An Analytical Model of Drain Induced Barrier Lowering Effect for SiC MESFETs

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Abstract

Based on an analytical solution of the two-dimensional Poisson equation in the subthreshold region, the behavior of DIBL(Drain Induced barrier lowering) effect is investigated for short channel 4H-SiC MESFETs. An analytical model of accurate threshold voltage shift model for the asymmetry short channel 4H-SiC MESFET is presented and thus verified. According to the presented model, an analysis of threshold voltage for short channel device on the L/a(channel length/channel depth) ratio, drain applied voltage V_{DS} and channel doping concentration N_D is made, which provides a good basis for short channel device and circuit design.

Keywords:4H Silicon Carbide, Metal Semiconductor Field Effect Transistor, drain induced barrier lowering effect, short channel

1 Introduction

For the high saturated electron drift velocity (2.1×10^7 cm/s), high breakdown field ($2\text{-}4\times10^6$V/cm), high thermal conductivity (4.9W/cm.K) and wide bandgap (3.26eV). 4H-SiC is considered as the important material to fabricate the high power, compact, high temperature and high frequency devices.

4H-SiC MESFETs(Metal Semiconductor Field Effect Transistor) is one of important candidate devices of next generation for the applications of new generation Phased array Radar, base station, and satellite & aerospace based systems, for its superior characteristics of high power, compact, high frequency and high efficiency [1-6].

Recently, some research groups show several breakthrough progresses of 4H-SiC MESFET devices and circuits. S.Sriram reports the 4H-SiC MESFET with fmax of 42GHz[7], and Luo B. reports the output power of 56W with power efficiency of larger than 50%[8]. To make 4H-SiC MESFET operated in high frequency, the shorter channel device will be design and fabricated, as while as higher power with high drain voltage operation. 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 and RF characteristics change.

Drain induced barrier lowering (or "punch through") effect, one of the main issues of short channel effect, has been investigate in MOS transistor and GaAs or Si MESFET before. Some works of investigating and modeling the DIBL effect for 4H-SiC MESFETs have been made. Hirotake Honda gives an experimental investigation of RF characteristics for 4H-SiC MESFETs[9], and W.Liu presents 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 the DIBL effect model based on an analytical two-dimensional model for 4H-SiC MESFET. This model presents an analytical relationship of the threshold voltage shift and short channel length and drain applied voltage. 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 channel doping concentrations and different channel length and channel depth ratio.

2 Theory description

The cross-section of the n-channel 4H-SiC MESFET is shown 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.

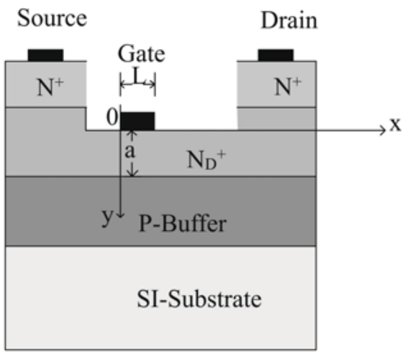

Fig.1 Cross section of SiC MESFET

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

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

where $\Phi(x,y)$ is the total electrostatic potential, N_D^+ is the ionization doping concentration (assumed to be uniform, and the "freeze effect" of 4H-SiC is

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considered), q is the electronic charge, and ε is the permittivity.

And, the boundary condition of the rectangular region is given

$$\phi(0,y)=\phi_{ss}=\phi_{n^+\text{-}i} \tag{2-1}$$

$$\phi(L,y)=\phi_{ss}+V_{DS} \tag{2-2}$$

$$\phi(x,0)=U(0)=\phi_{s0} \tag{2-3}$$

$$\frac{\partial\phi(x,a)}{\partial y}+\frac{\partial U(y)}{\partial y}=0 \tag{2-4}$$

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

According the approach in Ref.[11] and Ref.[12], the potential Φ(x,y) in Eq.(1) above is expressed as a superposition of two functions, U (x,y) and Ψ(x,y), such that

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

where U (x,y) and Ψ(x,y) are satisfy the following condition

$$\frac{\partial^2\psi(x,y)}{\partial x^2}+\frac{\partial^2\psi(x,y)}{\partial y^2}=0 \tag{4-1}$$

$$\frac{\partial^2 U(x,y)}{\partial x^2}+\frac{\partial^2 U(x,y)}{\partial y^2}=-\frac{qN_D^+}{\varepsilon} \tag{4-2}$$

The solution to Eq.(1) is obtained using the perturbation method [12] and only consider the first term of series (For the summation of series is dominated by the first term), Φ(x,y) can be obtained [12].

