Optimization of Forward Voltage Drop for Si, SiC, and GaN High Voltage Diode

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***Abstract*- A power electronic device for a converter must possess a low specific on-resistance. The specific on-resistance of a bipolar device is related to the base width and doping concentration of the lightly doped drift region (n^- base). Therefore, the doping concentration and the width of the low-doped base region in a bipolar device must be carefully considered to achieve a desired avalanche breakdown voltage and on-resistance (conduction characteristics). This work presents an improved method for calculation of the minimum depletion layer width for a given breakdown voltage of Si, SiC, and GaN structures and further investigates the optimum width of their depletion layers for different blocking voltages to achieve a minimal forward drop. The results show that an optimization of the forward voltage drop by using the optimal doping concentration for corresponding breakdown voltages is necessary for the proper design of a Si diode but is not necessary for wide band gap material devices.**

Keywords- Forward Voltage Drop; Si; SiC; GaN

NOMENCLATURE

A_i	Amplitude parameter of ionization coefficient (cm^{-1})
α_i	General ionization coefficient (cm^{-1})
α_{eff}	Effective ionization coefficient (cm^{-1})
b_i	Exponential electric field ionization fit parameter of ionization coefficient (V/cm)
d_1	Depletion region thickness in n^+ cathode region (cm)
d_2	Depletion region thickness in p^+ anode region (cm)
E_G	Bandgap energy of semiconductor (eV)
ε	Dielectric permittivity (F/cm)
$\mathscr{E}$	Electric field strength (V/cm)
h_n	n^+ emitter recombination parameter ($cm^{-4}s^{-1}$)
h_p	p emitter recombination parameter ($cm^{-4}s^{-1}$)
K	Pre-factor coefficient for effective ionization coefficient (cm^6/V^7)
m_i	Exponent fit parameter of ionization coefficient for various materials
M	Number of terms of Fourier series
μ_n	Electron mobility ($cm^2V^{-1}s^{-1}$)
μ_p	Hole mobility ($cm^2V^{-1}s^{-1}$)
n_i	Intrinsic carrier concentration (cm^{-3})
N_{D1}	Impurity doping concentration in the lightly-doped n-base (cm^{-3})
N_{D2}	Impurity doping concentration in the n^+ cathode (cm^{-3})
N_A	Impurity doping concentration in the p^+ anode (cm^{-3})
p_{x1}	Depletion region boundary charge carrier density (cm^{-3})
p_{x2}	Depletion region boundary charge carrier density (cm^{-3})
$p_{T(k)}$	Average charge carrier density in the k^{th} region of the segmented n-base (cm^{-3})
q	Charge of electron ($\cong 1.6 ? \ 0^{-19} C$)
V_{appl}	Applied external voltage (V)
V_{BD}	Breakdown voltage due to impact ionization (V)
V_F	Forward voltage drop during conduction (V)
V_{j1}	Voltage drop across cathode to n-base pseudo-junction (V)
V_{j2}	Voltage drop across n^- base to anode junction (V)
V_{n^-}	Voltage drop across n^- base region (V)
V_{seg}	Voltage drop across a segment of the n^- base region (V)
v_{sat}	Carrier (hole and electron) saturation velocity (cm/s)
V_T	Thermal voltage = kT/q (V)
W	n^- base width, also depletion width associated with depleted base (cm)
W_{min}	Minimum width of the depletion layer in n^- base at breakdown (cm)

I. INTRODUCTION

One of the requirements for choosing a proper power electronic device for a converter is that it must possess a low specific on-resistance. The specific on-resistance of a bipolar device is related to the base width and doping concentration of the lightly doped drift region (n^- base) [1]. This means that the doping concentration and the width of the low-doped base region in a bipolar device must be carefully considered to achieve a desired avalanche breakdown voltage and on-resistance (conduction characteristics). In order to accurately determine the technological parameters of a semiconductor device, 2D and 3D finite element analyses are recommended. In the case of power semiconductor devises, the charge profile in the thick drift region can be assumed as one-dimensional for more than 90% of its volume, which makes the analysis simple [2]. Therefore, one-dimensional analysis is used in this work to calculate the minimum depletion layer width, W_{min}, for a given breakdown voltage, V_{BD}, of Si, SiC and GaN $p^+n^-n^+$ structures and further investigate to determine the optimum width of their depletion layers for different blocking voltages to achieve a minimal forward drop.

The avalanche breakdown voltage, V_{BD}, for an abrupt parallel plate junction is a function of the background doping and the semiconductor properties, such as dielectric constant, energy band gap, and impact ionization coefficient. Breakdown occurs when the carrier multiplication becomes greater than unity. Impact ionization coefficients empirically describe the exponential relationship of the applied electric field and associated charge carrier creation. The impact ionization coefficients for electrons and holes have different values, and for semiconductor materials of interest are obtained empirically. The general ionization coefficient has been determined to have a theoretical form that is exponential [3] and represented by

$$\alpha_i = A_i e^{-\left(\frac{b_i}{\mathscr{E}}\right)^{m_i}}, \tag{1}$$

where $\mathscr{E}$ is the electrical field (V/cm), A_i is the amplitude parameter (cm^{-1}), b_i is the ionization energy parameter related to the mean free path between collisions (V/cm), and m_i is an additional fit parameter for use with a multitude of semiconductor materials [4, 5]. These parameter values depend on the semiconductor material and whether electrons or holes are considered. For Si, SiC, and GaN, m_i has been determined to be 1 for both electrons and holes [4, 5].

