Physics and Engineering of CMOS Devices

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Requirements

- Basics of Quantum Mechanics
 - Quantum Confinement Effects
 - Scattering of electrons with phonons etc.
- Electromagnetic
 - Gauss's Law
 - Poisson's Equation
- Fundamentals of Solid-State Physics
 - Band Structure of Semiconductors (Effective Mass, Density of States etc.)
 - Basics of Semiconductor Physics (pn junctions, semiconductor statistics)

Class Objective

This class provides the fundamentals of advanced nanoscale MOS transistors. Firstly, the operation of MOS transistors fabricated on bulk Si substrate will be explained. The impact of shrinking device dimensions on device performance will be discussed. Then, the concept of equivalent scaling, which is important in modern MOS transistors, will be introduced. As an example of the equivalent scaling, mobility booster technologies and high-k&metal gate stack will be discussed. By taking this class, it is expected that students get familiar with physics and engineering of modern, advanced CMOS devices.

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Class Schedule (Tentative)

- Fundamentals of MOSFETs (6 Classes)
- Mobility (2 Classes)
- Strained MOSFETs (2 Classes)
- MOSFETs with High-κ Gate Dielectrics (1 Class)
- Fabrication Process (1 Class)
- Other Advanced Topics (1 Class)

Class Schedule –cont'd

- Fundamentals of MOSFETs (6 Classes)
 - Simple Analytical MOSFET Model
 - MOS Capacitor
 - MOSFET Models (Charge Sheet Model)
 - Substrate Bias Effects
 - Scaling Strategy of MOSFETs
 - Short Channel Effects

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Grading

- Exercises during the class (20%)
- Term-end Examination (80%)

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MOSFETs as Switches in VLSIs

Ideal switch has infinite resistance in the off state, whereas zero resistance in the on state.



Strategy to Enhance VLSI Performance

Requirements against Switches

- Reduction in ON resistance.
- Reduction in dimensions.
- Reduction in leakage current.

The performance of MOSFETs are improved by reducing transistor dimensions (sizes), while keeping leakage current as small as possible.

Structure of MOSFETs



p-type Si substrate

- Metal-Oxide-Semiconductor Structure
- Field-Effect Transistor

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Schematics of MOSFET Operation



Two pn junctions are connected in series. One is reversely biased and the other is forward biased.



Positive gate bias generates surface inversion layer, which forms Ohmic contacts with source/drain diffusion layers.

Basic Equations for Describing MOSFET Characteristics

Poisson's Equation

$$\nabla^2 \phi = -\frac{\rho}{\kappa_s \varepsilon_0}$$

Carrier Transport Equation

$$\mathbf{J}_n = q\,\boldsymbol{\mu}_n n\mathbf{E} + qD_n \nabla n$$

- ϕ : potential
- ρ : charge density
- κ_s : dielectric constant
- \mathcal{E}_0 : permittivity in vacuum
- μ_n : mobility
- q : elemental charge
- D_n : diffusion constant
- G_n : generation rate
- R_n : recombination rate

Current Continuity Equation

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \mathbf{J}_n - R_n + G_n$$

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Basic Equations



These equations should be solved self-consistently; they are solved numerically.

Coordinate in MOSFETs



The origin is located at the source edge of the MOS interface. The Y axis is located at the MOS interface and is along the channel direction.

The X axis is normal to the MOS interface.

The Z axis is at the MOS interface and is along the width direction. Physics and Engineering of CMOS Devices, Ken Uchida, April 7, 2010

Assumptions for deriving MOSFET Model

- Recombination and generation of carriers are negligible; current continuity equation is not taken into account.
- Diffusion current is much less than drift current.
- Normal Electric field is much greater than lateral electric field. (Gradual Channel Approximation: GCA)
 Poisson's equation is reduced to





Velocity and Mobility



 10^{4}

Electric Field (V/cm)

10

10⁶

10⁵

The velocity of charged carriers (electrons, holes) is proportional to electric field.

$$v_e = \mu E$$

However, at electric field greater than $3x10^3$ V/cm, the none-linearity is observed. This effect will be taken into account in later lectures.

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 10^{6}

electron holes

10⁵

Simple Analytical MOSFET Model (I) $V_d \approx 0$

By introducing threshold voltage (V_{th}) , Poisson's equation can be replaced by the following equation.

$$-qn_{l} = -WC_{g}\left(V_{g} - V_{th}\right)$$

 n_l : number of charges per unit length $I_d = -qn_\mu_e E$ $=WC_{g}\left(V_{g}-V_{th}\right)\mu E$ This is valid when V_d is very small. $= \mu_e C_g W \left(V_g - V_{th} \right) \frac{V_d}{I}$ $= \mu_e C_g \frac{W}{I} \left(V_g - V_{th} \right) V_d$ $(V_d \approx 0)$

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Simple Analytical MOSFET Model (II) -cont'd

$$\int_0^L I_d dy = \int_0^{V_d} WC_g \left(V_g - V(y) - V_{th} \right) \mu_e dV(y)$$

$$I_{d} = \mu_{e} C_{g} \frac{W}{L} \left[\left(V_{g} - V_{th} \right) V_{d} - \frac{1}{2} V_{d}^{2} \right]$$
(1)

Eq (1) is not valid when V_d is greater than V_g - V_{th} .

$$I_{d} = WC_{g} \left(V_{g} - V(y) - V_{th} \right) \mu_{e} \frac{dV(y)}{dy}$$

When $V_d > V_g - V_{th} \quad \left(V_g - V_d - V_{th} < 0\right)$

Because in the depletion condition the equation above suggests hole accumulation! This is not true. Physics and Engineering of CMOS Devices, Ken Uchida, April 7, 2010

Simple Analytical MOSFET Model (II) -cont'd



In semiconductor, inversion-layer is formed when V_g is greater than V_{th} . If V_g is between V_{FB} and V_{th} , not hole accumulation layer but depletion layer is formed. Our simple equation, $C_g(V_g-V_{th})$, does not represent the depletion condition.

Eq. (1) is valid, when $V_d > V_g - V_{th}$ Physics and Engineering of CMOS Devices, Ken Uchida, April 7, 2010

Simple Analytical MOSFET Model (II) -cont'd



Carriers reaching at the pinchoff point are immediately transferred to the drain. Therefore, the current is obtained by integrating the formula from source to the pinch-off point.

$$I_{d} = \mu_{e}C_{g}\frac{W}{L}\left[\left(V_{g} - V_{th}\right)V_{d} - \frac{1}{2}V_{d}^{2}\right] \qquad \left(V_{d} \le V_{g} - V_{th}\right)$$
(1)
$$I_{d} = \frac{1}{2}\mu_{e}C_{g}\frac{W}{L - \Delta L}\left(V_{g} - V_{th}\right)^{2} \qquad \left(V_{d} > V_{g} - V_{th}\right)$$
(2)

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Simple Analytical MOSFET Model -cont'd



Implicit assumptions are

- Constant mobility
- Linea relationship between velocity versus field

Insufficient treatments are as follows.

- Distribution functions are not used to calculate carrier numbers.
- Effect of substrate impurity is not considered.
- One-dimensional electrostatics is used to calculate potential distribution.

21

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