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*Full Paper*

# Estimation of power dissipation of a 4H-SiC Schottky barrier diode with a linearly graded doping profile in the drift region

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**Abstract :** The aim of this paper is to establish the importance of a linearly graded profile in the drift region of a 4H-SiC Schottky barrier diode (SBD). The power dissipation of the device is found to be considerably lower at any given current density as compared to its value obtained for a uniformly doped drift region. The corresponding values of breakdown voltages obtained are similar to those obtained with uniformly doped wafers of 4H-SiC.

**Keywords :** Schottky barrier diode, 4H-SiC, power dissipation, breakdown voltage

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## Introduction

Compared to silicon, silicon carbide (SiC) has certain physical properties that put it on a higher platform for use in solid-state power devices. A low intrinsic carrier concentration of the order of $10^{-7}$ per cc, a 10x higher breakdown electrical field, typically about 3 MV/cm, and a 3-fold higher thermal conductivity coupled with a large saturated drift velocity of $2*10^{7}$ cm/s [1] are some of the salient features of SiC. These devices are extremely attractive in applications requiring blocking voltages ranging from 300 V to 3 kV [2]. High-voltage SiC devices are thinner and can be heavily doped if needed. At equivalent breakdown voltages, they offer specific on-resistance ($R_{on\text{-}sp}$) which may be up to two orders of magnitude lower compared to silicon devices [3].

The forward voltage drop of SiC devices is well below 2.5 V for a 600V Schottky barrier diode (SBD) even at a current density of 4000 A/cm$^2$ and $R_{on\text{-}sp}$ of these devices, due to the thinner drift region, is 200 times less than that of the silicon counterparts [4].

The comparison of 6H-SiC with 4H-SiC would reflect a major advantage which the latter offers with respect to the electron mobility, which is twice or 10 times that of the former in the direction perpendicular to or along the 6H-SiC c-axis respectively [5]. Obviously 4H-SiC SBD's have lower $R_{on\text{-}sp}$ at high voltages (greater than 200 V) compared to SBD's made from other semiconductors such as Si, GaAs and even 6H-SiC [4-5].

Experimentally obtained $R_{on\text{-}sp}$ for 4H-SiC diodes is as low as 1.5 mΩ-cm$^2$ at forward current density of 732 A/cm$^2$ at 2 V, with a breakdown voltage of 1400 V , a 10-μm-thick epitaxial drift layer doped with 7.5x10$^{15}$ atoms/cc and argon-edge termination [6]. More recent achievements of $R_{on\text{-}sp}$ for 4H-SiC SBD's are 2 mΩ-cm$^2$ and 1.4 mΩ-cm$^2$ at breakdown voltages of 1000 V and 800 V respectively [7-8].

$R_{on\text{-}sp}$ of a SBD is the sum of the n-type epitaxial drift layer and the n+ substrate resistance given by [9] :

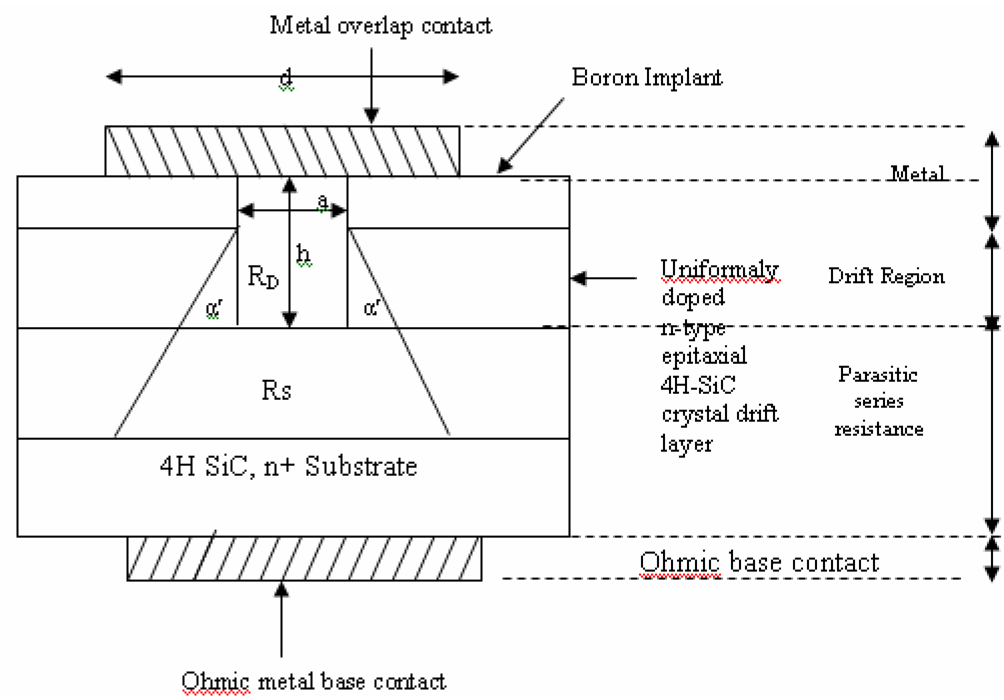
$$R_{on-sp} = \frac{W}{eN_D\mu_n} \qquad (1)$$

