Mobile Space Charge Effect in 4H Silicon Carbide IMPATT Diodes

S. Mukhopadhyay, Student Member, IEEE, Soumen Banerjee, J. Mukhopadhyay and J. P. Banerjee, Senior Member, IEEE

***Abstract*—The effect of mobile space charge in the depletion layer of 4H SiC p^+nn^+ IMPATT diode has been investigated through computer simulation method.The simulation is based on drift-diffusion model to study DC properties of the device at different bias current densities. The device is designed to operate at millimeter wave frequencies. It is observed that a maximum DC to microwave conversion efficiency of 22.82% is obtained at a bias current density of 4.4×10^7 A.m^{-2}. The DC to microwave conversion efficiency of Read and Quasi Read High-low SDR diodes has also been estimated and compared with that of Flat profile p^+nn^+ diode at the same bias current density of 4.4×10^7 A.m^{-2}.**

***Index terms*—Conversion efficiecy, Drift-diffusion model, 4H Silicon Carbide, Mobile space charge effect**

I. INTRODUCTION

SILICON Carbide (SiC) is an excellent wide band gap material for high-power and high-frequency applications because of its high critical field, high electron saturation velocity and high thermal conductivity[1]-[5]. Microwave oscillation in 4H SiC IMPATT diodes has been experimentally demonstrated by Vassilevski *et al.*[1] for single drift p^+nn^+ structure in X-band at a threshold current of 0.3A. SDR IMPATT diodes with high-low doping profile have been fabricated by Yuan *et al.* [2]. They obtained 1mW RF power output at 7.75GHz. The mobile space charge effect plays an important role at high bias current density in IMPATTs. Simulation studies have been carried out to obtain the optimum bias current density of Flat doping profile p^+nn^+ single drift region IMPATT diode for high DC to microwave conversion efficiency operation. Then the peak efficiency of p^+nin^+ diode is determined for different doping density and width of n-layer. The peak efficiency of $p^+nn^-n^+$ diode is then determined for different high to low doping density ratios. The above mentioned three structures of 4H SiC IMPATTs have been designed and simulated with respect to maximum DC to microwave conversion at millimeter wave frequencies.

The abstract was submitted to IWPSD, 2007 on 31st May (Thursday), 2007 by e-mail. The notification of acceptance was sent by Prof. Dinesh Sharma by e-mail on 20th August (Monday), 2007.

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II. DESIGN AND SIMULATION

Single drift p^+nn^+ , p^+nin^+ and $p^+nn^-n^+$ structures of 4H SiC IMPATTs have been designed by using computer simulation experiment for operation at and around 35GHz window frequency by Transit-time formula of Sze and Ryder [6] which is $\mathbf{W=0.37\upsilon_{sn}/f}$; W, υ_{sn} and f are the total depletion layer width, saturation velocity of electron and operating frequency respectively.The doping concentration of n-region and total depletion layer width have been adjusted in the simulation programme to obtain nearly nonpunch through diode behavior. Recently reported impact ionization rates of charge carriers for different electric field ranges [7] and other relevant material properties [8]-[12] of 4H SiC have been used in the simulation programme. The simulation programme is based on a double iterative field maximum method. Simultaneous Numerical solution of Poisson's equation, Combined continuity equation and Mobile space charge equation [13] is carried out subject to boundary conditions of electric field and current density at the depletion layer edges. The double iteration is initiated at field maximum position which is continued till the boundaries are reached. The electric field profiles are thus obtained from the simulation. The DC to microwave conversion efficiency is calculated for each bias current density using Scharfetter-Gummel Semi quantitative formula [14] which is $\boldsymbol{\eta = (1/\pi)V_D/V_B}$;V_D and V_B are drift voltage and breakdown voltage respectively. The results show that a maximum DC to microwave conversion efficiency (22.82%) is obtained when a bias current density of 4.4×10^7 A.m^{-2} is driven through 4H SiC p^+nn^+ IMPATTs.

