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Numerical modelling of anisotropy in 4H-SiC MESFET's

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A numerical model for 4H-SiC MESFET anisotropy is presented in this paper and the device performances, such as breakdown, temperature and transient characteristics, are demonstrated. The simulation results show obvious effects of the anisotropy for 4H-SiC and are in better accordance with the experimental results. The anisotropy for 4H-SiC should be involved in the device design to acquire better performances.

Keywords: 4H-SiC, MESFET, anisotropy, numerical model
PACC: 7210, 7220, 7280, 4410

1. Introduction

The 4H-SiC MESFET is one of the most promising materials for high-power, high-temperature or high-frequency applications because of its excellent properties. The high saturation velocity and fairly good mobility results in a higher current density compared to traditional silicon devices. The high thermal conductivity and breakdown electrical field are also favourable parameters for high power devices.

With the hexagonal polytype as the basic material, the effect of anisotropy is observed in the results of both experimental tests and Monte Carlo modelling.[1,2] As to the simple one-dimensional devices such as pn diodes and Schottky barrier diodes, the optimization can be accomplished by choosing the appropriate crystal direction for the current flow and the simulation model can be approximately considered as isotropic. But, as to the 4H-MESFET, in which there is a more complicated distribution of electric field and current, an anisotropic model is needed for simulation and optimization of the devices.

Typically, 4H-SiC is grown in the Si phase. Alternatively, it can be grown in the C phase by varying the growth condition. Owing to the anisotropy of the material, the performance of the devices made in Si phase and C phase is quite different. So far, little work has been done to compare and estimate the difference.

In this paper, a numerical model including anisotropy property is presented. Using this model, the breakdown, temperature and transient characteristics of the device are simulated. The results show the effects of the anisotropy and explain the discrepancy between the experimental and calculated results.

2. Model

In the simulation, a two-dimensional drift-diffusion model in the MEDICI device-simulator is used.[3] Since the anisotropy influences the device on its breakdown, temperature and transition characteristics notably, the carriers transport equations, impact ionization coefficients and heat flow equation must be extended to tensor equation. The interrelated equations are presented as follows:

$$\boldsymbol{J}_\alpha = qc_\alpha \mu_\alpha \nabla \phi_\alpha \quad (\alpha = \mathrm{n}, \mathrm{p}), \tag{1}$$

$$\beta_{\alpha,ii} = \beta^{\infty}_{\alpha,ii}(T) \cdot \exp\left[- \left(\frac{E^{\mathrm{crit}}_{\alpha,ii}(T)}{E_{\alpha,\|}} \right)^{\exp,\mathrm{II}} \right] \ (\alpha = \mathrm{n}, \mathrm{p}), \tag{2}$$

$$\rho c \frac{\partial T}{\partial t} = H + \nabla(\lambda(T)\nabla T), \tag{3}$$

where the mobility μ, impact ionization coefficient β and thermal conductivity are changed into the following form:

$$A = \begin{pmatrix} A_\perp & 0 & 0 \\ 0 & A_\| & 0 \\ 0 & 0 & A_\perp \end{pmatrix} \tag{4}$$

with $A_\perp$ and $A_\|$ representing the parameters parallel and perpendicular to the C-axis, respectively.

The anisotropy of 4H-SiC material results from the anisotropic electronic structure in non-cubic crystal, which leads to different effective masses and scattering rates along different high-symmetric directions. Figure 1 shows the crystal and Brillouin zone structure. Some experimental results about transportation and impact ionization anisotropy have been obtained by Baliga and Schaffer.[1,4] On the other hand, the theoretical calculated anisotropic coefficients have also been reported recently.[2] In table 1, values used in our model are presented.

