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4H-SiC 쇼트키 다이오드의 해석적 항복전압과 온-저항 모델

(Analytical Models for Breakdown Voltage and Specific On-Resistance of 4H-SiC Schottky Diodes)

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요 약

4H-SiC의 전자와 정공의 이온화계수 α와 β로부터 유효이온화계수 γ를 추출함으로써 4H-SiC 쇼트키 다이오드의 항복전압과 온-저항을 위한 해석적 모델을 유도하였다. 해석적 모델로부터 구한 항복전압을 실험 결과와 비교하였고, 도핑 농도 함수의 온-저항도 이미 발표된 결과와 비교하였다. 항복전압은 $10^{15}\sim10^{18}$ cm^{-3}의 도핑 농도 범위에서 실험 결과와 10% 이내의 오차로 잘 일치하였다. 온-저항을 위한 해석적 결과는 $3\times10^{15}\sim2\times10^{16}$ cm^{-3}의 범위에서 실험 결과와 매우 잘 일치하였다.

Abstract

Analytical models for breakdown voltage and specific on-resistance of 4H-silicon carbide Schottky diodes have been derived successfully by extracting an effective ionization coefficient γ from ionization coefficients α and β for electron and hole in 4H-SiC. The breakdown voltages extracted from our analytical model are compared with experimental results. The specific on-resistance as a function of doping concentration is also compared with the ones reported previously. Good fits with the experimental results are found for the breakdown voltage within 10% in error for the doping concentration in the range of about $10^{15}\sim10^{18}$ cm^{-3}. The analytical results show good agreement with the experimental data for the specific on-resistance in the range of $3\times10^{15}\sim2\times10^{16}$ cm^{-3}.

Keywords : 4H-SiC, Effective ionization coefficient, Breakdown voltage, Epilayer thickness, Specific on-resistance.

I. Introduction

Silicon carbide(SiC) has received increased attention because of its potential 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]. There exist a large number of crystal polytypes of SiC. However, the two polytypes that have received considerable attention recently are 6H-SiC and 4H-SiC.

The most significant difference between 6H-SiC and 4H-SiC is that the electron mobility in 4H-SiC is two times that of 6H-SiC perpendicular to the c-axis and almost 10 times that of 6H-SiC parallel to the c-axis[2]. This fact alone explains the increased importance of 4H-SiC. Various 4H-SiC devices, such as a pn junction diode[3], a Schottky diodes[4~12], a UMOSFET[13], a TIGBT[13], a BJT[13], a SITh[13], and a GTO[13], have been reported recently.

Avalanche ionization coefficients for electrons, α and for holes, β in SiC are fundamental quantities in designing SiC devices. However, calculation of the avalanche breakdown voltage through the numerical ionization integral using different values of α and β is considerably involved and not so easily incorporated in device design. And, although the

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breakdown voltage is one of the most important parameters of semiconductor devices, an analytical formula or expression of the breakdown voltage for a device design has not been reported yet.

The purpose of this paper is to report simple analytical model of the breakdown voltage and specific on-resistance for 4H-SiC Schottky diodes by employing an effective ionization coefficient. Since no measurements for 4H-SiC avalanche ionization rates have been reported, the impact ionization parameters[1] for 6H-SiC are used[13]. The experimental results for 4H-SiC Schottky diodes[4~12] and for 6H-SiC diodes[1, 12, 14~20] are used to verify the analytical variation of the breakdown voltage for 4H-SiC Schottky diodes. The specific on-resistance and the breakdown voltage as functions of doping concentration are compared with the ones[4~9] reported previously, respectively.

II. Modeling for Breakdown Voltage and Specific On-Resistance

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

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

where W is the depletion layer width, α and β are the ionization coefficients[1] for electron and hole, respectively.

$$\alpha = 1.66\times 10^6 \exp\left(-\frac{1.273\times 10^7}{|E|}\right) cm^{-1}, \qquad (2)$$

$$\beta = 5.18\times 10^6 \exp\left(-\frac{1.4\times 10^7}{|E|}\right) cm^{-1}, \qquad (3)$$

where E is the electric field in the range of 1×10^6 ~ 5×10^6 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 to one parameter, effective ionization coefficient, γ. Therefore γ is approximated from α and β in terms of electric field and is given as:

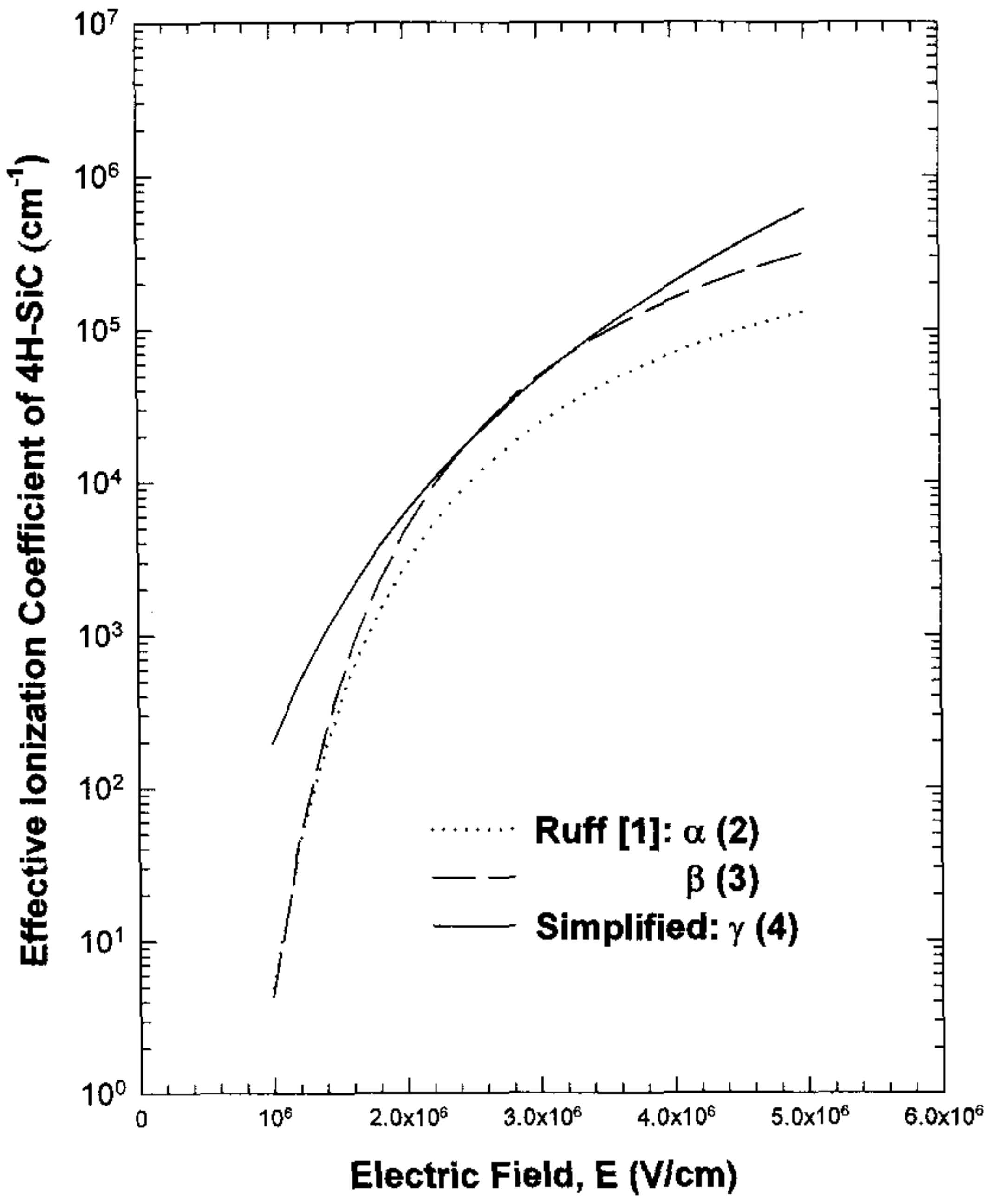

그림 1. 전자와 정공의 이온화계수 α 및 β[1]와 비교한 전계 함수의 유효이온화계수

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

$$\gamma = 1.94\times 10^{-28} E^5 \ cm^{-1}, \qquad (4)$$

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

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

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

$$\int_0^W \gamma dx = 1, \qquad (5)$$

where W is the depletion layer width. Solving the Poisson's equation gives an electric field distribution in depletion layer, as expressed by:

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

where q is the electronic charge, N_D is the epilayer doping concentration, ϵ_r and ϵ_o are, respectively the relative permittivity in 4H-SiC and the dielectric constant in free space and x is the distance from junction.

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

$$W_{BD} = 2.27 \times 10^{10} N_D^{-5/6}\ cm. \tag{7}$$

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

$$E_{cr} = 4.25 \times 10^{3} N_D^{1/6}\ V/cm. \tag{8}$$

The critical breakdown field from equation (8) is shown as a function of doping concentration in Fig. 2. It should be noted that the calculated critical breakdown field correspond to the electric field (1×10^6 ~ 5×10^6 V/cm) used for the ionization coefficient. A fairly good agreement between the evaluated critical breakdown field from our model and the experimental data[3, 6, 8-12, 21] is observed.

For $x = 0$, breakdown voltage of 4H-SiC is obtained by substituting equation (7) into equation (9):

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

Therefore, the breakdown voltage is derived as:

$$V_{BD} = 4.82 \times 10^{13} N_D^{-2/3}\ V. \tag{10}$$

The breakdown voltage from equation (10) is shown as a function of doping concentration in Fig. 3.

Good accordance may be observed with the

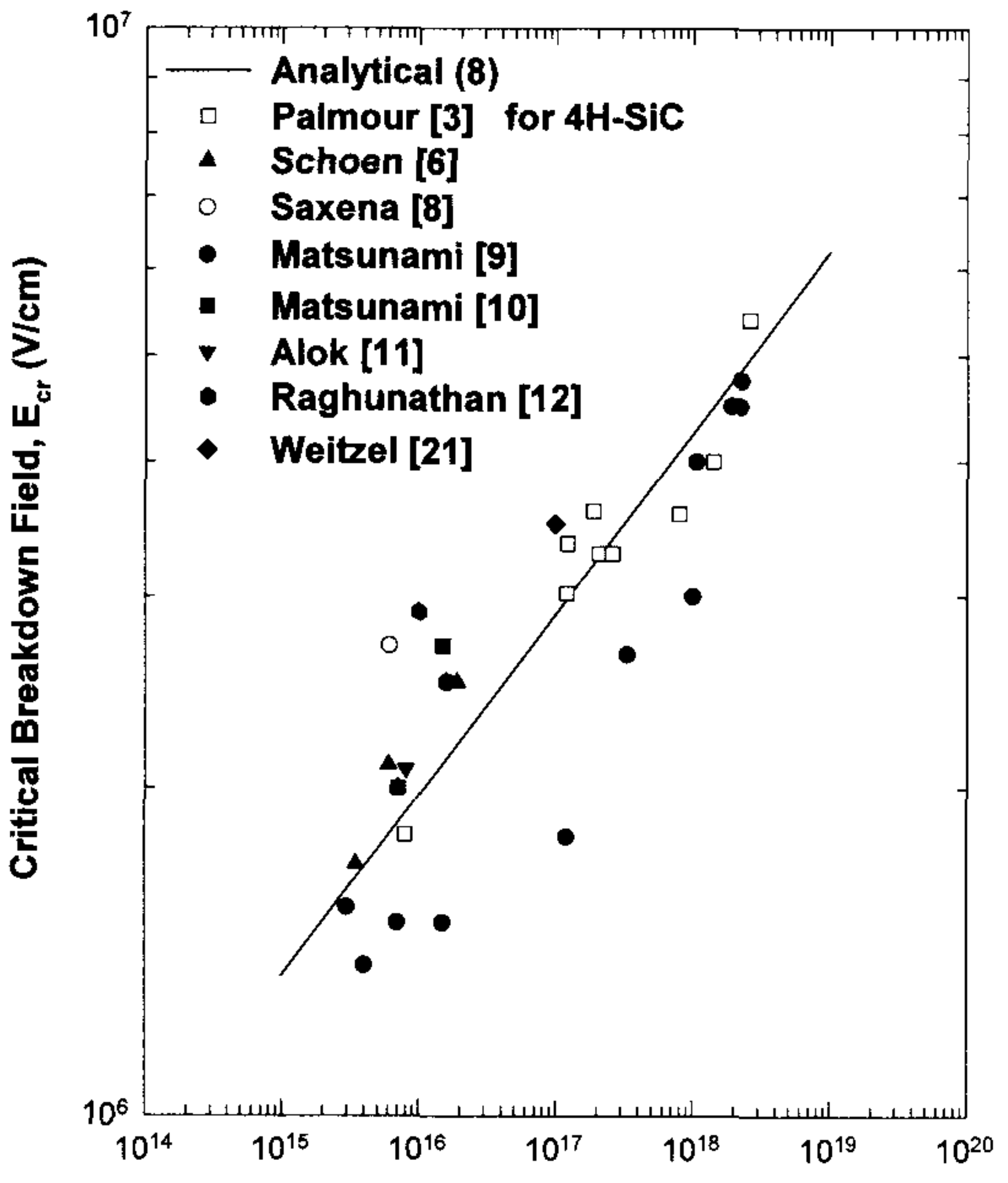

그림 2. 도핑 농도에 따른 임계 항복 전계의 해석적 결과와 실험 항복 전계[3, 6, 8~12, 21]의 비교

Fig. 2. Comparisons of the analytical result of the critical breakdown field with the experimental breakdown field[3, 6, 8~12, 21] as a function of doping concentration.

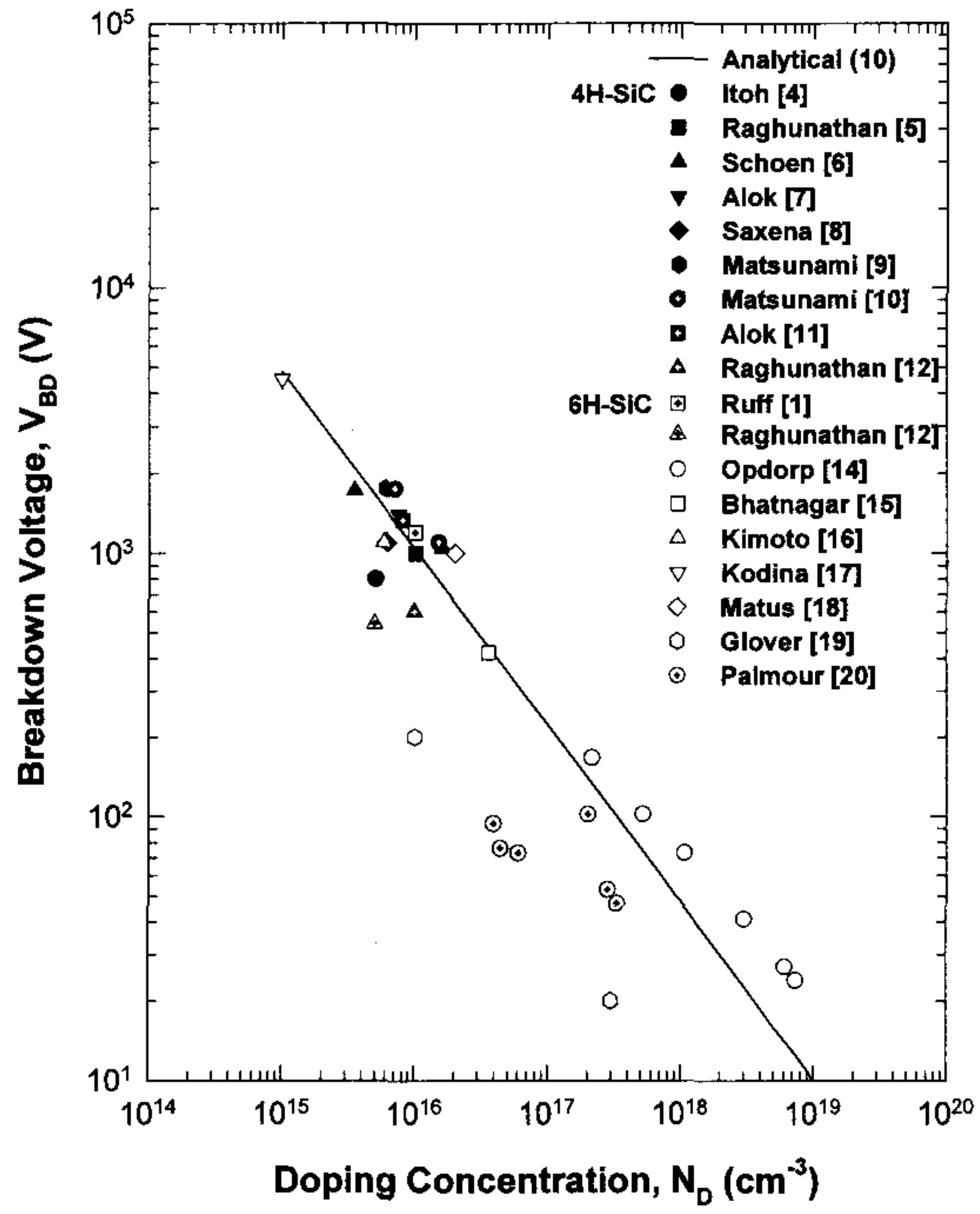

그림 3. 도핑 농도에 따른 항복전압의 해석적 결과와 4H-SiC 쇼트키 다이오드[4~12] 및 6H-SiC 다이오드[1, 12, 14~20]의 실험 결과의 비교

Fig. 3. Comparisons the analytical result for the breakdown voltage with the experimental results of 4H-SiC Schottky diode[4~12] and of 6H-SiC diode[1, 12, 14~20] as a function of the doping concentration.

experimental results for 4H-SiC Schottky diodes[4~12] and for 6H-SiC diodes[1, 12, 14~20] in the range of about 10^{15}~10^{18} cm^{-3}.

The breakdown voltage of a Schottky diodes depends on the semiconductor critical field, epilayer doping, epilayer thickness. Therefore, the breakdown voltage may be used to determine the epilayer doping and thickness under parallel plane avalanche breakdown conditions. The desired epilayer doping is the maximum doping that will sustain the specified breakdown voltage.

The relationship[22] for the epilayer doping is

$$N_D = \frac{\epsilon_s E_{cr}^2}{2qV_{BD}}, \qquad (11)$$

where N_D is the epilayer doping concentration, ϵ_s is the semiconductor dielectric constant($=\epsilon_r\epsilon_o$), E_{cr} is the semiconductor critical breakdown field, q is the electron charge, and V_{BD} is the breakdown voltage.

The corresponding epilayer thickness is the reverse bias depletion width at the breakdown voltage. The relationship[22] between minimum epilayer thickness, the critical field, and the breakdown voltage is

$$t_{epi} = \frac{2V_{BD}}{E_{cr}} = W_{BD}, \qquad (12)$$

where t_{epi} is the minimum epilayer thickness, and is equal to equation (7).

The specific on-resistance of the Schottky diodes is given by:

$$R_{on,sp} = \frac{W_{BD}}{qN_D\mu_n}, \qquad (13)$$

where μ_n is the mobility for electrons. Using $\mu_n = 800\ cm^2/Vsec$[21] for electrons and substituting equation (7) in equation (13), the specific on-resistance can be expressed as:

$$R_{on,sp} = 1.771\times10^{26} N_D^{-11/6}\ \Omega cm^2, \qquad (14)$$

at 300K. The specific on-resistance obtained from equation (14) is provided together with the experimental results[4~9] in Fig 4.

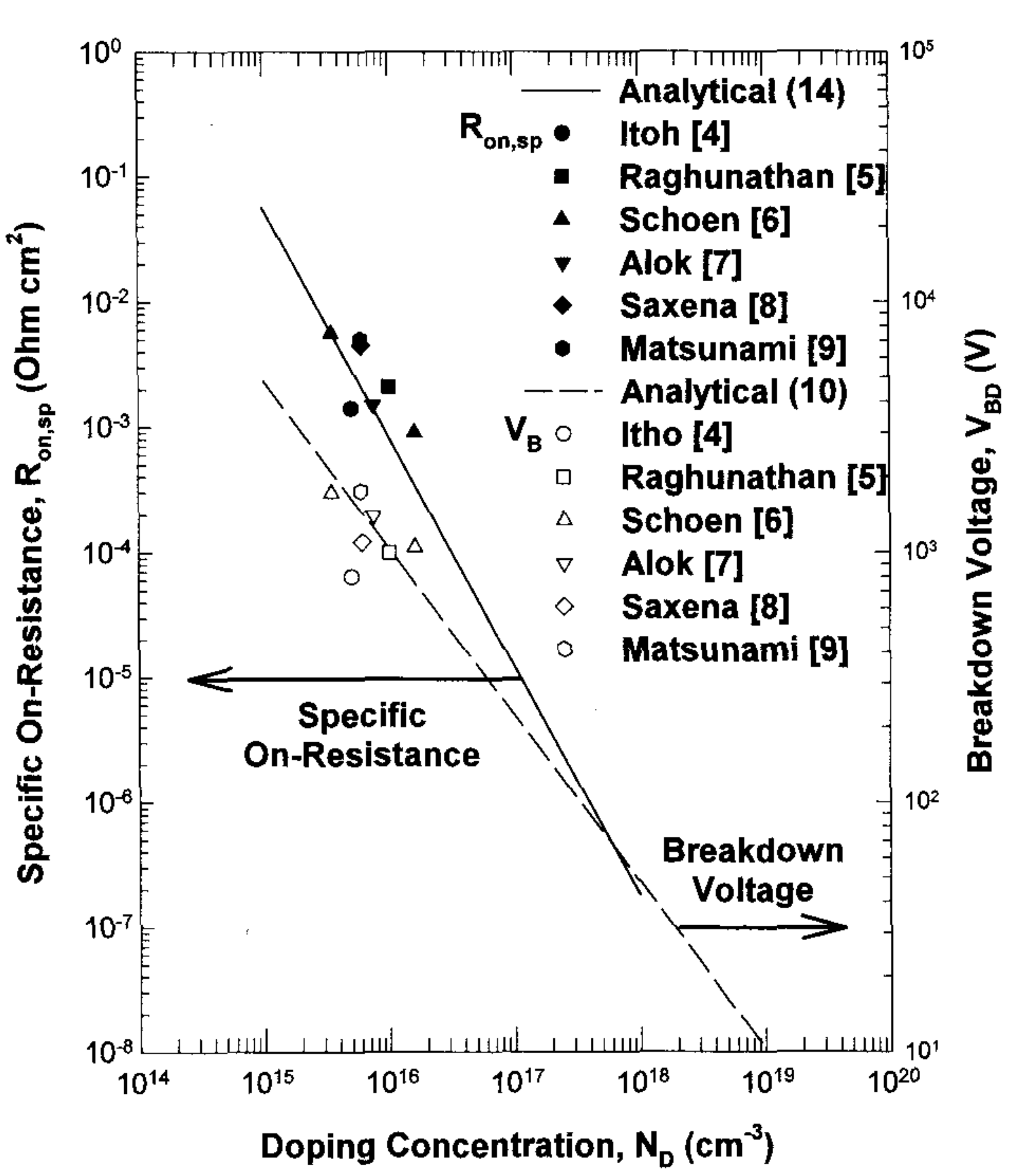

그림 4. 도핑 농도에 따른 해석적 항복전압 및 온-저항과 실험 결과[4~9]의 비교

Fig. 4. Comparison the analytical breakdown voltage and specific on-resistance as a function of doping concentration with the experimental results[4~9], respectively.

Also, in the figure, breakdown voltage as a function of doping concentration are shown with the experimental results[4~9]. A good accordance within 10% in error may be observed in the region of 3×10^{15} ~ 2×10^{16} cm^{-3}.

III. Conclusion

In summary, a simple analytical models for the breakdown voltage and the specific on-resistance of 4H-SiC Schottky diodes have been provided by employing the effective ionization coefficient. The analytical breakdown voltage agrees fairly well with the experimental data in the literature within 10% in error for the doping concentration in range of 10^{15}~10^{18} cm^{-3}. An analytical expression for the specific on-resistance is also presented and compared with the results reported previously. The analytical results show good agreement with the experimental data of within 10% for the specific on-resistance in the region of $3\times10^{15}\sim2\times10^{16}$ cm^{-3}. The breakdown voltage from our model may be useful for the practical design of 4H-SiC power devices.

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