



Extension of Bandgap Broadening Model for Quantum Mechanical Correction in Sub-Quarter Micron MOS Devices To Accumulation Layer

Paul Vande Voorde, Soo-Young Oh
Zhiping Yu*, Robert W. Dutton*
Ultra Large Scale Integration Laboratory
HPL-96-42
March, 1996

MOS device,
quantum-mechanical
effect

We report in this paper an extended bandgap broadening analytical model for quantum mechanical (QM) correction in MOS structures with sub-quarter micron feature size, which is applicable to both inversion and accumulation layers. Device simulation shows excellent agreement with the measured C-V data for MOS capacitors with oxide thickness of $\sim 30\text{\AA}$.

Extension of Bandgap Broadening Model for Quantum Mechanical Correction in Sub-Quarter Micron MOS Devices To Accumulation Layer

Zhiping Yu and Robert W. Dutton

Center for Integrated Systems, Stanford University, Stanford, CA 94305

Phone: (415) 725-3644, E-mail: yu@ee.stanford.edu

Paul vande Voorde and Soo-Young Oh

ULSI Lab, HP Labs, HP Co., 3500 Deer Creek Rd., Palo Alto, CA 94303

Abstract – We report in this paper an extended bandgap broadening analytical model for quantum mechanical (QM) correction in MOS structures with sub-quarter micron feature size, which is applicable to both inversion and accumulation layers. Device simulation shows excellent agreement with the measured C-V data for MOS capacitors with oxide thickness of $\sim 30\text{\AA}$.

In the sub-quarter micron CMOS regime, the combination of ultra-thin gate oxide (less than 60\AA) and high channel doping level (above $5 \times 10^{17}\text{cm}^{-3}$) results in non-negligible quantum mechanical (QM) effects in the channel region. From the device characteristics point of view, these QM effects manifest themselves mainly in the shifting of threshold voltage (bigger) and gate capacitance (smaller) as much as $15 \sim 20\%$.

The physical picture behind these QM effects is the alteration of the carrier distribution in the channel region in both the real (away from the Si-SiO₂ interface) and energy (quantized discrete levels rather than continuous band) spaces. For the same amount of channel charge, such carrier profile requires higher gate voltage. Various analytical approaches have been proposed to phenomenologically model this consequence, including the introduction of effective oxide thickness, which is larger than the physical one, and imposing of a Gaussian-like carrier profile in the channel [1]. By far, the most successful analytical model is the “bandgap broadening” model proposed by van Dort [2]. This model adds to the bandgap in the surface region of the substrate a correction term, which is proportionally determined by the vertical surface electric field. The model has been applied to the inversion layer of MOS structures with gate oxide thickness from 40\AA to 70\AA and been verified by more detailed QM analysis [3]. However, so far in the literature this model has only been applied to the inversion layer, and there is no experimental evidence that a direct extension of the model to the accumulation layer works well.

For the first time, we extended this bandgap broadening model to the analysis of the MOS accumulation layer and agreement between the simulation using this model and measurement for ultra-thin gate oxide MOS capacitors is extremely good (even better than in the inversion layer where the poly-gate depletion complicates the overall MOS capacitance analysis). The rationale for this extension is that in the accumulation layer (*n*MOS structure, for example) it is the valence band that forms the quantum well for holes and the intensity of the quantization is also determined by the surface electric field. The following formula is used for the correction to the bandgap due to the QM effects:

$$\Delta E_g(y) = \kappa\beta \left(\frac{\epsilon_{Si}}{4qkT} \right)^{1/3} |\mathcal{E}_n|^{2/3} F(y) \quad (1)$$

where $|\mathcal{E}_n|$ is the absolute value of the transverse electric field at the Si-SiO₂ interface, $\beta = 4.1 \times 10^{-8}\text{eV}\cdot\text{cm}$ [4], and the transition function (in [5], see also Fig. 1):

$$F(y) = \frac{2e^{-(y/L)^2}}{1 + e^{-2(y/L)^2}} \quad (2)$$

where y is the coordinate in the normal direction away from the Si-SiO₂ interface into the substrate and L is the characteristic length of typical value 250\AA . The coefficient κ has a theoretical value of $13/9$, but can be treated as a fitting parameter in the simulation. In our simulation $\kappa \approx 1 \sim 1.75 \times \frac{13}{9}$. The comparison of simulated and measured C-V curve for MOS capacitors with gate oxide thickness of $31 \pm 2\text{\AA}$ by ellipsometer measurement is shown in Fig. 2. The peak channel doping concentration is about 10^{18}cm^{-3} . It can be seen that with $\kappa = 13/9$, gate oxide thickness of 33\AA with QM effects included gives almost perfect fit, while using the same oxide thickness but without QM has discrepancy as much as 15% especially in the accumulation region. To use the oxide thickness of 31\AA , κ has to be $1.75 \times \frac{13}{9}$ to fit the data (Fig. 3).

