The On-Resistance Model of Silicon Carbide Merged PiN Schottky (MPS) Diodes

Qiwen Du¹, Xuehui Tao*  
School of Soochow University, Suzhou 215000, China  
*Corresponding author e-mail: xhtao@suda.edu.cn, ¹120174246016@stu.suda.edu.cn

Abstract. A novel resistance model of silicon carbide (SiC) merged PiN Schottky diodes (MPS) is presented in this study. With this model, the device characteristics and power dissipation can be predicted. The on-resistance in the three operating modes, namely, unipolar, low-injection and high-injection modes, is calculated. In the unipolar and low-injection modes, the effect of temperature on carrier mobility and conduction angle are added to the factors that need to be considered, whereas the influence of current density is considered in the high injection mode. The carrier distribution in the high injection mode is analyzed and applied to determine the resistance. The model is verified experimentally via comparison of the calculated and measured characteristics.

1. Introduction
Silicon carbide (SiC) is a new semiconductor material characterized by a wide band gap, high thermal conductivity, high breakdown field and high electron saturation velocity. These properties make SiC the best choice for manufacturing power devices [1-4]. The three classes of SiC power diodes include the (a) SiC Schottky (SBD) diode, (b) SiC PiN diode and the (c) SiC merged PiN Schottky (MPS) diode [5]. SiC SBD is the most suitable SiC product due to its high switching speed, low forward voltage, short reverse recovery time and simple manufacturing process [6]. However, the reverse leakage current of SBD is too large in practical applications [7]. SiC PiN diode, which has low leakage current and high breakdown voltage compared with the Schottky diode, was the first diode used in high-voltage systems. The main disadvantages of the PiN diode include a large amount of stored charge during transition from the on state to the reverse blocking state which greatly increases the switching time of the PiN diode and a large forward voltage drop [8, 9]. SiC MPS is a new kind of power semiconductor device that takes advantages of the properties of SBD and PiN. SiC MPS offers Schottky-like low turn-on voltage, large on-current, rapid switching, PiN-like low leakage and high blocking voltage [10]. SiC MPS has become the most popular SiC diode.

An accurate and reliable device model of the SiC MPS is required to fully utilize the features of MPS for circuit designers. Out of 20 SiC diode models reviewed in [11-16], but only one physical model which is suitable for the unipolar mode has been developed for the resistance of the MPS diode while others are behavioral models which simulate power devices without considering their physical mechanism of operation. Since the structure and working principle of MPS are different from those of SBD, PiN and other types of diodes, the physical model of the resistance of the diode cannot be used
universally. The relationship between mobility and temperature is considered in the resistance model of the MPS diode in [17], but the model is also only applicable to unipolar mode.

The three modes are distinguished according to the applied reverse bias voltage $V_f$ and the distribution of carriers in the drift region. When $V_f$ is low, only the portion of the Schottky region is turned on, the PN junction is not turned on, the carrier concentration change is negligible, and the MPS operates in the unipolar mode. When $V_f$ is close to the turn-on voltage of the PN junction, the PN junction is turned on and the carrier concentration change is negligible. The MPS is in a low injection mode. When the reverse bias voltage is much larger than the turn-on voltage of the PN junction, the carrier concentration in the drift region changes drastically, and the conductance modulation effect occurs in the drift region, which is a high injection state. In this paper, a detailed on-resistance model at steady state is presented based on the resistance model in [17]. The effect of temperature on mobility, conduction angle, doping concentration and forward voltage is considered in the model when MPS operates in the unipolar and low-injection modes. Mobility has a major impact on the on-resistance. The model predicts the temperature characteristics of the on-resistance with consideration to mobility. In the case of the high-injection mode, the effect of conductance modulation on carrier concentration is considered. The conductance modulation effect reduces the resistance via increasing the carrier concentration.

Although a variety of other resistance models have been introduced in the past, the model presented in this paper is the only resistance model of SiC MPS that is derived from the principle of the resistor, considers the effect of temperature on mobility and is applicable to three operating modes.