where W is the thickness of the drift region , $N_D$ is the epitaxial layer doping density and $\mu_n$ is the electron mobility. The magnitude of $N_D$ is set so that the drift layer punch-through occurs at the same voltage at which avalanche breakdown takes place. For a constant drift layer thickness W, it is possible to reduce $R_{on\text{-}sp}$ of the SBD by either increasing the value of $\mu_n$ in equation (1) using models similar to the ones prepared for 4H- and 6H-SiC [10] or by changing the doping profile in the drift region of the device. Doping-dependent mobility as well as high- and low-field mobility models well suited for simulation and device design have been proposed by Roschke and Schwierz [11]. However, high-field mobility values in 4H-SiC are generally low and somewhat difficult to increase. To date the most reliable experimental data for velocity-field profile of 4H-SiC have been reported by Khan and Cooper [12]. Accordingly, the reduction of $R_{on\text{-}sp}$ may be done by increasing the magnitude of the drift layer doping, i.e. $N_D$ or $N_A$.

A novel way for reduction of $R_{on\text{-}sp}$ is suggested in this paper which uses a linearly graded profile in the drift region with a low doping level near the metal–semiconductor contact at the top of a 4H-SiC SBD and a higher doping level near the substrate. Such a drift layer would give a moderately high mobility as estimated from the effective doping level of the drift region obtained by integrating the linear function within its limits. The high doping level near the substrate would provide a low-series parasitic resistance of the drift layer. The overall effect would result in a reduction of $R_{on\text{-}sp}$ and power dissipation of the device. The results of power dissipation reduction at an on-state current density of 1000 amperes/cm$^2$ for the uniformly doped drift region of SBD's are compared with linearly graded drift region of SBD's with comparable levels of carrier concentration. It is estimated that there is a drop of 74.4% to 7.74% in power dissipation with linearly graded drift region of the devices.

## Theory

The common device structure of a 4H-SiC SBD is shown in Figure 1 and it's equivalent circuit is also drawn in Figure 2. The SBD shown in Figure 1 consists of a block of n-type 4H-SiC crystal with a given height 'h'. The metal contact at the top has a cross-sectional area 'A' and there is a base contact which may be formed using a metal or an alloy. Boron implant is made for edge termination on either side of the Schottky contact. An overlap exists between the top metallic contact of width 'd' and the contact length 'a'. The current flow from the top contact is considered trapezoidal in shape spreading through the drift region by an angle '$\alpha'$' with the vertical at the corner edge of the boron implant beneath the contact. A standard value of $\alpha'=26^{O}$ is taken for this model [13], which allows a small spread of current from the top contact to uniformly flow into the $n^+$-substrate below. The equivalent circuit shown in Figure 2 of the SBD has $R_{on\text{-}sp}$ which is the sum of the series $R_{on\text{-}sp}$ of the drift region ($R_D$) and the parasitic series resistance ($R_s$) with uniform current flow. Beneath this region is the $n^+$-type heavily doped substrate region whose resistance may be considered to be zero.



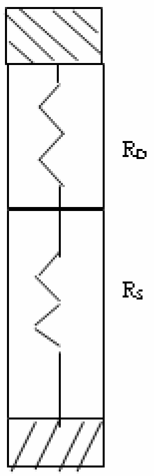


**Figure 1.** The structure and regions of a 4H-SiC SBD

**Figure 2.** Equivalent circuit of SBD shown in Figure 1

The equation to evaluate $R_{on\text{-}sp}$ of the device can be given by [13] :

$$R_{on-sp} = \rho_D \frac{d}{\tan\alpha'} \ln[1 + \frac{2h}{a}\tan\alpha']$$

$$R_{on-sp} = \rho_D \frac{a}{\tan\alpha'} \ln[1 + \frac{2h}{a}\tan\alpha'] \qquad (2)$$

where d = a for minimum overlap of contact metal considered and

$$\rho_D = \frac{1}{\mu_N e N_D} \tag{3}$$

where $N_D$ is the donor density in the n-type epitaxial layer.

In the model proposed here for the 4H-SiC SBD, the epitaxial layer is not uniformly doped but is linearly graded with a gradient α. Near the contact, the device has the lowest doping level ($N_o$), which increases with the gradient to any desired doping level (N) at the substrate. This is shown in Figure 3. The equivalent circuit of the device is similar to Figure 2, with $R_D$ replaced by $R_D{}'$ and the new $R_{s'}$ (< $R_s$) being used. $R_{s'}$ has a lower value than $R_s$ as the doping level is nearer to the substrate than the contact at the top of the device. The doping level $N_D$ of the epitaxial layer has to be replaced by the effective doping level $N_{eff}$ of the linearly graded drift layer.

