Chapter-2

Literature Review
Literature Review

Part A: A Brief Review on IMPATT Diodes

2.1 Introduction

IMPATT (Impact ionization Avalanche Transit Time) devices are basically reverse-bias $p-n$ junctions which exhibit high-frequency negative resistance due to the phase delay produced by the avalanche multiplication process and transit time required by the charge carriers to cross the depletion layer of the devices. Two physical phenomena which are responsible for IMPATT operations are Impact Ionization and Transit Time. Fundamental physical processes for the operation of IMPATT diodes are discussed in section 2.2. A variety of new diode structures have been proposed by different researchers and are presented in section 2.3. The efficiency, frequency coverage and RF power delivery have been enhanced to high level through proper computer aided design of the device and through advancement of various fabrication technologies. This is reviewed and discussed in section 2.4. A brief report on Oscillator performance is discussed in section 2.5.

As mentioned in introduction, Gunn diode also has the potential to operate as a high frequency signal generator. Thus, a detailed review on Gunn diode, its potential, oscillator performance etc. is presented in this thesis in section 2.6 – 2.12.

2.2 Fundamental Physical Process

The minority carriers, while traversing through the active zone of a reverse bias $p-n$ junction, gets multiplied by impact ionization and attaining a proper reverse bias, the condition of avalanche breakdown is fulfilled for the diode, leading to the generation of large reverse current. The reverse breakdown bias voltage is dropped across the depletion zone of the diodes giving the electrostatic field profile. The field
profile has a maximum value near the junction and it tapers down to zero value depending on the diode structure. When AC electric field is superimposed with DC electric field, the condition for generation of microwave negative resistance is satisfied owing to two physical phenomena. These are the transit of charge carriers with saturated drift velocity and avalanche multiplication of charge carriers due to impact ionization in the high field zone. The avalanche breakdown of the junction occurs, when the multiplication of carrier population in the depletion layer reaches a very large value. The carrier build up process lags behind the RF voltage because the former depends on the carrier concentration and carrier ionization rates. The delay involved in building up avalanche multiplication process ($\tau$) together with the transit time $\tau_t$ required by carriers (moving with saturated velocity) to cross the depletion layer, leads to the desired phase difference between the current and voltage wave forms and gives rise to high frequency negative resistance [6, 21-24]. These aspects of the IMPATT action will be discussed in this section.

2.2.1 Saturated Drift Velocity of Charge Carriers

Electrons gaining energy from the electric field in a semiconductor undergo collisions with crystal lattices. At low fields, the principal scattering agencies are acoustic phonons when the resultant drift velocity of carriers become proportional to the electric field and the relation $v_d = \mu E$ is valid. As the field increases, low energy acoustic phonon scattering becomes an inefficient process and electrons lose their energy through the emission of optical phonons. Thus, the average drift velocity falls below the linear projection of low field characteristics of drift velocity and becomes proportional to the square root of the electric field.

At high field ($>10^6$V/m), the energy gained by the carriers from the applied field is almost totally transferred to crystal lattice through the emission of optical
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phonons. The drift velocity, then, will approach a limiting value known as the scattering limited velocity $v_s$ [9,21] and is given by

$$v_s = \frac{8\varepsilon_{op} \tanh(\varepsilon_{op} 2KT_0)}{3\pi m^*}$$

(2.1)

where $T_0$=Lattice Temperature, $K$=Boltzmann Constant, $\varepsilon_{op}$ = Characteristics of optical phonon energy (0.063eV for Si) and $m^*$ = effective mass of carriers.

The measured values of drift velocities of electrons and holes for silicon [9] and their variation with electric field are shown in figure 2.1. The expression for carrier velocity as a function of electric field is approximately given by [9, 21]

![Fig 2.1 Drift Velocities of Electrons and Holes at 300° K in Silicon as functions of Electric Field](image-url)
\[ v(E) = v_s \left[ 1 - \exp \left( - \frac{\mu E}{v_s} \right) \right] \] (2.2)

where \( v(E) \) is the carrier drift velocity at field \( E \), \( v_s \) is the saturated velocity and \( \mu \) is the mobility of the charge carriers. This expression reasonably fits with the experimental \( v-E \) characteristics for both the charge carriers in case of Si and SiC.

### 2.2.2 Impact Ionization and Avalanche Breakdown Condition

Avalanche multiplication through impact ionization sets in when a semiconductor is subjected to an electric field in excess of \( 10^7 \text{V/m} \). The charge carriers increase their population by creating additional electron-hole pairs through collision with neutral atoms of the semiconductor lattice.

The parameters characterizing the magnitude of impact ionization are the ionization rates \( \alpha \) for electrons and \( \beta \) for holes which represent the number of ionizing collision experienced by a single carrier per unit distance of travel in the direction of electric field. The ionization rates are quite sensitive to electric field. Several authors [22-24] have carried out theoretical investigations on the field dependence of carrier ionization rates in silicon. Experimentally measured values of these rates [10] for silicon materials can be approximately fitted to an exponential form of variation with electric field [25]. Thus the ionization rates of electrons and holes for silicon [10] can be fitted to the exponential form [6]

\[ \alpha_{n,p} = A_{n,p} \exp \left[ - \left( \frac{b_{n,p}}{E} \right)^m \right] \] (2.3)

where \( A_{n,p} \), \( b_{n,p} \) and \( m \) are constants for electrons and holes.

These constants have different values for different temperatures and for different field ranges for different semiconductors. We have used the realistic data for the different material parameters. Different parameters of ionization rate and velocity-field characteristic are presented in chapter 3 for Si and GaN from different research papers.
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The minority electrons and holes flow from respective sides of \( p-n \) junction under the influence of reverse electric field constituting the reverse saturation current. The minority carriers on entering the active region experience a forward electric field from which, they gain energy. When they attain a threshold energy for impact ionization, they are capable for producing additional electron-hole pair. Owing to the large values of ionization rates near the junction (where electric field is very high), the carriers undergo rapid multiplication. The avalanche breakdown condition is attained when carrier current multiplication factor \( i.e. \) the ratio of generated current to initiating current becomes very large.

Lee et al [26] have given a generalized breakdown condition for a \( p-n \) junction considering the initiation of multiplication by both types of charge carriers. The process of avalanche multiplication is shown in figure 2.2.

The thermal saturation current densities of electrons \((J_{sn})\) and of holes \((J_{sp})\) enter the active layer from \( p- \) and \( n \)-sides respectively and get multiplied to electron current density \((J_n)\) and hole current density \((J_p)\) at the other edges of the depletion layer. Thus, the corresponding multiplication factors are \( M_n = J_n / J_{sn} \) for electrons and \( M_p = J_p / J_{sp} \) for holes. Let a small width of \( dx \) be considered (figure 2.2) in the depletion layer and the changes in carrier current densities within this small width can be obtained as,

\[
dJ_n = -dJ_p = \alpha_n J_n dx + \alpha_p J_p dx
\]

(2.4)
Taking total current density $J = J_p + J_n$ and from equation 2.4 we get

$$\frac{dJ_n}{dx} = \alpha_n J_n + (J - J_n)\alpha_p$$

or

$$\frac{dJ_n}{dx} = (\alpha_n - \alpha_p)J_n = \alpha_p J$$

Using the general solution of equation 2.5, the multiplication factor [27] can be determined and can be given by

$$1 - \frac{1}{M_n} = \int_0^w \alpha_n \exp \left[ - \int_0^x (\alpha_n - \alpha_p) \, dx' \right] \, dx$$

(2.6)

for electrons and

$$1 - \frac{1}{M_p} = \int_0^w \alpha_p \exp \left[ - \int_0^x (\alpha_n - \alpha_p) \, dx' \right] \, dx$$

(2.7)

for holes. $W$ is the width of the active region.

Avalanche breakdown condition is satisfied when the multiplication factors become infinite and the conditions of breakdown are given by

$$\int_0^w \alpha_n \exp \left[ - \int_0^x (\alpha_n - \alpha_p) \, dx' \right] \, dx = 1$$

(2.8)

and

$$\int_0^w \alpha_p \exp \left[ - \int_0^x (\alpha_n - \alpha_p) \, dx' \right] \, dx = 1$$

(2.9)

This reduces to the following simple form [28]

$$\int_0^w \alpha \, dx = 1$$

(2.10)

when the ionization rates for both types of carriers are identical i.e. $\alpha_n = \alpha_p = \alpha$. The above two mechanism namely drift of charge carriers and carrier multiplication
under avalanche breakdown condition form the basis for generation of microwave negative resistance by the diode under IMPATT action.

