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DDR Pulsed IMPATT Sources at MM-Wave Window Frequency: High-Power Operation Mode

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Abstract

The high-power generation capability of pulsed mode Silicon Double Drift Region (DDR) IMPATT devices has been studied by using generalized simulation software developed by the authors. The software is based on drift-diffusion modeling scheme, incorporating thermal design. After optimization of the device design, it is observed that a maximum efficiency of 9% with an output power of 15W can be achieved from pulsed DDR IMPATT based on Si. It is also observed that the best power output and efficiency occur at higher frequencies in the pulsed mode than in the CW mode. Simulated results are compared with experimentally reported results and quantitative agreement is demonstrated between theory and experiment. Transient thermal resistance of the diodes under pulsed mode operation has also been estimated by using computer simulation technique. Junction temperature of the pulsed diodes has been evaluated under actual operating condition. These results are useful for experimental realization of pulsed high power IMPATTs suitable for guided missiles and seekers.

Keywords: *Si DDR IMPATT, Pulsed operation, Thermal design, drift-diffusion technique, high-power operation, MM-wave window frequency*

1. Introduction

Millimeter wave systems offer many advantages, such as, smaller size, lighter weight, improved accuracy, greater resolution and smaller antenna size. MM-wave systems also provide greatly improved signal penetration through cloud, smoke and dust. Most of the current activities for MM-wave systems are centered on and around 35 and 94 GHz, where atmospheric attenuation is relatively low. The key element in MM-Wave Transmitter systems is the solid-state pulsed sources. These sources, because of their small size, light weight, and low voltage power supply requirements, are now finding applications as transmitters in many radar systems. In recent years, researchers have focused their attention on the development of high-power pulsed Silicon (Si) **IMP**act **A**valanche **T**ransit **T**ime (IMPATT) diodes in the MM-wave window frequency region, because these have emerged devices are emerged as the most powerful microwave and MM-Wave sources for application in radar and guided missiles.

Double Drift region (DDR) structures are chosen for generating high-power at MM-wave frequencies, since DDR IMPATTs provide more output power than Single Drift Region (SDR) diodes. The authors in this paper have designed a p^{++} p n n^{++} IMPATT diode structure for pulsed mode of operation. The authors have also designed the MM-wave DDR IMPATT structure for CW operation at the window frequency and the performances of CW IMPATTs are compared with those of pulsed IMPATTs. To verify the design, the simulated results are compared with published experimental results. The pulsed double drift diodes are generally fabricated using silicon multiple epitaxy technique by first growing an n-layer on top of the n^{++} substrate, followed by p-layer growth and shallow boron diffusion. Ion Implantation process may also used for this fabrication purpose. The Si wafer is then metalized on both sides. Photolithography is subsequently used in defining and etching circular mesa diodes of diameter 120-125μm, for pulsed W-band devices. An individual diode is then thermal compression bonded to a gold plated copper heat-sink. The diode processing is finally completed by packaging the IMPATT diode in a small ceramic or quartz ring, followed by ribbon bonding and capping [1].

Since the efficiency of the IMPATT diode is relatively low, a large fraction of the dc power is dissipated as heat and consequently the junction temperature increases. As junction temperature increases, the reverse saturation current rises exponentially ad eventually leads to thermal runaway resulting the burning out of the devices. Larger the band-gap of the semiconductors smaller the reverse saturation current and consequently higher the burn-out temperature of the junction. Thus Ge (E_g = 0.7 eV) IMPATTs are lower power devices than either Si (E_g = 1.12 eV) or GaAs (E_g = 1.43 eV). The amount of dc power, P_{max}, that can be dissipated in a diode is determined by the burn-out temperature T_B and thermal resistance, R_{th}: $P_{max} = (T_B - T_0)/R_{th}$, where, R_{th} is defined as the temperature rise produced at the junction by the dissipation of one Watt of power. Also R_{th} is determined by size and shape of the diode and the thermal conductivity of the heat-sink to which it is bonded. Properly designed diode and heat-sink are required for generating high-power from the pulsed oscillators. The authors have developed a simulation technique to estimate the thermal resistance and junction temperature of the pulsed devices.

