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

1. 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”.
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

\[ A = ZW \]  
\[ W_t = h + W_j \]  
\[ \varepsilon_{ox} = 3.97 \times \varepsilon_o \]  
\[ \varepsilon_{sic} = 9.70 \times \varepsilon_o \]  
\[ C_{ox} = \frac{\varepsilon_{ox}}{T_{ox}} \]  
\[ E_c = 1.95 \times 10^4 N_d^{0.131} \]  

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](Image)

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

![Figure 4. Redrawn labeled structure of DIMOSFET](Image)

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:

\[ P_D = \frac{1}{2} \left( J_{on}^2 A R_{on-sp} + V_B A \right) \]  

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

\[ P_D = \frac{1}{2} \left( J_{on}^2 A R_{on-sp} \right) \]  

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

\[ P_D = \frac{1}{2} \left( J_f^2 A R_{on-sp} \right) \]  

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

\[ I_{DS} = \frac{W \mu_s}{2L[1+(\mu_s/2v_{sat}L)V_{ds}]} \left[ V_{ds}[2C_{ox}(V_{gs}-V_T)-(C_{ox}+C_{do})V_{ds}] \right] \]  

where \( W \) is the device width, \( L \) is the channel length, \( \mu_s \) 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 \( 2 \times 10^7 \) 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

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

where \( \mu_n \) is the mobility at the effective doping level, \( N_{eff} \).
After solving eq. (11), we get
\[ I_{DS} = \frac{W[I_{n}\cos(V_{ch}) + 78 - V_{ch}]}{2V_{sat}L + \mu_{n}V_{ch}} \]  
(12)

eq (3.12) can be written as
\[ W[I_{n}\cos(V_{ch}) + (\mu_{n}I_{DS} - 78W[I_{n}\cos(V_{ch})])V_{ch} + 2V_{sat}L_{DS} \]
(13)
eq (3.13) is again a quadratic equation the value of \( V_{ch} \)
could be evaluated as:
\[ V_{ch} = \frac{-(\mu_{n}I_{DS} - 78W[I_{n}\cos(C_{ox})] + \sqrt{(\mu_{n}I_{DS}78W[I_{n}\cos(C_{ox})])^2 - 8WI_{DS}\mu_{n}C_{ox}C_{ch}}}}{2\mu_{n}V_{sat}C_{ox}} \]
(14)
The voltage drops across regions A, B and C have derived
and found to be of the form:
\[ V_{A} = \frac{I_{DS}(W_{j} + W_{d})}{W(L_{diff} + W_{n})\mu_{n} - I_{DS} / E_{c}} \]
(15)
\[ V_{B} = \frac{I_{DS}}{WeN_{eff}L_{n}} \log \left[ \frac{WeN(x)\mu_{n}(L_{diff} + L_{p}) - I_{DS} / E_{c}}{WeN_{eff}\mu_{n}L_{diff} - I_{DS} / E_{c}} \right] \]
(16)
\[ V_{C} = \frac{I_{DS}(W_{f} - W_{j} - W_{d} - L_{p} \tan \alpha)}{WeN_{eff}\mu_{n}(L_{n} + 2L_{p}) - I_{DS} / E_{c}} \]
(17)
where \( L_{diff} \) is the separation of p-bodies with \( N_{eff} \) being doping level of drift region. Here \( W_{i} = h \), 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 \( V_{diff} = V_{A} + V_{B} + V_{C} \) and \( V_{DS} = V_{diff} + V_{ch} \). The device height, \( h \) has been set by setting the punch through depletion region width equal to that at the avalanche breakdown voltage.

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

\[ R_{on-sp} = RA = \rho l = \left( \frac{W_{i} - W_{j} - W_{d} - L_{p} \tan \alpha'}{\mu_{eff}eN(x)} \right) \]
(18)
where \( \alpha' \) is the angler of the slope of the drift region narrowing and \( \mu_{eff} \) has been obtained from corresponding effective concentration of \( N_{eff} \) of the linearly graded drift region. Thus \( N_{eff} \) and \( \mu_{eff} \) give the overall average value of doping level and carrier mobility in the drift region respectively. A fixed value of device current \( I_{on} = I_{ch} \) 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 \( P_{b} \) was calculated by knowing \( R_{on-sp} \), \( I_{ch} \) and the device cross sectional area \( A \). Values of \( P_{b} \) 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
\[ V_{diff} = V_{A} + V_{B} + V_{C} \]
(19)
The drain to source voltage \( V_{DS} \) is given by:
\[ V_{DS} = V_{diff} + V_{ch} = V_{ch} + (V_{A} + V_{B} + V_{C}) \]
(20)
where \( V_{diff} \) is the voltage drop across the drift region. Finally, the forward voltage drop can be calculated using the equation
\[ V_{f} = V_{on} R_{on-sp} \]
(21)
Where, \( J_{f} \) is forward current density
\[ V_{f} = J_{f} / A \]
(22)
Where, \( V_{f} \) is forward voltage drop

