Simulation of Advanced n-MOSFET Emphasizing Quantum Mechanical Effects on 2-D Characteristics

Yutao Ma(1)*, Lifeng Chen(1), Bo Jiang(1), Min Zhang(1), Lilin Tian(1), Zhiping Yu(2),
Litian Liu(1), Zhijian Li(1)
(1) Institute of Microelectronics, Tsinghua Univ. Beijing, P.R.China 100084
(2) Integrated IC Lab. Stanford Univ. Stanford CA. U.S.A.
* Email: mayt@263.net

Abstract

Advanced n-MOSFET structure with featured size of 90nm channel length is simulated using a newly developed Quantum Mechanical (QM) correction model based on Modified Airy Function (MAF) method. The influences of Quantum Mechanical Effects (QMEs) on the carrier distribution in the whole channel is included and the output as well as the transfer characteristics are compared with and without QM correction. It is demonstrated that QMEs result in more severe short channel effects such as threshold voltage roll off and DIBL effects .

1 Introduction

The Quantum Mechanical Effects (QMEs) on the characteristics of modern MOSFET's with thin gate oxide and high substrate doping level become more and more significant. Simulation of 2-D characteristics of MOSFET including QMEs is necessary. In the existing 2-D QM correction models, some are too simple to give accurate information of carrier distribution and subband structure and carrier occupation information[1].Some other models are too time consuming to be applicable to practical 2-D device simulation due to the high computation burden of fully numerically solving Schrodinger equations as an eigenvalue problem[2].

In this work, Schrodinger equation is solved with Modified Airy Function (MAF) method[3] and a new QM correction model in the whole channel region in MOSFET is developed. Due to the semi-analytical nature of MAF method, the numerical computation task is substantially reduced. The output characteristics of 90nm channel length Well-Tempered MOSFET[4] is simulated with and without QMEs to manifest the influences of QMEs on device characteristics. A series of MOSFET structures[5] with different gate lengths are simulated and it is shown that QMEs renders more severe short channel effects.

2 Quantum Mechanical Correction Model based on MAF

Accurate determination of carrier distribution and potential profile in quantized inversion and accumulation layer in MOS structure requires solving coupled Schrodinger and Poisson equations. Usually, Schrodinger equation is solved numerically as an eigenvalue problem. But it is very time-consuming. MAF method provides the semi-analytical solution of Schrodinger equation and was widely used in wave guide analysis. Accurate energy levels and wave functions of arbitrary number of subbands can be obtained while keeping satisfied efficiency due to the analytical nature of the method.

The wave function from solution of Schrodinger equation by MAF method is[3]:

$$\psi_i(x) = A\cdot\left(d\xi_i/dx\right)^{1/2} Ai\left(-\xi_i(x)\right) \tag{1}$$

where Ai is the Airy function, A is constant and:

$$\xi_i(x) = \left\{1.5\cdot\int_x^{x_0}\left[\left(2m_i^*/\hbar^2\right)\left(E_i - V(t)\right)\right]^{1/2} dt\right\}^{2/3} \tag{2}$$

in which $V(\cdot)$ is potential, E_i is energy level. x_0 is the position where $E_i = V(x_0)$. The energy level E_i is obtained from the boundary condition of $\psi_i(0) = 0$. That is, one needs to solve E_i from the equation:

$$Ai_0^i = \left\{1.5\cdot\int_0^{x_0}\left[\left(2m_i^*/\hbar^2\right)\left(E_i - V(t)\right)\right]^{1/2} dt\right\}^{2/3} \tag{3}$$

in which Ai_0^i is the i-th zero point of Ai.

