EPFL

EE-557
Semiconductor devices I

Metal-Oxide-Semiconductors

Génie Electrique et Electronique
Master Program
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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

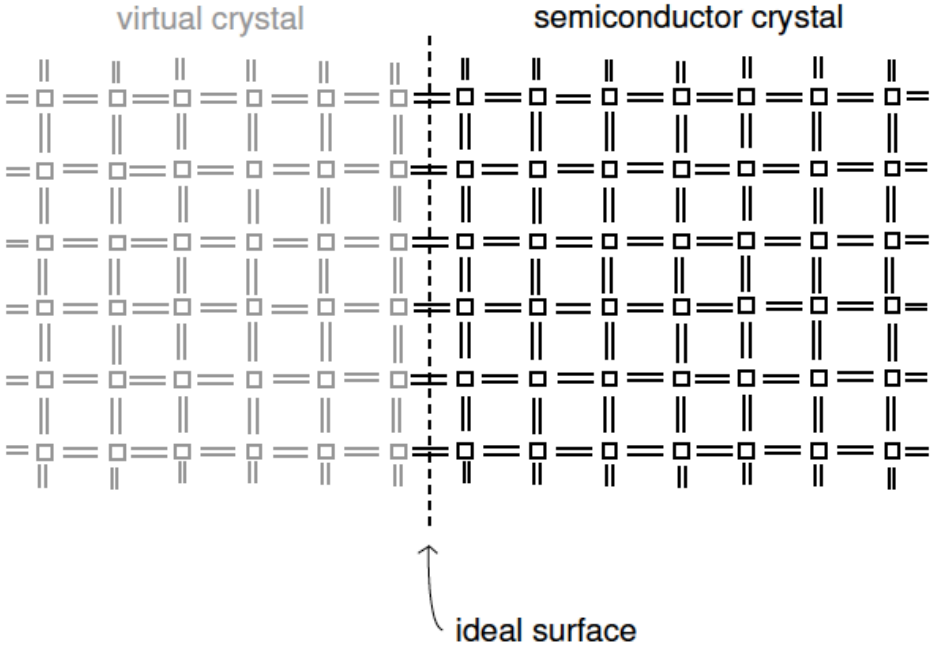
- How does the surface of a semiconductor look like at the atomic level?
- If one assembles a metal-oxide-semiconductor structure and sets it up at zero bias, what is the band structure?
- How does this picture change for different choices of metal work function?

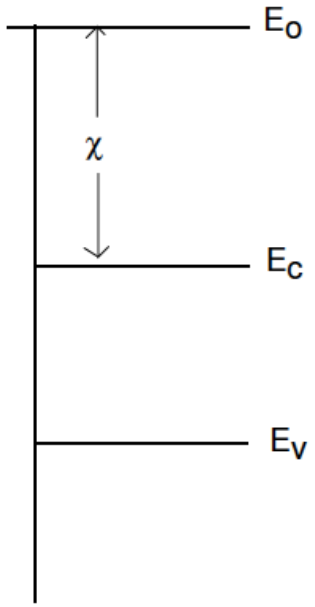
Semiconductor Surface

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.





