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Analysis of Power Dissipation of 6H Silicon Carbide Double Implanted MOSFET with Linearly Graded and Uniformly Doped Profile at Breakdown Voltage of 10kV

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Abstract: *This paper describes analysis of power dissipation of vertical 6H-DIMOSFET with Uniformly doped profile and linearly graded profile at a breakdown voltage of 10kV. The effect of a uniformly doped and linearly graded drift region in a 6H SiC vertical DIMOSFET on the power dissipation of the device has been discussed. The mathematical calculations of power dissipation and percentage saved for both the profile has been done separately at a doping concentration of* $3.91x10^{14}$ *and* $2.15x10^{15}$*. In this paper, calculations for both the profile are made at breakdown voltage of 10 kV.*

Keywords: *Silicon Carbide, Power Dissipation, DIMOSFET*

1. INTRODUCTION

Silicon-based devices are so mature and inexpensive to manufacture, it might be hard to believe that any material could shake silicon from its perch. But silicon carbide is quite special. Many of the material's most attractive properties stem from a single physical feature: SiC's bandgap, the energy needed to excite electrons from the material's valence band into the conduction band. Silicon carbide electrons need about three times as much energy to reach the conduction band, a property that lets SiC-based devices withstand far higher voltages and temperatures than their silicon counterparts.

One of the biggest advantages this wide bandgap confers is in averting electrical breakdown .Because electrons in SiC require more energy to be pushed into the conduction band; the material can withstand much stronger electric fields, up to about 10 times the maximum for silicon. As a result, a SiC-based device can have the same dimensions as a silicon device but withstand 10 times the voltage [1]. Also, a SiC device can be less than a tenth the thickness of a silicon device but carry the same voltage rating, because the voltage difference does not have to be spread across as much material [11-13]. These thinner devices are faster and boast less resistance, which means less energy is lost to heat when a silicon carbide diode or transistor is conducting electricity [15].

Thus, SiC a promising material for high power devices, such as wide bandgap (~ 3eV), high breakdown field of 3MV/cm and good thermal conductivity (3W per cm K) [2]. Some of the prominent devices are the inversion [5-6] and accumulation mode DIMOSFET's and accumulation mode UMOS [3-4] have already being successfully developed and tested.

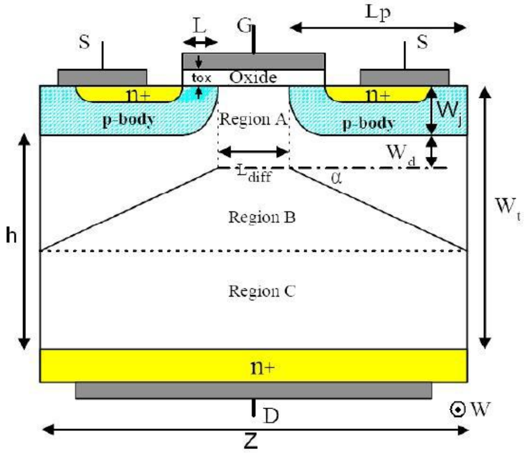


Figure 1: The power dissipation, P_D for a 50% duty cycle of these two devices for various current densities can then be calculated using the basic equations

2. UNIFORM DOPING AND LINEARLY GRADED PROFILE IN DIMOSFET

The structure of Double Implanted Metal-Oxide Semiconductor (DIMOS) [9] labeled with the device dimensions using suitable symbols as shown in Fig.1.

$$P_D = \left(J^2_{on}.A.R_{on,sp} + J_L.A.V_B \right) \qquad (1)$$

where, J_{on} is the on state current density, JL is the reverse leakage current density of the p-body/n-drift region junction located in region B (Fig.1), V_B is the breakdown voltage of the DIMOSFET and A is the device area. Since J_L is negligible in SiC diode [8], eq(1) can be simplified

$$P_D = (J^2_{on}.R_{on,sp}.A) \qquad (2)$$

Writing J_f as the forward current density considered to be the same as J_{on}, eq (2) gives,

$$P_D = (J_f^2.R_{on,sp}.A) \qquad (3)$$

The channel current I_{ch} which equals the drain current I_{DS} in on-state can be expressed by [9]:

$$I_{ch} = I_{DS} = \frac{W\mu_{neff}}{2L\left[1 + (\mu_{neff} /2V_{sat} L\right]} V_{ch}\left[2C_{ox}(V_{GS} - \quad {}_{T}) \quad (C_{ox} - \quad {}_{do})V_{ch}\right] \qquad (4)$$

where W is the device width, L is the channel length, μ_{neff} is the effective zero field doping dependent carrier mobility corresponding to doping level N_B of the drift region obtained from[8], V_{ch} is the voltage across the channel region, v_{sat} is the saturated drift velocity of the carrier taken to be $2x10^7$ 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.

