Chapter 18.

NONIDEAL MOS

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CONTENTS

Physics of Non-ideal MOS-C

//

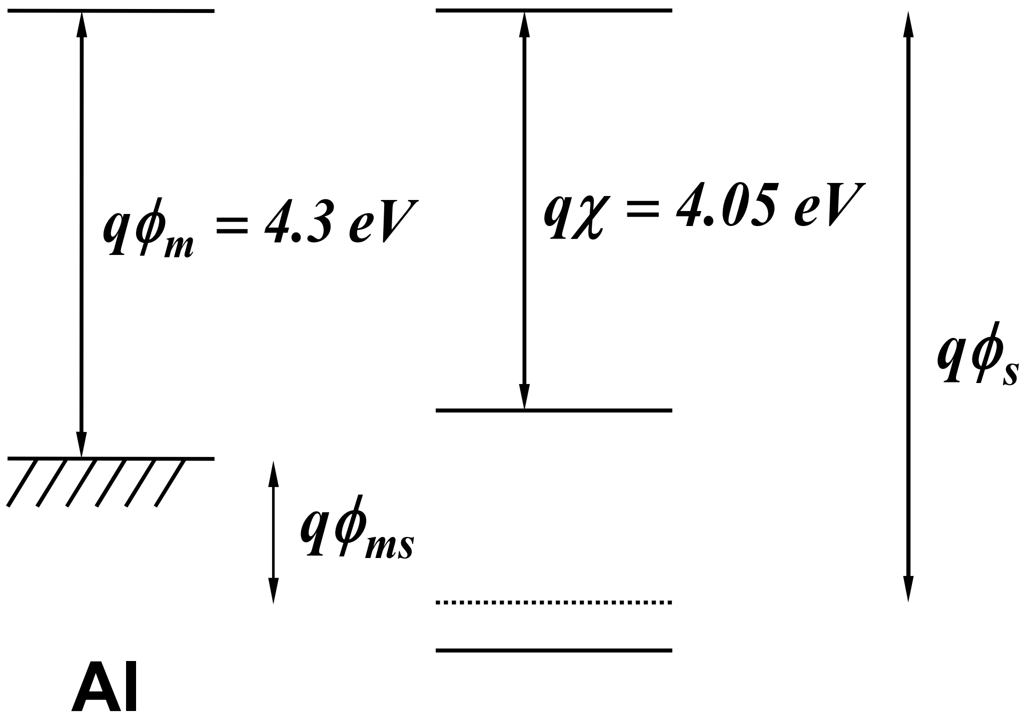
" real "

① $\phi_{ms} \neq 0$

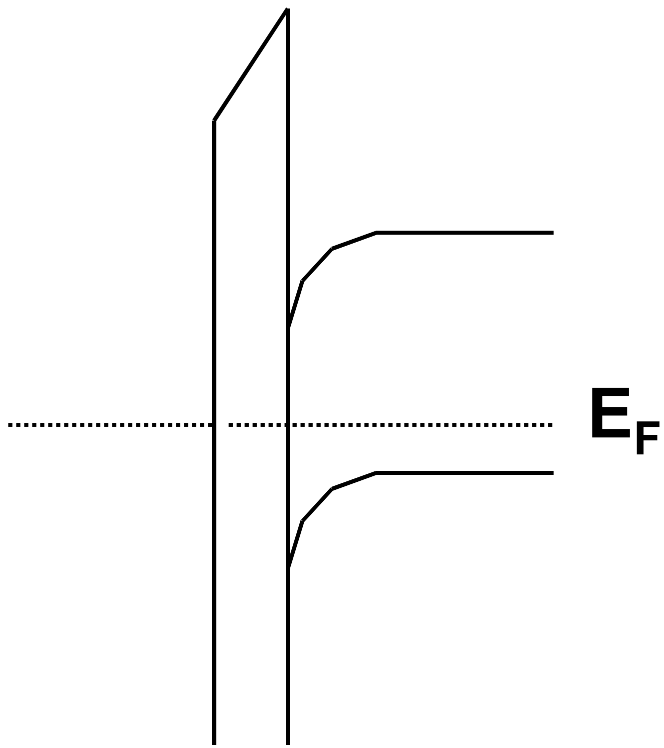
② charges exist in SiO_2

Workfunction Difference

- Workfunction :
  - the minimum energy required to bring an electron from the Fermi level to the vacuum level.
  - for $A\ell$, $q\phi_m = 4.3\ e$V.
- Electron affinity :
  - the energy difference between conduction band edges of the semiconductor and the vacuum level.
  - for silicon, $q\chi = 4.05\ e$V.