![Diagram of carrier current density and electric field profile in the active layer of a reverse bias p-n junction.](image)

**Fig 2.2** The variation of carrier current density and electric field profile in the active layer of a reverse bias p-n junction.
2.2.3 Mechanism of IMPATT Operation

The resistance of a slab of a semiconductor between two electrodes is positive when the current and voltage waveforms across the terminals are in phase unison and it then dissipates power. There are a number of ways to introduce a phase shift between the current and voltage waveforms to produce a negative resistance at the frequency of a RF wave. A device will exhibit negative resistance when the AC current lags behind the voltage by a phase angle lying between $90^\circ$ to $270^\circ$. This desired phase difference in IMPATT devices is produced by the inherent delay associated with the avalanche build up process and the transit time delay produced by transit time taken by the charge carriers in traversing the depletion region. Diodes of various doping profile like Read diode [29], $p$-$i$-$n$ diode [30] and $p$-$n$ junction diode [2] exhibit negative resistance at microwave frequencies due to the above mentioned processes, under the condition of avalanche breakdown.

The transit time delay due to transit of charge carriers with saturated velocity depends on the width of the active zone and the carrier velocity. The width of the active zone is calculated as the distance between the junction point and the $n^+n$ ($p^+p$) interface. The avalanche phase delay however, depends on the diode structure, the electric field profile, the impurity profile and other operating conditions. The changes in the diode parameters changes the amount of avalanche phase delay and hence the high frequency negative resistance obtained from an IMPATT diode can be enhanced by increasing the amount of phase delay through modulation of diode structures which, in turn, optimizes the IMPATT action of the devices.
2.3 Different IMPATT Diode Structures

A number of IMPATT diode structures fabricated experimentally and proposed by several workers. The prediction for the first time made by W. T. Read [29] in 1958 for the generation of microwave power from p+n+ structure was experimentally verified in 1965 when Lee et al [10] demonstrated microwave oscillations from Read diode in X-band. In the same year, Johnston et al [2] reported the generation of microwave power from p+ n junction diode and indicated that a complicated Read structure was not essential to produce IMPATT oscillations. T. Misawa [30] carried out a small- signal analysis of a uniformly avalanching p-i-n diode and the existence of microwave negative resistance in this structure. In this diode avalanching and drifting of charge carriers take place simultaneously in the entire depletion layer.

The conventional and commonly used IMPATT structure is of the form of an one sided abrupt p-n junction having the doping patterns of the form n+ n p+ or n+ p p+ which are mostly fabricated from homo-structure and hetero-structure materials. Homostructure IMPATT is fabricated using only one base semiconductor and heterostructure IMPATT can be realized by using different semiconductors for different layers of the diode. These structures have only one drift layer where only one type of carrier drifts through the drift region (electrons in n+ n p+ and holes in n+ p p+ diode) and these are thus known as single drift region diodes (SDR diodes). The avalanche zone near the p+ n or n+ p junction in this case extends up to a definite sizeable portion of the depletion layer. The dc field profile in an SDR diode has the shape of a triangle with the field maximum is located close to the junction. The field profiles, structures and doping patterns are shown in figure 2.3. The avalanche delay and transit time delay together determine the phase relation between RF current and
voltage at a particular position of the depletion layer which can be obtained through a computer analysis for a given doping profile. The negative resistance obtained from the diode depends on the avalanche zone and drift zone. The single drift diode is usually fabricated through diffusion process or through ion implantation process. The depletion layer width is thinned down for high frequency operation of the diode. Microwave oscillations from X-band to a frequency of 341 GHz in fundamental mode [1] and 423 GHz in harmonic mode [31] have already been reported from silicon single drift IMPATTs.

In 1970, Scharfetter et al [32] proposed a double drift region (DDR) IMPATT structure of the form $n^+p^+$. Having two drift zones one for electron and the other for the holes where opposite charge carriers move in opposite direction. The drift regions are interspaced by a central avalanche zone around the junction. This type of
structure was proposed as both type of charge carriers in semiconductor could be utilized to produce microwave power. In the same year Siedal et al [25] fabricated DDR IMPATT by ion implantation technique for operation at 50 GHz. A typical flat profile DDR structure, its doping profile and field profile are shown in figure 2.4. The double drift diodes are found to deliver approximately twice the power delivered by a SDR diode because microwave power is contributed by electrons and holes separately due to transit of electrons in the electron drift layer and holes in the hole drift layer.

![Schematic diode structure, doping profile and field profile of a double drift flat profile diode.](image)

Fig. 2.4. Schematic diode structure, doping profile and field profile of a double drift flat profile diode.
This enhancement of power in case of DDR would also cause an increase of device efficiency. The additional drift region in case of DDR diode provides the basic advantage of this structure over the single drift counter parts such as higher breakdown voltage, higher drift voltage and larger depletion layer. The central avalanche region causes a reduction in minority carrier storage effect and thereby increases the efficiency of double drift devices. The DDR diode can be fabricated for very high frequency of operation. A CW output power of 1 W (η = 14.2 %) at 50 GHz from double drift diode as against the corresponding output power of 0.53 W [25] from single drift diode provides an indication as regards superior performance of DDR diodes. At higher frequency also DDRs show their superiority by producing high power. A CW output power of 50mW at 220 GHz from a DDR diode as against the corresponding output power of 25mW from the corresponding SDR diode has been reported [5]. Although DDRs remain as promising sources of high microwave power, the SDR diodes will retain their importance because of ease in fabrication of SDR diodes. Both flat profile single drift and double drift devices are now used for generation of power at mm-wave and sub mm-wave frequencies. The avalanche regions of flat profile SDR and DDR diodes occupy nearly 40 to 60 % of the total depletion layer at very high frequency of design which limit the efficiencies of these structures.

It was suggested by several workers [e.g. 33,34] that the efficiency of SDR and DDR diodes could be enhanced by localizing the avalanche zone through modification of doping profile of the high resistive region in these diodes. The necessary modification in the doping profile is achieved by introducing impurity bumps (a region of high doping density) at various positions of the diode. An impurity bump adjacent to the junction produces high-low (hi-lo) doping profile and when the
bump is situated slightly away from the junction, the doping profile is known as low-high-low (lo-hi-lo) doping profile. The presence of impurity bump enhances the electric field near the junction and reduces the width of high field region. These modified profiles push the value of field maximum. Thus the electric field distribution is enhanced within the avalanche zone which, in turn augments the carrier multiplication process due to high value of carrier ionization rates near the metallurgical junction. This phenomena localizes the avalanche zone and hence provides a higher drift voltage and diode negative resistance enhancing both the device efficiency and power output. Typical doping profiles and field profiles of high-low DDR and low-high-low DDR are shown in figure 2.5. Chang et al [33] were the first to predict an efficiency of 19% from a 50GHz low-high-low Si DDR structure. The realization of different high efficiency diode structures from different materials like GaAs and InP are also seen in literature [e.g. 35]

In the later part of the last decade, studies on hetero-structure IMPATTs have been reported in literature [36,37] Compound, ternary and quaternary semiconductors with tolerable crystal mismatch has been explored and several hetero-structure IMPATTs have been shown to have high-efficiency and to be capable of producing high power. Diode structures having two avalanche zones and one drift zone called Double Avalanche Region (DAR) diode of the structural form \( n^+ p v n p^+ \) (\( v \) is low doped n-region) or \( n^+ p \pi n p^+ \) (\( \pi \) is low doped p-region) have been studied and the results are available in the published literature. The DAR IMPATT was first proposed by Som et al [38] in 1974. Subsequently, it was extended by Datta et al [12], Chakrabarti et al [39] and Pati et al [40]. The DAR diode has two avalanche regions on the two sides of a centrally located drift region. Both the type of charge carriers are subjected to avalanche multiplication twice in the two avalanche zones of
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the DAR diode and the drift zone (v- or \( \pi \)-region) serves the common passage for both type of charge carriers. The analyses of DAR IMPATT show that these structures are little effected by increase in current density due to cancellation of mobile space charge in the common drift region, Further these structures have been found to possess negative conductance in widely different frequency bands which permits for selective tuning of this device.

The heterostructure IMPATT was first proposed by Culshaw et al [41] in 1976. The base semiconductors in the heterostructure IMPATTs are taken different for the central avalanche zone and the two drift zones. The base semiconductors are selected on the basis of band gap energy and crystal structure in a way to obtain perfect lattice matching between them and to realize further localization of avalanche zone. Hicks et al [42] have demonstrated the feasibility of heterostructure IMPATT with GaAlAs for the drift region and GaAs for the avalanche region. Although there was good crystal lattice matching between GaAs and GaAlAs the results remain inconclusive due to non availability of experimental reports relating to determination of material parameters at that time. Ge/ GaAs heterostructure with Ge for the avalanche region and GaAs for the drift region also figured in [41]. At a temperature of 300 K crystal matching between Ge and GaAs is satisfactory (within 0.004 \( \AA^0 \)). Due to lower value of permittivity of GaAs compared to that of Ge (by about 40\%) and crystal mismatch at higher field the structure could not become attractive. Later on GaInAs and GaInAsP have emerged as suitable materials for heterostructure IMPATT because of their suitability of being properly crystal matched to InP and GaAs producing good quality interface.
Fig. 2.5 Schematic diode structure, doping profile, typical field profile of (a) high-low and (b) low-high-low DDRs.
2.4 Fabrication Process: Ion Implantation

The p-n junctions which is capable of producing microwave power through IMPATT mechanism, are to be fabricated with advanced technology like diffusion and ion implantation technologies.

