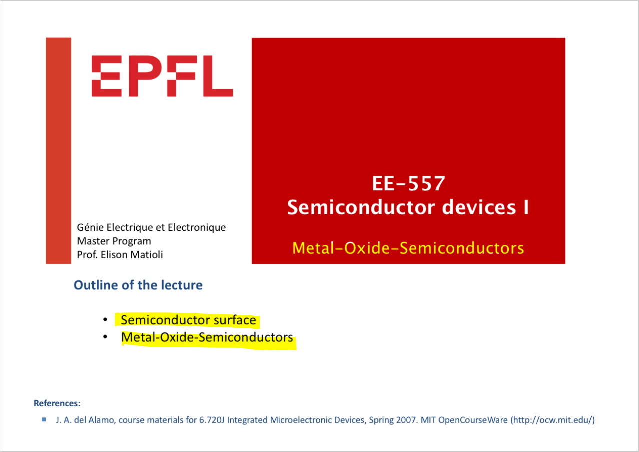
Course 20

Monday, 27 November 2023 14:24

EE557
Course 20...



EE-557
Semiconductor devices I

Metal-Oxide-Semiconductors

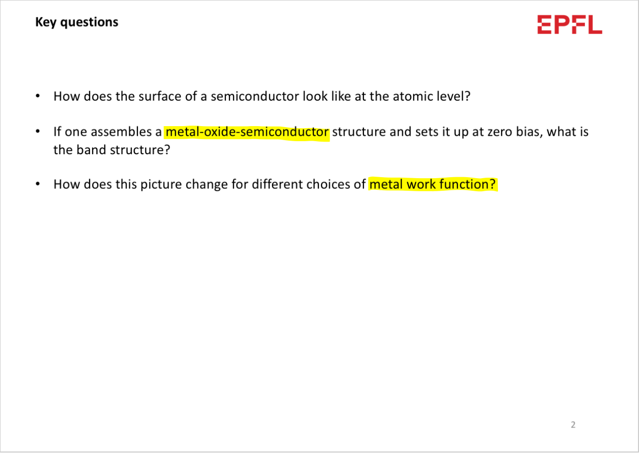
Génie Electrique et Electronique
Master Program
Prof. Elison Matioli

Outline of the lecture

- Semiconductor surface
- Metal-Oxide-Semiconductors

References:

- J. A. del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/)



Key questions

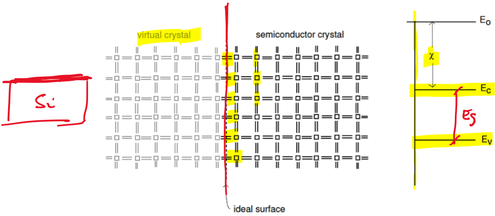
- How does the surface of a semiconductor look like at the atomic level?
- If one assembles a metal-oxide-semiconductor structure and sets it up at zero bias, what is the band structure?
- How does this picture change for different choices of metal work function?

Metal-Oxide-Semiconductor Structure

Semiconductor Surface

At a surface, perfect crystalline periodicity of solid comes to an abrupt end. What happens?

Ideal semiconductor surface
Semiconductor comes to an end, but bulk properties unaffected → bonding arrangement at surface unchanged from bulk.


Si
virtual crystal
semiconductor crystal
ideal surface
E_o
χ
E_c
E_g
E_v

Zero carrier current normal to surface; other than that, carriers unaffected by surface.

Metal-Oxide-Semiconductor Structure

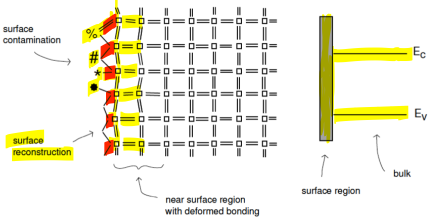
Semiconductor Surface

Real surface
In ideal surface, four-fold coordination of atoms cannot be preserved
⇒ broken bonds ⇒ surface is very reactive.

Atoms “want” to lower their energy by emulating a four-fold coordination.

