Lecture 25 - The Si surface and the Metal-Oxide-Semiconductor Structure (cont.)

The ”Long” Metal-Oxide-Semiconductor Field-Effect Transistor

November 1, 2002

Contents:

1. Three-terminal MOS structure
2. Introduction to MOSFET
3. Inversion layer transport

Reading assignment:

del Alamo, Ch. 8, §§8.5-8.6; Ch. 9, §9.1

Announcements:

Quiz 2: November 5, Rm. 50-340 (Walker), 7:30-9:30 PM; lectures #13-24 (or Chapters 6-8 but excluding three-terminal MOS structure). Open book. Calculator required.
Key questions

• What happens to the electrostatics of the MOS structure if we contact the inversion layer and we apply a bias to it?
• How does a MOSFET look like and how does it work (roughly)?
• How does lateral transport through the inversion layer take place?
1. Three-terminal MOS structure

Introduce contact to inversion layer:

Can now apply bias to inversion layer with respect to substrate, $V_{SB}$.

Source-body junction: $n^+\text{-}p$ junction $\rightarrow$ only reverse bias desired, $V_{SB} \geq 0$.

Interested only in inversion regime: apply $V_{SB} \geq 0$ keeping $V_{GB}$ constant.
Energy band diagrams:

\[ \phi_s(V_{SB}) = \phi_s(V_{SB} = 0) + V_{SB} \]

Application of \( V_{SB} > 0 \), increases \( \phi_s \), and also \( |Q_d| \).
$V_{SB} > 0 \Rightarrow x_d \uparrow \ |Q_d| \uparrow \phi_s \uparrow$ (as in reverse bias p-n junction).

Total potential difference from G to B fixed:

$$\phi_{bi} + V_{GB} = \phi_{ox} + \phi_s$$

Hence: $\phi_{ox} \downarrow \Rightarrow \varepsilon_{ox} \downarrow \varepsilon_s \downarrow$
But:

\[ E_s = -\frac{Q_s}{\epsilon_s} \]

Hence: \(|Q_s| \downarrow\)

In summary:

\[ |Q_s| \downarrow \quad |Q_d| \uparrow \Rightarrow \quad |Q_i| \downarrow \]

equivalent to \( V_{th} \) shifting positive.

Key conclusion: *application of a body bias turns inversion layer off!*

Important implications for device and circuit design and operation.
• $V_{th}$ model that accounts for body bias

Go to Poisson-Boltzmann formulation and change:

$$\phi_{sth} \rightarrow \phi_{sth} + V_{SB}$$

Then:

$$V_{th} = V_{FB} + \phi_{sth} + V_{SB} + \gamma \sqrt{\phi_{sth} + V_{SB}}$$

For MOSFET operation, interested in threshold in $V_{GS}$:

$$V_{GB} = V_{GS} + V_{SB}$$

Then:

$$V_{th}^{GS}(V_{SB}) = V_{th}^{GB} - V_{SB} = V_{FB} + \phi_{sth} + \gamma \sqrt{\phi_{sth} + V_{SB}}$$

Can easily rewrite as:

$$V_{th}^{GS}(V_{SB}) = V_{th}^{GS}(V_{SB} = 0) + \gamma (\sqrt{\phi_{sth} + V_{SB}} - \sqrt{\phi_{sth}})$$

Note: $V_{SB} \uparrow \Rightarrow V_{th}^{GS} \uparrow$
**Back bias effect** important in MOSFETs and CMOS.

Ideally, the body of every MOSFET should be tied to its source, but that’s expensive. What are the trade-offs?

Focus on M3 (nMOSFET) of NAND gate:

- with local body contact: $V_{SB} = 0$ always $\Rightarrow$ $V_{th}$ predictable

- with global body contact: sometimes $V_{SB} > 0$ $\Rightarrow$ slower switching, "jitter"
2. MOSFET Introduction

Cross section and layout of n-channel MOSFET (NMOS):

Inversion layer links source and drain underneath gate.
Inversion layer current depends on:

- lateral field across inversion layer (set to first order by drain-to-source voltage)
- electron concentration in inversion layer (set to first order by gate-to-source voltage)

Key design parameters:

- gate length, $L \simeq$ electrical channel length
- gate oxide thickness, $x_{ox}$
- source and drain junction depth, $x_j$
- doping level in body, $N_A$
3. Inversion layer transport

In general, inversion layer current flows through:

- drift, if lateral field set up across;
- diffusion, if electron concentration changes along inversion layer.

If electric field not too big:

\[
J_{ey}(x, y) = qn(x, y)\mu_e\mathcal{E}_y(x, y) + qD_e\frac{\partial n(x, y)}{\partial y}
\]

Interested in current carried as a whole by inversion layer:

\[
\int_{0}^{x_{inv}} J_{ey}(x, y)dx = q\int_{0}^{x_{inv}} n(x, y)\mu_e\mathcal{E}_y(x, y)dx + q\int_{0}^{x_{inv}} D_e\frac{\partial n(x, y)}{\partial y}dx
\]
Several comments:

- Upper limit of integral can be extended to \( x = \infty \) since \( n(x) \) very small in body.
- No vertical current through inversion layer (oxide prevents it).
- Assume \( \mu_e \) and \( D_e \) to be independent of \( x \).

