Chirp Band-Width Estimation of MM-Wave Pulsed-MPATT: A Study on the Dependence of Device Diameter and Bias Pulse-Width

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Abstract

In this work, the authors have studied the dependence of chirp bandwidth viz. intra pulse change in frequency on the bias pulse width and on the diode junction diameter of pulsed IMPATT diodes. Using a small signal simulation model and a suitable thermal model, intra pulse diode susceptance are computed and from the sustained oscillation condition, the circuit susceptance presented at the device terminal is calculated and frequency chirp bandwidth is estimated. The results are presented in details and would be useful for design optimization of pulsed IMPATTs at W-band.

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Keywords: Chirp-bandwidth; pulsed-IMPATT; W-band; window frequency; admittance characteristic.

1. Introduction

IMPATT diodes have been used in microwave and millimeter wave communication systems and in tactical defense applications. IMPATTs provide high oscillator output power in Si monolithic millimeter-wave integrated circuit. The reported frequency range of IMPATT oscillators extends from below X Band to the sub-millimeter wave region \cite{1}. The current activities for mm-wave systems are focused at around atmospheric window frequencies, particularly at 94 GHz window, where attenuation is significantly low. Solid-state pulsed sources—particularly short pulse low duty operations are key-element in many mm-wave systems. One of the inherent properties of pulsed IMPATTs is the frequency chirp-bandwidth i.e. intra–pulse variation of oscillation frequency. IMPATT diodes being low efficiency devices, substantial amount of heat is generated during the pulse on-period resulting in substantial change of the device susceptance leading to frequency variation in a fixed tuned mm-wave oscillator circuit. The maximum frequency shift within the pulse is defined as chirp bandwidth. Diode junction temperature, which varies considerably with device-diameter and pulse duration, affects the chirp-bandwidth. The purpose of the
The study is to present a generalized analysis on the dependence of chirp-bandwidth on varying diode diameters and pulse-duration. The present analysis is based on a generalized drift-diffusion model and it incorporates the mobile-space charge as well as elevated temperature effects. The authors have developed a physics-based model to estimate the intra-pulse junction-temperature profile of IMPATTs operating under low-duty factor short pulses (50ns < τ < 150ns). The effects of variation of diode diameters and pulse-duration on chirp-bandwidth are further studied with a newly proposed simulation technique.

2. Theory of Simulation Study

2.1. DC and Small-signal Analysis Scheme:

Silicon DDR (Double Drift Region) diodes are first designed and optimized through a double iterative simulation technique used for analysis of IMPATT diode [2]. The method involves iteration over the magnitude of field maximum (E_m) and its location in the depletion layer. The electric field and carrier current profiles are obtained through simultaneous solution of Poisson’s equation, combined continuity equation and equation involving the mobile space charge in the depletion layer. The experimental values of material parameters, i.e., field dependence of carrier ionization rates, drift velocities, and high field mobility of charge carriers in Si at 300K < T_j < 650K [3] are taken as input parameters in the simulation program. The device dimension, doping profile and operating current density of the diode are all optimized for the device operation at and around 94 GHz after several trials and corresponding computer runs. The effect of carrier diffusion in the active layer of the device is also incorporated in the present study. The high frequency analysis of IMPATT diodes is carried out through a double iterative simulation method [2], based on Gummel Blue technique which numerically solves two simultaneous second order differential equations involving diode resistance and reactance subject to appropriate boundary conditions at the edges of electron and hole depletion layers. The admittance characteristics, device negative resistance and quality factor (Q_p = B / G) of the optimized Si DDR diode are simulated by this technique [2]. The maximum RF power output (P_RF) from the device is proportional to negative conductance of the diode [2].

The double drift Si IMPATT diode structure analyzed for thermal modeling is shown in Figure 1. Transient Junction Temperature rise may be described as[4].

2.2 Chirp-Bandwidth Computation Scheme

The well known oscillation condition of IMPATT diodes, mounted in a reduced height waveguide cavity is as follows: i) For oscillation to start and grow, device conductance (G_D) be negative and its magnitude should be greater than the driving point circuit conductance (G_C). ii) For sustained oscillation: |G_D| = G_C and B_D + B_C =0.

The second equation determines the frequency of oscillation and the first one determines the magnitude of oscillation and hence the power output. The intra-pulse variation of junction-temperature is considered as the starting point for the chirp-bandwidth estimation. At the beginning of a flat bias current pulse (Figure 2), diode junction temperature remains at low-temperature viz. the ambient temperature and increase sharply up to 10 ns. Thereafter gradually heats up with its thermal time constant and saturates reaching a maximum value at the end of the pulse. The intra-pulse maximum frequency variation is the chirp bandwidth. The frequency-chirp depends on bias current density, junction area, pulse width and thermal resistance. During the pulse, as the diode heats-up, device suscceptance changes appreciably. But the circuit susceptance remains un-affected for a fixed tuned oscillator circuit. From a set of admittance plots of the device at different junction temperature at different interval of pulse, the authors have
estimated the chirp-bandwidth corresponding to a particular value of $B_C$. To validate the modeling, the simulated results are further compared with experimental data [4] and the agreement is reasonably good.

