Chapter-II
CHAPTER II

AN OVERVIEW OF DIFFERENT PHYSICAL PHENOMENA GOVERNING THE PROPERTIES OF IMPATTs BASED ON DIFFERENT MATERIALS

2.1 Introduction

The present thesis is concerned with the investigations on (i) the effects of some physical phenomena on the high frequency properties of Impatts and (ii) design and simulation of Impatts based on emerging semiconducting materials like 4H-SiC, Si_{1-x}Ge_{x}/Si and GaN along with InP. The important physical phenomena which control the DC and high frequency properties of Impatt diodes are large mobile space charge at high bias current, tunnelling, diffusion, saturation of carrier drift velocity and saturation of carrier ionisation rates at high electric field, avalanche noise and increased leakage current with optical illumination. The present thesis is concerned with studies of these physical phenomena limiting the performance of Impatt diode and the same will be presented in section 2.2. Remarkable progress in the research and development of Impatt diodes has been achieved in respect of DC to RF conversion efficiency, RF output power, thermal resistance and noise at millimeter wave frequencies over the past three decades. Impatts based on wide band gap materials are potential sources of power at terahertz frequencies. A review on the possibility of use of these materials for Impatt action will be presented at the end of this chapter.

2.1.1 Important Millimeter-wave frequencies for communication

The microwave frequency ranges from 3-30 GHz are becoming saturated with land-based and satellite-based communication system, due to the ever increasing demand of communication. Millimeter waves undergo considerable attenuation while propagating in the atmosphere. Hence, communication is generally carried out at and around window frequencies with low atmospheric attenuation. The atmospheric attenuation for mm-waves against frequency is
shown in Fig.2.1. From the figure, it is evident that the atmospheric attenuation is low in the frequency bands around 35 GHz, 94 GHz, 140 GHz and 220 GHz. So, Impatt diodes already developed and the ones yet to come are targeted around these atmospheric window frequency bands. Around 60 GHz, a peak is observed in the figure having maximum atmospheric attenuation. So, this 60 GHz band is normally used for the secure communication in defence applications.

2.2 An overview of different Impatt structures and physical phenomena governing the properties of Impatt diode

2.2.1 a) Flat profile single drift structures of Impatt diodes

The simplest and the most commonly grown structure of Impatt for CW operation at mm-wave frequencies is a flat profile single drift region (SDR) p⁺nn⁺ structure. This structure is now commercially available for device operation at 94 GHz and above. The single drift p⁺nn⁺ structure is preferred to the complementary n⁺pp⁺ structure because nn⁺ Silicon substrate is more easily available than pp⁺ substrate. Further the extent of the undepleted region between the edge of the depletion layer and the interface of epitaxy and substrate (unswept epitaxy) which contributes positive parasitic resistance and thereby dissipates microwave power is smaller in p⁺nn⁺ structure than in the complementary n⁺pp⁺ structure. Thus higher microwave power output can be obtained from p⁺nn⁺ diode as compared to that from n⁺pp⁺ diode.

The structure, doping profile and the field profile of typical single drift structures of Impatt diodes are shown in Fig.2.2. These structures have been fabricated by various techniques such as diffusion, ion implantation, molecular beam epitaxy (MBE) and metallorganic vapour phase epitaxy (MOVPE) techniques. The most common semiconductors used for fabrication of SDR structures of Impatt diodes are Ge, Si and GaAs. InP is also another important semiconducting material for fabrication of mm-wave Impatt diodes due to the possibility of high power generation from InP Impatts. Some wide band gap
Fig. 2.1: Atmospheric attenuation of millimeter-waves.
Fig. 2.2: Schematic diagram of (a) structure (b) doping profile and (c) electric field profile of SDR Impatt diode.
materials like 4H-SiC and GaN are also suitable for high power Impatt diode at millimeter wave and Terahertz frequency regions.

The depletion layer of an SDR p+nn+ Impatt diode consists of (i) an avalanche zone near the p+n junction where impact ionisation and avalanche multiplication take place at high electric field and (ii) a drift region where the electric field is neither too high nor too low to enable the carriers to cross the region with saturated drift velocity, but without suffering avalanche multiplication. The magnitude of the electric field in the avalanche region is greater than $10^7\, \text{V/m}$ while that in the drift region is in the range of $10^6\, \text{V/m}$ and $10^7\, \text{V/m}$. The field profile of SDR structure exhibits the shape of a right angled triangle at normal current density. The structures are normally just punched through or slightly punched through at breakdown. The avalanche zone occupies about 30% of the depletion layer under normal operating conditions. The width of the avalanche zone depends on the material parameters, doping profile, bias current density and the type of structure.

It has been reported that n+pp+ structure has narrower avalanche zone than p+nn+ structure of Silicon Impatts [23] which leads to higher conversion efficiency of n+pp+ Silicon Impatt diodes. But in case of InP and GaAs Impatts the situation is just reversed. Banerjee et al. [24] showed from computer simulation that the p+nm+ structures of both InP and GaAs Impatts have narrower avalanche zones and higher conversion efficiency than their n+pp+ counterparts. The fabrication of InP and GaAs SDR Impatts has been done mostly with p+nn+ structures because these structures have the potential advantages of better avalanche characteristics, lower power dissipation due to parasitic resistance arising from unswept epitaxy and easier and more advanced n+ Silicon substrate technology. The widths of the avalanche zone is narrower and DC to RF conversion efficiency is higher in Silicon SDR n+pp+ Impatts than those in Silicon SDR p+nm+ Impatts because the ionisation rates of electrons are higher than those of holes ($\alpha_n > \alpha_p$) in Silicon according to the reported experimental results [25]. On the other hand the
experimental results show that $\alpha_p > \alpha_n$ in Indium phosphide [26] and thus the avalanche zone width is wider and conversion efficiency is lower in InP n$^{+}$pp$^{+}$ Impatts than those in InP p$^{+}$nn$^{+}$ Impatts.

b) Flat profile double drift structures

A remarkable development regarding the performance of Impatt diodes took place in 1970 when Scharfetter et al. [34] proposed a double drift region (DDR) Impatt diode which is characterised by a central avalanche zone surrounded by two drift zones, one for electrons and the other for holes. The typical structure of a reverse biased p$^{+}$nn$^{+}$ DDR Impatt diode, its doping profile and field profile are shown in Fig.2.3. The electric field $E(x)$ is a function of the distance $x$. The ionization rates for electrons ($\alpha_n$) and holes ($\alpha_p$) are very strong functions of the electric field $E$. Thus ionization rates are functions of the distance $x$, represented in Fig.8.1 in page no.213 in chapter VIII obtained in the computer simulation and they are very much dependent on the location in the depletion layer. The avalanche multiplication of charge carriers takes place in the central high field avalanche zone around the metallurgical junction and the generated electrons and holes drift in opposite directions through the respective drift regions on n and p sides of DDR diode and are finally collected at n$^{+}$ and p$^{+}$ contact regions. In DDR Impatt diodes both electrons and holes contribute to negative resistance and microwave power while drifting in opposite directions on either side of the avalanche zone. But in SDR Impatt diodes only one type of charge carrier, i.e., either electrons or holes contribute to microwave power when they cross the respective drift layers. Thus compared to SDR diodes, DDR diodes are expected to deliver higher RF power.

The superior performance of DDR Impatts as compared to SDR Impatts at higher mm-wave frequencies can also be understood from the basic $P f^2 X$ law. This law shows that a power-frequency trade off exists in Impatt diodes which is given by
\[ Pf^2 X = \left( \frac{V_s^2 E_m}{16\pi} \right) = \text{Constant} \]

If the reactance \( X \) is constant then \( Pf^2 = \text{Constant} \).

Here \( P \) is the output power at a frequency \( f \), \( V_s \) is the saturated drift velocity and \( E_m \) is the peak field at the junction. Thus for the same circuit impedance level (\( X=\text{Constant} \)), the output power decreases with the increase of frequency following \( 1/f^2 \) rule. The basic power capability of DDR diodes in terms of \( Pf^2X \) product is quadrupled with respect to that of SDR diodes at a particular frequency due to the following reasons: The DDR diode has an additional drift region and therefore the width of the drift layer (\( w_D \)) and the voltage across this layer (\( v_D \)) are doubled with respect to those of SDR diodes. The output power of Impatt diodes is proportional to the drift zone voltage for a fixed device dimension and a constant bias current density. Therefore the output power of DDR Impatts is twice that of SDR Impatts at a particular frequency if the efficiency is assumed to be same for SDR and DDR diodes.

The effective shunt capacitance (\( C \)) of DDR diode is halved as compared to that of SDR diode since the depletion layer width of DDR diode is nearly twice that of SDR diode. The capacitive reactance of DDR diode is thus doubled and the frequency at which the diode is impedance limited increases by an octave. The basic \( Pf^2X \) product of DDR diode is then four times higher than the conventional SDR diode. At higher mm-wave frequencies, SDR diodes are impedance limited but DDR diodes are thermally limited.

At very high electric field dislocations, vacancies may arise in the device resulting in decreasing rate of ionizing collisions; this in turn increases the avalanche response time and degrading the negative resistance and hence output power. But the junction of the device is located away from the surface in case of DDR device. The surface is the source of dislocation and voids. High electric field exists in the avalanche zone near the junction then it falls rapidly to the edge, as seen from the electric field profile. So, the surface electric field is very much low.
Fig. 2.3: Schematic diagram of (a) structure (b) doping profile and (c) electric field profile of flat profile DDR Impatt diodes
So there is no chance of the limitation of reliability of the device due to high electric field resulting creation of dislocations, vacancies etc. However, there may be some limitations on reliability in case of SDR diodes.

The superior performance of DDR Impatt diodes for 50 GHz CW operation was experimentally demonstrated by Seidel et al. in 1971 [38]. They reported a CW output power of 1W with 14.2% conversion efficiency from flat profile DDR diodes and 0.53 W power with 10.3% conversion efficiency from SDR diodes at 50 GHz frequency. Thus both power and efficiency of DDR diodes are higher than those of SDR diodes. The additional drift region of DDR diodes provides the basic advantage over SDR diodes as regards higher breakdown voltage, higher drift zone voltage and larger depletion layer width. The other advantage is that the central avalanche zone of DDR diode reduces the minority carrier storage effect and thereby increases the efficiency of the device.

