Physical Modeling and Scaling Properties of 4H-SiC Power Devices

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Abstract— **4H silicon carbide (4H-SiC) has great potential for use as a material for power devices owing to its superior electrical properties. The distinctive feature of 4H-SiC is the high avalanche breakdown field and its anisotropy. In order to realize 4H-SiC power devices that make the best use of the excellent physical properties, device simulation, considering anisotropic physical properties is indispensable. This paper reports on the modeling of anisotropic impact ionization coefficients for device simulation, and the effect of anisotropic impact ionization coefficients on the avalanche breakdown of 4H-SiC power devices. We show that the avalanche breakdown voltage is degraded due to the anisotropy of impact ionization coefficients, which is caused by the lateral field at the termination structure. In addition, we precisely evaluate the effect of the high avalanche breakdown field of 4H-SiC on the performance of power devices. Scaling theory is applied for the design of power devices. A new figure of merit (HFOM) is derived as an invariant of scale transformation, which is a function of avalanche breakdown field and regarded as a measure of the performance of the power device.**

I. Introduction

Among many wide-band-gap semiconductor materials, 4H silicon carbide (4H-SiC) has great potential for use as a material for power devices owing to its crystal maturity and superior electrical properties such as nearly isotropic low-field mobility and high avalanche breakdown electric field. In order to realize SiC devices that make the best use of the excellent physical properties, device simulation technology for SiC devices is indispensable. Drawing on the pioneering work by Ruff [1], the device simulation of SiC devices is commonly used for the design of SiC power devices. Much work has been devoted to the improvement of the accuracy of SiC device simulation and the expansion of its scope [2,3]. However, the physical modeling of 4H-SiC for device simulation is still developing although many studies on physical properties of 4H-SiC have been reported. The distinguishing feature of SiC is the anisotropy of the physical properties such as mobility, dielectric constant and breakdown field, which originate from the hexagonal crystal structure. Recently, we reported on the impact ionization coefficient of 4H-SiC and discussed its anisotropic nature [4]. In this paper, we show how anisotropic impact ionization coefficients are modeled in the device simulator. Further, the effect of anisotropic impact ionization coefficients on the performance of 4H-SiC power devices is discussed. In addition to the device modeling issues, we discuss the design principle of 4H-SiC power devices, which is the underlying base of their design using TCAD. We show how the scaling law of electric devices works in the case of the design of power devices. A new figure of merit of power devices is derived based on the scaling theory, which can be used for precise evaluation of the performance of the designed power device instead of the well-known Baliga's figure of merit [5].

II. Modeling of Anisotropic Impact Ionization Coefficients of 4H-SiC

A. Brief summary of experimental results [4]

The breakdown voltages of the p^+n diodes on (0001) and $(11\bar{2}0)$ face of 4H-SiC are different if the doping density of the n-layer is the same. From the experiment, the following empirical expression for the breakdown voltage and avalanche breakdown field is derived:

$V_{BD} = 1940 \times (10^{16}/N_D)^{0.8}$, $F_C = 2.70 \times (10^{16}/N_D)^{-0.1}$ for p^+n diodes on (0001) face, and

$V_{BD} = 1200 \times (10^{16}/N_D)^{0.8}$, $F_C = 2.19 \times (10^{16}/N_D)^{-0.1}$ for p^+n diodes on $(11\bar{2}0)$ face,

where N_D (cm^{-3}) denotes the doping density of an n-type layer. The breakdown voltage of a p^+n diode on a $(11\bar{2}0)$ wafer is 60% of that on a (0001) wafer in the case that the doping density of an n-type layer is the same.