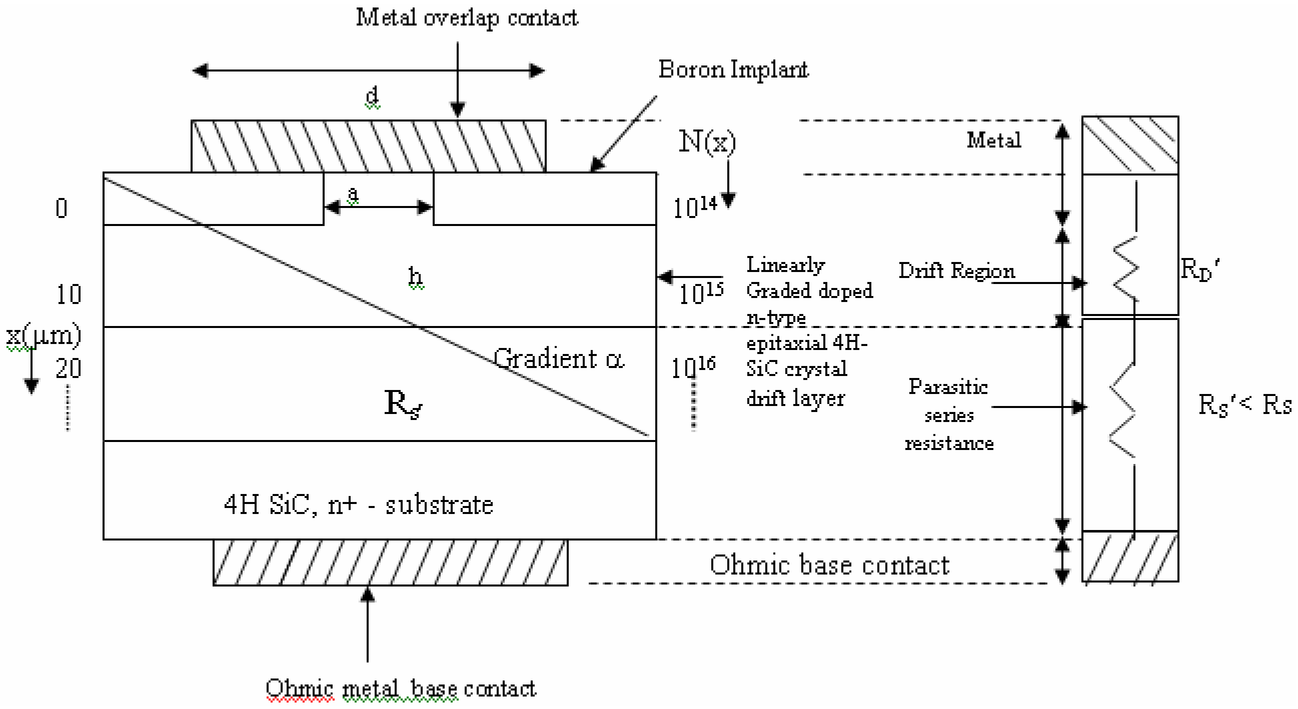


**Figure3.** The 4H-SiC SBD with linearly graded drift region doping profile with gradient α

**Figure 4.** The equivalent circuit of the SBD shown in Figure 3

*Formulation of $N_{eff}$*

Consider the cross section of the epitaxial layer of Figure 3 as shown in Figure 5. The resistance dR of a thin element of thickness dx at a distance x from the top of this device can be expressed as

$$\mathrm{dR} = \frac{1}{\mu_n{}' e N(x)} \frac{dx}{A} \tag{4}$$

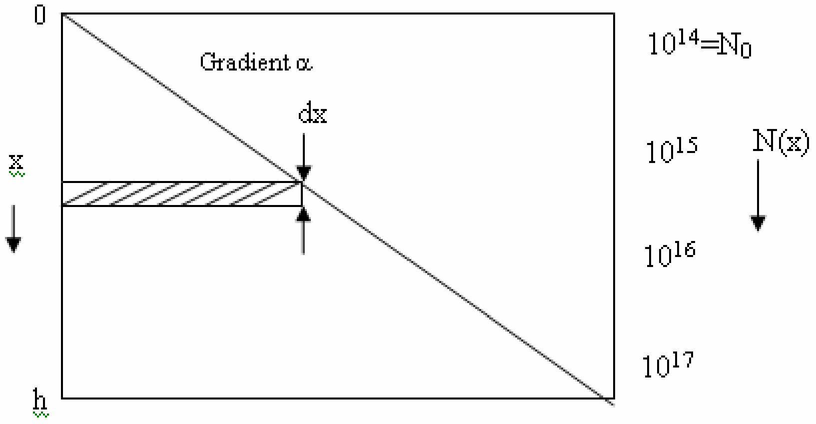


**Figure 5**. Cross section of drift region of a 4H-SiC SBD with linearly graded profile and gradient α

where A is the cross-sectional area in the direction perpendicular to the figure. The total resistance R of this layer can be evaluated by writing $N(x) = N_0 + \alpha x$ and integrating within limits of x from 0 to h, where h is the height of the device. This gives

$$R = \int_0^h \frac{1}{\mu_n' eA} \frac{dx}{(N_0 + \alpha x)} \tag{5}$$

Writing $Z = N_0 + \alpha x$ , then $dZ = \alpha dx$, which gives

$$R = \frac{1}{\mu_n' eA} \int_{N_0}^{N_0+\alpha h} \frac{dZ}{\alpha Z} = \frac{1}{\mu_n' eA\alpha} \ln\left[\frac{N_0 + \alpha h}{N_0}\right] = \frac{1}{\mu_n' eA\alpha} \ln\left[1 + \frac{\alpha h}{N_0}\right] \tag{6}$$