Near the breakdown condition, little error is introduced by equating the impact ionization coefficients of electrons and holes to an effective ionization coefficient, α_{eff}. In this case, the breakdown voltage is defined as the applied voltage at which the summed effects described by the ionization coefficient acting over the depletion width, W, create more free charge carriers. The boundary at breakdown is when the integral (2) achieves a value of unity [5]. The associated breakdown condition in terms of the effective ionization coefficient is:

$$\int_0^W \alpha_{eff}\, dx = 1. \tag{2}$$

Evaluation of this integral using (1) is very difficult; and no analytical expressions result, thus limiting its usefulness for device design. However, a simplified (and purely empirical) polynomial expression for the ionization coefficient in terms of the electric field is widely used [5]:

$$\alpha_{eff} = K\mathscr{E}^7. \tag{3}$$

The two previous fit parameters, A_i and b_i, are absorbed into the prefactor, K. The coefficient K is expressed in terms of new parameters, A, b, and m, that are averages of the previous A_i, b_i, and m_i values, expressed in Equation (1), for holes and electrons [4] by

$$K = 9\times10^{-38}\,\frac{A\times216^m}{b^{0.85}E_G^{15}}. \tag{4}$$

E_G is the bandgap energy (eV) for the semiconductor material of interest. For a one-sided abrupt p^+-n^- junction, the electrical field and the voltage across the lightly doped region are functions of the depletion distance and depend on the impurity doping concentration, N_{D1}, in the lightly doped n^- base. W is the depleted n^- base width. The electric field and voltage relations are presented in Equations (5) and (6), respectively.

$$\mathscr{E}(x) = \frac{q}{\varepsilon}N_{D1}(W-x) \tag{5}$$

$$V(x) = \frac{q}{2\varepsilon}N_{D1}(W-x)^2. \tag{6}$$

The maximum electrical field is observed at the junction (x = 0). Using this and substituting Equation (5) in (3) and then into the integral (2), one can obtain the minimum width of the depletion layer, $W_{\min}$, at breakdown [5] as

$$W_{\min} = \left(\frac{K}{8} \frac{q^7}{\varepsilon^7} N_{D1}^7 \right)^{-1/8} . \tag{7}$$

The corresponding breakdown voltage can then be determined from Equation (6) as:

$$V_{BD} = \left(2K \frac{q^3}{\varepsilon^3} N_{D1}{}^3 \right)^{-1/4} . \tag{8}$$

It should be noted that the permittivity is correctly placed in the denominator in Equation (8), not in the numerator as was presented in the expressions from [4] due to typographical error.

To reduce the lightly doped region width and maintain the same breakdown voltage requires the addition of a highly-doped n^+ buffer layer at the end of the drift (n^- base) region to create a $p^+n^-n^+$ structure. This will modify the expressions for the minimum width of the depletion layer, $W_{\min}$, and the corresponding breakdown voltage, V_{BD}. Reducing the width of the base region will decrease the effective on-resistance during conduction and reduce the volume of stored charge, thus decreasing the turn-off (and turn-on) time.

The objective of this work is to investigate these modifications of the governing equations derived in Equations (7) and (8) when using a complete structure appropriate for power devices.

II. CALCULATION OF W_{MIN} AND V_{BD} FOR A $P^+N^-N^+$ STRUCTURE

Consider a two-dimensional $p^+n^-n^+$ structure under equilibrium conditions with the doping profile sketched in Figure 1. The electric field in the different regions can be obtained by substituting the charge densities into Poisson's equations and then integrating:

$$\mathscr{E} = \begin{cases} (q/\varepsilon) N_{D2} x & 0 \le x \le d_1 \\ (q/\varepsilon)\left(N_{D1} x + d_1 \left(N_{D2} - N_{D1} \right) \right) & d_1 \le x \le d_1 + W \\ (q/\varepsilon) N_A (d_1 + W + d_2 - x) & d_1 + W \le x \le d_1 + W + d_2 \\ 0 & x \le 0 \ \ and \ d_1 + W + d_2 \le x \end{cases} \tag{9}$$

where the respective impurity doping concentrations for the $n^+n^-p^+$ regions are N_{D2}, N_{D1}, and N_A. The corresponding depletion region thicknesses of each section are d_1, W, and d_2.

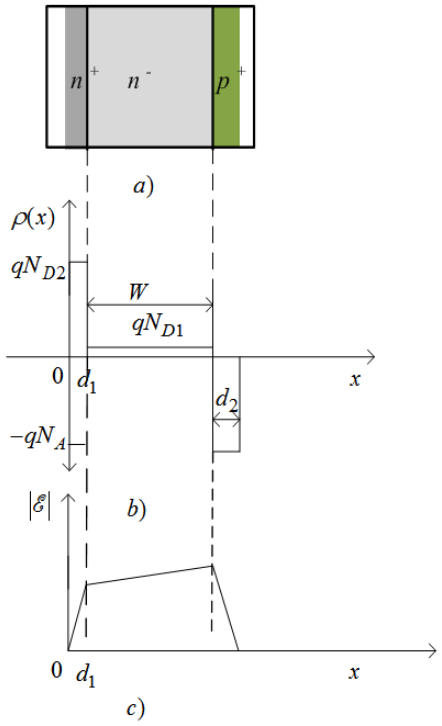


Fig. 1 a) A $p^+n^-n^+$ structure highlighting the depleting region under a large reverse applied voltage; b) doping profile of the $p^+n^-n^+$ structure with charge density as a function of position; c) electrical field as a function of position

The maximum electric field of the $p^+n^-n^+$ structure will be at the n^-p^+ junction $(x = d_1 + W)$. Charge neutrality from (9) gives the depletion thickness, d_2, of the p^+ region as:

$$d_2 = \left(N_{D1}W + N_{D2}d_1\right)/N_A . \tag{10}$$

Since $\mathscr{E} = -dV/dx$, the electrical potential applied to the structure is obtained by integrating the electrical field from 0 to $d_1 + W + d_2$ resulting in:

$$V_{appl} = \frac{q}{\varepsilon}\left[\frac{N_{D2}^2 + N_{D2}N_A}{2N_A}d_1^2 + \left(\frac{N_{D1}N_{D2}}{N_A} + N_{D2}\right)d_1W + \left(\frac{N_{D1}^2 + N_AN_{D1}}{2N_A}\right)W^2\right] \tag{11}$$