Ion implantation is an important technology in the fabrication of thin electronic and optical devices. Highly energetic ions are bombarded into a target (substrate material) which can change the doping of the wafer. The depth at which the ions are to be implanted is determined by the energy of the ions. The particle flux of the ions being implanted determines the doping concentration of the implanted layer. [13]. The thickness of the layer can be determined from the energy spread of the implanted dose. The flux of the ion implant and energy of the ion beam are the controlling parameters of this technology. The doping profile of an ion implanted layer assumes a Gaussian shape. For multi layered structure several doses of ions are implanted in appropriate sequence and at appropriate positions.

Some of the advantages which make the ion implantation technique suitable for the introduction of the impurities into the wafers are, (1) Precise control of the total amount of impurity introduced, (2) Accurate control of the junction depth and distribution profile of the dopant, (3) Better lateral registration and (4) involvement of low temperature in the process.

The disadvantage of this method is the creation of damage or disordered region within the bulk of the implanted target. At higher ion doses disorder may overlap to change ultimately the crystalline form to an amorphous state. However, effective annealing techniques may be used to recover the crystalline nature of these damaged regions.
An impurity concentration profile of the implanted ions within a limited energy of ion beam can be calculated from a Gaussian distribution [43]

\[ \eta(x) = \frac{N_0}{(2\pi\sigma_P^2)^{1/2}} \exp \left[ -\left( \frac{x - R_P}{\sqrt{2}\sigma_P} \right)^2 \right] \]  \hspace{1cm} (2.11)

where \( R_P \) is the projected range and \( \sigma_P \) is the straggle of the distribution, \( n \) is the ion concentration and \( N_0 \) is ion dose given in ions/\( \text{m}^2 \).

It should be pointed out that the single Gaussian profile specified by \( R_P \) and \( \sigma_P \) gives only a first order approximation to the true profile. For more critical applications, more accurate approaches have been developed [44,45]. The Gaussian approximation will suffice when the objective is to obtain the average location and average extent of the distribution. Experimentally, it is found that the implanted impurity distribution is not symmetrical (Gaussian) but skewed and possesses tails due to channeling of ions. This type of profile (impurity distribution) of the ions can be calculated by the higher order moments of statistical theories.

Winterbon et al [45] used the third moment approach to obtain the ion implantation profiles. It is enough to provide sufficient information to construct accurate impurity distribution when the asymmetry is not excessive (less than the standard deviation) [45]. In this case the profile can be represented by two half Gaussian, each with a different standard deviation \( \sigma_1 \) and \( \sigma_2 \) for its straggling and modal range \( R_m \). This method is used to specify the implanted impurity distribution, of all impurities except boron at higher energy. For boron implantation and its distribution at higher energy one has to use modified Pearson type IV [45] distribution function which is usually called as fourth moment approach. The values of \( R_P \), \( \sigma_P \), third moment of \( R_P \) (CM3P) and third moment ratio at different energies are given in [46] and is also shown in figure 2.6 for most used species B, P, As and
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Sb and the fourth moment data are available in [47] Thus, depending upon the nature and range parameters, Gaussian distribution, third moment approach and Pearson type IV distribution can be used to determine the doping profile.

In case of silicon mm-wave IMPATT diodes, ion implantation offers important advantages in controlling junction depth and doping level [48-52]. Although a simple abrupt $n^+n^p^+$ junction can operate as an IMPATT diode, improved results can arise from an implanted junction [25] because the junction can made uniform and shallow for improved heat dissipation. It can provide a controlled junction depth, reduce thermal resistance and can be used to reduce the contact resistance in the n+ substrate [53]. In addition, the annealing of the P+(n+) implant can be performed at 900° C, which is low temperature and thus will not effect the epitaxial n( P) or n$^+$ (p$^+$) layer is overcompensated by a factor of 2 using a multiple boron implant [13]. A shallow diffuse P$^+$ layer was used as the contact. The resulting diode reported by Siedel et al [25] oscillate at 50 GHz with an efficiency of 14.2 % giving the highest value of figure of merit and efficiency amongst the those available CW microwave sources. A DC to RF conversion efficiency of 37% with an output power of 3.4W at 3.3GHz was obtained from an ion implanted GaAs low-high-low IMPATT [31]. The ion implanted during profile across the p-n junction would influence the device performance which can be optimized through variation of ion implantation parameters.

The candidate has reviewed it and decided to obtain the generalized fourth moment approach ion implantation distribution profiles. The results obtained from such study with the model developed by us (shown in chapter 3) is presented in Chapter 4 of the thesis.
2.5 Report on IMPATT Oscillator Performance

The present status of IMPATT diode as regards RF power, efficiency and frequency of operation has been achieved through intense research activities in three decades. Johnston et al [2] were first to report microwave oscillation from an abrupt \( p^+n \) junction in 1965. \( X \)-band microwave oscillation was first obtained by Lee et al [10] from a more complex Read diode structure in the same year. A realistic and brief report on oscillator performance of IMPATT devices is presented in this section. In 1966, Misawa [30] by means of a small signal analysis showed that a negative resistance could be possessed by a junction diode of any arbitrary doping profile. Several fabrication processes have been used to fabricate a variety of diode structures having different doping profiles. These reports showing realization of microwave power from IMPATT diodes have lead intense research works by scientists to devise ways to push the power output, device efficiency and frequency of operation from different IMPATT structures. In 1967, Swan [54] found that a series of combination of two diodes on diamond heat-sink produced CW power output of \( 4.5W \) at \( 13GHz \) with 6.4\% efficiency. In the same year Misawa [55] found a CW output power of \( 1.1W \) at \( 12GHz \) with 7.7\% efficiency with copper heat sink arrangement. Again in 1968, Misawa [21] obtained a power of \( 100mW \) in the mm-wave range \( 50-80GHz \) from \( Si SDR \) oscillator with an efficiency of 3\%. In the next year \( i.e. \) in 1969, Edward and others [22] reported oscillation from silicon \( n^+np^+ \) SDR at \( 110GHz \) with a power output of \( 75mW \).

In 1970, Cowley [23] fabricated \( X \)-band SDR IMPATT diodes with junction area 2 times \( 10^4cm^2 \) and a breakdown voltage ranging 65 to \( 80V \) showing a power output of \( 0.7W \) with 7\% conversion efficiency. In the same year Misawa et al [24] fabricated a SDR IMPATT diode by shallow boron diffusion into a 0.5\( \mu \) thick
epilayer with a donor density of $1.5\times10^{17}\text{cm}^{-3}$ which had a breakdown voltage of $10\text{V}$. The junction area of the diode was $2.5\times10^{6}\text{cm}^2$. The device had a frequency of operation of $111\text{GHz}$ with an output power of $74\text{mW}$ in the CW mode with a conversion efficiency of $3.2\%$. Seidel et al [25] improved the conversion efficiency by fabricating double drift region (DDR) IMPATT diodes with two drift layer interspaced by an avalanche layer. The DDRs were fabricated by the technique of ion implantation along with diffusion. These diodes at CW mode showed a maximum conversion efficiency of $14.2\%$ and $0.93\text{W}$ at a frequency of $50\text{GHz}$. From 1971 onwards research work led to the enhancement of power, efficiency and the frequency of operation. In 1972, Udelson et al [56] showed from a computer simulation that $n^+pp^+\text{ SDR}$ has a better oscillator performance than the $n^+np^+\text{ SDR}$ for silicon. In this year, Smith [57] fabricated $n^+np^+$ diodes by a shallow boron diffusion at $1000^\circ\text{C}$ into an epitaxial layer grown by Silane process at $1000^\circ\text{C}$. A power output of $0.5\text{W}$ with a conversion efficiency of $9.5\%$ at $Q$-band was extracted from the diode. The result indicated considerable improvement of efficiency and power output from SDR diodes.

