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Design of High Breakdown Voltage and Power Dissipation of 6H-SIC DIMOSFET using Uniformly Doped Profile of Drift Region

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***Abstract*— In this paper a novel approach for designing of High Breakdown Voltage and Power Dissipation of 6H-SiC DIMOSFET Using Uniformly Doped Profile of Drift Region has been presented. All the calculations& graphs for Forward Voltage, Power Dissipation, On Resistance and Drain to Source Voltage at different levels of doping for different values of Current Density have been observed using MATLAB 7.0 .**

***Index Terms*—DIMOSFET, Forward Voltage, Power Dissipation, On Resistance, Drain to Source Voltage, Current Density, Doping, MATLAB**

I. INTRODUCTION

Silicon carbide is a WBG semiconductor that possesses extremely high thermal, chemical, and mechanical stability. It is so thermally stable that dopant impurities cannot be diffused at any reasonable temperature; so chemically stable that it is impervious to any known chemical etchant; and so mechanically stable that it is used as a coating for drill bits and saw blades.

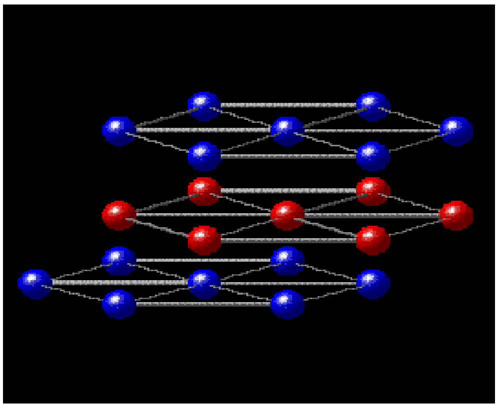

Figure 1: Primitive crystal structure of SiC

The silicon carbide (SiC) is replacing Si material very quickly in the semiconductor industry because of its superior intrinsic properties like lower intrinsic carrier concentration (10-35 order of magnitude), higher electric break down field (4-20 times) higher thermal conductivity (3-13 times), larger saturated electron drift velocity (2-2.5times); which is suitable for fast device operation with high voltage and high switching frequency.

DIMOS transistors are common in silicon power device technology where the p-base and n+ source regions are formed by diffusion of impurities through a common mask opening. However, impurity diffusion is impractical in SiC because of the very low diffusion coefficients at any temperature. The first DMOS transistors in SiC using ion implantation to introduce dopants for the p-base and the n+ source. The implanted DMOSFET requires that separate masks be used to define p-base and the n+ source. The construction is a vertical structure with a drift layer built on a highly conductive n+ layer. The n-drift region is designed to give the forward blocking capabilities. The forward blocking capability is achieved by the pn junction between p-base region and n-drift region[15]. During the device operation, a fixed potential to the p-base region is established by connecting it to the source metal by the break in the n+-source region. By short-circuiting the gate to the source and applying a positive bias to the drain, the p-base/n-drift region junction becomes reverse-biased and this junction supports the drain voltage by the extension of depletion layer on both sides. However due to the higher doping level of the p-base layer, the depletion layer extends primarily into the n-drift region. On applying the positive bias to the gate electrode, the conductive path between n+-source region and the n-drift region is formed.

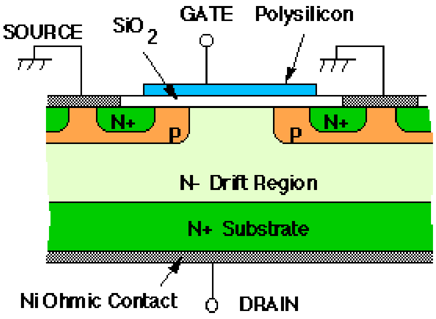

Figure 2: Cross section of a SiC ion-implanted "DIMOS".

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II. UNIFORM DOPING PROFILE IN DIMOSFET

Calculation for 8kV uniformly doped drift region DIMOSFET using the basic equations and its related graphs are discussed as under

A. BASIC EQUATIONS USED IN UNIFORMLY DOPED PROFILE

$$A = Z.W \qquad (1)$$

$$W_t = h + W_j \qquad (2)$$

$$\varepsilon_{ox} = 3.97 \times \varepsilon_o \qquad (3)$$

$$\varepsilon_{sic} = 9.70 \times \varepsilon_o \qquad (4)$$

$$C_{ox} = \varepsilon_{ox} / T_{ox} \qquad (5)$$

$$E_c = 1.95 \times 10^4 N_d^{0.131} \qquad (6)$$

Where, E_c critical electric field developed in the device (volt/cm),

N_d doping concentration in the drift region (/cc).