Substituting (10) into (9) and using the result to calculate the ionization coefficient (3), we can reevaluate the ionization integral (2) as:

$$\begin{aligned} &N_{D2}^7 d_1^8 + \frac{N_{D2}^8 d_1^8}{N_A} + \left(\frac{N_{D1}}{N_A} + 1\right)(8N_{D2}^7 d_1^7 W + 28N_{D1}N_{D2}^6 d_1^6 W^2 \\ &+56N_{D1}^2 N_{D2}^5 d_1^5 W^3 + 70N_{D1}^3 N_{D2}^4 d_1^4 W^4 + 56N_{D1}^4 N_{D2}^3 d_1^3 W^5 + \\ &+28N_{D1}^5 N_{D2}^2 d_1^2 W^6 + 8N_{D1}^6 N_{D2} d_1 W^7 + N_{D1}^7 W^8) = \frac{8\varepsilon^7}{Kq^7} \end{aligned} \tag{12}$$

For a given breakdown voltage, V_{BD}, the thicknesses of the drift region, W, can be calculated numerically using Equations (11) and (12).

III. BREAKDOWN VOLTAGE MODELING

The average ionization parameters (A, b, and m) and the constant K for Si and GaN, as given in [5], are presented in Table 1. For 4H-SiC, the data for the electron and hole ionization parameters are taken from [4], averaged together, and included in the table. The coefficient K is calculated using (4). It can be noted that the calculated value of K for 4H-SiC (4.58E-42) is similar to the value given in [6] as 3.9E-42.

TABLE 1 AVERAGE IONIZATION COEFFICIENT

Materials	***A* (cm^{-1})**	***b* (V/cm)**	***m***	***K* (cm^6/V^7)**
Si	1.07E+06[3]	1.65E+06[2]	1[3]	1.9E-35[2]
4H-SiC	3.15E+06[5]	1.04E+07[5]	1.23[5]	3.9E-42[7]
GaN	8.85E+06[3]	2.60E+07[3]	1[3]	9.1E-43[2]

Figure 2 presents the results calculated for the required minimum width of the lightly doped drift region (W_{min}) as a function of base doping concentration (N_{D1}) for a $p^+n^-n^+$ structure at breakdown, for various designed breakdown voltages applied to the device and different semiconductor materials (Si, 4H-SiC, and GaN). This design necessarily requires the depletion region to punch through to the n^+ region, otherwise the device acts like a p^+-n^- diode. Equation (7), associated with a planar p^+n junction, is also plotted in Figure 2 for comparison. It can be concluded from the simulation results that there are significant differences in the calculated values of the base width for the two structures (p^+n or $p^+n^-n^+$) for the same doping concentration, and for a given designed breakdown (blocking) voltage for all three semiconductor materials. Note that for theoretical base doping values below 3×10^{13} cm^{-3} for Si, 2.5×10^{15} cm^{-3} for 4H-SiC, and 5×10^{15} cm^{-3} for GaN, there is little effect on the required minimum base width for a given breakdown voltage.

Increasing the base doping concentration in each of the three semiconductor materials above these values significantly increases the required base width for a given designed breakdown and results in a decreasing value of d_1 (depletion width in the n^+ region) to the point that it disappears where the structure reverts to the standard p^+n device. This phenomenon for a 3-kV-designed breakdown is observed for Si at a doping concentration of approximately 4.5×10^{13} cm^{-3}, for 4H-SiC at approximately 6×10^{15} cm^{-3}, and for GaN at approximately 9×10^{15} cm^{-3}. Lower breakdown voltage values allow for an increased doping concentration before the limiting effect is obtained. For the same blocking voltage, the highest doping concentration allowed in the drift region is for a GaN $p^+n^-n^+$ structure. This is expected since GaN has the largest bandgap energy of the three semiconductors. A 4H-SiC device has a slightly lower doping concentration than GaN, while a Si device has a significantly lower doping concentration requirement, approximately 100 times smaller than GaN and 4H-SiC $p^+n^-n^+$ devices at a given breakdown voltage.

