Chapter-IX
CHAPTER IX
CONCLUSIONS AND OUTLOOK

The effects of some physical phenomena such as high bias current and mobile space charge effect, optical illumination and enhancement of leakage current, avalanche noise, on the DC and small signal properties of Impatt diodes based on different semiconducting materials like InP, SiC, SiGe and GaN have been investigated and presented in this dissertation. In course of the investigation, the software used for the simulation of device properties for SDR and DDR structures of Impatt diodes based on different materials has been developed by the author as described in Chapter III. The realistic, experimentally measured and well-documented material parameters of the semiconductors are considered in the simulation study.

In Chapter IV, the computer aided design and analysis for the InP DDR diodes have been presented for the design frequencies of 60, 94 and 140 GHz which comprises the lower half of the millimeter wave (30-300 GHz) frequency band. The optimized structural parameters of InP DDR avalanche diodes are obtained from this study. The effect of mobile space charge on the properties and performance of Impatt diodes have been studied at high bias currents in detail. This study provides the optimum currents in realizing maximum efficiency and maximum small signal negative conductance for each of the 60, 94 and 140 GHz InP DDR diodes. A study on the spatial variation of the high frequency negative resistance in the active layer of InP DDR Impatts is also included in Chapter IV. The negative resistance profiles characterized by two peaks are in each of the drift layer opposite to the metallurgical junction of the device and a central negative resistance minimum located very close to the junction. In this case the peaks in the hole drift layer are larger in amplitude than those in the electron drift layer, which has been explained qualitatively in that chapter. At high bias currents, the space charge dependence of the negative resistance profiles has also been studied.
which shows that with the increase of bias currents the peaks of negative resistance profiles diminishes in magnitude and appreciably when the central avalanche zone expands. The study also shows that with further increase of bias current density the negative resistance peak in the electron drift layer becomes almost equal to the central negative resistance minimum resulting in a single peak R(x) profile with the peak situated in the hole drift layer.

In Chapter V, primarily, the DC analysis in respect of the break down characteristics of Impatts based on 4H-SiC has been studied. The results indicate sharp fall of avalanche breakdown voltage $V_B$ and depletion layer width $W$ with increase in background doping concentrations which is in agreement with the results i.e., the variations of $V_B$, $W$ and $E_m$ by Sze and Gibbons [112] for a one sided abrupt junction in Ge, Si and GaAs. The breakdown voltages and the DC to RF conversion efficiencies of these Impatts have been compared with that of Si Impatt diode for the comparable physical parameters and specifications. Results indicate that Impatt diodes can be designed and fabricated using SiC material in order to enhance efficiency but because of high breakdown voltage of SiC compared to that of Si, they also deliver higher power. Here 4H polytype is only considered as it is more appropriate for the fabrication of Impatt diodes due to higher and nearly isotropic electron mobility. So it can be inferred that the design and development of Impatt diodes using a new material, SiC, presented in this work, are capable of providing high RF power and high DC to RF conversion efficiency at high voltage levels and at microwave frequencies.

The DC properties of SDR 4H-SiC computer aided designed Impatts at X-band for several values of $J_0$ in the range of $1 \times 10^7$ Am$^{-2}$ to $1.1 \times 10^9$ Am$^{-2}$ have been studied. It is observed that, due to the combined effect of the appearance of a maximum in drift zone voltage in the specified range of bias current and appreciable expansion of the avalanche zone at high bias current the DC to RF conversion efficiency ($\eta$) attains a peak value of 21.91% at $J_0 = 4 \times 10^8$ Am$^{-2}$, thereafter $\eta$ decreases slowly with increasing $J_0$ for simulation carried out upto
$J_0 = 1.1 \times 10^9 \text{ Am}^{-2}$. The silicon carbide SDR diode under consideration maintains a large value of $\eta$ (17.49%) even at a high bias current as $J_0 = 1.12 \times 10^9 \text{ Am}^{-2}$ indicating that the effect of the mobile space charge does not deteriorate the performance of the device even at such high bias current levels. In fact, it is observed that the electric field profile gets only a little distorted from its triangular shape due to the presence of mobile charge carriers in the depletion layer, when $J_0$ exceeds $4 \times 10^8 \text{ Am}^{-2}$. Hence it may be concluded that Impatt diodes based on silicon carbide are capable of delivering high power output with high DC to RF conversion efficiency at high bias current levels.

