 10^9 Am^{-2}, Depletion Layer Width = 75.0 nm, Epilayer Doping = 2.85 x 10^{24} m^{-3}, DC Breakdown Voltage = 23.0 V)

<table>
<thead>
<tr>
<th>Diode type</th>
<th>$M_n$ or $M_p$</th>
<th>$x_p$ (nm)</th>
<th>$-G_p$ (10^8 Sm^{-2})</th>
<th>$P_{max}$ (10^{-11} Wm^{-2})</th>
<th>$-Z_{ep}$ (10^{-10} Ω m^{-2})</th>
<th>$f_p$ (THz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilluminated (M_n = 10^6, $M_p = 10^6$)</td>
<td>27.0</td>
<td>51.0</td>
<td>3.37</td>
<td>2.8</td>
<td>1.126</td>
<td></td>
</tr>
<tr>
<td>Illuminated TM diode ($M_p = 10^6$)</td>
<td>20.0</td>
<td>50.0</td>
<td>3.30</td>
<td>2.6</td>
<td>1.128</td>
<td></td>
</tr>
<tr>
<td>Illuminated FC diode ($M_n = 10^6$)</td>
<td>18.2</td>
<td>48.0</td>
<td>3.17</td>
<td>2.5</td>
<td>1.132</td>
<td></td>
</tr>
<tr>
<td>Illuminated TM diode ($M_n = 10^6$, $M_p = 10^6$)</td>
<td>23.0</td>
<td>11.3</td>
<td>0.75</td>
<td>1.73</td>
<td>1.180</td>
<td></td>
</tr>
<tr>
<td>Illuminated FC diode ($M_n = 10^6$)</td>
<td>22.0</td>
<td>6.0</td>
<td>0.40</td>
<td>0.60</td>
<td>1.300</td>
<td></td>
</tr>
</tbody>
</table>

Table 8.2
Simulation results of shift of ATT phase delay in illuminated GaN-based IMPATT diode in THz-region.

<table>
<thead>
<tr>
<th>Diode type</th>
<th>$M_n$ or $M_p$</th>
<th>Peak Frequency ($f_p$) THz</th>
<th>Position of peak from junction ($x_j$) (nm)</th>
<th>$\delta_{TM}$ (10^{-2} π)</th>
<th>$\delta_{FC}$ (10^{-2} π)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilluminated (M_n = 10^6, $M_p = 10^6$)</td>
<td>$f_1 = 1.126$</td>
<td>$x_j = 35.0$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Illuminated TM diode ($M_p = 10^6$)</td>
<td>$f_{21} = 1.128$</td>
<td>$x_{21} = 37.0$</td>
<td>2.326</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Illuminated FC diode ($M_n = 10^6$)</td>
<td>$f_{31} = 1.180$</td>
<td>$x_{31} = 42.0$</td>
<td>4.738</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Illuminated FC diode ($M_n = 10^6$, $M_p = 10^6$)</td>
<td>$f_{22} = 1.132$</td>
<td>$x_{22} = 39.0$</td>
<td>-</td>
<td>10.15</td>
<td>-</td>
</tr>
<tr>
<td>Illuminated FC diode ($M_n = 10^6$)</td>
<td>$f_{32} = 1.300$</td>
<td>$x_{32} = 50.0$</td>
<td>-</td>
<td>25.59</td>
<td>-</td>
</tr>
</tbody>
</table>
The magnitudes of $\delta_{TM}$ and $\delta_{FC}$ are calculated from the respective $R(x)$ profiles (Figures 8.4 and 8.5) for different values of $M_n$ and $M_p$. The variation of $\delta_{FC}$ and $\delta_{TM}$ with $M_p$ and $M_n$ are shown in Table 8.2. It is observed from these figures and table that the magnitudes of the peaks of the negative resistivity profiles decrease and their locations shift towards the nn$^{++}$ edge of the depletion layer with the decrease of $M_n$ or $M_p$. The depression of the peaks and the shift of the $R(x)$ profiles are less pronounced in TM diode structure (Figures 8.4) than in the FC diode structure (Figures 8.5). This is reflected in the larger shift of ATT phase delay in the FC diode ($\delta_{FC} > \delta_{TM}$), where the photo-generated leakage current is dominated by holes. The enhancement of leakage current due to optical illumination leads to a premature build up of avalanche current and consequently avalanche phase delay decreases. This decrease in avalanche phase delay is accompanied by an increase of transit time delay due to drift of carriers, so that the proper phase relationship between the voltage and AC current for producing maximum negative resistance is maintained. The early injection of avalanche current in the drift layer due to optical illumination thus leads to a shift of the negative resistivity peaks towards the nn$^{++}$ edge of the drift layer. The variation of $\delta_{FC}$ and $\delta_{TM}$ with $M_p$ and $M_n$ are shown in Figures 8.6. It is found that the shift of ATT phase delays increase with the decrease of $M_n$ or $M_p$ for both the TM and FC diodes.