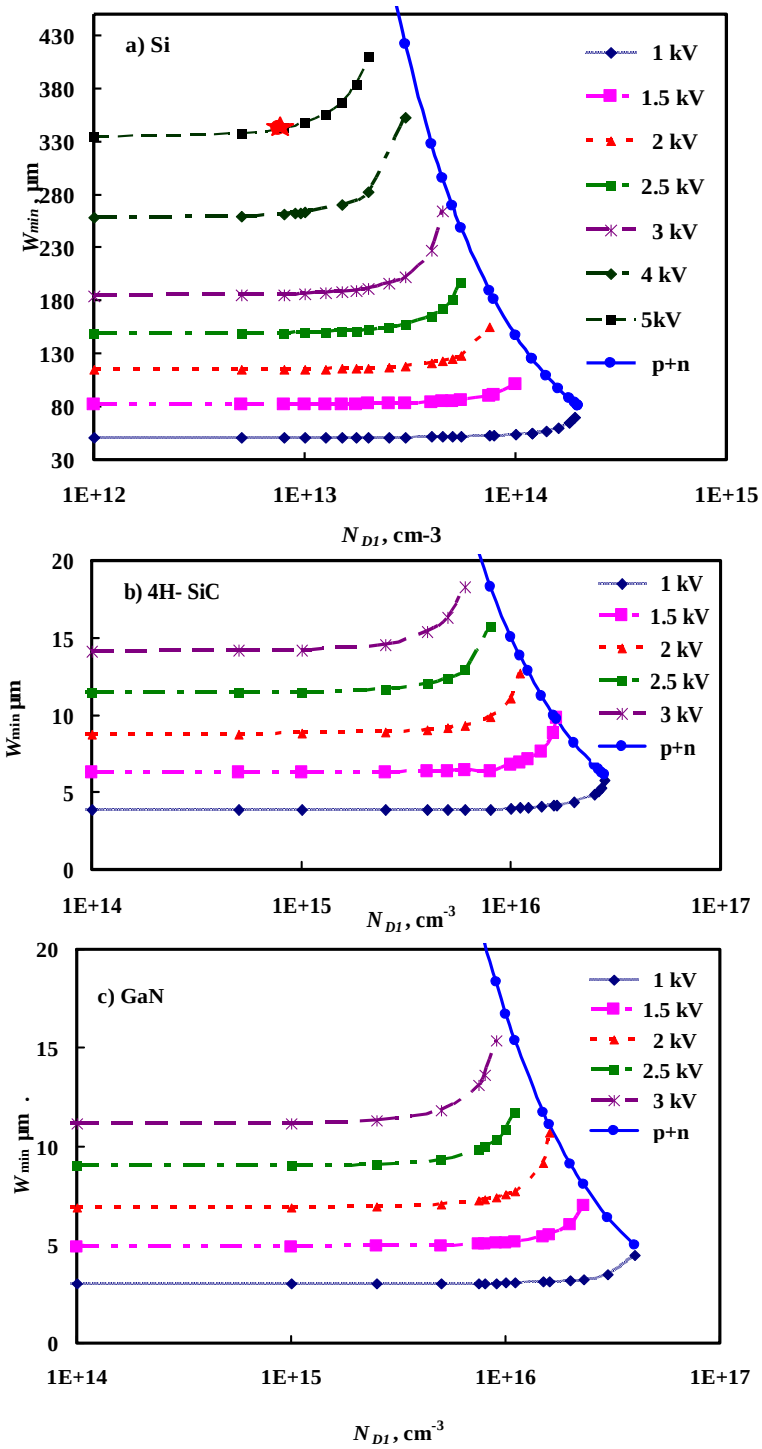


Fig. 2 The minimum width of the lightly doped drift region (W_{min}) as a function of doping concentration (N_{D1}) for a p^+n diode and a $p^+n^-n^+$ structure for different applied voltages and different semiconductor materials: a) Si, b) 4H-SiC, and c) GaN

Figure 3 presents the results calculated (family of curves using different n^- base widths at breakdown) for the breakdown voltage as a function of doping concentration (N_{D1}) for a $p^+n^-n^+$ structure, again using (9) and (10), and the p^+n structure using (6) for Si, 4H-SiC, and GaN semiconductors. It can be seen from Figure 3 that as technology improves to allow for lower base doping values, the estimation of a breakdown voltage rating from the analysis of the p^+n structure is inadequate. As is shown, doping concentrations less than 5×10^{13} for Si, 2×10^{15} for 4H-SiC, and 5×10^{15} for GaN for the same drift region width do not significantly affect the breakdown voltage.

Loh et al. [6] have calculated the breakdown voltage for an ideal $p^+n^-n^+$ 4H-SiC diode for different thicknesses of the lightly doped drift region as a function of its doping concentration using their local model, including impact ionization parameters. Their results show a trend similar to our analysis wherein the breakdown voltage is relatively independent of N_{D1}

values for ultra-low doping concentrations in the base region. This indicates independent validation of our approach. However, our work has expanded to include the behavior and optimization for GaN and extends the level of detail and correctness for Si beyond what has been previously reported. From both of these results, for a 4H-SiC device with a 10 μm *n*-base region width, the doping concentration that separates the region of "constant" breakdown voltage from the region where the concentration strongly affects the breakdown voltage is approximately 10^{16} cm^{-3}.

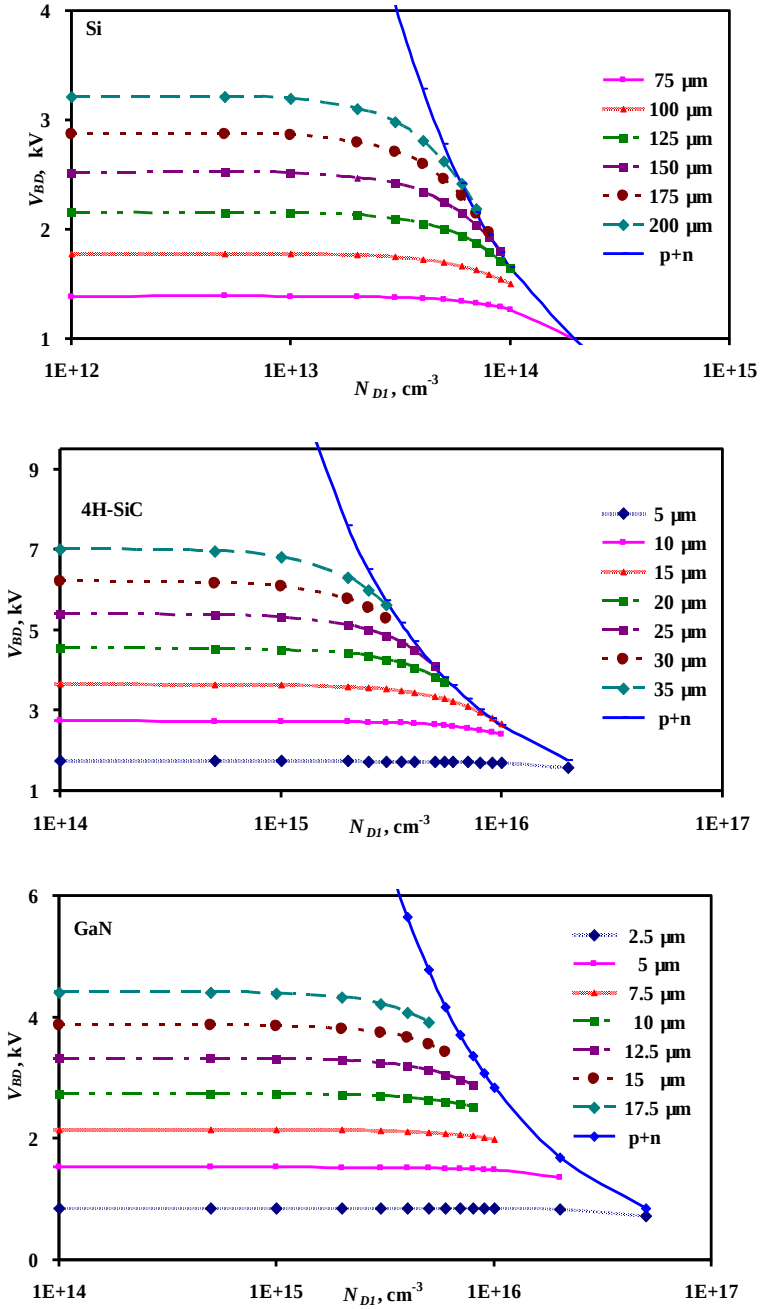


Fig. 3 The breaking voltage as a function of doping concentration (N_{D1}) for a p^+n diode and a $p^+n^-n^+$ structure for different n^- base widths and different semiconductor materials: a) Si, b) 4H-SiC and c) GaN

