Chapter I

Introduction and Scope of the Thesis

About a century and three decades ago, Maxwell laid the mathematical foundation for electromagnetic waves. Later these waves were generated by Hertz, Lodge, Bose and Marconi through simple laboratory experiments. In India, the legendary work of Sir J.C. Bose, reported in May 1895 at Calcutta (Asiatic Society of Bengal) is a milestone in the history of ‘Millimeter Waves’. He succeeded in generating electromagnetic waves with a wavelength of 6 millimeter and coined the word ‘Millimeter Waves’. He showed through his experiment that these ‘electric waves’ possessed all the characteristic optical properties of light waves.

Now-a-days, the spectrum of millimeter waves is generally defined as the frequency range from 30 to 300 GHz, corresponding to wavelengths of 10 mm to 1mm. The millimeter waves lie between the microwave and infrared portion of the electromagnetic spectrum.

Millimeter wave system development based on solid state sources has recently been increasing at a rapid space. A wide range of applications of these systems are in *Radars, missile seeker and guidance, short-range communication, satellite based wireless communication, battle field communication, electronic warfare, radio astronomy, remote sensing, all weather imagery, plasma diagnostics, spectroscopy, automotive collision-avoidance system, wireless cable television, electronic news gathering, robotic vision, aircraft landing, biological and medical technology*. Millimeter
wave systems offer many advantages over both microwave and electro-optical systems. In comparison with microwave systems, millimeter wave systems have smaller size, lighter weight, better accuracy, greater resolution and smaller antenna size. Also in comparison with electro-optical or infrared systems, millimeter wave systems provide greatly improved penetration through cloud, smoke and dust. Most of the current activities on millimeter wave system are centered around the window frequencies of 36 GHz, 94 GHz and 140 GHz where atmospheric attenuation is relatively low. The author has selected the first window frequency of 36 GHz for his entire work reported in this thesis.

The successful use and application of millimeter waves depend to a large extent on the availability of appropriate sources of millimeter wave power. Power generation at mm-wave frequencies is possible by using both vacuum tubes and solid-state sources. Both types of sources have their inherent advantages and disadvantages. In general, vacuum tubes provide higher power levels (up to several kilowatts) as compared to solid-state sources. But fabrication of the vacuum tube sources at higher operating frequency is not an easy task. Further the requirement of high anode voltage, high magnetic field for focusing the beam and special electron guns add to the weight and cost of these tubes. Hence, the vacuum tube sources are not preferred to certain applications – specially for space and military applications where the size and weight impose limitations to the choice of components. On the other hand, solid-state sources, although deliver limited output power, require low voltage for operation, and are very light and compact.

A number of letter band designations are commonly used to define the specific frequency ranges. The frequency band designations in common usage by various technical community are Ka - band: 26.5 – 40 GHz, Q – band: 33 – 50 GHz,
110 GHz. The author has carried out his investigations on the design and 
development of IMPATT diodes as Ka-band solid state sources capable of 
generating power within the frequency range of 26.5 to 40 GHz.

The generation of microwave power from an IMPATT diode was first 
suggested in 1958 by W. T. Read of Bell Telephone Laboratories [1]. IMPATTs 
(IMPact ionization Avalanche Transit Time) are basically p-n junction diodes, reverse 
biased to avalanche breakdown, which exhibits high-frequency negative resistance 
due to impact avalanche breakdown and electron transit time effect. When mounted 
in a suitable microwave / mm-wave cavity the device exhibits oscillation in 
microwave / mm-wave frequency bands under appropriate biasing condition. In 
recent years, the solid-state devices like Gunn, MESFET, HEMT and IMPATT have 
replaced the conventional vacuum tube devices in a number of low and medium 
power radar and communication applications due to their compactness, low cost and 
reliability. Among various microwave / millimeter wave solid-state devices IMPATTs 
have an advantage so far as higher power output and higher frequency of operation 
is concerned. IMPATTs are presently being widely used in driver stages of low and 
medium power transmitters, as active elements in phased array radars and also in 
various other microwave and millimeter-wave digital communication systems.

The first experimental observation of microwave oscillations in IMPATTs 
based on ordinary p-n junctions was reported in 1965 by Johnson et al. [2]. Lee et 
al. [3] observed IMPATT oscillations for Read structure, modeled by Read [1] in 
1958. A large amount of research has been directed towards the improvement of 
device performance, fabrication technique and associated circuit designs in terms of 
power output, efficiency, frequency range, and also evaluation technique [4-6].
Research and development over the years in the field of solid-state device have been concentrated on two important aspects. One such aspect is the device physics, where the aim is to understand the basic physical phenomena and the modes of operation of various types of device structures. In this approach one seeks to optimize the device technology in order to achieve the best performance from each device structure. The other aspect is to investigate the role of associated circuit in which the device is embedded since an appropriate circuit governs the performance of the device and its subsystem as regards generation of power in the microwave or millimeter wave frequency bands.

Millimeter wave oscillators can be developed with IMPATT diode as an active source by mounting the diode either in a coaxial line or in a section of waveguide. The resonant-cap technique of mounting the IMPATT diode in a full-height waveguide circuit is popular even in recent times because it offers many desirable features. Although a number of investigators have carried out investigations on various aspects of resonant-cap IMPATT oscillators, still there remains a lot of scope for further work on this topic particularly at Ka-band. The author has carried out theoretical and experimental investigations on Ka-band IMPATT diodes and oscillators. The present thesis is concerned with a coherent account of these studies and investigations on the design, fabrication and characterization of Ka-band IMPATT device along with the design, optimization and modeling of the oscillator circuit. The thesis contains nine chapters which provide both theoretical study and experimental work carried out by the author on Ka-band IMPATT diode and oscillator.
Chapter I

Chapter I deals with a general introduction of millimeter waves and IMPATT diode, the usefulness of millimeter wave and the reason for choice of IMPATT diode as the solid state device and the importance of Ka-band frequency.

