Chapter IX

CONCLUSION

The thesis is concerned with some theoretical and experimental investigations on Ka-band IMPATT diodes and oscillators. The following studies have been carried out by the author (i) design of SDR of IMPATT device from DC and Small signal simulation (ii) fabrication of the device through diffusion technique and characterization of fabricated device (iii) design and fabrication of integrated heat sink cum resonant cap mount (iv) mechanical and electronics tuning characteristics of IMPATT oscillator for optimum performance (v) three dimensional modeling and (vi) simulation of oscillator by using High Frequency Structure Simulator software (vi) the effect of series resistance on Ka-band. The results of the investigation presented in the thesis are summarized below.

The author has used generalized DC and Small signal simulation method for the design of Ka-band IMPATTs taking into the effect of mobile space-charge in the depletion layer and realistic field and temperature dependent ionization rates and drift velocities. The method is a generalized one and applicable for all types of doping profile, device structure, operating frequency and base material of IMPATT diode. The method is free from numerical instability. Both SDR and DDR IMPATT diode have been designed for operation at the window frequency of 36 GHz in Ka-band. The effect of high bias current densities on the admittance properties of IMPATT diode at Ka-Band has been studied. The dc current density is increased in
steps of $0.5 \times 10^7$ A/m$^2$ from $9.0 \times 10^7 - 1.2 \times 10^8$ A/m$^2$. This study reveals that the peak negative conductance increases from $-4.1561 \times 10^6$ mho/m$^2$ to $-4.8163 \times 10^6$ mho/m$^2$ while the corresponding susceptance for the above mentioned increase of bias current density. The optimum frequency at which negative conductance attains its peak value increases from 37.00 GHz to 40.0 GHz when bias current increases from $9.0 \times 10^7$ A/m$^2 - 1.2 \times 10^8$ A/m$^2$.

The author selected silicon epitaxial n/n$^+$ wafers having specification appropriate to the design data obtained from dc and small signal simulation for fabrication of Ka-band SDR IMPATT diode. The junction is formed using diffusion method. The diode is fabricated by following the process steps standardized in the laboratory. Each process step is described in detail in chapter IV. The DC and RF characterization of the fabricated device are carried out by embedding the device within a resonant cap cavity. It is observed that the device delivers RF power output of 14.65 mW at a frequency of 35.70 GHz and a bias current of 85 mA. The reverse breakdown voltage of the device is 31 volt. The frequency of operation of the fabricated diode (35.70 GHz) closely matches with the design frequency (36.5 GHz).

The millimeter wave oscillator circuit with IMPATT diode is developed by mounting the device in a resonant waveguide cavity and matching the capacitive impedance of the device with the inductive impedance of the circuit to satisfy the necessary resonant condition for oscillator operation. The dimensions of the rectangular wave-guide cavity with centrally mounted resonant cap structure for operation at Ka-band (36GHz), are designed and taken as $a = 7.12$ mm, $b = 3.56$ mm and $d = 5.1346$ mm. In practical system the used wave-guide length is 25 mm to provide appropriate integrated heat-sink for the diode and excite the appropriate mode using a sliding short tuner. An integrated heat sink with wave guide mount of
A dimension (2.5×2.5×4.5) cm³ is fabricated which is capable of dissipating a power of 4 watt approximately. The author uses a π-section co-axial type low pass filter having a cut off frequency of 2.646 GHz, which allows the d.c bias to reach the IMPATT diode but prevents the mm-wave signal generated by the diode to reach the d.c power supply. The measured impedance of the cavity is 50.53 ohm and Cavity Q is around 4509 at a frequency of 36 GHz. The measurement is done by Network Analyzer.

Mechanical and electronic tuning characteristics of the oscillator have been studied for optimum performance of the oscillator. Mechanical tuning is carried out by changing the cap diameter, cap height and sliding short position while the electronic tuning is carried out by changing the d.c. bias current. A wide tunable range of 3.15 GHz is achieved by sliding short tuner whereas tunable ranges of 1.75 GHz and 1.5 GHz are obtained by varying cap diameter and cap height respectively at and around the centre frequency of 36 GHz lying in Ka-band. The design and development of Ka-band IMPATT oscillator have been done by using a resonant-cap wave guide structure. The values of cap-diameter and cap height of the wave guide are important parameters which determine the optimum output power from the device at the design frequency of operation. The approximate relation between cap diameter and wavelength under optimized condition is observed to be $D = \frac{\lambda}{2}$ which matches with the theoretical relation $D/\lambda = 0.58$. The power output from the device and its operating frequency depend very much on the sliding short position. The optimum condition is achieved when the sliding short position is at distances which are multiples of $\frac{\lambda}{2}$. In course of tuning by sliding short, sudden frequency jump occurs at certain positions with high power gain. Utmost care is therefore taken to
tune the oscillator by sliding short. In electronic tuning the dc bias current is varied keeping the optimized cavity parameters, i.e. cap diameter $D = 4.0 \text{ mm}$ and cap height $h = 1.6 \text{ mm}$ fixed. It is observed that the variation of oscillation frequency and power output with dc bias current is characterized by three ranges of bias current. In the first range I, both the output power and frequency increase slowly. In the second range II, both the output power and frequency increase sharply. In the third range III, the output power decreases whereas frequency increases. The operating bias current of the oscillator in the third range III, should normally be avoided to prevent the thermal runway and burn out phenomenon of IMPATT diode which occurs very frequently while tuning the IMPATT oscillator.

