Dynamic Characterization and Noise Analysis of 4H-SiC Impatt Diode at Ka Band

Joydeep Sengupta, Girish Chandra Ghivela, Monojit Mitra

Abstract--The microwave as well as the small signal noise properties on a one dimensional n+npp+ DDR structure 4H-SiC IMPATT Diode have been studied using advanced computer simulation program developed by us and compared at different frequency of Ka band by taking the area of the diode as $10^{-8} m^2$. Also the theory for the diode current noise associated with the electron hole pair generation and recombination in the space charge region of the diode is presented. This paper can help to know about the small signal behavior as well as noise behavior of IMPATT diode along with power density at the Ka band and will be helpful for designing the 4H-SiC based IMPATT diode depending upon the microwave applications.

Index Terms--Impact ionization, efficiency, mean square noise voltage, quality factor, noise spectral density, power density, noise measure.

I. INTRODUCTION

In recent years, IMPATT(Impact Avalanche and Transit Time) diodes have proved as a major source of microwave and millimetre wave power generator. Thus, designers are concentrating on the best semiconductor materials for the optimized design of the diode. For our design, we have choose 4H-SiC material for the IMPATT because of high electron mobility and have recently been established as technologically important materials for both electronic and optoelectronic devices[1]-[2]. Also the advantages of SiC-based IMPATT devices over traditional Si,GaAs,InP based IMPATT at Ka-band were presented in [3]. However, the noise generated by the statistical nature of impact ionization in the active space charge region limits the potential of IMPATT diode as a microwave generator for various applications[4]. So, the understating of the noise generation mechanism and its behaviour at small signal conditions is very important in establishing optimized design and operating conditions for IMPATT diodes.

II.SIMULATION METHOD

The three stage computer simulation method using MATLAB consists of DC analysis, small signal analysis and noise analysis are carried out on a one-dimensional n^+npp^+ DDR model of 4H-SiC based IMPATT diode throughout the Ka band. The device structure is shown in figure1.The equations involved in the analysis are nonlinear in nature, and thus their solutions are more complex. So the IMPATT diode is considered as consisting of several small space points for the analysis. The active layer width of the diode is divided into number of steps each of size 0.055 nm.

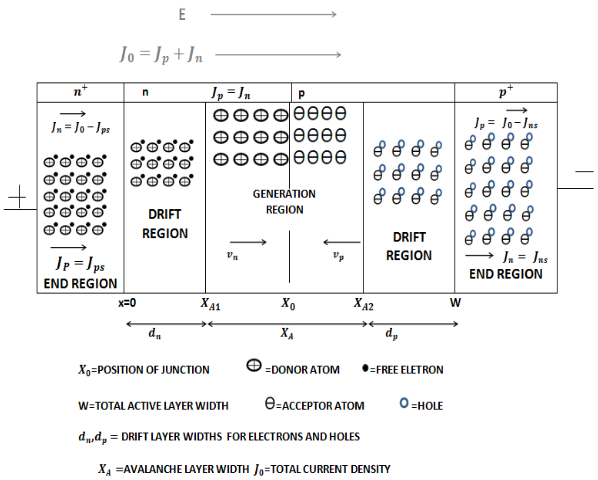

Figure1:The Active Layers of a Reverse Biased p-n Junction

1 DC ANALYSIS

To obtain the DC parameters such as break down voltage, carrier current profiles, electric field profiles etc., dc analysis is done here by solving Poisson equation, the space charge equation and the carrier continuity equation simultaneously over the double drift structure of the diode[5]. The values of the material parameters of 4H-SiC are taken as a standard one, which are enlisted in table1 and the design parameters are shown in table 2 . The Computer simulation method for DC analysis is initiated from the position X_0 of the field maximum E_m in the depletion layer which is situated near the metallurgical junction. In the location of the field maximum i.e. at $x = X_0$,where $dE/dx = 0$,the value of the maximum electric field E_m and its location X_0 in the depletion layer are initially chosen suitably for the taken doping profile and dc current density(J_0)(table1(B)). Then by using this the initial value of the mobile space charge($P(X_0)$) is determined. After that the Poisson equation and the carrier continuity equation are solved simultaneously through the numerical approach[6] by taking space steps of very small width(0.055nm). Iteration over E_m and X_0 are carried out till boundary conditions are being satisfied at both edges (at $x = X_0$ and W) of the depletion layer. The numerical approach is started from the point $x = X_0$ (field maxima) and moving towards the right side of the junction(p-region) till the field boundary conditions, in carrier current and electric field are satisfied at $x = W$. Now the computation again started at field maximum point and it proceed towards the left side