A unique property of the pulsed IMPATT oscillator is the frequency chirp during the bias pulse. This effect is a direct consequence of the IMPATT junction temperature variation during pulse, which results in change of diode impedance. For a flat current pulse, the diode junction is at a low temperature at the beginning of the pulse and gradually heats up with its thermal time constant. This temperature variation depends on current density, junction area, and thermal resistance. As the diode heats up a large transient thermal resistance is developed and the rate of chirp increases. Thus the transient thermal characteristics of the pulsed IMPATT oscillators are also addressed in this paper. A generalized simulation method developed by the authors, is adopted for this purpose.

2. Simulation Methodology

A. Small-Signal design of CW and pulsed IMPATT diodes

In the simulation scheme, one dimensional p-n junction diode equations (Poisson and current continuity equations), considering the mobile space charge effect, have been solved by a double iterative computer method satisfying appropriate boundary conditions as described earlier [2]. IMPATT operation is strongly current dependent; the frequency for peak negative conductance is a function of the operating bias current density. As the current density increases, the optimum frequency increases and so does the diode output power. For CW diodes the maximum current density is limited thermally, but for pulsed diodes this limit is extended many times depending on the pulsed width and duty factor. The current density can be extended until space-charge effects cause power saturation and efficiency reduction. Thus it is necessary to predetermine the operating current by to properly designing a pulsed diode. The authors have carried out small-signal analysis of pulsed IMPATTs, for different bias current densities and the diode design is optimized on the basis of the extensive analysis of the diode characteristics under different operating conditions. The design parameters for pulsed IMPATT diodes are shown in Table 1. Strictly speaking, optimum diode design requires knowledge of the large-signal characteristics of the devices, which in turn is strongly dependent on the circuit parameters. Since an exact analysis and accurate prediction of the circuit response is quite difficult to achieve in millimeter wave ranges, a first-order diode design, has been carried out by using small-signal drift-diffusion technique. Further optimization of the diode design can be achieved by RF measurement and characterization of the diode in a slandered test circuit.

The static characteristics, such as, electric field profile and normalized current density profile of the designed diode are obtained following the method described elsewhere [2]. With the static output parameters as input, the spatial variation of diode negative resistivity (R) and the reactivity (X) in the depletion layer have been obtained solving two second order differential equation in R and X, described elsewhere [2]. A double iterative simulation technique is adopted for solving the two equations [2]. The total integrated negative resistance (Z_R) and reactance (Z_X) of the diodes at a particular frequency f_0, can be determined from the numerical integration of the resistivity (R) and the reactivity (X) profiles over the depletion layer, as described earlier [2]. The space-step for the present simulation technique is taken as $\sim 10^{-9}$ m. During its operation at MM-wave region, IMPATT diode generates a substantial amount of heat, which results in an increase of the diode junction temperature that plays a significant role on the performance of the IMPATT diode. The authors have considered a junction temperature T = 500K and corresponding values of saturated drift velocity and mobility of charge carrier in Si [3] for the present analysis. Experimental ionization rate data of charge carriers [3] at 500K, available in published literature, are incorporated in the simulation. Realistic doping profiles at the junction as well as at n^{++} n interface region have been incorporated in the analysis [2].

The conversion efficiency (η) is calculated from the semi-quantitative formula [4],

$$\eta\ (\%) = (V_D \times 100) / (\pi \times V_B) \qquad (1)$$

where, V_D = Normalized voltage drop, i.e. $V_D = V_B - V_A$, where, V_A = voltage drop across the avalanche region, and, V_B = breakdown voltage. A small-signal based power (P_{RF}) evolution is carried out from the following equation [4]:

$$P_{RF} = (V_B/2)^2 \times G_P \times A/2 \qquad (2)$$

Where, G_P is device negative conductance at peak frequency and the device area (A) is considered as 10^{-9} m^2. CW power can also be calculated from the following equation: P_{CW} =

V_B x J_0 x A x η.