The theoretical estimation of the avalanche breakdown voltage ($V_B$) from the device simulation is found to agree well with the experimentally measured [18] value at the same bias current level.

It is also observed that the magnitude of negative conductance attains a peak value at a particular value of bias current density for a fixed frequency and the magnitude of the peak decreases with its location shifting towards higher values of bias current density for higher design frequency. Further the range of the bias current density for which the device exhibits oscillation increases with increasing frequency. The negative conductance also exhibits a peak at a particular frequency for a fixed bias current density. The magnitude of the peak decreases with decreasing bias current density with its position shifting towards lower values of frequency for lower current density. Thus the frequency for peak negative conductance, i.e., optimum frequency gradually decreases with decrease of bias current density. It may be noted that the frequency band for which the device exhibits negative conductance is wider for lower range of bias current density. Thus the operating frequency and bias current density for optimum negative conductance of the device can be obtained from these results.

It is found that the device susceptance increases very sharply with increasing frequency for a lower range of operating frequency but the rate of
increase slows down at higher values of operating frequency. The specific negative resistance exhibits a peak value at a particular value of \( J_0 \) and then falls sharply with increasing \( J_0 \) and exhibits smooth peaks which shift to higher frequency values for higher values of \( J_0 \). It is also observed that the magnitude of the peak is higher for lower \( J_0 \) and the position of the peak shifts to the higher range of frequencies with increase of \( J_0 \). These results show that the specific negative resistance attains a maximum value \((1.55 \times 10^{-7} \, \Omega \text{m}^2)\) at \( J_0 = 0.95 \times 10^{7} \, \text{Am}^{-2} \) and \( f = 12 \, \text{GHz} \).

The DC to microwave conversion efficiency becomes maximum (22%) for \( J_0 = 2 \times 10^{7} \, \text{Am}^{-2} \) at \( f = 22 \, \text{GHz} \). Microwave power increases from 300 mW to 1.5 W (5-times) when current density increases from \( 0.95 \times 10^{7} \, \text{Am}^{-2} \) to \( 3 \times 10^{7} \, \text{Am}^{-2} \) (3-times). It has been experimentally reported [18] that a power output of 300 mW is obtained at \( 0.95 \times 10^{7} \, \text{Am}^{-2} \) from a similar device structure with identical doping profile at the same bias current level. Thus the simulated results are in fair agreement with the experimental results. When the bias current density increases from \( 0.95 \times 10^{7} \, \text{Am}^{-2} \) to \( 4 \times 10^{7} \, \text{Am}^{-2} \) the peak power increases from 300 mW at 14 GHz to 3.2 W at 22 GHz. Although the reported experimental result as regards output power is in close agreement with the simulation results presented, the same is much less than that estimated from power-frequency relation of IMPATTs. However, a number of measures will have to be taken in order to extract more power from the device by

(i) enhancing the bias current level to such a value as to avoid the destruction of the device

(ii) maintaining a constant current during the bias pulse

(iii) selecting the optimum area of the device for maximum power and

(iv) optimizing the circuit parameters of microwave cavity and bias line.
Studies have also been carried out on the DC and high frequency properties of DDR Impatt diodes based on 4H-SiC at the operating millimeter wave frequencies of 60 and 94 GHz after modelling of the devices and the results are presented in chapter V. Structural parameters and doping profiles are designed for maximum DC to RF conversion efficiency alongwith optimum punch-through factor at normal bias current density (J₀). The results show that the normalized avalanche layer width (xₐ/W) of DDR 4H-SiC Impatt diodes remains nearly constant for both the design frequencies keeping the corresponding current densities at their normal values.

In section 4.4(a) it has been shown that, at very high bias current density the presence of large amount of mobile space charge in the active layer of symmetrically doped DDR InP Impatts, leading to a distortion of the electric field profiles deteriorates the high frequency performance of the device at millimeter wave frequencies like 60 and 94 GHz. In section 5.5.2 studies on the effect of large mobile space charge at high bias current on the DC and RF properties of symmetrically doped flat profile DDR 4H-SiC Impatts are presented for two important millimeter wave frequencies of 60 and 94 GHz. E(x) and P(x) profiles of 4H-SiC DDR Impatts have been simulated at these design frequencies over a range of J₀ (from 9 × 10⁷ to 4 × 10⁹ Am⁻²) using the software developed by the author. From the field profiles of 60 GHz device [Fig. 5.18] it has been revealed that the maximum electric field is located very close to the metallurgical junction (x₀ ≈ 10⁻⁵ μm) lying on the n-side of the depletion layer. With the increase of bias current, the peak of the electric field is depressed and its location is shifted further away from the junction. The electric field is nearly triangular in shape and falls linearly to nearly zero value at both edges of the depletion layer of DDR 4H-SiC Impatts at a bias current level of 9 × 10⁷ Am⁻² and design frequency of 60 GHz. As J₀ increase the field gradient decreases due to the increase in net mobile space charge density [q(p-n)] resulting to a spreading of the high field avalanche region at increased bias current level. The appreciable concave upward shape of the
electric field profile on p-side only of the 4H-SiC DDR Impatts at high current levels reveals that the effect of large space charge leads to the distortion of the profile on p-side at high bias currents while there is negligible distortion of the profile on n-side. This behaviour is characteristic to the Impatts based on 4H-SiC only. This phenomenon may be explained on the basis of variation of hole and electron ionization rates with increase in electric field at high bias current levels.

The conductance-susceptance plots of millimeter-wave DDR 4H-SiC Impatt diodes show continuous increase of conductance and optimum frequency with bias current density upto $4 \times 10^9$ Am$^{-2}$.

It has been found that the effect of mobile space charge is not appreciable to a high current level of $1 \times 10^9$ Am$^{-2}$ for the 4H-SiC Impatts designed for both V-band and W-band frequencies. The expansion of the avalanche zone is appreciable for both type of Impatts designed at 60 and 94 GHz at bias current densities greater than $1 \times 10^9$ Am$^{-2}$. The maximum values of DC to RF conversion efficiency obtained are 17% for the 60 GHz diode and 16.4% for the latter. Although the magnitudes of quality factor are greater than 1, the results of the simulation of RF properties of the designed Impatts of V-band and W-band reveals that Impatts based on 4H-SiC have the potentiality of being used as source of millimeter-wave power with high breakdown voltage, high power with high efficiency.

From the results of the investigation carried out with the Si$_{1-x}$Ge$_x$ Impatts presented in Chapter VI, it reveals that the unstrained Si$_{1-x}$Ge$_x$ Impatt diodes capable of generating higher RF power due to higher negative resistance for both the values of mole fraction $x = 10\%$ and $x = 30\%$ in the millimeter wave frequency bands. So Impatt diodes can be fabricated using Si$_{1-x}$Ge$_x$/Si heterostructure.

The comparison of SDR p$^+$-n-n$^+$ Si$_{1-x}$Ge$_x$ diodes with SDR p$^+$-n-n$^+$ Si diodes shows that the DC to RF conversion efficiency increases if one introduces Ge in Si, but since the breakdown voltage of Si Impatt is higher than those for


Si$_{1-x}$Ge$_x$ Impatts, so the output power delivered by the Si$_{1-x}$Ge$_x$ diode will be smaller than that by Si Impatt diode.

Thus it can be concluded that the design and development of Impatt diodes using a new material viz., unstrained Si$_{1-x}$Ge$_x$ presented in Chapter VI will be useful in Si-based Microwave Monolithic Integrated Circuits (MMICs) to integrate the low cost, high reliability, advanced and easy technology of silicon with low-power, highly advanced heterostructure technology to have low-power high speed wireless RF circuits. Therefore, Si$_{1-x}$Ge$_x$ based Impatt devices have enormous potential to revolutionize the millimeter wave communication systems and radar systems in the present century.

In recent years, the optical control of Impatt diodes is an area of growing research interest since apart from electrical control through the variation of bias current the different DC and mainly RF properties of Impatts may be controlled through the variation of optical illumination of the active area of the device. In Chapter VII, primarily p$^+$-n$^-$-n$^+$ Impatt diode based on an important emerging wide band-gap semiconducting material 4H-SiC has been illuminated by appropriate optical beam in two configurations viz., Flip-Chip and Top-Mounted. The properties of the illuminated device has been studied and compared with those of the unilluminated device. From the results, it has been observed that both the electron and the hole dominated photocurrents influence the breakdown voltage, efficiency, optimum frequency, negative resistance and negative conductance of the device. Due to the effect of illumination, the optimum frequency for maximum negative conductance shifts towards lower and higher values for electron and hole dominated photocurrents. The negative resistance increases while negative conductance decreases for both TM and FC configurations. The effect of illumination is found to be more pronounced for hole dominated photocurrent than for electron dominated photocurrent. Hence by optical illumination the optimum frequency may be shifted either upwards or downwards with an increase in negative resistance and microwave power depending on the configuration of
illumination. The results are important and can be used for optical switching of operating frequency and consequent alteration of microwave power of 4H-SiC Impatt diodes.

Flat profile SDR InP Impatt at W-band frequencies has been designed by computer method. Different DC and RF properties are obtained by computer simulation. The Impatt devices are based on the mechanism of impact ionization and avalanche multiplication of charge carriers. Hence, avalanche noise is inherent in the mechanism. The objective of this section in Chapter VII is to study the effect of illumination on the avalanche noise and also the relative dependence of the avalanche noise on the photo-generated electron- and hole-dominated leakage currents. The mean square noise voltage per bandwidth $<V^2>/df$ and the avalanche noise measure $M$ are calculated for the device. It is observed that the effect of the hole-dominated leakage current is more significant on the avalanche noise measure, optimum frequency, Q-factor and the power output of the device than the effect of electron-dominated leakage current. Thus, the $p^+\text{-}n\text{-}n^+$ device should be illuminated from the junction side so that the photo-generated leakage current is dominated by electrons in order to reduce the effect of optical illumination on the avalanche noise measure and negative resistance and hence the power output of the device.

In the next section of Chapter VII, studies have been carried out by realistic analyses of the millimeter-wave properties of photo-illuminated DDR InP Impatts at two important window frequencies of 94 and 140 GHz by taking elevated junction temperature as high as 500 K to which the device can be limited with a proper heat-sink arrangement and circular ring geometries described in Section 8.5 in Chapter VIII in page no. 227. The design of the devices is optimized through a double iterative simulation technique used for analysis of Impatts considering the effect of mobile space charge and carrier diffusion. It is observed that the DDR InP Impatt diode is capable of generating a maximum of 427.0 mW (diode area = $10^{-10}$ m$^2$) and 358.4 mW (diode area = $0.5 \times 10^{-10}$ m$^2$) CW power
with DC to RF conversion efficiency of 14.5% and 13.0% at the optimum frequencies of 95 and 145 GHz respectively. The study reveals that the photo-generated leakage current reduces the RF power output and negative resistance of the devices along with an upward shift of operating frequency for both the Flip-Chip and Top-Mounted illumination configurations. The simulation study also shows that the optical modulation of mm-wave properties of Flip-Chip configuration is more pronounced than that of Top-Mounted configuration at both 94 and 140 GHz window frequencies. The device designed at higher window frequency (140 GHz) is more sensitive to optical modulation than the device designed at lower window frequency (94 GHz). This study will be useful for the optical control of DDR InP IMPATTs in millimeter-wave communication systems, radar tracking and missile guidance.