From the information calculated and presented in Figures 2 and 3, it can be concluded that the estimation of the minimum lightly doped drift region thicknesses required in a $p^+n^-n^+$ structure using Equation (7) is not suitable. For example, if a 2 kV Si device is designed with a drift region doping concentration of 4.5×10^{13} cm^{-3}, using the p^+n structure, Equation (7), the thickness is 296 μm, while the base thickness is only 123 μm when using the $p^+n^-n^+$ structure. For a 2 kV 4H-SiC device with a drift region doping concentration of 6×10^{15} cm^{-3}, the base thickness is 23.6 μm when using Equation (7) and only 9.4 μm when using the $p^+n^-n^+$ structure analysis. Similarly, for a 2 kV GaN device with a drift region doping concentration of 9×10^{15} cm^{-3}, the thickness is 18.33 μm when using Equation (7) and only 7.4 μm when using the $p^+n^-n^+$ structure.

IV. MODELING OF FORWARD VOLTAGE DROP

The IGBT under an inductive load switching condition is simulated in Matlab® and Simulink®. The circuit schematic is plotted in Figure 4. A freewheeling $p^+n^-n^+$ diode is employed in the simulation. The $p^+n^-n^+$ diode model described extensively in [7, 8] is used for the simulation of Si, SiC, and GaN diodes for different design voltages. In [7], the diode model is used to study the role of the avalanche during snappy recovery, while in this work, for different simulation conditions such as blocking voltage and doping concentration of lightly doped drift region the thickness of the doped drift region is calculated and the data is used to obtain the forward voltage drop from the simulation results. Then the results are used to determine the optimum width of the drift region for different blocking voltages to achieve a minimal forward voltage drop.

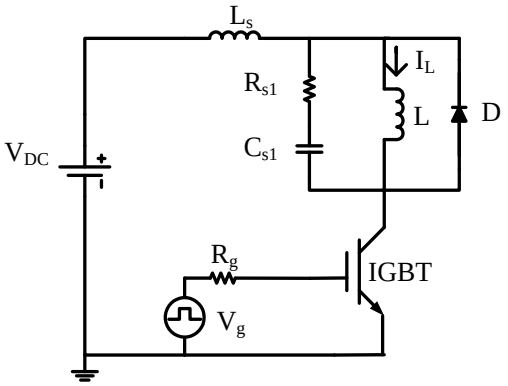


Fig. 4 Schematic of inductive load switching with free-wheeling diode, D

The Fourier-based solution is used to solve the ambipolar diffusion equation that describes the carrier distribution $p(x)$ in the lightly doped drift region. The diode parameters for the simulation are presented in Table 2. The supply voltage, V_{DC} = 300 V, and the load current, I_L = 50 A, are used for all of the simulations.

TABLE 2 SIMULATION PARAMETERS

Parameters	**Si**	**SiC**	**GaN**
N_{D2} (cm^{-3})	10^{19}	10^{19}	10^{19}
N_A, (cm^{-3})	10^{18}	10^{18}	10^{18}
n_i, (cm^{-3})	$1.48x10^{10}$	$6.84x10^{-11}$	$1.82x10^{-11}$
τ, (μs)	0.44	0.15	0.15
h_p (cm^4s^{-1})	10^{-14}	10^{-14}	10^{-14}
h_n, (cm^4s^{-1})	10^{-14}	$1.3x10^{-14}$	$1.3x10^{-14}$
μ_n ($cm^2V^{-1}s^{-1}$)	1400	900	1000
μ_p, ($cm^2V^{-1}s^{-1}$)	450	100	200
ε, ($F\ cm^{-1}$)	11.8	10	8.9
v_{sat}, (cm/s)	10^7	$2.7x10^7$	$2.2x10^7$

The forward voltage drop, V_F, of a $p^+n^-n^+$ diode is calculated as the sum of the two junction voltages, V_{j1} (n^+-n^-) and V_{j2} (n^--p^+), and the voltage drop across the lightly doped n^- drift region:

$$V_F = V_{j1} + V_{j2} + V_{n^-} \tag{13}$$

For a given semiconductor material, the junction voltages, V_{j1} and V_{j2}, depend on the doping concentration of the drift region and correspondingly to the boundary carrier densities, p_{x1} and p_{x2}

$$V_{j1} = V_T \ln\left(\frac{p_{x1}N_{D1}}{n_i^2}\right) \tag{14}$$

$$V_{j2} = V_T \ln\left(\frac{p_{x2}}{N_{D1}}\right). \tag{15}$$

The voltage drop in the n^- drift region is calculated by dividing the drift region into equal segments and calculating the voltage drop in every segment using the carrier concentrations at the end of each segment. The carrier distribution at each point can be generated through the inverse Fourier transformation, while the carrier distribution between two points is a linear approximation (Figure 5):

$$p_T = p_{T1} + (p_{T2} - p_{T1})\frac{x}{\Delta x}. \tag{16}$$

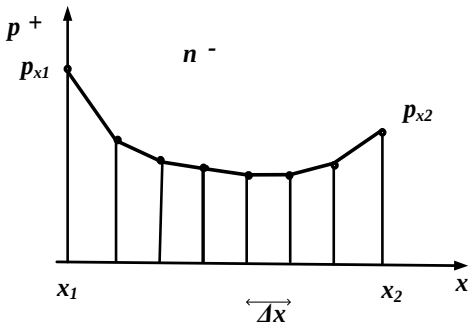


Fig. 5 The carrier distribution in n^- region during the forward conduction state