The values of V_{ch} can be evaluated by using equation (4). For this equation, the value of C_{do} is much less than C_{ox} and can be neglected.

The voltage drops across regions A, B and C have derived [9] and found to be of the form:

$$V_A = \frac{J_d\,(W_j+W_d)}{W(L_{diff}\ qN_d)\mu_{neff}-J_d/E_c} \qquad (5)$$

$$V_B = \frac{J_d}{WqN_d\ \mu_{neff}\cot\alpha}\log\left[\frac{WqN_d\,\mu_{neff}(L_{diff}+L_p)-J_d/E_c}{WqN_d\,L_{diff}\ \mu_{neff}-J_d/E_c}\right] \qquad (6)$$

$$V_C = \frac{J_d(W_t - W_j - W_d - L_p\tan\alpha)}{W(L_{diff}-L_p)qN_d\mu_{neff}-J_d/E_c} \qquad (7)$$

where the symbols are the same as those shown in Fig. 1 and L_{diff} is the separation of p-bodies with Neff 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 predesigned breakdown voltage of 10kV. Wj 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 the addition of the following: 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 break down voltage. The quantity 'Ec' in equations (6) and (7) is the critical field for avalanche breakdown [16].

For the case of DIMOSFET with a linearly graded drift region with a gradient, N_{eff} had been derived [14] and found to be expressed as

$$N_{eff} = \frac{h\alpha}{\ln(1+\dfrac{\alpha h}{No})} \qquad (8)$$

where No is the value of the n-drift region doping level at the p-base /n-drift region junction assumed to be 10^{14} or 10^{15} per cc[14]

Lastly, the specific on-resistance of the DIMOSFET can be expressed using Fig.1 as [9]:

$$R_{on,sp} = \frac{W_t - W_j - W_d - L_p\tan\alpha}{qN_d} \qquad (9)$$

where α is the angler of the slope of the drift region narrowing and μ_{neff} has been obtained from [7,8] corresponding to the effective concentration of Neff of the linearly graded drift region. Thus N_{eff}[10] 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. Finally R_{on-sp} was calculated using eq. (9).

The magnitude of power dissipation P_D was calculated by knowing R_{on-sp}, Jon and the device cross sectional area A. Values of P_D for different doping levels for uniformly doped drift regions and concentration gradients for linearly graded profiles were calculated for different current levels. The value of V_B and V_C were then calculated using eqs. (6) and (7). The magnitude of V_{ch} was obtained knowing a preset value of I_{DS} from eq.(4). The drain to source voltage V_{DS} is given by: $V_{DS}= V_{drift}+V_{ch}= V_{ch} + (V_A+V_B+V_C)$, where V_{drift} is the voltage drop across the drift region. Finally, the forward voltage drop

$V_f=J_{on}.R_{on-sp}$

3. CALCULATIONS AND RELATED GRAPH

The device dimensions of 6H DIMOSFET have been set so that the height h ~ Wt equals the depletion region width, W_d under a reverse bias. The dimensions of other variables as shown in Fig.1 have been taken to be: Wj=1µm, Lp=25µm, =25°, where is the angle of slope of drift region narrowing and a smaller value of corresponds to be wider spread of the current from the accumulation region A has been used here. The quantity Wj has been taken to be 10 x 10^{-4} cm 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.

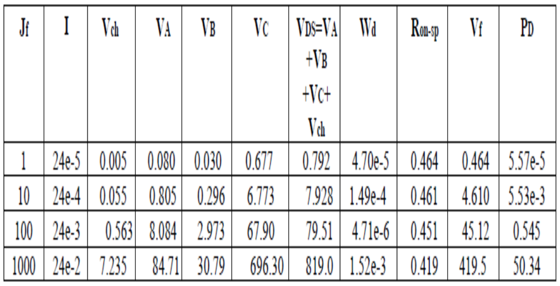
Calculations of the 6H-SiC DIMOSFET with a uniform doping and linearly graded drift region has been made by using a doping profile with a doping level of 10^{14} per cc near the source to 10^{18} per cc near the drain of the device height W_t=h. The device height 'h' had been set at 166µm for the uniformly doped profiles as graded profiles yield smaller depletion region width at a given voltage than uniformly doped profiles as graded profiles yield smaller depletion width at a given voltage than uniformly doped regions. The specific R_{on-sp} is obtained by calculating N_{eff} from eq.(8), finding the effective value of mobility [6], μ_{neff} from the µ versus field plot [8] and using eq.(9) with =25°.