Pfund et al [58] in 1973 designed and fabricated silicon DDR IMPATT diodes for microwave and mm-wave frequency range. Such diodes delivered power of $16\text{W}$ with $16.3\%$ efficiency in $X$-band, $11\text{W}$ with $14\%$ in $Ku$-band and $6.4\text{W}$ with $5.3\%$ conversion efficiency in $K$-band. In 1974, Swartz et al [59] fabricated $p$-type SDR silicon IMPATT diodes from epitaxially grown silicon, which delivered $700\text{mW}$ at $29.6\text{GHz}$ with $10.9\%$ conversion efficiency in CW mode. Ohomri et al [60] obtained $217\text{mW}$ power with efficiency $2.6\%$ in $80\text{GHz}$ band in the same year. In 1975, Wen et al [61] reported to have obtained a CW power of $198\text{mW}$ at $62.9\text{GHz}$ with a conversion efficiency of $7.3\%$ from $n^+pp^+$ Si IMPATT diode fabricated.
from a multi layer epitaxially grown silicon structure. Another report [62] showed realization of \(85mW\) of power at \(161GHz\) from \(Si\) \(n^+np^+\) oscillator. Silicon SDR IMPATT diode which operates continuously in between \(200\) and \(300GHz\) bands have been reported in 1976. Ino et al [63] fabricated \(n^+np^+\) structure by ion implantation and a CW power output of \(7.5mW\) at \(285GHz\) and \(78mW\) at \(185GHz\) were reported. English et al [64] extracted \(620mW\) power at \(10GHz\) with a conversion efficiency \(7.7\%\) from a DDR silicon IMPATT having a diamond heat-sink. In this year Hirachi et al [65] obtained a stabilized RF power of \(1.6W\) at \(55.5GHz\) with \(11.5\%\) efficiency from a Si DDR oscillator.

In 1977, Chao et al [48] described the packaging and circuit techniques used to attain high power pulsed oscillator above \(200GHz\). A maximum power of \(400mW\) at \(212GHz\) with a conversion efficiency of \(2.6\%\) was reported by them. Ino et al [66] again fabricated silicon IMPATT which showed \(7.5mW\) output power at \(285GHz\). The operation range of the device extended upto \(394GHz\). In the same year, Ishibashi et al [67] tested the harmonic mode of operation upto \(430GHz\) with \(N_2\) cooled Si-DDR IMPATT diodes and obtained \(2.2mW\) at \(412GHz\) with a breakdown voltage of \(0.6\) to \(0.7V\).

Lang-Chee-Chang et al [68] suggested DDR IMPATT diodes with a low-high-low doping profiles and through numerical calculations showed that devices with such doping profiles would have conversion efficiency of \(25\%\) for \(12GHz\), \(24\%\) for \(18GHz\) and \(19\%\) for \(50GHz\). Nagao et al [69] in 1978 realized \(100-150mW\) output power at \(80GHz\) from a silicon DDR IMPATT diode. In 1979 Ino et al [70] obtained more than \(1W\) of CW power output at \(80GHz\) using liquid \(N_2\) cooled Si DDR IMPATT diodes mounted over a diamond heat sink. The impurity concentration on each drift region was taken to be \(3x10^{17} cm^3\). Nagao et al [71] also obtained more
than 1W of CW power output at 80GHz with 4% conversion efficiency from a DDR silicon IMPATT diode mounted on diamond heat-sink. In 1980, Yu-Dao-Heng it et al [72] obtained an output power of 800mW in CW mode at 7.7GHz with 6.5% conversion efficiency from a double mesa-silicon IMPATT diode. Upto 1980, there has been a steady progress in CW operation of Si DDR oscillators with achievement of CW power of 2.25mW at 40GHz, 980mW at 100GHz and 50mW at 220GHz from Si flat profile double drift diodes [5].

The power output obtained from a single IMPATT diode may be low. But the diodes may be combined in series and/or parallel to increase the power output. Such composite structures have been observed to produce very high power. Realization of 40W of power at 96GHz from a combination of 4 Si diodes [73] and 1.05W of peak power from two silicon diodes can be mentioned as significant achievements as regards power output from combination of IMPATT diodes [74].

In 1981, Leistener et al [75] fabricated a p-type SDR IMPATT diode on a copper heat sink with a quartz standoff package. The diode was mounted on a resonant cap wave guide structure and a maximum CW output power 0.5W at 68GHz with an efficiency of 8.7% was obtained.

With the increase in the cost of the fabrication of equipment and of materials like gold used for contact and diamond used for heat sink, the cost of the fabricated device increased. In 1982 Marin et al [76] described a low cost high yield production of silicon IMPATT diodes provided by a new process involving (a) double mesa etching, (b) inexpensive metallization, (c) simple passivation, and (d) wafer probing after mesa etching. Silicon n+np+ SDR diodes were fabricated on two inch diameter wafers with a 70-80% yield. The minimum CW power obtained was 0.5W for X-band with a 6-7% conversion efficiency.
In 1983, Wenger [77] fabricated silicon SDR IMPATT diode at D-band frequencies with \( n^+np^+ \) structure formed by thermal diffusion of boron. A CW power output of \( 70mW \) at \( 137GHz \) with a conversion efficiency of \( 3.2\% \) was obtained. The diodes were packaged with a quartz standoff configuration on a copper heat sink and mounted into a cap type wave guide resonator.

In 1984, Leistner et al [78] fabricated SDR \( n^+np^+ \) high power Silicon IMPATT diode by a simple diffusion process for operation as diamond heat sinks. From this diode, a maximum power output of \( 0.5W \) at \( 90GHz \) was obtained. In 1985, Pierzina et al [79] fabricated high power pulsed beam lead Si SDR diodes. These diodes deliver more than \( 10W \) of output power at \( 73GHz \) with \( 5\% \) conversion efficiency. In 1986, Luy et al [80] fabricated CW IMPATT diodes for W-band operation using the molecular beam epitaxy technique. Active layer of single drift structure was grown at \( 750^\circ C \) and \( 550^\circ C \). These diodes were mounted in a hermetically sealed package on a diamond heat sink and delivered \( 450mW \) power at \( 87GHz \). In this year, for the first time Luy et al [81] fabricated Si DDR IMPATT diode by Si-MBE process. The precise control of doping by MBE helped them to grow complex doping structure like low-high-low diode. These diodes with unoptimized structure delivered a CW power output of \( 600mW \) at \( 94GHz \) with \( 6.7\% \) efficiency.

In 1988, Mehdi et al [82] used Silicon Carbide instead of pure silicon as a substrate because of its thermal and electronic properties. Finally a comparison between DDR IMPATT devices having SiC and silicon substrate was made at various frequencies and it is found that SiC substrate IMPATTs produced more power than ordinary silicon IMPATT diodes in the CW mode. In the same year, Luy et al [83] realized a monolithically integrated co planer silicon IMPATT oscillator for W-band
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CW operation. They reported a power output of only 1mW from an initial measurement.

In 1990, Behr et al [3] fabricated pulsed Si DDR IMPATT diodes mounted on diamond heat sinks. The diode delivered 42W at 96GHz. Same year Pao et al [84] fabricated and tested DDR silicon IMPATT diodes with hybrid Read profiles by using VPE technique. They realized 1.95W with 11.7% efficiency at Q-band (40.6GHz), 1.05W with 13.6% efficiency at V-band and finally 612mW with 5.7% efficiency at 93GHz. For long pulse operation, 1.08W peak power was obtained at 96GHz.

In 1991, Luy et al [85] experimentally realized the DDR low-high-low structure by growing layers with silicon through MBE fabrication parameters in millimeter wave range (40-60GHz) and obtained maximum conversion efficiency of 14.3% at low DC current density.

In 1992, Luy et al [86] designed flat profile and low-high-low Si IMPATTs for 94GHz and layers were grown by Si-MBE. They obtained an efficiency of 17.6% at 67GHz with a double low-high-low diode.

In 1993, Mitra et al [87] have experimentally study the electrodepositing of gold metal on the silicon wafer for the formation of an integral heat sink of IMPATT diodes. The optical control of IMPATT oscillator also gained momentum in this year. Biswas et al [88] have explained different aspects of IMPATT oscillators from the optical control of the diode.

In the year 1994, Ganguly et al [89] showed that substrate thinning is a necessary step for the fabrication of IMPATT diode. They have done it by both chemical etching and mechanical etching and the results are presented for 8-26GHz.
frequency range. In the same year, Curow [90] have proposed an IMPATT device structure for D-band applications by using hydrodynamic transport model.