Chapter II

A short account of basic IMPATT phenomena and a review of the performance characteristics of IMPATT diode and oscillators with various microwave/millimeter circuits have been presented in this chapter. The review will specially cover the details of the earlier work on the design, fabrication and oscillator circuit design based on IMPATT diode since the present investigation is mainly concerned with this topic. High field properties of charge carriers in IMPATT devices i.e. saturation of drift velocity, impact ionization, avalanche multiplication and avalanche breakdown have been described in details. IMPATT mode of operation in various structures i.e. Read diode, SDR, DDR, DAR and Hetero structures has been presented briefly. Impedance properties based on the equivalent circuit of IMPATTs along with the noise and instabilities in the device and the circuit have also been discussed. Major factors affecting IMPATT diode performance i.e. effects of tunneling, thermal and series resistance have been discussed in this chapter.

Chapter III

In this chapter the methods of DC and small signal simulation of IMPATT devices used by the author will be presented. The method is simple, fast, accurate and free from numerical instability as the boundary conditions are satisfied by starting the computation from the position of field maximum near the metallurgical
junction. The output from d.c. analysis is fed as input data for small signal simulation. The DC and small signal simulation methods described in this chapter are quite general in nature and can be used for simulation of various types of IMPATT structures and doping profiles at different frequency band. The electric field profile, normalized current density, doping profiles and admittance plots are obtained from the simulation for the design of silicon Ka-band SDR and DDR IMPATT diodes which will be presented in this chapter. The results of the study of the effect of mobile space charge at high current densities on the admittance properties of Ka-band IMPATT diode will also be presented in this chapter.

**Chapter IV**

In this chapter the details of the technological process steps of Si (p+nn+) SDR Ka-band IMPATT diode based on the design carried out in Chapter III will be presented by following the diffusion route of junction formation. Standardized process steps carried out in the laboratory starting from (i) wafer cleaning (ii) activation of boron nitride (iii) stabilization (iv) pre-deposition of boron (v) drive in diffusion (vi) low temperature oxidation (vii) Cr-Au metallization of p+ side (viii) electroplating of p+ side (ix) thinning of n+ side (x) Cr – Au metallization of n+ side (xi) photolithography (xii) mesa etching (xiii) chip separation (xiv) die and wire bonding will be described in this chapter. Finally the DC and RF characterization of the fabricated IMPATT diode at Ka-band will be presented.

**Chapter V**

In order to develop a millimeter wave oscillator with IMPATT diode, the device is to be mounted in a suitable millimeter wave circuit so that the capacitive impedance of the device matches with the inductive impedance of the circuit thereby
forming the necessary resonant system for oscillator operation. In chapter V the
details of the design and fabrication of the oscillator mount in which the IMPATT
diode is embedded in a resonant-cap cavity within a full-height waveguide will be
presented. The design of waveguide resonator particularly - cavities, heat-sink and
bias filter will also be presented. Constructional details of the resonant cap mount
along with the engineering drawing of Ka-band IMPATT oscillator have been
provided. Results of performance of bias filter, oscillator impedance and cavity Q are
also presented.

Chapter VI

In chapter VI the author presents his experimental investigation on tuning,
optimization and characterization of the resonant-cap Ka-Band IMPATT oscillator.
The Ka-band test bench for characterization of IMPATT oscillator and load pulling
along with calibration technique has been presented. The detailed procedure of
various tuning and measurement technique has also been described. The optimum
cap diameter and height for realizing maximum millimeter wave power output from
the oscillator with normal and modified resonant cap have been studied for a given
IMPATT diode. Further, a qualitative discussion of the observed tuning properties of
the oscillator has been included in this chapter. Change in oscillation frequency of
the free running oscillator under various loads has been studied in the load pulling
experiment, which is very important from system application point of view. The
phase noise of the oscillator is important to improve the overall system performance.
In developing high quality, low cost oscillators, the accurate determination of phase
noise is necessary. The author has measured the phase noise of the indigenous Ka-
band IMPATT oscillator by injection locking technique. Finally, the author has studied
the efficiency of Ka-band IMPATT diodes and oscillator around optimized condition. The simulated and experimental results will be presented in this chapter.

Chapter VII

In this chapter author presents the modeling, simulation and optimization of a Ka-band IMPATT oscillator by using High Frequency Structure Simulator (HFSS) software. Modeling of IMPATT oscillator which involves the appropriate design of the oscillator by considering its 3-dimensional behavior. This is followed by simulation and optimization of the cavity parameters with the help of HFSS software for analysis of the electromagnetic behavior of the structure. Finally, the simulated results are verified with experimental results.

Chapter VIII

The effect of package parameters for the determination of series resistance of Ka-band IMPATT diodes has been studied and presented in this chapter. The equivalent models of IMPATT diode with and without package parameter are also presented in this chapter. The series resistance obtained from simulation is compared with the experimentally determined values which are found to be in close agreement. The effects of package parameters and series resistance on the admittance properties of Ka-band IMPATT diodes have been studied by varying the current density it is observed that the peak frequency shifts upwards for both packaged and unpackaged diodes.

In the last Chapter, a summary of the work and the important results obtained from the Investigation will be presented. The future scope of work based on the studies presented in this thesis is given at the end.