B. Theoretical Analysis:

The basic structure of the DIMOSFET as shown in Figure 3.

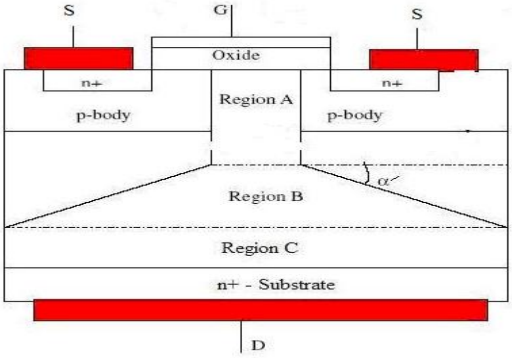

Figure 3. Basic structure of the DIMOSFET

It is redrawn labeled with the device dimensions using suitable symbols and is shown in Fig. 4.

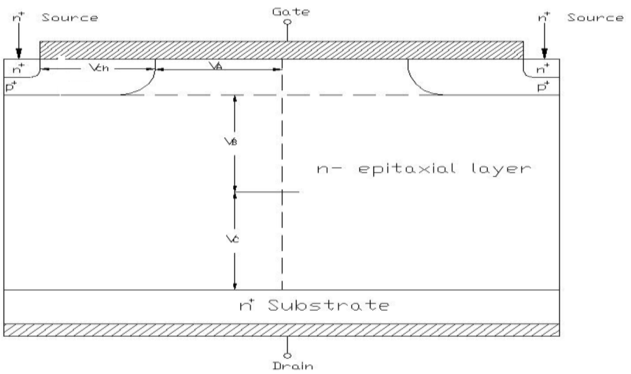

Figure 4 Redrawn labeled structure of DIMOSFET

The power dissipation, P_D for a 50% duty cycle of these two devices for various current levels can then be calculated using the basic equations:

$$P_D = \frac{1}{2}\left(J_{on}^2 A R_{on-sp} + V_B A\right), \qquad (7)$$

where, J_{on} is the on state current density, J_L is the reverse leakage current density of the p-body/n-drift region junction located in region B, V_B is the breakdown voltage of the DIMOSFET and A is the device area. Since J_L is negligible in SiC diode , eq(7) can be simplified

$$P_D = \frac{1}{2}\left(J_{on}^2 A R_{on-sp}\right). \qquad (8)$$

Writing J_f as the forward current density considered to be the same as J_{on}, eq (3.8) gives,

$$P_D = \frac{1}{2}\left(J_f^2 A R_{on-sp}\right) \quad \ldots\ldots(9)$$

The channel current I_{ch} which equals the drain current I_{DS} in on-state can be expressed by :

$$I_{DS} = \frac{W\mu_n}{2L[1+(\mu_n/2v_{sat}L)V_{ch}]} V_{ch}[2C_{ox}(V_{GS}-V_T)-(C_{ox}+C_{do})V_{ch}]$$

(10)

where W is the device width, L is the channel length, μ_n is the effective zero field doping dependent carrier mobility corresponding to doping level N_B of the drift region obtained from, V_{ch} is the voltage across the channel region, v_{sat} is the saturated drift velocity of the carrier taken to be 2×10^7 cm per sec, C_{ox} is the oxide capacitance per unit area, V_{GS} is the gate to source voltage, C_{do} is the body depletion capacitance considered to be much less than C_{ox} and can be neglected[1]. The values of V_{ch} can be evaluated by using equation (10). For this equation, the value of C_{do} is much less than C_{ox} and can be neglected and the value of V_{GS}=40V and V_T=1V, the equation (10) now becomes

$$(11) \qquad I_{DS} = \frac{W\mu_n C_{ox} V_{ch}[78 - V_{ch}]}{2L[1+(\mu_n/2v_{sat}L)V_{ch}]}$$

where μ_n is the mobility at the effective doping level, N_{eff}. After solving eq. (11), we get

$$I_{DS} = \frac{W\mu_n C_{ox} V_{ch}[78 - V_{ch}]}{2V_{sat}L + \mu_n V_{ch}} \qquad (12)$$

eq. (3.12) can be written as

$$W\mu_n V_{sat} C_{ox} V^2{}_{ch} + (\mu_n I_{DS} - 78W\mu_n V_{sat} C_{ox})V_{ch} + 2V_{sat} LI_{DS} = 0 \qquad (13)$$

eq.(3.13) is again a quadratic equation the value of V_{ch} could be evaluated as:

$$V_{ch} = \frac{-(\mu_n I_{DS} - 78W\mu_n V_{Sat} C_{ox}) \pm \sqrt{(\mu_n I_{DS} 78W\mu_n V_{Sat} C_{ox})^2 - 8LWI_{DS}\mu_n V_{sat}^2 C_{ox}}}{2W\mu_n V_{sat} C_{ox}} \qquad (14)$$