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of the junction (n-region) till boundary condition is satisfied. Thus, the DC electric field and carrier current distribution profiles for the 4H-SiC IMPATT diode operating at the taken current density ($4\times10^{8}Am^{-2}$) are obtained from the final solutions of the E_m and X_0. The method described above gives the avalanche breakdown characteristics of the IMPATT diode. The avalanche layer width X_A is obtained by taking the condition $P(\mathrm{x})$=0.95, i.e. 95% growth of the electron and hole carrier current. The operating frequency of IMPATT diode essentially depends on the transit time of the charge. Computer simulation using MATLAB is carried out at operating frequencies of 26.5 GHz to 40 GHz and the width of the epilayers are accordingly chosen using the transit time formula [Sze and Ryder,(1971)[7]] $W_{n,p}=0.35\times V_{ns,ps}/f$; where $W_{n,p}$ is the penetration of depletion layer towards n and p-sides, $V_{ns,ps}$; are the saturation velocity for electron, hole respectively and f is the operating frequency. The depletion layer width of the diode is obtained as $W=|W_n|+|W_P|$ and drift region width is obtained as $W-X_A$. The voltage drop across the diode zones, i.e. breakdown voltage of the diode V_B and avalanche voltage drop V_A are determined by integrating the electric field over the corresponding zone layer. Then, the voltage drop across the drift zone is calculated by as $V_D=V_B-V_A$. The DC to RF conversion efficiency of the diode can be obtained from the expression,

$$\eta(\%)=\frac{2mV_D}{\pi V_B} \qquad (1)$$

where m is the modulation index and the breakdown voltage is calculated by integrating the spatial field profile over total depletion layer width as then the results obtained from the DC analysis are used in the small signal analysis.

$$V_B=\int_0^W E(x)dx \qquad (2)$$

Table1(A,B): Material parameters used for the analysis (at 300K) (A)

A_n $(\times10^{10}m^{-1}$	B_n $(\times10^{9}Vm^{-1}$	A_p $(\times10^{8}m^{-1}$	B_p $(\times10^{9}Vm^{-1})$	V_{ns} $(\times10^{5}ms^{-1})$	V_{ps} $(\times10^{5}ms^{-1})$
4.57	5.24	5.13	1.57	2.508	2.5

(B)

J_0 $(\times10^{8}Am^{-2}$	N_D $(\times10^{23}m^{-3}$	N_A $(\times10^{23}m^{-3}$	μ_n (m^2Vs^{-1})	μ_p (m^2Vs^{-1})
4	2.8	2.9	0.12	0.12

2 Small Signal Analysis

The high frequency performance of the IMPATT diode can be obtained by doing the small signal analysis of the diode. The DC parameters such as electric field profile and current profile, which are obtained from the DC analysis, are fed as input data for the small signal analysis. In small signal condition the ac field developed across the diode is assumed to be much smaller than the breakdown field. As a result the ionization rates with electric field can be assumed to be linear. Therefore, small signal solutions can be obtained by linear zing the complex diode equations. The drift velocities of the charge carriers are assumed to be saturated and the diffusion current is not considered in the small signal analysis, but considered in the noise analysis. The small signal parameters like negative conductance($-G$), susceptance (B), the diode impedance $Z(x,\omega)$, quality factor (Q_P) and range of frequency over which the diode exhibit the negative conductance can easily be computed numerically through the Gummel-Blue approach, where the model takes into account, the contribution from each space points and effectively determines the parameters of the diode after satisfying the boundary conditions. The real part $R(x,\omega)$ and imaginary part $X(x,\omega)$ are obtained by splitting the diode impedance $Z(x,\omega)$ using Gummel-Blue method and thus two different equations are framed [8]-[11]. Then by using modified Runga-Kutta method the solutions of these two equations are found through a double iterative simulation scheme.

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

$$-Z_R=\int_0^W -Rdx \quad \text{and} \quad -Z_X=\int_0^W -Xdx$$

The diode impedance Z is obtained by,

$$Z(\omega)=\int_0^W Z(x,\omega)dx=-Z_R+jZ_X \qquad (3)$$

The diode admittance is obtained as

$$Y=\frac{1}{Z}=-G+jB=\frac{1}{-Z_R+jZ_X} \quad \text{or,}$$

$$-G=\frac{Z_R}{Z_R^2+Z_X^2}$$

$$\text{and} \quad B=\frac{Z_X}{Z_R^2+Z_X^2} \qquad (4)$$

$-G$ and B are both normalized in accordance with the diode area $(10^{-8}m^2)$ taken in our analysis.