2. Carrier Mobility
The mobility of the low electric field is a function of the doping concentration and temperature. The mobility of the carrier is independent of electric field intensity at less than $10^3 V.cm^{-1}$ [18]. The empirical expression of the electron mobility for the low field [16, 19] is as follows:

$$\mu_e = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + \left(\frac{N}{N_{ref}}\right)^\alpha}$$  \hspace{1cm} (1)

Where $N$ is the total doping concentration, and the parameters $\mu_{min}$, $\mu_{max}$, $N_{ref}$ and $\alpha$ are fitting parameters. At low electric fields, which in the 4H SiC material are as follows [20]:

$$\begin{cases} 
\mu_{min} = 950 \times \left(\frac{T}{300 K}\right)^{-2.4} cm^2/Vs \\
\mu_{max} = 40 \times \left(\frac{T}{300 K}\right)^{-0.5} cm^2/Vs \\
N_{ref} = 2 \times 10^{17} \times \left(\frac{T}{300 K}\right) cm^3 \\
\alpha = 0.76 
\end{cases}$$  \hspace{1cm} (2)

A widely used empirical expression for the whole mobility $\mu_p$ was proposed as follows [7]

$$\mu_p = 15.9 + \frac{MUP}{1 + \left(\frac{N}{1.76 \times 10^{19}}\right)^{0.34} \left(\frac{T}{300 K}\right)^{-2.15}}$$  \hspace{1cm} (3)

Where $MUP$ is the empirical parameter, which is $108.9 cm^2/Vs$ in 4H-SiC [7].
The carrier mobility in each region as a function of temperature is obtained by substituting the carrier concentration of each region into equation (1) or (3), and the effect of temperature on mobility is considered in the resistance model by substituting the mobility model into the resistance model.

3. Resistance model of the unipolar mode

The basic unit cell of an MPS diode is shown in Figure. 1. At low forward bias, the Schottky region is turned on first, and MPS operates in the unipolar mode. The forward current is mainly generated by the thermal electron emission effect of the Schottky region. The characteristics of MPS are similar to Schottky diodes, and the minority carriers in the drift region are negligible. Therefore, the carrier concentration of the drift region is approximately equal to the doping concentration. To illustrate the working principle of MPS in detail, the simplified equivalent circuit of MPS in unipolar mode is shown in Figure. 2. In general, the parameters with the subscript 1, subscript 2, and subscript 3 refer to the parameters in the unipolar mode, low-injection mode and the high-injection mode.

- $s$ is two times the width of the P+ region, $x_j$ is the depth of the P+ region, $m$ is the distance between the two P+ regions, $w$ is the width of the depletion region, $2d$ is the width of the JFET region, $t$ is the thickness of the drift region, $t_{sub}$ is the thickness of the substrate region, and $\alpha$ is the conduction angle of the current in the drift region. The resistance of each part is analyzed as follows.
3.1. Resistance of the JFET region and substrate

The width of the JFET area $2d$ is expressed as $2d=m+s−2w$ obtained using Figure. 1. The depletion layer width of the JFET region is

$$w = \sqrt{\frac{2e_e(V_{in}−V_f)}{qN_d}}$$

(4)

Where $N_d$ is the doping concentration of the drift region, $V_{in}$ is the built-in junction potential.

$$V_{in} = \frac{kT}{q} \ln\left(\frac{N_d}{n_i}\right)$$

(5)

Where $kT/q$ and the intrinsic carrier concentration are taken as values under normal temperature conditions, $kT/q=0.0259$ and $n_i=5\times10^9 cm^{-3}$ [20]. $N_d$ is the doping concentration of the P+ region. Respectively, the specific on-resistance of the JFET region the substrate region are as follows:

$$R_{jffe,sp} = \frac{(x_s + w)(s + m)}{2dq\mu_{jffe}N_d}$$

(6)

$$R_{sub,sp} = \frac{t_{sub}}{q\mu_{sub}N_{sub}}$$

(7)

Where $N_{sub}$ is the doping concentration of the substrate region. $\mu_{jffe}$ and $\mu_{sub}$ are the electron mobility of JFET region and substrate.

3.2. Resistance of the drift region

The angle between the direction in which the current is diffused and the vertical direction is assigned as the conduction angle $\alpha$ as shown in Figure. 1. The conduction angle of the current is assumed to increase linearly with temperature in the drift region. The parameters $k_t$ and $b_t$ take account of this effect. Thus, the current distribution in the drift region is a trapezoid or a trapezoid with a rectangle in the unipolar mode. The resulting specific on-resistance of the drift region in the unipolar mode is given by

$$R_{d,sp} = \frac{(m + s)}{2\tan(k_tT + b_t)q\mu_{dfe}N_d}\ln\left(\frac{d + L\tan(k_tT + b_t)}{d}\right) + \frac{t - L}{q\mu_{dfe}N_d}$$

(8)

Where $\mu_{dfe}$ is the electron mobility of the drift region and the parameter $L$ is the high of the trapezoid which is expressed as

$$L = \begin{cases} \frac{t - w}{2}\tan(k_t + b_t) & T_i < T < T_1 \\ \frac{e}{2\tan(k_t + b_t)} & T_1 < T < 448K \end{cases}$$

(9)

Where $T_i$ is the temperature at which the current just reaches the N+ substrate and spreads to the entire cell width.

Figure. 2 shows that the total specific on-resistance in the unipolar mode can be obtained using equation (10).
4. Resistance model of the bipolar mode

4.1. Low injection mode

The drift region is in the low-injection state when $V_f$ is slightly larger than the turn-on voltage of the PN junction. The simplified equivalent circuit is shown in Figure 3. In general, a low-injection mode means that the minority carrier concentration is much smaller than the background doping concentration. The lost majority carrier concentration and the minority carrier concentration are negligible compared with the background doping concentration in the P+ region and substrate. The substrate resistance is the same as that of the unipolar mode. The specific on-resistance of the P+ region in the low-injection mode is given by

$$ R_{on,p} = \frac{(m + s) \ln d + L \tan(kT + b)}{2 \tan(kT + b) q \mu_{opt} N_d^d} + \frac{t - L}{q \mu_{opt} N_d} + \frac{x_j (s + m)}{2 dq \mu_{opt} N_d} + \frac{t_{sub}}{q \mu_{opt} N_{sub}} $$

(10)

4.2. High injection mode

As $V_f$ continues to increase, the concentration of holes in the drift region exceeds the background doping concentration $N_d$, and MPS operates in the high injection mode. The electrically neutral...
condition requires the equal concentration of electrons and holes, and the electron concentration of the drift region increases to maintain the electrical neutrality of the drift region [21]. The large concentration of free carriers reduces the resistance of the drift region. Therefore, the carrier distribution of MPS in the high-injection mode must be understood first to solve the resistance model.

1) Carrier distribution in the drift region

The transport of carriers is considered as one-dimensional. The dimensional coordinate system defined is shown in Figure. 4.

The continuous equations of the electron concentration \( n(x) \) and the whole concentration \( p(x) \) in the drift region are as follows:

\[
\frac{\partial^2 n}{\partial x^2} - \frac{n}{L_n^2} = 0 \tag{13}
\]

\[
\frac{\partial^2 p}{\partial x^2} - \frac{p}{L_p^2} = 0 \tag{14}
\]

Where \( L_n \) and \( L_p \) are the diffusion length of electrons and holes, respectively. \( L_n \) and \( L_p \) are assumed as constant at a given current density in the drift region, and the thickness of the drift region is greater than the diffusion length of the carriers. Therefore, equations (13) and (14) are constant coefficient differential equations. Assuming that the width of the depletion region is zero in the high-injection state.

![Figure 4. Coordinate systems used in developing the MPS model](image)

![Figure 5. Carrier distribution in the drift region](image)

In the high-injection mode, the carrier distribution in the drift region is similar to that in Figure. 5. The concentrations of electrons and holes in the drift region are not equal everywhere. The entire drift region can still be considered electrically neutral. The concentration of electrons and holes is assumed to satisfy the quasi-neutral condition (\( n(x) = p(-x) \)).

The injected carriers are completely recombined in the drift region because its thickness is greater than the diffusion length of the carriers. At the junction of the drift region and the P+ region \((x=-t/2)\), the total current is completely generated by the transport of holes. At the junction of the drift region and the substrate region \((x=t/2)\), the total current is completely produced by the transport of electrons. The solutions of equations (13) and (14) are as follows:
\[ n(x) = A \exp(x/L_n) \quad (15) \]
\[ p(x) = D \exp(-x/L_p) \quad (16) \]

Where the constants \( A \) and \( D \) depend on the boundary conditions of the drift region. Equation (17) is obtained utilizing the quasi-neutral condition.

\[ n(t/2) + p(t/2) = A[\exp(-t/2L_n) + \frac{L_p}{L_n} \exp(-t/2L_p)] \quad (17) \]

From (17) the concentration of electrons and holes can be written in terms of the total carrier concentration at \( x=t/2 \).

\[ n(x) = \frac{[n(t/2) + p(t/2)]L_n \exp(x/L_n)}{L_n \exp(t/2L_n) + L_p \exp(-t/2L_p)} \quad (18) \]
\[ p(x) = \frac{[n(t/2) + p(t/2)]L_p \exp(-x/L_p)}{L_n \exp(t/2L_n) + L_p \exp(-t/2L_p)} \quad (19) \]

The carrier distribution of the drift region can be determined as long as the sum of the concentrations of electrons and holes at \( x=t/2 \) is obtained. \( J_p(t/2) \) is subtracted from \( J_n(t/2) \) to express \( n(t/2) + p(t/2) \). The drift current component is negligible because of the low electric field intensity in the drift region. The following expression is obtained for the current density at \( x = t/2 \):

\[ J_r = J_n(t/2) = q[D_n dn/dx + D_p dp/dx]|_{x=t/2} \quad (20) \]

Total current density \( J_T \) is equal everywhere. \( n(t/2) + p(t/2) \) is described in terms of the parameter \( J_T \) using (15) and (16).

\[ n(t/2) + p(t/2) = \frac{J_T[L_n \exp(t/2L_n) + L_p \exp(-t/2L_p)]}{q[D_n \exp(t/2L_n) - D_p \exp(-t/2L_p)]} \quad (21) \]

The concentration distribution of electrons and holes in the drift region are expressed as follows

\[ n(x) = \frac{J_T L_n \exp(x/L_n)}{q[D_n \exp(t/2L_n) - D_p \exp(-t/2L_p)]} \quad (22) \]
\[ p(x) = \frac{J_T L_p \exp(-x/L_p)}{q[D_n \exp(t/2L_n) - D_p \exp(-t/2L_p)]} \quad (23) \]

2) Resistance of the drift region

Assuming that the distribution of carriers in the drift region conforms to the carrier distribution law in (22) and (23), the distribution of carriers in the entire drift region is uniform, and the drift region is regarded as a resistor. The distribution of resistance of MPS diodes is shown in Figure.6. A simplified equivalent circuit is shown in Figure. 3.
At a given current density, \( L_n \) and \( L_p \) are assumed as constant in the drift region. Using (22) and (23), the carrier concentration increases rapidly as \( J_T \) increases, which leads to a decrease in carrier lifetime and mobility. Reduced carrier lifetime results in reduced diffusion length [21]. The mobility is assumed to be constant, and the diffusion length decreases as \( J_T \) increases as described in the equation as follows:

\[
L_n = L_p = 10^{-4} \times [1.8 \left( \frac{J_T}{10000} \right)^{-0.28} + 0.12]
\]

(24)

\[4 \times 10^4\]

\[2.4 \times 10^4\]

\[2.2 \times 10^4\]

\[2.0 \times 10^4\]

\[1.8 \times 10^4\]

\[1.6 \times 10^4\]

\[1.4 \times 10^4\]

\[1.2 \times 10^4\]

\[1.0 \times 10^4\]

\[0 \quad 1 

\[1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \]

**Figure 6.** Plot of diffusion length versus \( J_T/10,000 \)

Formula (24) is obtained using the curve fitting of MATLAB, which is justified as follows: (i) The 1-3μm is selected because the diffusion length is smaller than the thickness of the drift region and slowly decreases as \( J_T \) increases [15]; and (ii) the power function is selected because the type of curve in equation (24) should make the curve of the total on-resistance monotonous and smooth according to the forward static characteristics of MPS [5]. The plot of diffusion length versus \( J_T/10,000 \) is shown in Figure 6.

\( \mu_{n3} \) and \( \mu_{p3} \) are the mobility of electrons and holes in the high-injection mode. The specific on-resistance of the drift region is

\[
R_{on,p3} = A \int_0^{\frac{\mu_{n3}}{L_n}} dx + A \int_0^{\frac{\mu_{p3}}{L_p}} dx \\
\approx A \int_0^{\frac{\mu_{n3}}{L_n}} dx \frac{x}{L_n} \exp\left(\frac{x}{L_n}\right) + A \int_0^{\frac{\mu_{p3}}{L_p}} dx \frac{x}{L_p} \exp\left(\frac{x}{L_p}\right) \\
= A \left( \frac{L_n}{\mu_{n3}\mu_{p3}L_p} \right)^{\frac{1}{2}} \arctan\left( \frac{\mu_{n3}L_n}{\mu_{p3}L_p} \right)^{\frac{1}{2}} + A \left( \frac{L_p}{\mu_{n3}\mu_{p3}L_n} \right)^{\frac{1}{2}} \arctan\left( \frac{\mu_{p3}L_p}{\mu_{n3}L_n} \right)^{\frac{1}{2}} \\
A = \frac{D_n \exp(\tau/2L_n) - D_p \exp(\tau/2L_p)}{J_T}
\]

(25)

(26)

The carrier mobility is a function of the carrier concentration. If the relationship between resistance and temperature is continuously derived, the formula is too cumbersome and the integration is very
difficult. However, the relationship between resistance and temperature at a given temperature can be calculated.

3) Total specific on-resistance

In the high-injection mode, the carrier concentration of the MPS diode from the JFET region to the substrate region is continuous, and the carrier concentration of the JFET region and the substrate region increases approximately linearly \[22\]. The assumptions are as follows: (i) the carriers of the JFET region are electrons, and the electron concentration increases linearly from the background doping concentration to \(n_j\) as \(x_p\) increases in the JFET region; (ii) the carriers of the substrate are electrons, and the concentration of carriers increases linearly from \(n_s\) to \(N_{sub}\) as \(x_s\) increases in the substrate; and (iii) the carriers of the P+ region are holes, and the hole concentration is linearly reduced from the background doping concentration to \(n_j\) as \(x_p\) increases in the P+ region. \(n_j\) represents the carrier concentration at \(x=-t/2\) \((n_j=n(-t/2)+p(t/2))\). \(n_s\) represents the concentration of carriers at \(x=t/2\) \((n_s=n(t/2)+p(t/2))\). From Figure. 3 and these effects, the following equation of the total specific on-resistance in the high injection mode is obtained.

\[
R_{on,y,x} = \frac{1}{q\mu_s s(n_j-N_j)} + \frac{t_{sub} \ln \left(\frac{N_{sub}}{n_j}\right)}{q\mu_s s(n_j-N_j)} + \frac{t_{sub} \ln \left(\frac{N_{sub}}{n_j}\right)}{q\mu_s s(n_j-N_j)} \\
+ A \left(\frac{1}{\mu_s \mu_p L_p} \right)^2 \arctan \left[ \frac{\mu_s L_p}{\mu_s \mu_p L_p} \right] + A \left(\frac{1}{\mu_s \mu_p L_p} \right)^2 \arctan \left[ \frac{\mu_s L_p}{\mu_s \mu_p L_p} \right]
\]

(27)

5. The model verification and analysis

Calculations and the measurements of the SiC MPS diode IDM10G120C5 were performed to verify the accuracy of the resistance model. The data of the measurements is obtained from the datasheet of IDM10G120C5. The various parameters of the MPS diode IDM10G120C5 are listed in Table 1 [23]. Comparison results of the MPS diode investigations are presented in Figures. 7–9. The points and the solid lines denote the data of the measurements and the calculations, respectively.

In Table 1, \(t_s\) is the length of the buffer layer and \(S_1\) is the effective cross-sectional area of the MPS diode. The value of the mobility was calculated using the formulas (1) and (3) for \(T=298K\), \(N=1\times10^{19} \text{cm}^{-3}\).

| Parameter | Value | Unit |
|-----------|-------|------|
| \(N_a\)   | \(1\times10^{19}\) | \(\text{cm}^{-3}\) |
| \(N_d\)   | \(1.2\times10^{16}\) | \(\text{cm}^{-3}\) |
| \(N_{sub}\)| \(1\times10^{19} \text{cm}^{-3}\) | \(\text{cm}^{-3}\) |
| \(x_j\)   | \(1\times10^{-4}\) | \(\text{cm}\) |
| \(s\)     | \(10\times10^{-4}\) | \(\text{cm}\) |
| \(m\)     | \(10\times10^{-4}\) | \(\text{cm}\) |
| \(t\)     | \(10\times10^{-4}\) | \(\text{cm}\) |
| \(t_{sub}\)| \(110\times10^{-4}\) | \(\text{cm}\) |
| \(S_1\)   | \(0.67\times10^{-2}\) | \(\text{cm}^2\) |

By substituting these parameters into formula (10) and multiplying with \(S_1\), the calculation curve of the unipolar mode is obtained as shown in Figure. 7. The calculation curve of the on-resistance in the
low-injection state is obtained by substituting these parameters into formula (12) and multiplying with $S_i$. The calculation curve of the on-resistance in the low-injection mode is shown in Figure 8. Substituting these parameters into formula (27) and multiplying with $S_i$, the calculation curve in the high-injection mode is obtained as shown in Figure 9.

The dependence of the resistance of MPS diode on temperature in the unipolar and low injection modes is shown in Figures 7 and 8, respectively. In the unipolar and low-injection modes, an increase in temperature greatly reduces the mobility of carriers, which leads to an increase in on-resistance. The conduction of the PN junction increases the cross-sectional area of the current distribution, resulting in a lower on-resistance of the low-injection mode than that of the unipolar mode. Figure 9 shows the dependence of resistance on current density in the high-injection mode for MPS diodes at 25 °C. In the high-injection state, the greatly increased carrier concentration of the drift region reduces the on-resistance of MPS, and the on-resistance of the high-injection state is the lowest among the three modes. Because there are some assumptions in the model derivation process and the packing resistance is neglected, there is a small difference in Figures 7–9. In general, Figures 7–9 show that the qualitative agreement between the calculated and measured characteristics is obtained.

**Figure 7.** Calculated and measured resistance versus temperature of MPS in the unipolar mode

$V_f = 1.5V$

**Figure 8.** Calculated and measured resistance versus temperature of MPS in the low-injection mode

$V_f = 2.5V$
In order to observe the characteristics of the carrier concentration distribution in the drift region more clearly and verify the quasi-neutral assumptions proposed above, the calculated carrier distribution of the drift region in the high-injection state is shown in Figure 10. The carrier distribution was derived from equations (22) and (23) at \( J_T = 10^6 \text{A/cm}^2 \). In Figure 10, the red and blue curves represent the concentration of holes and of the electrons, respectively. The electron and hole concentration curves are symmetric about the y-axis, which is consistent with the quasi-neutral assumption.
The comparison of the contribution of the resistance in the unipolar mode, low-injection mode and high-injection mode at 25 °C is shown in Figure. 11. By substituting $T=298K$ and $V_f=1.5V$ into Equations (6), (7), and (8) (three addition terms of Equation (10)), a histogram of the unipolar mode can be obtained. A histogram of the low injection mode can be obtained by substituting the $T=298K$ and $V_f =2.5V$ into the three addition terms of Equation (12), respectively. A histogram of the high injection mode can be obtained by substituting the $J_T=7\times 10^4$ into the three addition terms of Equation (27), respectively. In the three operating modes, the resistance contributed by the drift region of the MPS diode is the largest. The on-resistance is gradually reduced in the three operating modes, which is caused by the gradual decrease in the resistance of the drift region. Table 1 shows that the thickness of the substrate region is 11 times that of the drift region. However, the low doping concentration of the drift region results in its much larger resistance compared with that of the substrate region. The resistance of the substrate region does not change greatly in the three operating mode. The total resistance of the remaining areas is larger in the unipolar mode and smaller in the bipolar mode, which is caused by parallel resistance in the bipolar mode.