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

Semiconductor Surface

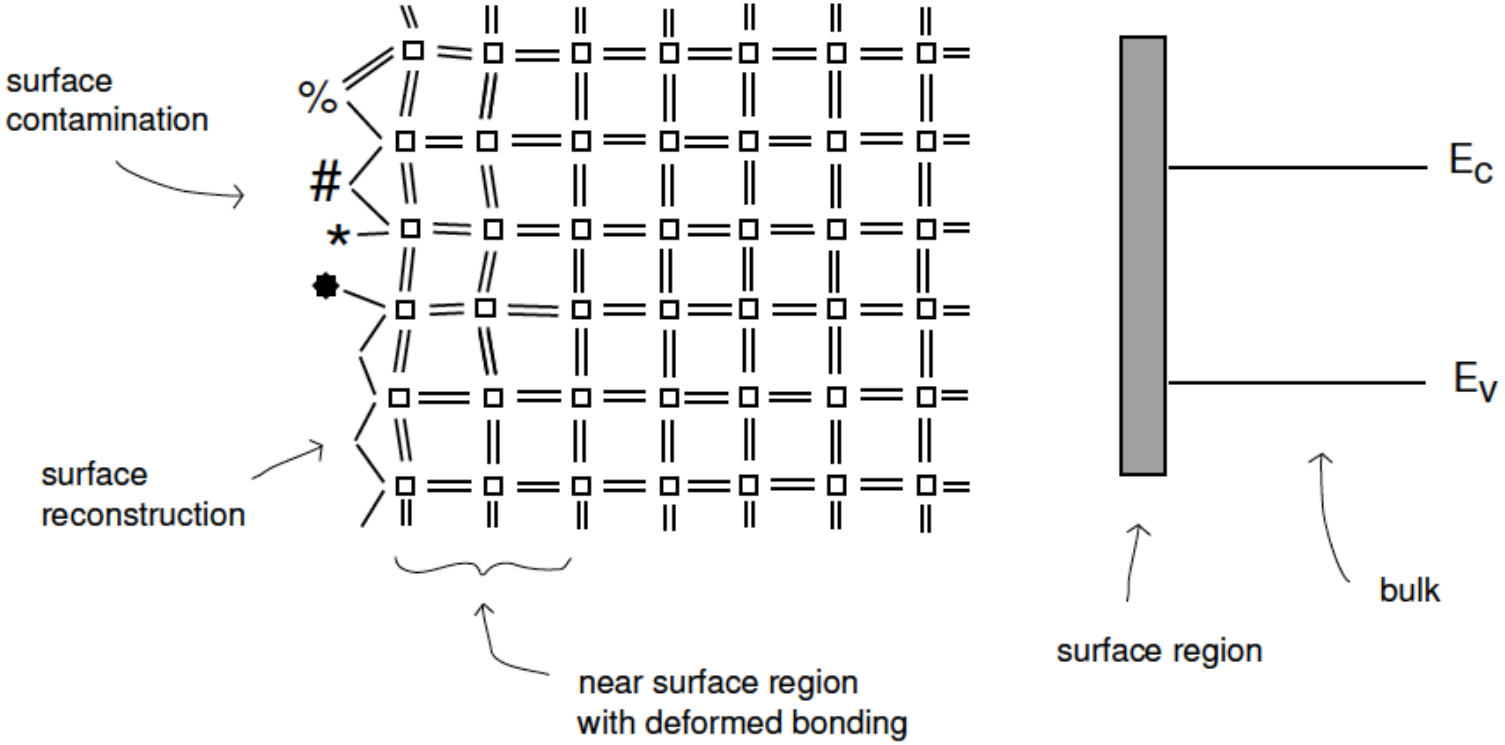
Real surface

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:

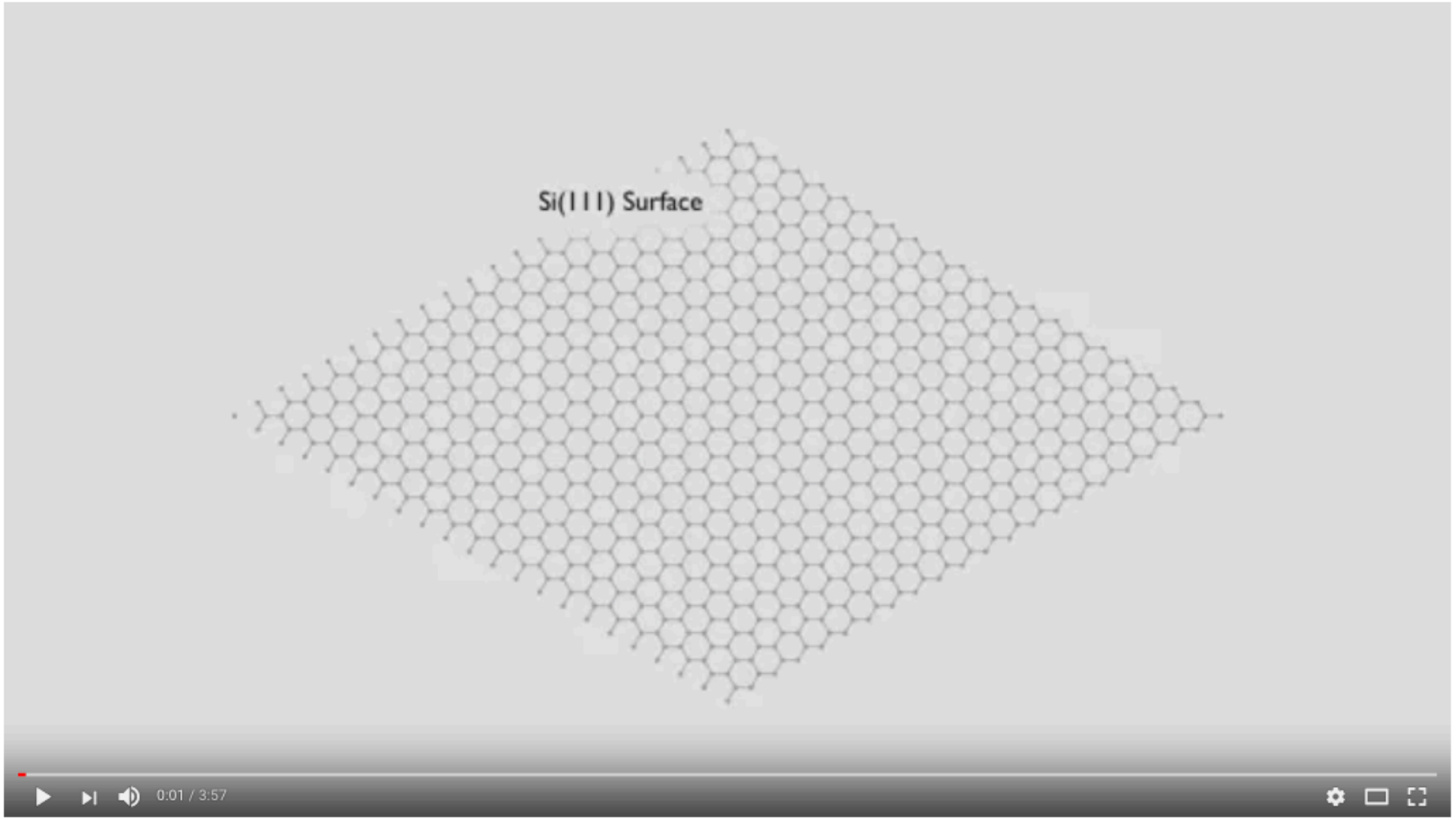
- **surface contamination:** absorption of O, C, and other foreign atoms and molecules
- **surface reconstruction:** surface atoms bond among themselves.