In summary, the extended bandgap broadening model can be applied to the analysis of all operation regions of MOS structures with high accuracy. There are some other issues, such as the AC simulation and proper modeling in the depletion region, which will further be addressed in the presentation. The authors would like to acknowledge HP ULSI personnel in assistance of device fabrication and measurement. This work was also supported by ARPA and SRC.

References

- [1] R. Rios and N. D. Arora, Dig. *IEDM '94*, p. 613.
- [2] M. J. van Dort, P. H. Woerlee, and A. J. Walker, *Solid-State Electronics*, **37**, 411 (1994)
- [3] S. A. Hareland, *et al.*, *IEEE Trans. Elec. Dev.*, **ED-43**, 90 (1996).
- [4] M. J. van Dort *et al.*, *IEEE Trans. Elec. Dev.*, **ED-39**, 932 (1992).
- [5] S. Selberherr, *IEEE Trans. Elec. Dev.*, **ED-36**, 1464 (1989).

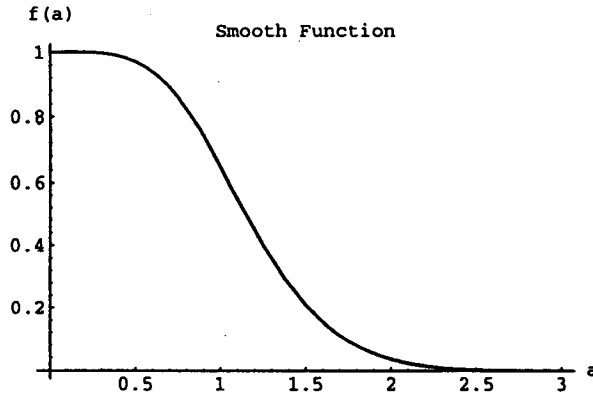


Figure 1: Transition function $F(y)$ in the form of $f(a = y/L)$ vs. a in Eq. (1). It is clear that the surface effects start to diminish at $y \approx L$.

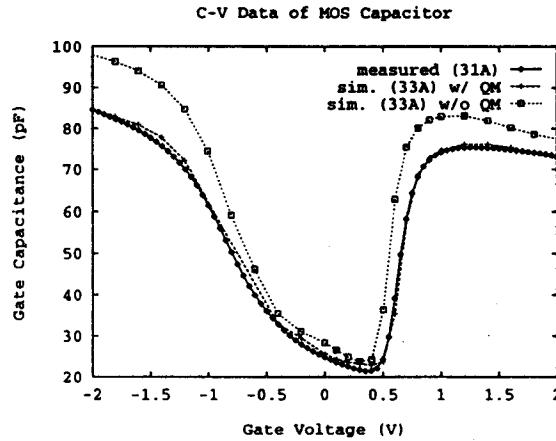


Figure 2: Simulated vs. measured C-V data for n -MOS capacitor with measured oxide thickness $t_{ox} = 31 \pm 2 \text{ \AA}$. Simulation using $t_{ox} = 33 \text{ \AA}$ with QM correction gives perfect fit.

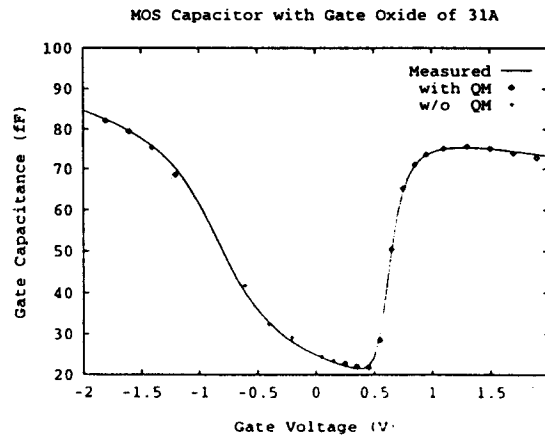


Figure 3: Simulated C-V data using $t_{ox} = 31 \text{ \AA}$ as measured. To fit the measured data, $\kappa = 1.75 \times 13/9$ in Eq. (1) and QM correction is turned off in the depletion region during simulation.