The pronounced effect of hole dominated leakage current in modulating the THz characteristics of GaN IMPATT diode can be interpreted on the basis of the relative magnitudes of hole and electron ionization rates in WZ-GaN for the operating electric field ranges. The effects of predominate hole and electron photo-currents in the FC and TM diodes on the static and dynamic characteristics of the device can be explained from the ionization integral:

$$\int_{0}^{x_a}(\beta - \alpha)dx$$, where, $\alpha$ and $\beta$ are electron and hole ionization rates. The upper limit of the ionization integral, $x_a$ is avalanche zone width, which is found to decrease with decreasing $M_n$ or $M_p$ (Table 8.1). The avalanche zone is found to be narrower in TM diode than in a FC diode, as shown in Table 8.1 and Figure 8.2. Also the magnitude of $\beta$ is larger than $\alpha$ [6.29] for the entire electric field range in the avalanche zone of the WZ-GaN IMPATT. Since the above integral depends on $x_a$ and $(\beta - \alpha)$, the value of the integral will be larger for the hole dominated photo-current corresponding to the FC diode structure than for the electron dominated photo-current, corresponding to the TM diode structure. This explains why the THz characteristics of illuminated GaN IMPATT diode are more sensitive to photo-generated hole leakage current in FC configuration. On the other hand, in case of illuminated Si IMPATT, electron dominated photo-current (in TM structure) is found to play the dominant role in modulating the RF characteristics [1.30]. This is because, the electron ionization rate is greater than the hole ionization rate in Si. Although GaN and Si IMPATTs show opposite effects with respect to electron and hole
dominated photo-currents, the nature of optical modulation is similar in both the diodes, as far as the
decrease of power density, up-shift of optimum frequency, and shift of ATT phase delays are concerned.

Figure 8.1: Plots of electric field profiles for WZ-GaN SDR IMPATT diodes for different
values of current multiplication factors. The distance of the n-side from the
metallurgical junction has been considered as negative.
Figure 8.2: Variation of avalanche zone width with current multiplication factors, $M_n$ and $M_p$ in WZ-GaN IMPATT.
Figure 8.3: Variation of $Z_{rp}$ and $Q_p$ with $M_n$ and $M_p$ in WZ-GaN IMPATTs in the THz region: (a, c) corresponds to TM illumination and (b, d) corresponds to FC illumination.
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Figure 8.4: 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: $M_n = 50$, $M_p = 10^6$, $f_p = 1.128$ THz, c: $M_n = 25$, $M_p = 10^6$, $f_p = 1.132$ THz.

Figure 8.5: Negative resistivity profiles of the unilluminated Wz-GaN flat profile SDR IMPATT diode (a) and the illuminated diode (b-c) for different values of $M_p$ 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: $M_n = 10^6$, $M_p = 50$, $f_p = 1.180$ THz, c: $M_n = 10^6$, $M_p = 25$, $f_p = 1.300$ THz.
8.3 Shift of ATT Phase Delay Due to Photo-generated Carriers in IV-IV SiC Based THz IMPATT Diode:

4H-SiC-based SDR (p++ n n++) IMPATT diodes are designed to operate at around 1.0 THz. Background doping concentrations, width of the n-epilayer and bias current densities are optimized to get highest efficiency and power-density from this device at the particular design frequency. The diode design data are as follows: background doping concentration = $8 \times 10^{24}$ m$^{-3}$, bias current density = $12 \times 10^9$ Am$^{-2}$ and depletion layer width = 50 nm. The field dependent ionization rate, drift velocities and mobility of charge carriers in 4H-SiC are incorporated in the present analysis. The detailed discussion of the material parameters of 4H-SiC are presented in Chapter 4. The effect of mobile space-charge is
incorporated in the present analysis. A double iterative computer method, as described in Chapter 3 has been used for the design and optimization of the device in THz-region. The distribution of DC electric field in the depletion region of the un-illuminated and illuminated diodes are obtained by the double iterative computer method which is used for a simultaneous solution of Poisson and combined current continuity equations, subject to appropriate boundary conditions, described in Chapter 3 and has been briefly outlined in Section 8.1. The negative resistivity profiles of the diodes corresponding to Case (a-c), as shown in sub-section 8.1.1.1, are obtained by high-frequency analysis of the diodes through a generalized simulation method, detailed in Chapter 3. The accuracy of the simulation investigation is increased by incorporating small space step ~0.1 nm.

8.3.1 Results and Discussions:

In Figure 8.7, plots of E(x) profiles of the flat-profile SiC-based SDR IMPATT diodes are shown for different values of multiplication factors, \( M_n \) and \( M_p \). It is found that the decrease of peak electric field is comparatively more in case of FC-diode. The variation of the avalanche zone width with the lowering of \( M_n \) and \( M_p \) are shown in Figure 8.8. It is evident from this figure that the avalanche zone is becoming narrower in case of the TM-diode than in case of the FC diode. The small-signal results for the diode are shown in Table 8.3. It is found that the SiC-based diode is capable of delivering an output power density of \( 1.35 \times 10^{11} \, \text{W/m}^2 \) at 1.05 THz. It is found that peak frequency shifts upward by 40 GHz and 150 GHz, with the decrease of \( M_n \) or \( M_p \) from \( 10^6 \) to 25, respectively. It is observed that device quality factors degrade more seriously in FC diode due to hole dominated saturation-current. It is earlier mentioned that output power density depends on the device negative resistance whereas the overall high-frequency characteristics of the oscillator depends on its quality factors. A smaller value of \( Q_p \) is desirable for obtaining higher efficiency and better stability of oscillation. The present study reveals that \( P_{\max} \) obtained from the SiC-based diode in THz-region decreases under illumination. The decrease of \( |G_p| \) and \( P_{\max} \) are nearly 37%, when the device is illuminated from the junction side, i.e. in case of Top Mounted configuration, while \( |G_p| \) and \( P_{\max} \) decrease by ~47%, when the optical radiation is incident from the substrate side in Flip Chip configuration. It is evident from Table 8.3 that \( Q_p \) is lowest for the un-illuminated diode.
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Table 8.3
Effects of photo-illumination on small-signal properties of 4H-SiC based THz-IMPATT diode. (Bias Current Density = 12 x10⁹ Am⁻², Depletion Layer Width = 50.0 nm, Epilayer Doping = 8.0x10²⁴ m⁻³, DC Breakdown Voltage = 26.0 V)

<table>
<thead>
<tr>
<th>Diode type</th>
<th>Mₙ &amp; Mₚ</th>
<th>x₀ (nm)</th>
<th>-Gₚ (10⁸ Sm⁻²)</th>
<th>P_max (10¹¹ Wm⁻²)</th>
<th>-Z₀p (10⁻¹¹ Ω m⁻²)</th>
<th>fₚ (THz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilluminated</td>
<td>Mₙ = 10⁶ \ Mₚ = 10⁶</td>
<td>37.0</td>
<td>16.0</td>
<td>1.35</td>
<td>3.5</td>
<td>1.05</td>
</tr>
<tr>
<td>Illuminated TM diode (Mₚ = 10⁶)</td>
<td>Mₙ = 50</td>
<td>30.3</td>
<td>14.0</td>
<td>1.18</td>
<td>2.6</td>
<td>1.085</td>
</tr>
<tr>
<td></td>
<td>Mₙ = 25</td>
<td>26.0</td>
<td>10.0</td>
<td>0.85</td>
<td>1.9</td>
<td>1.09</td>
</tr>
<tr>
<td>Illuminated FC diode (Mₙ = 10⁶)</td>
<td>Mₚ = 50</td>
<td>34.0</td>
<td>11.0</td>
<td>0.93</td>
<td>1.33</td>
<td>1.180</td>
</tr>
<tr>
<td></td>
<td>Mₚ = 25</td>
<td>32.0</td>
<td>8.5</td>
<td>0.72</td>
<td>0.99</td>
<td>1.200</td>
</tr>
</tbody>
</table>

Table 8.4
Simulation results of shift of ATT phase delay in illuminated 4H-SiC based IMPATT diode in THz-region.