The impact ionization coefficients are obtained by the combined fitting procedure of the multiplication measurement [6] and breakdown voltage-doping density measurement. In the fitting, the impact ionization coefficient model suggested by Chynoweth [7] is assumed:

$\alpha = a_e \exp(-b_e/F)$, $\beta = a_h \exp(-b_h/F)$,

where α and β denote the impact ionization coefficients for an electron and a hole respectively, and F represents the magnitude of the electric field. Other parameters are fitting parameters. The obtained parameters of the electron and hole impact ionization coefficients model are summarized in Table 1. The device simulation using these parameters reproduces the

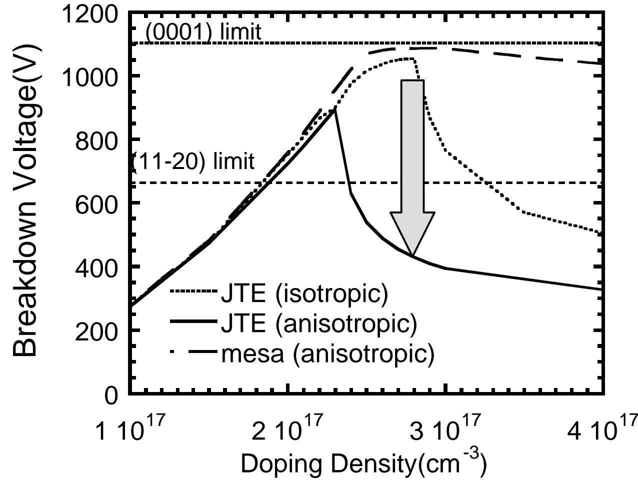

Fig.1 Breakdown voltage of a SBD as a function of a doping density of the termination structure

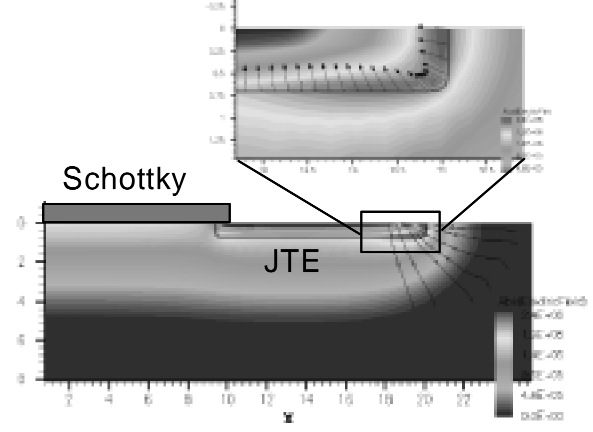

Fig.2 Electric field distribution of the reverse-biased SBD in which the avalanche breakdown begins to takes place.

observed breakdown voltage of p^+n diode on 4H-SiC.

Parameter	a_e	a_h	b_e	b_h
Unit	cm^{-1}		V/cm	
$\langle 0001 \rangle$	1.76×10^8	3.41×10^8	3.30×10^7	2.50×10^7
$\langle 11\bar{2}0 \rangle$	2.10×10^7	2.96×10^7	1.70×10^7	1.60×10^7

Table 1: Calibrated parameters of electron and hole impact ionization coefficients model

B. Interpolation formula of the anisotropic impact ionization

In this subsection, we show how anisotropic impact ionization coefficients are modeled in the device simulator. In order to introduce anisotropy of impact ionization coefficients into two- or three-dimensional device simulation, the impact ionization coefficients for any direction should be specified. In fact, we have to derive interpolation formula for impact ionization coefficients between <0001>-direction and <11$\bar{2}$0>-direction based on device physics. It should be noted that carrier heating due to high electric fields triggers the impact ionization. Thus, considering the energy balance equation and anisotropic mobility of 4H-SiC, generalized expression of anisotropic impact ionization coefficients in any direction of electric field $(F_{<11\bar{2}0>}, F_{<0001>})$ is derived;

$$\alpha(F_{<11\bar{2}0>}, F_{<0001>}) = a \exp\left(-\frac{b}{F}\sqrt{1 - A^2\left(\frac{bF_{<0001>}F_{<11\bar{2}0>}}{Fb_{<0001>}b_{<11\bar{2}0>}}\right)^2}\right), \qquad (1)$$

where $F^2 = F_{<11\bar{2}0>}{}^2 + F_{<0001>}{}^2$,

$$F^2/b^2 = F_{<11\bar{2}0>}{}^2/b_{<11\bar{2}0>}{}^2 + F_{<0001>}{}^2/b_{<0001>}{}^2,$$

$$a = a_{<11\bar{2}0>}^{(b^2F_{<11\bar{2}0>}{}^2)/(b^2_{<11\bar{2}0>}F^2)}\, a_{<0001>}^{(b^2F_{<0001>}{}^2)/(b^2_{<0001>}F^2)} \text{ and}$$

$$A = \ln\left(a_{<0001>} / a_{<11\bar{2}0>}\right),$$

where the parameters for the impact ionization coefficients in the device simulation are given for the <0001>- direction and the <11$\bar{2}$0>-direction, respectively:

$\alpha(\mathbf{F}) = a_{<0001>}\exp(-b_{<0001>}/F)$: for $\mathbf{F}$ // <0001>

$\alpha(\mathbf{F}) = a_{<11\bar{2}0>}\exp(-b_{<11\bar{2}0>}/F)$: for $\mathbf{F}$ // <11$\bar{2}$0>,

where $\mathbf{F}$ and F denote the electric field vector and the magnitude of the electric field. The detail of the derivation of these formulas is given in the APPENDIX. It should be noted that this expression is valid for the drift-diffusion scheme although we implicitly consider the energy-balance and carrier temperature.

C. Example of device simulation using anisotropic impact ionization coefficients

The effect of anisotropic impact ionization coefficients on performance of 4H-SiC power devices is examined using Synopsys's device simulator DESSIS. Figure 1 shows the results of breakdown voltage of 4H-SiC Schottky diodes as a function of the doping density of the termination region. The depth of the termination region is 0.5 micron. The termination structures, which we have examined, are the planar-type (Junction termination extension, JTE) and mesa-type structures. These device simulation results suggest that JTE cannot fully exploit the potential performance of 4H-SiC power devices. Around the doping density of 3×10^{17} cm^{-3}, breakdown voltage of anisotropic simulation is much lower than that of isotropic simulation. This breakdown voltage degradation is due to lateral field at JTE edge shown in the inset of Fig. 2. In the case of the mesa-type termination, the degradation of breakdown voltage due to anisotropy of the breakdown field is totally suppressed, because the depletion region does not extend outside the edge of the mesa when the reverse bias is applied. The electric field is perpendicular to the surface at the edge area if the dose of the p-type termination is larger than the critical value. Thus, the mesa-type termination is more suitable for SiC power devices than JTE.

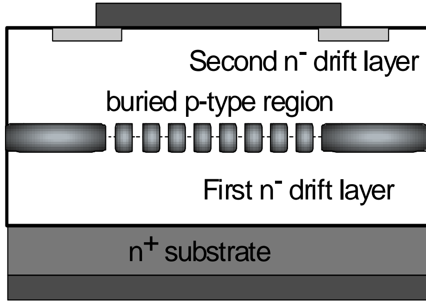

Fig.3 Cross section of a floating junction SBD (Super-SBD)

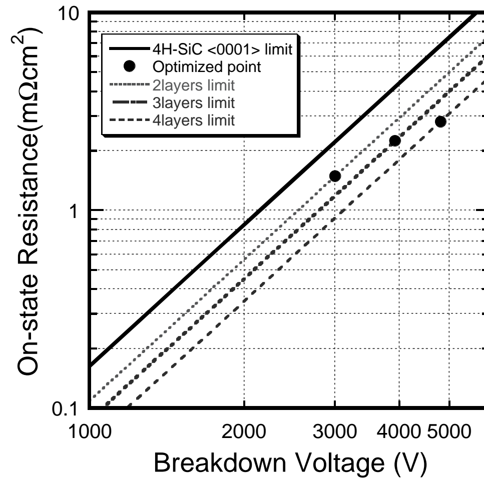

Fig.4: The performance limit of Super SBD's. The extrapolating lines are obtained by the scaling theory of power devices.