The small signal quality factor (Q_P) is calculated by

$$-Q_P = \frac{B_p}{-G_P} \tag{5}$$

The expected RF power delivery from the diode can be calculated by using the relation

$$P_{RF} = (V_{RF})^2 \left|G_P\right| \times A/2 \tag{6}$$

The power density P_A is taken as P_{RF}/A,. where A is the area of the diode. Under small signal condition V_{RF} can be approximated as as $V_B/2$ for 50% modulation. G_P is the device negative conductance at peak frequency.[4].

3 Small Signal Noise Analysis

The generation of noise in IMPATT diode arises mainly from the statistical nature of the generation of electron-hole pairs in the avalanche region. The disturbances in the electric field distribution, voltage and current is due to the random nature of impact ionization process. These fluctuation are assumed as the constituent of shot noise current fluctuation due to avalanching multiplication process and considered as small signal in nature[12]-[13]. Since the noise fix the lower limit to the microwave signals to be amplified, it is important to study the effect of noise and its characteristic along the diode structure is computed using the simulation program in our analysis[14]-[16]. The noise characteristic like noise spectral density i.e. mean square noise voltage per bandwidth ($<V^2>/df$) and noise measure(NM) of the diode are computed from this analysis. Let $\gamma_N(x')$ be the noise generation rate at x' (position of noise source) in the generation region giving rise to mean square noise current deviation over a frequency interval df as

$$<dI_N^2> = 2qdI_N(x')df \;=\; 2\mathrm{q}^2 Adf\,\gamma_N(x')dx' \tag{7}$$

in the space interval dx' of the depletion layer;

where $dI_N(x') = Aq\gamma_N(x')$. The noise source $\gamma_N(x')$ located at x' in the avalanche region, generates a noise electric field $e_N(x,x')$ at every point in the depletion region of the diode. The noise electric field $e_N(x,x') = e_{NR}(x,x') + je_{NX}(x,x')$ contributed from each space point is computed by solving two simultaneous second order equations on $e_{NR}(x,x')$ and $e_{NX}(x,x')$ at each space point

$$D^2 e_{NR}(x,x') + [\alpha_n(x) - \alpha_p(x)]De_{NR}(x,x') - \frac{2r_n\omega}{\bar{v}}De_{NX}(x,x')$$
$$+[\frac{\omega^2}{\bar{v}^2} - H(x)]e_{NR}(x,x') - \frac{2\bar{\alpha}(x)\omega}{\bar{v}}e_{NX}(x,x') = \frac{2qr_p\gamma_N(x')}{\bar{v}\varepsilon} \tag{8}$$

and

$$D^2 e_{NX}(x,x') + [\alpha_n(x) - \alpha_p(x)]De_{NX}(x,x') + \frac{2r_n\omega}{\bar{v}}De_{NR}(x,x')$$
$$+[\frac{\omega^2}{\bar{v}^2} - H(x)]e_{NX}(x,x') + \frac{2\bar{\alpha}(x)\omega}{\bar{v}}e_{NR}(x,x') = 0 \tag{9}$$

here

$$D = \frac{\partial}{\partial x}\,, H = (\alpha_p{}' - \alpha_n{}')DE_m + \frac{2\alpha' j}{\bar{v}\varepsilon}\,,\ \bar{v} {=} (\sqrt{v_n - v_p})\,,$$

$$r_n = \frac{v_n - v_p}{2v},\ r_p = \frac{v_n + v_p}{2v}\,,\ \bar{\alpha} {=} \frac{\alpha_p v_p + \alpha_n v_n}{2v}$$

Initially, the noise generation source is assumed to be located at the left-hand edge of the active zone at $x_i{}'$, where i=1. Iterations over the initial chosen values of $e_{NR}(x,x')$ and $e_{NX}(x,x')$ in the left hand edge of the diode depletion layer are carried out till the boundary conditions are satisfied at the right hand edge. The profiles of noise field $e_{NR}(x,x')$ and $e_{NX}(x,x')$ can be obtained from the solutions of equations(8) and (9). This method is repeated to get the integrated noise field profile and noise voltage due to noise source successively located at $x = x' + ndx'$, where n=2,3,4,...... Thus, the noise generation along the complete depletion layer can be obtained separately for each noise source located in various space points of the active zone. Thus, the terminal voltage produced due to noise generating source $\gamma_N(x')$ located at x' is computed through the relation.

