International Journal of Soft Computing and Engineering (IJSCE)
ISSN: 2231-2307, Volume-3, Issue-2, May 2013

Analysis of Ka Band DDR Impatt Diode Based On Different Solidstate Materials

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Abstract— IMPATT diode is a $p^+ - n$ junction diode reversed bias to breakdown and can generate microwave power when embedded in a resonant cavity. From the date of its inception it is increasingly proving its worth as a prime solid state source for microwave and mm-wave frequency. The available structures of IMPATT are SDR, DDR, DAR, lo-high-lo, etc which shows gradually better efficiency and power output for different materials like Wz-GAN, InP, GaAs, Si, Ge. A detailed study in terms of the following parameters like (i) Electric field profile [E(x)] (ii) Normalized current density profile [P(x)] (iii) Doping Profile (iv)Susceptance Vs Conductance characteristics (v) RF power output (vi) Negative resistivity profile [R(x)] (vii) Quality factor profile [Q(x)] of the diodes through simulation scheme. It is being observed that the wide band gap semiconductors are with higher efficiency (12.09 %) compare to normal Si, Ge at Ka-band and because of the relatively high breakdown voltage also power output is highest as 14.3142 W for InP compare to other material.

Index Terms— Ka-band IMPATT, IMPATT with wide band gap materials, DDR IMPATT, Small signal Analysis of Ka band IMPATT.

I. INTRODUCTION

IMPATT is a specially designed and doped $p^+ - n$ junction diode shows the negative resistance due to impact avalanche ionization and transit time effect. This diode generates rf power in the microwave, mm-wave and sub-mm wave range of frequencies as a result of that it involves wide application in the field of communication RADARs. Vehicular collision avoidance system and in many more. To cope with these applications researchers are trying to develop solid state sources capable of delivering high power at low window frequency zone like Ka-band. Silicon (Si), Germanium (Ge) are conventional low band gap materials for IMPATTs producing considerable output power and frequency. However the wide band gap semiconductors like Gallium Nitride (GaN), Indium Phosphate (InP) and Gallium Arsenide (GaAs) offers interesting alternative to these heat due to unconverted dc power can be extracted from the device. As the dielectric constant (ε) determines the device impedance and band gap energy (Eg) thus in turn determines upper temperature limit for the safe operation of the device.Thus these two are important parameters for analysis. Here the DDR structure of Si, Ge, GaAS, InP and Wz-GaN IMPATT diodes is considered to simulate the dc and small signal behaviors for optimized operation at 36 GHz.

Manuscript received on May, 2013.

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The device dimensions, doping and current densities are also optimized for Ka band frequencies using a detailed computer analysis.

II. MATERIAL PARAMETERS AND SIMULATION METHOD

In the dc analysis of IMPATT diode, the values of the material parameters of Si, Ge, InP, GaAs, Wz-GaN are taken as a standard one and which are enlisted in Table-1 and the design parameters are shown in Table-2. The doping profile and Electric field profile of DDR IMPATT diode is shown in Figure-1. DDR structure of IMPATT diode is designed and optimized through a generalized double-iterative simulation method based on drift diffusion model. The operating frequency of IMPATT diode essentially depends on the transit time of charge. Computer simulation is carried out at an operating frequency of 36 GHz and the width of the epilayers are accordingly chosen using the transit time formula [Sze and Ryder,(1971)] W = 0.35 vsn/f; where W, V_{ns} and f are the total depletion layer width, saturation velocity of electrons and operating frequency respectively.

Table-1(A,B,C): Material parameters used for the analysis (at $300^0 K$)

(A)

Material	A_n (m^{-1})	B_n $(\frac{V}{m})$	A_p (m^{-1})	B_p $(\frac{V}{m})$
Wz-GaN	$3.65x10^8$	$.99x10^8$	$6.44x10^9$	$1.57x10^8$
InP	$.62x10^8$	$1.08x10^8$	$2.0x10^8$	$1.97x10^8$
GaAs	$1.8x10^8$	$1.85x10^8$	$1.8x10^8$	$1.85x10^8$
Si	$9.8x10^8$	$1.75x10^8$	$1.25x10^8$	$1.0x10^8$
Ge	$1.55x10^9$	$1.53x10^8$	$1.0x10^8$	$1.28x10^8$

(B)

Material	V_{ns} $(10^5 \frac{m}{s})$	V_{ps} $(10^5 \frac{m}{s})$	μ_n $(\frac{m^2}{Vs})$	μ_p $(\frac{m^2}{Vs})$
Wz-GaN	2	.7	.055	.051
InP	.6	.76	.14	.038
GaAs	.12	.1	.96	.002
Si	1	1.7	.135	.038
Ge	.6	1	.39	.09