If the effective concentration of this layer is $N_{eff}$, then R may also be written as

$$R = \frac{1}{\mu_n' \, e \, N_{eff}} \frac{h}{A} \tag{7}$$

Comparing equations (6) and (7), $N_{eff}$ may be written as

$$N_{eff} = \frac{\alpha h}{\ln(1 + \frac{\alpha h}{N_0})} \tag{8}$$

The magnitude of $R_{on\text{-}sp}$ of the linearly graded drift layer, i.e $R'_{on\text{-}sp}$, can be obtained from equation (2) with $\rho_D$ replaced by $\rho_D'$ :

$$R'_{on-sp} = \rho_D' \frac{a}{\tan \alpha'} \ln[1 + \frac{2h}{a} \tan \alpha'] \tag{9}$$

$$\text{where } \rho_D' = \frac{1}{\mu_n' e N_{eff}} \tag{10}$$

with $\mu_n'$ being the value of mobility corresponding to doping level $N_{eff}$ of the drift region.

*Device height 'h'*

The height 'h' of the device has been set using a specific value of reverse bias voltage as the punch-through breakdown voltage. This is also set close to the avalanche breakdown voltage of the device using the condition $\alpha_p W = 1$, the condition for avalanche breakdown, and has been set equal to W, the depletion width at punch-through. The $\alpha_p$ is the hole impact ionisation coefficient, wherein it is assumed that hole in n-type wide depletion region in the drift layer started the ionisation process [14].

*Calculation of power dissipation ($P_D$)*

The equation for power dissipation $P_D$ can be written as [9]:

$$P_D = \frac{1}{2}\left(J_{on}{}^2 A R_{on-sp} + J_L A V_B\right) \qquad (11)$$

where $J_{on}$ is the on-state current density, A is the device cross-sectional area for current flow, $V_B$ is the reverse blocking voltage and $J_L$ is the leakage current density. For a 50% duty cycle, the magnitude of $J_L$ in SiC devices is too small compared to that in silicon devices and hence the second term in equation (11) can be neglected giving :

$$P_D = \frac{1}{2}(J_{on}{}^2 A R_{on-sp}) \qquad (12)$$

*Evaluation of the on-state current density ($J_{on}$)*

The current-voltage equation of the Schottky diode using thermionic emission theory has been given by Bethe [15] :

$$J_F = J_S[\exp(eV_D / \eta kT) - 1] \qquad (13)$$

where $J_F$ is the on-state forward current density and $V_D$ is the voltage drop across the Schottky diode and $J_s$ is the reverse leakage current density given by

$$J_s = A^* T^2 \exp(-e\,\varphi_B/\eta kT) \qquad (14)$$

where $A^*$ is the Richardson constant in amperes $cm^{-2}K^2$, $\varphi_B$ is the barrier height in volt and T is the device temperature in $^oK$.

The basic current–voltage equation for such a diode has been derived by Bhatnagar et al. [16]. The diode forward voltage drop (including drift layer) $V_F$ can be expressed as

$$V_F = V_D + J_F R_{on-sp} \qquad (15)$$

Combining equations (13) through (15) and writing $J_{on}$ for $J_F$, the voltage $V_F$ may be expressed as

$$V_F = \frac{\eta kT}{e}\ln\left(\frac{J_{on}}{A^* T^2}\right) + \varphi_B + J_F R_{on-sp} \qquad (16)$$

Values of $J_{on}$ for different values of $V_F$ in the on state of the diode can be obtained by iteration with a simple technique and C++ program [17]. Under forward bias and in the on state, the magnitude of $V_D$ and $V_F$ is small, and thus the effect of barrier height lowering, $\Delta\phi$, has not been included in equations (14) and (16) above.

The calculation of power dissipation has been performed, knowing $N_D$, $N_{eff}$, $R_{on\text{-}sp}$, $R'_{on\text{-}sp}$ and the magnitude of $J_{on}$ and $V_F$, for both uniformly doped and linearly graded drift layers of the 4H-SiC SBD's.