B. Thermal design of pulsed IMPATT diodes

As discussed earlier, IMPATT diode generally dissipates several times as much power in the form of heat as is converted to MM-Wave power. In our analysis, we have considered the diode as shown in Figure 1. For the analysis we shall assume an ideal thermal contact between all the metallic layers and that negligible spreading of the heat flux occurs in the thin layer of the gold and nickel on the copper. This permits the simplified picture shown in Figure 1 to be used. We have further assumed that all the heat flux passes through the bottom contact to the semi-infinite heat-sink. The total value of R_{th} for the circular heat-source of radius r is given by:

$$R_{th} = L_S / (\pi r^2 K_S) + L_M / (\pi r^2 K_M) + 1 / (\pi r_H K_H) \quad (3)$$

where, r and r_H are radius of the diode and heat sink, respectively, K_M is the thermal conductivity of the metal contact, K_S is thermal conductivity of Si and K_H is the thermal conductivity of heat sink, L_S is diode width, L_M is the width of the metal contact. The symbols are defined in Figure 1. The value of diode radius is taken as 60μm (for pulsed mode operation) and that of heat sink is taken as 40 times of diode radius. The last term in equation (3) gives the thermal spreading resistance for the semi-infinite heat-sink and assumes that temperature is uniform over the contacting area. The diode is considered to be under a periodic heating and cooling cycle caused by the bias pulses. It can be shown that the transient thermal resistance related to the maximum temperature at the centre of the diode and at the end of a heating cycle is given by [5]:

$$R_{th,T} = (2/\pi r K_S) + (\alpha\, d\, t_1)^{1/2} / (\pi r^2 K_S) \{ 2/ (\pi d)^{1/2} (1- \exp(-r^2 /4 \alpha t_1) - (r / (\alpha t_2)^{1/2} + I + r / (\alpha d t_1)^{1/2} \operatorname{erfc} [r / 2 (\alpha t_1)^{1/2}]\} \quad (4)$$

Where, $I = (2 / \pi d). \int_0^{\infty} \frac{e^{-dx^2} \{e^{-(1-d)x^2} - e^{-x^2}\}\{1 - \cos[r x^2 \sqrt{(\alpha t_2)}]\}}{x^2 (1 - e^{-x^2})} dx$

d= t_1 / t_2 is the duty factor. The first term is a dc term, proportional to the CW thermal resistance: the remainder of the terms consists of a dc contribution as well as an ac contribution following the heat pulse. For copper K = 396 W m^{-1} C^{-1} and α = thermal diffusivity = 1.14×10^{-4} m^2 s^{-1}. Using these values, $R_{th,T}$, as a function of pulse width for four diode radii, is estimated through a computer analysis. The value of $R_{th,T}$ is calculated for 0.5% duty factor. The diode junction temperature is then calculated from the following equation [1]:

$$T_j = 300 + R_{th\,(total)} (1 - \eta) V_B J_0 (\pi r^2) \quad (5)$$

TABLE 1: DESIGN PARAMETERS OF SI PULSED DDR IMPATT UNDER DIFFERENT OPERATING CONDITIONS

Pulsed DDR diode	Epilayer doping conc. (n -region) (10^{23} m^{-3})	Epilayer doping conc. (p -region) (10^{23} m^{-3})	Width of the epilayer (n region) (μm)	Width of the epilayer (p region) (μm)	Bias current (considering diode area = 10^{-9} m^2)
Set I	1.4	1.4	0.295	0.275	6.0
Set II	1.7	1.7	0.400	0.350	10.0
Set III	2.5	2.5	0.300	0.270	15.0
Set IV	2.5	2.0	0.275	0.250	16.5

3. Results and Discussions

The DC and small-signal results of the CW IMPATT diode are shown in Table 2. The experimentally observed data are also shown in the same table, in order to make a comparison. A close agreement between simulated results and experimental observation are found, as far as breakdown voltage and efficiency are concerned. The CW power for the designed CW diode is 20% higher than that was found experimentally. The experimental power level is almost 80-85% of the simulation predicted data. The 15% - 20% discrepancy between theoretical and experimental results may be due to the adopted small-signal approach, thermal limitations, impedance matching problem, and improper heat-sink arrangement.