(C)

Material	E_g (eV)	K $(\frac{W}{cmK})$	ε_r $(\frac{F}{m})$
Wz-GaN	3.39	225	9

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InP	1.34	68	12.4
GaAs	1.44	46	12.9
Si	1.1242	148	11.9
Ge	1.12	60	16

2.1 DC ANALYSIS

For the analysis of DDR IMPATT at Ka-band following assumptions are made: (a) One dimensional model of the $p^+ - n$ junction is treated; (b) The electron and hole velocities are taken to be saturated and independent of the electric field throughout the space charge layer. dc analysis yields electric field profile, normalized current density profile, doping profile and static parameters which are required for small signal analysis of the designed diodes are obtained by the distribution of dc electric field. Carrier currents in the depletion layer are obtained by a double-iterative method, which involves iteration over the magnitude of field maximum (E_m) which is obtained at metallurgical junction and its location in the depletion layer. At each point in the depletion layer simultaneous solutions of Poisson and carrier continuity equations, the space charge equation are keenly taken care. The field boundary conditions are given by,

$$E(-x_1)=0 \text{ and } E(x_2)=0 \qquad (1)$$

Where $-x_1$ and x_2 represent the edges of the depletion layer in n+ and p+ regions, respectively. The boundary conditions for normalized current density P(x), are given by,

$$P(-x_1) = \left(\frac{2}{M_p} - 1\right) \text{ and } P(x_2) = \left(1 - \frac{2}{M_n}\right) \qquad (2)$$

where, $M_n = \frac{J}{J_{ns}}$, $M_p = \frac{J}{J_{ps}}$; J_{ns} and J_{ps} are electron and hole leakage current densities, respectively. M_n and M_p are electron and hole current multiplication factors, respectively

Where $P(x) = \frac{(J_p - J_n)}{J}$, where J_p = hole current density, J_n = electron current density and J total current density. Thus the dc electric field and current profiles are obtained by solving simultaneously the Poisson and carrier continuity equations, within the boundary conditions (1) and (2). The realistic field dependence of electron and hole ionization rates, carrier mobility and the drift velocities of electron and hole are also considered in the simulation program. The dc to mm-wave conversion efficiency [Aritra Acharyya et al., (2011)] is calculated from the approximate formula,

$$\eta(\%) = \frac{2mV_D}{\pi V_B} \qquad (3)$$

Where, V_D =voltage in the drift region. Also $V_D = V_B - V_A$, where V_A = voltage across the avalanche region, and V_B = breakdown voltage and m=modulation index. Avalanche breakdown occurs at the junction when the electric field is large enough such that the charge multiplication factors (M_n, M_p) become very large. The depletion layer of an IMPATT diode is commonly divided in to a high-field avalanche region of width W_A and low-field drift region of width W_D . The avalanche zone width is customarily defined as the region where 95 % of the impact ionization takes place. The breakdown voltage is calculated by integrating the spatial field profile over the total depletion layer width. Large number of charge carriers emerges from the avalanche zone and interacts with the field while crossing the drift zone. This interaction leads to the generation of high frequency oscillations. Now

$$V_B = \int_{-x_1}^{x_2} E(x)dx \qquad (4)$$

results of the dc analysis are then used in the small signal analysis.