The high-frequency IMPATT diodes operating in the TUNNETT (Tunneling Transit Time) mode have been found to have increasing applications these days. Eisel et al [91,92] have studied the enhanced performance of TUNNETT diode oscillators above 100GHz by using diamond heat sinks and reported their studies in 1994 and 1995. They have obtained an RF output power of more than 70mW with an efficiency of 4.9% at 105.4GHz from these diode structures in 1995. MITATT mode InAs$_{0.88}$Sb$_{0.12}$ devices was explored by Dash et al [93,94] with 32% efficiency in 1999. A detailed study on DAR diode [95] and IMPATTs noise characteristics were heavily studied and presented towards end of the century [96,97] and is seen in different literature. Heterostructure DAR (InP-based) and Si-based diode was also seen at the beginning of the century designed theoretically by Pattanaik et al [98] and Dash et al [99] respectively. Non linear analysis and structure Optimization of a DAR IMPATT diode which includes two avalanche regions inside the diode was studied by Zemaliak et al [100]. The admittance and energy characteristics of a DAR diode were analyzed in between 30 to 360 GHz and optimized for the second frequency band near 220 GHz. Kasper et al [101] integrated monolithic IMPATT diodes combined with coplanar waveguide resonator on unthinned silicon wafers to form simple oscillators for mm-wave operation around 90 GHz. De et al [102] has studied the effect of punch through on the microwave series resistance of n$^+$np$^+$ Si IMPATT diodes around the X-band. S-parameter measurements were performed to characterize IMPATT diodes integrated in coplanar waveguides, up to a maximum frequency of 40GHz [103].

Gradually, the focus changes towards the high band gap semiconductors to use as IMPATTs from traditional Si and GaAs-based IMPATTs. Two semiconductors,
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namely GaN and SiC becomes the important material for the IMPATT devices. The GaN-based IMPATT devices were seen in the literature for the first time in 1999 [104]. In the mean time, III-Vth compound semiconductor based heterostructure IMPATTs also played the major role as the signal generators. The researchers have started developing large signal analysis and is seen in the literature recently. Using this model, In 2000, El-Syed et al [105] have found the effect of the peak value of the microwave signal on the IMPATT operation. A Monte Carlo Particle (MCP) bipolar model for 4H-SiC consisting of three electron and two hole bands was developed to simulate the millimeter wave power generation by 4H-SiC IMPATT diodes by Zhao et al [106].

More report on Tunnelling Assisted Noise is presented by Dash et al [97] for Read type of GaN-based IMPATTs. The GaN-based IMPATTs noise characteristics were studied by Panda et al [16,17] in 2001. Yuan et al [107] in the same year observed an X band SiC IMPATT diode.

Similarly, SiC-based IMPATT devices are recently fabricated by Vassilevski et al [108,109]. However, theoretical results are not available in the literature except very few [106,110]. Further, different polytypes of SiC are available, namely, 3C-SiC, 4H-SiC, and 6H-SiC. The author has attempted to add to the present state of art of IMPATT diodes as regards to high band gap based materials with a view to suggesting methods for the betterment of IMPATT performance.

In 2004, the prospects of InP/GaInAs heterojunction was explored by Mishra et al [98] for application as a DAR IMPATT diode as well as for Si/SiGe heterostructure [102]. This leads to think for more efficiency and high power from base semiconductor material and evolves the study on high band gap-based IMPATTs.
With the publications of Panda et al [16,17] on GaN-based IMPATTs, more work on the same material based IMPATTs are seen in the literature in recent years [111-114].

The high band gap SiC-based IMPATTs are seen in the literature from 2005 onwards and the preliminary results are presented by Pattanaik et al [110]. Reliability of terahertz-frequency (~1.0THz) characteristics of wide-band gap (WBG) wurtzite (Wz)-GaN- and 4H-SiC-based p++nn++-type SDR IMPATT devices is compared through a simulation scheme by Moumita et al [112].

In 2008, Mukherjee et al [111] analyze photosensitivity of GaN and SiC THz IMPATT oscillators, compared theoretical reliability and studied experimental feasibility. The same author [113,114] had designed SDR, DDR, p'+nn+ type 3C-SiC/β-SiC and hexagonal (4H & 6H) SiC based IMPATT diode. In the same year, Xu et al [115] describes the properties of monolithic W-band IMPATT oscillator for Automotive Radar applications.

In 2009, Shi et al [116] investigate the dynamic performance of a Si/SiGe-based impact ionization avalanche transit time photodiode(PD) fabricated on a standard Si substrate that operates at 830 –nm wavelength. Effect of Punch –Through on Terahertz frequency characteristics of 4H- SiC based p++pnn++ IMPATT devices through a generalized simulation technique was studied by Mukherjee [117] in that year. Tripathy et al [118] studied the wide band gap semiconductor SiC with their superior electrical properties through advanced computer simulation experiment on hexagonal (both 4H and 6H) SiC based double drift IMPATT diodes and after comparison it was concluded that flat profile 4H-SiC DDR diode would emerge a good candidate for high power with high frequency under mm-wave operation. Mukherjee et al [119] carried out extensive simulation experiments to study the
effects of optical illumination on the terahertz (> 1.0 THz) characteristics of GaN-based IMPATT oscillator.

Mukherjee [120] in that year studied the effect of photo-irradiation on the high frequency characteristics of III-V hexagonal GaN based Top-Mounted and Flip-Chip IMPATT oscillators at MM-wave window frequency (140 GHz). The effect of mobile space charge on the high frequency properties and performance of DDR p⁺nn⁺ Wz-GaN IMPATT diodes at THz frequency has been investigated by Mukherjee et al [121]. Thus a lot of scope is still there to see the potentiality of IMPATTs on high band gap semiconductors and is the scope of the thesis. This is why the author along with the guides decided to work exhaustively on such diode and present in this thesis.
Part B: A Brief Review on Gunn Diode

2.6 Introduction

The operation of the Gunn Diode or the Transferred Electron Diode (TED) is based on the existence of a negative differential conductance in a class of semiconductors [122-127]. The mechanism for producing the negative conductance was proposed by Ridley and Watkins [128] in 1961 and by Hilsum [129] in 1962. It is based on electron transfer from a low energy, high mobility conduction band valley to a high energy, low mobility valley. This intervalley transfer occurs when the electric field is above a threshold level and results in a decrease of the average velocity. The region above the threshold field corresponds to a negative differential mobility region.

In 1963, Gunn [130] observed experimentally current oscillations in GaAs samples. The onset of these oscillations occurred at a threshold field of 2-4 kV/cm and had a frequency inversely proportional to the length of the sample. Subsequent capacitive-probe measurements [131-132] of the potential distribution along a 270μm long GaAs sample revealed the existence of an electric field in-homogeneity moving from the cathode to the anode (positively biased with respect to the cathode). Hydrostatic pressure experiments on GaAs [133] and GaAs$_x$P$_{1-x}$ [134] demonstrated that the threshold field decreases as the separation between the conduction band valleys is reduced. The observations provided evidence that the transferred electron effect is the underlying mechanism behind Gunn oscillations.
2.7 **Fundamental Physical Process**

Consider a uniformly doped n-type semiconductor with conductivity $\sigma$. The response to a perturbation of the carrier density $n(x, t)$ from its equilibrium $n_0(x,t)$ is described by the following set of equations

$$\rho(t) = \rho_{(t=0)} e^{-\frac{t}{\tau_r}}$$

and

$$\rho(x) = \rho_{(x=0)} e^{-\frac{x}{L_D}}$$

where $\rho(x,t) = q(n-n_0)$ is the space charge density at $x$ and time $t$ and $\tau_r$ is the 'dielectric relaxation time'

$$\tau_r = \frac{\varepsilon}{\sigma} = \frac{\varepsilon}{qn\mu}$$

where $\varepsilon$ is the material dielectric constant and $\mu$ is the mobility. $L_D$ is called the Debye length and is related to the dielectric relaxation time by

$$L_D = (D\tau_r)^{\frac{1}{2}}$$

where $D$ is the diffusion coefficient. $\tau_r$ and $L_D$ represent the time and distance over which the space charge perturbation decays for a semiconductor with positive conductivity $\sigma$. This is not the case for a semiconductor with a negative differential mobility where $\tau_r$ becomes negative. Any charge imbalance will grow until the field readjusts itself and equilibrium is reached. In a Gunn device such a space charge layer forms either an accumulation layer or a dipole domain layer. The accumulation layer consists of a localized region with an excess of carriers whereas
the dipole domain layer consists of an accumulation region followed by a depletion region. Current oscillations result from a repeated cycle of nucleation, travel across the sample, and collection at the anode off these space charge layers. The oscillations frequency is inversely proportional to the transit time across the sample.