In order to testify the accuracy of MAF, two approaches are used to solve Schrodinger equation. One is using fully numerical method to calculate the eigenvalues and eigenfunctions of discretized Schrodinger equation, the other is suing MAF method. Then MOS devices are simulated. Fig.1 shows the energy levels calculated by MAF method and by fully numerical method as a function of inversion layer carrier sheet density. E_{ij} in the legends denotes the j-th level in the i-th valley. Carrier density profiles in the channel region calculated by MAF method and by fully numerical method are shown in fig.2. It is clearly shown that MAF has satisfied accuracy.

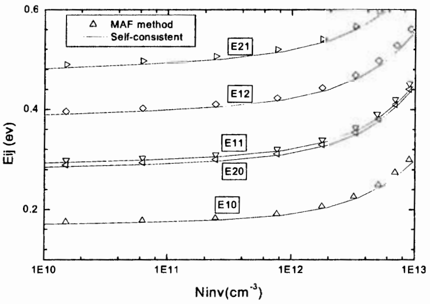


Fig.1: Energy levels calculated by MAF method and by full numerical solution of Schrodinger equation

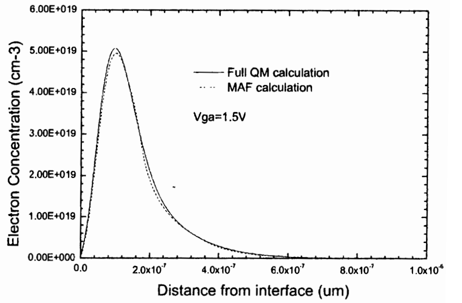


Fig.2: Carrier profile calculated by MAF method and by full numerical solution of Schrodinger equation.

In our 2D model, Schrodinger equation is solved with MAF method to calculate the subband energies and carrier wavefunctions and then obtain the quantum mechanical electron profile in the channel. Then Poisson equation is solved to get new voltage potential. After convergence of the iteration between Schrodinger and Poisson equations, the current continuity equations for electrons and holes are solved to adjust the current density.

3 Simulation results of short channel MOSFET's

The well-tempered MOSFET [4] with featured channel length of 90 nm is used as the test structure. The subband information in the whole channel region is presented in Fig.3. The results show clearly the asymmetric of the subband structure along the channel especially with large source drain bias. The output and transfer characteristics (fig.4 and fig.5) of the device are presented as illustration of the application of the simulator. It is shown that the reduction of output current due to QMEs can be as large as 10 percent of the total value. The results in this work clearly demonstrate the necessity of including QMEs in simulation of advanced MOSFET.

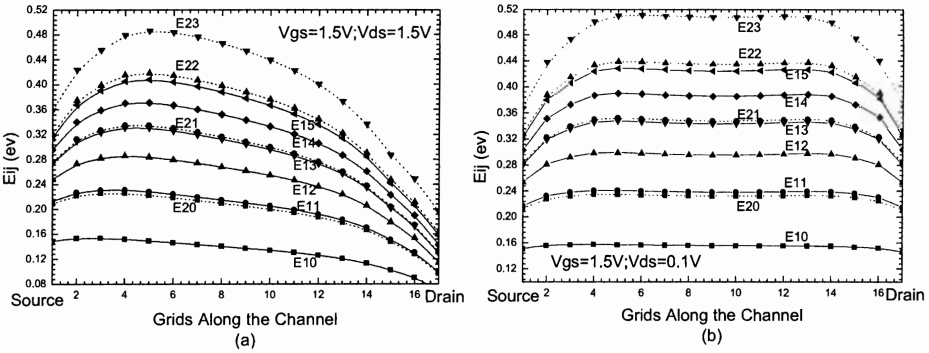
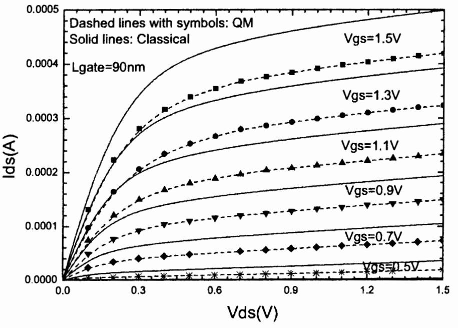


Fig.3: Energy levels in the whole channel. (a) is for Vds=1.5v and (b) is for Vds=0.1v.