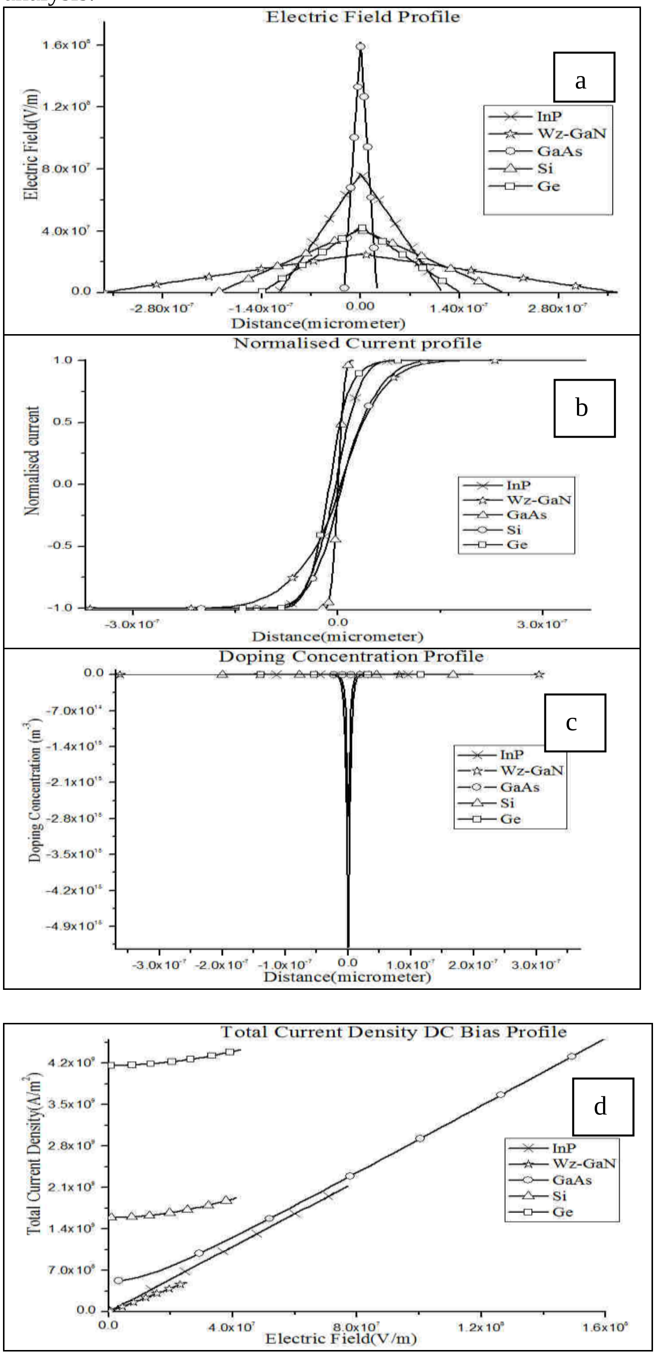


Figure 1: Comparative DC Analysis of the DDR IMPATT diodes for the materials Wz-GaN, InP, GaAs, Si, and Ge respectively.

(a)Electric field profile (b) Normalised current density profile (c) Doping profile (d) dc Bias Current density profile

2.2 SMALL SIGNAL ANALYSIS

The small signal analysis of the IMPATT diode provides an insight into the high frequency performance of the diode. The range of frequencies exhibiting negative conductance of the diode can easily be computed by Gummel-Blue method [1]. The dc electric field and current profiles, as obtained from the dc analysis, are fed as input data for the small signal analysis. The real part R(x, ω) and imaginary part X(x, ω) are obtained by splitting the diode impedance Z(x, ω) using Gummel-Blue method and thus two different equations are framed [Mukherjee et. al, 2007]. Then, by using modified Runga-Kutta method the solutions of these two equations are found following a double iterative simulation scheme. The small signal parameters like negative conductance (-G), susceptance (B), impedance (Z) of the diode, frequency band width, and the quality factor (Q) of the diode are obtained satisfying the boundary conditions.

The diode negative resistance ($-Z_R$) and reactance ($-Z_X$) are computed through numerical integration of the –R(x) and –X(x) profiles over the active space charge layer. Thus

$$-Z_R = \int_{-x_1}^{x_2} -R\,dx \text{ And } -Z_X = \int_{-x_1}^{x_2} -X\,dx$$

The diode impedance Z is given by,

$$Z(\omega) = \int_{-x_1}^{x_2} Z(x,\omega)\,dx = -Z_R + jZ_X \qquad (5)$$

The diode admittance is expressed as

$$Y = \frac{1}{Z} = -G + jB = \frac{1}{-Z_R + jZ_x} \text{ or, } -G = \frac{Z_R}{Z_R^2 + Z_x^2} \text{ and}$$