Surface can lower its energy by:

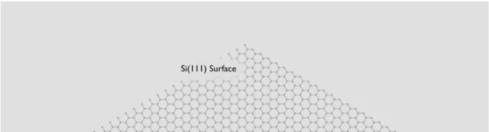
- **surface contamination:** absorption of O, C, and other foreign atoms and molecules
- **surface reconstruction:** surface atoms bond among themselves.


surface contamination
%
#
*
surface reconstruction
near surface region with deformed bonding
E_c
E_v
surface region
bulk

Metal-Oxide-Semiconductor Structure

surface reconstruction:

- Surface atoms bond among themselves.
- Silicon (111) reconstructs itself in a diamond-shape 7x7 arrangement

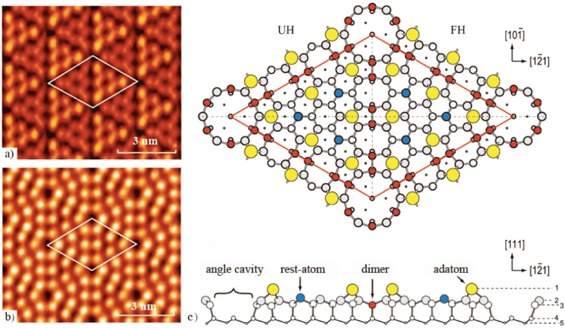

Si(111) Surface

https://www.youtube.com/watch?v=BXdC0NhAMBY

Metal-Oxide-Semiconductor Structure

surface reconstruction:

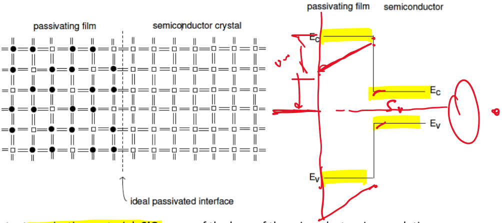
- surface atoms bond among themselves.
- Silicon (111) reconstructs itself in a diamond-shape 7x7 arrangement


a)
3 nm
b)
3 nm
c)
UH
FH
[10 1̄]
[1 2̄ 1]
[111]
[1 2̄ 1]
angle cavity
rest-atom
dimer
adatom
1
2
3
4
5

Metal-Oxide-Semiconductor Structure

Passivated surface

"Coating" of semiconductor surface with passivating layer so **bulk bonding prevails** for surface atoms.


passivating film
semiconductor crystal
ideal passivated interface
passivating film
semiconductor
E_C
E_C
E_V
E_V

Most important passivating material: SiO_2 - one of the keys of the microelectronics revolution:

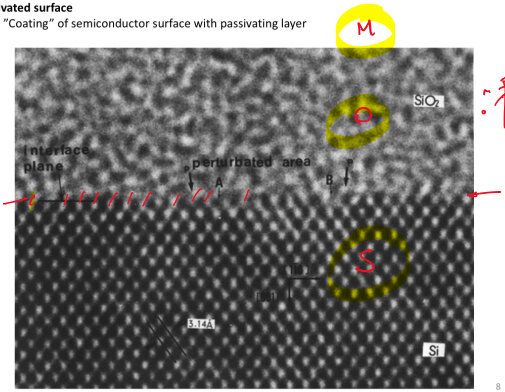
- Natural product of Si oxidation ("Si rusts!")
- Amorphous dielectric: only short-range order
- Exceptional chemistry nearly ideal interface with Si

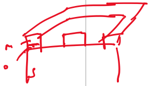
Wide energy gap of SiO_2 prevents carriers from escaping from semiconductor.

