4.1.1 Qs(phis) relation: quantum theory

Goal;

- Quantum Mechanical effect on $Q_s(\psi_s)$ and C-V characteristics

Ref. General Issues and Trend

1. S-H. Lo, et.al., Modeling and Characterization of n+ and p+ Polysilicon Gated Ultra Thin Oxide(21-26Å) VLSI Technology, 1997.

- CMOS scaling trend requires reduction of T_{ox} in order to suppress the short channel effect(related with the electrostatics)

- Reduction in T_{ox} induces the nonideal phenomena to the device characteristics
  - Tunneling current through the thin oxide and the gate overlapped drain region increases the standby current (< $1A/cm^2$)
  - Effective T_{ox} degradation due to QM effect in the inversion layer and the depletion effect in the poly silicon gate

A. Effective T_{ox} degradation due to the quantum mechanical effect

– First order theory assumes that the surface potential is fixed to $2\phi_f$ which means that the inversion capacitance is infinite after the "classical V_T".

Then, $C_G = C_{ox}$ since C_{inv} is infinite.

$$C_{inv} = \frac{\Delta Q_s}{\Delta \Psi_s} = \frac{\Delta Q_n}{\Delta \Psi_s}$$

However, there is certainly $\Delta \Psi_s$ in order to induce ΔQ_n which means that C_{inv} is finite. Then, C_{eff} and T_{eff} are defined as,

$$Q_n = - C_{eff}(V_G - V_T)$$

$$T_{eff} = \frac{\varepsilon_{ox}}{C_{eff}}$$

. It should be noticed that the capability of storing Qn in the inversion layer is reduced due to the finite inversion layer capacitance

B. Modeling of $Q_s(\Psi_s)$ including the quantum mechanical effect

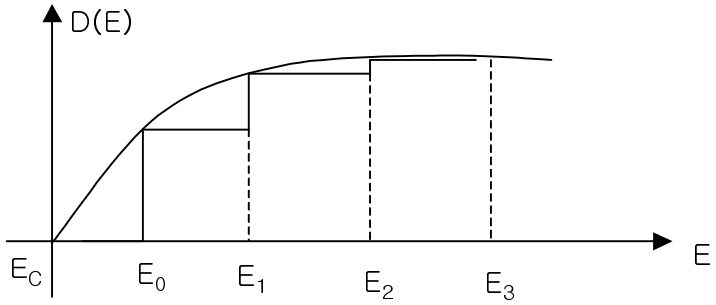
ref. F. Stern, "Self consistent results for n-type Si inversion layers," Phys. Rev. B5, p.4891,1972.

– In order to know the expression for C_{eff}, $Q_n(\Psi_s)$ should be known. Three approaches can be taken; Classical approach with MB(Maxwell Boltzmann statistics) which is our approach in eq. (2) of §2.1, Classical approach with FD(Fermi Dirac statistics), Quantum mechanical approach.

– Quantum Mechanical Approach

The electron wave function is quantized in the potential well so that the energy states in the potential well are quantized in the depth direction. The net effect is the D(E) is not proportional to $\sqrt{E - E_c}$ in the conduction band, but constant

between the quantized energy level as shown in the figure below. This sometimes is called the "2D quantization".



In the 2dimensional gas, the DOS of the *i*th subband (per unit area, unit energy) is

$$D_i(E) = \begin{cases} \dfrac{m^*}{\pi\hbar^2} g_v & \text{for} \quad E \geq E_i \\ 0 \end{cases}$$

where g_v is the band degeneracy.

The total DOS is

$$D(E) = \sum_{i=0}^{\infty} D_i(E)$$

Now areal electron density in the *i*th subband is

$$N_i = \int D_i(E) f(E) dE = \int_{E_i}^{\infty} \frac{m^*}{\pi\hbar^2} \frac{1}{1 + e^{(E_F - E_i)/k_B T}}$$
$$= \frac{m^* k_B T}{\pi\hbar^2} \ln\left[1 + e^{(E_F - E_i)/k_B T}\right]$$

and total Q_n is

$$Q_n = -q \sum_{i=1}^{\infty} N_i$$

Now E_i can be only known from the Schrodinger equation as,

$$\left[-\frac{\hbar^2}{2m^*} \frac{d^2}{dx^2} + V_p(x) \right] \Psi_i(x) = E_i \Psi_i \qquad (1)$$

and $V_p(x)$ is the total potential energy as the result of the Poisson equation with

with $$\rho = q(p - n + N_D) \quad (2)$$

where $$n(x) = \sum_{i=0}^{\infty} N_i |\Psi_i(x)|^2 \quad (3)$$

(1) and (2) constitute the loop to be solved numerically.
Net effect of the quantization is the reduction of the density states thereby reducing Q_n for a given Ψ_s (surface potential) V_T is higher than the classical theory.