The resistive voltage drop for every segment, V_{seg}, is calculated by:

$$V_{seg} = \frac{J}{q(\mu_n + \mu_p)} \int_0^{\Delta x} \frac{dx}{p_T}. \tag{17}$$

The total voltage drop in the n^- drift region is calculated as a sum of the voltage drop of each segment [7] and is presented by

$$V_{n^-} \approx \frac{I_A}{qA(\mu_n + \mu_p)} \frac{x_2 - x_1}{M-1} \sum_{k=0}^{M-1} \left[\frac{1}{p_{T(k)} - p_{T(k-1)}} \ln\left(\frac{p_{T(k)}}{p_{T(k-1)}} \right) \right] - V_T \left(\frac{\mu_n - \mu_p}{\mu_n + \mu_p} \right) \ln\left(\frac{p_{x2}}{p_{x1}} \right), \tag{18}$$

where A is the cross-section area of the drift region, M is the number of terms of the Fourier series, and the carrier distribution, $p_{T(k)}$, is calculated by

$$p_{T(k)} = p\left(x_1 + \frac{k(x_2 - x_1)}{M-1} \right) + \frac{\mu_n N_{D1}}{\mu_n + \mu_p}. \tag{19}$$

V. SIMULATION RESULTS

As described above, there is little change to the minimum base width required for a given breakdown voltage (Figure 4) for donor impurity doping concentrations at or below 3×10^{13} cm^{-3} for Si, 2.5×10^{15} cm^{-3} for 4H-SiC, and 5×10^{15} cm^{-3} for GaN. Also, if the junction voltages, V_{j1} and V_{j2}, as calculated using Equations (14) and (15), are summed, the total junction voltage becomes:

$$V_{j12} = V_T \ln\left(\frac{p_{x1} p_{x2}}{n_i^2} \right). \tag{20}$$

The total junction voltage, V_{j12}, does not directly depend on the doping concentration of the lightly doped drift region, N_{D1}. However, there is a dependency between the boundary values of the excess charge concentrations, p_{x1} and p_{x2}, and the impurity doping level that determines junction voltage values. Also, the excess carrier concentrations, p_{x1} and p_{x2}, depend on the emitter recombination parameters; but because the analysis focuses on the influence of the doping concentration of the lightly doped drift region, N_{D1}, on the forward voltage drop and the doping concentration of the other two regions are assumed as constants, the emitter recombination parameters are taken as constants too. They are included in the model for calculation of the total forward voltage drop [4].

To obtain the minimum forward voltage drop during conduction, V_F, the minimum width of the drift region, corresponding to the minimum doping concentration, should be used. However, the results from the simulation do not agree with this simple assertion from (20). Increasing the doping concentration, N_{D1}, for the same breakdown voltage leads to a decrease of V_F to a minimum value, after which further increases in the doping concentration cause an increase in the forward voltage drop. Higher doping concentrations, N_{D1}, lead to reduced injection efficiencies of the higher doped p^+ and n^+ emitters into the drift region, and, therefore, decrease the values of the carrier densities, p_{x1} and p_{x2}, at the region boundaries. From (20) it can be seen that as the boundary charge concentrations are reduced, the contribution of the junction voltages to the total forward drop tends to cause a reduction in V_F. Simulation results for the boundary carrier densities, p_{x1} and p_{x2}, of a diode designed to breakdown at 5 kV are shown in Figure 6 and confirm the relationships. The boundary carrier density, p_{x1}, decreases by 3.7% as the doping concentration, N_{D1}, increases from 10^{12} to 1.5×10^{13} cm^{-3}, while correspondingly, p_{x2} decreases by 3.1 %. This explains the difference in the rate of change of the junction voltage, V_{j1}, when compared to V_{j2}, both as a function of base impurity doping.

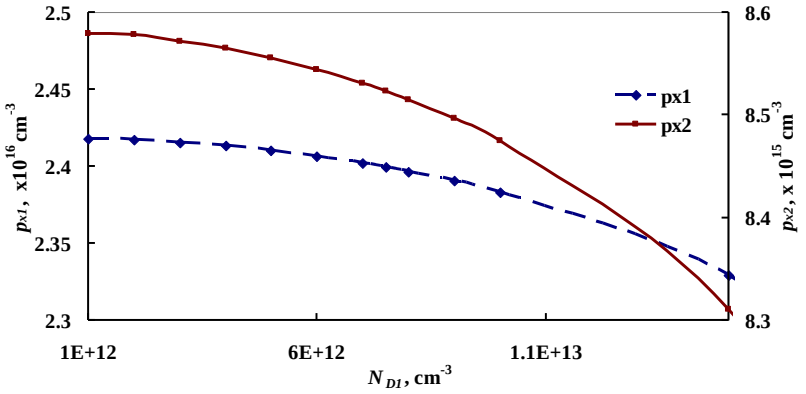


Fig. 6 The boundary carrier densities, p_{x1} and p_{x2}, of the lightly doped drift region as a function of the doping concentration, N_{D1}, for a 5 kV $p^+n^-n^+$ structure during the on-state

The voltage drop across the n^- drift region, V_{n^-}, depends on the boundary carrier densities, p_{x1} and p_{x2}, and the doping concentration, N_{D1}, of the lightly doped drift region, as shown in (18) and (19). The simulation results for the voltage, V_{n^-}, are plotted in Figure 7a) along with the total junction voltage for comparison. The magnitude of change due to the contribution of the drift region voltage is much greater than the contribution from the junction voltage drops. Thus, the net effect on the total forward voltage drop, V_F (sum of junction and drift region drops), tends to follow that of V_{n^-} and is illustrated in Figure 7b).