The voltage drops across regions A, B and C have derived and found to be of the form:

$$V_A = \frac{I_{DS}(W_j + W_d)}{W(L_{diff} eN_{eff})\mu_n - I_{DS}/E_c} \qquad (15)$$

$$V_B = \frac{I_{DS}}{WeN_{eff}\mu_n \cot\alpha} \log\left[\frac{WeN(x)\mu_n (L_{diff} + L_p) - I_{DS}/E_c}{WeN_{eff}\mu_n L_{diff} - I_{DS}/E_c}\right] \qquad (16)$$

$$V_C = \frac{I_{DS}\left(W_t - W_j - W_d - L_p \tan\alpha\right)}{WeN_{eff}\mu_n (L_s + 2L_p) - I_{DS}/E_c} \qquad (17)$$

where L_{diff} is the separation of p-bodies with N_{eff} being doping level of drift region. Here W_t=h, the device height which has been set by using the maximum depletion region width i.e the punch through width at a pre designed breakdown voltage of 10kV. W_j is the p-body thickness and W_d is the depletion region width under on-state condition, the drain to source voltage V_{DS} is obtained by adding V_{ch}, V_A, V_B and V_C. The drift region voltage drop $V_{drift}=V_A+V_B+V_C$ and $V_{DS}=V_{drift}+V_{ch}$. The device height, h has been set by setting the punch through depletion region width equal to that at the avalanche breakdown voltage. The quantity 'E_c' in equations (15) to (17) is the critical field for avalanche breakdown.

Lastly, the specific on-resistance of the DIMOSFET can be expressed as:

$$R_{on-sp} = RA = \rho l = \frac{\left(W_t - W_j - W_d - L_p \tan\alpha'\right)}{\mu_{neff} eN(x)} \qquad (18)$$

where $\alpha^{/}$ is the angler of the slope of the drift region narrowing and μ_{neff} has been obtained from corresponding to the effective concentration of N_{eff} of the linearly graded drift region. Thus N_{eff} and μ_{neff} give the overall average value of doping level and carrier mobility in the drift region respectively. A fixed value of device current $I_{DS}=I_{ch}$ was used and W_d was obtained by iteration from eq. (15). Finally R-on-sp was calculated using eq(18).

The magnitude of power dissipation P_D was calculated by knowing R_{on-sp}, J_{on} and the device cross sectional area A. Values of P_D for different doping levels for uniformly doped drift regions and concentration gradients for different graded profiles were calculated for different current levels. The value of V_B and V_C were then calculated using eqs.(16) and (17). The magnitude of V_{ch} was obtained knowing a preset value of I_{DS} from eq.(14). The drift region voltage drop

$$V_{drift}=V_A+V_B+V_C \qquad (19)$$

The drain to source voltage V_{DS} is given by:

$$V_{DS}= V_{drift}+V_{ch}= V_{ch} + (V_A+V_B+V_C) \qquad (20)$$

where V_{drift} is the voltage drop across the drift region. Finally, the forward voltage drop can be calculated using the equation

$$V_f=J_{on} \cdot R_{on-sp} \qquad (21)$$

Where, J_f is forward current density

$$V_f = J_f / A \qquad (22)$$

Where, V_f is forward voltage drop

$$\text{And} \quad W_d = \sqrt{\frac{2\varepsilon_{sic} V_{DS}}{eN_B}} \qquad (23)$$

C.The Critical Field, Ec and the Breakdown Voltage (VBPT and VBAV)

The critical field E_c for avalanche breakdown for uniformly doped drift region was calculated using eq(3.6). The depletion region width at breakdown was estimated by first estimating the depletion region width for punch through breakdown voltage, V_{BPT} and was obtained using the equation

$$W = \sqrt{\frac{2\varepsilon_s (V_{BPT} + V_{bi})}{eN_B}} \approx W = \sqrt{\frac{2\varepsilon_s V_{BPT}}{eN_B}}, \qquad (24)$$

where V_{bi} is the built in potential for uniformly doped case as $V_{bi} \ll V_{BPT}$.

For the case of a uniformly doped drift region, the breakdown voltage for avalanche breakdown V_{BAV} is obtained by knowing the depletion width W from eq. (3.24) and using the equation $V_{BAV} = \frac{1}{2} E_C W$.