3. Results and Discussions

The design parameter of the diode is optimized after several computer run. The doping concentration of the diode is: $0.15 \times 10^{23}$ m$^{-3}$, width of n and p region is taken as 0.34 $\mu$m and 0.32 $\mu$m, respectively. The bias current density is optimized for an optimum punch-through factor and it is $8 \times 10^8$ Am$^{-2}$. Through a simulation technique, the variation of junction temperature, for a fixed diode diameter ($\sim 100 \mu$m) within the pulse duration of 0 - 150 ns [5] (Figure 3) has been estimated. Figure 4 compares the admittance plots of the devices at different junction temperature within the wide range of 300K – 630K. It is observed that negative conductance of the device decrease significantly with the increasing junction temperature, on the other hand, diode susceptance increases and as a result the quality factor of the device degrades. It can be predicted from the diode admittance plots that the increasing junction temperature, degrades the expected RF power output, since it is proportional to negative conductance.

Figures 5 (a-c) show the variation of diode susceptance, $B_D$ for three different pulse duration. With the increasing intra-pulse junction temperature, the driving point circuit susceptance ($B_C$) remains constant. However, $B_D$ varies considerably and variation of $B_D$ within the oscillation range for different junction temperature is plotted in Figure 5. It is observed that $B_D$ gradually increases with frequencies. The authors have considered the curves corresponding to junction temperature of 300K and the highest temperature, at the end of the pulse. From the graphs, the corresponding diode susceptances are obtained and $B_C$ is considered as equal in magnitude of that of the $B_D$ to satisfy the sustained oscillation condition. At first, the device susceptance value at tuning frequency at the end of the pulse duration is considered (point A in the Figures 5(a-c)). Since $B_C$ does not change with intra-pulse temperature variation, the magnitude of $B_C$ is taken as equal to the magnitude of $B_D$ for that tuning frequency. Since the device is capacitive at the oscillation frequency, the driving point circuit susceptance is inductive and its magnitude equals to $B_D$. Circuit susceptance being inductive is inversely proportional to frequency and the value of $B_C$ at nearby frequency (92 GHz) is calculated (point Q in Figures 5 (a-c)) and the a straight line joining A and Q in B vs. 1/f plot. The line cuts the 300K curve at one point, denoted as C. The difference of frequencies between A and C determines the chirp-bandwidth. Following this procedure, the authors have studied the chirp-bandwidth. Figure 6 show that the chirp bandwidth increases with increasing pulse duration. It is found that at 50 ns pulse duration, chirp is 1.5 GHz, it increases to 1.8 GHz when pulse duration is 100ns and the highest chirp bandwidth ~ 2.2 GHz is observed when the pulse duration is 150 ns.

In the next phase of the work, the authors have studied the device diameter variation effects on the junction temperature. It is found that the increasing diode diameter decrease the junction temperature. The study reveals that the junction temperature varies from 500K to 630K, for the variation of device diameter from 90 $\mu$m to 120 $\mu$m. Figure 7 shows the junction temperature and diode chirp bandwidth variation with diode diameter, corresponding to pulse-width of 100 ns. The study reveals that for the junction diameter 90$\mu$m to 120 $\mu$m, junction temperature decrease from 630K to 500K and the chirp-bandwidth reduces from 2.4 GHz to 1.5 GHz. So the increasing junction diameter decreases the chirp-bandwidth. The study reveals by varying the diode diameter and pulse duration time, chirp bandwidth can be controlled. It is found that chirp-bandwidth increases with increasing pulse duration but decreases with increasing diode diameter.
4. Conclusion

The authors have studied in details the effects of diode-diameter and pulse duration on frequency chirp-bandwidth. The study will be useful for design optimization of 94 GHz – band IMPATT diodes.

Figure 1: Device structure considered for chirp-bandwidth analysis

Figure 2: Schematic diagram of rectangular current pulse.

Figure 3: Intra-pulse junction temperature variation [5]

Figure 4: Admittance plots of Si DDR pulsed IMPATT at W-band

Figure 5(a): Chirp-bandwidth calculation in Si pulsed IMPATT for pulse duration 50 ns (diode diameter = 105 μm)

Figure 5(b): Chirp-bandwidth calculation in Si pulsed IMPATT for pulse duration 100 ns (diode diameter = 105 μm)
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