The output results of pulsed IMPATT diodes operating at different bias current are shown in Table 3. The electric field profiles of the diodes are shown in Figure 2. It is observed from the electric field profiles that due to the variation of current density from 6 A to 16.5 A, space charge effect has not become prominent and the efficiencies for the designed diodes varies slightly from 8% to 10%, due to the variation of operating condition. The admittance plots of the designed diodes are shown in Figure 3. It is observed that peak operating frequency as well as negative conductance increases with increasing operating current density. It is observed from Figure 3, that the optimum frequency of operation is very close to the design value (W-band, centre frequency 94 GHz) at a current density of $J_0 = 6x10^8$ Am^{-2}. The pulsed output results of Set 1, may further be compared with experimental devices under almost similar operating condition [8]. The simulated results are in both qualitative and quantitative agreement with experimental results. The authors have further estimated the thermal resistance from equation (3). The simulation analysis depicts that the value of R_{th} for Cu heat sink is 1.2^0CW^{-1}. Transient thermal resistance of the pulsed diode (Set I) as a function of pulse width for several diode junction diameters is shown in Figure 4. For most homing and tracking radar applications, narrow pulse-width is generally required to handle the target. The normal pulse width requirement is typically less than 100 ns with a repetition rate less than 50 kHz. The total thermal resistance of the W-band pulsed IMPATT diode including the transient thermal spreading resistance (pulse width 100 ns) is found to be ~ 1.8^0CW^{-1}.

Considering this value of $R_{th,\,(total)}$, the junction temperature is estimated from equation (5). It is found that under pulsed operating condition, T_j is almost 520K, well below 575K, which is maximum operating temperature for Si IMPATT diode.

4. Conclusion

A detailed analysis of the MM-wave characteristics of Si based high power pulsed IMPATT diodes are reported at W-band. In conclusion, the operation of IMPATT diodes at current densities, which shift the avalanche resonance frequency even beyond the operation frequency, has led to output power of 15W at 96 GHz and 40W at 115.0 GHz. The present simulation results may further be used for experimental realization of pulsed high power IMPATT oscillator for application in MM-wave communication systems.

TABLE 2: SI BASED DDR IMPATT FOR CW OPERATION AT WINDOW FREQUENCY: COMPARISON OF SIMULATION RESULTS WITH EXPERIMENTAL PUBLISHED DATA

Parameters	Simulation Results	Experimental Results	
Design Frequency	W-band (96.0 GHz)	W-band (Experiments by *Dalle et. al.* [6])	W-band (Experiments by *Luy et al.* [7])
N_D (10^{23} m^{-3})	1.4	1.5	2.0
N_A (10^{23} m^{-3})	1.4	1.5	1.8
J_0 (Am^{-2})	$4x10^8$	$4.5\ x10^8$	$4.0\ x10^8$ -$5.0x10^8$
W_n (µm)	0.30	0.30	0.30
W_p (µm)	0.28	0.25	0.30
A (m^{-2})	10^{-9}	10^{-9} (35µm diameter)	10^{-9} (35µm diameter)
V_B	18.0	-	16.5
η (%)	8.5%	8%	6.7%
P_{CW} (V_B x J_0 x η xA)	680 mW	> 500 mW	600 mW

TABLE 3: SMALL-SIGNAL OUTPUT OF PULSED IMPATT DIODES UNDER DIFFERENT OPERATING CONDITIONS

DDR diode type	Set I	Set II	Set III	Set IV
Peak electric field (E_m) (10^7 Vm^{-1})	6.2	6.16	6.4	6.67
Breakdown voltage (V)	20.2	22.0	20.48	19.98
Efficiency (%)	9.0	10.2	9.5	8.2
Peak negative conductance (-G_P) (10^6 Sm^{-2})	42.3	66.2	102.4	104.0
Diode negative resistance at peak frequency (-Z_{RP}) (Ω)	0.75	0.71	0.59	0.53
RF power output (W)	15.0	40.05	53.68	51.70
Quality factor (-Q_P)	1.2	1.3	0.81	0.89
Peak operating frequency (GHz)	96.0	115.0	150.0	155.0

