Investigation of current transport parameters of Ti/4H–SiC MPS diode with inhomogeneous barrier*

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(Received 24 October 2010; revised manuscript received 11 December 2010)

The current transport parameters of 4H–SiC merged PiN Schottky (MPS) diode are investigated in a temperature range of 300–520 K. Evaluation of the experimental current–voltage (I–V) data reveals the decrease in Schottky barrier height $\Phi_{\rm b}$ but an increase in ideality factor n, with temperature decreasing, which suggests the presence of an inhomogeneous Schottky barrier. The current transport behaviours are analysed in detail using the Tung's model and the effective area of the low barrier patches is extracted. It is found that small low barrier patches, making only 4.3% of the total contact, may significantly influence the device electrical characteristics due to the fact that a barrier height of 0.968 eV is much lower than the average barrier height 1.39 eV. This shows that ion implantation in the Schottky contact region of MPS structure may result in a poor Ti/4H–SiC interface quality. In addition, the temperature dependence of the specific on-resistance ($R_{\rm on-sp}$), $T^{2.14}$, is determined between 300 K and 520 K, which is similar to that predicted by a reduction in electron mobility.

Keywords: 4H–SiC, MPS, barrier inhomogeneity, specific on-resistance

PACS: 73.30.+y, 73.40.Sx, 73.50.–h **DOI:** 10.1088/1674-1056/20/5/057301

1. Introduction

Silicon carbide (SiC) is an attractive material for power device applications due to its excellent material properties, including high critical electric field and high thermal conductivity.[1−3] These allow devices to possess high power capacity, lower series resistance and lower power dissipation.[4] 4H–SiC merged PiN Schottky (MPS) rectifiers as a key device in power conversion applications have also been widely investigated in recent years.[5−7] The MPS diode has a Schottky rectifier structure with p–n junction grids integrated into the drift region. The schematic of the MPS cross section is shown in Fig. 1. The main advantages of the MPS are the Schottky-like on-state and fast switching characteristics together with the off-state characteristics having a lower leakage current similar to that of the PiN rectifier. In SiC, the conduction loss of an MPS is much lower than that of the PiN diode.[8]

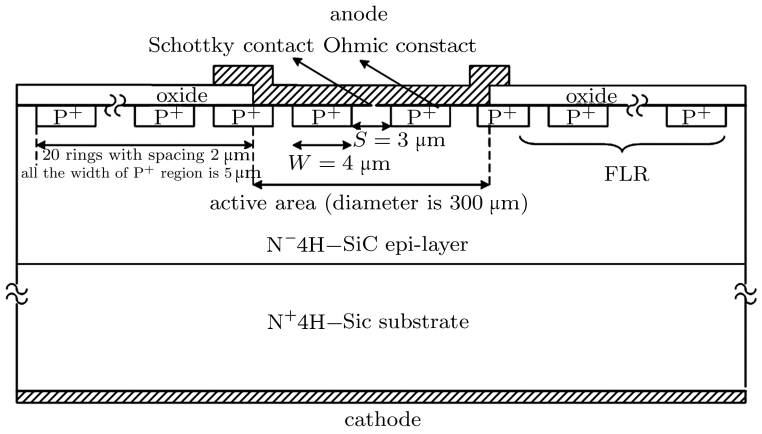


Fig. 1. Schematic cross section of 4H–SiC MPS rectifier.

*Project supported by the National Natural Science Foundation of China (Grant No. 61006060) and the 13115 Innovation Engineering of Shanxi Province of China (Grant No. 2008ZDKG-30).

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In the last decade, several studies concerning both ohmic and rectifying contacts on SiC have been performed to investigate the physical mechanism of current transport and, ultimately, to find the optimal conditions for specific applications.[9,10] In particular, the issues of the inhomogeneous Schottky barrier height (SBH) behaviour in metal/SiC Schottky contact have become the focus that many researchers are paying close attention to. Indeed, the electrical behaviour of a Schottky contact has been observed to be strongly dependent on the quality of the metal/semiconductor interface.[11] The mainstream explanation for deviations from the ideal behaviour in the electrical characteristics of such a Schottky contact on SiC is the inhomogeneities and/or residual processing-induced contamination in the interfacial region. An accurate model used to describe the non-ideal electrical characteristics of metal/semiconductor Schottky barrier was proposed by Tung,[12] in which taken into account is the possible presence of a distribution of nanometer-size 'patch' with a lower barrier height embedded in a uniform high barrier background. This approach has been used to explain a large series of abnormal experimental results on metal/semiconductor contact and it is also accepted by most people.