### 2.7.1 Historical Background

Gunn Diodes, which are solid-state oscillators based on the negative differential resistance (NDR) principle, provide a solution for a low-cost, low noise and high power microwave radiation sources [135]. Such devices are extensively used in intrusion alarms, microwave test instruments and automotive collision avoidance systems. Gunn diodes usually fabricated on GaAs and InP, which are III-V, direct bandgap semiconductor materials exhibiting NDR. Although, the devices based on these materials have proven to be reliable, they are limited in power and operation frequencies due to the fundamental limitation of the band structure of the materials. For higher frequency and high power applications like military radar, high-speed communications and biological agent detection, it is necessary to use other semiconductor materials. One such material that is being investigated for these applications of Gunn diodes is GaN. As mentioned, GaN is a wide bandgap semiconductor material whose Velocity-Field characteristics exhibit NDR. The advantages of using GaN over GaAs and InP, in terms of increased power handling capability and higher operation frequency, are directly related to its larger intervalley energy gap and higher peak and saturation velocities. Although in GaN, further confirmation is needed regarding the presence of a transferred-electron effect (which causes NDR) and the processing technology of GaN is immature, it has a lot of potential and thus should be investigated.
2.7.2 Negative Differential Resistance

Gunn diode oscillators operate on the principles of the Gunn Effect. The generalized Gunn Effect describes the mechanism of electron transfer leading to negative differential conductivity (resistance) in a homogeneous, bulk semiconductor material [135]. These diodes are unipolar devices and, generally do not exhibit the distinctive diode characteristics of p-n junctions. The semiconductor materials that exhibit the Gunn Effect must be direct bandgap materials that have more than one valley in the conduction band and the effective mass and the density of states in the upper valley(s) must be higher than in the main valley.

2.7.3 Inter valley transfer of electrons

Two Valley Transfer Mechanism:

Gunn diode can be obtained from those materials which have the inter valley electron transfer mechanism. In such cases, the main valley of the conduction band is where the electrons initially reside with little or no external electric field applied as shown in figure 2.6(a). If the external field is increased to a value above a threshold field, (figure 2.6(b)), many of the electrons acquire enough energy to be scattered ("transferred") into the upper satellite valley. Since the effective mass in the upper satellite valley is larger than in the main valley, the mobility, and the average drift velocity of the electrons is reduced. The mobility is given by

\[ \mu = \frac{e \tau}{m^*} \]  

(2.16)

where \( \tau \) is the relaxation time and \( m^* \) is the effective mass. The differential mobility, \( \mu_d = d\nu/dE \), becomes negative when the electric field is above the threshold value. This leads to the negative differential resistance (NDR shown in fig 2.7). As the field
is continually increased beyond the saturation field, the drift velocity of the electrons saturates when all the electrons are transferred to upper valley (figure 2.6(c)).

Fig 2.6. (a)–(c) Simplified energy-band diagram for a direct two-valley semiconductor showing electron transfer.

Fig 2.7. Generalised velocity-field characteristics of a transferred electron device showing differential negative resistivity

**2.7.4 Gunn diode operation**

To see how microwave frequencies can be produced from a bulk semiconductor material exhibiting the transferred electron effect as described above, further analysis is needed in the region of negative differential mobility, which is between the threshold field and the velocity saturation field in figure 2.7. A sample of bulk semiconductor material biased in the negative differential mobility region, (under uniform doping concentration and uniform electric field) is thermodynamically unstable. In an attempt to establish a steady state, an energetically more favorable state is reached if, instead of having a homogeneous distribution of charge over the sample length, the charges split up into space charge regions [135]. Any existing
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Space charge inhomogeneity, $Q(x,t)$, traveling at the velocity, $v$, will follow an exponential law given in Eq. 2.22 that can be derived from Maxwell's equations [6].

$$Q(x,t) = Q(x - vt,0) \exp\left(-\frac{t}{\tau}\right)$$  \hspace{1cm} (2.17)

$\tau$ is the energy relaxation time given by:

$$\tau = \frac{\varepsilon_s}{\sigma} = \frac{\varepsilon_s}{|q|N_D\mu_d}$$  \hspace{1cm} (2.18)

where $N_D$ is the doping concentration and $\mu_d$ is the differential mobility.

From Eq. 2.17 it is clear that at low electric fields, when $\mu_d > 0$, the charge inhomogeneity decays with $\tau = \tau_d$, the dielectric relaxation time. At electric fields above the threshold value, when $\mu_d < 0$, the charge inhomogeneity can grow. The growth factor is given by

$$\frac{\ell}{(\nu)(\tau)} = \frac{\varepsilon_s|N_D\mu_d}{|q|\varepsilon}\geq 1$$  \hspace{1cm} (2.19)

where $\ell$ is the device length and $\nu$ is the electron velocity. Equivalently,

$$N_D\ell \geq \frac{\varepsilon_s\nu}{|q|\mu_d}$$  \hspace{1cm} (2.20)

If the growth factor given by Eq.2.20 exceeds the threshold level, then the charge inhomogeneity reaches a significant level and grows into a dipole domain. From Eq. 2.20 it is clear that the design of Gunn diodes lies in choosing the device length, $\ell$, and the doping concentration, $N_D$. One would want to choose $\ell$ as small as possible to minimize the electron transit time from cathode to anode and $N_D$ as large as possible to satisfy Eq. 2.20. However, there is a lower limit on choosing the device length, called the "dead space layer". The dead space layer arises, due to the fact that the scattering of electrons into the upper satellite valley occurs over a finite distance.
It is well known that using a method of hot electron injection can reduce the dead-space layer and enhance the performance of Gunn diodes [6]. Furthermore, to avoid formation of static domains at the anode, $N_D$ should not exceed the critical doping concentration given by

$$N_{CRIT} = \frac{s \times F_{TH}^2}{q}$$

(2.21)

In Eq.2.21, $F_{TH}$ is the threshold electric field. Equations 2.20 and 2.21 are central to the design of Gunn diodes.

From the above discussion, since the charge is inhomogeneous in the negative differential mobility region, the electric field distribution over the sample length is also inhomogeneous. A typical electric field distribution in a Gunn diode is shown in figure 2.8 (a).

It can be seen from figure 2.8(a) that there is a region of high electric field surrounded by a region of low electric field. The corresponding charge distribution is shown in figure 2.8(b). In figure 2.8(b) the accumulation of charge in the region where the electric field is increasing is a result of significant decrease in mobility caused by scattering of electrons into the upper valley. In the region of the sample where the electric field is decreasing, the electrons accumulated in the upper valley lose energy and scatter back into the lower valley of the conduction band. When this happens, a depletion region is created. The accumulation and the depletion regions together form the dipole domain. The dipole domain forms near the cathode and propagates along the length of the device to the anode as shown in figure 2.9.
When the domain reaches the anode it collapses and a new domain is formed at the cathode. The process of domain build-up, propagation, and extinction is repeated. In this way, transit-time current oscillations are produced in the external circuit which have a fundamental frequency given by

$$f_r = \frac{1}{\tau} = \frac{\nu}{L} \approx \frac{\nu_D}{L}$$  \hspace{1cm} (2.22)$$

where, $\nu_D$ is the electron drift velocity and $L$ is the length of the active region of the diode. The fundamental frequencies of these devices can be well within the microwave region for velocities on the order of $10^7$ cm/s and sample lengths in the micron range making them suitable for microwave signal sources.
2.8 Different modes of Operation

The mode of operation described in the previous section corresponds to the transit time mode. Various other modes of operation have been reported [136-143] which depend on the doping, the biasing conditions, the device length, and the resonant circuit. Unlike the transit time mode, the oscillation frequency in these modes is controlled by the circuit. A high rf-impedance resonant circuit results in a large swing of the device terminal voltage which influences the space charge dynamics. In the "quenched domain mode" [143], the field swings below threshold before the dipole layer reaches the anode. The dipole-domain layer is extinguished or quenched and a new domain is nucleated when the field rises above threshold. Oscillation frequencies higher than the transit time frequency are possible with this mode. When the quenched space charge layer is an accumulation layer instead of a dipole domain, the operation mode is referred to as the limited space charge accumulation mode (LSA) [139]. The upper frequency limit of the LSA mode is predicted to be about 20GHz [144,145] in GaAs devices. This relatively low frequency limit is due to the slow process of quenching the space charge layer. It is also possible to operate Gunn devices at a frequency lower than the transit time frequency by delaying the nucleation of the space charge layer. Such mode of operation is referred to as the delayed-domain mode. However, we are considering a generalized model without giving much importance to different modes for which the mathematical model is developed and presented in chapter 3 of the thesis.

2.9 Oscillator Performance and State of the Art Gunn Diodes

Currently, the commercial Gunn diodes in use for microwave local oscillators are made of GaAs and InP due to advanced growth and etching technologies already
developed for these materials. These devices have excellent noise properties and medium output power [146]. Figure 2.10 summarizes the state of the art RF power levels from InP and GaAs Gunn devices.

![Graph showing RF power levels from GaAs and InP Gunn devices.](image)

**Fig. 2.10** Published state-of-the-art results from GaAs and InP Gunn devices under CW operation in the frequency range of 30-400 GHz. Numbers next to the symbols denote dc-to-RF conversion efficiencies in percent. (After Ref. 146)

The RF power levels in figure 2.10 were generated for the fundamental mode and are the highest reported to date from any Gunn device.

In 1990, Rydberg *et al* [147] experimentally investigated InP-TED oscillations for frequency between 170-279 GHz using second and third harmonic mode operations. The conversion efficiencies are comparable to GaAs TED. The output powers, conversion efficiencies, and tuning ranges (more than 22%) are highest reported for InP TED's at these frequencies.