Silicon

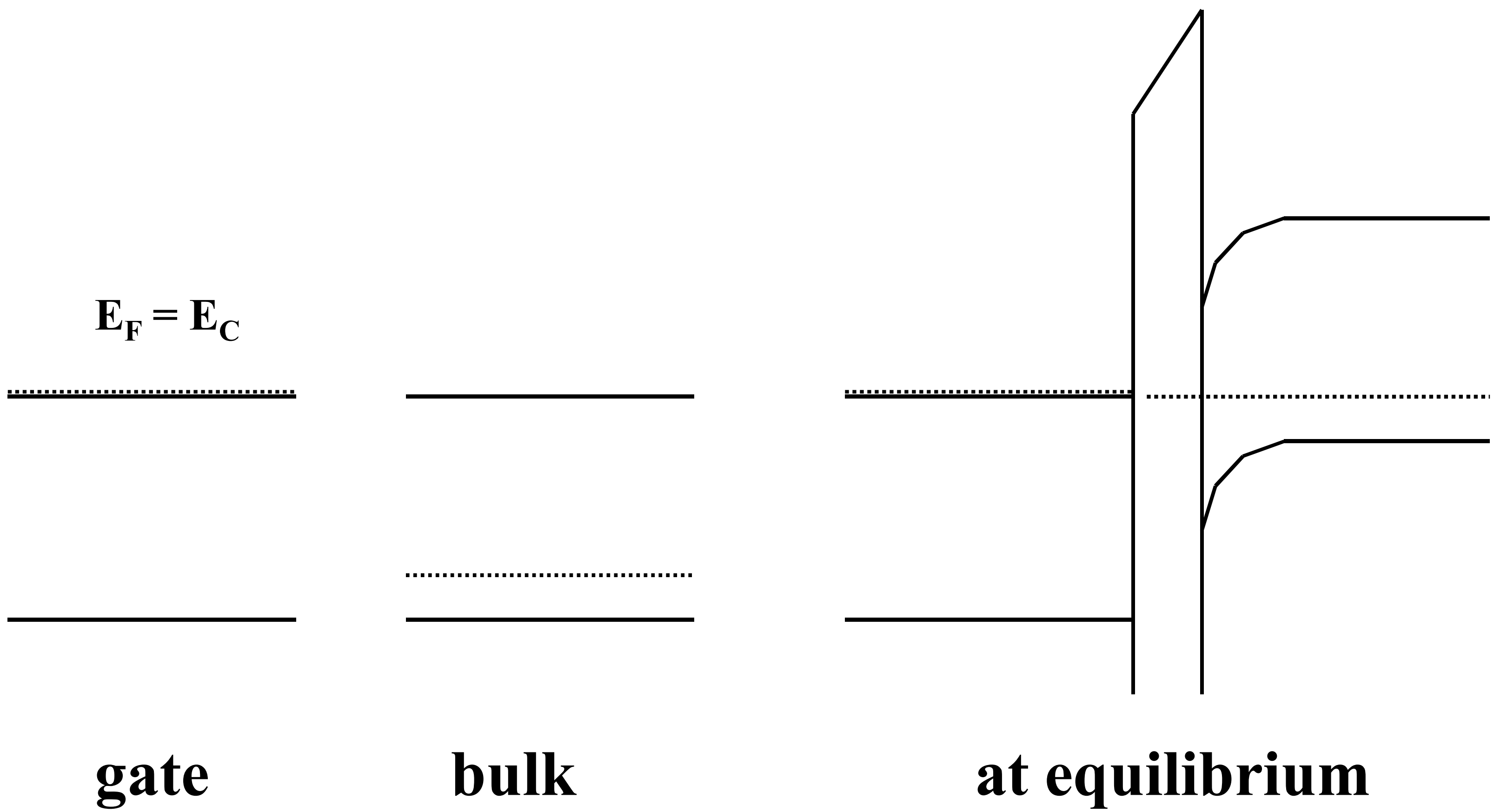


Equilibrium

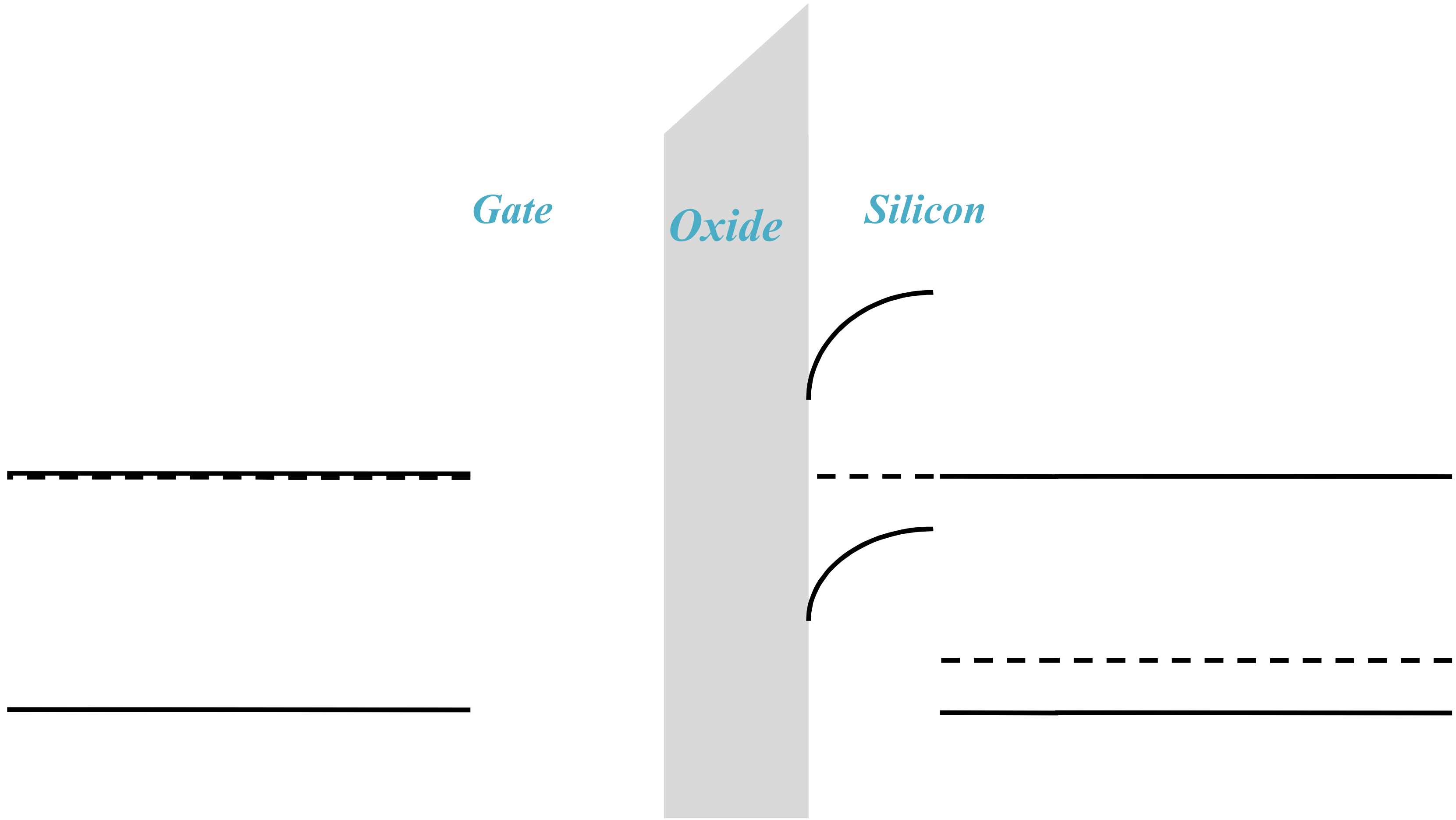
$$\phi_m \neq \phi_s$$

$$V_{FB} = \phi_{ms}$$

