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6H-SiC PN 다이오드의 항복전압과 온-저항을 위한 해석적 표현

(Analytical Expressions for Breakdown Voltage and Specific On-Resistance of 6H-SiC PN Diodes)

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(Yong-Sung Chung)

요 약

6H-SiC 전자 및 정공의 이온화계수로부터 유효이온화계수를 추출하여 6H-SiC PN 다이오드의 항복전압과 온-저항을 위한 해석적 표현식을 유도하였다. 해석적 모형으로부터 구한 항복전압을 $10^{15} \sim 10^{18}$ cm^{-3}의 도핑 농도 범위에서 실험 결과와 비교하여 10% 이내의 오차로 일치하였고, 농도 함수의 온-저항의 해석적 결과도 $5 \times 10^{15} \sim 10^{16}$ cm^{-3}의 범위에서 이미 발표된 수치적 결과와 매우 잘 일치하였다.

Abstract

Analytical expressions for breakdown voltage and specific on-resistance of 6H-SiC PN diodes have been derived successfully by extracting an effective ionization coefficient from ionization coefficients for electron and hole in 6H-SiC. The breakdown voltages induced from our analytical model are compared with experimental results. The variation of specific on-resistance as a function of doping concentration is also compared with the one reported previously. Good fits with experimental results are found for the breakdown voltage within 10% in error for the doping concentration in the range of $10^{15} \sim 10^{18}$ cm^{-3}. The analytic results show good agreement with the numerical data for the specific on-resistance in the region of $5 \times 10^{15} \sim 10^{16}$ cm^{-3}.

Keywords : 6H-SiC, Effective ionization coefficient, Breakdown voltage, Specific on-resistance.

I. Introduction

Silicon carbide(SiC) has received considerable attention as a potential material with many advantages for high temperature, high power, high frequency and high voltage applications due to its wide band gap, high breakdown field, high thermal conductivity and high saturation velocity[1~3]. It has been reported that crystal growth and junction formation in SiC are rather difficult. 6H-SiC is a promising material because the junction may be easily formed by epitaxial growth technology[4]. Various 6H-SiC devices, such as a PN junction diode[5], an Schottky diode[6] and a MOSFET[7] have been reported recently.

Avalanche ionization coefficients α for electron and β for hole in 6H-SiC are fundamental quantities in designing 6H-SiC devices. However, calculation of the avalanche breakdown voltage through the numerical ionization integral using different values of ionization coefficients α and β is considerably involved and not so easily incorporated in device

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design. And, although the breakdown voltage and specific on-resistance are the most important parameters of semiconductor devices, an analytical formulas or expressions of the breakdown voltage and specific on-resistance of 6H-SiC for a device design have not been reported yet.

The purpose of this paper is to report simple analytical formulas of the breakdown voltage and specific on-resistance for 6H-SiC PN diodes by extracting an effective ionization coefficient in 6H-SiC. The numerical[8] and experimental results[5-6,9-14] are used to verify the analytical variation of the breakdown voltage. The decrease in the breakdown voltage and specific on-resistance with doping concentration is respectively compared with the numerical[1] and experimental[6,9~10, 13] ones reported previously.

II. Theoretical Result and Discussion

The breakdown in device occurs when the ionization integral approaches to 1, as expressed by:

$$\int_0^W \beta \exp\left(\int_0^x (\alpha-\beta)dx\right)dx = 1, \tag{1}$$

where W is the layer width, α and β are the ionization coefficients[2] for electron and hole, respectively in 6H-SiC.

$$\alpha = 4.65\times10^4 \exp\left(-\frac{1.2\times10^7}{|E|}\right)\ cm^{-1}, \tag{2}$$

$$\beta = 4.65\times10^6 \exp\left(-\frac{1.2\times10^7}{|E|}\right)\ cm^{-1}, \tag{3}$$

where E is the electric field in the range of $1\times10^6\sim4\times10^6$ V/cm. Since α and β differ by considerably less than an order of magnitude over a wide ranges of electric fields, no serious error is obtained by putting $\alpha\approx\beta\approx\gamma$. So the ionization integral can be solved by reducing the two parameters of the reported ionization coefficients α and β for electron and hole in 6H-SiC to one parameter, effective ionization coefficient, γ. Therefore, γ is approximated from α and β in terms of electric field and is given as:

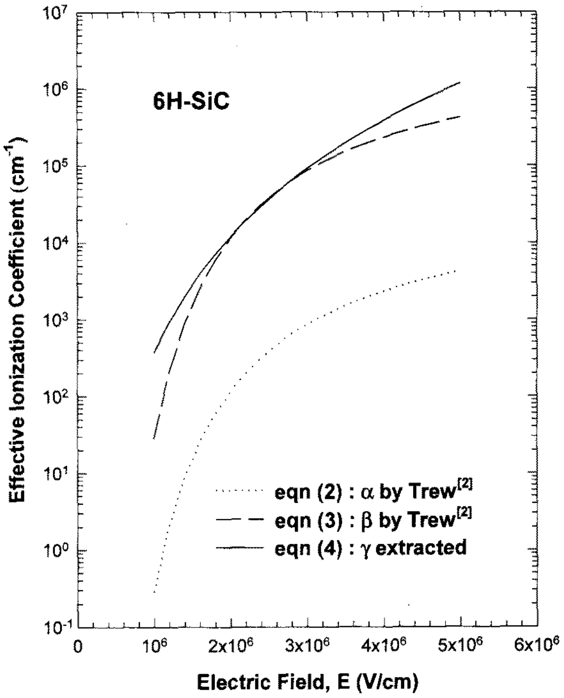

그림 1. 전자와 정공의 이온화계수 α, β[2]와 비교한 전계 함수의 유효 이온화계수

Fig. 1. The effective ionization coefficient as a function of electric field, compared to the ionization coefficients, α and β[2] respectively for electron and hole.

$$\gamma = 3.74\times10^{-28}E^5\ cm^{-1}, \tag{4}$$

where E is the electric field. In Fig. 1, γ is plotted as a function of electric field, as compared to α and β[2]. A reasonable agreement of γ with $\alpha\approx\beta$ is observed, where the electric field is used from 1×10^6 to 5×10^6 V/cm.

The range of the electric field is chosen as that of the breakdown field for the doping concentration $10^{15}\sim10^{18}$ cm^{-3}.

The ionization integral employing the effective ionization coefficient in eqn (4) can be reduced to:

$$\int_0^W \gamma dx = 1, \tag{5}$$

where W is the layer width.

Solving the Poisson's equation gives an electric field distribution in depletion layer, as expressed by:

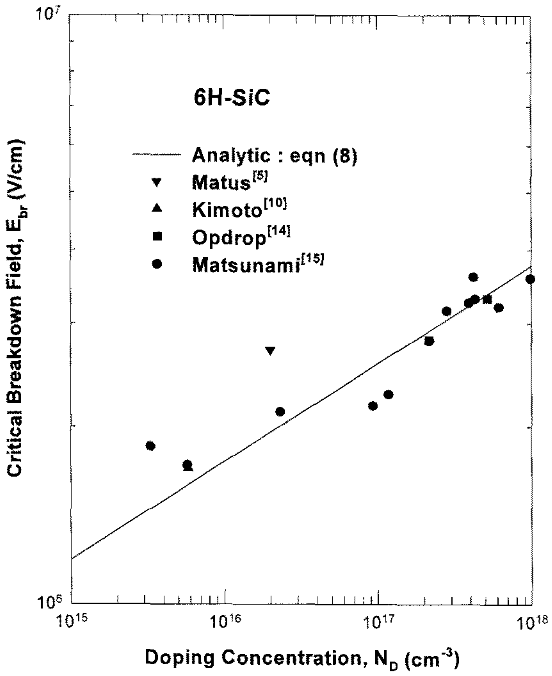

그림 2. 농도 함수의 해석적 임계 항복 전계와 실험 전계값[5,10,14,15]의 비교

Fig. 2. Comparison of the analytical result of the critical breakdown field with the experimental breakdown fields[5,10,14,15] as a function of doping concentration.

$$E(x) = \frac{qN_D}{\epsilon_r \epsilon_o}(W - x), \tag{6}$$

where q is the electronic charge, N_D is the doping concentration, ϵ_r and ϵ_o are respectively, the relative permittivity in 6H-SiC and the dielectric constant in free space and x is the distance from junction.

Inserting eqn (6) and eqn (4) into eqn (5) provides the depletion layer width at breakdown, as expressed by:

$$W_{br} = 2.12 \times 10^{10} N_D^{5/6}\ cm. \tag{7}$$

Substituting eqn (7) into eqn (6) for $x = 0$ gives the critical breakdown field as:

$$E_{br} = 3.76 \times 10^{3} N_D^{1/6}\ V/cm. \tag{8}$$

The critical breakdown field from eqn (8) is shown as a function of doping concentration in Fig. 2. It should be noted that the calculated breakdown field corresponds to the electric field($1\times10^6 \sim 5\times10^6$ V/cm) used for the ionization coefficient. A fairly good agreement between the evaluated critical breakdown field from our model and the experimental data[5, 10, 14~15] is observed.

For $x = 0$, breakdown voltage of 6H-SiC is obtained by substituting eqn (7) into eqn (9):

$$V = \frac{qN_D W^2}{2\epsilon_r \epsilon_o}. \tag{9}$$

Therefore, the breakdown voltage is derived as:

$$V_{br} = 3.99 \times 10^{13} N_D^{-2/3}\ V. \tag{10}$$

The breakdown voltage from eqn (10) is shown as a function of doping concentration in Fig. 3. Good accordance may be observed with the numerical result[8] and the experimental data[5~6, 9~14] in the range of $10^{15} \sim 10^{18}$ cm^{-3}.