<table>
<thead>
<tr>
<th>Diode type</th>
<th>Mₙ or Mₚ</th>
<th>Peak Frequency (fₚ) THz</th>
<th>Position of peak from junction (nm)</th>
<th>Δₜₘ (10² π)</th>
<th>Δₑ (10² π)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilluminated</td>
<td>Mₙ = 10⁶ \ Mₚ = 10⁶</td>
<td>f₁ = 1.050</td>
<td>x₁ = 15.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Illuminated TM diode (Mₚ = 10⁶)</td>
<td>Mₚ = 50</td>
<td>f₂₁ = 1.085</td>
<td>x₂₁ = 19.0</td>
<td>4.87</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Mₙ = 25</td>
<td>f₂₂ = 1.090</td>
<td>x₂₂ = 20.0</td>
<td>6.05</td>
<td>-</td>
</tr>
<tr>
<td>Illuminated FC diode (Mₙ = 10⁶)</td>
<td>Mₚ = 50</td>
<td>f₃₁ = 1.180</td>
<td>x₃₁ = 19.0</td>
<td>-</td>
<td>6.67</td>
</tr>
<tr>
<td></td>
<td>Mₚ = 25</td>
<td>f₃₂ = 1.200</td>
<td>x₃₂ = 22.0</td>
<td>-</td>
<td>10.65</td>
</tr>
</tbody>
</table>
The variation of $Q_p$ and $|Z_{rp}|$ with different values of $M_n$ and $M_p$ are shown in Figure 8.9. It is evident that as $M_n$ or $M_p$ decreases from the high value of $10^6$, the magnitude of the Q-factor increases while $|Z_{rp}|$ decreases. In case of the FC diode, as $M_p$ decreases from $10^6$ to 25 due to hole dominated leakage current, $|Z_{rp}|$ reduces by 71.7%, whereas in case of the TM diode, a similar decrease of $M_n$ due to electron dominated leakage current, reduces $|Z_{rp}|$ by 45.7%. It is also evident that compared to its value in case of the un-illuminated IMPATT, $|Q_p|$ increase by 1.83 times and 2.7 times, respectively in Top Mounted and Flip Chip diodes as $M_n$ or $M_p$ reduces by a factor of $4 \times 10^4$ as a result of photo-illumination.

Negative resistivity profiles of the Top-Mounted and Flip-Chip diodes are shown in Figures 8.10 and 8.11. It is discussed earlier that the spatial distribution of $R(x)$ in the depletion region provides important information regarding the relative contribution of the avalanche region and drift region in the output power density. It is clear from the figures that drift zone contributes maximum negative resistance and the same decrease with the decrease of current multiplication factor. The decrease of negative resistivity peaks in the drift region is more pronounced for the Flip Chip diodes than for the the Top Mounted diodes. It is also observed that substrate-epitaxy (nn++) interface region contributes minimum output power density. The most important factor to note is that the position of negative resistivity peaks in the drift region shifts gradually towards the nn++ interfaces as a result of photo-illumination of the devices. These values of the spatial shifts of the peaks may be calculated from Figures 8.10 and 8.11. The position of the peaks and the calculated values of shift of ATT phase delay in TM and FC diodes are shown in Table 8.4. The method of finding the shift of ATT phase delay ($\delta_{TM}$ and $\delta_{FC}$) in TM and FC diodes is discussed earlier. Following the method, author has calculated the values of ATT phase delay due to optical-illumination in 4H-SiC based THz-diodes, for the first time. It is interesting to note that the magnitude of $\delta_{TM}$ in a TM diode is comparatively smaller than $\delta_{FC}$ in a FC diode. The variation of $\delta_{TM}$ and $\delta_{FC}$ with $M_n$ or $M_p$ are shown in Figure 8.12. The ratio of $\delta_{FC}$: $\delta_{TM}$ is lower in 4H-SiC diode for a particular multiplication factor than this in a GaN-based diode, shown in Table 8.2. In case of TM configuration, for a particular value of $M_n$ ($M_p = 10^5$), $\delta_{TM}$ is found to be higher in 4H-SiC-based diode than in the WZ-GaN IMPATT. This explains why the 4H-SiC based devices are more photo-sensitive than their WZ-GaN counterpart, when they are illuminated from the junction side. On the other hand, in case of the FC diodes, $\delta_{FC}$ is found to be much higher in WZ-GaN IMPATT than in SiC IMPATT, for a particular value of $M_p$ ($M_n = 10^5$). This is in accordance with the results obtained from the simulation investigation, which shows that the photo-sensitivity of GaN based IMPATTs increases remarkably when these are illuminated from the substrate side.
CHAPTER 8: STUDIES OF ATT PHASE DELAY DUE TO PHOTO-ILLUMINATION ON THz-IMPATTS