The electric field profile of a symmetrically doped flat profile DDR diode has the shape of an isosceles triangle at normal bias current density and the peak field at the junction is located at the vertex of the triangle. The magnitude of the peak field of DDR diode is lower than that of SDR diode at the same frequency of operation and same bias current density. The electric field profiles of DDR silicon Impatt diodes at X-band are distorted at higher current densities due to the effect of space charge. The effect of mobile space charge on the electric field profiles and the DC and RF properties of DDR InP Impatts has been investigated by the author at 60, 94 and 140 GHz frequencies. Sridharan and Roy [39] showed that the avalanche zone of X-band silicon DDR Impatts widens with the decrease of device efficiency and peak negative conductance due to mobile space charge at higher current densities. Pati et al. [40] further reported that the negative resistance of the two drift layers of mm-wave DDR silicon Impatts falls appreciably at high values of current density.
A detailed investigation of the space charge influenced DC and RF properties of flat profile DDR InP Impatts at 60, 94 and 140 GHz window frequencies will be presented in Chapter IV of this thesis.

c) Quasi read structures of Impatt diodes

The efficiency of Impatt diodes can be improved considerably through suitable modification of the flat doping profiles [98, 99]. A highly doped region (impurity bump) can be introduced at various positions of the depletion layer of the diode. A bump located beside the junction will give rise to a high-low (HL) doping profile. When the bump is slightly away from the junction and surrounded by two lightly doped regions on either side, a low-high-low (LHL) doping profile results. The HL and LHL doping profiles of Impatt diodes are known as quasi-Read or Read like profiles. The main idea behind the introduction of impurity bumps in the flat doping profiles of Impatt diodes is to localise or constrict the avalanche zone and increase the device efficiency. The typical doping profiles and field profiles of single drift high-low and low-high-low Impatt diodes are shown in Fig.2.4. The peak electric fields at the p-n junctions of both HL and LHL diodes are pushed up with respect to that of flat profile diodes. The higher fields within the avalanche zones of these quasi-Read Impatt diodes augment the carrier multiplication process due to the increase of ionisation rates which, in turn, constrict the avalanche zone and increase the device efficiency. Most of the theoretical and experimental investigations on these quasi-Read HL and LHL SDR structures have been made with GaAs Impatts. Nishitani et al. [100] carried out theoretical and experimental studies on single drift GaAs HL diodes. Goldwasser et al. [101], Heaton et al. [102] and Bozler et al. [103] studied the RF performance of LHL SDR GaAs Impatts. They reported high efficiencies of these quasi-Read Impatt diodes.

The performance of flat profile DDR Impatts can also be improved with respect to output power and efficiency with HL and LHL doping profiles. Thus
Chang et al. [78] theoretically designed the LHL profiles of DDR Silicon Impatts and predicted an efficiency of 19% at 50 GHz.

### 2.2.2 Space charge effect at high bias current

At high bias current, the space charge of the accumulated electron bunch in the drift zone modifies the electric field profile as shown in Fig. 2.5. The electric field is depressed behind the electron bunch and is increased in front of the pulse in such a way that the area under the field curve remains unchanged. The change in field $\Delta E$ between the leading and trailing edges of the pulse is related to the total charge in the pulse $Q$ by Gauss’s law.

$$\Delta E = Q/\varepsilon$$  \hspace{1cm} (2.1)

where $\varepsilon$ is the permittivity of the material.

As the electron bunch moves across the zone from left to right the amount of field depression behind the pulse decreases, but the field in front of the charge pulse steadily increases. This field distortion produces a deleterious effect in the avalanche zone limiting the power generated from the drift zone [152].

The reduced field at the junction leads to premature decay of avalanche pulse as Fig. 2.5 shows the peak field in the avalanche zone, the voltage at the diode terminals, and the external current as functions of time. The field in the avalanche zone drops prematurely below the breakdown field at time $t_1$ and the avalanche multiplication ceases to occur. However, the voltage waveform is unaffected by the redistribution of field within the device due to space-charge effect. Thus, the current flows in the device during the positive half cycle of ac voltage and a.c. power is dissipated during this time interval ($\Delta T$). In addition, since the electron transit time is one-half of the period of the a.c. cycle, the current turns off before the a.c. voltage returns to zero. Clearly the efficiency of the device is degraded. As the current level increases, effect of mobile space-charge is more pronounced and the efficiency degradation gets worse.
Fig. 2.4: Schematic diagram, doping profile and electric field profile of (a) single drift high-low structure (b) single drift low-high-low structure Impatt diodes.
In the drift space two effects are important. As the electron bunch approaches the anode the field in front of the pulse increases sharply due to the carrier space charge. This occurs during the part of the cycle when the a.c. field is increasing and approaching the d.c. level. To avoid impact ionisation at this point in the structure, the field at the leading edge of the pulse must always be less than the breakdown value. If ionisation is allowed to take place at the anode, a pulse of holes will be produced which will then drift towards the cathode during the subsequent half-cycle and induce a current in the external circuit when the a.c. voltage is positive, causing a.c. power dissipation. An upper limit for the total charge $Q$ in the electron pulse is obtained by setting the field rise at the anode $\Delta E$, equal to the breakdown field $E_B$. Clearly this somewhat overestimates the maximum allowable charge, but we are assuming that the d.c. field in the drift zone is small compared with the breakdown field. Then by Gauss's law

$$Q_{\text{max}} = \varepsilon E_B$$  \hspace{1cm} (2.2)

One electron pulse is produced each cycle and therefore the dc current density $J_0$ is given by

$$J_0 = Qf$$  \hspace{1cm} (2.3)

where $f$ is the frequency of oscillation. Thus the maximum current density to prevent ionisation in the drift space is, from (2.2) and (2.3),

$$J_0 (\text{max}) = \varepsilon E_B f$$  \hspace{1cm} (2.4)

For current densities greater than this value the avalanche diode will not oscillate in the IMPATT mode. In practical devices, at low frequencies (below about 50 GHz), the current density is limited by heating effects to values well below this critical value. However, at millimeter-wave frequencies the operating current density may approach or even be limited by the critical value. We shall return to
Fig. 2.5 (a): Effect of mobile space charge on electric-field profile.

Fig. 2.5 (b): Effect of space charge on field, voltage and current.
this point again when we discuss the power frequency relationship for the IMPATT oscillator.

The field depression behind the electron pulse in the drift zone may also degrade the performance of the device. The field must everywhere remain above the value required to produce velocity saturation for optimum operation in the IMPATT mode. The field depression is greatest as the electron pulse emerges from the avalanche region, but the minimum in the a.c. field swing occurs when the electron pulse is halfway across the drift space. Thus the position within the drift zone at which the field is a minimum depends on the relative magnitudes of the a.c. swing and the field modulation produced by the carrier space charge. If the field is allowed to drop below the saturation value, the electrons at the trailing edge of the pulse will slow down. The electron bunch will spread out and eventually collapse, destroying the phase relationship between the voltage and current in the external circuit.

When breakdown occurs and oscillation starts at appropriate conditions in Impatt diode, the voltage decreases and bias current increases. The S-type instability of bias current continues to persist during oscillations with change in bias current within the burn-out limit. Under oscillation conditions at breakdown the change in bias current causes a slight change in frequency and RF output power.

2.2.3 Thermal limitation of Impatt Diodes

The output power and efficiency of both SDR and DDR Impatt diodes decrease sharply at higher mm-wave and sub mm-wave frequencies. The efficiency of Si Impatt device falls from 11% to 5% when the frequency increases from 50 GHz to 100 GHz. Therefore a large fraction of input power of the device is dissipated as heat which causes a rise of junction temperature above the ambient. When the temperature rises to a certain level, thermal runaway occurs leading to burn-out failure of the diode. The rise of junction temperature depends
on the thermal resistance ($R_{th}$) which is defined as the temperature rise per unit power dissipation i.e., $R_{th} = (T_B - T_0)/P_{dis}$.

where $T_B$ is the burn-out temperature, $T_0$ is the ambient temperature and $P_{dis}$ is the amount of microwave power dissipated as heat. The junction temperature $T$ of an Impatt diode under large signal CW operation is given by [41]

$$T = 300 + R_{th} (1 - \eta) V_{dc} J_{dc} A$$

where $\eta$ is the conversion efficiency, $V_{dc}$ is the dc voltage, $J_{dc}$ is the direct current density and $A$ is the area of diode. The thermal resistance of DDR Impatts is given by [41]

$$R_{th} = (2/\pi K_{hs} d) + R_{pkg} + (4l_1 T_1/120 \pi d^2) + (4l_2 T_2/300 \pi d^2)$$

where $d$ is the device diameter, $K_{hs}$ is the thermal conductivity of the heat sink material, $R_{pkg}$ is the thermal resistance due to packaging and bonding, $l_1$ is the substrate thickness, $T_1$ is the average temperature of the substrate, $l_2$ is the active layer thickness and $T_2$ is the average temperature of the active region. The first term of the above equation corresponds to the spreading resistance between the diode and the heat sink [42]. The third term is the thermal resistance of the substrate and agrees well with Olson's expression and experimental data of Maycock [43,44].

It may be noted that higher output power can be derived from SDR and DDR Impatt diodes in pulse mode of operation as compared to CW mode of operation. In pulsed Impatt diodes a rapid transient rise of temperature takes place during each power pulse with a slower increase of temperature in the heat sink. The pulse width may be less than a microsecond while the temperature of the heat sink may require hundreds of microseconds to reach thermal equilibrium state. A number of transient thermal analysis of Impatt diodes has been reported by several authors [45, 46]. Olson showed from one dimensional analysis that the transient response depends on the chip size and the temperature changes significantly for
the time intervals ranging from less than 0.1 μs to several microseconds [43]. Holway [167] calculated the temperature in a pulsed X-band DDR Impatt diode not only as a function of position and time but also as a function of pulse width and duty factor by using numerical techniques. He also defined the thermal resistance of pulsed diodes taking into account of the reliability of the diode.

Thermal analysis is very much important in designing proper heat-sink for the IMPATT diodes based on different semiconducting materials operating at different millimeter-wave and sub-millimeter wave frequencies including THz frequencies and will be presented in details in Chapter VIII.

A large current flows through the active layer of the Impatt diode based on different materials, which ranges from $10^8$ A/m$^2$ to $10^9$ A/m$^2$ for a wide range of operating frequencies. The breakdown voltage ranges from 376 V to 15 V. The power density is extremely high ($10^8$ to $10^{10}$ W/m$^3$) in these cases. The efficiency of the Impatt diode is relatively low; hence a large fraction of the DC power is dissipated as heat in the high field region in the device. The temperature at the junction of the Impatt diode rises above the ambient and the output power of the oscillator is limited by the rate at which the heat can be extracted from the device. So for the reason stated above, there exists a temperature gradient in the device having the peak of the temperature at the junction. As the junction temperature increases, the reverse saturation current rises exponentially and eventually leads to thermal runaway resulting in the destruction of the device. Unlike the avalanche current the reverse saturation current does not require a large voltage to sustain it; hence the voltage begins to decrease as the junction gets hot enough for the reverse current to constitute a significant fraction of the total current. A thermally induced DC negative resistance is produced causing the current to concentrate in the hottest part of the diode. This leads to the eventual burn-out of the junction but the increased saturation current at elevated temperatures produces degradation in the oscillator performance at power levels below the burn-out value. The increased reverse saturation current produces a faster build-up of the avalanche
current and degrades the negative resistance of the device. Thus in general, the oscillator efficiency will begin to decrease at power levels just below the burn-out power. The larger the band-gap of the semiconductor the smaller is the reverse saturation current and consequently the higher is the burn-out temperature of the junction. Thus Impatts based on Ge \([E_g=0.66 \text{ eV}]\), Si\(_{0.7}\)Ge\(_{0.3}\) \([E_g=0.98 \text{ eV}]\) and Si \([E_g=1.12 \text{ eV}]\) are lower power devices than InP \([E_g=1.35 \text{ eV}]\) and GaAs \([E_g=1.42 \text{ eV}]\) devices. In contrast to these, Impatts based on WBG semiconductors such as 4H-SiC Impatts \([E_g=3.26 \text{ eV}]\) and Wz-GaN Impatts \([E_g=3.36 \text{ eV}]\) are higher power devices.