And
\[ W_{d} = \sqrt{\frac{2eN_{b}V_{DS}}{\epsilon}} \]
(23)

C. The Critical Field, \( E_{c} \) 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
Design of High Breakdown Voltage and Power Dissipation of 6H-SiC DIMOSFET Using Uniformly Doped Profile of Drift Region

\[ W = \sqrt{\frac{2e_s (V_{BPT} + V_{bi})}{eN_B}} \approx \sqrt{\frac{2e_s V_{BPT}}{eN_B}}, \]

where \( V_{bi} \) is the built-in potential for uniformly doped case as \( V_{bi} = V_{BPT} \).

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

\[ V_{BAV} = \frac{1}{2} E_C W. \]  

\[(25)\]

D. Calculations & Related Graphs:
The device dimensions of 6H DIMOSFET have been set so that the height \( h \approx W \) 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:

\[ W_j = 1\mu m, L_p = 25\mu m, \alpha/A = 64\mu \text{m}, \]

where \( \alpha/A \) is the angle of slope of drift region narrowing and a smaller value of \( \alpha/A \) 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 1\mu m as implant depth in 6H-SiC is of this order.

The device cross-sectional area is taken with width \( x \) length as 300x80\mu m\(^2\) = 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

<table>
<thead>
<tr>
<th>( J_F )</th>
<th>( I )</th>
<th>( V_{ch} )</th>
<th>( V_A )</th>
<th>( V_B )</th>
<th>( V_C )</th>
<th>( V_{DS} = V_A + V_B + V_C + V_{ch} )</th>
<th>( W_d )</th>
<th>( R_{on-sp} )</th>
<th>( V_f )</th>
<th>( P_D )</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>12e-5</td>
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<td>0.0016</td>
<td>0.0586</td>
<td>0.0908</td>
<td>0.1538</td>
<td>4.0625e-5</td>
<td>0.1244</td>
<td>0.1244</td>
<td>7.4640e-6</td>
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<td>0.0157</td>
<td>0.5862</td>
<td>0.9084</td>
<td>1.5378</td>
<td>1.2846e-4</td>
<td>0.1234</td>
<td>1.234</td>
<td>7.4040e-4</td>
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<tr>
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<td>9.0883</td>
<td>15.3888</td>
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<td>58.996</td>
<td>93.357</td>
<td>157.0408</td>
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<td>0.1096</td>
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Table 2: Values of different parameters for \( N_B = 10^{16} \) doping level

<table>
<thead>
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<th>( J_F )</th>
<th>( I )</th>
<th>( V_{ch} )</th>
<th>( V_A )</th>
<th>( V_B )</th>
<th>( V_C )</th>
<th>( V_{DS} = V_A + V_B + V_C + V_{ch} )</th>
<th>( W_d )</th>
<th>( R_{on-sp} )</th>
<th>( V_f )</th>
<th>( P_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12e-5</td>
<td>0.0029</td>
<td>0.0001</td>
<td>0.0062</td>
<td>0.0096</td>
<td>0.0188</td>
<td>4.4915e-6</td>
<td>0.0132</td>
<td>0.0132</td>
<td>7.9200e-7</td>
</tr>
<tr>
<td>10</td>
<td>12e-4</td>
<td>0.0292</td>
<td>0.0017</td>
<td>0.0621</td>
<td>0.0963</td>
<td>0.1893</td>
<td>1.4252e-5</td>
<td>0.0132</td>
<td>0.132</td>
<td>7.9200e-5</td>
</tr>
<tr>
<td>100</td>
<td>12e-3</td>
<td>0.2949</td>
<td>0.0167</td>
<td>0.6216</td>
<td>0.9629</td>
<td>1.8961</td>
<td>4.5107e-5</td>
<td>0.0132</td>
<td>1.32</td>
<td>0.0079</td>
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<tr>
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<td>3.2966</td>
<td>0.1668</td>
<td>6.2157</td>
<td>9.8522</td>
<td>19.5313</td>
<td>1.4477e-4</td>
<td>0.0131</td>
<td>13.1</td>
<td>0.7860</td>
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Table 3: Values of different parameters for \( N_B = 10^{17} \) doping level