The SiC MPS structure is comprised of alternating Schottky contact and ohmic contact. Although there have been many papers available concerning both ohmic and Schottky contacts on SiC, few of them have systematically researched the current transport property of this kind of composite structure.

In this paper, the electrical I–V characteristics of 4H–SiC MPS rectifying contacts are reported in a temperature range of 300 K–520 K. The temperature dependent current transport characteristics of the diodes are explained on the basis of the presence of inhomogeneous contact using the Tung's theory. Additionally, the temperature dependence of the specific on-resistance ($R_{\rm on-sp}$) on $T^{2.14}$ is also determined between 300 K and 520 K, which is similar to that predicted by reduction in electron mobility.

2. Device fabrication

Figure 1 shows the schematic cross section of a 4H–SiC MPS diode. The epitaxial layers were grown on 3-in 4H–SiC substrates with a resistivity of $0.018\ \Omega\cdot$cm, which were cut 8° off the [0001] axis. The n-type epitaxial layer was 10 μm thick, with a doping concentration of 1.65×10^{15} cm^{-3}. The p^+ wells in the field limiting ring (FLR) and MPS region were formed simultaneously by multiple aluminum implantations and annealed at 1600 °C. Ti/Ni/Al was used to form the backside and the front ohmic contact and subsequently annealed 1200 °C in argon for 2 min. Titanium was used to form the front Schottky metal contact. The MPS has an active area of 0.07 mm^2. The current–voltage (I–V) characteristics were measured between –20 V and 5 V using an HP-4156B semiconductor parameter analyser in a temperature range of 300 K–520 K.

3. Results and discussion

Figure 2 shows the measured I–V characteristic of 4H–SiC MPS rectifiers at different temperatures, which can be used to determine the significant parameters governing the current transport across the MPS rectifying contact, namely, the ideality factor (n) and the Schottky barrier height ($\Phi_{\rm b}$), according to the thermoionic theory (TE)

$$I=\left(\frac{W+S}{S}\right)AA^*T^2\exp\left(-\frac{q\Phi_{\rm b}}{kT}\right)\times\left[\exp\left(\frac{qV_{\rm F}}{nkT}\right)-1\right], \quad (1)$$

where W and S are the width of inner P^+ ring and the spacing between the inner P^+ rings (shown in Fig. 1), $V_{\rm F}$ is the applied voltage, I is the forward current, T is the absolute temperature, k is the Boltzmann constant, n is the ideality factor, q is the electron charge, $\Phi_{\rm b}$ is the Schottky barrier height (SBH), A is the contact area and A^* is the Richardson constant.

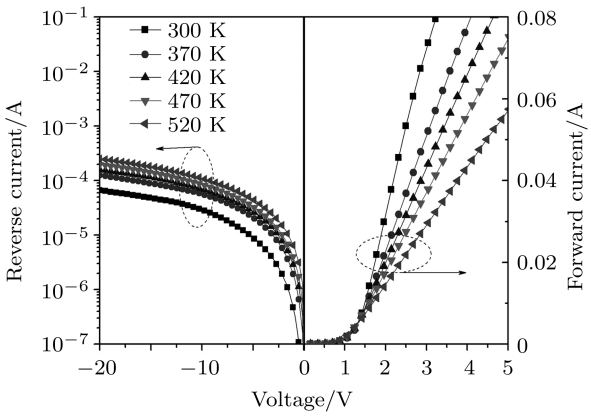


Fig. 2. I–V characteristics of 4H–SiC MPS measured from 300 K to 520 K.

The values of n and $\Phi_{\rm b}$ obtained at different temperatures are shown in Fig. 3. As can be clearly

seen, the value of $\Phi_{\rm b}$ increases, while n decreases with the increase of temperature. The typical values are $\Phi_{\rm b} = 0.69$ eV and $n = 2.1$ at 300 K and $\Phi_{\rm b} = 0.99$ eV and $n = 1.64$ at 520 K. Such temperature dependences of n and $\Phi_{\rm b}$ are indicative of deviation from the typical TE theory. One reason for this occurrence may be due to the decrease in forbidden band gap of SiC and conductivity of SiC as temperature increases. The other primary reason is the inhomogeneous Schottky barrier height (SBH) at the MPS rectifying contact. Indeed, similar temperature dependences of n and $\Phi_{\rm b}$ have been reported for Si and GaAs and 4H–SiC Schottky rectifiers.[13−15] The presence of an inhomogeneous Schottky barrier at the metal/semiconductor contact has been widely conceived as the major cause for this abnormal electrical characteristic. In such a contact, the current transport is dominated mainly by the average barrier height ($\Phi_{\rm b-ave}$) in high temperature condition, while the low barrier height or the effective SBH ($\Phi_{\rm b-eff}$) becomes dominated with temperature decreasing due to the barrier in-homogeneities.

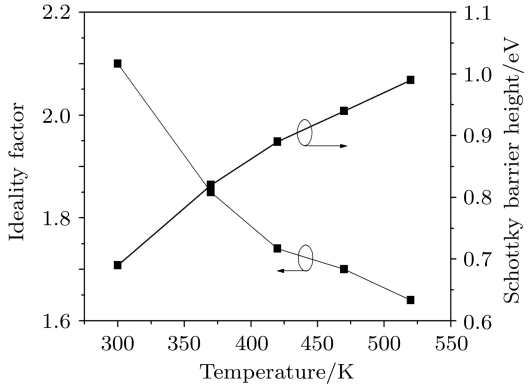


Fig. 3. Temperature dependences of ideality factor and SBH from a 4H–SiC MPS diode.

Figure 4 illustrates the relationship between barrier height and ideality factor, displaying their linear correlation. Extrapolating a linear fit of the data to ideality factor $n = 1$ reveals the average SBH ($\Phi_{\rm b-ave}$). In Ref. [16], this relationship was first reported and this behaviour was ascribed to the deviation of SBH from the characteristic value of a uniform interface. By the extrapolation of $\Phi_{\rm b}$ at $n = 1$ of the experimental data presented in Fig. 4, a value of $\Phi_{\rm b-ave} = 1.39$ eV was determined. According to the Tung's theory, the current transport is dominated by this average SBH in high temperature operation condition.

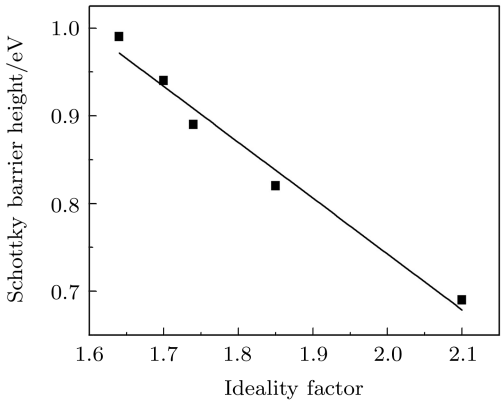


Fig. 4. Barrier height against ideality factor, showing that the extrapolation to $n = 1$ via a linear fit yields the average SBH $\Phi_{\rm b-ave} = 1.39$ eV.

Figure 5 shows the Richardson plot for Ti/4H–SiC MPS diode, with $\ln(J_{\rm s}/T^2)$ plotted against the inverse temperature, where $J_{\rm s} = I_{\rm s}/A$ and $I_{\rm s}$ is determined from the extrapolation at $V = 0$ of experimental I–V data. The effective barrier height is found to be 0.968 eV from the slope of the linear fit of the Richardson plot. The average behaviours of the MPS contact at different temperatures have been taken into account during the process of extracting the barrier height. Therefore, the Schottky barrier height obtained from the slope of the $\ln(J_{\rm s}/T^2)$ vs. $1000/T$ (Richardson plot) may be regarded as the effective SBH of the 4H–SiC MPS.

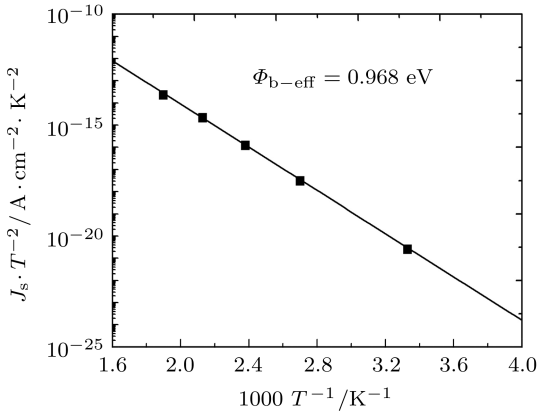


Fig. 5. Richardson plot, $\ln(J_{\rm s}/T^2)$ vs. $1000/T$. A SBH $\Phi_{\rm b-eff}$ of 0.968 eV is extracted from the slope of the linear fit.

