An insight into the high frequency analysis of work function modulated cylindrical surrounding gate MOSFET

Biswajit Jena

Device Simulation Lab,
Department of Electronics and Communication Engineering,
Siksha ‘O’ Anusandhan University,
Bhubaneswar, 751030, India
Email: biswajit18590@gmail.com

Sidhartha Dash and Guru Prasad Mishra*

Department of Electronics and Communication Engineering,
Siksha ‘O’ Anusandhan University,
Bhubaneswar, 751030, India
Email: sidharthadash@soauniversity.ac.in
Email: gurumishra@soauniversity.ac.in
*Corresponding author

Abstract: The unique design along with greater accuracy in device performance has made cylindrical surrounding gate MOSFET (CSGM) a cutting edge device in the present VLSI technology. Due to its cylindrical geometry, this device provides higher packing density and higher scaling possibilities. In this work, a work function engineering based metal gate with continuous mole fraction variation along the z-axis in a cylindrical surrounding gate MOSFET (WMCSGM) is introduced. The proposed WMCSGM model exhibits improved RF performance as compared to conventional CSGM model. The static $g_{m}$-VGS curve and $C_{gg}$-VGS curves are investigated clearly. The relevant electrical parameters such as threshold voltage ($V_{th}$), drain current ($I_{d}$) and transconductance are extracted. Along with the electrical parameters, RF parameters and gain parameters (current gain and voltage gain) and different performance measures (cut-off frequency, maximum oscillation frequency) have been extensively investigated.

Keywords: cut-off frequency; maximum oscillation frequency; CSGM; WMCSGM; work function modulation.


Biographical notes: Biswajit Jena received his BTech in Applied Electronics and Instrumentation Engineering from the BPUT, Rourkela, Odisha, India in 2011. He completed his MTech in VLSI and ES from the SOA University, BBSR, India in 2015, where he is currently working toward his PhD in Electronics Engineering. His areas of interests are GAA-MOSFET and nanoelectronic devices.
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Sidhartha Dash received his BE in Electronics Engg. from the F.M. University and MTech from the KIIT University, Bhubaneswar, Odisha, India. He is currently working towards his PhD in Electronics Engineering. His areas of interest are TFET and nano electronic devices.

Guru Prasad Mishra received his BE in Electronics Engg. from the Utkal University and MTech from the NIT, Rourkela, Odisha, India. He completed his PhD in Electron Devices from the Jadavpur University, Kolkata, India in 2012. His current research interests include design and simulation of micro and nano device.

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1 Introduction

In the present CMOS era, cylindrical surrounding gate MOSFET (CSGM) has proved itself as a promising candidate to overcome few cons of previously proposed planar structures (Auth and Plummer, 1997; Chiang, 2005; Colinge et al., 2004). The drawbacks in the planar structures scaling can be assuaged by presenting different multi gate devices. Among those challenging three dimensional architectures, CSGM impressed many researchers due to the excellent electrostatic control of the gate metal over the channel and good CMOS compatibility with quasi-ballistic characteristics (Kranti et al., 2001; Jimenez, 2010; Jena et al., 2015a, 2015b; Suk et al., 2005; Tian et al., 2007; Jiang et al., 2008; Ernst et al., 2008). Recent development in this device structure engrossed many researchers to add few pages for its future headway. CSGM has the ability to control the channel from all around as a result of which the sharing of charge among source and drain reduces as the length of the channel gets shorter (Pal and Sarkar, 2014; Borli et al., 2008; Pfister et al., 1990). As a result the threshold voltage reduces and can be effective in high-speed switching purposes. At the same time introducing some gate engineering techniques such as work-function engineering can reduce the threshold voltage significantly. Down scaling in device dimensions demand oxide thickness to reduce accordingly. A reduced oxide thickness less than 1.5 nm results in a number of defects like boron penetration, quantum effects and increase in off current (Lo et al., 1997; Lin et al., 2002). The boron penetration problem can be resolved using metal work function, however, the next two problems can be solved by selection of proper gate metal (Tsui and Huang, 2003). In case of a planar device, the electric field is generated either in longitudinal or transverse direction. But the scenario is different for multi-gate devices as it has multiple numbers of equivalent electric field in the transverse direction, because of the presence of gate metals in multiple directions. Further, the performance of the device can be enhanced by introduction of multi material structures. The multi material gate concept can be applied by introducing a work function modulated gate, having linear concentration variation from source end to drain end (Manna et al., 2012; Deb et al., 2012; Sarkhel and Sarkar, 2015).
Along with the electrostatic performance of the proposed device, accurate RF performance analysis is an important requirement for the low noise RF integrated circuit development and research. The improvement in complementary MOSFET technology (CMOS) has made it a work horse for system on chip (SoC) applications where MOS transistors have made their unique identity due to improved RF performances in terms of maximum oscillation frequency and cut-off frequency. Therefore introduction of WMCSGM device which is based on engineering of gate metal work function needs to explain the RF necessities, which is a key building block for future SoC design industry. As the design tradeoff in a typical device of semiconductor industry is based on a linear increment in on-current with an exponential increment of off-current, increment in on/off must be required to mitigate the scaling issues. Introduction of large charge density, enhanced carrier transport with improved mobility, higher possibilities of scaling limit and lower parasitic capacitance can improve the CV/I metric and improved drive current.