The thickness of the device is very much small that’s why the thermal resistance of the device is low; this in turn increases the temperature of the junction. For this reason heat sink with proper design has to be used in conjunction with the device in order to increase the thermal resistance of the system so that the temperature of the junction of the device can be restricted well below the burn-out temperature of the junction of the device based on the particular material or material system.

### 2.2.4 Effect of tunnelling on IMPATT diode performance at 100 GHz and above

At higher frequencies of operation above 100 GHz the active layer of an Impatt diode decreases considerably (< 2 \(\mu\)m) together with appreciable increase of peak electric field at the junction (> 10\(^3\) KV/cm). Under these conditions the tunnelling of carriers across the thin active layer becomes the significant mechanism of carrier generation. The tunnel current in Impatt diodes was considered by Read in a very early paper [47]. Kowk and Haddad [48], Dash and Pati [49] and Chive \textit{et al}. [50] studied theoretically the effect of tunnelling on Impatt diodes. The reverse breakdown in a diode is avalanche dominated for low electric fields <500 KV/cm and tunnel dominated for high electric fields > 1000 KV/cm. Three distinct modes of operation were identified by Elta and Haddad.
for different ranges of breakdown field and generation region widths. These modes are i) the normal Impatt mode (E<500 KV cm⁻¹), ii) the MITATT (mixed tunnelling and avalanche transit time) mode (500<E<1000 KV cm⁻¹) where both tunnelling and avalanche breakdown take place and iii) the TUNNETT (tunnel transit time) mode (E>1000 KV cm⁻¹) where pure tunnelling breakdown occurs. The common Impatt mode is inherently noisy but has a relatively large RF output power. The Tunnett mode is characterised by the injected current pulse being in phase with the RF voltage which results in lower negative resistance and RF output power. The Tunnett devices would be attractive for their low noise and medium power application. The Mitatt mode devices would exhibit a noise power trade off. Elta and Haddad [52] showed from large signal analysis of Read type structures of these devices that the efficiency of GaAs Read type Tunnett mode structures increased with frequency up to 6% at 100 GHz and then decreased with frequency. They further observed that Silicon Impatt have higher tunnelling frequency limit (~400 GHz) compared to GaAs Impatts (~75 GHz). GaAs Impatts operate in Mitatt mode for the frequency range of 75 to 150 GHz. The tunnelling current can also improve the high frequency performance of GaAs diodes for operation above 100 GHz.

Nishizawa et al. [53] verified experimentally that the above prediction is indeed true for GaAs Tunnett devices. They realised a pulsed output power of 10 mW at 338 GHz from these Tunnett diodes. GaAs Mitatt mode diodes were realised by Elta et al. [54] in 1980 who demonstrated 3 mW RF output power at 150 GHz with 1-2% conversion efficiency from Schottky barrier diodes. GaAs Tunnett mode devices were first realised in 1990 for CW operation at mm-wave frequencies but the RF performance of these devices was not satisfactory [55]. Significant improvement in the RF power performance of MBE grown GaAs Tunnett devices was demonstrated by Kidner et al. [56] at W-band frequencies. Further no saturation of RF output power and efficiency at the maximum bias current level was observed in majority of these Tunnett devices. These devices
were mounted on integral heat sinks and maximum operating junction temperature was limited to 250°C to ensure good reliability and long life time. Very recently Eisele and Haddad [57] mounted single drift GaAs Tunnett devices on diamond heat sink for further improvement of thermal resistance and output power. An RF output power of more than 70 mW at 105.4 GHz with an efficiency of 4.9% was obtained from MBE grown GaAs Tunnetts.

The aforementioned results on the performance of flat profile and Read type GaAs Impatts and Tunnetts at mm-wave V-band, W-band and D-band frequencies are exciting enough to explore the potentiality of these devices at still higher frequency bands. The high power capability of these devices at D-band and W-band frequencies can further be enhanced with proper design of diode and circuit parameters including the package and cavity.

2.2.5 Effect of increased leakage current on Impatt devices through optical illumination

The review of the experimental and theoretical studies of Impatt devices presented in the previous sections of this chapter show that the output power and frequency of oscillation of Impatt devices can be modulated by changing the bias current through the electrical terminal. The device properties are controlled electrically by tuning the bias current. Besides electrical control, the illumination of the active area of an Impatt diode by an optical signal through the optical terminal can also modulate various RF properties of the device. The author has studied the optical modulation of the millimeter wave properties of flat profile single drift and double drift Impatt diodes at different microwave and mm-wave frequencies. It will be most appropriate in this connection to present a brief review of the experimental and theoretical works in the field of optical control of Silicon and Gallium Arsenide Impatt diodes.

The optical illumination of an Impatt diode leads to an enhancement of reverse saturation current due to photogenerated carriers. The effect of reverse
saturation current on the dynamics of avalanche growth of carriers in a Read Type diode was studied by Misawa [58] in 1970. Avalanche build up time is determined by the magnitude of reverse leakage current entering the depletion layer of the diode. The increase of reverse leakage current due to optical illumination leads to a premature 'turn on' of avalanche current and thus the phase delay involved in the avalanche growth of charge carriers is reduced. Misawa showed that the conversion efficiency of the device degrades because the phase delay between the ac voltage and the avalanche current decreases from 90° to an angle less than 90°. Thus the net phase difference between the RF voltage and terminal current becomes less than 180°. The oscillator efficiency for a square wave current is

\[ \eta = \frac{2}{\pi} \left( \frac{V_{ac}}{V_{dc}} \right) |\cos \phi| \]

where \( V_{ac} \) = ac signal voltage and \( V_{dc} \) = dc bias voltage and \( \phi \) is the phase angle between current and voltage. When the leakage current is large \( \phi < 180^\circ \) and \(|\cos \phi| < 1\), so the efficiency decreases.

Decker et al. [59] studied the effect of increased leakage current on the performance of an avalanche diode having an imperfect ohmic contact. The enhancement of leakage current in this case is due to carrier injection across the metal semiconductor contact into the junction side of the avalanche diode. They showed a decrease of efficiency ranging from 1% to 9% due to the increase of reverse saturation current by 6% (injected current to total current ratio increases by 6%).

Analytical studies of Roy et al. [60] showed that if the carrier current multiplication factor (\( M \)) in the avalanche layer of Read type Impatt diode is lowered, the device negative resistance decreases and the avalanche resonant frequency increases for a fixed bias current density of \( J_0 = 1 \text{ KA cm}^{-2} \).
Experimental studies on the composition of leakage current

The first experimental study on the effect of enhanced leakage current on the oscillator characteristics of Impatt diodes was carried out by Borrego et al. [61] in 1972. They used ionising radiation to enhance the leakage current and varied the percentage of ionisation induced current over the bias current between 0.1% to 0.3% and observed a maximum 20% reduction of output power. Cottrell et al. [62] also experimentally studied the effect of increased leakage current due to irradiation of the active area by an electron beam on the behaviour of X-band GaAs and Silicon Impatt oscillators. They observed a decrease of RF power accompanied by an increase of oscillation frequency of the device under optical illumination.

Experimental studies on the electron versus hole photocurrent

Vyas et al. [63] experimentally and theoretically studied the effects of the magnitude and the composition of photogenerated leakage current on the properties and performance of Si Impatt diodes. They used He-Ne laser to illuminate the active region of p⁺nn⁺ SDR IMPATT diode through the optical window of the annular ring fabricated on the gold plated top contact of the device. The composition of leakage current was changed either to hole dominated or to electron dominated components by using two types of illumination configuration of p⁺nn⁺ devices. One of them is called a Flip-Chip (FC) device in which the junction is downwards and substrate is upwards. When light is incident on the top surface, photogenerated hole dominant leakage current is produced. The other type of p⁺nn⁺ device is known as Top-Mounted (TM) device in which the junction is upwards and substrate is downwards. In the TM device, photogenerated electron dominated leakage current is produced when light is incident on the top surface. Vyas [63] showed that a photocurrent of 500 μA could be generated by focussing He-Ne laser source (2.5 mW power) having λ = 6328Å with a plano convex lens on the optical window of the device.
The magnitude of the photogenerated leakage current was varied in their experiments by neutral density filters. The RF measurements showed that, without leakage current a pulsed power output, (pulse width = 200 ns) of 250 mW was obtained at a bias current density of 500 A/cm². They observed that a flat profile Silicon Impatt diode was more sensitive to electron leakage current than to hole leakage current of the same magnitude. For example RF power at the maximum bias current of 80 mA (≈ 500 A/cm²) decreased from 250 to 200 mW at about 50 μA photogenerated leakage current for a TM device while a similar reduction in RF output power of an FC device occurred at a photogenerated leakage current of 500 μA [63]. The increase in frequency of oscillations was nearly the same i.e., (≈10 MHz) for TM and FC devices at a factor of 10 difference in leakage current. The frequency increased from 9.88 to 9.99 GHz for a TM device for a 50 μA photogenerated leakage current and from 10.855 to 10.865 GHz for FC device at a leakage current of 500 μA. They also explained the above difference in sensitivity of power output and frequency of oscillation of Impatt diodes due to electron and hole dominated photocurrent by an order of magnitude from a large signal model developed by Cottrel. A good agreement was obtained between the experiment and the theory as regards RF power versus bias current characteristics.

The noise due to electron and hole dominated photocurrents in Si flat profile X-band Impatt oscillators was studied experimentally by Pinter et al. [64] who showed that the oscillator characteristics degrade more appreciably for the noise due to electron dominated photocurrent than for the noise due to hole dominated photocurrent. The experimental results also indicated that the fluctuations of effective leakage current levels of 0.1% significantly increased the oscillator noise level. The composition of the photogenerated leakage current plays an important role to control the properties of Impatt diodes.

The author has studied the effect of the composition of photogenerated leakage current on the DC and RF properties of flat profile single drift p⁺nn⁺ and double drift p⁺pnn⁺ Impatt diodes based on Indium Phosphide and p⁺nn⁺ (SDR)
4H-SiC Impatts in mm-wave frequencies. Studies on the optical control of device properties of GaN and InP Impatts in THz frequencies are also carried out. The study is based on a novel computer simulation method first suggested by the author. The results of these studies on Impatts in mm-wave frequencies are presented in Chapter VII and those in THz frequencies are presented in Chapter VIII of this thesis.

Optical injection locking

Optical injection locking of oscillators was first demonstrated in silicon bipolar transistors. The optical injection locking has several advantages over electrical injection locking. These advantages are that the i) locked and the locking sources are optically isolated and the ii) microwave and millimeter-wave waveguides are replaced by optical fibres. If the incident optical signal is modulated at a frequency close to that of the Impatt oscillator, phase locking takes place. Frequency change of oscillator due to optical illumination is within the locking range and microwave frequency is locked to the modulation frequency of the light source.

Seeds and Forrest [65] used the output of GaAlAs laser modulated at 2.6 GHz to lock injection at 7.8 GHz Impatt oscillator. They achieved a locking range of 1 MHz. Yen showed that a locking range of several MHz can be obtained by modulating CW GaAlAs laser at the subharmonics of the oscillation frequency of X-band (8-12 GHz) Impatt oscillators [66]. Daryoush et al. [67] in 1986 reported the result of indirect optical injection locking of two X-band oscillators. In the same year Herczfeld [68] reported results of indirect locking of a free-running 38 GHz Impatt oscillator over a locking range of 2-132 MHz by using a 12 GHz amplifier as a function of the injected power level (amplifier gain).
Optical modulation of amplitude and frequency of Impatts

Various experimental reports are available on the modulation of the oscillation frequency and RF output power of Impatt diodes due to optical illumination of the active area of the device with a light source of appropriate frequency. By changing the intensity of illumination the current is changed. In 1977 Yen et al. [69] experimentally studied the optical control of microwave properties of GaAs Schottky barrier Impatts at about 16 GHz. They found that the output power from an Impatt diode can either be enhanced or reduced depending on the bias condition, frequency of oscillation and the intensity of illumination of the incident light. A 10% increase in the intensity of illumination produced 75% enhancement of microwave output. The enhancement of microwave power output due to optical illumination of Impatt diode can be explained as follows. If the system of Impatt diode and the cavity is not optimised for maximum output power, the photogenerated current of appropriate magnitude can bring the system closer to optimum. But if the diode be biased above threshold and the cavity tuned to optimum power then the optical illumination will cause the diode to shift away from the optimum power so that the microwave power is reduced. Experimental report indicates a reduction of output power and efficiency of mm-wave GaAs Impatt diodes under optical illumination which is accompanied by an increase of the tuning range of the oscillator [70]. Singleton et al. [71] studied experimentally the frequency tuning in an illuminating W-band Impatt oscillator and observed a 10 MHz tuning range with a 20 µA photocurrent generated in the device.

2.3 Experimental results of Impatt diodes based on conventional and emerging materials

2.3.1 Impatts based on Silicon and Gallium Arsenide

Flat profile single drift Silicon Impatts are capable of generating mm-wave power upto a frequency of 341 GHz in fundamental mode [27] and 423 GHz in harmonic mode [28]. Thus at 40 GHz a CW output power of 2.25 W has been
reported [29]. These devices have been fabricated and their RF performance have been tested over the 100 GHz range [30]. Chang et al. [31] developed flat profile SDR Silicon Impatt diodes and power combiners by using a number of such diodes which can generate mm-wave power in both CW and pulsed modes of operation in the frequency range of 110-260 GHz. They measured a CW RF power output of 110 mW with 6% conversion efficiency from a single diode at 140 GHz. In the sub mm-wave frequency bands of 200 GHz and 300 GHz, CW operation of p+nn+ SDR Silicon Impatts has been demonstrated by Ishibashi et al. [2]. They reported a CW output power of 50 mW at 202 GHz with 1.3% conversion efficiency. The output power decreases to 1.2 mW at 301 GHz.

In pulsed mode of operation flat profile SDR Silicon Impatts are capable of providing higher RF power as compared to CW mode of operation. Pulsed Silicon Impatt devices have therefore been developed for long distance communication system and rapid advances have been made in this respect. Thus Ying et al. [32] reported peak output power of 10W at 35 GHz and 1W at 94 GHz. Chang et al. [31] measured 3W peak power output at 140 GHz, 1.3W at 170 GHz and 700 mW at 217 GHz from Single drift pulsed Silicon Impatts. The output power falls sharply at higher frequencies. Thus a suitable combiner system consisting of a number of Impatt diodes has been developed to increase the output power at mm-wave and sub mm-wave frequency bands. A peak pulsed power of 40W at 94 GHz and 1.05W at 217 GHz have been reported from power combiner systems having four diodes and two diodes respectively [33, 31].

Molecular Beam Epitaxy techniques are recently being used to fabricate flat profile SDR and DDR Impatt diodes at V band and W band mm-wave frequencies. Luy et al. [37] reported the fabrication of single drift Silicon Impatt diodes from silicon molecular beam epitaxy materials. These diodes delivered a maximum CW output power of 450 mW with an efficiency of 4.2% at 87 GHz (W-band) frequency when mounted on a diamond heat sink.
The proposal of flat profile DDR Silicon Impatts by Scharfetter et al. [34] in 1970 for improvement of device performance received immediate attention for practical realisation of the device.

Further improvement of output power from DDR Silicon Impatts was reported by Y. Hirachi et al. [35]. A stabilised output power of 1.6 W with 11.5% efficiency was obtained from DDR diodes at 55.5 GHz through modification of bias circuits to limit low frequency instability in these devices.

In 1976 Weller et al. [36] used ion implantation to fabricate double drift Silicon Impatts. They demonstrated CW oscillation from these devices for the 130-170 GHz frequency band. The quest for higher peak power in DDR Silicon Impatts at mm-wave frequencies continued through the improvement of devices and circuit technology which led to astonishing success in both CW and pulsed modes of operation. From flat profile double drift Silicon Impatts mounted on type II A diamond heat sinks CW powers of 2.25 W at 40 GHz, 980 mW at 100 GHz and 50 mW at 220 GHz have been obtained [29].

Since flat profile SDR Silicon Impatt diodes can deliver 10 W peak output power at 35 GHz and 1 W peak power at 94 GHz in pulsed mode [32], further improvement of pulsed power output is possible with flat profile DDR Silicon Impatts at mm-wave frequencies. Thus a pulsed output power of 23 W at 35 GHz, 15 W at 94 GHz, 3 W at 140 GHz and 520 mW at 217 GHz were obtained from flat profile DDR Silicon Impatt diodes [29,31,72].

In 1987 Luy et al. [1] reported for the first time MBE grown flat profile DDR Silicon Impatts at W band frequencies. A maximum CW output power of 600 mW with 6.7% conversion efficiency was obtained from an unoptimised DDR Silicon Impatt diode at 94 GHz. Similarly from MBE grown flat profile DDR Silicon Impatt diodes, a high pulsed output power of 40 W has been obtained at 96 GHz if an extraordinary high bias current density (250 KA cm\(^{-2}\)) be pushed through the device [73]. Conventional theory of DDR Impatt diodes failed to
explain such high values of output power because the oscillation frequency was at or below the avalanche resonance frequency. J.-F. Luy in 1990 [74] made an attempt to explain the above behaviour of pulsed DDR Si Impatts at high bias current densities. He suggested a p-i-n like Misawa mode of DDR devices at such high current densities which shift the avalanche resonance frequency close to the optimum operating frequency. The experimental results can be explained with a distributed avalanche and drift mechanism in the whole diode as originally suggested by Misawa for the p-i-n diode. Earlier in 1982 Classen and Harth [75] predicted theoretically that the device performance is considerably improved in some structures near the avalanche frequency.

Quasi Read Structure of Impatts based on Silicon and Gallium Arsenide

It has already been mentioned that improvement can be realised from Impatt diodes at mm-wave frequencies if flat doping profiles be replaced by quasi-Read HL and LHL doping profiles. But the realisation of these complex doping profiles at 94 GHz and above requires rigorous control of epitaxial growth particularly when the dimension of the active zone are in the submicron levels of mm-wave frequencies. This is an extremely difficult task. But due to the advancement of epitaxial growth through the advent of MBE and MOCVD methods the growth of submicron layers with quasi-Read doping profiles has become easier. Recent reports have demonstrated that high power 94 GHz Read doping profiles of Silicon Impatt diodes can be realised by means of molecular beam epitaxy and RF power levels up to 910 W have been achieved [76]. Dalle and Rolland [77] have recently investigated theoretically the RF performance of various quasi-Read and flat profile Silicon Impatt structures at 94 GHz for realisation of high power and high efficiency devices in these structures. The results show that Read doping profile structures at 94 GHz do not improve maximum achievable RF power levels of Silicon Impatt diodes in comparison to the flat doping profile structures at the same frequency.
Double drift quasi-Read LHL doping profile structures of Silicon Impatt diodes were proposed earlier in 1977 by Chang et al. [78]. They predicted an efficiency of 19% at 50 GHz from these devices from numerical calculations. The large signal analysis of these DDR LHL Silicon Impatts also confirmed the prediction of 19% efficiency from these devices [78]. Recently the theoretical and experimental studies on V-band Silicon double drift flat profile and double drift low-high-low Impatts have been reported by Banerjee et al. [7]. This is the first ever report of the realisation of complex double drift LHL doping profiles in the Silicon material system. The epitaxial layers of the diodes including the $p^+$-contact layer were grown by Silicon MBE. The theoretical design and analysis of the aforementioned complex structures of 60 GHz Silicon Impatts were carried out by using computer simulation methods. A maximum efficiency of 14.3% was realised from MBE grown V-band double drift LHL Silicon Impatts. The output power from 54 μm DDR LHL diode was reported to be 1260 mW with 11.6% efficiency. Further improvement of efficiency at V-band has recently been reported by Luy et al. [80] with DDR LHL Silicon Impatts whose epitaxial layers were grown by MBE methods. From a 47 μm solid circular diode a maximum efficiency of 17.6% was reported at 67 GHz for a bias current of 140 mA. A CW output power of 800 mW was reported from ring structures of DDR LHL Silicon Impatts at 59 GHz [80].

Oscillator performance of flat profile and Read type GaAs Impatts for millimeter-wave frequency bands

The review presented in the last section of this chapter shows that Silicon Impatt diodes are premier solid state sources of high RF power with high conversion efficiency at mm-wave frequencies. But at lower mm-wave frequencies below 50 GHz GaAs Impatts have a performance advantage over Silicon Impatts in output power, efficiency and noise. A comparison of the RF performance of Silicon and GaAs Impatts as regards power and efficiency has been made for microwave and mm-wave frequencies. It is observed that GaAs
Impatt has a performance advantage below 50 GHz while Silicon Impatt has the upper hand at 94 GHz and above. Till 1980s very little experimental success was reported from GaAs Impatt oscillators beyond 94 GHz frequency. In recent years significant progress in the RF performance has been achieved with GaAs Impatts at mm-wave V-band, W-band and D-band frequencies. A review of the performance of GaAs Impatt oscillators given below will reveal that GaAs Impatts can compete with their Silicon counterparts at a frequency of 94 GHz and above.

Most of the theoretical and experimental investigations on the performance of mm-wave GaAs Impatts are concerned with single drift flat profile and quasi-Read structures. Only a few reports are recently available on the fabrication and characterisation of double drift flat profile and Read type GaAs Impatt diodes at mm-wave frequency bands. An improved RF performance of GaAs Impatts over Silicon Impatts at lower microwave frequencies (< 15 GHz) was reported by several authors in early seventies [81-83].

These reports stimulated tremendous research interest at that time for the development of GaAs Impatts at frequencies above 15 GHz up to the mm-wave frequency bands. Thus Weller [84] and co-workers reported fabrication of flat profile $p^+nn^+$ and Schottky barrier GaAs Impatts for operation at Ka-band frequency (26.5-40 GHz). They achieved oscillator power as high as 680 mW with 12.4% efficiency at 34.8 GHz and efficiency as high as 16% with 390 mW power output at 29.5 GHz. A comparison of the RF performance of $p^+nn^+$ and Schottky barrier Impatt diodes showed that the former excels the latter as regards output power only but the efficiency and noise performance of the former are comparable with those of the latter device.

Gallium Arsenide Read type Impatt diodes provide the highest CW output power and efficiency of any solid state device at lower microwave frequencies. For example CW output powers of 6-10W in X-band and 4-5 W in Ka-band were
reported from GaAs Read Impatt diodes [85,86]. The DC to RF conversion efficiency was reported to be 25%, i.e., about twice that observed using flat profile diodes. It was therefore expected that mm-wave GaAs Read diodes should exhibit a performance advantage over flat profile diodes analogous to that observed at lower microwave X-band and Ku-band frequencies. In 1978 Adlerstein et al. [87] reported the design, fabrication and characterisation of GaAs Read Impatt diodes at mm-wave Ka-band (36-38 GHz) frequencies. CW output power as high as 710 mW and a maximum conversion efficiency of 9% was achieved with mm-wave Read type GaAs Impatts. Till 1980 very little success was achieved to enhance the RF power output from GaAs Impatts at and above the frequency of 94 GHz. A very low CW output power of 1 mW at 96 GHz was reported from Schottky barrier GaAs Impatts till 1978 [88]. It was believed that long intrinsic avalanche response time of GaAs limits the performance of GaAs Impatts at higher mm-wave frequencies.

The advent of better epitaxial growth technique by using MBE and MOCVD methods and the availability of advanced computer modelling technique led to remarkable success in achieving better RF performance from GaAs Impatts at higher mm-wave frequencies. Thus great efforts were made since 1980 to enhance the performance capability of GaAs Impatts in the frequency range of 60 to 200 GHz to achieve higher RF output power with higher conversion efficiency. These efforts culminated in some astonishing success with mm-wave GaAs Impatts as described below:

Owing to the tremendous importance of 60 GHz frequency for high data rate intersatellite links and secure terrestrial links, NASA’s Lewis’ Research Centre sponsored several research projects to reputed commercial firms, for the development of powerful and efficient solid-state sources of RF power at 60 GHz using Impatt diodes. Thus Hughes Aircraft’s Electron Dynamics Division (Hughes AEDD) and Microwave Associate Company (M/A-COM), Semiconductor Products, Inc. (Burlington, MA) were given the contract of
developing 1W 60 GHz GaAs Impatts. The advanced epitaxial growth technology like MBE was adopted by Hughes AEDD with conventional vapour phase epitaxy (VPE) as a back up technique while M/A-COM chose MOCVD method to achieve the goals of realisation of high power and high efficiency from 60 GHz GaAs Impatts. Table 2.1 shows the abovementioned programmes to develop 60 GHz Impatt diodes using GaAs and InP as the semiconducting materials [3].

<table>
<thead>
<tr>
<th>Contractor</th>
<th>Sponsor</th>
<th>Goals</th>
<th>Approach</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hughes</td>
<td>NASA/LeRC</td>
<td>1W, 15%</td>
<td>GaAs/MBE/DHS</td>
<td>1.03W, 13%</td>
</tr>
<tr>
<td>MA/COM</td>
<td>NASA/LeRC</td>
<td>1W, 15%</td>
<td>GaAs/MOCVD/DHS</td>
<td>0.3W 11%</td>
</tr>
<tr>
<td>Raytheon</td>
<td>AFWAL</td>
<td>2W, 15%</td>
<td>GaAs/MBE/DHS</td>
<td>1.7W, 4%</td>
</tr>
<tr>
<td>Varian</td>
<td>NRL</td>
<td>1W, 14%</td>
<td>InP/VPE</td>
<td>1.7W, 4% (1% duty cycle)</td>
</tr>
</tbody>
</table>

Double drift quasi-Read doping profile was chosen for fulfilling the goal of realisation of high power from GaAs Impatts in the above programmes. Double drift flat profiles were also grown but did not perform as expected. Single drift profiles using Schottky contacts were grown earlier in the programmes which suffered from large leakage current and burn-out at low bias. The MBE grown LHL DDR GaAs Impatt diodes showed sharp transitions and excellent uniformity within the layers. Instead of plated heat sinks, diamond heat sinks (DHS) were used for efficient removal of heat. Hughes AEDD developed a pill diode process for thinning and metallizing the diode for mounting on a diamond heat sink [3]. This process solved the problem of cracking of GaAs diodes due to excessive bonding pressure. The p-metallisation (Au/Zn) was very much critical because this metallisation should bond well to the metallised diamond without excessive
pressure or heal. The metallised diamond was not pressed into a copper stud and pill diode was thermo-compression bonded to the diamond. A metallized-quartz ring and preformed ribbon make the electrical connection. Finally the RF measurements were made in a coaxially coupled reduced height waveguide cavity. M/A COM however chose a “top-hat” circuit for RF testing due to its wideband capability and ease of changing diodes. The reported results on the performance of GaAs Impatt oscillators at V-band frequencies are given below:

In 1984 Ma et al. [89] obtained 300 mW output with a low efficiency of 6% from double drift Read (LHL) type GaAs Impatt diodes at 67 GHz. At about the same time Adlerstein and Chu [90] have shown that the efficiency of these devices can be increased to 11.4% with higher output power of more than 1W at 60 GHz frequency. Zhang and Freyer [91] showed that flat profile single drift \( p^+\text{nn}^+ \) GaAs Impatts can provide higher efficiency (12.5%) with higher output power (450 mW) compared to double drift Read type GaAs Impatts at about the same frequency. Zhang and Freyer reported the performance of flat profile \( p^+\text{nn}^+ \) GaAs Impatts at 50 GHz [91] and the upper V-band (72 GHz) frequencies [91]. These devices were fabricated and developed up to 72 GHz using the MBE method and the diodes were bonded on diamond heat sinks. The results show that these devices produce CW output powers of 700 mW at 50 GHz with 12.3% efficiency, 450 mW at 63 GHz with 12.5% efficiency and 350 mW at 72 GHz with 10% efficiency [91]. It is interesting to note that single drift flat profile GaAs devices of Zhang and Freyer exhibit better RF performance than double drift Read devices of Adlerstein and Chu [90] as regards conversion efficiency at V-band frequencies which is an unusual behaviour.

Efforts were made to extend the aforementioned performance of V-band (60 GHz) flat profile GaAs Impatts to W-band (94 GHz) frequencies. Earlier reports show a sharp deterioration in the performance of GaAs Impatts at higher frequencies although double drift or low-high-low structures were used. An output power of 0.5 mW at 89 GHz [92] and 5 mW at 130 GHz [6] could be obtained.
from GaAs Impatts. Since flat profile GaAs diodes can compete with more complicated Read diodes concerning efficiency at V-band frequency, Eisele and Freyer [4] tried to extend the use of flat profile diodes to higher W-band frequencies with remarkable success. They reported a maximum output power of 240 mW at 89.6 GHz with 4.1% efficiency. The following table summarises the results on the performance of single drift GaAs Impatt diodes in W-band and the earlier results of the same device in V-band obtained by Eisele and Freyer [4].

Table 2.2

Performance of GaAs Impatt Diodes from 60 to 90 GHz

<table>
<thead>
<tr>
<th>Diode No.</th>
<th>Frequency (GHz)</th>
<th>P (mW)</th>
<th>η (%)</th>
<th>I (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>62.8</td>
<td>450</td>
<td>12.5</td>
<td>290</td>
</tr>
<tr>
<td>I</td>
<td>82.3</td>
<td>220</td>
<td>0.41</td>
<td>400</td>
</tr>
<tr>
<td>II</td>
<td>72.2</td>
<td>350</td>
<td>10.0</td>
<td>285</td>
</tr>
<tr>
<td>III</td>
<td>72.2</td>
<td>300</td>
<td>0.85</td>
<td>285</td>
</tr>
<tr>
<td>III</td>
<td>82.0</td>
<td>255</td>
<td>0.48</td>
<td>415</td>
</tr>
<tr>
<td>III</td>
<td>87.0</td>
<td>260</td>
<td>0.45</td>
<td>450</td>
</tr>
<tr>
<td>IV</td>
<td>89.6</td>
<td>240</td>
<td>0.41</td>
<td>450</td>
</tr>
</tbody>
</table>

Eisele and Freyer observed that a frequency range from 60 to 90 GHz can be covered with the same epitaxial material and in part with the same diodes if the matching of the diode and the resonator is optimised. They also observed that both the output power and the efficiency of W-band p^nn^* GaAs Impatts increase monotonically with increasing bias current with no saturation effect up to a maximum current of 450 mA. Eisele and Grothe [93] observed saturation of efficiency but not the output power at a maximum bias current of 440 mA corresponding to a current density of 50 KA cm^-2. They reported 320 mW output power with an efficiency of 6% at 95 GHz from single drift GaAs Impatts. These
results clearly indicate that even on diamond heat sinks GaAs W-band Impatts are thermally but not impedance limited. The following table (Table 2.3) compares the best result from diodes with different doping concentrations of the active layer varied around the design of $2.4 \times 10^{23} \text{ m}^{-3}$. The maximum operating junction temperature was 530 K to ensure good reliability. Corresponding to the thermal resistance of 50 kW for the diode having a diameter of 33 μm [94].

Table 2.3

<table>
<thead>
<tr>
<th>n-doping ($\times 10^{23}$ m$^{-3}$)</th>
<th>Power (mW)</th>
<th>Efficiency (%)</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.05</td>
<td>240</td>
<td>4.1</td>
<td>89.6</td>
</tr>
<tr>
<td>2.05</td>
<td>250</td>
<td>4.5</td>
<td>91.2</td>
</tr>
<tr>
<td>2.40</td>
<td>270</td>
<td>6.2</td>
<td>94.3</td>
</tr>
<tr>
<td>2.40</td>
<td>280</td>
<td>6.0</td>
<td>92.6</td>
</tr>
<tr>
<td>2.40</td>
<td>280</td>
<td>6.0</td>
<td>92.0</td>
</tr>
<tr>
<td>2.40</td>
<td>270</td>
<td>5.7</td>
<td>95.0</td>
</tr>
</tbody>
</table>

Eisele [95] also studied the FM noise performance of single drift flat profile MBE grown GaAs Impatts at W-band frequencies and reported the noise measures of 20 dB at 20 mW and 26 dB at 200 mW (75% of the maximum output power) power levels. This excellent noise behaviour of W-band GaAs Impatt oscillators is comparable with that of Gunn oscillator.

The reported encouraging results on the power, efficiency and noise performance of GaAs Impatts at V-band and W-band frequencies stimulated interest in the development of these devices at still higher frequencies above 100 GHz. The first attempts to realise these devices at mm-wave D-band
frequencies were made by Elta et al. [54] and Chang et al. [6]. In 1992 Eisele and Haddad [96] reported the first experimental results of MBE grown flat profile GaAs Impatt diodes mounted on diamond heat sinks for CW operation at D-band frequencies. An RF output power of 15 mW with a conversion efficiency of 1.5% was achieved from GaAs Impatts at 135.3 GHz frequency. The devices showed sharp breakdown characteristics with a positive temperature coefficient of breakdown voltage due to the decrease of the ionisation rates of charge carriers at higher temperatures. These results indicate that tunnelling dominated breakdown does not take place in these devices even for peak electric field of 900 KV cm\(^{-1}\) at the p-n junction.

For high power operation of GaAs Impatts at D-band frequencies higher bias current should be pushed through the device. But the maximum bias current through the device is thermally limited due to thermal limitation of DC input power. At a fixed value of DC input power the bias current can be increased if the DC breakdown voltage be decreased. To achieve lower DC breakdown voltage Read type LHL structures are preferred to flat profile structures for high power generation. Very recently Tschernitz et al. [97] designed, fabricated and characterized GaAs Read type Impatt diodes for CW operation at D-band frequencies. The devices were MBE grown and mounted on the diamond heat sink. The novel module encapsulation technique which involves monolithic integration of the active device and the surrounding stand off structure was employed for packaging and heat sinking of the diodes. The whole module was thermo-compression bonded on the diamond heat sink in one step. RF output powers of 75 mW at 120 GHz and 8 mW at 144 GHz were realised from GaAs Read type Impatt devices. The highest oscillation frequency was observed to be 150 GHz with an RF output power of 1 mW at this frequency [97]. The devices were properly designed to prevent tunnel generation of carriers which essentially deteriorates the RF performance of the devices.
2.3.2 Millimeter wave InP Impatts

Advantages of Impatts based on InP are mainly because the fundamental material properties are very much suitable for high breakdown voltage, high RF output power and high efficiency.

Lower ionization rate (in comparison to those of Si and GaAs) of charge carriers at a given electric field, as shown in Fig.2.6, results in higher breakdown voltage, higher input power at a given bias current and hence higher output power in Impatts based on InP [24].

Higher values of efficiency can be achieved in InP Impatts due to higher maximum electric field in the depletion layer resulting in narrower avalanche zone and hence higher drift zone voltage.

Higher thermal conductivity of InP results in easier and quicker heat dissipation leading to higher output power.

J.J. Berentz et al. reported the fabrication of SDR p'nn+ Impatt by ion implantation technique and achieved a CW output power of 1.6 W with 11.1% efficiency at 9.78 GHz from unoptimised device in 1978 [9]. They showed that InP Impatts can sustain high temperature while delivering high output power at high mm-wave frequencies. Thus Varian Associates, a reputed commercial house in USA undertook a project of fabrication of Impatts at such high frequencies of mm-wave using vapour phase epitaxy techniques. Varian Associates successfully realised a pulsed output power of 1.7W with 4% conversion efficiency from InP Impatts at 60 GHz frequency. It was observed that InP Impatts are capable of sustaining relatively high operating temperatures. The breakdown and operating voltages of InP Impatts are greater than comparable GaAs Impatts. All these results indicated high power capability of InP Impatts at mm-wave frequencies. The programme of development of 60 GHz InP Impatts was undertaken by Varian and sponsored by Naval Research Laboratory owing to the importance of 60 GHz
Fig. 2.6: The ionization rates of electrons and holes as a function of electric field for (1) InP, (2) GaAs, (3) Si and (4) Ge.
for high data rate intersatellite links and secure terrestrial links. The VPE grown diodes exhibited 1.7 W pulsed power (1% duty cycle) with 4% conversion efficiency [3]. The low efficiency of 60 GHz InP Impatts was attributed to the technological problem with the p-layers. Efforts are underway to improve the efficiency of these devices. The advanced MBE and MOCVD technologies of epitaxial growth of these layers with accurate control of layer thickness together with the accurate design of diode parameters by using improved device modelling techniques would help to improve the RF performance of mm-wave InP Impatts at V-band frequencies. Very few experimental reports are available on the design, fabrication and characterisation of InP Impatts at and above 94 GHz. The author has undertaken studies on the design, analysis and explanation of the various DC and RF properties of DDR InP Impatts at important mm-wave and atmospheric window frequencies of 60, 94 and 140 GHz. These studies are based on accurate computer simulation methods based on a drift-diffusion model. The results are presented in Chapter IV of this dissertation.

2.3.3 Suitability of SiC as a base material for Impatt device

Research and development of 4H-SiC IMPATTs have been reported at lower microwave frequency band. Yuan et al. [19] realised single drift region (SDR) High-Low 4H-Silicon Carbide IMPATT diode. They observed a pulsed peak power ~1 mW at 7.75 GHz with a bias current amplitude 200 mA at a bias voltage of 100 V with a device area of 1.227 × 10^{-4} cm² i.e., a bias current density of 1.63 × 10^7 Am⁻². Vassilevsky et al. [18] also reported the fabrication and characterisation of SDR (p⁺m⁺ structure) flat profile 4H-SiC Impatts. They obtained a maximum of 300 mW power at 0.95 × 10^7 Am⁻² bias current density with avalanche breakdown voltage at 290 V.

Because of its high breakdown field, silicon carbide is an ideal semiconductor for the fabrication of high power microwave devices. One device, in particular, that benefits from the high breakdown field of SiC is the IMPact
Ionisation Avalanche Transit-Time (IMPATT) diode oscillator. IMPATT diodes deliver the highest RF power of any semiconductor microwave oscillators, and are used to produce carrier signals for microwave transmission systems, particularly airborne and ground-based radar. Depending upon the design, IMPATT diodes can operate from a few GHz to a few hundred GHz.

The power-squared frequency product \((p_i^2)\) of an IMPATT diode depends on the square of the breakdown field times the electron saturation drift velocity i.e., \((E_n V_{sn})^2\). In SiC, the critical field is about 10 times higher than in silicon or GaAs, and the saturation drift velocity is about 2 times higher. Thus, the power-squared frequency product (in the electronic limit) is theoretically expected to be about 400 times higher for SiC IMPATT diodes than for diodes in silicon or GaAs. A theoretical prediction on 6H-SiC Impatts has already been reported by Pattanaik et al. [108]

**Choice of polytype for Silicon Carbide**

Semiconductor device quality 4H-SiC and 6H-SiC are now commercially available. The material processing technology for both 4H and 6H-polytypes Silicon Carbide are similar. In case of Cubic polytype (3C-SiC) grown on silicon the processing temperature needs to be kept well below the melting temperature of silicon (1412°C).

It is generally accepted that higher carrier mobility and shallower dopant ionisation energies of 4H-SiC compared to 6H-SiC should make the former the polytype of choice for fabrication of Impatt devices, provided that the device processing, technology, performance and cost-related issues are equally competitive between the two polytypes.

**SiC device applications and benefits**

New developments in SiC technology are being achieved for a wide range of applications. SiC high temperature devices are developed for aircraft and
automotive engine sensors, jet engine ignition systems, transmitters for deep well drilling, and a number of industrial process measurement and control systems. SiC-based distributed smart electromechanical controls are capable of harsh-ambient operation and enable substantial jet-aircraft weight savings, reduced maintenance, reduced pollution, higher fuel efficiency, and increased operational reliability.

SiC high power devices offer promise in solid-state lamp ballasts, surge suppressors and power supplies. Performance gains from SiC electronics enable the public power grid to provide increased demand of consumer electricity without building additional generation plants and also improve power quality and operational reliability through smart power management. More efficient electric motor drives based on SiC power devices will benefit industrial production systems, transportation systems, nuclear-powered ships and electric automobiles.

SiC high frequency power devices are being used in high frequency power supplies, cellular phone base station, phased array radar systems, and small, lightweight RF and microwave transmitters, where conventional GaAs-based devices cannot operate efficiently due to high power density and high temperature demands.

The principal optoelectronic applications for SiC are low-intensity blue LEDs and substrates for gallium nitride (GaN) based high-intensity blue LEDs and blue laser diodes.

Electrical properties of SiC

Owing to the different arrangement of Si and C atoms within the SiC crystal lattice, each SiC polytype exhibits unique fundamental electrical properties. Within a given polytype, some electrical properties (e.g., electron mobility for 6H-SiC) may be non-isotropic, in the sense that they strongly depend on the crystallographic direction of the current flow and the applied electric field.
The advantages of SiC devices over Si devices for high temperature operation are –

1. Thermal conductivity

2. Breakdown field

3. Bandgap energy (E_g)

SiC has 3 to 13 times higher thermal conductivity than Si, an approximately three times wider bandgap than Si at 300 K. The electron saturation velocity (V_{sat}) of SiC is 2×10^7 cm s^-1. All the electrical properties of SiC are temperature dependent to varying extent. The low, anisotropic electron mobility in 6H-SiC is one of the primary reasons for emerging popularity of 4H-SiC which has a higher and much less anisotropic electron mobility. In fact \( \mu_\perp/\mu_\parallel \) is about 0.8 at 300 K in 4H-SiC, while the same ratio is about 5 in 6H-SiC.

The intrinsic carrier concentration \( n_i \) is directly proportional to \( N_c \) and \( N_v \), which are the conduction band and valence band density of states, respectively. However, as a result of thermal expansion of the lattice and electron-phonon coupling, \( n_i \) has an exponential dependence upon temperature as well as \( E_g \). The intrinsic carrier concentration is important in high temperature device applications, because p-n junction leakage currents in devices are normally proportional to \( n_i \) or \( n_i^2 \). Electron effective masses \( (m_\perp^* = 0.42 m_0 \) and \( m_\parallel^* = 0.39 m_0 \) in 4H-SiC) have not been analysed as a function of temperature. Typical bandgap values are obtained from photoluminescence studies performed at liquid He temperature (≈4.2 K) under very low pressures (≈10^{-11} T). High doping levels lead to band gap narrowing (BGN) in semiconductors, which has not been extensively studied in SiC. Thus the effective intrinsic carrier concentration \( (n_{ie}) \) at high level of doping is not yet known for SiC.
### Table 2.4
Comparison of electrical properties of SiC polytypes with Si

<table>
<thead>
<tr>
<th>Properties</th>
<th>Si</th>
<th>4H-SiC</th>
<th>6H-SiC</th>
<th>3C-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap energy $E_g$(eV)</td>
<td>1.12</td>
<td>3.26</td>
<td>3.03</td>
<td>2.40</td>
</tr>
<tr>
<td>Relative dielectric constant $\varepsilon$</td>
<td>11.9</td>
<td>9.7</td>
<td>9.66</td>
<td>9.72</td>
</tr>
<tr>
<td>Breakdown field $E_B$ [MV/cm]</td>
<td>0.3</td>
<td>3.0</td>
<td>3.2</td>
<td>&gt; 1.5</td>
</tr>
<tr>
<td>$[N_p=10^{17}/cm^3]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity K [W/cm K]</td>
<td>1.31</td>
<td>4.9</td>
<td>4.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Intrinsic carrier concentration $n_0[cm^{-3}]$</td>
<td>$9.65 \times 10^9$</td>
<td>$5 \times 10^{-9}$</td>
<td>$1.6 \times 10^{-6}$</td>
<td>$1.5 \times 10^{-1}$</td>
</tr>
<tr>
<td>Electron mobility $\mu_n$ [cm$^2$/V s]</td>
<td>1430</td>
<td></td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>$[N_p=10^{16} cm^{-3}]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hole mobility $\mu_p$ [cm$^2$/V s]</td>
<td>480</td>
<td>115</td>
<td>90</td>
<td>40</td>
</tr>
<tr>
<td>$[N_A=10^{16} cm^{-3}]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated electron velocity $V_{sem}[10^7 cm/s]$</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>Donor ionisation energy $\Delta E_d$ [meV]</td>
<td>P:45</td>
<td>N:50, 92</td>
<td>N:85, 140</td>
<td>N:50</td>
</tr>
<tr>
<td></td>
<td>As:54</td>
<td>P:54, 93</td>
<td>P:80, 110</td>
<td></td>
</tr>
<tr>
<td>Acceptor ionisation energy $\Delta E_a$ [meV]</td>
<td>B:45</td>
<td>Al:200</td>
<td>Al:240</td>
<td>Al:270</td>
</tr>
<tr>
<td></td>
<td>Al:67</td>
<td>B:285</td>
<td>B:300</td>
<td></td>
</tr>
</tbody>
</table>

**High Frequency Device Operation**

High frequency-high power devices based on SiC such as Impatts can be used to generate and amplify RF signals used in radar and communication applications. In particular, the high breakdown voltage and high thermal conductivity coupled with high carrier saturation velocity allow SiC microwave devices to handle much higher power densities than their Silicon or GaAs counterparts. A variety of microwave devices with impressive DC and RF performance such as metal-semiconductor field effect transistor (MESFETs),
static-induction transistors (SITs), heterojunction bipolar transistors (HBTs) and IMPATTs can be fabricated from SiC-based semiconductors.