The average SBH $\Phi_{\rm b-ave}$ and the effective SBH $\Phi_{\rm b-eff}$ of the 4H–SiC MPS diode have been extracted from the experimental results at different temperatures using the aforementioned extraction method. According to the Tung's model, the relationship between $\Phi_{\rm b-ave}$ and $\Phi_{\rm b-eff}$ can be expressed as follows:

$$\Phi_{\rm b-eff} = \Phi_{\rm b-ave} - \gamma \left(\frac{V_{\rm bb}}{\varepsilon_{\rm s}} q N_{\rm D} \right)^{1/3}, \qquad (2)$$

where γ is a parameter that is introduced to describe the in-homogeneity of the Schottky barrier height and includes the dimensions of the patch with a lower barrier and the deviation from the $\Phi_{\rm b-ave}$, $\varepsilon_{\rm s}$ is the permittivity of the material and $V_{\rm bb}$ is the band bending. Then from Eq. (2), the γ can be found to be 8.85×10^{-4} cm$^{2/3} \cdot$V$^{1/3}$.

Considering the presence of the lower SBH patches embedded in a region of high barrier, the conventional TE equation [Eq. (1)] should be rewritten as

$$I = \left(\frac{W+S}{S}\right) N A_{\rm eff} A^* T^2 \exp\left(-\frac{q\Phi_{\rm b-eff}}{kT}\right) \times \left[\exp\left(\frac{qV_{\rm F}}{nkT}\right) - 1\right], \quad (3)$$

where N is the number of patches in the contact area and $A_{\rm eff}$ is the area of a single patch of the low SBH. By comparison with Eq. (1), equation (3) shows that the whole contact area A is replaced with the product $N \cdot A_{\rm eff}$, which represents the total area of a contact made up of a low SBH. Here the effective area of the low SBH patch can be expressed as[17]

$$A_{\rm eff} = \frac{4\pi q\gamma}{9kT}\left(\frac{\varepsilon_{\rm s}}{qN_{\rm D}V_{\rm bb}}\right)^{2/3}. \quad (4)$$

Using the value of γ determined from Eq. (2), a value of $A_{\rm eff}$ is found to be 1.34×10^{-10} cm^2. Figure 6 shows the comparison between the experimental data and theoretical I–V characteristics using the rewritten current transport equation (3) between 300 K and 520 K, in which the theoretical curves are computed with $\Phi_{\rm b-eff} = 0.968$ eV and $N = 2.14 \times 10^5$. The effective area $N \cdot A_{\rm eff} = 2.88 \times 10^{-5}$ cm^2 is determined and makes up only 4.3% of total contact area. As can be seen, the calculated data are in agreement with measured results.

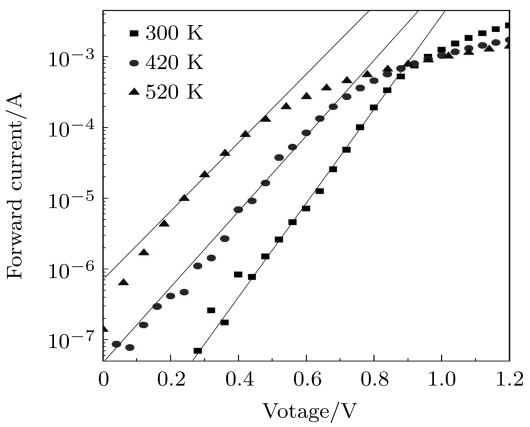


Fig. 6. Experimental current voltage characteristics at temperatures of 300 K, 420 K and 520 K and I–V curves calculated using Eq. (3).

It is found that even though the low barrier area is only a few percent fraction of the whole contact area, the current transport is influenced mainly by these regions. The proportion of the low barrier region ($N \cdot A_{\rm eff}$) in the whole Ti/4H–SiC MPS rectifying contact area is slightly bigger than that in the pure Ti/4H–SiC Schottky contact, in which the low barrier region area accounts for only 1%–2% of the total contact area.[17] It indicates that ion implantation in the Schottky contact region may result in the poor Ti/4H–SiC interface quality and more serious inhomogeneous Schottky barrier effect.