Metal-Oxide-Semiconductor Structure

Passivated surface

"Coating" of semiconductor surface with passivating layer


M
O
S
SiO2
interface plane
perturbated area
P
A
B
P
[110]
[001]
3.14Å
Si



http://anterroches.pagesperso-orange.fr/micro/Tem10_html.html

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Metal-Oxide-Semiconductor Structure

Ideal Metal-Oxide-Semiconductor structure at zero bias

MOS structures pervasive in modern microelectronics:

- heart of MOSFETs (from which CMOS is made)
- heart of DRAMs, Flash memories
- MOS structure is formed every time a metal line runs over a dielectric-coated semiconductor

MOS understanding is portable ⇒ view it as generic sandwich of
highly conducting material/dielectric/semiconductor (better name MIS)

MIS

insulator

- Al/SiO_2/Si (early MOSFETs)
- n^+-poly Si/SiO_2/Si (modern MOSFETs)
- Al/Si_3N_4/Si (metallines on Si)
- WSi/AlGaAs/InGaAs (modern high-frequency transistors)
- Ni/Al_2O_3/AlGaN/GaN (GaN high-frequency transistors)

Metal-Oxide-Semiconductor Structure

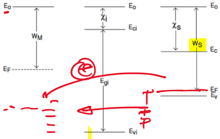
Energy band diagram (p-type substrate)

It does not make sense to draw the E_f for the insulator

In this case:

E_f in semiconductor is below E_f in metal:

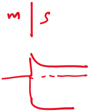
M O S

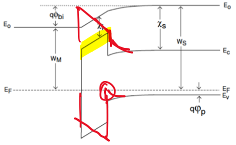

E_o
W_M
E_F
E_o
χ_i
E_{ci}
E_{gi}
E_{vi}
E_o
χ_S
W_S
E_c
E_F
E_v
e
+
+

a) metal, insulator and semiconductor far apart

if $W_m > W_s$

- Electrons flow from metal to semiconductor
- Metal: positively charged
- Semiconductor: negatively charged
- Dipole of charges bend bands in the insulator




E0
qφbi
E0
χ
χs
Ws
Ec
WM
EF
EF
Ev
qφp

b) metal, insulator and semiconductor in intimate contact

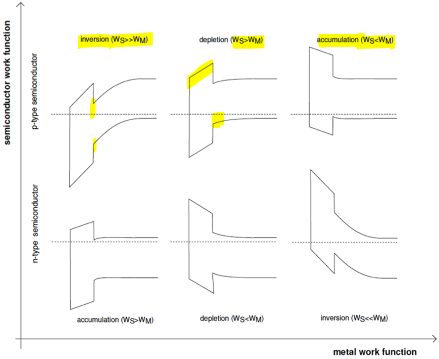
Note:
large band discontinuities at insulator-semiconductor interface.

$$q\phi_{bi} = W_S - W_M$$

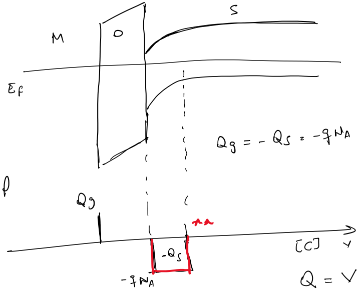
Metal-Oxide-Semiconductor Structure

Energy band diagram

Other possible band arrangements depending on relative values of W_S and W_M:


semiconductor work function
p-type semiconductor
n-type semiconductor
inversion (WS>>WM)
depletion (WS>WM)
accumulation (WS<WM)
accumulation (WS>WM)
depletion (WS<WM)
inversion (WS<<WM)
metal work function

$$\frac{\partial \mathcal{E}(x)}{\partial x} = \frac{\rho(x)}{\varepsilon} \quad \text{—} \quad C/cm^3$$


M
O
S
Ef
ρ
Qg
-Qs
-qNA
xd

$Q_g = -Q_S = -qN_A \cdot x_d \quad [C/cm^2]$

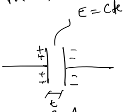
[C] V . F

$Q = V \cdot C$

capacitance per area = $\frac{\text{charge per area}}{\text{Voltage}}$

$\frac{}{cm^2}$ $\frac{}{cm^2}$

1) In the oxide



$C = \frac{\varepsilon . A}{t}$

$C/A = \varepsilon / t$

1) $\phi_{ox} = \frac{-Q_s}{C_{ox}}$, $C_{ox} = \frac{\varepsilon_{ox}}{t} = \frac{\varepsilon_r^{SiO_2} . \varepsilon_0}{t}$