III. RESULTS AND DISCUSSION

The optimum bias current density of 4.4×10^7 A.m^{-2} for p^+nn^+ diode is used as bias current density for Read diode and High-Low SDR diode to compare the performance of three structures of 4H SiC IMPATTs. The avalanche zone width and conversion efficiency of p^+nn^+ diode vary considerably for bias current densities in the range of 2.0×10^7 A.m^{-2} to 2.0×10^8 A.m^{-2}. Figure.1 shows that the efficiency initially increases with increasing current density ,attains a maximum value of 22.82% at a bias current density of 4.4×10^7 A.m^{-2} and then decreases. The peak electric field near the metallurgical junction remains nearly constant at 3.44×10^8 V.m^{-1} upto bias current density of 1.0×10^8 A.m^{-2}, but the peak electric field decreases on further increasing the bias current density and becomes 8.8×10^7 V.m^{-1} at bias current density of

978-1-4244-1728-5/07/$25.00

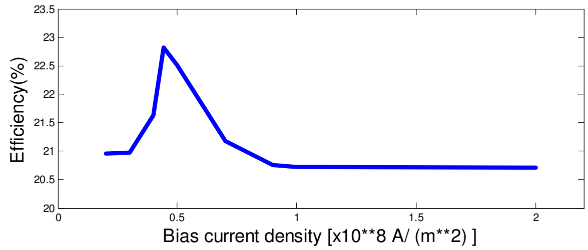

Fig. 1: DC to microwave efficiency vs Bias current density plot for Flat profile SDR IMPATT diode.

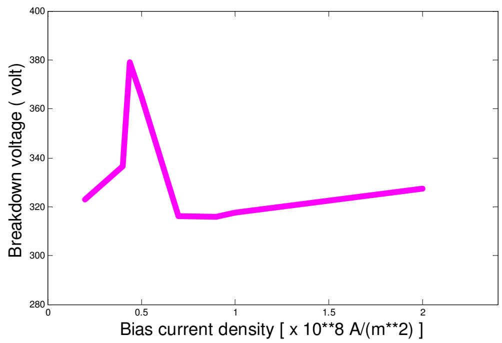

Fig. 2 : Breakdown voltage vs Bias current density for Flat profile SDR IMPATT diode of doping density $6.8\times10^{22}m^{-3}$ and width of depletion region 2.3μm.

$2.0\times10^8 A.m^{-2}$. This reduction in peak electric field occurs due to mobile *space charge effect* at bias current density greater than $1.0\times10^8 A.m^{-2}$. Thus the mobile space charge effect is pronounced above $10^8 A.m^{-2}$. The DC to microwave conversion efficiency of 4H SiC flat profile SDR IMPATT diodes degrades when the bias current density exceeds 10^8 $A.m^{-2}$.

Figure.2 shows that the breakdown voltage is 323.03 Volt at bias current density 2.0×10^7 $A.m^{-2}$ then it increases with bias current density, attains a peak of 378.92Volt at the optimum bias current density of 4.4×10^7 $A.m^{-2}$ and then sharply falls to a minimum of 316.17Volt at a bias current density of 7.0×10^7 $A.m^{-2}$. But at higher current density greater than $7.0\times10^7 A.m^{-2}$, the breakdown voltage slightly increases upto 327.23Volt due to *mobile space charge effect*. Thus 4H SiC IMPATT diodes generate microwave oscillation at higher breakdown voltages in comparison to IMPATTs based on Si. The DC to microwave conversion efficiency attains the peak at a bias current density of 4.4×10^7 $A.m^{-2}$ which is the optimum bias current density for device operation. The nature of the variation of conversion efficiency is nearly similar to that of the breakdown voltage for the same range of bias current densities.

Figure.3 shows that the percentage ratio of Avalanche width(X_A) to total depletion layer width(W) is around 14.73% for the range of bias current density of 3.0×10^7 $A.m^{-2}$ to 7.0×10^7 $A.m^{-2}$. Above 7.0×10^7 $A.m^{-2}$, the said ratio increases and attains a maximum value of 15.87% at 2.0×10^8 $A.m^{-2}$. This widening of avalanche zone is also due to *mobile space charge effect* which occurs at high bias current densities. The percentage ratio of Avalanche zone voltage and Drift zone voltage also decreases with

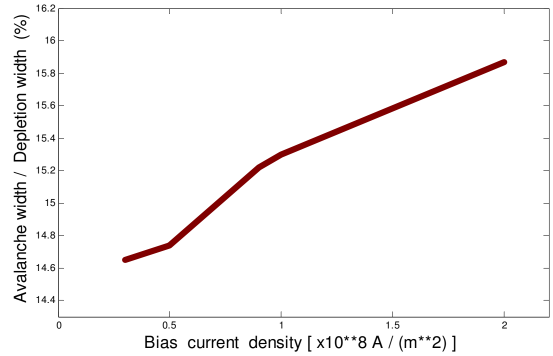

Fig. 3 : Ratio between Avalanche width and Depletion width vs Bias current density plot for Flat profile SDR IMPATT diode.