In 1991, Fjeldly *et al* [148] derive an approximate but very precise analytical solution of a generalized diode equations which can be used in the theory of semiconductor diodes, photo detectors, solar cells, field effect transistors, Gunn domain and other areas of device physics.
In 1991, Murica et al. [149] determined the variation of diffusion coefficient \( D(E) \) versus the electric field strength \( E \) at 300° K in n-type GaAs \( (N_D = 3 \times 10^{17}\text{ cm}^{-3}) \) using pulse high frequency noise measurements. The noise current is molded and found to be very sensitive in the \( D(E) \) variation law in the range of 2.5-4.0 kV/cm. The experimental and computed noise of real diodes were found to be quite satisfactory.

In 1992, Wang et al. [150] simulated numerically the generation and distribution noise in short GaAs Gunn devices operating under large signal conditions by the use of the impedance field method combined with the full hydrodynamic transport model.

In 1993, Hahn et al. [151] demonstrated the generation of current pulses in In\(_{0.53}\)Ga\(_{0.47}\)As transferred electron devices by short optical pulses. In the same year Ghione et al. [152] discussed about Numerical large signal simulations of the diffusion noise in GaAs Gunn devices.

In 1996, Hahn et al. [153] fabricated a monolithically integrated laser driver circuit incorporating an InGaAs transferred electron device (TED) and an InGaAsP mushroom stripe laser emitting at 1.3 \( \mu \text{m} \) wavelength. The thermal resistance of the TED had been calculated and an optimum device structure was proposed. In the same year Curow et al. [154] determined the characteristics of harmonic Gunn oscillations for applications at W-band frequencies by systematic large signal simulations. An accurate full hydrodynamic model to maximize computation speed has been developed by Monte-Carlo calculations of real active device structures.

In 1999, Jones et al. [155] presented theoretical and experimental analysis of a second harmonic InP transferred electron device for 63-170 GHz frequency band. High frequency structure simulator (HFSS) and drift diffusion harmonic balance
analysis (DDHB) are used to self consistently analyze the second harmonic TEO-operation.

In 2001, Twynam et al [156] considered the design of hetero junction bipolar transferred electron device (HBTED) for mm-wave Oscillator applications. In 2007, Khalid et al [157] showed the experimental realization of a 108GHz Planar gunn diode structure fabricated in GaAs/AlGaAs by molecular beam epitaxy and devices were made by electron beam lithography.

In 2008, Hopper et al [158] have done temperature measurement on Gunn diode samples using both IR (Infrared) and micro-Raman spectroscopy. Micro raman Spectroscopy was used to give high resolution temperature measurements on the active transit region of Gunn diode as compared to IR thermal measurements made across the mesa region and also on the metallized top contact of the diode. Liang et al [159] introduced an innovative nonlinear circuit model for gunn diode in oscillator based on the physical mechanism of Gunn diode. In the same year Kim et al [160] designed and fabricated GaAs Gunn diodes using the improved fabrication technology, the trench method to develop a Gunn voltage-controlled oscillator (VCO) for the generation of the frequency up to 75-110 GHz. Khalid et al [161] observed multiple oscillations in a planar Gunn diode fabricated using an AlGaAs/GaAs based quantum well structure.

Like that of IMPATTs, the focus on Gunn devices also switched towards high band gap materials. Since, GaN has the NDR characteristics, the focus remains on GaN-based Gunn devices only and the researchers started exploring this material to see the potentiality of GaN-based Gunn diodes. Yilmazoglu et al [20] observed for the first time bias oscillations of GaN-based Gunn diodes realized on a n^+n GaN substrate.
In the same year, Macpherson *et al* [162] used doping spikes for doping notch in GaN Gunn diodes to promote domain formation using Monte Carlo model and compared the results between functional doping spike with physically reasonable doping notch. Xu *et al* [163] analyzed the feasibility of Gunn oscillations in a planar nano-scale unipolar diode or a self-switching device (SSD) using Monte Carlo simulations.

In 2009, Yang *et al* [164] used AlGaN in the notch region of GaN Gunn diodes and showed that this type of Gunn diode structure without the low doping process is convenient for accurately controlling the dopant concentration of GaN epitaxial growth. In the same year Tang *et al* [165] analyse thermal effects on the optimization of GaN Gunn diodes.

In 2010, Barry *et al* [166] investigated the operation of a submicrometer GaN diode in the THz regime by a large signal computer simulation. Other work done by Litvinov *et al* [167] examines the use of GaN superlattice NDR structures for terahertz applications in the year 2010. The devices were modeled theoretically. The results for the frequency as a function of composition for an InGaN/GaN and AlGaN/GaN superlattice structures are shown in figure 2.11 and figure 2.12 respectively.
These results show that THz-range oscillations are possible using GaN based Gunn devices. However, the researchers have not developed a generalized model till now for the different structures such as Heterostructure, Forward bias reverse bias barrier injection, notch etc of GaN-based Gunn diode and hence the author is focused on such studies and presented in this thesis.
2.10 Limiting Mechanism for High Frequency Operation

Gunn devices have been used successfully in the microwave frequency region for the last three decades. A need for microwave sources as local pump oscillators in receiver systems resulted in an effort to extend the operation of Gunn devices to higher frequencies. In particular there is an interest in the sub-millimeter and terahertz region. There have been reports of microwave power above 200GHz resulting from a harmonic mode operation [147]. However there’s still a controversy over the high frequency limit in the fundamental mode. Experimentally this limit is estimated to be less than 70GHz for GaAs Gunn devise [168-170] and less than 110GHz for InP Gunn device [171,172]. Theoretically the high frequency limit is estimated to be much higher [173]. The fundamental mode of operation is preferred over harmonic operation because it is more efficient, results in more output power, and requires simpler circuit design. In order to identify the mechanisms that limit the high frequency operation of Gunn devices, it is necessary to examine the physics behind the operation of Gunn devices and the crucial mechanisms necessary for having negative resistance.

The principle of operation in many solid state devices revolves around the modulation of the current density by means of a controlling mechanism. Since the current depends on the carrier density and the average velocity, modulating the current may be achieved in two ways: 1) changing the carrier density or 2) changing the average velocity. IMPATTs, BARRITTs, and TUNNETTs are examples of devices whose operation is based on the first method. In this case, an excess of carriers is injected whenever a proper bias is applied across the device. The high frequency negative resistance results when a suitable drift region is included. Gunn device operation is based on the second method since it exploits the velocity versus
electric field relation. This relation is an intrinsic property of the semiconductor and the corresponding band-structure. In semiconductors such as GaAs, InP, and InGaAs, the band structure has a conduction valley centered around the \( k = 0 \) (\( \Gamma \) point) and a number of satellite valleys located at different points in the Brillouin zone. The energy separation between the \( \Gamma \)-valley and the satellite valleys should be larger than the thermal equilibrium energy and smaller than the band gap energy. The effective mass is small and the mobility is high in the \( \Gamma \)-valley and in the satellite valleys the effective mass is larger and the mobility is smaller.

The description of the Gunn operation described here is based on the assumption of a static velocity versus electric field relation. This is valid as long as the period of the signal is much longer than the time it takes the electrons to adjust to a sudden change in the electric field. We can define three characteristic times associated with the Gunn operation: (1) nucleation time of the space charge layer \( \tau_f \), (2) drift time \( \tau_d \) and (3) collection time \( \tau_c \). These characteristic times are not completely independent since they correspond to processes that overlap in time; however they serve the goal of identifying the high frequency limitations. Since these times depend on the properties of the semiconductor and the device structure (doping, dimension etc) we refer to the constraints they impose on the high frequency operation as intrinsic limitations. The extrinsic limitations are related to the epitaxial growth, process technology, mounting and packaging, thermal effects, and the resonant circuit design. The intrinsic limitations are considered first in more detail.

The frequency of operation of a Gunn device in the transit time mode is expressed as

\[
f = \frac{1}{\tau_f + \tau_d + \tau_c}
\]  

(2.23)
$\tau_f$ and $\tau_c$ are much smaller than $\tau_d$ at low frequencies and the oscillation frequency is given by the transit time frequency $\left(\frac{1}{\tau_d}\right)$. $\tau_f$ and $\tau_c$ become comparable to $\tau_d$ and eventually dominate as the frequency is increased.