Metal-Oxide-Semiconductor Structure

surface reconstruction:

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



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

Metal-Oxide-Semiconductor Structure

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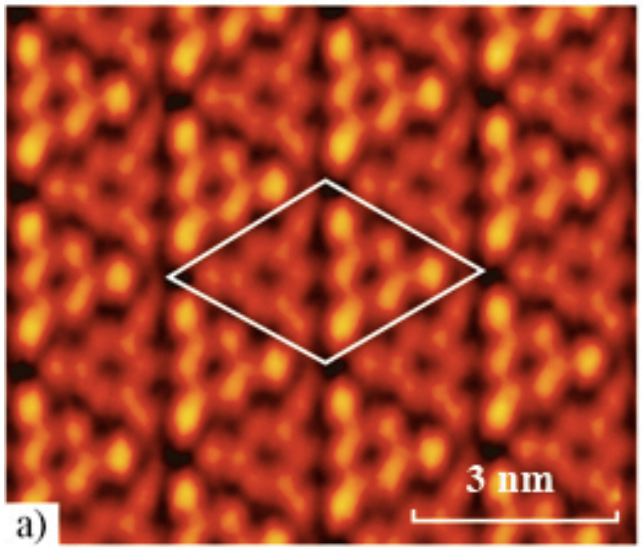
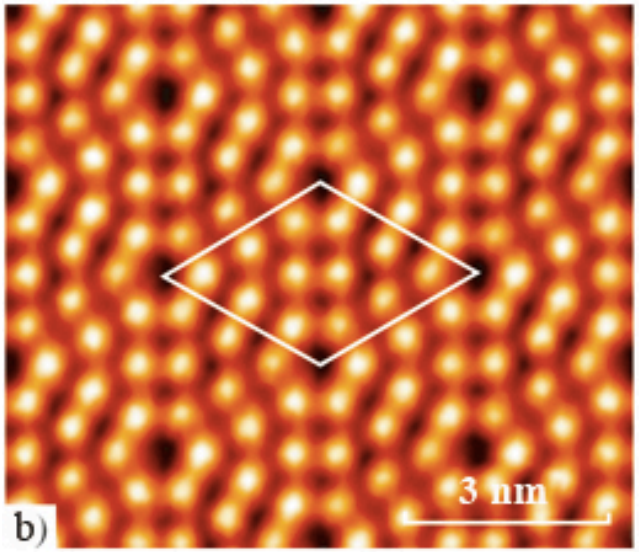
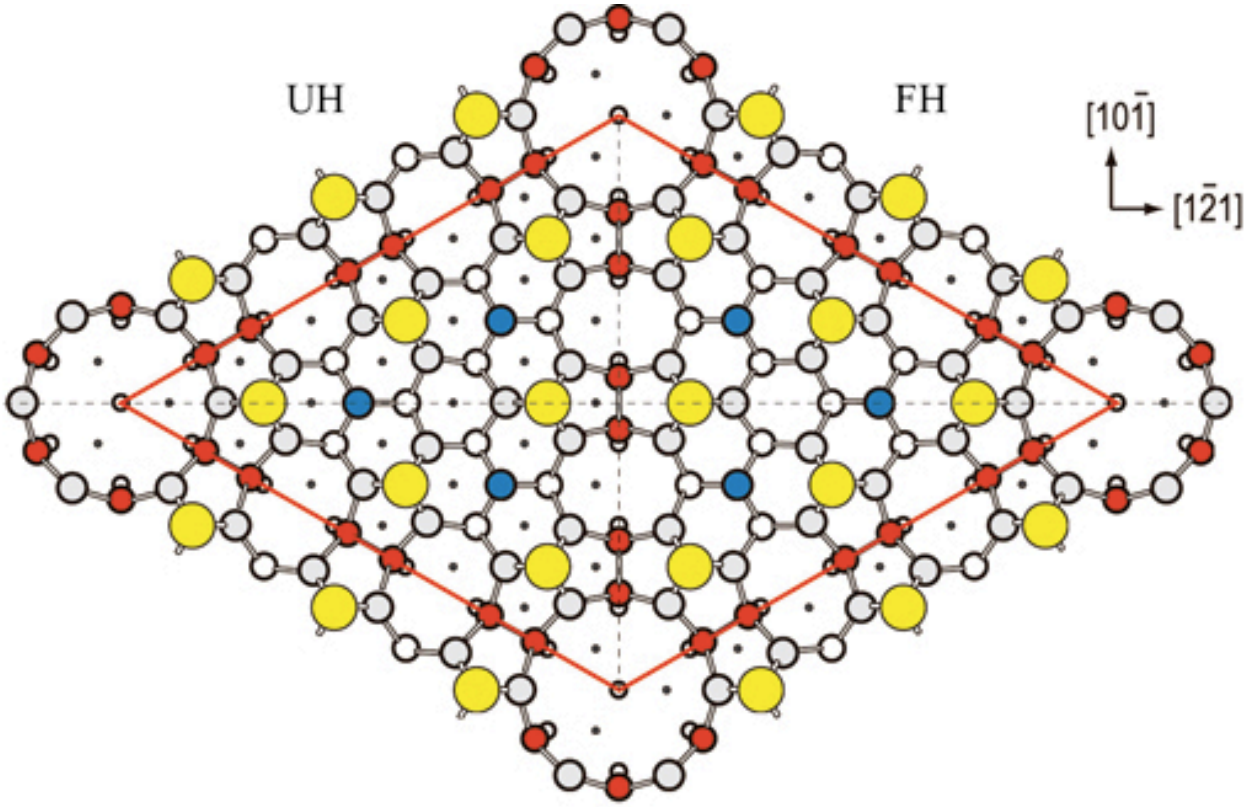
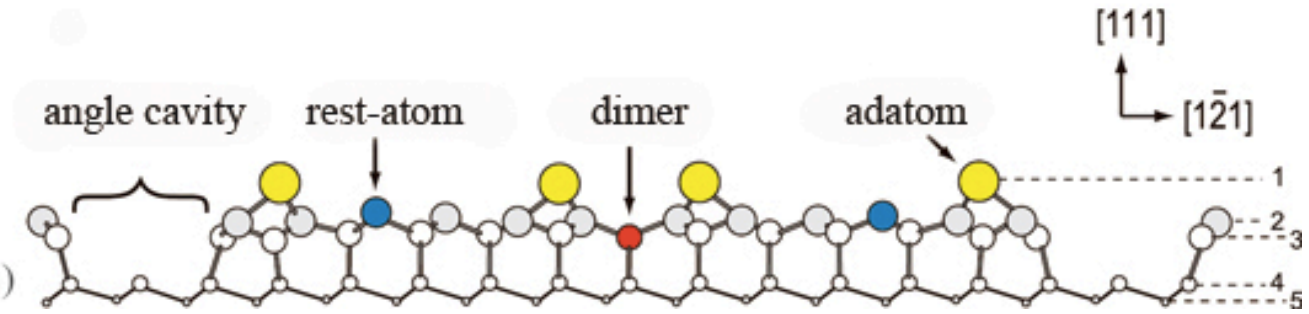