$$V_t(x') = \int_0^W e_N(x,x')dx = \int_0^W e_{NR}(x,x')dx + j\int_0^W e_{NX}(x,x')dx \tag{10}$$

Then by shifting the noise source to $x = x_i{}'$ for i=2,3,4,5.....; real part $V_{tR}(x')$ and imaginary part $V_{tX}(x')$ of the terminal voltage are calculated for individual noise sources. These values of $V_{tR}(x')$ and $V_{tX}(x')$ are then integrated for noise sources consider along the entire depletion layer.

$$\text{So, } V_R = \int_0^W V_{tR}(x')dx' \quad \text{and} \quad V_X = \int_0^W V_{tX}(x')dx' \tag{11}$$

From this the transfer impedance of the diode can be calculated as

$$\begin{aligned} Z_t(x') &= \frac{V_t(x')}{dI_N(x')} = Z_{tR}(x') + jZ_{tX}(x') \\ &= \frac{V_R(x')}{q\gamma_N(x')Adx'} + j\frac{V_X(x')}{q\gamma_N(x')Adx'} \end{aligned} \tag{12}$$

Now, the mean square noise voltage can be determined by

$$<V^2> = 2qdfA\int\left|Z_t(x')\right|^2 \gamma_N(x')dx' \tag{13}$$

and the noise measure(NM) of the diode as

$$NM = \frac{<V^2>/df}{4KT(-Z_R)} \tag{14}$$

where K is the Boltzmann constant, T is the absolute temperature and $(-Z_R)$ is the total negative diode resistance.

III. RESULTS AND DISCUSSIONS

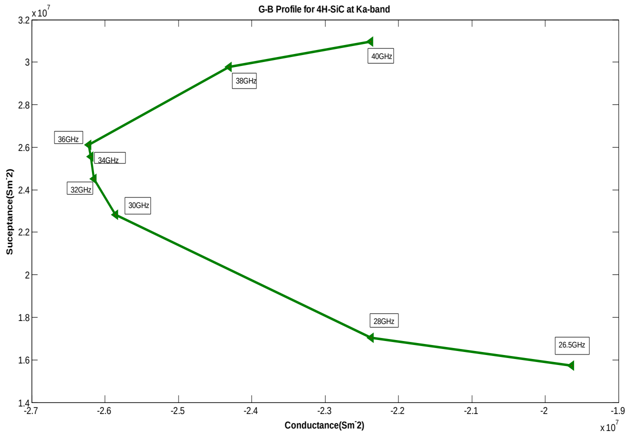
The electric field profile $E(x)$ and normalized current density profile $P(x)$ of the 4H-SiC based DDR structure IMPATT diode have been obtained and optimized at different frequencies of the Ka-band by using the DC simulation program developed by the authors. The optimized design parameters of the design diode are summarized in table2 and the efficiency, diode negative conductance, susceptance, small signal quality factor and power density obtained by small signal analysis are tabulated in table3.

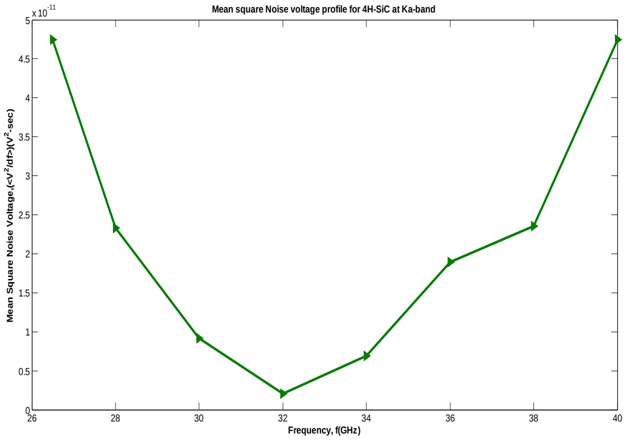
Table-2:Optimised design parameters (at $36\,GHz$ and $300K$)