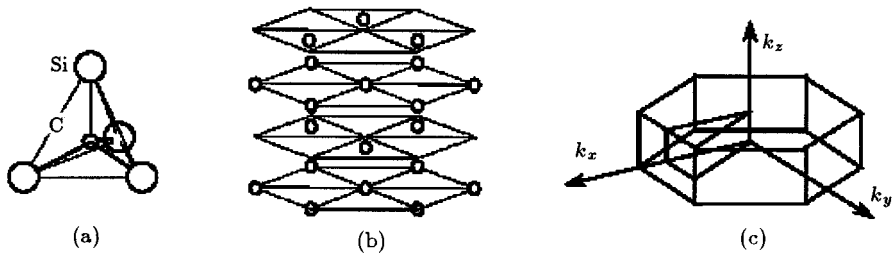


Fig.1. (a) The bonds between atoms in the SiC crystal; (b) The positions of atoms in the unity cell (only Si atoms plotted); (c) The Brillouin zone of 4H-SiC with the irreducible wedge plotted.

Table 1. Parameters used in simulation.[1,2,4]

	μ_n/(cm/V·s)	μ_p/(cm/V·s)	α_n^∞/(cm·K)	α_p^∞/(cm·K)	λ/(W/cm·K)
∥ C	$0.8\mu_{nchanal}$	$0.8\mu_{pchanal}$	4×10^5	3.2×10^6	3.3
⊥ C	$\mu_{nchanal}$	$\mu_{pchanal}$	4.8×10^7	8×10^7	4.8

3. Results and discussing

Figure 2 shows the cross-section of a recessed-gate MESFET structure. The material structure consists of an n-type substrate, p-type buffer (where N_A=1.4×10^{15}cm^{-3}), n-type channel epilayer (where the N_d=1.7×10^{17}cm^{-3}), and N$^+$ contact layer (where $N_d \geq 2\times10^{19}$cm^{-3}). The values of L_g, L_{gs}, L_{gd}, W and d_r are 0.7, 0.3, 0.8, 0.25 and 0.1μm, respectively.

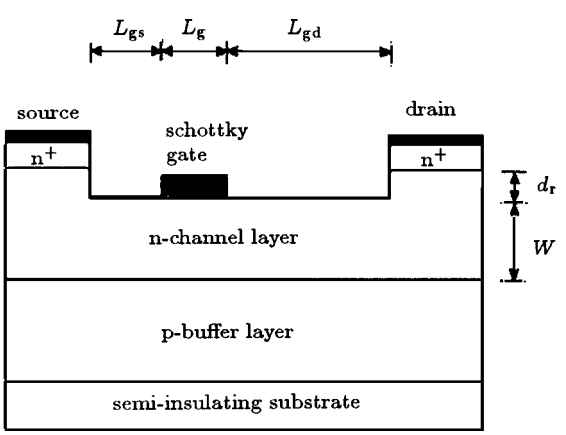


Fig.2. Schematic cross-section of the MESFET.

Using the above models, the performance of the device is simulated. In planar MESFET, the voltage drops abruptly in the gate drain space where the electric field reaches peak value. With increasing the drain bias, the avalanche impact ionization appears in this area. Figure 3(a) shows the comparison of the breakdown characteristics. The I-V characteristics of both the Si phase and the C phase devices are calculated with the anisotropic model (Fig.3(b)).

For the Si phase device, the calculated breakdown voltage is 110V, which is much less than the isotropic results of 225V. The discrepancy between the two results is accordant with the fact that the impact ionization coefficient parallel to the C-axis is less than that perpendicular to the C-axis. The orientation dependence of the device is so noticeable that some measures must be taken to avoid the pre-breakdown in the direction perpendicular to C-axis. The methods in common use are to change the epilayer growth direction or to polish the surface into a certain angle.

An interesting observation is that the simulated curve has two sections with a sharp change of the slope. It seems to be due to the abrupt increase of the gate current. The assumption needs further experimental confirmation.