2) $E_{ox} = \frac{\phi_{ox}}{x_{ox}} = \frac{-Q_s}{C_{ox} . \cancel{x_{ox}}} = \frac{-Q_s}{\frac{\varepsilon_{ox}}{\cancel{x_{ox}}} . \cancel{x_{ox}}} = \frac{-Q_s}{\varepsilon_{ox}}$

x_{ox} " t of oxide

C_{ox} " $\frac{\varepsilon_{ox}}{\cancel{x_{ox}}}$

In the semi conductor:

1) $\frac{\partial E(x)}{\partial x} = \frac{\rho(x)}{\varepsilon_s} = \frac{-Q_s}{\varepsilon_s} \Rightarrow E(x) = -\frac{Q_s}{\varepsilon}(x - x_d)$

2) $\varepsilon_{ox} . |\vec{E}_{ox}| = \varepsilon_s . |\vec{E}_s|$ at the interface

$E_s = \frac{\varepsilon_{ox} E_{ox}}{\varepsilon_s} = \frac{\cancel{\varepsilon_{ox}} . \frac{-Q_s}{\cancel{\varepsilon_{ox}}}}{\varepsilon_s} = \frac{-Q_s}{\varepsilon_s}$

Potentials:

$\frac{\partial \phi(x)}{\partial x} = - E(x)$

, in the oxide: $\phi_{ox} = - E_{ox} . x_{ox}$

$\phi_{ox} = \frac{q . N_A . x_d}{\varepsilon_{ox}} . x_{ox} = \frac{q . N_A . x_d}{C_{ox}}$

. in the semi conductor:

$\phi_s = \frac{q N_A}{\varepsilon_s}\left(\frac{x^2}{2} - x_d x\right) + a$

$x = x_d \Rightarrow \phi = 0$ (reference) $\Rightarrow a = \frac{q N_A}{2 \varepsilon_s} . x_d^2$

$\phi_s(x) = \frac{q N_A}{2 \varepsilon_s}(x^2 - 2 x_d x + x_d^2)$

at $x = 0 \Rightarrow \phi_s = \frac{q . N_A}{\varepsilon_s} . \frac{x_d^2}{2}$

Metal-Oxide-Semiconductor Structure

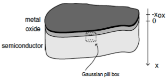
General relations for MOS electrostatics

- no charge in dielectric
- overall charge neutrality:

$$Q_g = -Q_s$$

- field inside dielectric uniform:

$$\mathcal{E}_{ox} = -\frac{Q_s}{\epsilon_{ox}}$$

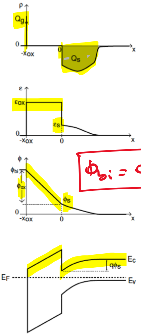

metal
oxide
semiconductor
Gaussian pill box
-xox
0
x

- normal component of displacement vector conserved at semiconductor/dielectric interface:

$$\epsilon_s \mathcal{E}_s = \epsilon_{ox} \mathcal{E}_{ox}$$

- Hence field at semiconductor surface:

$$\mathcal{E}_s = -\frac{Q_s}{\epsilon_s}$$


ρ
Qg
0
-xox
0
Qs
x
ε
εox
εs
0
-xox
0
x
ϕ
ϕbi
ϕox
ϕs
0
-xox
0
x
Ec
qϕs
EF
Ev

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

Metal-Oxide-Semiconductor Structure

General relations for MOS electrostatics

Total potential difference across structure:

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

drop across semiconductor, ϕ$_s$, called **surface potential**

Voltage drop in oxide:

$$\phi_{ox} = x_{ox} \mathcal{E}_{ox}$$

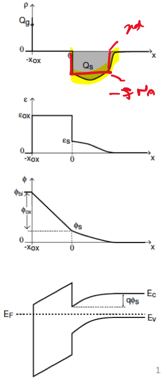
Define **oxide capacitance** per unit area:

$$C_{ox} = \frac{\epsilon_{ox}}{x_{ox}}$$

All together, total potential build-up across MOS:

$$\phi_{bi} = \phi_s - \frac{Q_s}{C_{ox}}$$

Key relationship between ϕ$_s$ and Q$_s$.