(25)

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D.Calculations & Related Graphs:

The device dimensions of 6H DIMOSFET have been set so that the height h≈W_t equals the depletion region width, W_d under a reverse bias of 5kV applied on the p-body/n-epitaxial layer junction. In other words the DIMOSFET is designed for a maximum blocking voltage of 5kV. The dimensions of other variables as shown in Fig.2 have been taken to be:

W_j=1μm, L_p=25μm, $\alpha^{/}=64^0$,

where $\alpha^{/}$ is the angle of slope of drift region narrowing and a smaller value of $\alpha^{/}$ corresponds to be wider spread of the current from the accumulation region A has been used here. The quantity W_j has been taken to be 1μm as implant depth in 6H-SiC is of this order .

The device cross-sectional area is taken with width x length as 300x80μm^2 =24000x10^{-8} cm^2. The device have been split into two by a vertical line bisecting the device, giving a single unit of calculations with a cross sectional area A=12000x10^{-8} cm^2.

Table 1: Values of different parameters for N_B =10^{15} doping level

For N_B =10^{15}, μ_n=530cm^2/V-sec, A=12000x10^{-8} cm^2, h=.0073

J_F	I	V_{ch}	V_A	V_B	V_C	$V_{DS}=V_A+V_B+V_C+V_{ch}$	W_d	$R_{on\text{-}sp}$	V_f	P_D
1	12e-5	0.0028	0.0016	0.0586	0.0908	0.1538	4.0625e-5	0.1244	0.1244	7.4640e-6
10	12e-4	0.0275	0.0157	0.5862	0.9084	1.5378	1.2846e-4	0.1234	1.234	7.4040e-4
100	12e-3	0.2782	0.1574	5.8649	9.0883	15.3888	4.0636e-4	0.1201	12.01	0.0721
1000	12e-2	3.1012	1.5862	58.996	93.357	157.0408	0.0013	0.1096	109.6	6.5760

Table 2: Values of different parameters for N_B =10^{16} doping level

For N_B =10^{16}, μ_n =500cm^2/V-sec, A=12000x10^{-8} cm^2, h=.0073

J_F	I	V_{ch}	V_A	V_B	V_C	$V_{DS}=V_A+V_B+V_C+V_{ch}$	W_d	$R_{on\text{-}sp}$	V_f	P_D
1	12e-5	0.0029	0.0001	0.0062	0.0096	0.0188	4.4915e-6	0.0132	0.0132	7.9200e-7
10	12e-4	0.0292	0.0017	0.0621	0.0963	0.1893	1.4252e-5	0.0132	0.132	7.9200e-5
100	12e-3	0.2949	0.0167	0.6216	0.9629	1.8961	4.5107e-5	0.0132	1.32	0.0079
1000	12e-2	3.2966	0.1668	6.2157	9.8522	19.5313	1.4477e-4	0.0131	13.1	0.7860

Table 3 : Values of different parameters for N_B =10^{17} doping level

For N_B =10^{17}, μ_n =300cm^2/V-sec, A=12000x10^{-8} cm^2, h=.0073

J_F	I	V_{ch}	V_A	V_B	V_C	$V_{DS}=V_A+V_B+V_C+V_{ch}$	W_d	$R_{on\text{-}sp}$	V_f	P_D
1	12e-5	0.0049	2.778e-5	0.0010	0.0016	0.0075	8.9710e-7	0.0022	0.0022	1.320e-7
10	12e-4	0.0487	2.778e-4	0.0104	0.0160	0.0754	2.8444e-6	0.0022	0.022	1.320e-5
100	12e-3	0.4928	0.0028	0.1035	0.1605	0.7596	9.0283e-6	0.0022	0.22	0.0013
1000	12e-2	5.6920	0.0278	1.0356	1.6414	8.3968	3.0017e-5	0.0022	2.2	0.1320

Table 4: Values of different parameters for $N_B = 10^{18}$ doping level

For $N_B = 10^{18}$, $\mu_n = 140 cm^2/V\text{-}sec$, $A = 12000 \times 10^{-8} cm^2$, h=.0073

J_F	I	V_{ch}	V_A	V_B	V_C	$V_{DS}=V_A+V_B+V_C+V_{ch}$	W_d	$R_{on\text{-}sp}$	V_f	P_D
1	12e-5	0.0104	5.95e-6	2.25e-4	4.70e-9	0.0106	3.37e-7	4.72e-4	4.72e-4	2.83e-8
10	12e-4	0.1044	5.95e-5	0.2251	4.70e-8	0.3296	1.88e-6	4.72e-4	4.72e-3	2.83e-6
100	12e-3	1.0639	5.95e-4	0.0225	4.70e-7	1.087	3.41e-6	4.72e-4	4.72e-2	2.83e-4
1000	12e-2	13.917	0.0060	0.2252	4.81e-6	14.149	1.23e-5	4.72e-4	4.72e-1	0.0283

Table 5: Values of critical field, E_c and the breakdown voltage for different values of doping.