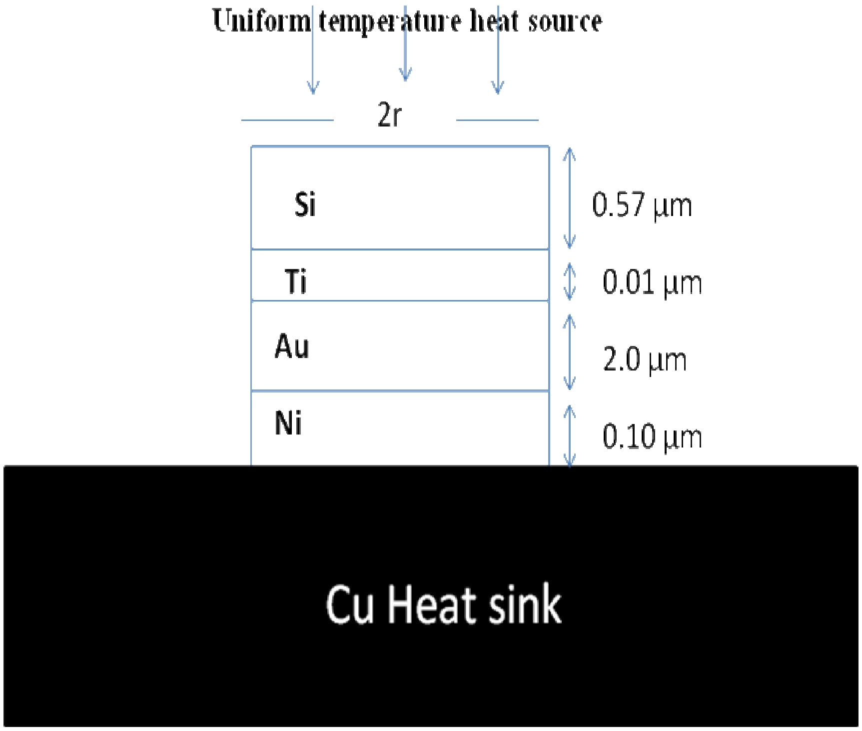

FIGURE1: SIMPLIFIED DIODE AND HEAT-SINK STRUCTURE

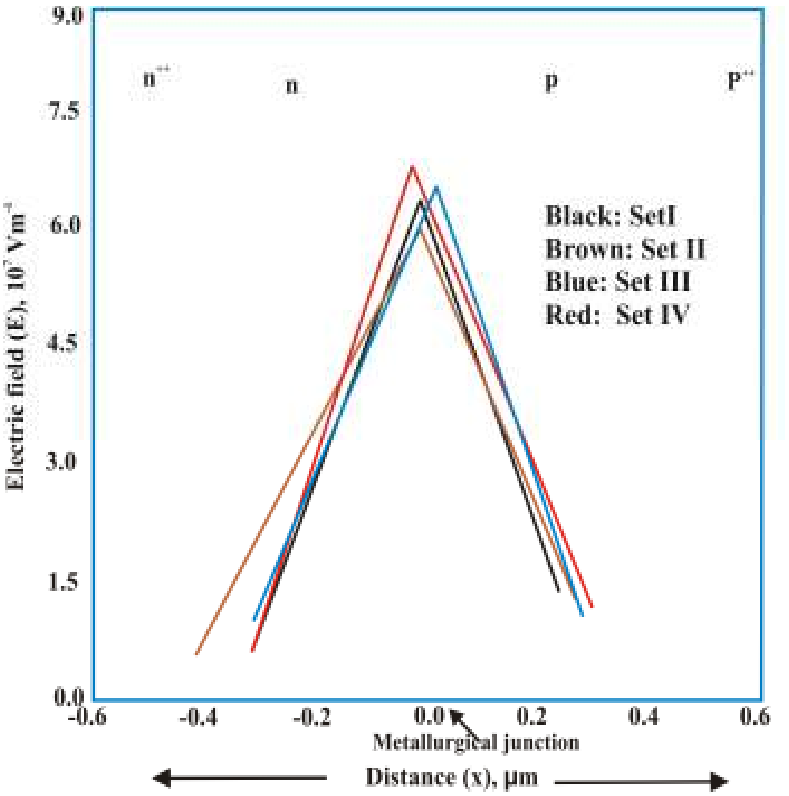

Figure 2. Electric field profiles E(x) of Si DDR IMPATT diodes for pulsed operation at 94.0 GHz