**High power operation of Silicon Carbide devices**

Solid state power devices based on SiC have very high voltage and current ratings because of its high breakdown field ($E_B$) of $1.5 \times 4 \times 10^6$ V/cm and high thermal conductivity of 2.3 – 4 W/cmK. The breakdown voltage of SiC junction diode is given by

$$V_B = \frac{E_B \cdot W}{2} = \frac{\varepsilon_s \cdot E_B^2}{2q \cdot N_B}$$

where $W$ is the depletion layer width and $N_B$ is background doping concentration.

The high breakdown field allows the use of much higher doping and thinner layers for a given voltage than those required in Si devices, resulting in lower specific on-resistances for SiC devices i.e., $1/300^{th}$ of equivalent Si devices.

$$R_{on,sp} = \frac{V_B^2}{\mu_n \cdot \varepsilon_s \cdot \left( \frac{3}{2E_B} \right)^3}$$

While SiC's smaller on-resistance and faster switching helps minimize energy loss and heat generation, SiC's higher thermal conductivity enables more efficient removal of heat from the active device region. Because heat energy radiation efficiency increases greatly with increasing temperature difference between the device and the cooling ambient, SiC's ability to operate at high junction temperatures permits much more efficient cooling to take place, so that heat sink needed to keep high-power devices from overheating can be made much smaller or even eliminated.
High Temperature operation of Silicon Carbide devices

The wide bandgap energy and low intrinsic carrier concentration of SiC allow SiC devices to operate at much higher temperatures than Si.

It is well known that the temperature range over which intrinsic carrier concentration does not increase significantly the conductivity is controlled by intentionally introduced dopant impurities.

The intrinsic carrier concentration $n_i$ is given by

$$n_i = \sqrt{N_c \cdot N_v \cdot \exp \left( -\frac{E_g}{2 \cdot k_B \cdot T_L} \right)}$$

With increasing temperature, the concentration of intrinsic carriers increases exponentially so that undesired leakage currents grow unacceptably large, and eventually at still higher temperatures, the semiconductor device operation is overcome by uncontrolled conductivity as intrinsic carriers exceed intentional device dopings. Depending upon specific device design, the intrinsic carrier concentration of silicon generally confines silicon device operation to junction temperatures less than 300°C. SiC’s much smaller intrinsic carrier concentration theoretically permits device operation at junction temperatures exceeding 800°C. SiC device operation has been experimentally demonstrated at 600°C.

High-Field Mobility and Velocity saturation in SiC

When strong electric fields prevail, the electron velocity is no longer proportional to the field, and can thus no longer be described by a field-independent mobility. The heating of free carriers at high electric fields results in the saturation of the drift velocity

$$v = \mu \cdot E$$
originating from various scattering mechanisms such as optical phonon scattering, phonon dispersion, phonon absorption as well as emission.

Little is known about the high-field mobility of SiC. The only experimental data was published by Khan and Cooper [134], where the drift velocity (n-doped at about $10^{17}$ cm$^{-3}$) was measured as a function of electric field using standard n-type and p-type 4H and 6H-SiC epilayers at different temperatures. All measured data refer to a current flow perpendicular to the c-axis.

The field dependence of the mobility can be modelled by the widely used expression of Canali et al. [79].

$$
\mu_{\nu,\perp,||}^{\text{high}} = \frac{\mu_{\nu,||}^{\text{low}}}{\left[ 1 + \left( \frac{\mu_{\nu,\perp,||}^{\text{low}} \cdot E_{\nu,||}}{\nu_{\text{sat}}^{\nu,\perp,||}} \right) \right]^{\alpha_{\nu}^{\text{sat}}}}
$$

where $E_{\nu,||}$ is the electric field component in the direction of the current flow as driving force, $\nu_{\text{sat}}^{\nu,\perp,||}$ is the saturation velocity, and $\alpha_{\nu}^{\text{sat}}$ is a constant specifying how abruptly the velocity goes into saturation.

The standard Si model is used to describe the temperature dependence of the saturation velocity $\nu_{\nu}^{\text{sat}}$, expressed by

$$
\nu_{\nu,\perp,||}^{\text{sat}} = \nu_{\nu,300,\perp,||}^{\text{sat}} \cdot \left( \frac{T_{L}}{300 \text{ K}} \right)^{\delta_{\nu}^{\text{sat}}}
$$

Recent simulations for 4H-SiC by including more precisely the nonparabolic band structure excellently agree to the measured data. In addition, these investigations reveal a lower electron saturation velocity.
\( v_{\text{sat}n||} = 1.8 \times 10^7 \text{ cm/sec parallel to the } c\text{-axis in 4H-SiC with an anisotropic factor of} \)

\[ \frac{v_{\text{sat}n\perp}}{v_{\text{sat}n||}} = 1.16 \]

Table 2.6

Parameters of the electron saturation velocity in 4H- and 6H-SiC

<table>
<thead>
<tr>
<th>Material</th>
<th>( v_{\text{sat}n,300} ) [cm/s]</th>
<th>( \alpha_{\text{sat}n,300} )</th>
<th>( \delta_{\text{sat}n} )</th>
<th>( \beta_{\text{sat}n} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4H-SiC</td>
<td>2.2x10^7</td>
<td>1.2</td>
<td>-0.44</td>
<td>1.0</td>
</tr>
<tr>
<td>6H-SiC</td>
<td>1.9x10^7</td>
<td>1.7</td>
<td>-1.0</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Impact Ionization rates of charge carriers in SiC

In order to acquire a clear understanding of the breakdown characteristics of SiC Impatts, it is important to have a clear understanding of impact ionization. The acceleration of free carriers within a high electric field finally results in generating free carriers by impact ionization. This process corresponds to the inverse process of Auger recombination. The Auger generation rate was evaluated by making use of the principle of detailed balance which holds in equilibrium. Impact ionization is, however, a typical non-equilibrium process which requires large electric fields. It is modelled by the reciprocal of the mean free path which is denoted the impact ionization coefficient. The corresponding avalanche generation rate can be expressed by

\[ G_{\text{ava}} = \frac{1}{q} \left( \alpha_n \cdot j_n + \alpha_p \cdot j_p \right) \]
The impact ionization coefficients $a_n$ and $a_p$ are expressed by Chynoweth's law

$$\alpha_\nu = a_\nu \cdot \gamma_a \cdot \exp \left( -\frac{b_\nu \cdot \gamma_a}{E_1} \right), \quad \nu = n, p$$

with

$$\gamma_a = \frac{\tanh \left( \frac{\hbar \omega_{op}}{2 \cdot k_B \cdot 300} \right)}{\tanh \left( \frac{\hbar \omega_{op}}{2 \cdot k_B \cdot T_L} \right)}$$

where $a_\nu$ and $b_\nu$ are temperature dependent measured parameters. The electric field component $E_1$ is in the direction of current flow. The factor $\gamma_a$ with the optical phonon energy $\hbar \omega_{op}/2\pi$ expresses the temperature dependence of the phonon gas against which the carriers are accelerated.

<table>
<thead>
<tr>
<th>Material</th>
<th>$a_n$ [cm$^{-1}$]</th>
<th>$b_n$ [V/cm]</th>
<th>$a_p$ [cm$^{-1}$]</th>
<th>$b_p$ [V/cm]</th>
<th>$\hbar \omega_{op}$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4H-SiC</td>
<td>3.44x10$^6$</td>
<td>2.58x10$^7$</td>
<td>3.5x10$^6$</td>
<td>1.7x10$^7$</td>
<td>106</td>
</tr>
<tr>
<td>6H-SiC</td>
<td>1.66x10$^6$</td>
<td>1.27x10$^7$</td>
<td>2.5x10$^6$</td>
<td>1.48x10$^7$</td>
<td>106</td>
</tr>
</tbody>
</table>

A review of measured data on impact ionization coefficients in $\alpha$-SiC has been first published by Ruff et al. [109] and later by Bakowski et al. [110] but most recently measured data compiled by Raghunathan and Baliga [111] at different temperatures show an about 20% higher critical...
electric field compared to the previous reports. It seems that the impact ionization coefficients are decreasing with increasing temperature. This implies an increase of the breakdown voltage, which is a desirable property for SiC power devices.

The extracted average parameters are summarized in Table 2.7 which shows the impact ionization coefficients of electrons and holes at room temperature as a function of electric field.

It is important to note that the measured data rely on uniform avalanche breakdown with all possible influence of structural defects and edge termination excluded.

\[
\frac{\alpha_n}{\alpha_p} = 0.3, \quad \frac{\alpha_{n\perp}}{\alpha_{p\parallel}} = 1.
\]

**Figure of merit of SiC Devices**

The expected excellent performance of SiC devices is often expressed by a figure of merit. In the past, several analyses of the influence of material parameters on the performance of semiconductor devices have been performed. Johnson derived a figure of merit (JFOM)

\[
JFOM = \frac{E_B^2 \cdot v_s^2}{4\pi^2},
\]

which defines the power-frequency product for a low-voltage transistors. Here \(E_B\) is the critical electric field for breakdown in the semiconductor and \(v_s\) is the electron saturation velocity. Keyes' figure of merit (KFOM) provides a thermal limitation to the switching behaviour of transistors used in integrated circuits.
KFOM = $\kappa \cdot \sqrt{\frac{c \cdot v_s}{4\pi \varepsilon_s}}$

where $\kappa$ is the thermal conductivity, $c$ is velocity of light and $\varepsilon_s$ is the static dielectric constant. These figures of merit predict that SiC is an excellent material for high frequency devices [166]. Baliga derived a figure of merit (BFOM)

$BFOM = \varepsilon_s \cdot \mu \cdot E_g^3$

where $\mu$ is the mobility and $E_g$ is the bandgap of the semiconductor. From this figure of merit the excellent performance of high voltage unipolar devices in SiC can be predicted. Baliga also derived a high frequency figure of merit (BHFFOM) for unipolar switches

$BHFFOM = \mu \cdot E_B^2 \cdot \sqrt{\frac{V_G}{4V_B^3}}$

where $V_G$ is the gate drive voltage and $V_B$ is the breakdown voltage. This figure of merit demonstrates that a significant reduction in power loss can be achieved by using SiC devices for high frequency applications compared to other conventional semiconductor devices.
Table 2.8

Comparison of normalized figures of merit for α-SiC and Si

<table>
<thead>
<tr>
<th>Material</th>
<th>JFOM</th>
<th>KFOM</th>
<th>BFOM</th>
<th>BHFFOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>400</td>
<td>5.1</td>
<td>560</td>
<td>69</td>
</tr>
<tr>
<td>6H-SiC</td>
<td>400</td>
<td>5.1</td>
<td>240</td>
<td>29</td>
</tr>
</tbody>
</table>