The values of power dissipation, P_D was then calculated at current densities, J_F =1, 10, 100, 1000 amperes per cm^2. The results for uniform doping profile are shown in Table 1, 2 and for linear graded profile are shown in Tables 3 to 4 for doping level 3.91e14 and 2.15e15.

Values for Uniform Doping Profile

Table I

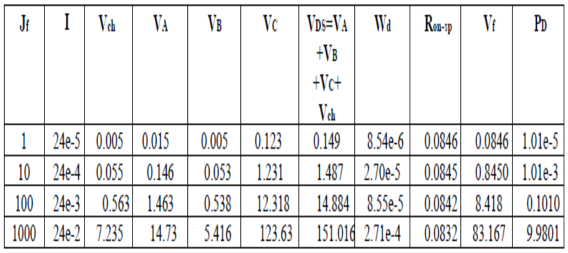
For 10^{15}-10^{14}, h=0.0166, N_{eff}=3.91x10^{14}/cc, μ_{neff}=530cm^2/V-sec, **α** =25°, A=24000x10^{-8} cm^2



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-sp}	V_f	P_D
1	24e-5	0.005	0.080	0.030	0.677	0.792	4.70e-5	0.464	0.464	5.57e-5
10	24e-4	0.055	0.805	0.296	6.773	7.928	1.49e-4	0.461	4.610	5.53e-3
100	24e-3	0.563	8.084	2.973	67.90	79.51	4.71e-6	0.451	45.12	0.545
1000	24e-2	7.235	84.71	30.79	696.30	819.0	1.52e-3	0.419	419.5	50.34

Table II

For 10^{16}-10^{14}, h=0.0166, N_{eff}=2.15x10^{15}/cc, μ_{neff}=530cm^2/V-sec, **α**=25°, A=24000x10^{-8} cm^2

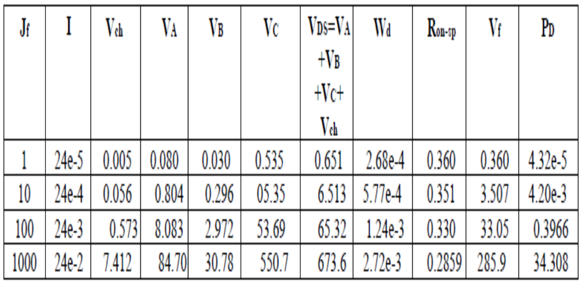


J_f	I	V_{ch}	V_A	V_B	V_C	$V_{DS}=V_A+V_B+V_C+V_{ch}$	W_d	R_{on-sp}	V_f	P_D
1	24e-5	0.005	0.015	0.005	0.123	0.149	8.54e-6	0.0846	0.0846	1.01e-5
10	24e-4	0.055	0.146	0.053	1.231	1.487	2.70e-5	0.0845	0.8450	1.01e-3
100	24e-3	0.563	1.463	0.538	12.318	14.884	8.55e-5	0.0842	8.418	0.1010
1000	24e-2	7.235	14.73	5.416	123.63	151.016	2.71e-4	0.0832	83.167	9.9801

Values for Linear Graded Profile

Table III

For 10^{15}-10^{14}, h=.01337, N_{eff}=3.91x10^{14}/cc, μ_{neff}=530cm^2/V-sec, **α**=25°, A=24000x10^{-8} cm^2, G=6.72 x10^{16} cm^{-4}



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-sp}	V_f	P_D
1	24e-5	0.005	0.080	0.030	0.535	0.651	2.68e-4	0.360	0.360	4.32e-5
10	24e-4	0.056	0.804	0.296	05.35	6.513	5.77e-4	0.351	3.507	4.20e-3
100	24e-3	0.573	8.083	2.972	53.69	65.32	1.24e-3	0.330	33.05	0.3966
1000	24e-2	7.412	84.70	30.78	550.7	673.6	2.72e-3	0.2859	285.9	34.308