*Calculation of breakdown voltages*

The punch-through breakdown voltage ($V_{PBV}$) is determined at a high reverse bias voltage ($V_R$) for a uniformly doped semiconductor of 4H-SiC SBD and the depletion region width (W) at this voltage is set equal to the device height (h). The avalanche breakdown voltage is obtained using the condition $\alpha_p W = 1$, to give the magnitude of $\alpha_p$.The critical field ($E_c$) corresponding to this value of $\alpha_p$ is obtained from [18]. The magnitude of the avalanche breakdown voltage ($V_{AvBV}$) is then obtained using the equations:

$$V_{AvBV} = \frac{1}{2} E_c W \text{ , for uniformly doped drift region of SBD, and} \qquad (17)$$

$$V_{AvBV} = \frac{2}{3} E_c W' \text{ , for linearly graded drift region of SBD} \qquad (18)$$

The depletion region width in the two cases is calculated using the formula:

$$W = \sqrt{\frac{2\varepsilon_S (V_{bi} + V_R)}{eN_D}} = \sqrt{\frac{2\varepsilon_S V_R}{eN_D}} \text{ , for uniformly doped drift region of SBD,} \qquad (19)$$

where $V_{bi}$ is the built-in potential and $V_{bi} << V_R$, the applied reverse voltage which is equal to the avalanche breakdown voltage, and

$$W' = \sqrt[3]{\frac{12\varepsilon_S (V_g + V_R)}{e\alpha}} = \sqrt[3]{\frac{12\varepsilon_s V_R}{e\alpha}} \text{ , for linearly graded drift region of SBD,} \qquad (20)$$

where $V_g$ is the gradient voltage and $V_g << V_R$, the applied reverse voltage which is equal to the avalanche breakdown voltage. In the two equations, $\varepsilon_s$ denotes the permittivity of 4H-SiC and α in equation (20) is the concentration gradient which is $10^{14}$ near the top of the device, and increases linearly to $10^{15}$, $10^{16}$ ------, near the substrate over the device height (h).

The calculation of $E_c$ for avalanche breakdown in a linearly graded profile is made using equation [20]:

$$E_C = \frac{e\alpha W'^2}{8\varepsilon_S} \qquad (21)$$

where $W'$ is the depletion region width at breakdown.

*Calculations and related graphs*

The device height 'h' is set equal to the maximum depletion region width 'W' corresponding to a breakdown voltage of 5 kV for the uniformly doped epitaxial layer with the lowest doping level of $10^{14}$ per cc using equation (19). This gives a value of 231μm for the device height 'h' taking $\varepsilon_s = 9.7$ for 4H-SiC. The doping-dependent mobility value is obtained from Roschke and Schwierz [11]. The magnitude of $R_{on\text{-}sp}$ is calculated using equation (2) with angle $\alpha' = 26^o$ and Schottky contact of length 'a' equal to 100 μm. The contact width is equal to 78.5 μm. The device cross-sectional area 'A' is then 78.5 x $10^{-6}$ cm$^2$. Specific values of the on-state current density ($J_{on}$) ranging from 100 to 1000 amps/ cm$^2$ are used and the corresponding values of power dissipation ($P_D$) are calculated using equation (12). This is repeated for doping levels of $10^{15}$, $10^{16}$ and $10^{17}$ per cc. The results are shown in Table 1(A).

**Table 1(A).** Calculation of power dissipation ($P_D$) of 4H-SiC SBD with uniformly doped drift region

| Current density (amps /cm$^2$) | $N_d$ = 1x $10^{14}$ atoms/cc | $N_d$ = 1x $10^{15}$ atoms /cc | $N_d$ = 1x $10^{16}$ atoms/cc | $N_d$ = 1x $10^{17}$ atoms/cc |
|---|---|---|---|---|
| | $\mu_n$= 960 cm$^2$ per Vs | $\mu_n$= 950 cm$^2$ per Vs | $\mu_n$= 900 cm$^2$ per Vs | $\mu_n$= 600 cm$^2$ per Vs |
| | $R_{on\text{-}sp}$ =1.577 Ω-cm$^2$ | $R_{on\text{-}sp}$ =159.38x$10^{-3}$ Ω-cm$^2$ | $R_{on\text{-}sp}$ =16.82x$10^{-3}$ Ω-cm$^2$ | $R_{on\text{-}sp}$ =2.52 x $10^{-3}$ Ω-cm$^2$ |
| $J_{on}$ | $P_D$(1) Watts | $P_D$(2) Watts | $P_D$(3) Watts | $P_D$(4) Watts |
| 100 | 0.6195 | 62.55x$10^{-3}$ | 6.601 x $10^{-3}$ | 989.1 x $10^{-6}$ |
| 200 | 2.478 | 0.2502 | 26.40 x $10^{-3}$ | 3.956 x $10^{-3}$ |
| 400 | 9.912 | 1.0008 | 0.1056 | 15.82 x $10^{-3}$ |
| 600 | 22.302 | 2.2518 | 0.2376 | 35.607 x $10^{-3}$ |
| 800 | 39.649 | 4.0032 | 0.4225 | 63.30 x $10^{-3}$ |
| 1000 | 61.95 | 6.255 | 0.660 | 98.91 x $10^{-3}$ |

In the case of linearly graded profiles, the device height 'h' is kept the same as in the case of the uniformly doped epitaxial layers (i.e 231 μm). The concentration gradients selected arbitrarily are $10^{14}$-$10^{15}$, $10^{14}$-$10^{16}$, $10^{14}$-$10^{17}$ and $10^{14}$-$10^{18}$ over the device height of 231μm. This gives the concentration gradient 'α' in each case. The effective carrier concentration '$N_{eff}$' for linearly graded epitaxial layer is calculated using equation (8). The value of the average doping dependent carrier mobility ($\mu_n'$) for any specific concentration gradient is obtained from Roschkc and Schwierz [11]. $R'_{on\text{-}sp}$ is then calculated using equation (9), treating the medium doping level as equal to $N_{eff}$. The depletion region width 'W' for a reverse bias voltage of 5 kV is calculated using equation (20). The power dissipation for a given concentration gradient at the same current density levels in the case of the uniformly doped epitaxial layer device above is calculated using equation (12) with the same value of the device cross-sectional area 'A' and the corresponding values of $R'_{on\text{-}sp}$. The results are shown in Table 1(B).