Heavily-doped polysilicon gate



Heavily-doped polysilicon gate



$$\phi_{ms} = -E_g/2 - \phi_F$$

$$= -E_g/2 - \frac{kT}{q} ln\left(\frac{N_A}{n_i}\right)$$

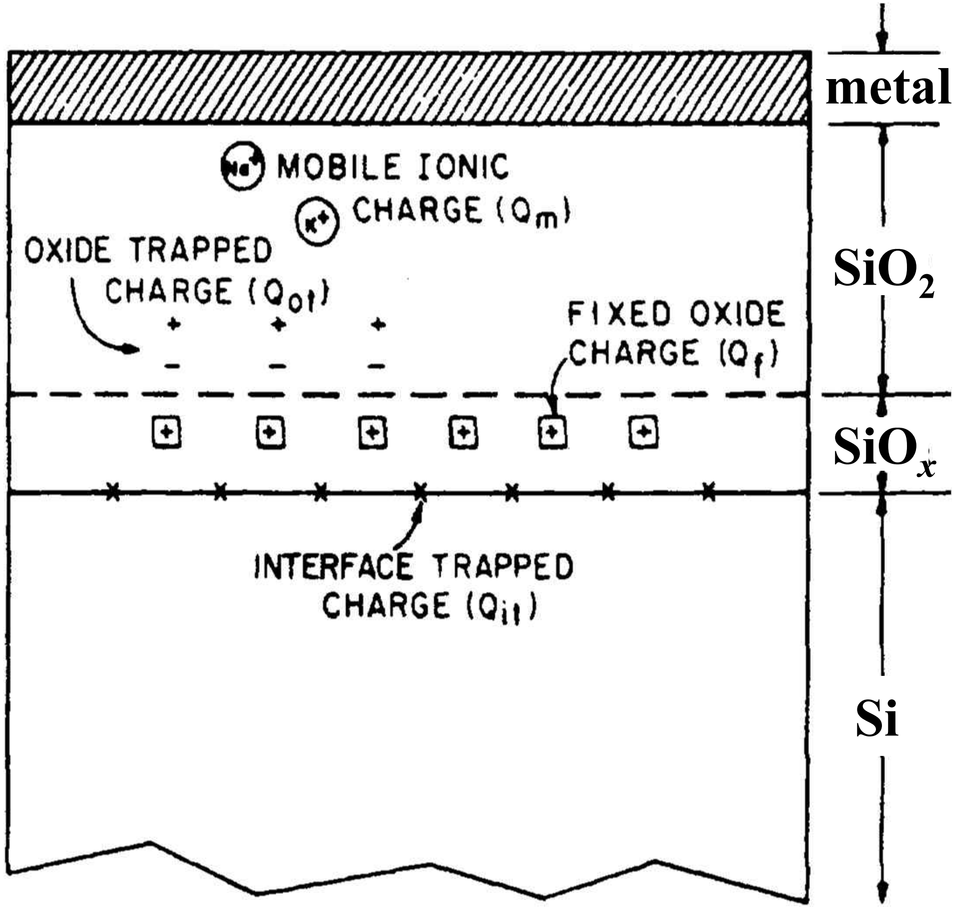
약 -900 mV

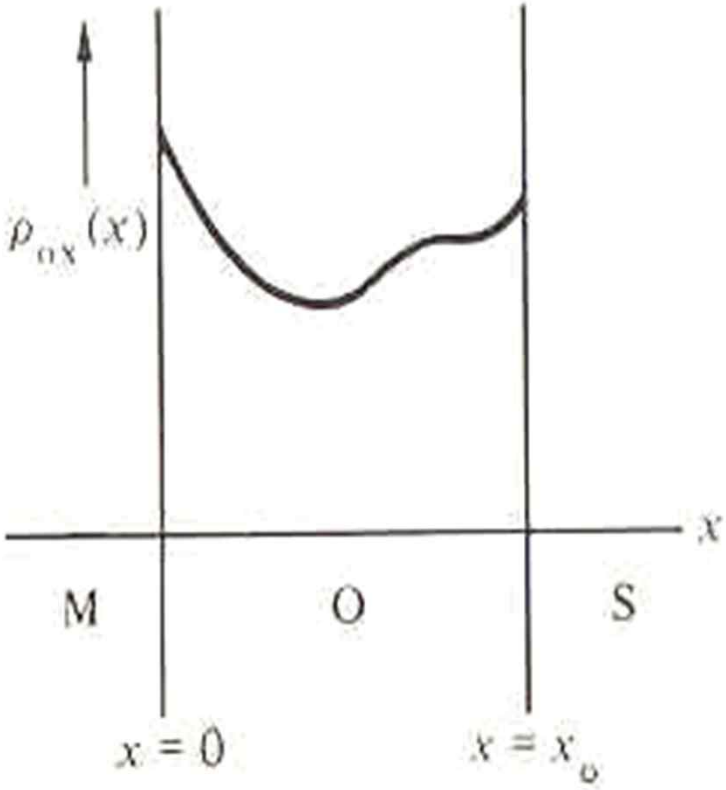
~ 560mV (↑ $E_g/2$)