Table IV

For 10^{16}-10^{14}, h=.01337, $N_{eff}=2.15\times10^{15}$/cc,$\mu_{neff}$ =530cm^2/V-sec, α=25°, A=24000x10^{-8} cm^2, G= 2.45 x10^{18}cm^{-4}

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-sp}	V_f	P_D
1	24e-5	0.005	0.080	0.030	0.535	0.651	2.68e-4	0.360	0.360	4.32e-5
10	24e-4	0.056	0.804	0.296	05.35	6.513	5.77e-4	0.351	3.507	4.20e-3
100	24e-3	0.573	8.083	2.972	53.69	65.32	1.24e-3	0.330	33.05	0.3966
1000	24e-2	7.412	84.70	30.78	550.7	673.6	2.72e-3	0.2859	285.9	34.308

4. POWER SAVED

The power dissipation calculated in tables (I) to (IV) for uniformly doped and linearly graded profile is for a given voltage ,i.e., 10 KV.

Equation used for the calculation of percentage power saved is given by:

Percentage Power Saved =

$$\left[\frac{\text{Power in Uniform} - \text{Power in Graded}}{\text{Power in Uniform}}\right]_{\text{at fix } J_f} \times 100 \qquad (10)$$

Comparison between Uniform and Graded Profiles

Table V shows the comparison between Power Dissipation for Uniformly doped and linearly graded profile. Also, Result is shown via Plot of power dissipation against Current Density for different values of gradient (in linearly graded profile) and Plot of Power Dissipation against Current Density for different values of doping (in uniform doping profile).

Table V

Jf	**P (Watt)**		
	Unifomly Doped	**Linearly Graded**	**Percentage Save**
	Nd = 3.91e1/cm^3	**G = 7.52e16 cm-4** **Neff =**	
1	5.57e-05	4.32e-05	22.2332
10	5.53e-03	4.20e-03	20.9849
100	0.5415	0.3967	20.7786
1000	50.3409	34.3089	20.7417

Table V shows the comparison between Power Dissipation for Uniformly doped and linearly graded profile. Also, Result is shown via Plot of power dissipation against Current Density for different values of gradient (in linearly graded profile) and Plot of Power Dissipation against Current Density for different values of doping (in uniform doping profile).

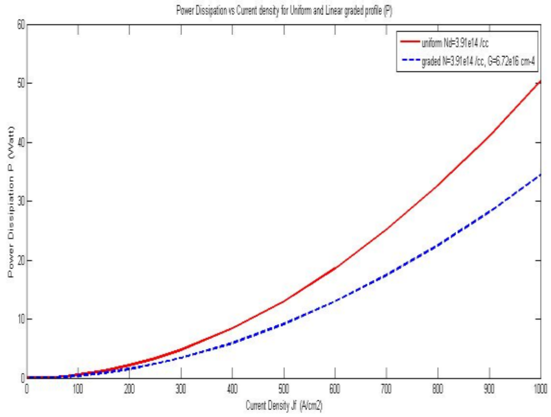


Figure 2: Plots of Power Dissipation against Current Density for (3.91e14 /cm^3) values of doping in uniform and graded profile both.

5. CONCLUSION & DISCUSSION

The analysis of power dissipation values, P_D of uniformly doped and linearly graded drift regions of the 6H-DIMOSFET presented in Tables I to IV .Table I and IV shows that increasing current levels for a given drift region doping level cause an increase in the magnitudes of Vch, V_A, V_B, V_C and consequently V_{DS}. An increase in VDS causes an increase in magnitude of the depletion region width, Wd, the forward drop, Vf and the power dissipation, P_D. However, the magnitude of R_{on-sp} decreases with an increase in the value of Wd and can be verified from eq. (9).

For, the devices with a linearly graded doping profile in the drift region, the power dissipation, P_D is significantly low corresponding to those obtained with uniformly doped profiles, being as low as 50 to 34 W at a value of Jf of 1000 amperes per cm^2.

Comparison of plots of power dissipation with current density shown in Figure 2. We can also conclude that linearly graded drift region devices exhibit higher breakdown voltages.

Table V gives the comparison of calculated values of power dissipation and percentage saved for uniform and linearly graded profile at a different current densities 1, 10, 100 and 1000 A/cm^2. In conclusion, it may be stated that 6H-SiC DIMOSFET's having linearly graded drift regions have significantly low values of power dissipation, P_D at any current level than uniformly doped drift region devices.

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