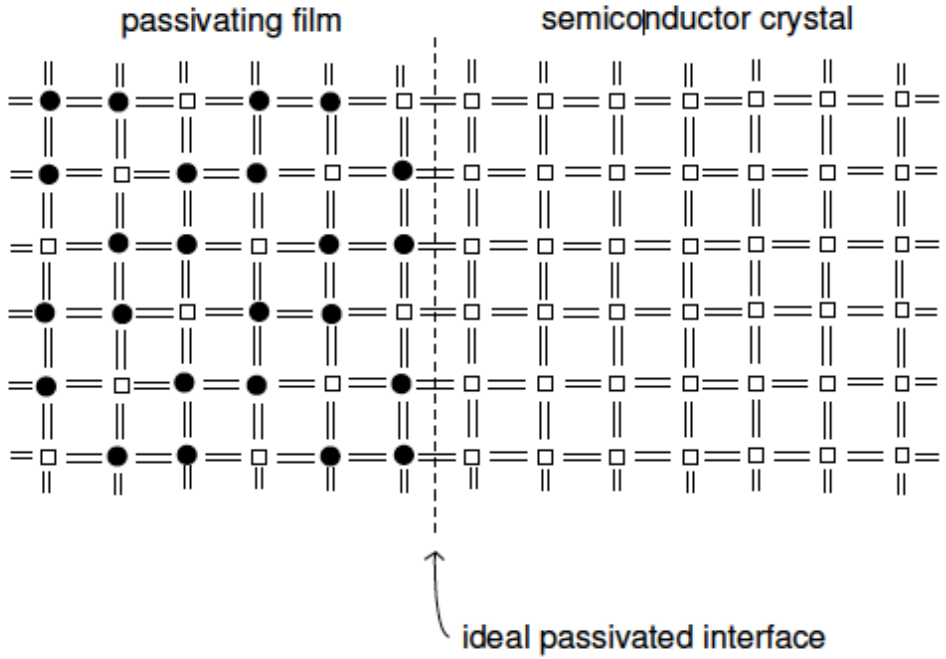


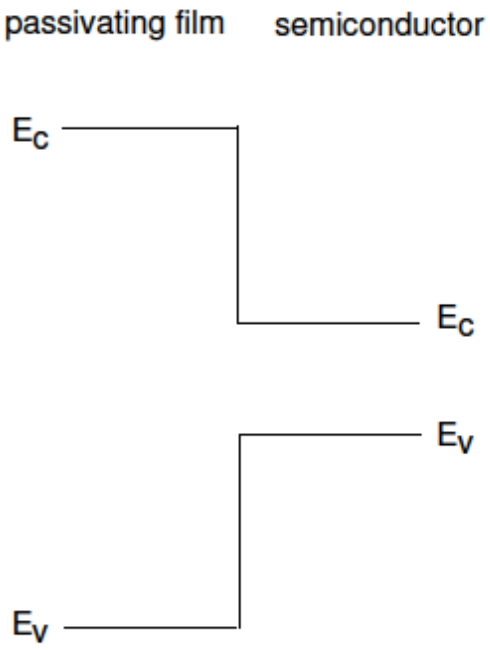




Passivated surface

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





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

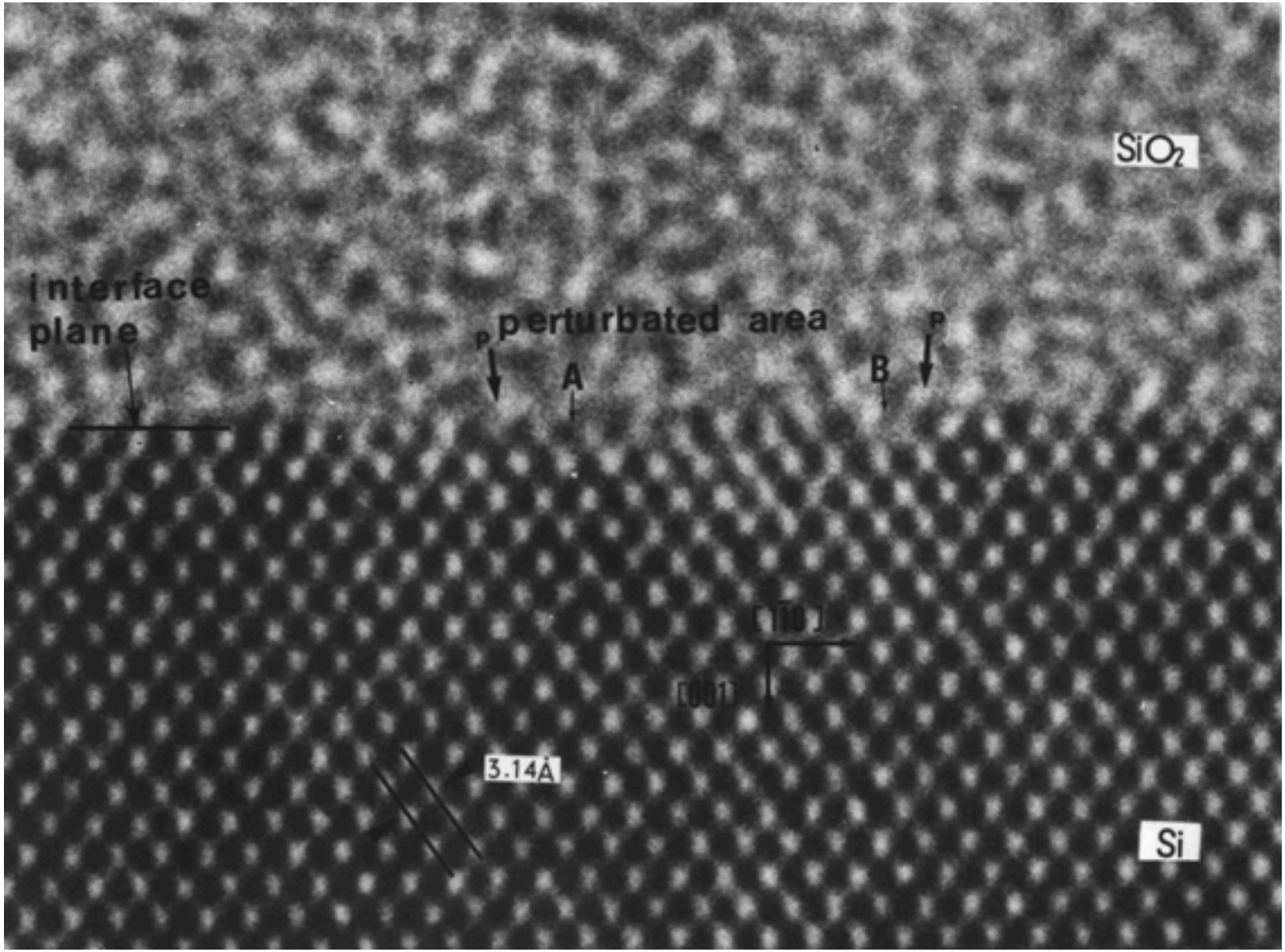
- Natural product of Si oxidation ("Si rusts!")
- Amorphous dielectric: only short-range order