The specific on-resistance of PN junctions is the

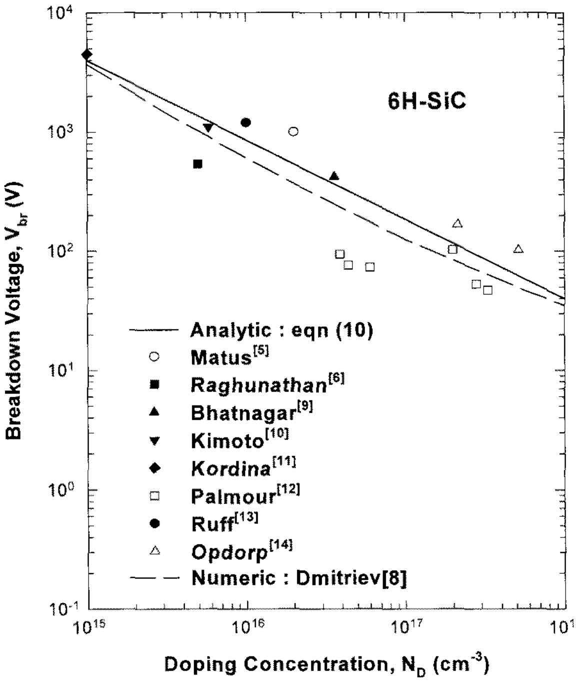

그림 3. 실험 결과[5~6,9~14] 및 수치적 결과[8]와 비교한 농도 함수의 해석적 항복 전압

Fig. 3. The analytical result of the breakdown voltage with the experimental breakdown voltages[5~6,9~14] and the numerical result[8] as a function of the doping concentration.

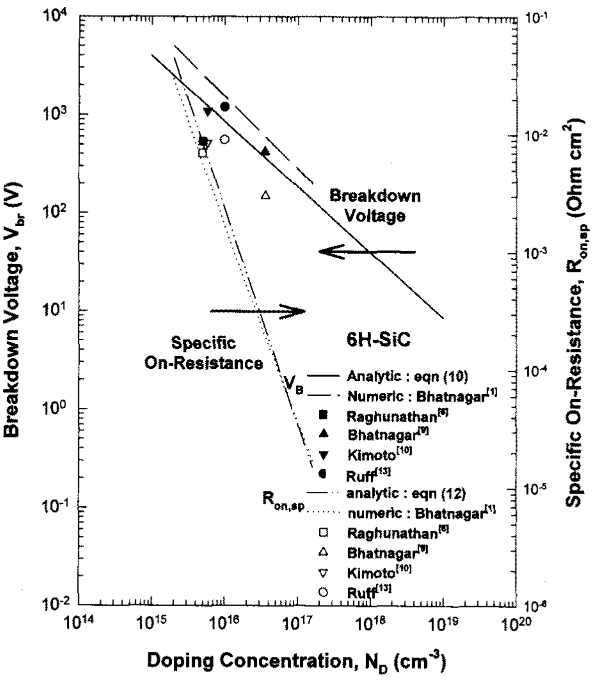

그림 4. 실험 결과[6,9,10,13] 및 수치적 결과[1]와 비교한 농도 함수의 해석적 항복 전압과 온-저항

Fig. 4. The analytical breakdown voltage and specific on-resistance as a function of doping concentration with the experimental results[6,9,10,13] and the numerical result[1], respectively.

sum of the epitaxial drift layer and the N^+ substrate resistance, both of which are calculating using eqn (11), where W is layer thickness, N_D is layer doping, and μ_n is electron mobility[1].

$$R_{on,sp} = \frac{W}{qN_D\mu_n} \tag{11}$$

Substituting $\mu_n = 260(T/300)^{-2}\ cm^2/V \cdot s$[16] for electron, eqn (7) into eqn (11), the specific on-resistance can be expressed as:

$$R_{on,sp} = 5.09 \times 10^{26} N_D^{-11/6}\ \Omega \cdot cm^2, \tag{12}$$

at 300K. The specific on-resistance obtained from eqn (12) is provided together with the numerical result[1] and the experimental results[6, 9~10, 13] in Fig 4.

Also, in this figure 4, breakdown voltage and specific on-resistance are shown in the same doping concentration with the numerical[1] and the experimental[6, 9~10, 13] results, respectively. A good accordance may be observed in the region of $5\times10^{15}\sim10^{16}$ cm^{-3} rather than numerical result in breakdown voltage and specific on-resistance.

III. Conclusion

In summary, employing the effective ionization coefficient has provided analytical simple models for breakdown voltage and specific on-resistance of 6H-SiC PN diodes.

The analytical breakdown voltages agree fairly well with the experimental data in the literature within 10% in error for the doping concentration in range of $10^{15}\sim10^{18}$ cm^{-3}.

An analytical expression for specific on-resistance is also presented and compared with the results reported previously. The analytical results for the specific on-resistance show good agreement with the experimental data in the region of $5\times10^{15}\sim10^{16}$ cm^{-3} rather than numerical result.

The breakdown voltage and specific on-resistance from our model may be useful for the practical design of 6H-SiC devices.

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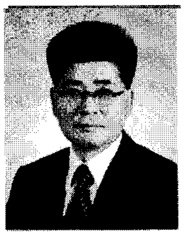
저자소개



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