ECE606: Solid State Devices
Lecture 32: MOS Electrostatics

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Outline

1. Background
2. Band diagram in equilibrium and with bias
3. Qualitative Q-V characteristics of MOS capacitor
4. Conclusion

REF: Chapters 15-18 from SDF
Outline of the Course

Device-specific system design ← Application specific device operation ← Physical Principle of device Operation ← Foundation in Physics

- TFT for Displays
- CMOS-based Circuits for mP
- LASERS for Disk Drives
- MEMS for Read heads

Resistors (5 wk)
Diodes (3 wk)
Bipolar (3 wk)
MOSFETs (3 wks)

Quantum Mechanics + Statistical Mechanics → Transport Equations

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Scaling of MOSFETs

- **Vacuum Tubes**: 1906-1950s
- **Bipolar**: 1947-1980s
- **MOSFET**: 1960-until now
- **Now ??**
  - Spintronics
  - Bio Sensors
  - Displays ....

Graph showing the evolution of temperature from 1900 to 2020 with different technologies:
- Tubes
- Bipolar
- MOS

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Basic Configuration of a MOSFET

Almost like a lateral bipolar transistor!
Symbols

No channel when $V_G = 0$

Channel when $V_G = 0$
Background

Strained MOSFET

High-k/metal gate MOSFET

Sources:
IBM J. Res. Dev.
Google Images
Intel website
Outline

1. Background

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## Topic Map

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Electrostatics of MOS Capacitor in Equilibrium

Schottky barrier with an interposed dielectric
Idealized MOS Capacitor

Substrate (p)

Gate

Vacuum Level

$q \chi_i$

$q \Phi_m$

$q \chi_s$

$E_C$

$E_F$

$E_V$

EC

EF

EV

P-Semiconductor

Metal

Insulator
Potential, Field, Charges

\[ V_{bi} = 0 \]

\[ q\chi_i \]

\[ q\Phi_m \]

\[ q\chi_s \]
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Electrostatics under Bias

Accumulation
Dep. Inversion

$V_G > V_{T'}$

Exposed Acceptors
Electrons
Where do charges come from?

• Integrate charge to find potential.

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Response Time

Dielectric Relaxation

\[ \tau = \frac{\sigma}{\kappa_s \varepsilon_0} \]

SRH Recombination-Generation

\[ R = \frac{np - n_i^2}{\tau_n (p + p_1) + \tau_p (n + n_1)} \rightarrow \frac{-n_i}{\tau_n + \tau_p} \]

Ref. Lecture no. 15
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Charges and Surface Potential

\[ \log_{10} \left| Q_S (\psi_S) \right| \]

\[ \sim e^{-q\psi_S / 2k_BT} \]

\[ \sim \sqrt{\psi_S} \]

\[ \sim e^{q\psi_S / 2k_BT} \]

\[ \psi_S = 0 \]

Depletion Inversion accumulation

V_G' = 0

\[ E_C \]

\[ E_F \]

\[ E_V \]
Solution of $Q_S(\psi_S)$

$$\nabla \cdot \vec{D} = \rho$$

$$\nabla \cdot (\vec{J}_n / -q) = (G - R)$$

$$\nabla \cdot (\vec{J}_p / q) = (G - R)$$

Poisson equation

$$\frac{d^2 \psi}{dx^2} = \frac{-q}{\kappa_{Si} \varepsilon_0} \left[ p_0(x) - n_0(x) + N_D^+ - N_A^- \right]$$
(Depletion) Potential, Field, Charges

\[ V_G = V_{ox} + \psi_S \]
Surface Potential

\( \psi_s = \frac{1}{2} \left( \frac{q N_A W}{\kappa_s \varepsilon_0} \right) \)

\( W = \left( \frac{q N_A W^2}{2 \kappa_s \varepsilon_0} \right) \)

\( W = \sqrt{\frac{2 \kappa_s \varepsilon_0 \psi_s}{q N_A}} \)

\( \mathcal{E}(0^+) = -\frac{q N_A W}{\kappa_s \varepsilon_0} \)

\( \mathcal{V}_G = \mathcal{V}_{ox} + \psi_s \)
Gate Voltage /Surface Potential in Depletion Region

\[ V_G = \varepsilon_{ox}(0^-)x_0 + \left( \frac{qN_A W^2}{2\kappa_s \varepsilon_0} \right) \]

\[ = \left[ \frac{qN_A W}{\kappa_{ox} \varepsilon_0} \right] x_0 + \left( \frac{qN_A W^2}{2\kappa_s \varepsilon_0} \right) \]

\[ = \frac{qN_A x_0}{\kappa_{ox} \varepsilon_0} \sqrt{\frac{2\kappa_{ox} \varepsilon_0}{qN_A}} \sqrt{\psi_s} + \psi_s \]

\[ \equiv \mathcal{B} \sqrt{\psi_s} + \psi_s \]

......because \[ \psi_s = \left( \frac{qN_A W^2}{2\kappa_s \varepsilon_0} \right) \]

\[ V_G \text{ known, determine } \psi_s \]
Gate Voltage and Depletion Charge

\[ Q_S(\psi_s) = -qN_A W = \sqrt{2qN_A \kappa_{Si} \varepsilon_0 \psi_S} \]

\[ \log_{10} |Q_S(\psi_s)| \sim \sqrt{\psi_S} \]

\[ \sim e^{q\psi_S / 2k_B T} \]
Surface Potential and Induced Charge

\[ \log_{10}|Q_s(\psi_s)| \] C/cm²

\[ \sim e^{q\psi_s/2k_BT} \]

Why did we not see these phenomena in p-n junctions?

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MOSFET is the dominant electronic device now, not because it is superior to BJTs in terms of performance, but because it consumes far less power and allow denser integration.

MOSFET is an inherently 2D device. We separate out the vertical and horizontal components to qualitatively explore the mechanics of its operation.

We explored relation between gate voltage and induced charge for a MOS-C today. We will continue this discussion in the next class.