III. Scaling Properties in the Design of Power Devices

The scaling properties of the basic equations of semiconductor devices constitute the fundamental principles of the design of MOSFETs for digital circuits and, indeed, for the design of any semiconductor device. In this section, we show that the scaling theory leads to the guideline for the optimization of the design of the voltage withstanding structure of a power device. We should note that the breakdown voltage and the on-state resistance depend on the design of the voltage withstanding structure and, they are trade-off characteristics, which represent the performance of a power device. Conventionally, Baliga's figure of merit (BFOM $\equiv \varepsilon\mu E_C^3 \propto V^2{}_{BD} / R_{ON}$, where V_{BD} and R_{ON} are breakdown voltage and on-state resistance, respectively) has been used in order to evaluate the performance of a power device [3]. We should note that BFOM implicitly assumes that the breakdown field is constant. However, in general, breakdown field E_C is a function of a doping density N_D of the drift layer of power devices ($E_C = 2.70 \times (10^{16} / N_D)^{-0.1}$ MV/cm in the case of 4H-SiC) [4]. As shown below, we can define a new figure of merit of power devices (HFOM), which is the extension of BFOM, based on the scaling properties of semiconductor devices.

The scaling invariant condition for Poisson equation under the scaling transformation $\rho = K_N \rho'$, $\psi = K_V \psi'$, $r = K_L r'$ is as follows;

$$K_L^2 \cdot K_N / K_V = 1. \quad (2)$$

It should be noted that the characteristic length of a power device is the depletion layer width at breakdown, which is a function of the doping density and the breakdown field. If the doping density of the drift layer of a power device is changed, the physical structure of a power device is rescaled according to the new characteristic length, and this device shows the rescaled breakdown voltage: $V_{BD} = K_V V_{BD}'$. We also note that the following equation is derived from the doping dependence of the characteristic length, considering the doping dependence of the breakdown field:

$$K_L = K_N^{-0.9} \quad (3)$$

Scaling transformation also affects the on-state resistance as follows:

$$R_{ON} = K_L / K_N \; R_{ON}' \quad (4)$$

HFOM is defined as an invariant of the scale transformation. The following equation is derived from Eqs. 2, 3 and 4:

$$\text{HFOM} \equiv V_{BD}^{2.375} / R_{ON} = \left(K_N^{-0.8*2.375} / K_N^{-1.9}\right) V'^{2.375}_{BD} / R'_{ON} = V'^{2.375}_{BD} / R'_{ON}.$$

HFOM is useful for the optimization of a power device, because HFOM describes the "quality" of the optimization of a power device structure.

The optimization of a SiC Schottky barrier diode with the floating junction structure (Super-SBD), which is shown in figure 3, has been performed using HFOM. The results are shown in Fig.4. The performance of the optimized Super-SBD surpasses the performance limit of 4H-SiC devices with the conventional structure in every range of breakdown voltage. The extrapolating lines are obtained by the scaling theory of power devices as has already been shown.

IV. Conclusion

The modeling of anisotropic impact ionization coefficients for device simulation is presented, and the effect of anisotropic impact ionization coefficients on the avalanche breakdown of 4H-SiC power devices is examined. We show that the avalanche breakdown voltage is degraded due to the anisotropy of impact ionization coefficients. Scaling theory is applied for the design of power devices. A new figure of merit (HFOM) is derived as an invariant of scale transformation. HFOM is regarded as a measure of the performance of the power device.

Appendix I

Derivation of Interpolation Formula of the Anisotropic Impact Ionization Coefficients

High electric fields induce the increase of carrier temperature, and hot carriers that have greater energy than band gap trigger impact ionization. An impact ionization coefficient is primarily a scalar function of carrier temperature, even if the impact ionization coefficient is anisotropic for the applied electric field. Therefore, if the impact ionization coefficient is the same for the different applied electric fields **F1**//<11$\bar{2}$0>, **F2** //<0001>;

$$\alpha_{<11\bar{2}01>}(\mathbf{F1}) = \alpha_{<0001>}(\mathbf{F2}),$$

the carrier temperature for the carrier ensemble under the electric field **F1** is equal to that under electric field **F2** applied parallel to y-axis. The following Fig. 5 shows the position of **F1** and **F2**.