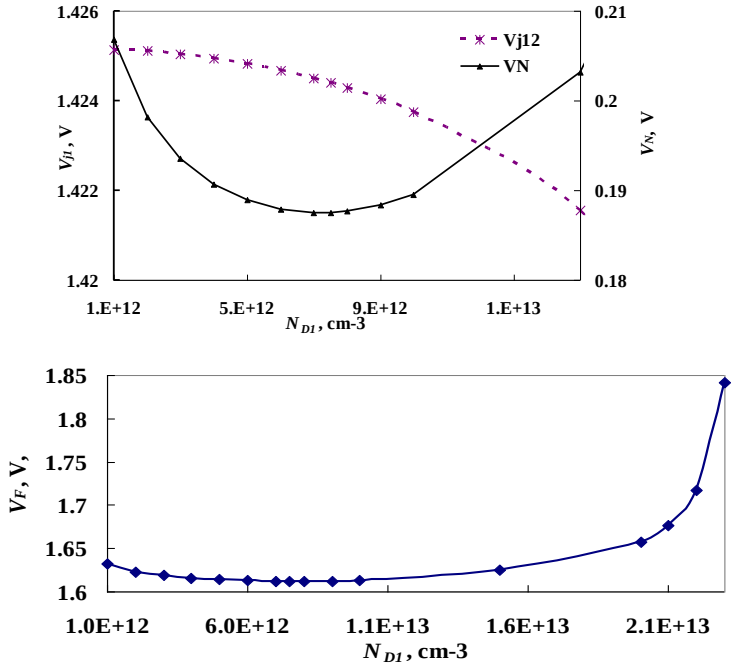


Fig. 7 The simulation results of a Si $p^+n^-n^+$ structure for a designed breakdown voltage of 5 kV: a) the total junction voltage and the voltage drop across the n^- drift region as a function of the doping concentration of the lightly doped drift region; b) the total forward voltage drop as a function of the doping concentration

Thus, an analytical optimization is possible by determining the best doping concentration and base width that simultaneously provide the appropriate voltage breakdown value and the minimal associated forward voltage drop during conduction. From Figure 7b), the minimum forward voltage for this diode design is at a doping concentration of $N_{D1} = 8 \times 10^{12}$ cm^{-3} (with V_F = 1.615 V). This point is also shown as a star in Figures 2a) and 10a). Note that typical impurity doping concentrations for high-voltage Si devices correspond to the right-most part of the graph in Figure 7b). The analysis shows that optimization of the doping concentration to minimize V_F would mean a reduction of 0.23 V or more, a reduction of more than 12% in the forward drop.

A similar result for the wide bandgap device (designed in GaN) is not present as it was in Si. Figure 8 indicates that reducing the base-doping concentration below 10^{15} cm^{-3} reduces the forward voltage drop by less than 1%. Hence, it is clear that enforcing this optimization scheme for SiC and GaN to tie the n^- base doping to the breakdown voltage and the associated forward voltage drop is not necessary. This allows a device designer additional freedom when optimizing for particular performance criteria in wide bandgap materials.

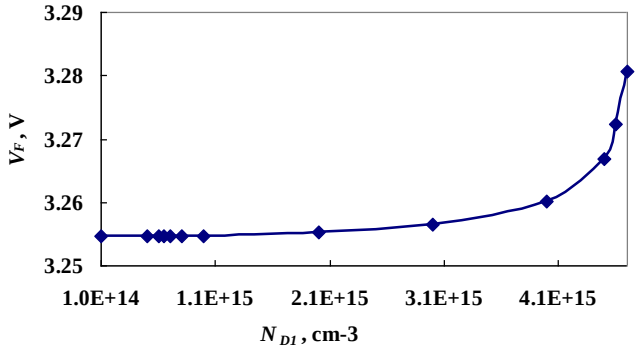


Fig. 8 The simulation results for the total forward voltage drop as a function of the doping concentration of a GaN $p^+n^-n^+$ structure for a designed breakdown voltage of 5 kV

Similar analyses of Si, SiC, and GaN $p^+n^-n^+$ diodes were performed for breakdown voltages from 1 to 10 kV. In Figure 9, the results of the (optimum required) doping concentration of the lightly doped drift region, N_{D1}, as a funcion of the designed breakdown voltage, V_{BD}, to achieve the minimum forward voltage drop possible, are plotted. It can be seen from the simulation results that as the desired breakdown voltage increases from 1 to 10 kV, the optimum concentration, N_{D1}, decreases for the Si diode from 1.98×10^{14} to 3.35×10^{12} cm^{-3}, for the SiC diode from 2×10^{16} to 3×10^{13} cm^{-3}, and for the GaN diode from 4×10^{16} to 7×10^{13} cm^{-3}.

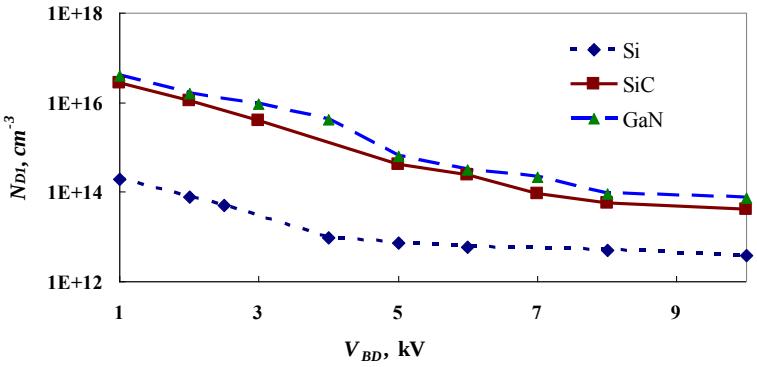
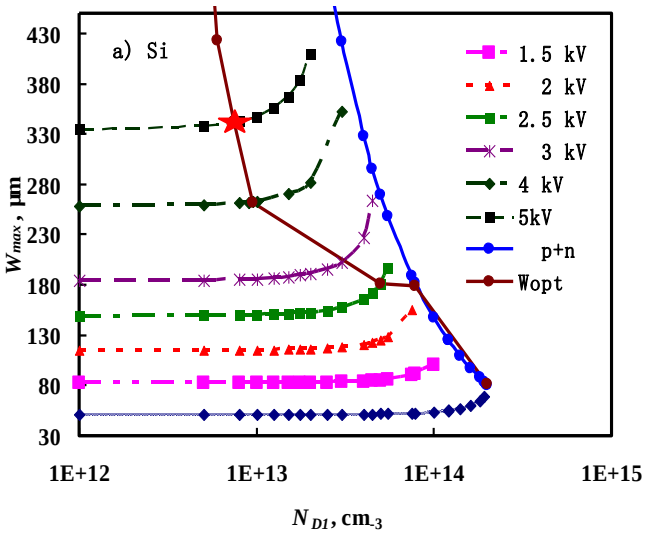