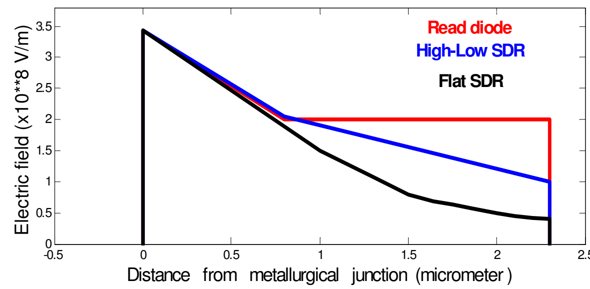

Fig. 4 : Electric field Profile for flat SDR diode, READ diode and High-Low SDR diode at doping density of 6.8×10^{22} m^{-3} for Flat SDR, n-layer of READ and higher doped region of High-Low SDR diode. Doping density ratio of High-Low SDR diode = 10, total depletion layer width = 2.3μm.

increase of bias current density and becomes minimum 39.55 at 4.4×10^7 $A.m^{-2}$ and then increases.

Figure.4 shows the distortion in the electric field profile of flat SDR diode due to *mobile space charge effect* near the interface. The optimum current density of $4.4\times10^7 A.m^{-2}$ obtained for flat SDR diode is used as the bias current density for both Read diode and High-Low SDR diode in our simulation. The electric field profile of flat SDR diode of doping density 6.8×10^{22} m^{-3} shows the punch through behavior. Also the electric field profile of High-Low SDR diode shows punch through behavior near interface.

The i-layer of p^+nin^+ structure (Read diode) is low doped (nearly intrinsic) ν-type layer.The n^- layer of High-Low SDR diode has doping density of 6.8×10^{21} m^{-3}.The electric field profiles of Read diode and High-Low diodes are not distorted. So, the mobile space charge effect is pronounced for higher doping density.

The range of doping density of n layer of Read diode is from $4.0\times10^{22}m^{-3}$ to $2.4\times10^{23}m^{-3}$. The efficiency is optimized by varying the width of the bump keeping the doping ratio fixed. For each doping concentration of n layer, the peak efficiency is determined by varying the width of n layer. Figure.5 shows that for a particular doping density of n layer, the efficiency increases with the increase of the width of n layer, attains a peak and then decreases. As doping density increases, the n layer width for peak efficiency decreases. A maximum peak efficiency of 28.01% is obtained for n layer width of 0.33μm and doping concentration of $2.4\times10^{23}m^{-3}$.

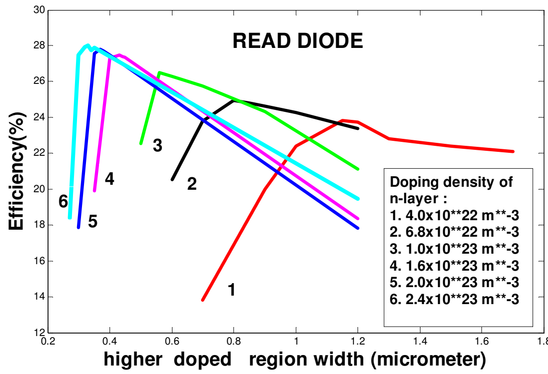

Fig. 5 : DC to microwave conversion efficiency vs Higher doped region width of READ diode for different doping density of n-layer. Total depletion layer width is 2.3μm.

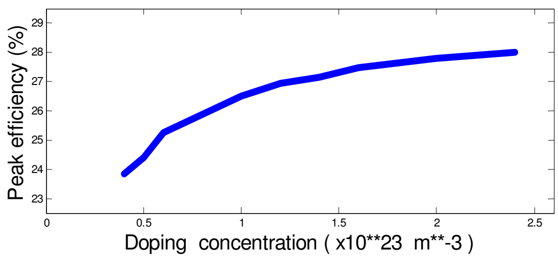

Fig. 6 : Peak efficiency (for each doping concentration) vs corresponding doping concentration for Read diode of total depletion layer width of 2.3μm.

For a particular doping concentration of n layer of Read diode, the peak efficiency is determined by varying the width of the n layer i.e. the bump. Figure.6 shows that the peak efficiency increases initially with increasing the corresponding doping concentration of n layer of the Read diode and then saturates at higher doping concentration of the n layer.