The forward current density–voltage (J–V) characteristics in a high voltage range ($V_{\rm F} > 1$ V) are shown in Fig. 7. In this voltage range, the current-voltage relationship can be described by Ohm's law, which can be written as $J = (1/R_{\rm on-sp}) \cdot V_{\rm F}$. From these curves, the diode specific on-resistance can be extracted and shown in Table 1. It can be seen that the on-resistance increases with the temperature increasing. An $R_{\rm on-sp}$ value of 16.049 m$\Omega\cdot$cm^2 is found at room temperature and increases to 49.135 $\Omega\cdot$cm^2 at 520 K. This temperature dependence of the specific on-resistance can be explained as follows: when temperature increases, more impurities are ionized and the mobility limited by the phonon scattering becomes dominant mechanism, which causes the conductivity of 4H–SiC to decrease and consequently leads the series resistance to increase.

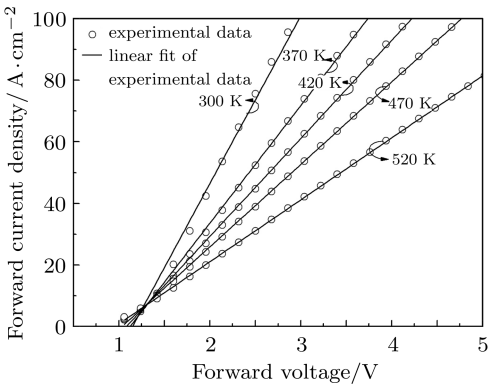


Fig. 7. Forward J–V characteristics in a high voltage range ($V_{\rm F} > 1$ V) where the symbols represent measured data and the solid lines denote the linear fit to the data.

Table 1. Extracted Ti/4H–SiC MPS specific on resistance at different temperatures.

Temperature/K	$R_{\rm on-sp}$/m$\Omega\cdot$cm^2
300	16.049
370	24.198
420	30.556
470	37.119
520	49.435

Figure 8 shows the current flow pattern in the SiC MPS diode during operation in the on-state. According to the current flow pattern in the MPS rectifier, the on-resistance includes three different components:[18] channel resistance R_{D1}, spreading region resistance R_{D2} and drift region resistance R_D. Thus the series resistance can be expressed as

$$\begin{aligned} R_S &= R_{epi} + R_{sub} + R_C \\ &\approx (R_{D1} + R_{D2} + R_{D3}) + R_{sub}, \end{aligned} \tag{5}$$

where R_{epi} is the epitaxial layer resistance and R_{sub} is the substrate resistance. Here, the ohmic contact resistance R_c is neglected due to the fact that its value is far smaller than those of epitaxial layer resistance and substrate resistance. The specific on-resistance R_{on-sp} is shown as follows:

$$\begin{aligned} R_{on-sp} = {} & \frac{x_j(W+S)}{qN_D\mu_n S} + \frac{(W+S)}{qN_D\mu_n}\ln\left(\frac{W+S}{S}\right) \\ & + \frac{t - w/2 - x_j - 2d}{qN_D\mu_n} + \frac{t_{sub}}{qN_{sub}\mu_n}, \end{aligned} \tag{6}$$

where x_j is the depth of the junction, N_D and N_{sub} are the doping concentrations of epi-layer and substrate, respectively, t and t_{sub} are the thicknesses of epi-layer and substrate, d is the junction depletion width and μ_n is the electron mobility that can be expressed as[19]

$$\mu_n = \frac{947 \times \left(\dfrac{T}{300}\right)^{\alpha}}{1 + \left(\dfrac{N_D^+}{1.94 \times 10^{17}}\right)^{\beta}}\ (\mathrm{cm^2 \cdot V^{-1} \cdot s^{-1}}), \tag{7}$$

where N_D^+ denotes the total concentration of ionized impurities, T is the absolute temperature, $\alpha = -2.4$ and $\beta = 0.61$. Because the donor levels and the acceptor levels in 4H–SiC are deep compared with the thermal energy at room temperature, the impurities in 4H–SiC cannot be completely ionized even at high temperature. So the effect of incomplete ionization of the impurities cannot be neglected in the calculation of the dependence of specific on-resistance on temperature. The concentration of ionized impurities can be given by

$$N_D^+ = \frac{\sqrt{1 + 4N_D\dfrac{g_c}{N_C}\exp\left(\dfrac{\Delta E_D}{kT}\right)} - 1}{2\dfrac{g_c}{N_C}\exp\left(\dfrac{\Delta E_D}{kT}\right)}, \tag{8}$$

where N_D is the doping concentration of donors, E_D is the dopant activation energy, g_c is the degeneracy factor ($g_c = 2$ for electrons) and N_C is the density of the states in the conduction band.