- Exceptional chemistry nearly ideal interface with Si

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



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

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)

- 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

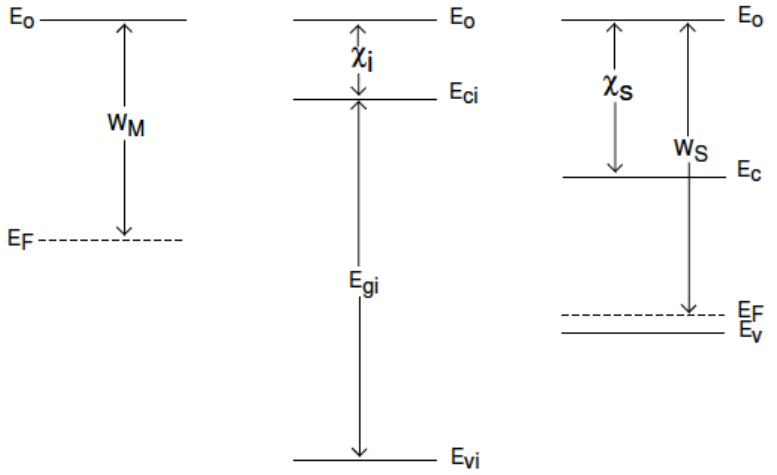
Energy band diagram (p-type substrate)