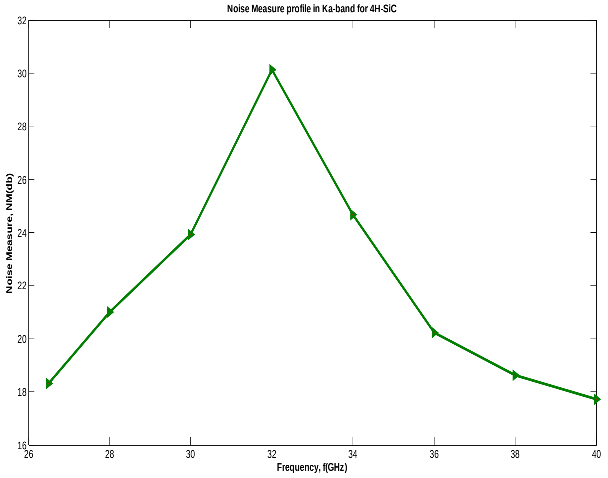
E_m $(\times10^8 Vm^{-1}$	V_D (V)	V_B (V)	V_A (V)	$\eta(\%)$
1.963	29.929	71.407	41.477	26.672

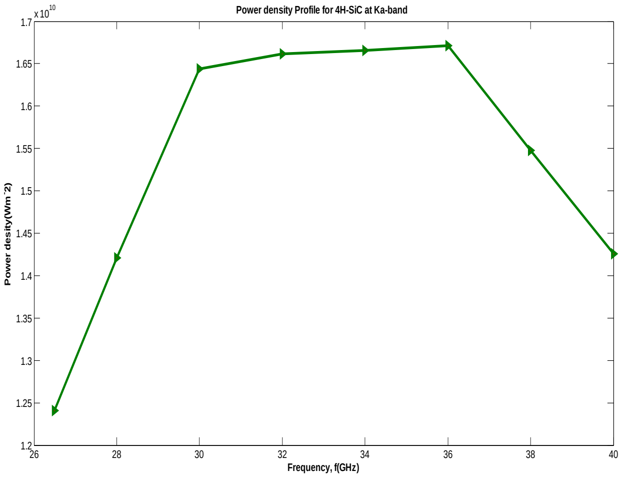
Table3:Results of small signal analysis and small signal noise analysis (at 300K)

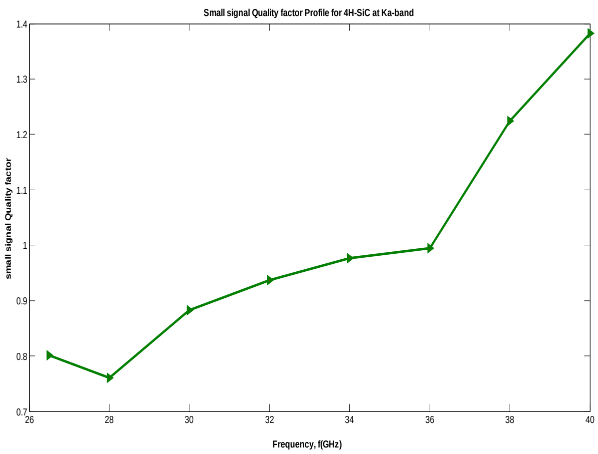
f (GHz)	$G\,(\times10^7)$ (Sm^{-2})	$B\,(\times10^7)$ (Sm^{-2})	Q_P	P_{RF}/A $(\times10^{10})$ (Wm^{-2})	$<V^2>/df$ $(\times10^{-11})$ $(V^2-\sec)$	NM (db)
26.5	-1.964	1.573	0.801	1.241	4.742	18.32
28	-2.237	1.704	0.761	1.421	2.333	21.01
30	-2.586	2.284	0.883	1.644	0.932	23.93
32	-2.615	2.451	0.937	1.662	0.205	30.13
34	-2.619	2.557	0.976	1.666	0.691	24.68
36	-2.622	2.610	0.995	1.671	1.895	20.22
38	-2.431	2.978	1.224	1.548	2.352	18.62
40	-2.238	3.097	1.383	1.426	4.742	17.71











IV.CONCLUSIONS

The simulation results provides a clear view of conductance-susceptance profile as well as variation of mean square noise voltage, noise measure, power density and small signal quality factor throughout the Ka band. The results shows that at 36 GHz the DC to RF conversion efficiency of the diode is 26.672% , G-B value best optimized, Power handling capacity per unit area is more $1.671\times10^{10}\,Wm^{-2}$ and noise measure(20.22 db) is also in moderate level as compared to other frequency in the Ka-band. So, at the 36 GHz the operation of IMPATT diode is satisfactory considering all those parameters. The analysis of this paper may be considered to be extremely helpful for the design of compound semiconductor based DDR IMPATT diode at Ka band for many civilian and military applications. As from this paper we are getting a clear cut idea about the effect of noise at Ka band. So the efficiency of the IMPATT diode can be improved by choosing proper operating frequency.

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