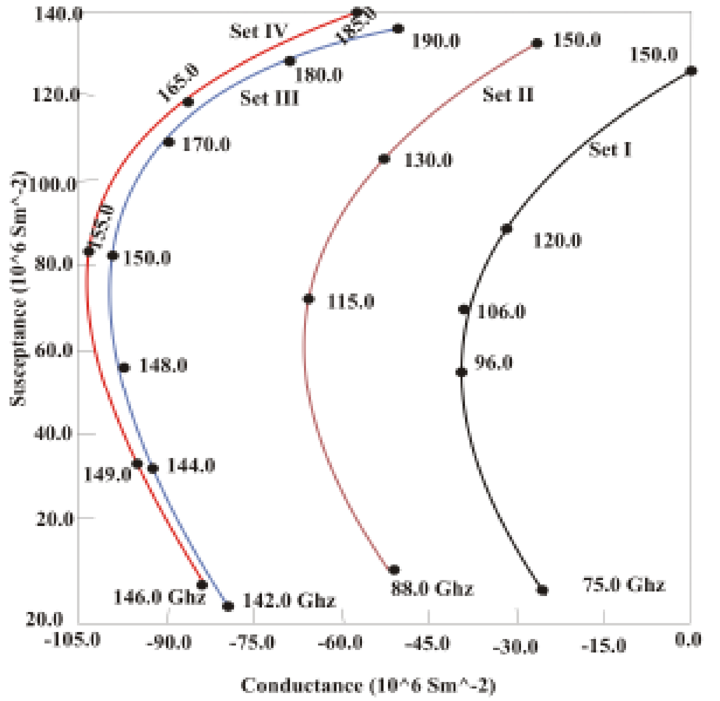

Figure 3. Admittance plots of Si DDR IMPATT diodes for pulsed operation at 94.0 GHz (under different operating conditions)

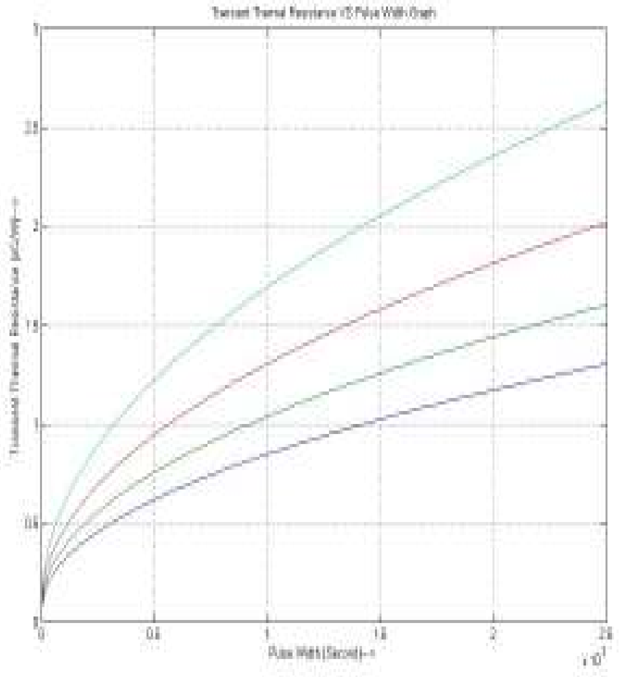

Figure: 4. Transient thermal resistance vs. pulse width for different diode diameter. From higher to lower curves, diode diameters are: 87.5 µm, 100µm, 112.5µm and 125µm.

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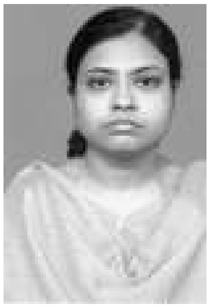

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