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

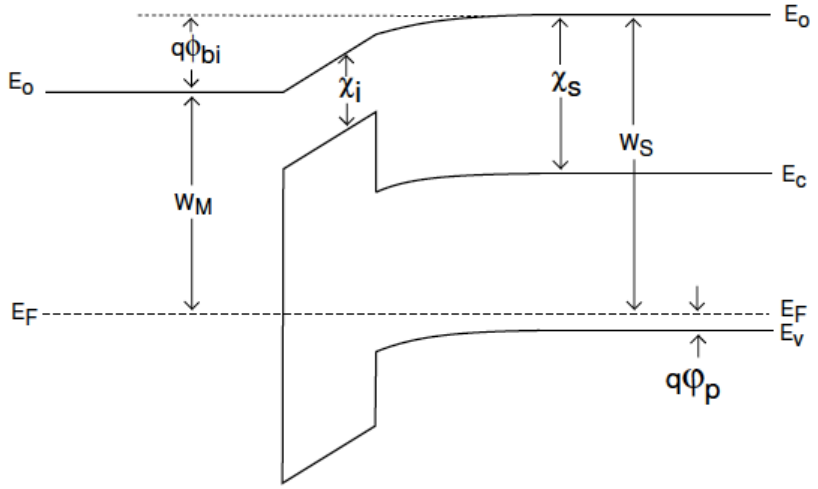
In this case:

E_f in semiconductor is below E_f in metal:

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



a) metal, insulator and semiconductor far apart



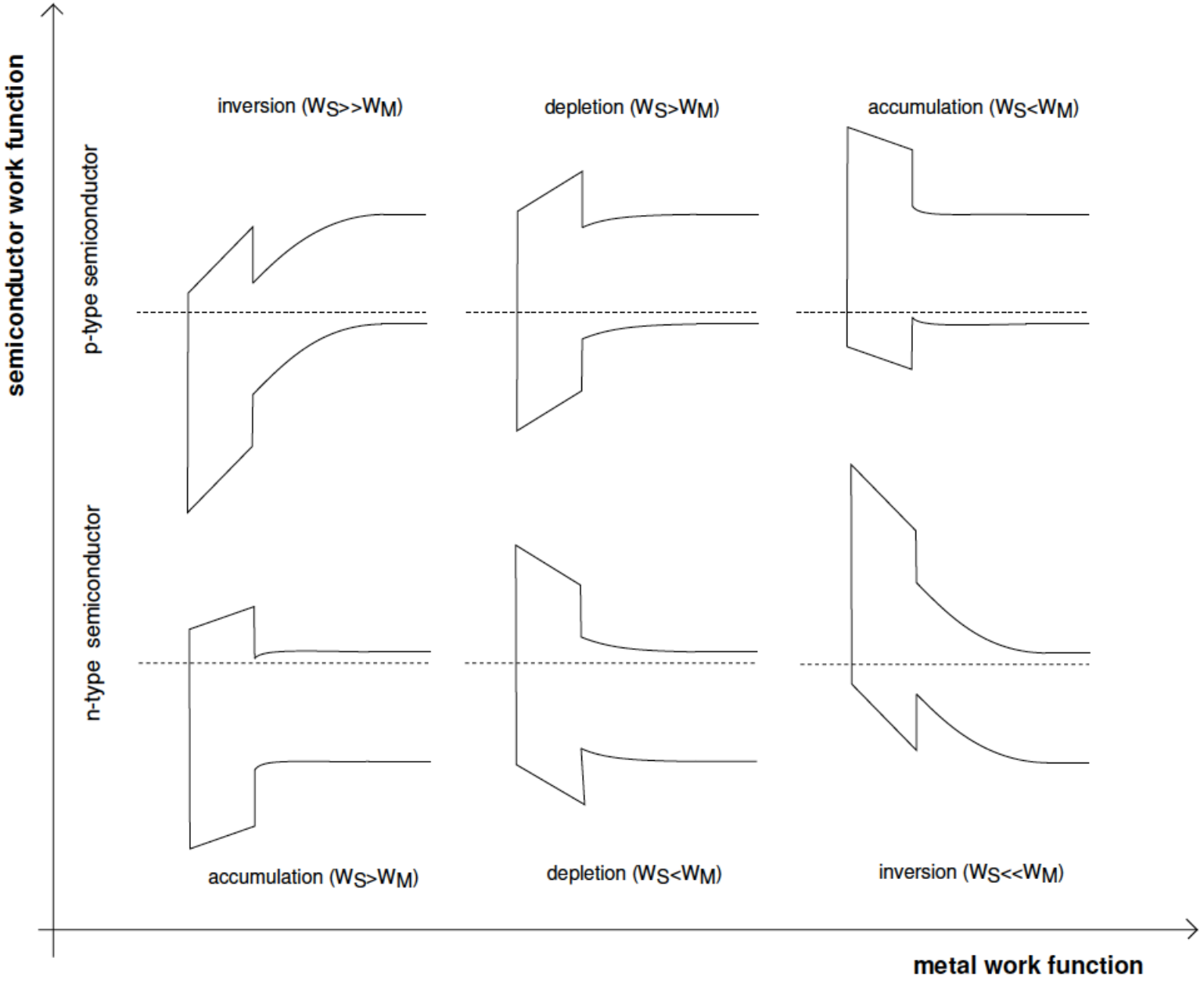
b) metal, insulator and semiconductor in intimate contact

Note:
large band discontinuities at insulator-semiconductor interface.