ρ
Qg
0
-xox
0
Qs
x
ε
εox
εs
0
-xox
0
x
ϕ
ϕbi
ϕox
ϕs
0
-xox
0
x
Ec
qϕs
EF
Ev

x_d

$-qN_A$

$Q_s = q N_A x_d$

Metal-Oxide-Semiconductor Structure

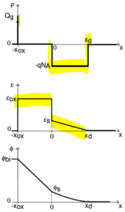
Depletion approximation:

Integrated semiconductor charge:

$$Q_s \simeq -qN_A x_d$$

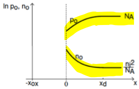
Field at semiconductor surface:

$$\mathcal{E}_s \simeq \frac{qN_A x_d}{\epsilon_s}$$


ρ
Qg
0
-xox
0
xd
x
-qNA
ε
εox
εs
0
-xox
0
xd
x
ϕ
ϕbi
ϕs
0
-xox
0
xd
x

Field in insulator:

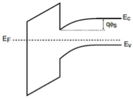
$$\mathcal{E}_{ox} \simeq \frac{qN_A x_d}{\epsilon_{ox}}$$



ln p_o, n_o
p_o
NA
n_o
$\frac{n_i^2}{N_A}$
-xox
0
xd
x

Surface potential:

$$\phi_s \simeq \frac{qN_A x_d^2}{2\epsilon_s}$$



Everything in terms of x_d, but don't know x_d!

Metal-Oxide-Semiconductor Structure

Demand ϕ_{bi} be the right amount from energy considerations:

$$\phi_{bi} = \frac{1}{q}(W_S - W_M) = \phi_s + \phi_{ox} \simeq \frac{qN_A x_d^2}{2\epsilon_s} + \frac{qN_A x_d}{C_{ox}}$$

Solve for x_d:

$$x_d \simeq \frac{\epsilon_s}{C_{ox}}\left(\sqrt{1+\frac{4\phi_{bi}}{\gamma^2}}-1\right)$$

Where γ is body-factor coefficient:

$$\gamma = \frac{1}{C_{ox}}\sqrt{2\epsilon_s q N_A}$$

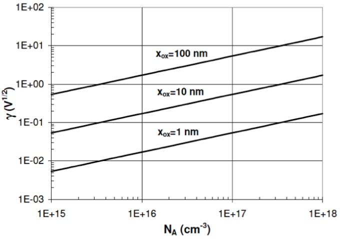
Key dependencies: $\phi_{bi} \uparrow \rightarrow x_d \uparrow$

$N_A \uparrow \rightarrow x_d \downarrow$

Metal-Oxide-Semiconductor Structure

body-factor coefficient γ:

$$\gamma = \frac{1}{C_{ox}}\sqrt{2\epsilon_s q N_A}$$



γ depends on:

- doping of body
- capacitance of insulator

⇒ relative magnitude of depletion capacitance and oxide capacitance.

In well designed MOSFETs, γ ~ 0.1–1 $V^{1/2}$.

Key conclusions

Si/SiO$_2$ interface nearly ideal: most Si bonds satisfied but interface is about two monolayers rough.

MOS structure: depletion, accumulation or inversion.

Surface potential, ϕ_s: total potential build-up across semiconductor.

General relationships for MOS electrostatics:

Overall charge neutrality: $Q_g = -Q_s$

Continuity of normal component of displacement vector: $\epsilon_s \mathcal{E}_s = \epsilon_{ox} \mathcal{E}_{ox}$

Total potential difference must add up to

$$\phi_{bi} = \phi_s - \frac{Q_s}{C_{ox}}$$