2 Device structure and simulation

Figure 1(a) and 1(b) show the simulated 3D geometry and cross-sectional view of the proposed WMCSGM model. The device design and simulation are carried out, using TCAD device simulator from synopsys. Sentaurus device is an advanced multi-dimensional device simulator, having the capability to simulate electrical, thermal and optical characteristics of semiconductor devices. Simulator has the ability to perform a wide variety of semiconductor transport models including thermodynamics and hydrodynamic models. Out of various transport models, the drift-diffusion carrier transport model is used as the basic and default model in Sentaurus device. The basic mobility model is used in this simulation to study the effect of transverse electric field, high-field saturation and different doping concentration. The intrinsic carrier concentration is determined by silicon band gap narrowing model (Sentaurus Device User Guide, 2013). Here the channel length is considered to be 90 nm with extension in source/drain of 20nm. Uniform doping profile with concentration of $N_S = N_D = 10^{20} \text{cm}^{-3}$ has been used for source and drain with pentavalent impurities. The channel region is lightly doped in the order of $10^{16} \text{cm}^{-3}$ with trivalent impurity. The model is having a cylindrical silicon channel of diameter 10 nm. The thickness of silicon dioxide ($\text{SiO}_2$) layer is considered as 2 nm.

The AC small-signal analysis is performed to calculate different RF figure of merits (FOMs) applied frequency range of 0.1GHz. The RF simulation of WMCSGM is performed and the results are compared with that of CSGM. The RF analysis of both the models used the total capacitance ($C_{gg}$), transconductance ($g_m$), and cut-off frequency ($f_t$) to illustrate other FOMs. The RF FOMs are basically controlled by three parameters such as gate resistance, gate parasitic capacitance and source/drain series resistance. In designing a RF circuit in the range of GHz, the gate metal resistance should be reduced. The gate resistance parameter can be controlled by introducing some work function engineering to the metal gate. In this model, a work function modulated gate is introduced to enhance the device FOMs.
Figure 1 (a) Simulated 3D geometry (b) Cross-sectional view of work function modulated CSGM (WMCSGM) (see online version for colours)
3 Results and discussions

The featured RF analysis of the suggested model is compared with the conventional model in this section. The parameters which play vital roles in device radio frequency (RF) analysis are thoroughly analysed. For RF applications, apart from device design and dimensions, some device FOMs such as high intrinsic gain, high cut-off frequency, and good transistor matching are necessary and sufficient in RF circuit design.

**Figure 2** Comparison of the valence band and conduction band cut section of the proposed WMCSGM model with conventional CSGM model (see online version for colours)
The energy band diagram plays a major role during the electrostatic performance analysis of a semiconductor device. Position of valence band and conduction band can narrate the device performance easily. Figure 2 illustrates the cross-sectional view of the two models with simulated conduction and valence band. By analysing the band structure of the two models, the superiority of WMCSGM over CSGM can easily visualise.

Figure 2(a) and 2(b) illustrates the valence band simulated view of the proposed and conventional model respectively. Both the models have apparently similar energy values near the source and drain. However, the proposed model has small spikes in the channel region that indicates towards steeper valence band. Similarly, Figure 2(c) and 2(d) illustrates the conduction band simulated view of the two models. The depletion width of the proposed (WMCSGM) model is smaller compared to conventional (CSGM) model.

As a result of which the scattering effect will reduce and hence electron mobility will be improved. Again more number of small spikes is observed in the channel region of WMCSGM model which indicates the steeper conduction band for better insights towards short channel effect reduction. In addition to this, the steeper band structure also results in lower threshold voltage.

Figure 3 Comparison of the electron mobility (eMobility) for through cross-sectional view of the two models at $V_{GS} = 1V$ and $V_{DS} = 0.1V$ (see online version for colours)

Observation in electron mobility of the two models exhibits two different behaviour due to gate metal work-function engineering. Since the gate metal work function controls electron mobility partially, insights to the analysis of metal work function engineering are illustrated in Figure 3. From the Figure 3, it can be perceived that the electron mobility is higher in source side of the conventional model due to high diffusion and gradually decreases due to scattering. However, in case of WMCSGM the electron mobility is lower at the source side but increases gradually due to work-function modulation. This increased mobility is due to very small depletion width of the proposed model. Figure 4 illustrates the distribution in electric field of the two models for a gate voltage of 1V. A high electric field distribution is observed in the channel region with a small spike exactly at the centre of the WMCSGM channel. However, this spike is flat and more prominent in case of CSGM model. As this spike indicates lower electric field and this distribution at the oxide/channel interface leads to lower electron mobility, hence current driving capability reduces. As both the models are assumed with the conditions that at the centre electric field is zero and high at the surface of oxide and channel interface, so higher electric field at the surface make WMCSGM a superior device.
Figure 4  Comparison of the electric field of the two models as a function of $V_{GS}$ at $V_{DS} = 1\text{V}$ (see online version for colours)