The plots of power dissipation versus current density for uniformly doped and linearly graded epitaxial layers of 4H-SiC SBD are obtained from the data given in Tables 1(A) and 1(B) and are shown in Figure 6 .

**Table 1(B).** Calculation of power dissipation ($P_D$) of 4H-SiC SBD with linearly graded drift region

| Current density (amps /cm$^2$) | $N_{eff}$ = 3.905 x 10$^{14}$ atoms/cc | $N_{eff}$ = 2.148 x10$^{15}$ atoms/cc | $N_{eff}$ = 1.446 x10$^{16}$ atoms/cc | $N_{eff}$ = 1.085 x10$^{17}$ atoms/cc |
|---|---|---|---|---|
| | $\mu_n'$= 960 cm$^2$ per Vs | $\mu_n'$= 950 cm$^2$ per Vs | $\mu_n'$= 900 cm$^2$ per Vs | $\mu_n'$= 600 cm$^2$ per Vs |
| | $R_{on\text{-}sp}$ =0.04038 Ω-cm$^2$ | $R_{on\text{-}sp}$ =0.07418 Ω-cm$^2$ | $R_{on\text{-}sp}$ = 11.63 x10$^{-3}$ Ω-cm$^2$ | $R_{on\text{-}sp}$ =2.325 x10$^{-3}$ Ω-cm$^2$ |
| | $P_D(1)$ Watts | $P_D(2)$ Watts | $P_D(3)$ Watts | $P_D(4)$ Watts |
| $J_{on}$ | | | | |
| 100 | 0.15849 | 29.115e-3 | 4.565e-3 | 912.56e-6 |
| 200 | 0.63396 | 0.1164 | 18.260e-3 | 3.650e-3 |
| 400 | 2.5358 | 0.4658 | 73.042e-3 | 14.60e-3 |
| 600 | 5.7056 | 1.048 | 164.34e-3 | 32.85e-3 |
| 800 | 10.143 | 1.863 | 0.29217 | 58.40e-3 |
| 1000 | 15.849 | 2.9115 | 0.4565 | 91.25e-3 |

It is seen that linearly graded profiles give theoretically a much lower power dissipation ($P_D$) than do the uniformly doped profiles in 4H-SiC SBD's. The percentage fall in power dissipation between two adjacent graphs of linearly doped and uniformly doped profiles in Figure 6 ranges from 7.74% to 74.4% for $J_{on}$ of 1000 amps/cm$^2$. This is shown in Figure 7.

The punch-through breakdown voltage ($V_{PBV}$) is set at 5 kV for the case of uniformly doped epitaxial layer with a doping level of $10^{14}$ per cc and a depletion region width 'W' of 231μm. The condition for avalanche breakdown represented by $\alpha_p W = 1$ gives the value of $\alpha_p$. The magnitude of the electrical field for avalanche breakdown ($E_c$) is obtained from Ayalew [18] from the plot of $\alpha_p$ versus E for 4H-SiC. The value of $V_{AvBV}$, the avalanche breakdown voltage, is then obtained from equation (17). This is repeated for doping levels of $10^{15}$, $10^{16}$ and $10^{17}$ per cc, as shown in Table 2(A).

The punch-through breakdown voltage for the linearly graded epitaxial layer is obtained from the depletion region width 'W′' at 5 kV for a given concentration gradient 'α' of 3.88 x $10^{16}$cm$^{-4}$. The value of the critical field ($E_c$) for linearly graded profile is calculated using equation (21) and the value of W′ obtained at 5 kV is treated as the depletion width for avalanche breakdown. The magnitude of $V_{AvBV}$ is then calculated using equation (18).This is repeated for other values of α and the results are shown in Table 2(B).

