Threshold Voltage Shift by Quantum Confinement in Ultra-thin Body Device

Yang-Kyu Choi, Daewon Ha, Tsu-Jae King and Chenming Hu
Department of Electrical Engineering and Computer Sciences
University of California, Berkeley, CA 94720, USA
Phone : 1-510-643-2558, E-mail : ykchoi@eecs.berkeley.edu

Introduction

Ultra-thin body (UTB) single or double gate MOSFET with raised S/D was proposed to suppress the short-channel effects in future CMOS device [1][2][3]. Any potential well can cause sub-band splitting (between 2-fold and 4-fold valleys of the conduction band, light and heavy hole bands of the valence band) when the quantum confinement happens [4][5]. The sub-band splitting results in a smaller density of states so that more energy-band bending is required to attain a desired inversion-charge density as compared to a thicker body device. The increase in threshold voltage has been observed in thin-body structure device [7][8]. Previous works calculated the threshold voltage shift numerically [7][8] and treated the quantum effect with the effect of a high-doping concentration [4][5]. A simple analytical model is desirable for understanding the experimental data and providing quick guide to the threshold voltage adjustment for UTBFET.

Modeling

The inversion charge has been numerically analyzed with Poisson equation and Schrodinger equation solved self-consistently or analytically solved for a high body-doping bulk device with a triangular potential approximation (see Fig. 2a) [3][4][5][6]. However, the potential shape in UTB device is closer to rectangular because of a light body-doping (Fig. 2b). Light doping improves mobility and reduces the doping fluctuation effect. Even heavy-doping would not be effective for the threshold voltage adjustment due to the thin thickness. A closed analytical model with the rectangular and triangular potential approximation is developed and compared with the measured data instead of numerical calculation in this work. While the threshold voltage is usually defined as $\varphi_s=2\varphi_B$ in the classical mode, it is appropriate to define the threshold voltage as the gate voltage when the same amount of charge is acquired in the quantum mechanical mode [6]. A closed from expression for the threshold voltage shift vs. UTB thickness (T_{Si}) can be shown to be

$$\Delta V_t^{QM} = (1+3T_{ox}/T_{si})\cdot kT/q\cdot \ln(h^2 N_{c,v}/[4\pi q\mathscr{E}_s \sum_{i,n} g_i m_{di} e^{-E_{in}/kT}]) \text{ where } E_{in} = h^2 n^2/8m_{zi}T_{si}^2$$

E_{in} are energy-eigen values while $E_{in} = (3hq\mathscr{E}_s/4\sqrt{2m_{zi}}\cdot(n+3/4))^{2/3}$ for the triangular well.

The threshold voltage is measured at 100nA/um of drain current [2] and the UTB thickness is measured with NanoSpec/DUV at each point and calibrated with TEM pictures. Fig. 1 shows the TEM picture of a 3nm ultra-thin body SOI device. The threshold voltage difference is taken to be $\Delta V_t = V_t^{QM}(\text{thin body}) - V_t^{QM}(\text{thick body})$ in UTB device. The rectangular well model is closer to the measured data than the triangular well model as shown in Fig. 3a and 3b. Fig. 4 shows opposite trends of the threshold voltage shift for UTB and bulk device. More shift in bulk device is at a higher body-doping concentration because the confinement is stronger. The threshold voltage shift is caused by the confinement effect of the thin body in the UTB device. A higher body-doping makes the threshold voltage of the thick-body UTB device larger due to sub-band splitting. Therefore the threshold voltage *shift,* effect of reduction of the UTB body thickness, is reduced (even though the threshold voltage is larger). The threshold voltage shift is predicted to be larger in double gate device than single gate device for the same argument.

Conclusion

The threshold voltage shift caused by quantum confinement in UTB is observed experimentally. An analytical model is proposed and shows a good agreement with the experimental data of both PMOSFET and NMOSFET. It predicts a larger threshold voltage shift for a lighter body-doping, which is opposite to the trend in the bulk device. This threshold voltage shift must be taken into account in the design of UTB device, including the double gate MOSFET.

Acknowledgement

This research is partially sponsored by the DARPA AME Program under Contract N66001-97-1-8910 and SRC under Contract 2000-NJ-850

References

[1] Y.-K. Choi et. al., *EDL*, p. 254, 2000.
[2] Y.-K. Choi et al., *58th DRC.*, p.23, 2000
[3] X. Huang et al., IEDM, p.67, 1999
[4] F. Stern, *Physical Review B*, p. 4891, 1972
[5] F. Stern et al., *Phys. Rev.*, v.163, p.816, 1967
[6] Y. Taur et al., Fundamentals of Modern VLSI Devices, Cambridge University Press, 1998
[7] H. Hajima et al., *IEDM*, p. 379, 1999.
[8] Y. Omura et al., *EDL*, p. 190, 1997.