Figure 5  Variation in drain current and transconductance w.r.t. gate voltage of both the models (see online version for colours)

Figure 5 illustrates the variation in drain current and transconductance of the proposed and conventional model having the same gate length of 90 nm. For both the models, the drain current is calculated by keeping the drain to source voltage (VDS) constant at 1 V. From the figure we can observed that, the proposed model experiences higher drain current with nearly equal off state current. Transconductance is defined as the ratio
between the drain current change to the gate voltage change over a small interval on V-I characteristic curve. It is observed from Figure 5 that the present model exhibits higher transconductance as compared to CSGM. This is because of the higher mobility as validated in Figure 3. Transconductance of MOSFET is the first derivative of drain current which is measured in the linear region. It indirectly monitors the inversion carrier mobility in the device. The higher transconductance leads to increase in voltage gain and better amplification. Higher value of transconductance leads to higher cut-off frequency, higher transconductance generation factor (TGF) and higher maximum oscillation frequency.

**Figure 6** Variation of gate capacitance as a function of VGS for both models (see online version for colours)

![Graph of gate capacitance vs VGS for both models](image1)

**Figure 7** Comparison of the intrinsic voltage gain ($A_v$), current gain and Masson’s unit gain for the two models as a function of frequency (see online version for colours)

![Graph of gain vs frequency for both models](image2)

In MOS devices, the associated capacitance of the device plays a major role in the charge storing as well as in the calculation of cut-off frequency. Figure 6 demonstrates the
An insight into the high frequency analysis of work function variation of capacitance ($C_{gg}$) with gate-to-source voltage for both the structures. It is marked that the proposed model provides higher capacitance as compared to traditional CSGM. The variation in capacitance with respect to gate voltage for low ($10^8$ Hz) and high ($10^{12}$ Hz) frequency is shown in Figure 6. From the figure it can be observed that for low and high range of frequency, the WMCSGM model provides better capacitance compared to the traditional model. The intrinsic voltage gain is defined as the ratio between transconductance ($g_m$) and output conductance ($g_d$). From Figure 7, it is evident that WMCSGM exhibits higher intrinsic gain as compared to CSGM model at low frequencies. However both models have similar gain for high frequencies. The reduction in gain for CSGM is due to higher value of $g_d$. As a result of which drain induced barrier lowering (DIBL) effect will arise. But, the current gain of the suggested model is higher compared to the conventional model irrespective of the input frequency.

Figure 8  Comparison of the cut-off frequency as a function of gate voltage for both the models (see online version for colours)

Figure 9  Comparison of maximum frequency of oscillation frequency as a function of gate voltage for both the models (see online version for colours)
The cut-off frequency is one of the significant RF FOMs which is extracted for both the structures in Figure 8(a) and 8(b). Cut-off frequency is defined as the boundary in the frequency response of a system where the energy flowing through the system starts to decline. Here the proposed model shows larger cut-off frequency compared to CSGM due to higher transconductance.

Maximum frequency of oscillation is an essential FOM for RF analysis. It is also called unity power gain frequency. Figure 9(a) and 9(b) illustrates the variation in maximum frequency of oscillation with gate voltage for WMCSGM and CSGM models respectively. From the figure, it can be observed that the WMCSGM provides higher oscillation frequency compared to the conventional CSGM.

Figures 10 and 11 illustrate the input and output reflection coefficients $S_{11}$ and $S_{22}$ at a gate voltage of 1 V. Both the models are observed under equal feedback resistance of 100 KΩ and a frequency variation between 1GHz–10THz. Basically $S_{11}$ is used to describe the small signal characteristics of a device operating at high frequency. It is also
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matching parameters in RF circuits. The improvement in characteristic impedance and ports degrades the reflection coefficient due to marginal reflected power. From the enlarged view of Figures 10(b) and 11(b), lower value of reflection coefficient is observed in our proposed model which indicates the more stability of our proposed model. When there is a perfect match, then the reflection coefficients attend to zero. Introduction of work-function engineering on cylindrical gate, current driving ability of the device increases due to the redeployment of the electric field. As a result of which, the transconductance increases leading to enhancement in input and output reflection coefficient.

4 Conclusions

The present work investigates different RF FOMs analysis of work function modulated WMCSGM and compared the results with that of CSGM model. The results exhibit the superior RF performance of the proposed model at high frequency. Introduction of work-function modulation technique for gate metal results in higher cut-off frequency and maximum frequency of oscillation. At the same time, the extraction of RF parameters makes the proposed device more stable and a potential candidate for future semiconductor industry.

References