N_B /cc	W(µm)	E_c(V/cm)	V_{BAV}=(.5)(E_cW)	V_{BPT}
10^{15}	73	6.9760e-009	2.5462e-011	5kV
10^{16}	10	4.9390e-010	2.4695e-013	1kV
10^{17}	1.8	5.0159e-011	4.5143e-015	300V
10^{18}	.243	3.3549e-012	4.0762e-017	54.3V

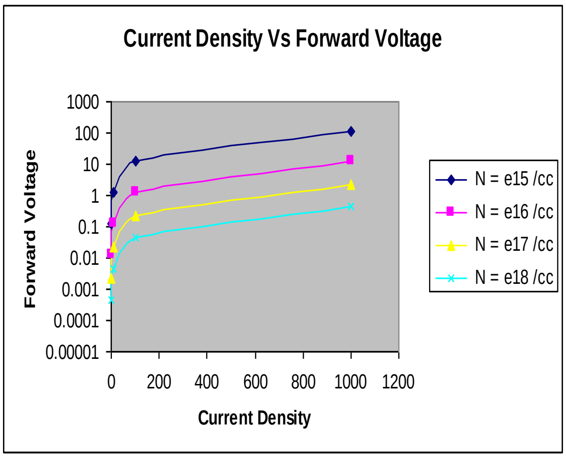

Figure 6 : Plot of Forward Voltage at different levels of doping for different values of Current Density

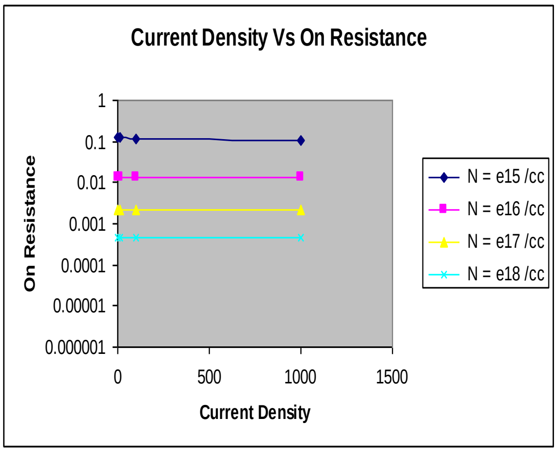

Figure 8 : Plot of On Resistance at different levels of doping for different values of Current Density

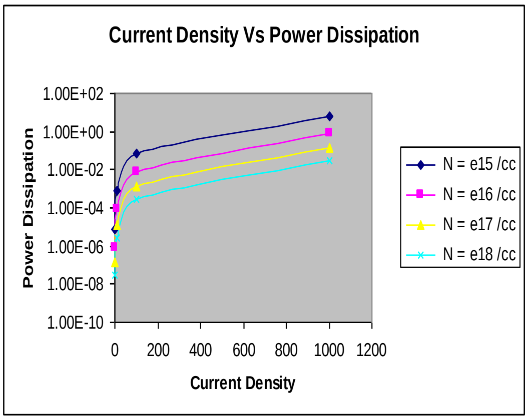

Figure 7 : Plot of power Dissipation at different levels of doping for different values of Current Density

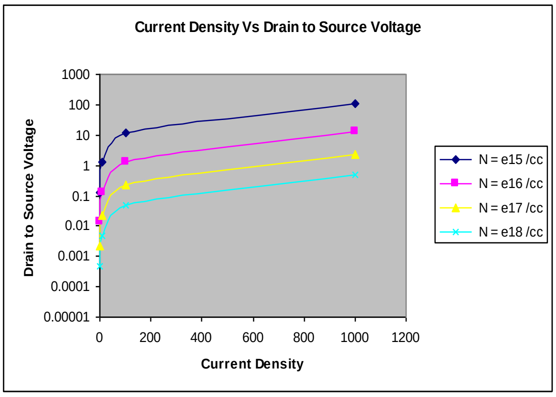

Figure 9: Plot of Drain to Source Voltage at different levels of doping for different values of Current Density

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