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

Energy band diagram

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



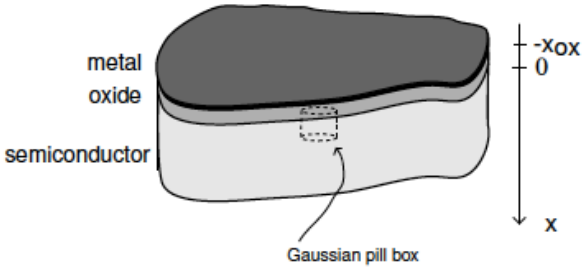
General relations for MOS electrostatics

- no charge in dielectric
- overall charge neutrality:

$$Q_g = -Q_s$$

- field inside dielectric uniform:

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

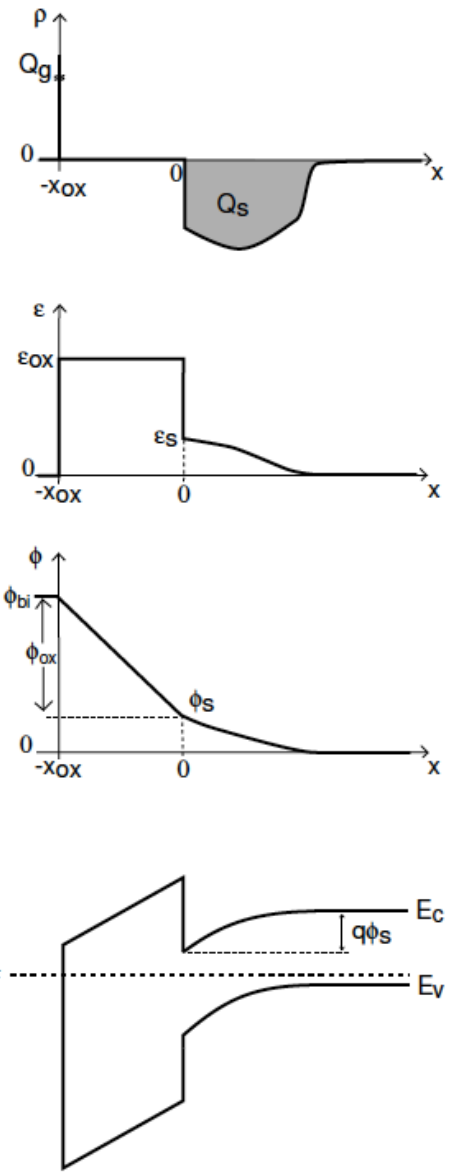


- normal component of displacement vector conserved at semiconductor/dielectric interface:

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

- Hence field at semiconductor surface:

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



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:

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

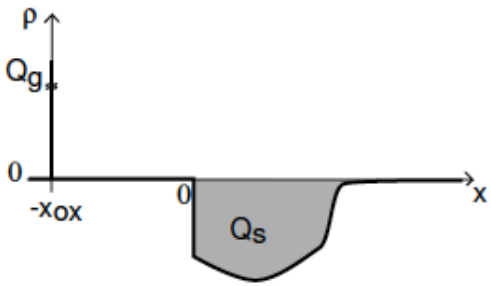
Define **oxide capacitance** per unit area:

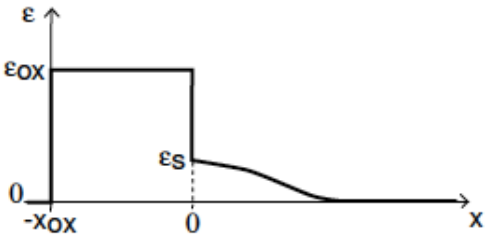
$$C_{ox} = \frac{\epsilon_{ox}}{x_{ox}}$$

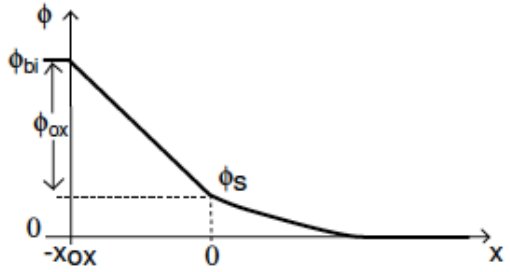
All together, total potential build-up across MOS:

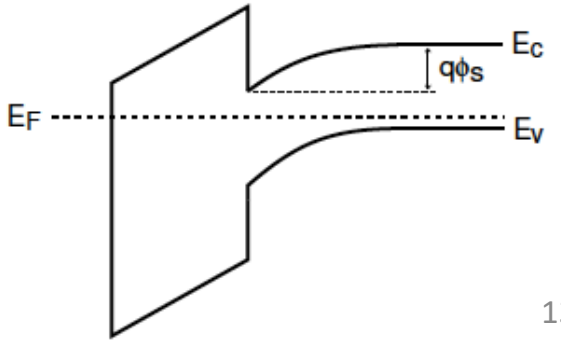
$$\phi_{bi} = \phi_s - \frac{Q_s}{C_{ox}}$$

Key relationship between ϕ_s and Q_s.