As discussed earlier, the predominance of hole leakage current over electron leakage current in modulating the THz-frequency characteristics of the devices can be explained from the ionization integral: \( \int_{0}^{x_a} (\beta - \alpha) dx \), the meaning of the symbols are described earlier. Now, Table 8.3 shows that \( x_a \) is narrower in the TM diode than this in the FC diode. Also in 4H-SiC, as mentioned in Chapter 5 and Chapter 6, \( \beta > \alpha \), for the operating electric field range [4.28]. Thus, the value of the integral is larger for an FC diode structure, where hole photo-current dominates over electron photo-current than for a TM diode structure, where the situation is just reversed. This explains why the high-frequency characteristics of the illuminated SiC-based devices are more sensitive to the photo-generated hole leakage current in an FC structure.

\[ \begin{align*}
\text{a: } & M_e = 10^4, M_h = 10^6 \\
\text{b: } & M_e = 25, M_h = 10^4 \\
\text{c: } & M_e = 10^6, M_h = 25
\end{align*} \]

Figure 8.7: Plots of electric field profiles for 4H-SiC-based IMPATT diodes for different values of current multiplication factors. The distance of the n-side from the metallurgical junction has been considered as negative.
**Figure 8.8**: Variation of avalanche zone width with multiplication factors, $M_n$ and $M_p$ in 4H-SiC IMPATT diode.
Figure 8.9: Variation of $Z_{ap}$ and $Q_p$ with $M_n$ and $M_p$ in 4H-SiC IMPATTs in the THz region: (a, c) corresponds to TM illumination and (b, d) corresponds to FC illumination.
Figure 8.10: 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 8.11: 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: $M_n = 10^6$, $M_p = 50$, $f_p = 1.18$ THz, c: $M_n = 10^6$, $M_p = 25$, $f_p = 1.20$ THz.
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Figure 8.12: Variation of shift of ATT phase delay with current multiplication factors, $M_n$ and $M_p$. 

4H-SiC based THz IMPATT
8.4 Summary:

For the first time the author has studied the shift of avalanche transit time phase delay due to optically injected carriers in SiC and GaN-based THz-frequency diodes. A computer method has been suggested by the author to study the shift of ATT phase delay in WBG-semiconductor based diodes in the THz-region. It is observed that optically injected holes would lead to a larger shift of ATT phase delay than the optically injected electrons in both of the diodes. The study has established that larger the phase shift due to optical injection, stronger is the THz-wave and optical interaction. Also it is found that optical modulation of the high-frequency characteristics of the devices depends very much on the above mentioned phase-shift. Further the shift of ATT phase delay in both the devices has been found to depend strongly on the ionization rates of the respective charge carriers. In both SiC and GaN, the hole ionization rate is greater than the electron ionization rate ($\beta > \alpha$) in the high-field avalanche zone of the respective diodes, therefore it is found that the photo-generated hole-leakage current produces a larger phase-shift than the corresponding electron current in both SiC and GaN-based IMPATT diodes. The study has importance in understanding of the interaction between the optical beam and THz-characteristics of the diodes. In addition, photo-sensitivity of the SiC and GaN-based Top Mounted and Flip Chip IMPATT diodes are compared from the quantitative knowledge of the phase delay in these photo-illuminated devices.
8.5 Bibliography: