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Simulation study on 4H–SiC power devices with high-k dielectric FP terminations

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ABSTRACT

The reverse blocking characteristics of 4H–SiC power devices with high dielectric constant (k) materials field plate (FP) terminations have been investigated by numerical simulations in this paper. The study makes a comparison between the breakdown characteristics of 4H–SiC power devices with different FP dielectrics comprising silicon oxide (SiO_2), silicon nitride (Si_3N_4) and hafnium oxide (HfO_2). The results show that the high-k dielectrics FP can significantly relieve the electric field enhancement at the junction corners and enhance the breakdown voltage of devices. The breakdown voltage as high as 2249 V, which reaches about close to more than 90% of theoretical value, is achieved in HfO_2 FP terminated 4H–SiC Schottky barrier diode. The maximum electric field in the dielectric layer can be greatly reduced from 7MV/cm for SiO_2 FP to 5.7MV/cm for Si_3N_4 FP and 3.6 MV/cm for HfO_2 FP. Meanwhile, it also implies that the high-*k* dielectrics FP terminations can efficiently suppress the sensitivity of the breakdown voltage to the interface states and improve the devices reliability compared with the conventional SiO_2 FP termination.

1. Introduction

Recently, silicon carbide (SiC) has attracted much attention for power device applications due to its superior material properties such as large band-gap, high critical electric field strength, high saturated electron velocity and high thermal conductivity [1,2]. These allow device with high power capacity, lower series resistance and lower power dissipation, and can be operated at high-voltage, high-frequency, and high temperature conditions.

To relieve the electric field enhancement effect and fully realize the voltage potential of material, suitable edge termination must be designed for SiC power devices. Recently, several edge termination technologies for SiC power devices have been investigated, including field plates (FP), guard rings (GR), single- and multiple-junction termination extension (JTE), mesa structure or mesa–JTE combination [3–6]. Among all of those, field plate is widely used due to its easy fabrication and no ion-implantation and subsequent high temperature anneals. Additionally, it can be simply combined with some other termination structure to further improve the blocking characteristics [7]. Conventional FP termination for SiC power devices to commonly utilize the SiO_2 as the dielectric suffers the premature breakdown and high electric field due to its low dielectric constant (k~3.9) and high density of interface state at the SO_2/SiC [8]. One approach to improve this problem is to use a dielectric material with a higher constant than SiO_2. The high-k dielectrics such as Al_2O_3, HfO_2, and Si_3N_4 etc. applied to the MOS and MIS devices have been studied widely [9,10]. Aluminum nitride (AlN) as FP dielectrics for 4H–SiC Schottky rectifiers [11] and AlGaN/GaN HFETs [12] also have been demonstrated recently and the devices exhibited excellent reverse blocking behaviors. However, to the best of our knowledge, there has no detail study on the Si_3N_4 and HfO_2 field plate in 4H–SiC power device. These dielectrics are considered as the possible replacement for SiO_2 duo to their excellent dielectric properties and process manufacturability. In this paper, we will focus on the utilization of Si_3N_4 and HfO_2 as field plate dielectrics to provide improved reverse blocking performance and devices reliability. Numerical simulations have been implemented using DESSIS-ISE for various FP designs with different dielectrics including SiO_2, Si_3N_4 and HfO_2. DESSIS-ISE is a multidimensional, electrothermal, mixed-mode device and circuit simulator for one-dimensional, two-dimensional, and three-dimensional semiconductor devices. It incorporates advanced physical models and robust numeric methods for the simulation of most types of semiconductor device [13]. To calibrate and confirm the physical models used in numerical calculations, the comparisons between the experimental data with the simulation results also are undertaken.

2. Device structure and physical models

In this present work, the Schottky junction with FP termination is used because it is the most basic one among all the SiC power devices with FP termination technology. The schematic cross section of the 4H–SiC Schottky barrier diode (SBD) with field plate termination is illustrated in Fig. 1. A Ti Schottky contact with a barrier height of 1.2 eV on an N-type 4H–SiC epi-layer is used. The thickness and doping concentration of the epi-layer are 40 μm and 1×10^{16} cm^{-3}, while the

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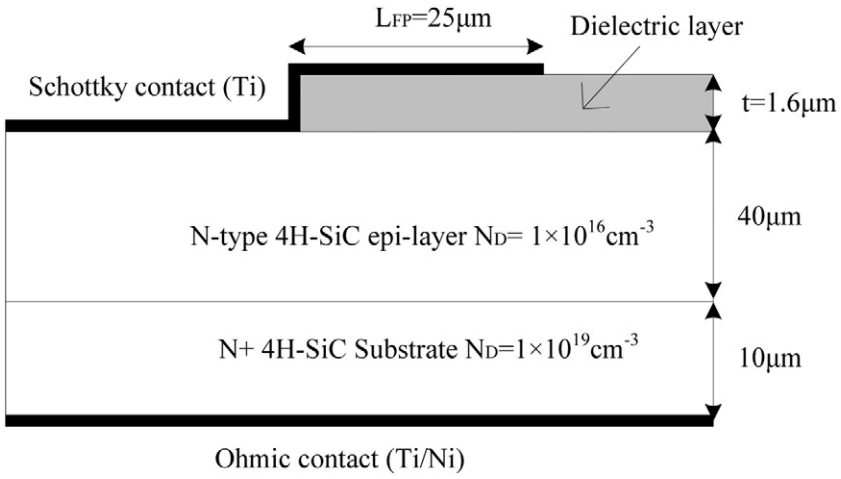

Fig. 1. Schematic cross section of the 4H–SiC SBD with field plate termination.

doping concentration of the substrate is $1\times10^{19}\,\mathrm{cm}^{-3}$. The $L_{FP}=25\,\mu m$ and $t=1.6\,\mu m$ are the length of the field plate and the thickness of the dielectric, respectively.

The device characteristics are performed using the physical based semiconductor device simulation software DESSIS-ISE. In the reverse blocking simulation, the avalanche breakdown occurs when

$$\int_0^w \alpha_p \exp\left[\int_0^x \left(\alpha_n-\alpha_p\right)dx'\right]dx = 1. \tag{1}$$

The ionization coefficients are strongly related to the electrical field ξ and the model proposed by Okuto and Crowell [14] is used in this work,

$$\alpha(\xi) = a\times[1+c\times(T-300K)]\times\xi^{\lambda}\times\exp-\left\{\frac{b[1+d(T-300K)]}{\xi}\right\}^{\kappa} \tag{2}$$

where a, b, c, d, λ and κ are the fitting parameters. The latest reported experimental measurements on 4H–SiC impact ionization coefficients were given in [14], which was measured by direct measurements of 4H–SiC avalanche photodiodes (APD). By fitting the experimental data in [15] with Eq. (2), the impact ionization coefficients α_n and α_p can be expressed as shown in Eqs. (3) and (4).

$$\alpha_n = 3.78\times10^6\ \mathrm{cm}^{-1}\cdot\left(1-1.47\times10^{-3}\ K^{-1}\cdot(T-300\ K)\right)\times\exp\left[-\left(\frac{1.05\times10^7\ V/\mathrm{cm}}{\xi}\right)^{1.37}\right] \tag{3}$$

$$\alpha_p = 4.51\times10^6\mathrm{cm}^{-1}\cdot\left(1-1.56\times10^{-3}\ \mathrm{K}^{-1}\cdot(T-300\ \mathrm{K})\right)\times\exp\left[-\left(\frac{1.05\times10^7\ \mathrm{V/cm}}{\xi}\right)^{1.1}\right] \tag{4}$$

Other fundamental physical models and parameters describing 4H–SiC, such as band energy, effective mass for electrons and holes, and incomplete ionization of impurities used in simulations are summarized in Table.1. The dielectric/4H–SiC interface fixed charge influenced by fabrication conditions affects both the reverse breakdown behaviors and surface leakage current, so the interface fixed charge are also taken into account during simulations.

3. Results and discussions

With the models present above, the reverse performance of the ideal and device un-terminated 4H–SiC SBD is simulated. Fig. 2 presents the comparison of simulated reverse breakdown voltage and critical field with theoretical results for ideal 4H–SiC SBD. The theoretical breakdown voltage and critical filed for the ideal SBD are calculated using the following equations

$$V_B = \frac{\varepsilon_{SiC}\varepsilon_0\xi_C^2}{2qN_D} \tag{5}$$

$$\xi_C = \frac{2.49MV/\mathrm{cm}}{1-\left(\frac{1}{4}\right)\log\left(\frac{N_D}{10^{16}\mathrm{cm}^{-3}}\right)}. \tag{6}$$

From Fig. 2, we can see that the theoretical results and the simulated results agree with each other at different doping concentration N_D. The simulated breakdown characteristic for un-terminated 4H–SiC SBD is given in Fig. 3, and it is consistent with the experimental results, which confirms that the presented models used in numerical simulations are suitable.

Fig. 4 shows the simulated reverse J–V behaviors of the 4H–SiC SBD with SiO_2, Si_3N_4 and HfO_2 FP terminations, respectively. For SiO_2, Si_3N_4 and HfO_2 used in the simulations with the following

Table 1
Physical models and parameters used for simulation.

Bandgap energy [16]	$E_G = 3.23\ \mathrm{eV}+7.036\times10^{-4}\ \mathrm{eV}\ K^{-1}\cdot\left[49.751K-\frac{T^2}{T+1509K}\right]$
Electron/hole mass [17]	$m_n=0.3713m_o, m_h=1.0001m_0$
Incomplete ionization of impurities [17]	$N_D^+ = \frac{N_D}{1+2\exp\left[E_{Fn}-E_C+0.067\ \mathrm{eV}-1.9\times10^{-8}\ \mathrm{eV\,cm}\cdot N_D^{1/3}\right)/k_BT]}$ $N_A^+ = \frac{N_A}{1+4\exp\left[E_{Fp}-E_V+0.019\ \mathrm{eV}-3.0\times10^{-8}\ \mathrm{eV\,cm}\cdot N_A^{1/3}\right)/k_BT]}$
Electron and hole bulk mobility [18]	$\mu_n = \frac{950\ \mathrm{cm}^2/Vs\cdot(T/300\ K)^{-2.8}}{1+\left(\frac{N_i}{2\times10^{17}\ \mathrm{cm}^{-3}}\right)^{0.76}}$, $\mu_p = \frac{124\ \mathrm{cm}^2/Vs\cdot(T/300K)^{-2.8}}{1+\left(\frac{N_i}{1.76\times10^{19}\ \mathrm{cm}^{-3}}\right)^{0.34}}$