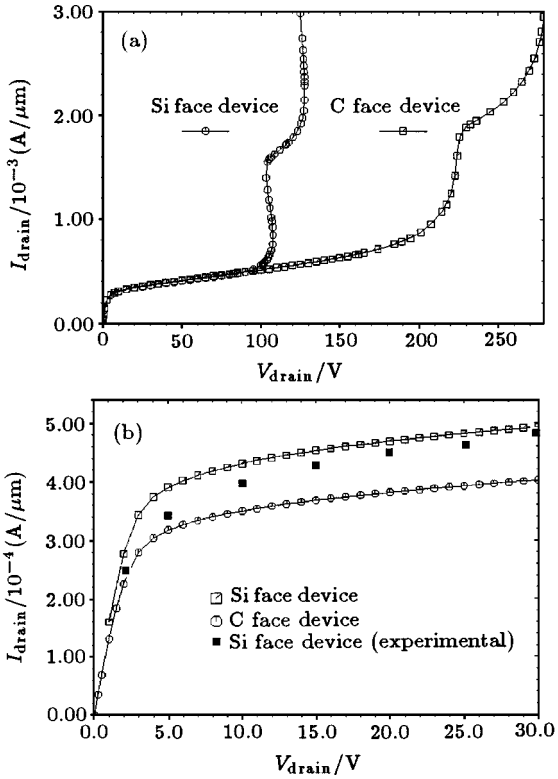


Fig.3. (a) The breakdown characteristics of the device (V_{gs}=0V); (b) The I-V transportation characteristics of the device (V_{gs}=0V).

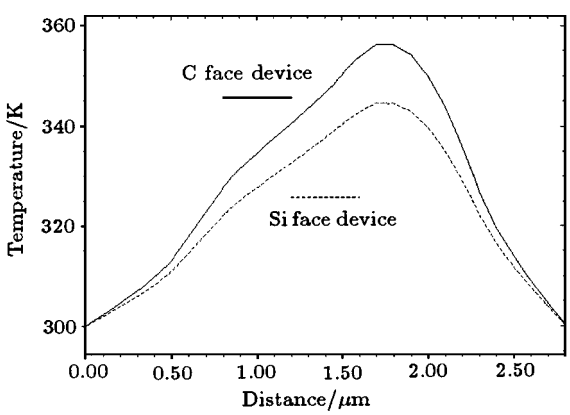


Fig.4. The thermal characteristics of the device (V_{gs}=0V).

Although the thermal design of SiC MESFET can be greatly simplified due to its high thermal conductivity, the thermal transportation and the temperature characteristics of the device should be simulated to optimize the device design. Anisotropy is a very important factor that effects the temperature distribution in the device. Fig.4 shows the thermal characteristics of the device (V_{gs}=0V, V_{ds}=30V). Anisotropy has obvious effects on the distribution of the temperature in the device. In the direction perpendicular to the C-axis, the thermal conductivity is higher and the power transports faster. The temperature in the Si phase device is lower than that in the C phase device. With this result, we can explain the discrepancy between the experimental result and the calculated isotropy results. In the thermal optimization design, the direction of the heat sink should be chosen in accordance with the direction in which heat and power are conducted more quickly.

As recently reported, the mobility anisotropy in 4H-SiC is not as serious as that in 6H-SiC.[4,5] However, it has affects on complex device structures, such as 4H-SiC MESFET. Figure 3(b) shows the anisotropy simulation of the I-V characteristics when the gate bias is 0V. Since the mobility in the direction perpendicular to the C-axis is higher than that parallel to the C-axis, the transport characteristics in Si phase is better than that in C phase. The simulation results are in agreement with the experiments.[6] In the electrical optimization design, the direction of the transport channel should be chosen in accordance with the higher mobility.

It can be observed in Fig.3(b) that there is a small discrepancy between the experimental and the calculated results. The slightly higher current in the simulation is due to the interface states and the series contact resistance. In our current simulation, the interface states and boundary contact are considered to be ideal and their effects are ignored. However, they will decrease the channel current and increase the on-state resistance in the actual performance.[7] In the future work, these effects will be included in the model and the influence discussed in detail.

4. Conclusion

The device performances, such as breakdown and temperature characteristics, are investigated using an anisotropic numerical model. In the above results, the optimized orientations for higher breakdown voltage and larger current conflict. To avoid the disadvantage, Lades[3] use the structure with predominant lateral current flow such as JFET. But JFET has the disadvantage of larger turn-on voltage and disadvantage in MMIC integration. Normally, 4H-SiC is grown in the Si phase and the optimization can be realized by polishing the surface into a certain angle.

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