Then, inversion layer ("channel") current:

\[
J_e \simeq \int_0^\infty J_{ey}(x, y) dx = q\mu_e \int_0^\infty n(x, y)E_y(x, y) dx + qD_e \int_0^\infty \frac{\partial n(x, y)}{\partial y} dx
\]

Two comments:

- Units of \( J_{ey} \) are \( A/cm^2 \), but units of \( J_e \) are \( A/cm \) \( \Rightarrow \) channel current scales with width of MOSFET.
- No sources or sinks inside inversion layer: \( J_e \) independent of \( y \).
\[ \square \text{The sheet-charge approximation} \]

Assume inversion layer is very thin in scale of all vertical dimensions.

Consequences:

- \( \mathcal{E}_y \) does not depend much on \( x \) \( \Rightarrow \) bring it out of first integral.
- Since limits of integrals are independent of \( y \), can bring term in \( \frac{\partial}{\partial y} \) out of second integral (Leibniz rule).

Then:

\[
J_e = q\mu_en_s(y)\mathcal{E}_y(0, y) + qD_e\frac{dn_s(y)}{dy}
\]

Where \( n_s \) is sheet electron concentration of inversion layer:

\[
n_s(y) = \int_0^\infty n(x, y)\,dx \quad [cm^{-2}]
\]

Can also write in terms of inversion layer sheet charge, \( Q_i \):

\[
J_e = -\mu_eQ_i(y)\mathcal{E}_y(0, y) - D_e\frac{dQ_i(y)}{dy}
\]

where:

\[
Q_i(y) = -qn_s(y) \quad [C/cm^2]
\]

Need to determine \( Q_i(y) \).
The gradual-channel approximation

Remember electrostatics of MOS structure in absence of lateral field:

Problem is 1D. Gauss’ law:

\[ \frac{dE_x}{dx} = \frac{\rho(x)}{\varepsilon_s} \]

Relationship between \( Q_i \) and \( V_G \):

\[ Q_i = -C_{ox}(V_G - V_{th}) \]
With lateral field applied along inversion layer:

Consequences of lateral field:

- There is a voltage drop along channel:

  \[ E_y(0, y) = -\frac{dV}{dy} \]

- Problem is 2D. Gauss’ law:

  \[ \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} = \frac{\rho(x, y)}{\epsilon_s} \]

  In general, \( E_x \) and \( E_y \) depend both on \( x \) and \( y \).
Gradual-channel approximation:

\[
\frac{\partial \mathcal{E}_x}{\partial x} \gg \frac{\partial \mathcal{E}_y}{\partial y}
\]

Gauss’ law becomes:

\[
\frac{\partial \mathcal{E}_x}{\partial x} \approx \frac{\rho(x, y)}{\epsilon_s}
\]

Identical to 1D problem in absence of lateral electric field.

Then \( Q_i \) related to \( V_G \) as in 1D problem:

\[
Q_i(y) \approx -C_{ox}[V_G - V(y) - V_{th}]
\]

\( Q_i \) depends on \( y \) through local inversion layer voltage \( V(y) \).

GCA allows break up of 2D electrostatics problem into two simpler quasi-1D problems:

- vertical electrostatics control inversion layer charge,
- lateral electrostatics control lateral flow of charge.

Note: \( V_{th} \) is function of \( y \) through body effect [will examine implications later].
Back to current model. From charge-control relationship:

\[
\frac{dQ_i(y)}{dy} \simeq C_{ox} \frac{dV(y)}{dy}
\]

Lateral field in inversion layer \(\Rightarrow\) gradient of inversion layer charge \(\Rightarrow\) diffusion!

Plug in current equation:

\[
J_e = \mu_e [Q_i(y) - \frac{kT}{q} C_{ox}] \frac{dV(y)}{dy}
\]

Since \(Q_i < 0\), diffusion aids drift.
Key conclusions

• Application of voltage to inversion layer with respect to substrate shifts threshold voltage: \( V_{SB} \uparrow \Rightarrow V_{th} \uparrow \).

• *Sheet-charge approximation*: inversion layer very thin in scale of vertical dimensions \( \Rightarrow \) current formulation in terms of \( Q_i \).

• *Gradual-channel approximation*: electric field changes relatively slowly along channel \( \Rightarrow \) GCA breaks 2D electrostatics problem into two quasi-1D problems:
  - vertical electrostatics control inversion layer charge
  - lateral electrostatics control lateral flow of charge

• Inversion layer current equation:

\[
J_e = \mu_e [Q_i(y) - \frac{kT}{q} C_{ox}] \frac{dV(y)}{dy}
\]