Following these figures of merit (Table 2.8 and 2.9) and increasing interest in high temperature, high power, and high frequency devices based on SiC, the need for numerical investigation pertaining to these devices is becoming important. Device simulation has gained increasing relevance for the design and optimization of electronic semiconductor applications due to the rising design complexity and the cost reduction achieved by reducing the number of experimental batch cycles. It has been a powerful and widely used tool in the investigation and improvement of narrow bandgap semiconductor devices, and it will be a driving force in the further development of both semi-conducting and semi-insulating SiC devices.
### Combined Figures of Merit

<table>
<thead>
<tr>
<th>Material</th>
<th>Combined Factor of Merit (CFOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1</td>
</tr>
<tr>
<td>GaAs</td>
<td>7.36</td>
</tr>
<tr>
<td>6H-SiC (disregarding anisotropy of mobility)</td>
<td>393</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>404</td>
</tr>
<tr>
<td>GaN</td>
<td>404</td>
</tr>
<tr>
<td>Diamond</td>
<td>30080</td>
</tr>
</tbody>
</table>

**Combined Figure of Merit for High Frequency / High Power**

$$ CFOM = \frac{\chi \varepsilon_0 \mu V E_B^2}{(\varepsilon_0 \mu V E_B^2)_{silicon}} $$

- $\chi$ is thermal conductivity
- $E_B$ is breakdown field
- $\mu$ low field mobility
- $\nu_s$ is saturation velocity
- $\varepsilon_0$ is dielectric constant
Device Design Consideration

A unique distinguishing feature of all semiconductor power devices is their high voltage blocking capability. Depending on the application, the breakdown voltage can range from 25 V for applications such as power supplies to over 6 KV for applications in power transmission and distribution. The ability to support high voltages is determined by the onset of avalanche breakdown, which occurs when the electric field within the device structure becomes strong. In power devices, high electric fields can occur both within the interior regions of the device where current transport takes place and at the edges of the devices. Proper design of devices requires careful attention to field distributions both at the interior and at the edges to ensure high voltage blocking capability. Since the forward voltage drop during current conduction is larger for devices with higher breakdown voltage capability, it is important to obtain a device breakdown voltage as close as possible to the intrinsic capability of the semiconductor material for optimum device performance.

In power devices, the voltage is supported across a depletion layer formed across either a p-n junction, a metal-semiconductor (Schottky barrier) interface, or a metal oxide semiconductor (MOS) interface. The electric field that exists across the depletion layer is responsible for sweeping out holes or electrons that enter this region by the process of either space charge generation or by diffusion from the neighboring quasi-neutral regions. When the voltage is increased, the electric field in the depletion region increases and the mobile carriers are accelerated to higher velocities. The basic p-n structure is the abrupt junction in which the doping concentration on one side of the junction is very large when compared with the other side. In this case, the depletion region extends primarily on the lightly doped side of the junction. When the breakdown field of the material is determined, one may calculate the breakdown voltage from:
SiC power devices are expected to show superior performance compared to devices made with conventional narrow bandgap semiconductors. This is primarily because SiC has an order of magnitude higher breakdown electric field \( (E_B = 2 - 4 \times 10^6 \text{ V/cm}) \) and higher temperature capability as already discussed in the former sections. The high breakdown electric field allows the design of SiC power devices with thinner and more heavily doped voltage blocking layers \( (W) \).

The more highly doped blocking layer (more than 10 times higher) provides lower resistance for SiC devices because more majority carriers are present than for comparably rated Si devices. The thinner blocking layer of SiC devices (a tenth that of Si devices) also contributes to the lowering of the specific on-resistance by a factor of 10. The combination of a tenth the blocking layer thickness with ten times the doping concentration can yield a SiC device with a factor of 100 advantage in resistance compared to that of Si devices. We assume that the semiconductor layer is thick enough to support the reverse-biased depletion layer width \( W_m \) at breakdown. If the semiconductor layer \( W \) is smaller than \( W_m \), the device will be punctured through; that is, the depletion layer will reach \( n-n^+ \) interface prior to breakdown. When the reverse bias increases further, the device will breakdown while the critical field \( E_B \) occurs at \( x=0 \) is essentially the same.
The breakdown voltage $V_B'$ for the punch-through diode can be calculated from:

$$
\frac{V_B'}{V_B} = \frac{\text{shaded area in Fig.2.7 (b)}}{\text{total area}} = \frac{\int E_{p} x + E_{n} \, dx}{E_{p} W_{m} / 2} = \left( \frac{W}{W_{m}} \right) \left( 2 - \frac{W}{W_{m}} \right)
$$

Hence, $V_B'$ becomes

$$V_B' = V_B \cdot \left( \frac{W}{W_{m}} \right) \cdot \left( 2 - \frac{W}{W_{m}} \right),$$

Here, the depletion layer width $W_{m}$ can be obtained from

$$W_{m} = \sqrt{\frac{2 \varepsilon_{p} \cdot V_B}{q \cdot N_{B}}}.$$

Punch-through occurs when the doping concentration $N_{B}$ in the epilayer becomes sufficiently low. For a given thickness the breakdown voltage approaches a constant value as the doping decreases.
2.3.4 Recent works on Si$_{1-x}$Ge$_x$ material and devices

The demands for the high speed wireless telecommunication systems such as wireless phones or wireless LANs are increasing rapidly. The portable equipment of wireless systems runs on batteries. Therefore, the devices used in the RF sections of the equipment require, low power dissipation along with high speed operation is strongly required. Small bipolar transistors are currently used in various circuits in the RF sections because their characteristics meet these demands. On the other hand, the high speed and low power performance of RF CMOS circuits is rapidly approaching to that of Si bipolar circuits due to the use of deep sub-micron gates. It is expected, however, that Si bipolar circuits will maintain an advantage over CMOS circuits, at least, in the near future, due to the continuing reduction in size and parasitic capacitance of transistors. Research work on the development of very small ultra-low-power Si$_{1-x}$Ge$_x$ based bipolar transistors has been reported. The parasitic capacitance of npn bipolar transistor with p-type Si$_{1-x}$Ge$_x$ base, has been drastically reduced by using a selectively grown Si$_{1-x}$Ge$_x$ base, a wedge-shaped CVD-SiO$_2$ isolation structure, and borophosphosilicate glass (BPSG)-refilled trench. Base-collector capacitance $C_{TC}$ is less than 1 fF and substrate capacitance $C_{TS}$ is 2.1 fF for transistors with an emitter area $A_E$ of 0.2 μm × 0.7 μm. These transistors exhibit a high maximum oscillation frequency $f_{max}$ of over 30 GHz at a very low current of less than 10 μA, and 70 GHz at 100 μA [140].

As the band gap of Si$_{1-x}$Ge$_x$ material reduces with the increase in $x$, there is an enhancement of optical properties of the material. It is reported that the electron and hole mobilities in Si$_{1-x}$Ge$_x$ are higher than those in silicon. This enhancement of carrier mobilities has helped in the development of high speed of Si$_{1-x}$Ge$_x$ based devices. In Si$_{1-x}$Ge$_x$ HBTs, higher hole mobility values decrease the base resistance while higher electron mobility increases the emitter efficiency.
and unity gain frequency. Consequently, there is a high current gain in CE mode and the collector current is higher than that with Si BJTs.

It is reported that lower the Ge composition, the higher is the mobility value of the carriers. The results from the cut-off frequency technique and magneto-transport technique [experiment performed in the University of Michigan, Ann Arbor, USA] that the minority electron mobilities decrease with increasing Ge composition in Si$_{1-x}$Ge$_x$ ($0.2 \leq x \leq 0.4$) alloys for the temperature range $5K \leq T \leq 300K$. The mobility values for carriers saturate and exhibit a negligible Ge composition dependence when $x$ becomes smaller than 0.2, the same report suggests.

The same experiment also shows that a lower Ge-composition in the base region is more attractive for high-speed operation of npn Si$_{1-x}$Ge$_x$/Si HBTs. Too small a Ge composition leads to significant degradation of current gain due to the band-offset reduction in the valence band.

The n-channel Si$_{1-x}$Ge$_x$/Si MODFETs have been constructed to combine low power, low noise, and low cost Si FET technology along with the performance enhancement due to heterostructure engineering and the device appears very promising for GHz range applications. The dc transconductance of Si$_{1-x}$Ge$_x$/Si n-MODFET is higher than that of GaAs/AlGaAs MODFETs, due to the higher electron mobility into the strained Si channel and to the excellent two-dimensional carrier confinement.

Recently strained Si$_{1-x}$Ge$_x$/Si quantum wells have attracted considerable interest due to their potential applications in optoelectronics. Due to the indirect band structure and creation of defects caused by the large lattice mismatch between Si$_{1-x}$Ge$_x$ layer and the Si substrate layer, it is quite a challenge for researchers to consider Si based alloys as a promising candidate for optoelectronic devices. However, the critical thickness limitation for strained layers can be weakened using the selective epitaxy. This method has enabled to grow the
dislocation free and fully strained $\text{Si}_{1-x}\text{Ge}_x$ layers much above the critical thickness. This growth technique is particularly interesting to fabricate LEDs using $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ heterostructures, where a much thicker $\text{Si}_{1-x}\text{Ge}_x$ active layer is suited for room temperature operation.

It is reported by Murtaza et al. [141] that the photocurrent for $\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ multiple quantum well (MQW) p-i-n diodes have a strong dependence on the reverse bias.

Most recently resonant tunnelling diodes have been fabricated using strained Si wells and strained $\text{Si}_{0.8}\text{Ge}_{0.2}$ n-type substrate, that demonstrate negative differential resistance at 298 K. Peak current density of 5 kA/cm$^2$ with peak-to-valley current ratio of 1.1 has been obtained. Theoretical modelling of the structure demonstrate that the major current peak results from the tunnelling of light-mass electrons from the relaxed substrate and not from the heavy-mass electrons in the emitter accumulation layer.

2.3.5 Recent works on GaN based devices

GaN based devices can generate and amplify signals in THz frequency bands. These are also used for mixing and multiplication. Recently Scientists at the University of Illinois at Urbana-Champaign have demonstrated Terahertz transistor based on InP/InGaAs which is claimed as the fastest transistor with a frequency of 845 GHz or 0.845 THz. This new transistor utilises a pseudomorphic grading of base and collector region thereby leading to an enhancement of electron velocity. Both the current density and charging time decrease due to the above reason.

High power heterojunction bipolar transistors based on AlGaN/GaN have been reported with excellent DC and high frequency performance [20]. The wide band gap nitrides are expected to emerge as better alternative to conventional III-V semiconductors like GaAs or InP for fabrication of Impatt diodes, although
no such reports on fabrication and characterisation of GaN Impatts are available in the literature to the best of author's knowledge. The high power-high efficiency capability of GaN Impatts is expected from very high critical field ($2 \times 10^8$ V/m), high saturation velocity ($2 \times 10^5$ ms$^{-1}$) and high thermal conductivity (0.13 KW/m) of GaN. GaN exists in nature in two most common polytypes (i) zincblende and (ii) wurtzite. These two polytypes have different material parameters.

GaN also exhibits negative differential mobility in its drift velocity versus electric field characteristics. GaN Gunn diodes have been reported for THz signal generation [107].

GaN ($\epsilon_g = 3.4$ eV) and their ternary alloys like Al$_x$Ga$_{1-x}$N have emerged as important materials for electronic and optoelectronic devices. High power transistors based on AlGaN/GaN have been reported with excellent DC and high frequency performance [20].