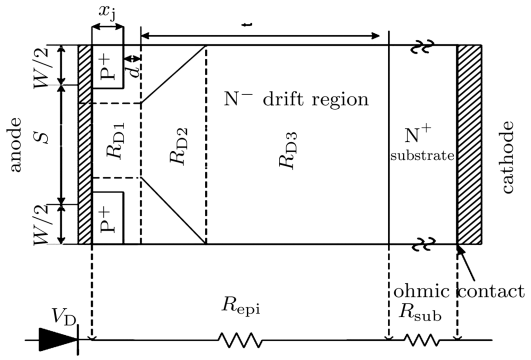


Fig. 8. Forward conduction model of 4H–SiC MPS rectifier.

The calculated relationship between R_{on-sp} and T using the analytical solution of R_{on-sp} Eq. (6) is presented in Fig. 9, which is similar to that experimental data proportional to $T^{2.14}$. In comparison, we can see that the experimental results are slightly bigger than the calculated results in a 300–500 K temperature range. We speculate that this discrepancy arises from being neglectful of the contribution from the back side ohmic contact resistance. A temperature dependence of the R_{on-sp}, $T^{2.14}$, is determined in the temperature range 300 K–520 K, which can be used for estimating R_{on-sp} values at different operational temperatures with ignoring ohmic contact resistances if perfect process is done. It has been demonstrated that the phonon scattering limited mobility is known to be proportional to $T^{-1.5}$ at high temperature. Here, the presence of defects in the materials is responsible for the increase of temperature coefficient of the R_{on-sp} in experiment.

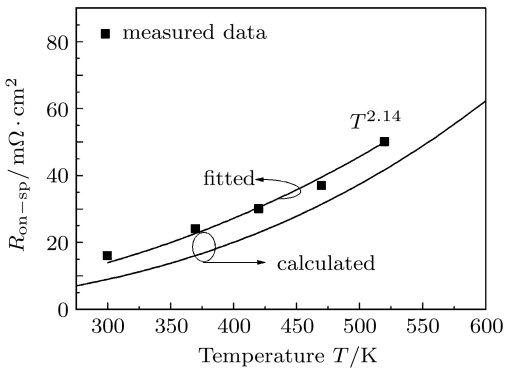


Fig. 9. Temperature dependences of specific on-resistance for 4H–SiC MPS diode at difference temperatures.

4. Conclusions

The high temperature electrical behaviours of Ti/4H–SiC MPS rectifier have been investigated by I–V measurements at various temperatures. Evaluation of the experimental I–V data reveals a decrease in

Schottky barrier height $\Phi_{\rm b}$ but an increase in ideality factor n, with temperature decreasing, which suggests the occurrence of an inhomogeneous Schottky barrier. The average SBH $\Phi_{\rm b-ave} = 1.39$ eV is obtained by analysing the linear relationship between $\Phi_{\rm b}$ and n and the effective barrier height $\Phi_{\rm b-eff}$ is found to be 0.968 eV from the slop of the linear fit of the Richardson plot. Applying the Tung model to experimental I–V–T data, the current transport behaviours of the Ti/4H–SiC MPS contact are analysed, which indicates that the P^+ region formed by ion implantation in the process of fabrication Ti/4H–SiC MPS contact may lead to the poor quality of the metal/4H–SiC interface and the more serious inhomogeneous Schottky barrier effect. Finally, the temperature dependence of the $R_{\rm on-sp}$, $T^{2.14}$, is determined in the temperature range 300 K–520 K, which is similar to that predicted by reduction in electron mobility and can be used for estimating $R_{\rm on-sp}$ at different operational temperatures while ignoring ohmic contact resistance if a perfect process is achieved.

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