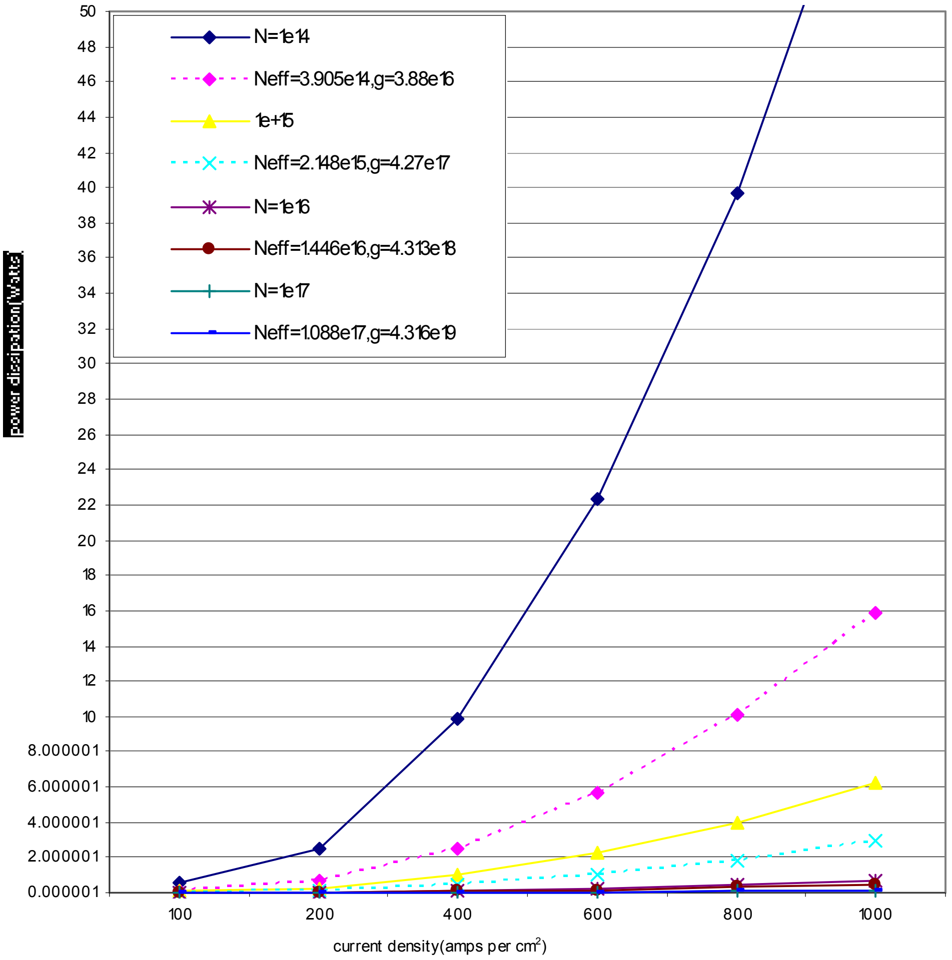


**Figure 6.** Plots of power dissipation versus on-state current density for uniformly doped and linearly graded drift region in 4H-SiC SBD

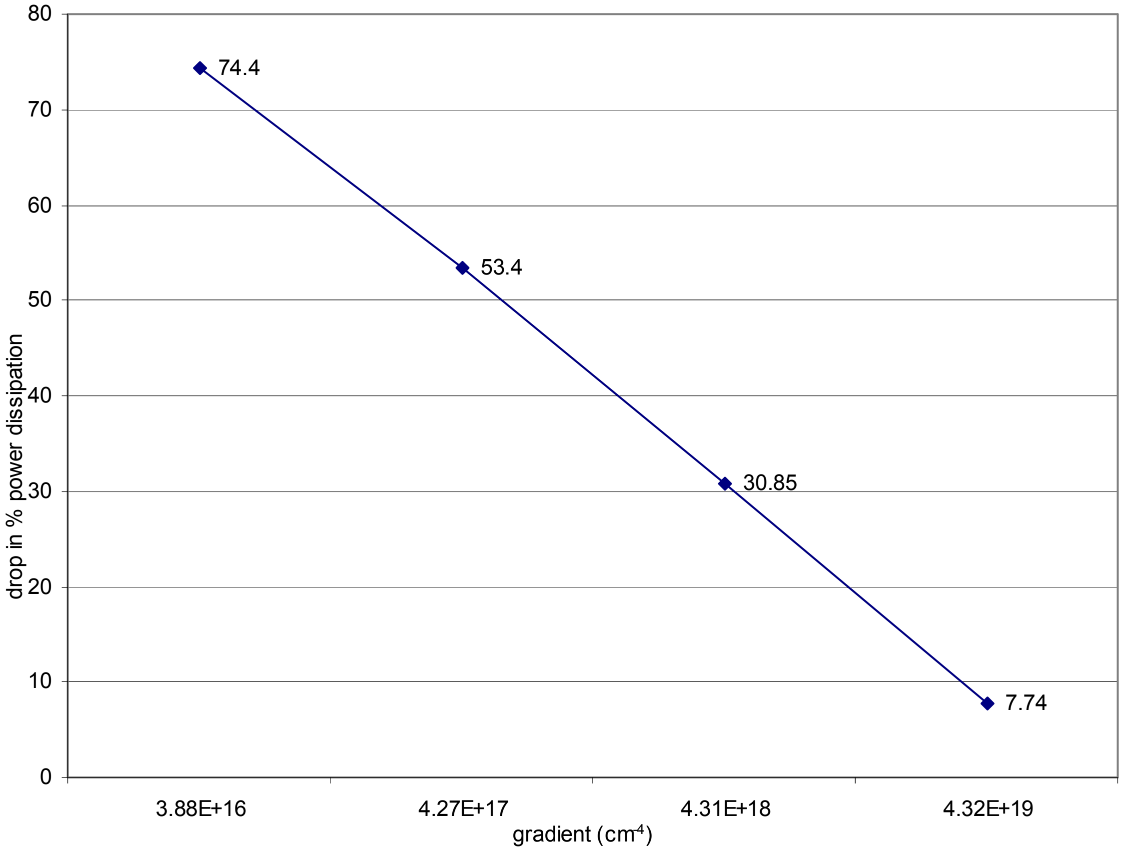


**Figure 7.** Percentage drop in power dissipation versus concentration gradient in 4H-SiC SBD compared to SBD with uniformly doped drift region