THz electronics emerges and finds prospect of important applications in the areas of imaging, communication and armed forces. This involves in generation, amplification, detection, mixing and multiplication of signals in the THz frequency bands. This employs mainly homo- and hetero-junctions of III-V binary and ternary semiconductors. In Chapter VIII of this thesis an attempt has been made by the author to compare the prospect of Impatt devices in the form of DDR diodes based on InP and Wurtzite GaN semiconductors as THz sources. Also, then the optical control of these devices have been studied in this chapter and the results are presented.

GaN DDR Impatt diodes are designed for 0.3 THz at $J_0=0.5 \times 10^8 \text{ Am}^{-2}$ and for 0.5 THz at $J_0=1.1 \times 10^8 \text{ Am}^{-2}$. The peak electric field is found to be very high $\sim 10^8 \text{ Vm}^{-1}$ and the DC to RF conversion efficiency is more than 15% for both the GaN diodes. The critical electric field for GaN Impatt is very high in comparison to that of InP Impatt. The avalanche breakdown voltage for the GaN Impatts are 110.26 V and 73.57 V in contrast to 14.68 V and 7.29 V for InP Impatts at 0.3 THz and 0.5 THz respectively.
From the results, it has been observed that the optimum frequency at which negative conductance attains peak value in the admittance plot (G-B plot) for DDR GaN Impatts is exactly equal to the design frequency of 0.3 THz at $J_0=0.5 \times 10^8$ Am$^{-2}$ and for 0.5 THz at $J_0=1.1 \times 10^8$ Am$^{-2}$. The peak negative conductance ($-G_p$) at optimum frequency for GaN Impatts is higher than corresponding values of ($-G_p$) of InP Impatts. The quality factor of THz InP Impatts is less than 1 and that for THz GaN Impatts is greater than 1 indicating that the growth rate of oscillation and the stability of the oscillation in InP Impatts is better than those in GaN Impatts at THz frequencies.

The effect of hole dominated photogenerated leakage current is more pronounced than the electron dominated leakage current in DDR InP Impatts at THz frequencies. The frequency chirping bandwidth is ~100 MHz in GaN THz Impatts while the same is ~1-2 GHz in InP Impatts.

Formulation of total thermal resistance for ordinary mesa structure IMPATT diode mounted on semi-infinite heat sink is also presented in Chapter VIII. Accuracy in determination of total thermal resistances actually provides accurate and optimum design of heat sinks for steady and safe operation of IMPATT oscillators in continuous wave mode which is capable of avoiding burn-out phenomena. Keeping in mind the cost of the whole system, typical equivalent heat sink designs are presented for IMPATT diode sources with different base materials operating at different frequencies by using both diamond [High Cost] and copper [Comparatively Low Cost].

**Outlook and future scope**

The studies presented in this thesis can be further extended for the design and development of SDR and DDR structures of Impatt diode based on different semiconducting materials at higher THz frequencies greater than 0.5 THz by incorporating the effects of tunneling, series resistance, etc. Further, WBG semiconducting materials like SiC and GaN which may be suitable for realization
of THz sources can be used along with the potentiality of InP as THz sources. A lot of scope exists for the experimental realization of millimeter-wave and THz IMPATTs based on the design, structural and performance parameters obtained from simulation results and presented in this thesis. As regards the experimental realization particularly the ohmic contacts, discussion has already been made in Chapters V (for 4H-Silicon Carbide) and VIII (for Gallium Nitride). The outline of fabrication described in details in Chapters V and VIII can be followed to realize the device experimentally. Measurement of RF characteristics of the fabricated device can then only be done to compare the experimental results with the theoretical results. So far as the author's knowledge is concerned, no experimental report is yet available as regards to the experimental results for most of the theoretical results simulated by the author. However, the designed results presented in the thesis may be useful to the future experimentalists to realize the expected performance from the IMPATT devices.