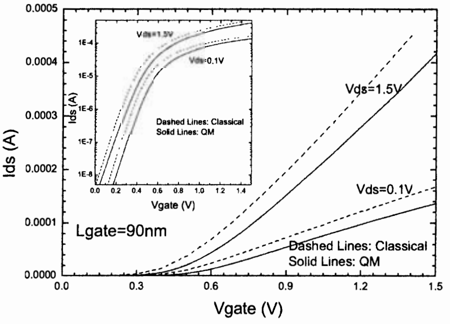


Fig.4: Output characteristics of MOSFET with and without QMEs.

Fig.5: Transfer characteristics of MOSFET with and without QMEs.

A group of devices [5] with different gate length and all the same other parameters are simulated to investigate the short channel effects including QMEs (Fig.6~8).

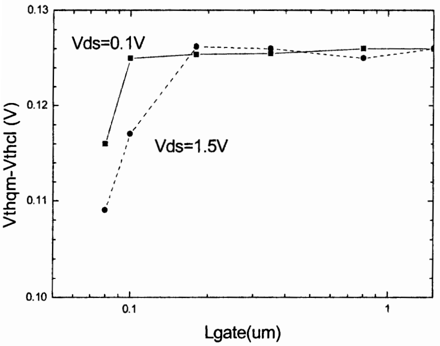


Fig.6: Threshold voltage shift due to QMEs for devices with different gate lengths.

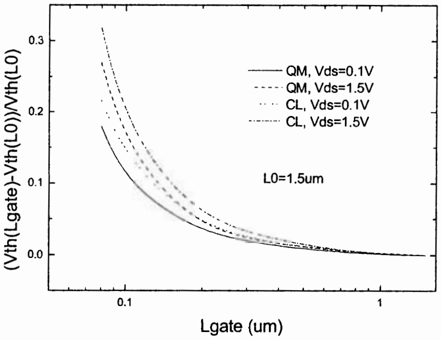


Fig.7: Vth shift due to SCE with and without QMEs.

Fig.6 gives the threshold voltage shift due to QMEs in devices with different gate lengths. Fig.7 shows the results of Vth roll off due to short channel effects in QM cases and semi-classical cases respectively. Fig.8 gives the results for DIBL effects. It can be seen from the figures that short channel effects are quite different with and without consideration of QMEs. So, in order to accurately characterize short channel MOSFET's, it is necessary to take into consideration of the influences of QMEs.

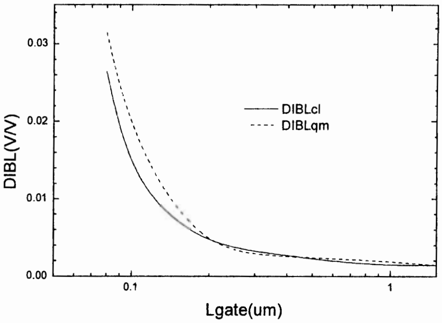


Fig.8: DIBL effects with and without QMEs.

References

[1] van Dort, M.J.; Woerlee, P.H.; Walker, A.J., Solid-State Electron., vol.37, no.3, p.435, 1994.

[2] Spinelli, Alessandro S.; Benvenuti, Augusto; Pacelli, Andrea. IEEE Transactions on Electron Devices. v 45, n 6, pp 1342-1349, 1998.

[3] A.K.Ghatak, et.al., Modified Airy Function and WKB Solutions to the Wave Equation. NIST Monograph.

[4] http://www-mtl.mit.edu/Well-tempered-mosfet\Well-Tempered Bulk-Si NMOSFET Device Home Page.htm

[5] G.Timp, et.al. ,"The ballistic Nano-transistor". IEDM99, p48.