6. Conclusion
Important improvements of a resistance model for SiC MPS diodes have been presented. The model has been validated by comparing measurement data with calculated data. The resistance model of SiC MPS ensures the qualitative agreement between the calculated and measured device characteristics. The temperature characteristics of the on-resistance are considered by introducing the influence of temperature on the carrier mobility. The resistance model is applied to each mode of operation by analyzing the carrier distribution of the MPS. The quasi-neutral hypothesis in the high-injection model is verified. The on-resistance of MPS over its entire working temperature range can be calculated using the novel model. Also, the calculation results of the resistance are analyzed. The MPS diode has the highest on-resistance in the unipolar mode and the lowest on-resistance in the high-injection mode. The resistance of the drift region accounts for a large proportion of the total on-resistance. The device designers can increase the doping concentration of the drift region and reduce the thickness of the drift region as much as possible to reduce the total on-resistance, while ensuring the breakdown voltage.

Acknowledgments
This work is supported by the National Natural Science Foundation of China (No.51307113) and National Science Foundation of Jiangsu Province (No.BK20130307).

References
[1] Junji Ke, Zhibin Zhao, “Analysis of Switching Clamped Oscillations of SiC MOSFETs,”
Journal of Power Electronics, Vol. 18, No. 3, pp. 892-901, May, 2018.

[2] Allen R. Hefner, Jr, Ranbir Singh, Jih-Sheng Lai, David W. Berning, Sébastien Bouché, and Christophe Chapuy, “SiC Power Diodes Provide Breakthrough Performance for a Wide Range of Applications,” IEEE Trans. Power Electronic, Vol. 16, No. 2, pp. 273-80, Mar. 2001.

[3] Tianxiang Dai, Chun Wa Chan, “4H-SiC trench MOSFET with integrated fast recovery MPS diode,” Electronics Letters. Vol. 54, No. 3, pp. 167-169, Feb. 2018.

[4] Mahbouba Amairi, Sameh Mtiet, Tarek Ben Salah, Hervé Morel, “Temperature dependence of silicon and silicon carbide power devices: An experimental analysis,” IEEE Mediterranean Electrotechnical Conference, pp. 97-98, 2012.

[5] B. Jayant Baliga, “Analysis of a High-Voltage Merged p-i-n/Schottky(MPS) Rectifier,” IEEE Electron Device Letters, Vol. 8, No. 9, pp. 407-409, Sep. 1987.

[6] He Qingyuan, Liao Tian, Zhang Kai, Luo Xiaorong, Fang Jian, Wang Jianming, et al, “Optimized Design of SiC Trench MPS Diodes,” Microelectronics, Vol. 34, No. 2, pp. 116-123, Apr. 2004.

[7] Miao Yongbin, Zhang Yuming, Zhang Yimen, “Merged PiN Schottky Diodes: A New Power Switching Diode,” Microelectronics, Vol. 48, No. 7, pp. 1442-1446, Jul. 2001.
[21] Donald A. Neamen, “Semiconductor Physics and Devices Basic Principles,” Publishing House of Electronics Industry, pp. 77-289, 2013.

[22] S. Sawant, B. J. Baliga. “4kV Merged PiN Schottky (MPS) Rectifiers,” in Proc IEEE ISPSD, pp. 297-300, 1998.

[23] Shanmuganathan Palanisamy, Susanne Fichtner, Josef Lutz, Thomas Basler, Roland Rupp, “Various structures of 1200V SiC MPS diode models and their simulated surge current behavior in comparison to measurement,” in Proc. IEEE ISPSD, pp. 235-238, 2016.