The resonant cap structure has been modified by incorporating various numbers of slots on the circumference of the disc. Using the modified structure the RF characteristics of the corresponding oscillator are measured by varying the cap dimensions (diameter and height) as well as number of slots and their dimensions. The maximum power output of the modified cap oscillator increases to $110 \text{ mW}$ as compared to that of normal unmodified structure. Further the optimum performance is achieved when the number of slots is four and the corresponding cap dimensions are, $D = 4 \text{ mm}$ and $h = 1.4 \text{ mm}$.

The load pulling characteristics of the free running oscillator has been studied. The maximum change in oscillation frequency is observed in the range of $110 \text{ MHz}$ to $135 \text{ MHz}$ due to a change of load $50 \text{ dB}$. This load pulling characteristics is useful from the point of view of system application.

The author proposes an alternative method for measurement of phase noise by Spectrum Analyzer only. The phase noise is determined by using empirical relation as well as by direct phase noise measurement system and a good
agreement is obtained between them. Following the alternative method described in this chapter and using the injection lock technique the phase noise of a free running oscillator is measured accurately when the facility of direct phase noise measurement is not available.

The efficiency of both Ka-band IMPATT diode and oscillator has been estimated under optimized condition. It is observed that the d.c. to r.f. conversion efficiency of SDR IMPATT diode decreases with the increase in field swing. The efficiency is found to be 8.98% for small signal operation which decreases to 7.84% for a field swing of 50%. It is also observed that the maximum value of negative conductance of the device decreases gradually while the device susceptance increases slowly with the increase in field swing. The experimentally obtained maximum output power from the oscillator is 90 mW at the optimized condition. Its magnitude falls rapidly with further increase in input d.c. bias current. The r.f. power from the IMPATT diode is estimated from which the circuit efficiency with respect to optimum output power is calculated for various values of field swing. It is observed that the circuit efficiency increases from 20.27% to 23.2% when the field swing increases upto 50% of the maximum field value, but the device efficiency decreases with the increase in field swing. The results obtained at the optimum condition give an insight regarding the interdependence of device and circuit efficiency. Low d.c. to r.f. conversion efficiency of the active device is mainly responsible for low efficiency of the whole system independent of the present resonant cap system. Although the performance of the oscillator system can be optimized with better design of the active device as well as the mounting system, more emphasis should be given to improve the conversion efficiency of the active device to realize higher power output at the optimized condition.
The author has carried out three dimensional modeling, simulation and optimization of a Ka-band resonant cap IMPATT oscillator by using High Frequency Structure Simulator (HFSS) software. This model has been optimized to obtain a high quality factor at an eigen frequency of 36 GHz by varying cap radius, cap height and sliding short position. It is observed that a cap radius of 2.1 mm, a cap height of 1.46 mm and sliding short position at 0 mm and 4.5 mm lead to the desired optimization. Experiment has been carried out to study the high frequency performance of Ka-band resonant cap IMPATT oscillator with various cap diameter, cap height and sliding short position. It is observed that maximum output power is obtained at and around the eigen frequency of 36 GHz when the cap diameter ranges from 3.8 – 4.2 mm and corresponding cap height ranges from 1.4 – 1.8 mm with sliding short position at 0 mm and 4.5 mm. The experimental results are in good agreement with simulation results.

The parasitic positive series resistance $R_s$ which originates from the unswept epilayer, package contacts and the passive circuit play important role in limiting the output power from an IMPATT source. The negative resistance of millimeter wave IMPATT diode is in the range of only a few ohms. The positive series resistance $R_s$ is therefore kept to a minimum possible value by appropriate technology in order to obtain maximum output power from the device. A direct measurement of series resistance $R_s$ by a network analyzer is difficult due to circuit modeling difficulties. The author has developed a computer simulation method to determine the series resistance $R_s$ of millimeter wave Ka-band packaged SDR IMPATT diode at threshold condition, when the Small signal conductance of the packaged diode just becomes negative and the device susceptance becomes just positive. The values of series resistance $R_s$ obtained from small signal simulation are compared with the values of
Series resistance $R_s$ obtained experimentally from the measured threshold current and threshold frequency of silicon Ka-band IMPATT diode. The calculated values of $R_s$ agree well with the experimental values. The series resistance is found to be close to 1.00 $\Omega$ for Ka-band SDR IMPATT diode.

**Future Scope**

The studies presented can be further extended for the design and development of SDR and DDR Silicon IMPATT diode and oscillator at the window frequency 94 GHz at W-band following theoretical design and corresponding experimental investigation as carried out for Ka-band.

Recently, Silicon carbide (SiC) has drawn considerable attention as a suitable semiconductor material for realization of high power, high frequency, high temperature and radiation resistant devices. The material properties of a semiconductor play an important role in determining the performance of the devices based on the particular material. In this respect, silicon carbide (SiC) IMPATT devices have advantages over silicon (Si) IMPATTs. Due to its large band gap (3.0 - 3.3 eV, depending on polytype), SiC possesses a very high breakdown field and low intrinsic carrier concentration, which consequently makes high voltage and high temperature operation possible. SiC is also suitable for high frequency device applications, because of the high saturation drift velocity and low permittivity. So silicon carbide (SiC) is a suitable semiconductor material for realization of mm-wave IMPATT diode in near future. In review chapter the preliminary works on SiC IMPATT diode reported in literature have mentioned.