Fig 9 The optimized doping concentration of the lightly doped drift region as a function of the designed breakdown voltage that results in a minimum forward voltage drop

In Figure 10 are presented the simulation results of the minimum n^- base width (W_{min}) as a function of doping concentration (N_{D1}) for a p^+n diode and a $p^+n^-n^+$ structure for different breakdown voltage designs in Si, SiC, and GaN. For breakdown voltages below a certain threshold (material dependent), the p^+n structure is preferred to achieve a minimal forward voltage drop. This threshold is 2 kV in Si, 2.5 kV in SiC, and 3 kV in GaN. Above these threshold values for breakdown voltage, a $p^+n^-n^+$ structure is preferable to achieve a minimal forward voltage drop. These optimal base widths are denoted as W_{opt} in Figure 10 at the associated impurity doping concentration for a given designed breakdown voltage rating.



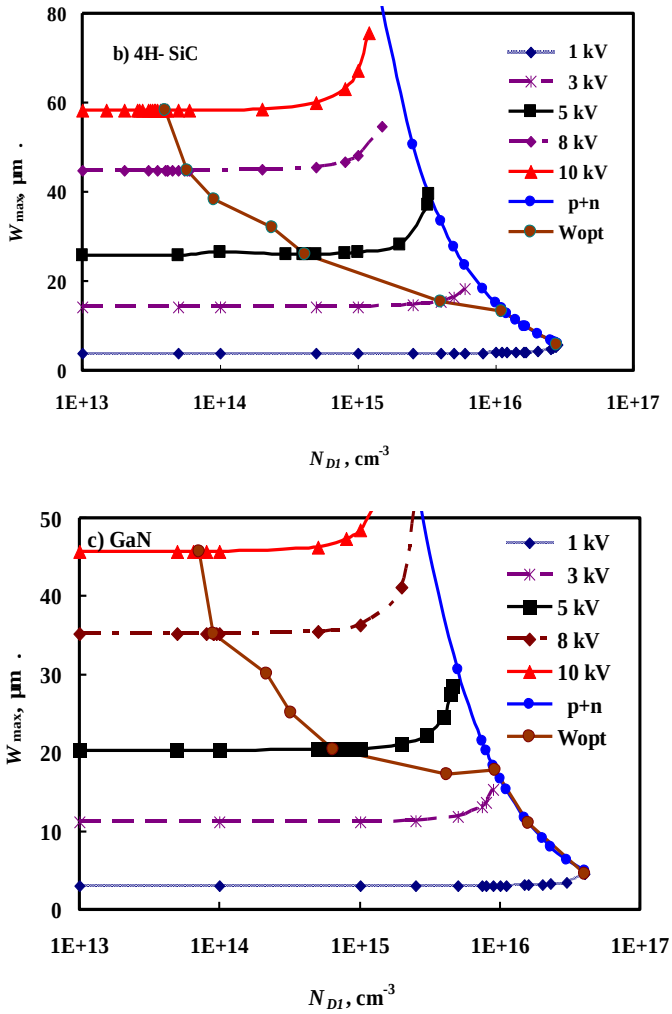


Fig. 10 Replot of results from Fig. 2 with an overlap of the optimum width, W_{opt}, of a $p^+n^-n^+$ structure for different designed breakdown voltages that minimize the forward voltage drop in different semiconductor materials: a) Si, b) 4H-SiC and c) GaN

Minimizing the drift region width strictly based on a voltage breakdown capability requirement from design equations derived using a p^+n structure erroneously gives an increase in forward voltage drop over the optimized width obtained by the process described above for the $p^+n^-n^+$ device. These results collectively provide a device designer with the correct and best first-order values for base region width and associated impurity doping concentration to give the desired breakdown voltage at minimum forward voltage drop in Si, SiC, and GaN.

VI. CONCLUSIONS

The complete one-dimensional model for calculation of the minimum depletion layer width, W_{min}, for a given breakdown voltage, V_{BD}, of a $p^+n^-n^+$ structure is developed and used to calculate the optimum width of the depletion layer for different blocking voltages to achieve a minimal forward drop. The results show that the calculations of the lightly doped drift region thicknesses, and associated breakdown voltages and forward voltage drops, lead to incorrect solutions when applied to high voltage $p^+n^-n^+$ structures using the simplified model equations. These simplified expressions were derived strictly for a p^+n structure and have historically been presented in most publications on the subject of power devices and avalanche breakdown. These results also indicate a minimal impurity doping concentration for $p^+n^-n^+$ structures, below which little improvement in breakdown capability can be achieved. This is to be expected as the impurity concentration becomes so small that the material can be little distinguished from intrinsic. Further, it has been shown that this optimization is appropriate for wide bandgap semiconducting materials such as SiC and GaN.

Specifically, the analysis shows for example that optimization of the doping concentration to minimize V_F in a 5 kV Si diode could result in more than a 12% decrease in the forward drop, while for SiC and GaN this decrease is insignificant, typically less than 1%. Therefore, an optimization of the forward voltage drop by using the optimal doping concentration for corresponding breakdown voltages is necessary for proper design of a Si diode, while for wide band gap material devices this optimization is not necessary.

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