~ 350mV (↑ $\frac{kT}{q} ln\left(\frac{N_A}{n_i}\right)$)

Oxide Charges and Traps

- Q_{tot} : total oxide charges (per unit area)



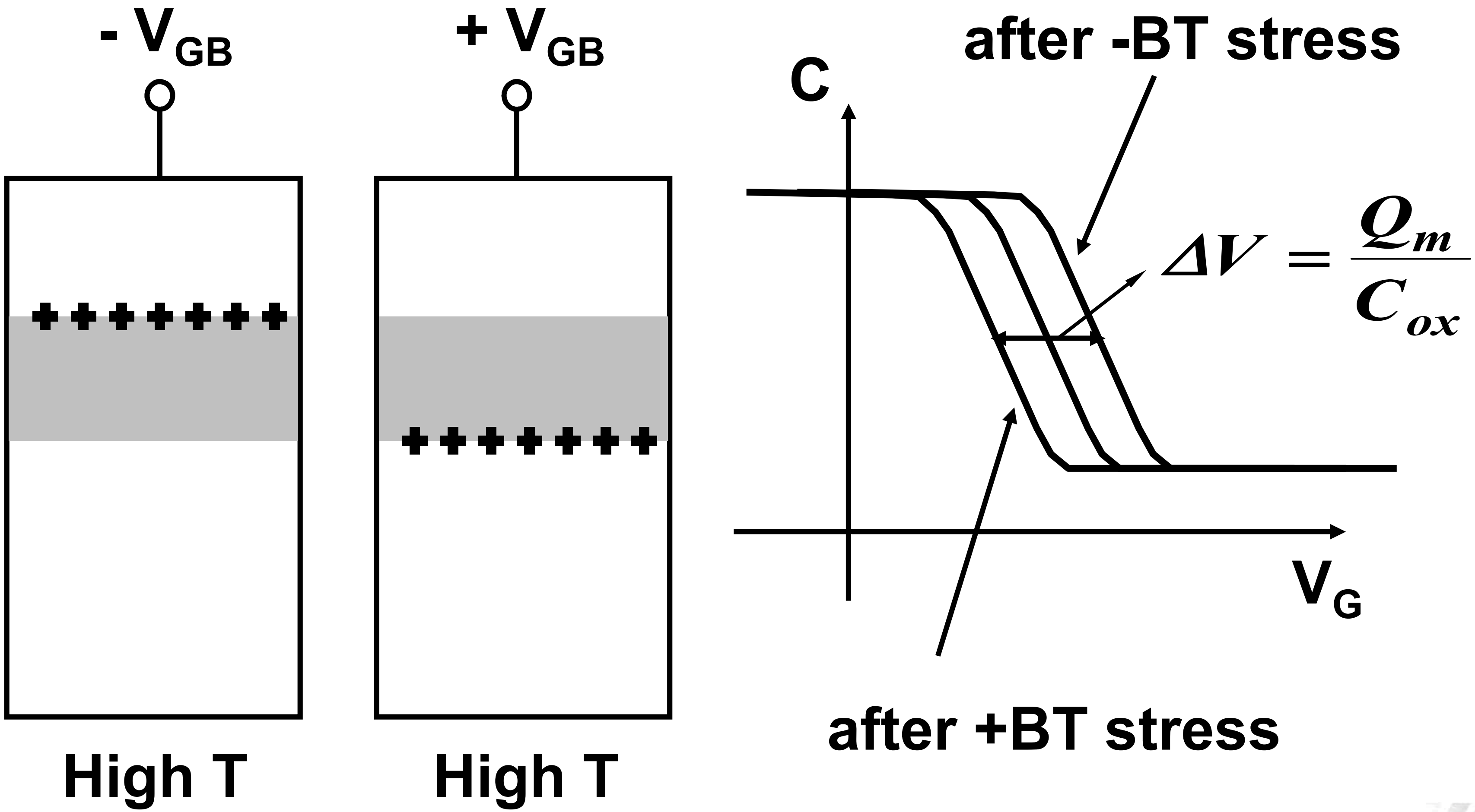


$$\Delta V_T = -\frac{1}{K_o \varepsilon_o} \int_0^{x_o} x \, \rho_{ox}(x) dx$$

Mobile Ionic Charges

- Na^+, K^+
- Very high diffusivities in the oxide even below 200 °C
  - V_T instability

- Test : MOS-C CV


- V_{GB}
+ V_{GB}
High T
High T
C
V_G
after -BT stress
after +BT stress
$\Delta V = \frac{Q_m}{C_{ox}}$

Fixed Oxide Charge

1. Located very close to the interface