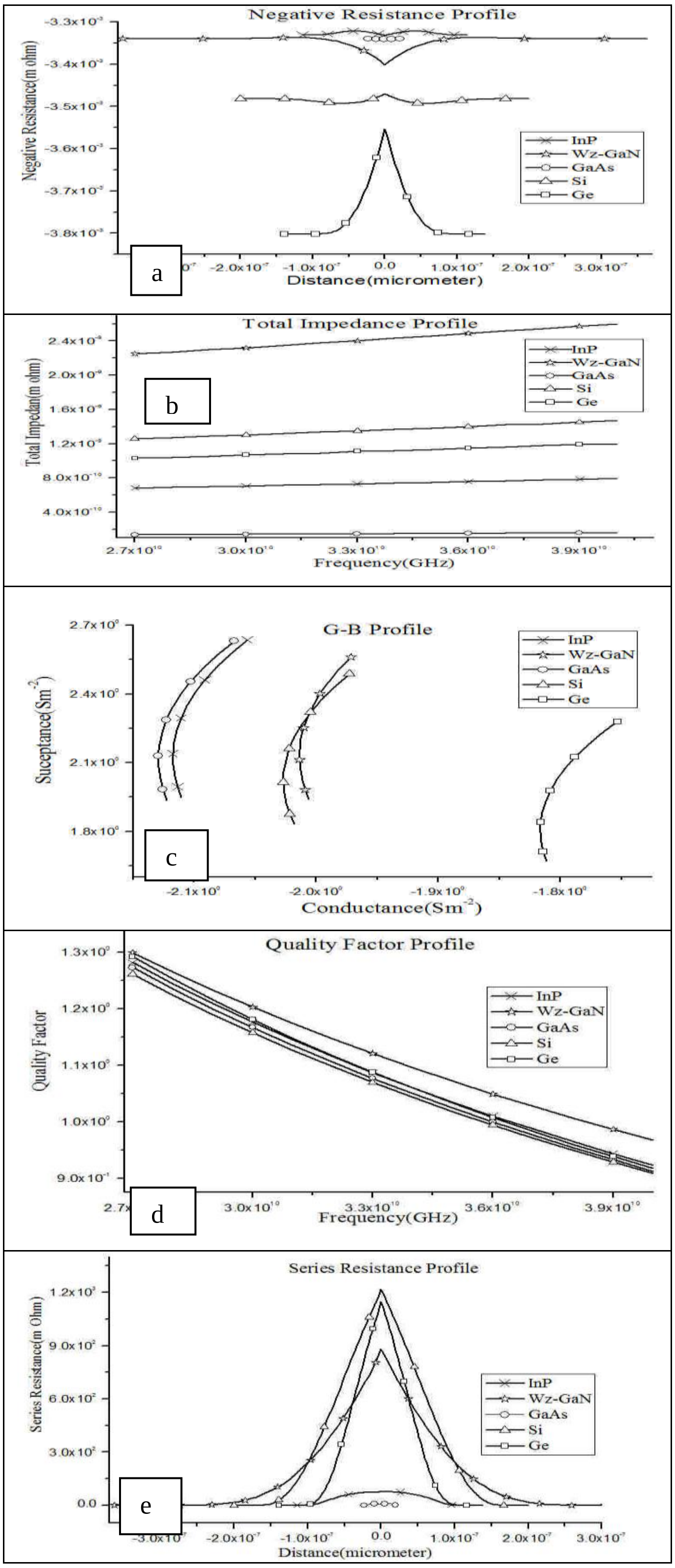
$$B = \frac{Z_x}{Z_R^2 + Z_x^2} \qquad (6)$$

-G and B are both normalized in accordance with the diode area.

The Avalanche (resonance) frequency (f_p) is a frequency at which the imaginary part, susceptance (B) of the admittance changes its nature from inductive to capacitive. The small signal quality factor (Q_p) is defined as the ratio of the imaginary part of the admittance (f_p), i.e.

$$-Q_p = \frac{B_p}{-G_p} \qquad (7)$$

At a given bias current density, the peak frequency (f_p) is the frequency at which the magnitude of the negative conductance of the diode is maximum. The maximum RF power (PRF) from the device is obtained from the expression [M.Mukherjee et.al, (2007)].The area of the diode is considered to be 10^{-8} m^2 . Under small signal condition VRF (the amplitude of the RF swing) is taken as V_B .



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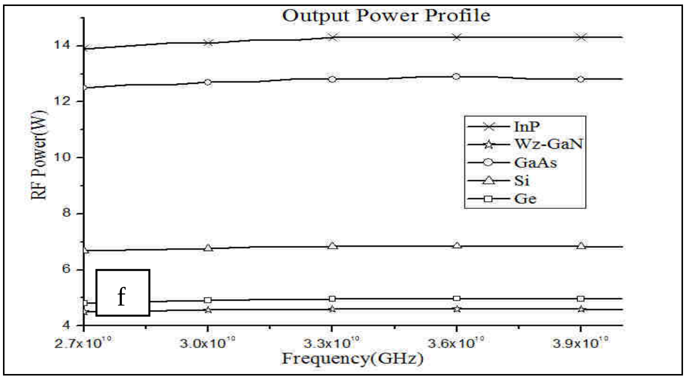

Figure2: Small signal Analysis of DDR IMPATT diodes for the materials Wz-GaN, InP, GaAs, Si, and Ge respectively. (a)Negative resistance profile (b) Total impedance profile (c) G-B profile (d) Quality factor profile (e) Series resistance profile (f) Power Profile

III. RESULTS AND DISCUSSIONS

The dc simulation program has been used here to obtain the electric field profile [E(x)] and normalized current density profile [P(x)] of the DDR IMPATT (for Si, Ge, InP, GaAs, Wz-GaN) diodes which are optimized at microwave frequency of 36 GHz. The optimized design parameters of the designed diodes are summarized in Table-2 and the efficiency, power output, impedance and Q-value obtained by small signal analysis are tabulated in Table-3.