- Simplified approach based on the triangular well

Other simplified approach (approach II) is assuming "the triangular potential profile" as

$$\Psi_s(x) = \Psi_s - qE_{eff}\, x$$

where E_{eff} is the Effective field defined in B-1-2.

Then the solution for the Schrodinger eq. can be found as Airy function as, ξ_i with the eigen energy as

$$E_i = \frac{3hq}{4\sqrt{2m}} \varepsilon_{eff} \left(i + \frac{3}{4}\right)^{2/3} \qquad \text{where } i = 0, 1, 2, \ldots$$

Then the n(x) can be found by

$$n(x) = \sum_{i=1}^{\infty} N_i |\xi_i(z)|^2$$

Here, $$N_i = \frac{m^* k_B T}{\pi \hbar^2} \ln\left[1 + e^{-\frac{E_F - E_i}{k_B T}}\right]$$

- Approach based on the Density Gradient Method

ref. S. Jin, A numerically efficient method for the hydrodynamic density-gradient model, SISPAD,pp.263-266 , 2003
SISPAD 2002. International Conference , pp.267-270 , 2002.

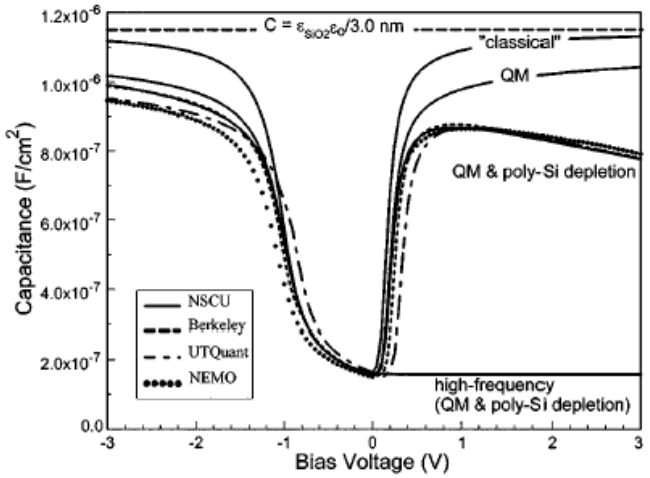


Fig. 1. Simulated *C–V* curves accounting for both QM confinement and poly-Si depletion. Simulated parameters are $t_{ox} = 3.0$ nm (2.987 nm for NEMO [10]), $N_{sub} = 3 \times 10^{17}$ cm^{-3}, and $N_{poly} = 5 \times 10^{19}$ cm^{-3}. A classical *C–V* with no QM confinement or poly-Si depletion and a QM *C–V* which accounts for QM confinement only are also shown for illustrative purposes.

Fig. C-V curve from various models. The net effect is the degradation in CV especially for VG>VT.

(Fig. 1. of C. Richter's, EDL p.35, Jan 2001)

$$
\begin{aligned}
F_{\mathrm{DT}} &= F_{1\to 2} - F_{2\to 1} \\
&= \frac{4\pi m_{yz} k_{\mathrm{B}} T}{h^3} \int_0^{E_b} dE_x TC\left(E_x\right) \ln\left[\frac{1+e^{(E_{F1}-E_{C1}-E_x)/k_{\mathrm{B}}T}}{1+e^{(E_{F2}-E_{C1}-E_x)/k_{\mathrm{B}}T}}\right]
\end{aligned}
$$

TC is the transmission coefficient representing the probability coefficient of the tunneling. There are several models to represent TC as function of Vox.
The transmission probability is traditionally modeled as

$$T = e^{-2\sqrt{\frac{2mq\Phi_B}{\hbar^2}}T_{ox}}$$

- Simple formula

From WKB approximation and assuming the parabolic energy band of SiO2,

T= exp[-B0 * f(zg)]

zg= [1-(1-zg)]**1.5/zg

where zg = Vox/phi b

-Gundlach's formula

- Lo's approach

For modeling the tunneling characteristics of electrons exhibiting the 2D nature, the transmission probability applicable to an incident Fermi gas of free electrons is no longer a meaningful concept and the well known WKB approximation and the integration of the Airy functions is no valid.

Fig. from the reference indicate the modeling results from the 1st order principle (so called the transverse resonant method).

<<<. Taur and Ning 의 그림2.44 p 96을 넣어 주세요>>>