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

Due to the extent electric field, it can assume the minimum surface electric field

$$E_{ys\min}=\frac{\partial\phi(x,y)}{\partial y}\Big|_{y=0,x=x0} \tag{5}$$

is located at

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

(where $\beta=\frac{L_{GS}+\frac{L}{2}}{L_{DS}}$, L_{GS} is the space between gate and source and L_{GD} between gate and drain) for the devices of asymmetry structure between gate and drain and high drain voltage operation, comparing to E_{ysmin} is nearly located at midpoint of channel for the device of symmetry structure between the source and gate terminal and low drain voltage operation.

From Φ(x,y, we can obtain

$$E_{ys\min}=\frac{\partial\phi(x,y)}{\partial y}\Big|_{y=0,x=\beta L}=\frac{qN_D{}^+}{\varepsilon_0\varepsilon_r}h(x)+\Delta E_{ys\min} \tag{7}$$

where

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

is the extent electric field induced by DIBL effect.

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

$$V_T{}'=V_T+a\Delta E_{ys\min} \tag{9}$$

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

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

$$V_T=V_{T0}+\lambda V_{DS} \tag{10}$$

where λ can be easily obtained for Eq.(9). Eq.(9) and Eq.(10) also show a principle of parameter λ in empirical model developed by Curtice[13]. From Eq.(10) one can easily calculate the threshold voltage with high operated drain voltage for SiC MESFET.

3 Results and discussion

From the experimental results given by Ref[9], the verification of the presented model is made. The device physical parameters are: channel doping concentration is $3.1\times10^{17}cm^{-3}$, the ohmic contact are made at drain and source, the channel depth is set to 0.24μm for the recess structure (original n-type channel layer is 0.29μm), L_{GS} and L_{GD} is set to typical value 0.5μm and 1.5μm. The channel length is changed from 0.3 to 1.5μm.

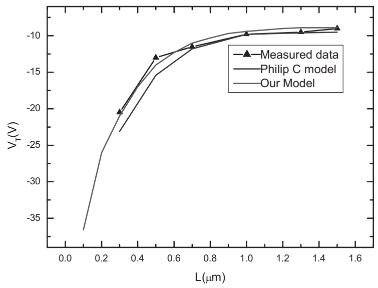

Fig.3 Comparison of simulated results and experimental data for threshold voltage shift of short channel 4H-SiC MESFET, drain voltage V_{DS} is 40V

Fig.3 shows a well agreement between simulated results and the measured data for threshold voltage model for short channel 4H-SiC MESFET.

Fig.4 shows the relationship of threshold voltage with drain applied voltage.

And, threshold voltage shift with different L/a ratio and different channel doping concentration, are presented in Fig.5. From Fig.5, it can be obtained that narrow channel structure and high doping concentration is needed to reduce the DIBL effect of 4H-SiC MESFET.

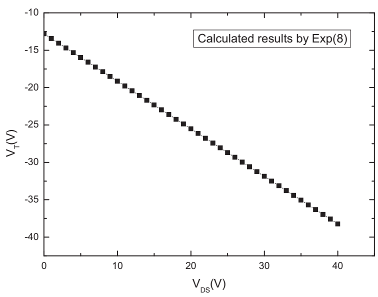

Fig.4 Relationship of threshold voltage(V_T) with drain applied voltage(V_{DS})

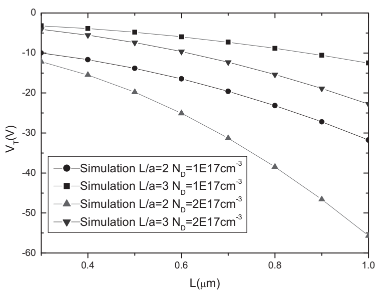

Fig.5 Relationship of threshold voltage(V_T) with different L/a ratio and channel doping density

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 4H-SiC MESFET DIBL effect, one of most important short channel effect, a relationship of threshold voltage model is derived based on an analytical solution of the two-dimensional 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 short channel device and circuit design.

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