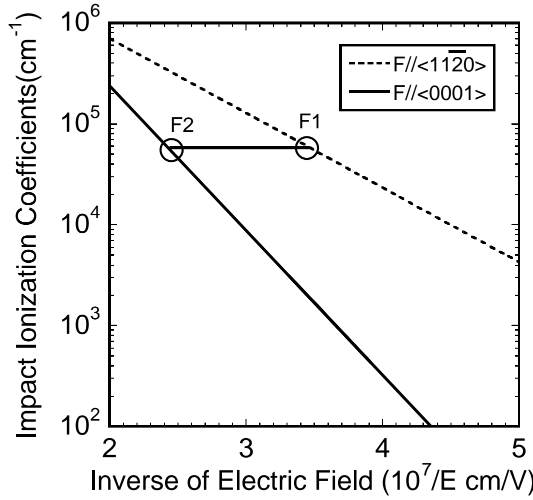

Fig.5: Electron impact ionization coefficient of 4H-SiC when the applied field is parallel to <0001> axis (solid line) and parallel to <11$\bar{2}$0> axis

From the energy balance equation of the carrier ensemble under the electric field **F1** and that under electric field **F2**, the following equation holds;

$$\mu_{<11\bar{2}0>}(F1)F1^2 = \mu_{<0001>}(F2)F2^2 = (k_B T_e - k_B T_L)/\tau_w, \quad \text{(A.1)}$$

where $\mu_{<11\bar{2}0>}(F1)$ is <11$\bar{2}$0 >-component of mobility vector for **F1**// <11$\bar{2}$0 >-axis, and $\mu_{<0001>}(F2)$ is <0001>-component of anisotropic mobility vector for **F2** // <0001>-axis. We also note that τ_w, T_e, and T_L are energy relaxation time, electron temperature and lattice temperature, respectively.

Now, we extend Eq. A.1 for the electric field of the arbitrary direction: $\mathbf{F}=(F_x,F_y)$. It should be noted that in this expression the suffixes x and y are used instead of <11$\bar{2}$0 > and <0001> for simplicity. We also define the anisotropic mobility vector: $\vec{\mu}(T_e)=(\mu_x,\mu_y)$. Let us assume that the carrier temperature of the carrier ensemble under the electric field $\mathbf{F}=(F_x,F_y)$ is equal to that under the electric field **F1** and **F2**. The following equation holds:

$$\mu_x(F1)E_x^2 + \mu_y(F2)E_y^2 = \mu_x(F1)F1^2 = \mu_y(F2)F2^2. \quad \text{(A.2)}$$

In order to derive Eq. A.2, we used the following relation; $\vec{\mu}(T_e) = (\mu_x, \mu_y) = (\mu_x(F1), \mu_y(F2))$.

This relation is based on the fact that the mobility under the high electric field is the function of the carrier temperature.

We can easily eliminate the mobility dependence from Eq. A.2.

$$F_x^2 / F1^2 + F_y^2 / F2^2 = 1.$$

In this relation, we eliminate *F2* by substituting the relation:

$$\alpha_x(F1) = \alpha_y(F2) \text{ or } F2 = \alpha_y^{-1}(\alpha_x(F1)).$$

Then, *F1* is expressed by F_x and F_y.

Substituting *F1* as a function of F_x and F_y into the following expression for the impact ionization coefficient;

$$\alpha_x(F1) = a_x \exp\{-b_x / F1\}.$$

In the end we can derive Eq.1 in the body text.

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References

[1] M. Ruff, H. Mitlehner, and R. Helbig: IEEE tran elec dev Vol41,1040(1994)

[2] M. Bakowski, U. Gustafsson, U. Lindefelt, "Simulation of SiC High Power Devices", phys. stat.sol., (a) vol. 162, 1997, pp. 421-440.

[3] M. Lades, Ph. D thesis, Modeling and Simulation of Wide Bandgap Semiconductor Devices: 4H/6H-SiC, 2000

[4] T.Hatakeyama, et al.: Appl. Phys. Lett. **85**, 1380 (2004)

[5] B.J. Baliga: J.Appl. Phys. **53**, 1759 (1982)

[6] A.O Konstantinov, Q. Wahab, N. Nordell, and U. Lindefelt: Appl. Phys. Lett. Vol. 71 (1997) , p. 90

[7] A. G. Chynoweth: Phys. Rev., vol. 109, no. 5 (1958), p. 1537

[8] B.J. Baliga: J.Appl. Phys. **53**, 1759 (1982)

[9] W. Saito, I. Omura, et al., Proc. of ISPSD 2002, (2002) pp. 33-36