Figure.7 shows that the peak efficiency is at and around 25.47% for High-Low SDR diode if the High to Low doping ratio varies from 1000 to 50 for a fixed n layer width of 0.8μm. For lower doping density ratio, the peak efficiency is smaller at smaller n layer width. The peak efficiency reduces to 24.04% for n layer width of 0.6μm and doping density ratio of 2. The bias current density is 4.4×10^{7} $A.m^{-2}$ for all structures High-Low SDR IMPATT diodes. The DC to microwave conversion efficiency is higher at lower bump width for small doping density ratio, but the peak efficiency is smaller. So, small doping density ratio is preferred for low bump width . As the doping density increases, the peak efficiency shifts to higher bump width.

In TABLE I, for each doping density ratio, the Avalanche voltage decreases with increasing bump width. Also, the breakdown voltage decreases with increasing bump width. The percentage of the ratio between Avalanche voltage and Drift voltage decreases with increasing bump width for any particular doping density ratio. For any particular bump width, the percentage of the ratio between avalanche width and total depletion layer width is nearly fixed for a range of doping density ratio from 10^{3} to 2.

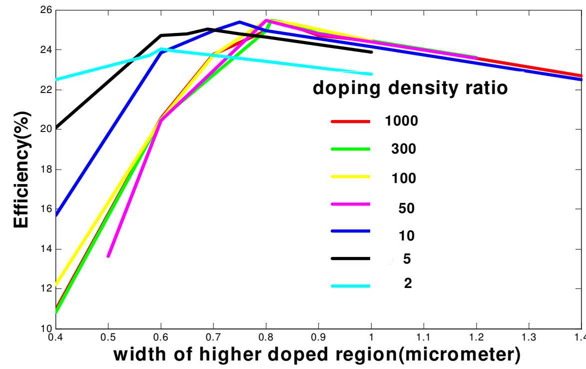

Fig. 7 : DC to microwave conversion efficiency vs width of the bump of High-Low SDR diode for different doping density ratio.

TABLE I

PEAK EFFICIENCY FOR DIFFERENT DOPING DENSITY RATIO FOR HIGH-LOW SDR IMPATTs

Doping density ratio	Width (μm) of the bump for peak efficiency	Peak efficiency (%)
1000	0.81	25.47
300	0.81	25.46
100	0.80	25.48
50	0.80	25.45
10	0.75	25.40
5	0.69	25.01
2	0.60	24.04

Figure.8 shows the peak efficiency of High-Low SDR diode increases with logarithm of doping density ratio and then saturates at 25.47% when the ratio exceeds a value of 10. The doping densities of the depletion layer of Flat SDR diode, n layer of READ diode and higher doped region of High-Low SDR diode are taken to be equal to 6.8×10^{22} m^{-3} and the total depletion layer widths of all the structures of SDR IMPATTs are calculated to be 2.3μm to compare the performance of the above three structures at millimeter wave frequencies.

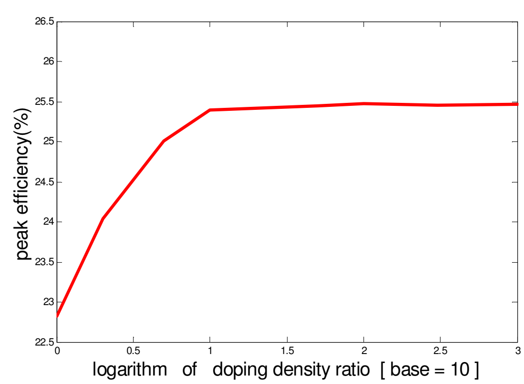

Fig. 8 : Peak efficiency vs Log (doping density ratio) for High-Low SDR IMPATT diode.

IV. CONCLUSION

4H SiC SDR IMPATTs generates microwave and millimeter wave frequencies at high conversion efficiency. The maximum DC to microwave conversion efficiencies of Flat profile SDR diode, Read diode and High-Low SDR diode are 22.82%, 28.01% and 25.48% respectively. Read diode is not practically realizable diode, but Flat profile SDR diode and High-Low SDR diode can be experimentally fabricated. So, between the two practically realizable diodes, High-Low SDR IMPATT diode is better than the Flat profile SDR IMPATT diode as regards the DC to microwave conversion efficiency at millimeter wave frequencies.

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