**Table 2(A).** Breakdown voltages of 4H-SiC SBD for uniformly doped epitaxial layer (Device height = h = W = 231 μm)

| Doping level ($N_D$ per cc) | W (μm) | $\alpha_p$ ($cm^{-1}$) | $E_c$ (V per cm) x $10^6$ | $V_{AvBV}$ (kV) | $V_{PBV}$ (kV) |
|---|---|---|---|---|---|
| $10^{14}$ | 227 | 44.05 | 1.33 | 14.94 | 5 |
| $10^{15}$ | 71.78 | 139.31 | 1.66 | 5.95 | 5 |
| $10^{16}$ | 22.7 | 440.05 | 1.82 | 2.06 | 5 |
| $10^{17}$ | 7.17 | 1394.7 | 2.12 | 0.7575 | 5 |

**Table 2(B).** Breakdown voltages of 4H-SiC SBD for linearly graded epitaxial layer
(Device height = h = W = 231 μm)

| Gradient $\alpha$ (cm$^{-4}$) | $W'$ (μm) | $E_C = \left(\frac{e\alpha W'^2}{8\varepsilon_S}\right)$ | $V_{AvBV}$ (kV) | $V_{PBV}$ (kV) |
|---|---|---|---|---|
| 3.88 x $10^{16}$ | 201.07 | 3.72 x $10^{5}$ | 4.986 | 5 |
| 4.27 x $10^{17}$ | 90.3 | 8.25 x $10^{5}$ | 4.966 | 5 |
| 4.31 x $10^{18}$ | 41.8 | 2.86 x $10^{6}$ | 4.966 | 5 |
| 4.31 x $10^{19}$ | 19.4 | 3.84 x $10^{6}$ | 4.966 | 5 |
| 4.4 x $10^{19}$ | 22.7 | 5.26 x $10^{6}$ | 7.960 | 8 |

## Discussion and Conclusions

The curves shown in Figure 6 show that the linearly graded epitaxial drift region of 4H-SiC SBD's have consistently lower power dissipation than the uniformly doped epitaxial layer devices. A tally of such an effect can be verified by comparing the power dissipation of the devices when evaluated at a current density of 1000 amps/cm$^2$. The comparison between the curve for the uniformly doped epitaxial layer device with a doping level of $10^{14}$ per cc and that for the linearly graded profile with a gradient of 3.88 x $10^{16}$ cm$^{-4}$ at $N_{eff}$ of 3.905 x $10^{14}$ shows that there is a 74.4% drop in power dissipation. When the drop in power dissipation is evaluated at other current density levels, it is found that the drop in per cent power dissipation remains at the same level. This is, however, not so for other sets of curves, where this type of tally shows a constant decline in per cent power dissipation for a given $N_{eff}$ compared to nearly similar levels of doping in the uniformly doped profiles. In other words, compared to the uniformly doped epitaxial layers, the linearly graded profiles show a significantly lower power dissipation. Figure 7 shows this in a different perspective where the percentage fall in power dissipation is found to increase with a decrease in concentration gradient from 74.4% at a gradient of 3.88 x $10^{16}$ cm$^{-4}$ to 7.74% at a gradient of 4.316 x $10^{19}$ cm$^{-4}$

Calculation of breakdown voltages shown in Table 2(A) shows that for uniformly doped epitaxial layer devices doped to a level of $10^{15}$ per cc, the punch-through and avalanche breakdown voltages are almost equal to 5 kV. Linearly graded epitaxial layer devices show a similar avalanche breakdown at 7.96 kV for a gradient of 4.4 x $10^{19}$ cm$^{-4}$ for which the punch-through breakdown voltage is 8 kV. This device can therefore have a breakdown voltage of 7.96 kV which is almost equal to the punch-through breakdown voltage of 8 kV.

An analysis of the results shown in Tables 2(A) and 2(B) shows that the critical field '$E_c$' increases with doping level in the case of uniformly doped epitaxial layer devices while it does with gradient $\alpha$ in the case of linearly graded epitaxial layer devices. However, the magnitude of $E_c$ in the former case is somewhat higher than that in the latter case. The depletion region width in devices with uniformly doped profiles is normally larger than that with linearly graded ones.

In conclusion it may be said that the 4H-SiC SBD's with linearly graded epitaxial layers have considerably lower power dissipation but need not necessarily provide a higher avalanche breakdown voltage. Lastly, the device height ‘h’ of 231µm used in this work may be difficult to grow in 4H-SiC using epitaxial technology. However, wafers with better crystalline perfection may be selected for making these devices.

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