There are several limitations associated with the nucleation of the space charge layer. An efficient and fast transfer of electrons from the $\Gamma$-valley to the upper valleys is necessary for the nucleation process. There are spatial and temporal aspects to this transfer. The spatial aspect manifests itself by the existence of a region near the cathode where electrons are mainly in the $\Omega$-valley. This region, referred to as the 'dead zone', is required for the electrons to gain enough energy from the electric field and transfer to the upper valleys. The length of the 'dead zone' region depends on the injection mechanism at the cathode and the strength of the electric field. The 'dead zone' can easily occupy half the active region in a typical operation of a 1.5µm Gunn device with an $n^+$ cathode contact. Since most of the electrons in the 'dead zone' are in the $\Gamma$ valley, they have a positive differential mobility which implies that this region corresponds to a series positive resistance. The temporal aspect refers to the electron transfer time from the $\Gamma$ valley to the upper valleys once the electrons acquired an energy comparable to the inter-valley separation. The electrons at the end of the 'dead zone' transfer to the upper valleys by means of the nonequivalent inter-valley scattering mechanism. The characteristic time for this process depends on the scattering rate from the $\Gamma$ valley to the L and X valleys which depends on the material and the operating temperature.

The drift time $\tau_d$ depends on the length of the active region and the average velocity in the space-charge region. At frequencies higher than 100GHz, the active...
region has to be in the submicron range from a transit time mode of operation. The nucleation of a space charge layer in a shorter active region requires a smaller dielectric relaxation time. This can be achieved by either increasing the doping density or using a material with higher negative differential mobility. The main problem associated with a higher doping is thermal limitations due to the larger current density. The effects on the external circuit are understood by considering the diode equivalent circuit. It consists of a negative conductance \(-G_D\) in parallel with a susceptance \(B_D\). In general as the frequency increases, \(B_D\) increases and \(G_D\) decreases. As a consequence as smaller device area is needed to match to a given load. A smaller cross section results in a higher series resistance which reduces the circuit efficiency and the output power.

The last characteristic time \(\tau_e\) represents the time it takes the accumulation layer or dipole domain to be collected at the anode. The collection process requires the electrons to transfer back to the \(\Gamma\) valley so that the electric field in the active region can rise again and a new cycle can start. This transfer is controlled by the scattering processes from the satellite valleys to the \(\Gamma\) valley as well as the cooling mechanisms in the \(\Gamma\) valley. For efficient collection, a very low electric field at the anode is required. A highly doped anode contact region can provide such a low field.

The extrinsic limitations play an increasingly important role at high frequencies. The epitaxial layer should be of very high quality (small number of defects, dislocations etc) in order to have reliable and high performance devices. The processing of the layer is also critical at high frequencies. Since the device area is increasingly small, the series resistance needs to be reduced [174]. There are two ways to achieve this goal; (1) by using a low band gap material (InGaAs) as a cap
layer [175] which results in a low contact resistance or (2) using etch stop layers between the substrate and the device layers which allows complete removal of the substrate. In a Gunn device most of the dc power is converted to heat because of very low conversion efficiencies. The diode performance degrades rapidly as the operating temperature increases and generally an upper limit of 500K is required for reliable devices. The operating temperature may be reduced by having a smaller device area or using a better heat sink material such as diamond. Although the thermal resistance increases as the device area is decreased, the temperature rise is reduced due to the much smaller input power.

Once the diode is processed, it needs to be mounted on a heat sink and bonded to a package. Two problems are encountered at high frequencies. First, the small device area makes bonding increasingly difficult and tedious. Second, the package parasitic reduce the extrinsic negative resistance and may prevent resonating the diode at very high frequencies. A possible solution to the bonding problem consists of adopting a beam lead process [176] which defines the leads by lithographic means. The package parasitics may be reduced by using quartz standoffs instead of ring packages.

2.11 Practical Issues of GaN Gunn Diodes

The theoretical studies of the fundamental properties of GaN show superior electrical properties over other materials like GaAs and InP, currently used for state of the art Gunn Diodes. However, significant additional efforts are required in the areas of material growth and characterization, as well as doping and processing technologies before the full potential of GaN can be utilized.
The development of the growth of GaN has been significantly challenging due to the lack of a suitable substrate material (with a reasonably close lattice match). Until recently, GaN material development for high power and high frequency electronics has concentrated on sapphire and SiC as the conventional substrates of choice. Both of these substrates have significant disadvantages for potential commercial applications. Even though sapphire has a long history of GaN material development and is a relatively medium cost substrate, it is a poor thermal conductor and results in thermally limited devices. SiC substrates are excellent thermal conductors and offer a very close lattice match to GaN, but SiC is excessively costly. Silicon substrates would be a good choice due to the low cost and good thermal conductivity but since there is a large lattice and thermal mismatch between GaN and silicon, GaN cannot be directly grown on silicon by epitaxial growth techniques. Usually a buffer layer is necessary between the Si substrate and GaN film due to the mismatches. Recently, there have been breakthroughs by the Nitronix Corporation on the buffer layer technology that allows the production of high quality GaN on silicon [74]. With this technique, it is possible to grow GaN films with thickness in excess of 2 μm on a silicon substrate.

Effective etching techniques are also essential to device fabrication [177]. GaN has very high bond energies (8.9eV/atom) and a wide bandgap, which makes it almost chemically inert at room temperature to bases and acids, which are low cost and highly available wet etchants used in silicon processing. There are various methods of dry etching involving sources of external energy to initiate and sustain the break up of the high-energy bonds in GaN. A few of the dry etching techniques used for GaN include, ion milling and reactive ion etching (RIE). Ion milling relies upon physical sputtering and is not very practical for GaN because of low etch rates and
extreme damage to the material caused by the purely physical process. The RIE method is a better technique of dry etching because it involves chemical etching in addition to physical etching. The etch rates for GaN using RIE with various etch chemistries range from 17 to 100 nm/min [177]. Wet etching is an important complement to dry etching methods by providing low damage etching, low cost, and complexity. Since conventional acids and bases cannot be used to etch nitrides, a recently developed technique called photo-electrochemical (PEC) wet etching was found to etch GaN with significantly high etch rates [177]. The PEC process, utilizes photo-generated electron-hole pairs to enhance oxidation and reduction reactions taking place in an electrochemical cell. A typical PEC etching setup is shown in figure 2.13

![Fig. 2.13 A typical photoelectrochemical (PEC) wet etching setup. (After Ref. [177)](image)

For the PEC etching, the etch rates of about 400 nm/min for KOH solution and about 40 nm/min for HCL solution were obtained. It was also found that the etch rates were proportional to the light intensity. PEC etching also allowed for highly anisotropic etching of GaN as shown in figure 2.14
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Fig. 2.14 Highly anisotropic GaN structures by PEC etching. (After Ref. [177])

A highly anisotropic etch profile like the one shown in Fig. 2.14 is a very effective technique for forming mesa structures for vertical designs of GaN Gunn diodes.

A few other issues in the processing of GaN include ohmic contact to the nitride material and also the consideration of power dissipation. Typically, Ti/Au contacts are widely used as low resistance contacts in GaN-based electronic devices, but the processing issues of these contacts are not thoroughly understood to allow proper standardization. Issues in creating a good contact include the source and the method of growth of the nitride material, the method of preparing the surface for the deposition of the contact metal, and the method of annealing the contact to achieve ohmic behavior among other issues [178]. Since the processing of ohmic contacts has not been standardized, it makes it difficult to get repeatable results in GaN devices.

GaN devices are high power devices and consequently, the large amount of current flowing in the device causes significant self-heating effects. The device performance can largely degrade if proper care is not taken to dissipate the heat. Silicon substrates would introduce the possibility of a heat sink (Si has a large thermal conductivity) that will result in a better heat flow away from the diode, if very high quality GaN could be grown on silicon substrates. Another solution to the power
dissipation problem was demonstrated by Sands et al [179]. GaN films grown on sapphire substrates were lifted off using a laser liftoff technique and successfully bonded to a silicon substrate [179].

Although technologies are developing for GaN based devices, still major improvements in material quality, availability and fabrication technologies are needed before devices for system applications can be developed.

2.12 Scope of GaN Gunn Diodes Study

A lot of practical issues are neither studied theoretically nor in fabrication as mentioned above. However, it is a true fact that GaN-based Gunn diode can operate at THz frequency ranges and has ample applications. A theoretical study with a generalized developed program showing the potentiality of GaN-based Gunn diode would naturally motivate the researchers to fabricate such device. Thus the goal of this study is to investigate the potentials of GaN Gunn oscillators at high frequencies. Such oscillators are necessary for the detection of high frequency signals. The detection of such signals emanating from space or the earth’s atmosphere results in valuable information about the molecular content and dynamics of the particular medium. For the detection purpose, a heterodyne receiver system is used which requires a local oscillator so that the signal can be down converted to lower frequencies. However, solid state oscillators with low noise and adequate power levels are rare in Terahertz region. It is very desirable to extend the Gunn operation to higher frequencies and hence real detailed theoretical study before the material is dedicated for fabrication of Gunn diode. The author has taken up this study, developed a model in chapter 3 and the results obtained from such study are presented in chapter 6 of the thesis which can be used as the first hand data for the experimentalist.