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Model and analysis of drain induced barrier lowering effect for 4H–SiC metal semiconductor field effect transistor*

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Based on an analytical solution of the two-dimensional Poisson equation in the subthreshold region, this paper investigates the behavior of DIBL (drain induced barrier lowering) effect for short channel 4H–SiC metal semiconductor field effect transistors (MESFETs). An accurate analytical model of threshold voltage shift for the asymmetric short channel 4H–SiC MESFET is presented and thus verified. According to the presented model, it analyses the threshold voltage for short channel device on the L/a (channel length/channel depth) ratio, drain applied voltage $V_{\rm DS}$ and channel doping concentration $N_{\rm D}$, thus providing a good basis for the design and modelling of short channel 4H–SiC MESFETs device.

Keywords: 4H silicon carbide, metal semiconductor field effect transistor, drain induced barrier lowering effect, short channel

PACC: 7210, 7330, 7360F

1. Introduction

For the high saturated electron drift velocity (2.1×10^7 cm/s), high breakdown field (2×10^6 V/cm–4×10^6 V/cm), high thermal conductivity (4.9 W/cm·K) and wide bandgap (3.26 eV), 4H–SiC is considered as the important material to fabricate the high power, compact, high temperature and high frequency devices. The 4H–SiC MESFETs (Metal Semiconductor Field Effect Transistor) is one of the important candidate devices of next generation for the applications of new phased array radar, base station, and satellite & aerospace based systems, for its superior characteristics of high power, compactness, high frequency and high efficiency.[1−6]

Recently, some research groups have shown several breakthroughs in the progress of 4H–SiC MESFET devices. S. Sriram reported the 4H–SiC MESFET with $f_{\rm max}$ of 42 GHz,[7] and Luo B. reported the output power of 56 W with power efficiency of larger than 50%.[8] To make 4H–SiC MESFET operated in high frequency, the shorter channel device will be designed and fabricated, as well as higher power with high drain operated voltage. Thus, the high drain operated voltage and short channel of devices lead to an obvious evidence of short channel effect, such as the threshold voltage shift.

Drain induced barrier lowering (DIBL) (or "punch through") effect, one of the main issues of short channel effect, has been investigated in metal oxide semiconductor (MOS) transistor and GaAs or Si MESFET before. Also, some works of investigating and modelling the DIBL effect for 4H–SiC MESFETs have been made. Hirotake Honda gave an experimental investigation of radio frequency (RF) characteristics for 4H–SiC MESFETs,[9] and W. Liu presented a simple discussion of DIBL effect using numerical method.[10] However, the operational principle and analytical model of DIBL effect for 4H–SiC MESFET under high drain voltage operated condition is still being investigated furthermore.

In this paper, we give an analytical model of the DIBL effect based on an analytical solution of two-dimensional Possion equation in subthreshold region for 4H–SiC MESFET. This model presents an analytical relationship of the threshold voltage shift and

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the short channel length, drain applied voltage, etc. In addtion, the presented model can be used to estimate the RF characteristics of short channel 4H–SiC MESFET, and to analyze the device performances of different $N_{\rm D}$ (channel doping concentrations) and different L/a (channel length and channel depth ratio).

2. Theory description

The cross section of the n-channel 4H–SiC MESFET is illustrated in Fig.1. The Ohmic contacts are made at the terminals of drain and source, the gate with the recessed structure is formed on N-type SiC channel with a Schottky contact, and the low p-type doping layer and SiC substrate are underneath the channel sequentially.

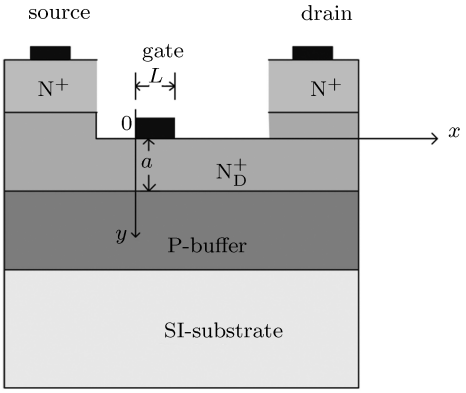


Fig.1. Cross section of SiC MESFET.

In the channel region, the two-dimensional Poisson equation is given by

$$\frac{\partial^2\phi\,(x,y)}{\partial x^2}+\frac{\partial^2\phi\,(x,y)}{\partial y^2}=-\frac{qN_{\rm D}^{+}}{\varepsilon}, \tag{1}$$

where $\phi(x,y)$ is the total electrostatic potential, $N_{\rm D}^{+}$ is the ionization doping concentration (assumed to be uniform, and the "freeze effect" of 4H–SiC is considered), q is the electronic charge, and ε is the permittivity.

Also, the boundary condition of the rectangular region is given by

$$\phi\,(0,y)=\phi_{\rm ss}=\phi_{\rm n^+-i}, \tag{2a}$$
$$\phi\,(L,y)=\phi_{\rm ss}+V_{\rm DS}, \tag{2b}$$
$$\phi\,(x,0)=U\,(0)=\phi_{\rm s0}, \tag{2c}$$
$$\frac{\partial\phi\,(x,a)}{\partial y}+\frac{\partial U\,(y)}{\partial y}=0, \tag{2d}$$

where $\phi_{\rm n^+-i}$ is the built-in potential across gate/drain-to-substrate, $U(y)$ is 1-D (one dimensional) Poisson solution, $V_{\rm DS}$ is applied drain voltage, $\phi_{\rm s0}$ is the potential at gate-channel surface, L and a are the length and depth of device channel, respectively.

According to the approach presented in Refs.[11] and [12], the potential $\phi(x,y)$ in Eq.(1) is expressed as a superposition of two functions, $U(x,y)$ and $\psi(x,y)$, such that

$$\phi\,(x,y)=U\,(x,y)+\psi\,(x,y)\,, \tag{3}$$

where $U(x,y)$ and $\psi(x,y)$ satisfy the following condition:

$$\frac{\partial^2\psi\,(x,y)}{\partial x^2}+\frac{\partial^2\psi\,(x,y)}{\partial y^2}=0, \tag{4a}$$
$$\frac{\partial^2U\,(x,y)}{\partial x^2}+\frac{\partial^2U\,(x,y)}{\partial y^2}=-\frac{qN_{\rm D}^{+}}{\varepsilon}. \tag{4b}$$

The solution of Eq.(1) is obtained by using the perturbation method,[12] thus $\phi(x,y)$ can be obtained if only the first term of series is applied (for the summation of series is dominated by the first term).[12]

At the threshold, all the field lines from the gate terminate on the ionized donor charges in the completely depleted channel. As the channel length reduced, a portion of the vertical field lines at the surface terminates on source instead of drain.[11]

Due to the extent of the electric field, we can assume that the minimum surface electric field

$$E_{ys\,\min}=\frac{\partial\phi\,(x,y)}{\partial y}\,|_{y=0,x=x_0} \tag{5}$$

is located at

$$x_0=\beta L, \tag{6}$$

where $\beta=\dfrac{L_{\rm GS}+L/2}{L_{\rm DS}}$, $L_{\rm GS}$ is the space between gate and source and $L_{\rm DS}$ between source and drain. For the devices of asymmetric structure between gate and drain and high drain voltage operation, $E_{ys\,\min}$ is nearly located at the midpoint of the channel for that of symmetry structure and low drain voltage operation.

From $\phi(x,y)$, we can obtain

$$\begin{aligned}E_{ys\,\min}&=\frac{\partial\phi\,(x,y)}{\partial y}\,|_{y=0,x=\beta L}\\&=\frac{qN_{\rm D}^{+}}{\varepsilon_0\varepsilon_{\rm r}}h\,(x)+\Delta E_{ys\,\min},\end{aligned} \tag{7}$$

where

$$\Delta E_{ys\,\min} = \frac{\pi}{2a\sinh(\pi L/2a)}\left\{\left[\frac{4(\phi_{ss}-\phi_{s0})}{\pi} - \frac{16}{\pi^3}\frac{qN_D^+}{\varepsilon}a^2\right]\sinh\left(\frac{\pi\beta L}{2a}\right) + \left[\frac{4(\phi_{ss}-\phi_{s0})+V_{DS}}{\pi} - \frac{16}{\pi^3}\frac{qN_D^+}{\varepsilon}a^2\right]\sinh\left(\frac{\pi(1-\beta)L}{2a}\right)\right\} \quad (8)$$

is the extent of electric field induced by DIBL effect.

In order to make the device off, a voltage must be applied to the gate to compensate for the electric field. Thus the threshold voltage can be expressed as follows:[11]

$$V_T = V_{T0} + a\Delta E_{ys\,\min}, \quad (9)$$

where $a\Delta E_{ys\,\min}$ is the DIBL-induced short-channel threshold voltage shift.

Moreover, one can obtain the relationship of threshold voltage with drain applied voltage from Eq.(9), such as

$$V_T = V_{T0} + \lambda V_{DS}, \quad (10)$$

where λ can be easily calculated from Eq.(9). Equations (9) and (10) also demonstrate a principle of calculating empirical parameter λ in the Curtice model.[13] Also, the relationship of threshold voltage shift with high operated drain voltage for 4H–SiC metal semiconductor field effect transistor can be easily calculated from Eq.(10).

3. Results and discussion

From the experimental results given by Ref.[9], the verification of the presented model is made. The physical parameters of the device are: channel doping concentration which is 3.1×10^{17} cm^{-3}; the Ohmic contact is made at drain and source; the channel depth which is set to 0.24 μm for the recess structure (original n-type channel layer is 0.29 μm); L_{GS} and L_{GD} which are set to typical value 0.5 μm and 1.5 μm respectively. The channel length is changed from 0.3 μm to 1.5 μm.

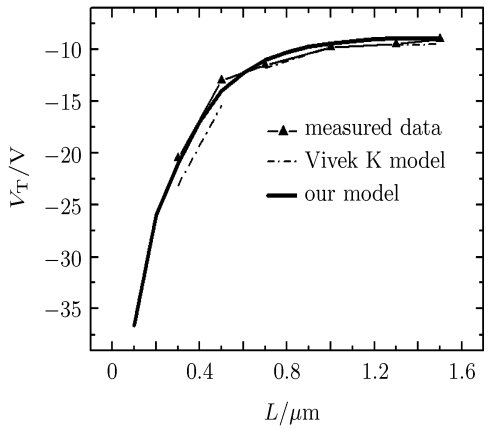


Fig.2. Comparison of simulated results and experimental data for threshold voltage shift of short channel 4H–SiC MESFET, drain voltage V_{DS} is 40 V.

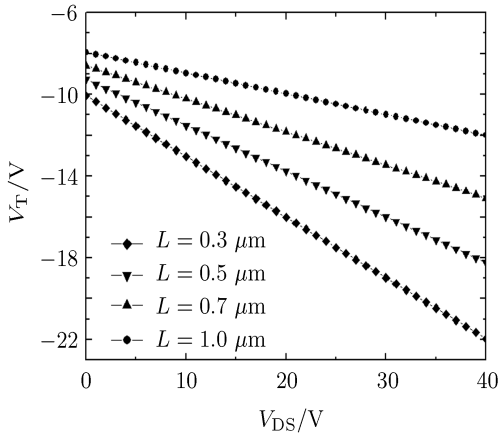


Fig.3. Relationship of threshold voltage (V_T) with drain applied voltage (V_{DS}).

Figure 2 shows a good agreement between simulated results and the measured data for threshold voltage model for short channel 4H–SiC MESFET.

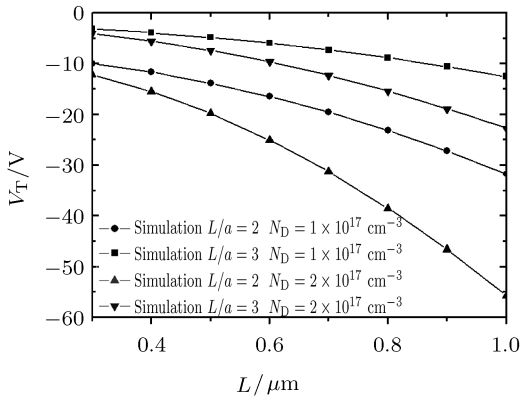


Fig.4. Relationship of threshold voltage (V_T) with different L/a ratio and channel doping density N_D.

The relationship of threshold voltage with drain applied voltage is illustrated in Fig.3. The device channel length is 0.3 μm, 0.5 μm, 0.7 μm and 1 μm respectively, and the other physics parameters of the device are the same as given above. It is shown that parameter λ in Eq.(10) is the slope of the line of threshold voltage (V_T) with drain applied voltage (V_{DS}). The simulated results also are comparable with the results presented in Refs.[14] and [15].

Also, the threshold voltage shift with different L/a ratio and different channel doping concentrations are presented in Fig.4, where the drain applied voltage $V_{DS} = 40$ V. From Fig.4, it can be observed that narrow channel structure and high doping concentration are needed to reduce the DIBL effect of 4H–SiC MESFET.

4. Conclusion

The DIBL effect will come forth when the channel length of 4H–SiC MESFET device decreases continually to get high operated frequency. To describe the 4H–SiC MESFET DIBL effect, one of the most important short channel effects, a relationship of threshold voltage versus drain applied voltage is derived based on an analytical solution of the 2D Poisson equation in the subthreshold region, and the behavior of drain induced barrier effect is investigated in short channel 4H–SiC MESFET. The viability of the presented DIBL effect model is also made. According to the presented model, an analysis of short channel device performance on the L/a (channel length/channel depth), doping concentration N_D is made, which provides a good basis for the design of short channel 4H–SiC MESFET device.

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