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Temperature Dependence of Performance of 6H-SiC Unipolar Power Devices

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Abstract: The temperature dependence of some performance of 6H-SiC unipolar power devices is analyzed theoretically. By employing the temperature-dependent ionization coefficient and mobility of a silicon carbide, the analytical expressions of the temperature-dependent performance, such as breakdown characteristics and on-resistance of 6H-SiC unipolar power devices are derived in a closed form. The analytical results are compared with the experimental results, with good accordance found in the breakdown characteristics.

Key words: wide band gap semiconductor devices; 6H-SiC; impact ionization coefficient; avalanche breakdown; on-resistance; temperature dependence of performance

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1 Introduction

Wide band gap semiconductor materials have attracted intensive attention due to their wide applications in military electronic devices, such as high power switching devices, high frequency, high power amplifier for radar and fire control systems, electronic warfare and multifunctional RF systems. These devices have been deployed commercially in the base stations of wireless networks, automotive and aviation electronics, power systems and electron vehicles in recent years[1-3]. Up to date, the most attractive candidate material for high power devices is the polytype SiC because of its high thermal conductivity and high critical breakdown field.

In order to clearly evaluate the performance of SiC devices at the different temperature, besides their static characteristics, their temperature-dependent performance should be taken into consideration as well. The experimental static breakdown voltage of SiC devices is consistent with the calculated one. However, as for the variation in the breakdown voltage according to the temperature, the experimental information does not agree with the theoretic result. For instance, many reports can be found on a Negative Temperature Coefficient of Breakdown Voltage (NTCBV)[4,5], while less can be found on Positive Temperature Coefficient of Breakdown Voltage (PTCBV) in SiC[6-8]. Recently, the strong dependence of the Temperature Coefficient of Breakdown Voltage (TCBV) on the material quality was reported[9,10]. The defects result in the NTCBV observed previously, while the hole's intrinsic impact coefficient in both 4H and 6H has a PTCBV. With the development of material processing technique, the PTCBV of SiC is desired to be widely used in the near future. In fact, Raghunathan and Baliga have verified the positive

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temperature dependence of the hole's impact ionization coefficient in good quality 4H and 6H-SiC[11]. With the development of material processing, the intrinsic PTCBV characteristics of SiC devices can be proved, too. In the application of power devices, PTCBV leads to an increase in the breakdown voltage with temperature. In addition to determining the off-state breakdown voltage, PTCBV can also influence the on-state drop of unipolar devices, because the special on-resistance of the drift region is in inverse proportion to the third power of the critical field. High operation temperature leads to a great loss in the on-state power. Therefore, one should find a good tradeoff in the design of the 6H-SiC power devices. How the temperature effect of ionization coefficient affects the performance of SiC power devices should be further discussed.

In this paper, a temperature-dependent impact ionization coefficient in 6H-SiC, which was obtained by Raghunathan and Baliga, is deployed to derive the closed-form expressions of the breakdown characteristics and on-resistance of silicon carbide at different temperatures. The analytical variation in the breakdown voltage and critical electrical field are compared with previous experimental results, with a good accordance obtained. The analytical expressions obtained are very useful in the design and evaluation of high-temperature SiC-related power and high-frequency devices.

2 Theoretical Analysis

It is well known that the avalanche breakdown in silicon carbide materials is mainly due to the impact ionization of the hole carriers rather than the electrons, and the ion of the impact ionization of electrons in 6H-SiC is suppressed due to the fine band structure.

Seemingly, the electrons in 6H-SiC have a lower effective mass and a higher mobility, compared with the holes, so it is believed they can be heated stronger than holes in a high field. In fact, the minimum conduction band of 6H-SiC is the M symmetry point, which is located at the edge of the Brillouin zone. Recent calculations on band structures[12,13] show that lower conduction band valleys are actually quite narrow in the momentum direction along the *C*-axis. In this direction, the band width is only about 0.5eV. It is clear that the electron heating and impact ionization in 6H-SiC are different from those in cubic materials. In low fields, the impact ionization of cubic materials is a type of ballistic ionization process, which is the Shockley's "lucky electron" model. Impact ionization is dominated by the carriers starting from the minimum energy, which are so "lucky" to entirely avoid all the phonon collision before reaching the ionization energy. The process accounts to the low-field asymptotic form of Thornber's relationship, $\alpha \propto \exp(-E/q\epsilon\lambda)$[14], where the exponent is the probability of the carriers in traveling a long path without any phonon collisions. The "lucky electron" model is not applicable to the electrons in 6H-SiC, if the electric field is parallel to the *C*-axis, because the band width is insufficient for ionization. In a very high field, the ballistic process is no longer significant for ionization; but the effect of the discontinuity of the conduction band still play an important role. Recently, through Monte-Carlo simulations, it is demonstrated that the mean electron energy in high fields becomes much lower as the discontinuity is involved in a band structure model[12,13]. The mechanism of carrier heating and impact ionization in a valence band of 6H-SiC is the same as that in cubic materials. Though the valence band of 6H-SiC is a little more complicated than that of the cubic materials, the upper valence subbands are wide and continuous, so the impact ionization by valence band holes is more effective than that by conduction band electrons in 6H-SiC.

In theory, the hole ionization plays a vital role in the determination of the breakdown voltage of 6H-SiC. The temperature dependence of ionization coefficient for holes in 6H-SiC is given[11] as:

$$\alpha_{6H\text{-}SiC} = (4.6\times10^6 - 7.4\times10^3 T)\exp(-1.5\times10^7/E) \tag{1}$$

where T is the absolute temperature in Kelvin and E is the electrical field in V/cm.

Similar to the famous Fulop approximation to the effective ionization coefficient of silicon[15], a power approximation to the ionization coefficient of the holes in 6H-SiC is proposed as well, with which, the analytical expressions for the breakdown characteristics of a 6H-SiC power device can be obtained. The temperature-dependent effective ionization coefficient is expressed as bellow:

$$\alpha_{\text{eff}}(T) = \theta(T)E^6 \tag{2}$$

where

$$\theta(T) = 1.95 \times 10^{-41}(4.6 \times 10^6 - 7.4 \times 10^3 T) \tag{3}$$

Obviously, $\theta = 4.6 \times 10^{-35}\,\text{cm}^{-1}$ when $T = 300\text{K}$[11]. The avalanche breakdown of a p^+-n diode will occur if the simple ionization integral satisfies

$$\int_0^W \alpha_{\text{eff}}\,dx \equiv 1 \tag{4}$$

For an abrupt p^+-n junction, the electrical field distribution can be written as:

$$E(x) = \frac{qN}{\varepsilon_{\text{SiC}}}(W_{\text{pp}} - x) \tag{5}$$

while the voltage distribution as

$$V = \frac{qN}{2\varepsilon_{\text{SiC}}}(W_{\text{pp}}^2 - x^2) \tag{6}$$

where q is the electronic charge; N is the doping concentration of the light doped n^- region; ε_{SiC} is the permittivity in 6H-SiC and W_{pp} is the maximum depletion width at breakdown. Substituting (5) into (4), we obtain the relationship between the doping concentration of the light doped n^- region and the maximum depletion width at breakdown, by using which, following expressions can be derived, they are for the breakdown voltage, the depletion width at breakdown and the critical electrical field, respectively.

$$E_c = 0.1446\theta(T)^{-1/7}N^{1/7} \tag{7}$$

$$W_{\text{pp}} = 9.96 \times 10^5\theta(T)^{-1/7}N^{-6/7} \tag{8}$$

$$V_b = 5.6 \times 10^4\theta(T)^{-2/7}N^{-5/7} \tag{9}$$

Figure 1 shows the critical electric field at breakdown as a function of doping concentration when $T = 100$, 300 and 500K. The critical field at breakdown increases with the temperature increasing because the mean free path is dependent on the temperature[9].

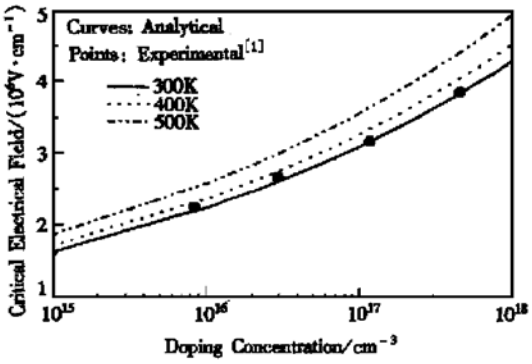

FIG. 1　Critical Field Versus Doping Concentration at Different Operation Temperature

An increase in the lattice temperature is known to lead a large magnitude in the heat phonons, as prevents the carrier from moving in the K-space with the decrease of the carrier energy. As a result, the mean free path of hole carriers has to decrease further. Consequently, the impact ionization coefficient of the hole carrier becomes lower. From Eq. (7), one can find that the critical field strength increases with the temperature increasing. The analytical results are in good agreement with the experimental ones when the doping concentration ranging from $1 \times 10^{16}\text{cm}^{-3}$ to $1 \times 10^{18}\text{cm}^{-3}$. It has been verified by using some devices, such as power MOSFET and Schottky barrier rectifiers[1,3,5].

Figure 2 demonstrates the dependence of the maximum depletion layer width at breakdown on temperature. Beyond our expectations, no significant change in the maximum depletion layer width can be seen at different temperature. However, there is still a slight increase in the maximum depletion layer width with the rise of the temperature.

Figure 3 shows the analytical results of the breakdown voltage as a function of the doping concentration when $T = 300$, 500 and 600K, respectively. It should be pointed out that the breakdown

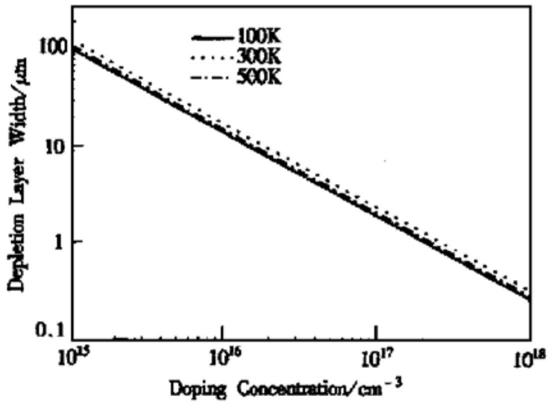

FIG. 2 Depletion Layer Width at Breakdown Versus Doping Concentration at Different Operation Temperatures

voltage of a device would increase with temperature increasing (as shown in Fig. 3) for obtaining stable and reliable behavior. The behavior requires a decreased impact ionization coefficient when the temperature is increased. According to the theoretical prediction, because of the increase of the critical field with temperature, the breakdown voltage of 6H-SiC devices can meet this condition. For the sake of comparison, some experimental values are also listed in Fig. 3. Good accordance can be observed at both low and high doping concentration when $T = 300$K, as proves our analytical method.

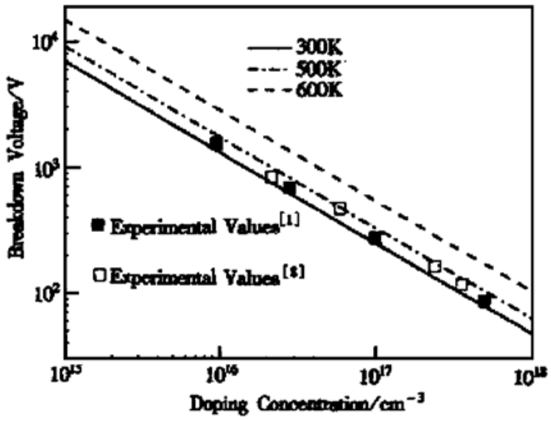

FIG. 3 Breakdown Voltage Versus Doping Concentration at Different Operation Temperature

The impact ionization coefficient can not only determine the avalanche breakdown voltage of a power device, but also influence the on-state voltage drop of power MOSFET or Schottky rectifier, because the specific on-resistance of the drift region is in inverse proportion to the Baliga figure of merit, $\epsilon_{SiC}\mu E_c^3$[16]. In order to minimize the resistance of unipolar power devices, W, the width of the lightly doped n^--layer, has to meet $W = W_{pp}$ at a given doping concentration. The temperature-dependent on-resistance of the unipolar power devices such as power MOS and Schottky devices is given as

$$R_{on} = \frac{W_{pp}}{qN\mu} \qquad (10)$$

where μ is the temperature-dependent mobility of the electrons in SiC devices.

For electrons, $\mu = 400\left(\frac{T}{300}\right)^{-3}\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$[1]. Combining the equations above (7) and (8), the temperature-dependent on-resistance can be expressed as

$$R_{on} = 7.7\times10^{9}\left(\frac{T}{300}\right)^{3}\theta(T)^{3/5}V_b(T)^{2.6} \qquad (11)$$

At room temperature, we obtain

$$R_{on} = 2\times10^{-11}V_b^{2.6} \qquad (12)$$

Similar expressions have been reported by Baliga[16]. Normalized on-resistance, $R_{on}/R_{on}(300\mathrm{K})$, as a function of the absolute temperature is shown in Fig. 4, which can compare with that of an optimal power MOSFET device at 500K below[1].

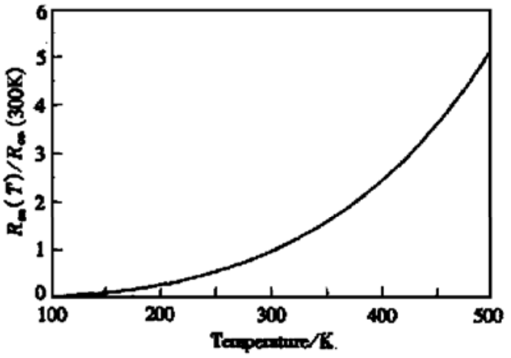

FIG. 4 Temperature Dependence of On-Resistance for Normalized Breakdown Voltage

3 Conclusion

In this paper, the theoretical temperature dependence of the SiC unipolar power devices has been investigated. The analytical expressions of the breakdown characteristics as functions of the temperature have been proposed. A good agreement is found between our analyses and the experimental results when the doping concentration ranging from $1\times10^{16}\mathrm{cm}^{-3}$ to $5\times10^{17}\mathrm{cm}^{-3}$. An analytical expression for the temperature-dependent on-resistance is also presented. These expressions we present here are very easy and useful in the evaluation of the characteristics of the power SiC devices at different operation temperatures.

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6H-SiC 单极功率器件性能的温度关系

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摘要: 基于碳化硅材料电离系数和迁移率的温度依赖性, 利用有效电离系数的 Fulop 近似, 推出了 6H-SiC 单极性功率器件击穿电压和比导通电阻的温度依赖性解析表达式. 理论预言的击穿电压和临界电场与先前的实验结果基本一致(误差小于 10%), 验证了理论模型的适用性.

关键词: 宽禁带半导体器件; 6H-SiC; 电离系数; 雪崩击穿; 比导通电阻; 温度关系

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