Table-2(A,B): Optimised design parameters (at $300^0 K$)

(A)

Material	E_{Max} $(\frac{V}{m})$	E_D $(\frac{V}{m})$	E_A $(\frac{V}{m})$	E_B $(\frac{V}{m})$
Wz-GaN	$2.51x10^7$	8.6442	.4598	9.104
InP	$7.70x10^7$	8.3355	.4434	8.7788
GaAs	$1.68x10^8$	3.5383	.1882	3.7265
Si	$4.11x10^7$	6.8093	1.4117	8.221
Ge	$4.26x10^7$	1.4363	4.4886	5.9249

(B)

Material	ε $(\frac{F}{m})$	D_W (μm)	α_n $(\frac{m^{-3}}{s})$	α_p $(\frac{m^{-3}}{s})$	J $(\frac{A}{m})$
Wz-GaN	$7.97x10^{-11}$	.726	$7.05x10^6$	$1.23x10^7$	$5.02x10^8$
InP	$1.1x10^{-10}$	.228	$1.53x10^7$	$1.55x10^7$	$2.12x10^9$
GaAs	$1.14x10^{-10}$	.460	$5.75x10^7$	$5.75x10^7$	$4.68x10^9$
Si	$1.05x10^{-10}$	.400	$1.10x10^7$	$1.10x10^7$	$1.93x10^9$
Ge	$1.42x10^{-10}$	.278	$4.28x10^7$	$4.96x10^6$	$4.43x10^9$

Table-3(A,B): Result of small signal analysis (at $300^0 K$)

(A)

Material	f_p (GHz)	η (%)	Z_{Total} $(10^{-8}\Omega m)$	G $(x10^8 Sm^{-2})$
Wz-GaN	36	12.0893	24.9	-2.77
InP	36	12.0893	758	-9.29
GaAs	36	12.0893	15.3	-46.3
Si	36	10.546	14	-5.07
Ge	36	5.1444	11.5	-6.53

(B)

Material	B $(x10^8 Sm^{-2})$	Q	P_{Out} (W)
Wz-GaN	2.91	1.049	4.5978
InP	9.38	1.010	14.3142
GaAs	46.3	1.000	12.8572
Si	5.04	.994	6.8491
Ge	6.62	1.013	4.967

IV. CONCLUSIONS

The simulation result provides a clear view of the contributions of depletion layer in the generation of microwave power at 36 GHz for Si, Ge, InP, GaAs, Wz-GaN based IMPATT diodes. The comparison shows that wide band gap semiconductor material IMPATT have higher efficiency and because of high applied electric field power output is also high. The analysis of this paper may be considered to be extremely helpful for the design of compound semiconductor based DDR IMPATT diodes at Ka-band for many civilian and military applications.

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Dr. **M. Mitra** did his B.Tech and M.Tech in Radio Physics and Electronics from Calcutta University in 1982 and 1984, he was awarded Ph.D. by Calcutta University in 1995. He was awarded H. L. Mitter Gold Medal as stood 1st in Physics honors from Calcutta University, S. N. Ghosh Silver Medal as stood faculty 1st amongst all the departments and National scholarship throughout the studentship. Presently he is working as a Head of the Department of Electronics and Telecommunication Engineering, Bengal Engineering and Science University, Shibpur, West-Bengal.

He had published four books so far, one on "Microwave Semiconductor Devices"(PHI) in 2003, another on "Satellite Communication"(PHI) in 2005, another on "Microwave Engineering (3rd Ed.)"(Dhanpat Rai) in 2006, and the last one on "Microwave & Radar Engineering" (Scitech- in press) will be published in 2013.

Over the last 25 years he is doing research in the field of Fabrication of Microwave semiconductor device IMPATT and developed microwave sources for the solid state radars using the fabricated diode. At present he is also doing research on collision avoidance system for vehicles using MIMO radar system at microwave frequencies. So far 3 students got their Ph.D. degree under his supervision and about 12 students are currently doing their Ph.D. work under his guidance. He had published more than 80 research papers in different reputed national and international journals. He is also member of different prestigious organizations.