<table>
<thead>
<tr>
<th>( J_F )</th>
<th>( I )</th>
<th>( V_{ch} )</th>
<th>( V_A )</th>
<th>( V_B )</th>
<th>( V_C )</th>
<th>( V_{DS} = V_A + V_B + V_C + V_{ch} )</th>
<th>( W_d )</th>
<th>( R_{on-sp} )</th>
<th>( V_f )</th>
<th>( P_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12e-5</td>
<td>0.0029</td>
<td>0.0001</td>
<td>0.0062</td>
<td>0.0096</td>
<td>0.0188</td>
<td>4.4915e-6</td>
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<td>7.9200e-7</td>
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<td>10</td>
<td>12e-4</td>
<td>0.0292</td>
<td>0.0017</td>
<td>0.0621</td>
<td>0.0963</td>
<td>0.1893</td>
<td>1.4252e-5</td>
<td>0.0132</td>
<td>0.132</td>
<td>7.9200e-5</td>
</tr>
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<td>100</td>
<td>12e-3</td>
<td>0.2949</td>
<td>0.0167</td>
<td>0.6216</td>
<td>0.9629</td>
<td>1.8961</td>
<td>4.5107e-5</td>
<td>0.0132</td>
<td>1.32</td>
<td>0.0079</td>
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<td>12e-2</td>
<td>3.2966</td>
<td>0.1668</td>
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<td>9.8522</td>
<td>19.5313</td>
<td>1.4477e-4</td>
<td>0.0131</td>
<td>13.1</td>
<td>0.7860</td>
</tr>
</tbody>
</table>
Table 4: Values of different parameters for $N_B=10^{18}$ doping level

For $N_B=10^{18}$, $\mu_n=140 \text{cm}^2/\text{V}\cdot\text{sec}$, $A=12000 \times 10^{-8} \text{cm}^2$, $h=0.0073$

<table>
<thead>
<tr>
<th>$J_F$</th>
<th>$I$</th>
<th>$V_{ch}$</th>
<th>$V_A$</th>
<th>$V_B$</th>
<th>$V_C$</th>
<th>$V_{DS}=V_A+V_B+V_C+V_{ch}$</th>
<th>$W_d$</th>
<th>$R_{on-sp}$</th>
<th>$V_f$</th>
<th>$P_D$</th>
</tr>
</thead>
<tbody>
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<td>2.778e-5</td>
<td>0.0010</td>
<td>0.0016</td>
<td>0.0075</td>
<td>8.9710e-7</td>
<td>0.0022</td>
<td>0.0022</td>
<td>1.320e-7</td>
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<td>0.0160</td>
<td>0.0754</td>
<td>2.844e-6</td>
<td>0.0022</td>
<td>0.022</td>
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<td>2.2</td>
<td>0.1320</td>
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Table 5: Values of critical field, $E_c$ and the breakdown voltage for different values of doping.

<table>
<thead>
<tr>
<th>$N_B$/cc</th>
<th>$W$(μm)</th>
<th>$E_c$(V/cm)</th>
<th>$V_{BAV}=0.5(E_cW)$</th>
<th>$V_{BPT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{13}$</td>
<td>73</td>
<td>6.9760e-009</td>
<td>2.5462e-011</td>
<td>5kV</td>
</tr>
<tr>
<td>$10^{16}$</td>
<td>10</td>
<td>4.9390e-010</td>
<td>2.4695e-013</td>
<td>1kV</td>
</tr>
<tr>
<td>$10^{17}$</td>
<td>1.8</td>
<td>5.0159e-011</td>
<td>4.5143e-015</td>
<td>300V</td>
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<tr>
<td>$10^{18}$</td>
<td>.243</td>
<td>3.3549e-012</td>
<td>4.0762e-017</td>
<td>54.3V</td>
</tr>
</tbody>
</table>

Figure 6: Plot of Forward Voltage 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 8**: Plot of On Resistance 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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**REFERENCES**