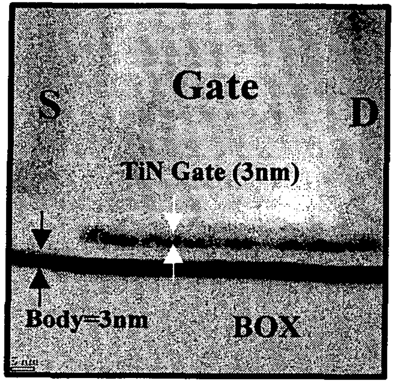
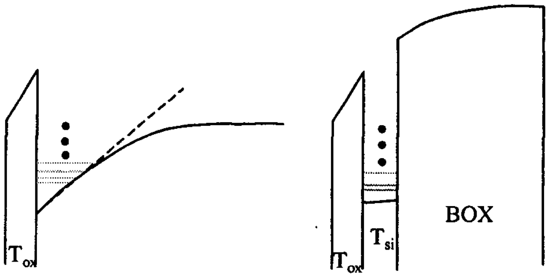
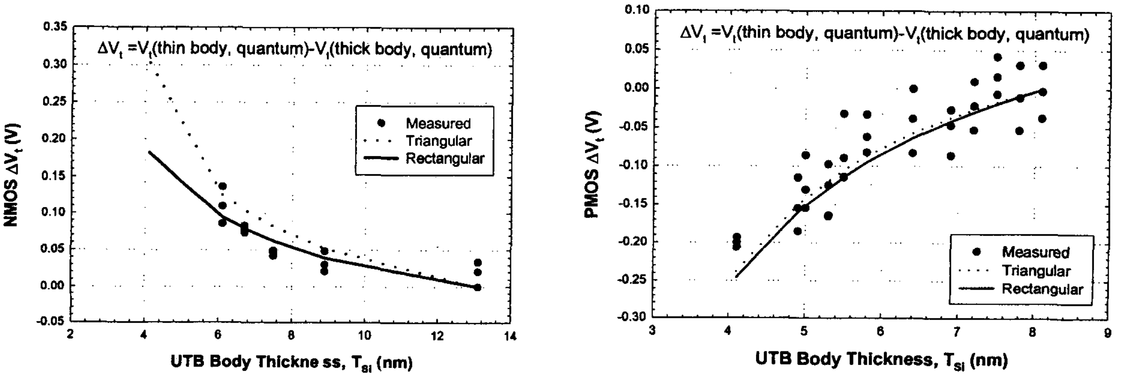


Figure 1. TEM picture of ultra-thin body (3nm) SOI device.



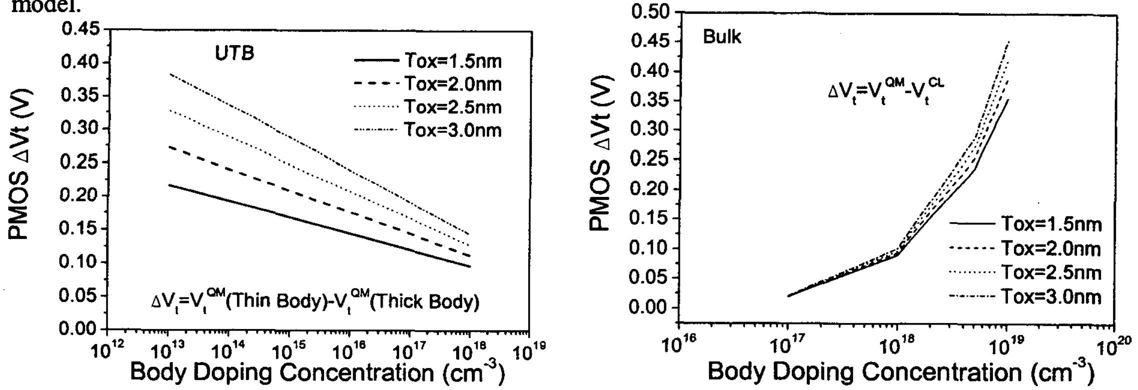
(a) Bulk (b) UTB

Figure 2. Energy band diagram of (a) bulk device and (b) UTB SOI device.



(a) NMOS (b) PMOS

Figure 3. Comparison of analytical model and measurement data of UTBFET for (a) NMOS and (b) PMOS The rectangular potential well model matched the measured data better than the triangular potential well model.



(a) UTB (b) Bulk

Figure 4. Threshold voltage shift vs. body-doping concentration in (a) UTB device and (b) bulk device. Larger threshold voltage shift is predicted for lighter body-doping UTB and heavier body-doping bulk device.