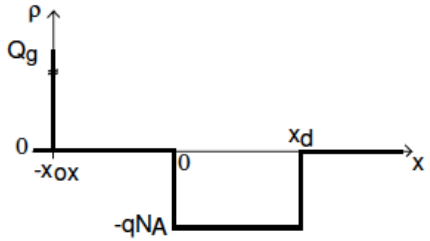


Metal-Oxide-Semiconductor Structure

Depletion approximation:

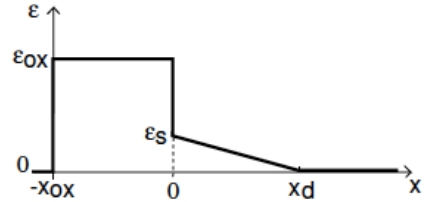
Integrated semiconductor charge:

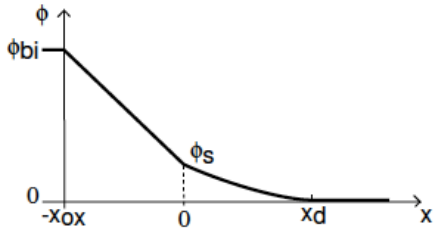
$$Q_s \simeq -qN_A x_d$$



Field at semiconductor surface:

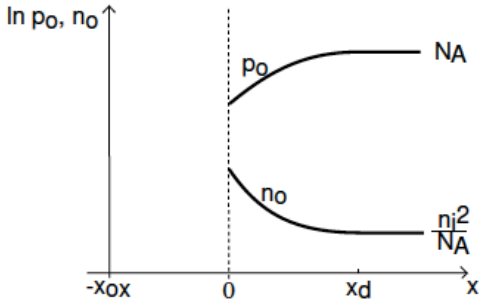
$$\mathcal{E}_s \simeq \frac{qN_A x_d}{\epsilon_s}$$





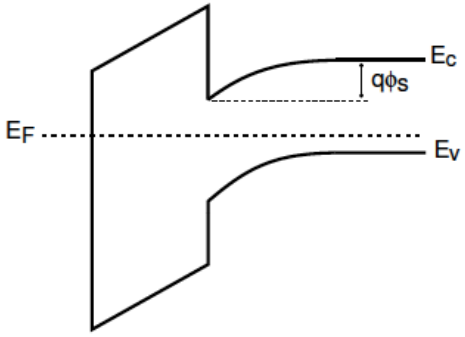
Field in insulator:

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



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:

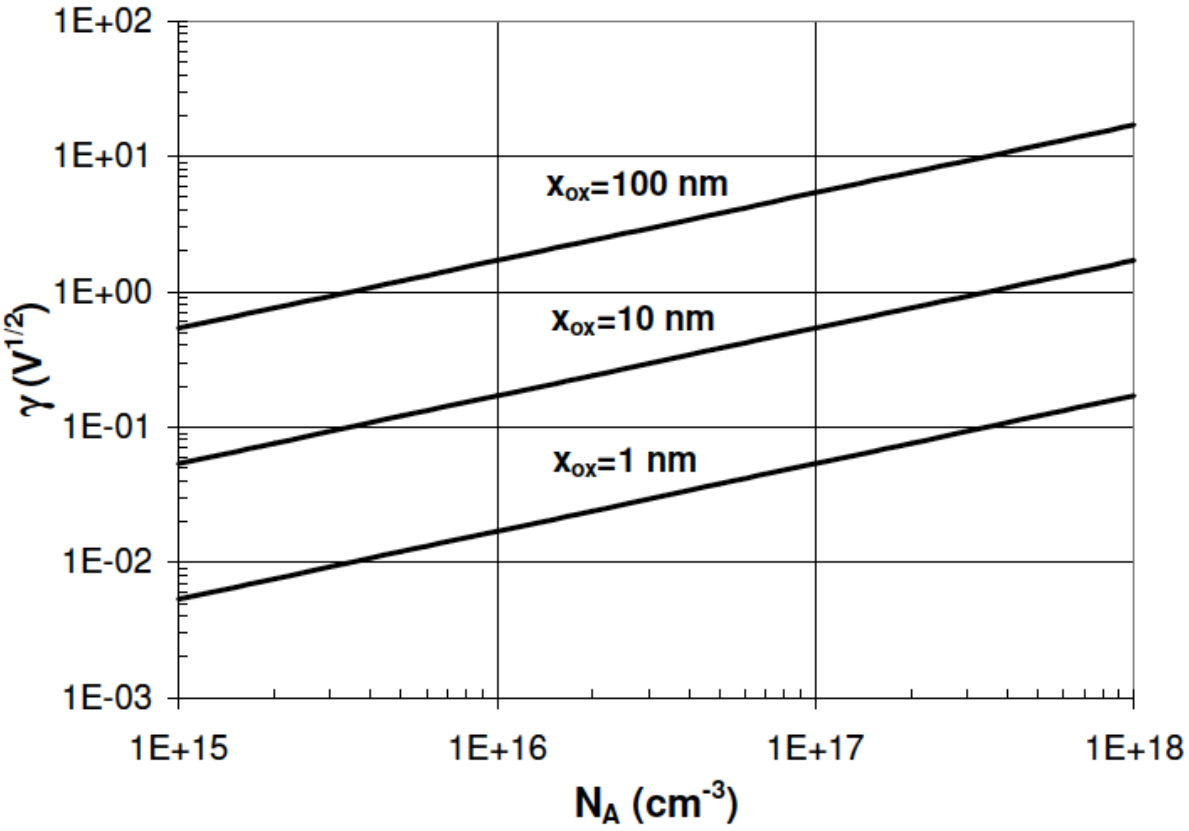
$$\gamma = \frac{1}{C_{ox}}\sqrt{2\epsilon_s q N_A}$$

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

$$N_A \uparrow \rightarrow x_d \downarrow$$

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