2. Associated with the structure of the interfacial between Si and SiO_2
3. Function of substrate orientation, oxidation temperature (anneal condition)

(111) > (110) > (100)

↑

$1\times10^{10}\ cm^{-2}$ $\therefore$ **(100) wafers are used for MOS IC**

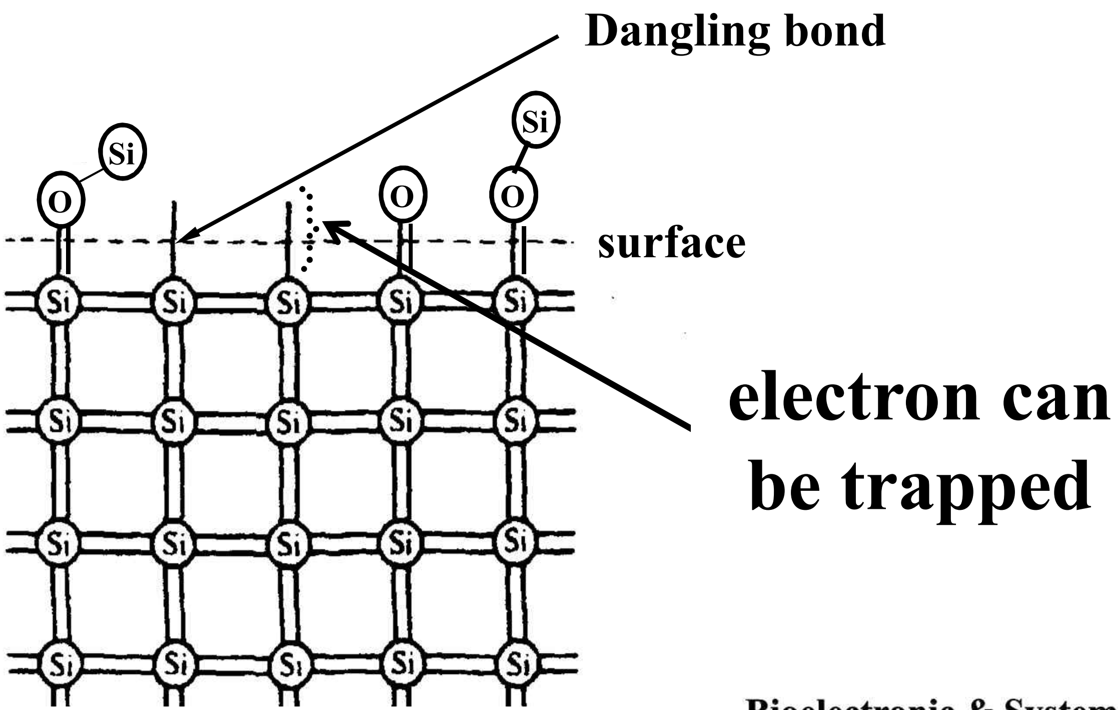
$$\Delta V_T = \frac{-Q_f}{C_{ox}} = \frac{-qN_f}{C_{ox}}$$

$$(100)\quad t_{ox} = 50\text{Å},\quad C_{ox} = \frac{K_{ox}\varepsilon_o}{t_{ox}} = \frac{3.9\times8.854\times10^{-14}\ \text{F/cm}}{50\times10^{-8}\ \text{cm}} = 690\ \text{nF/cm}^2$$

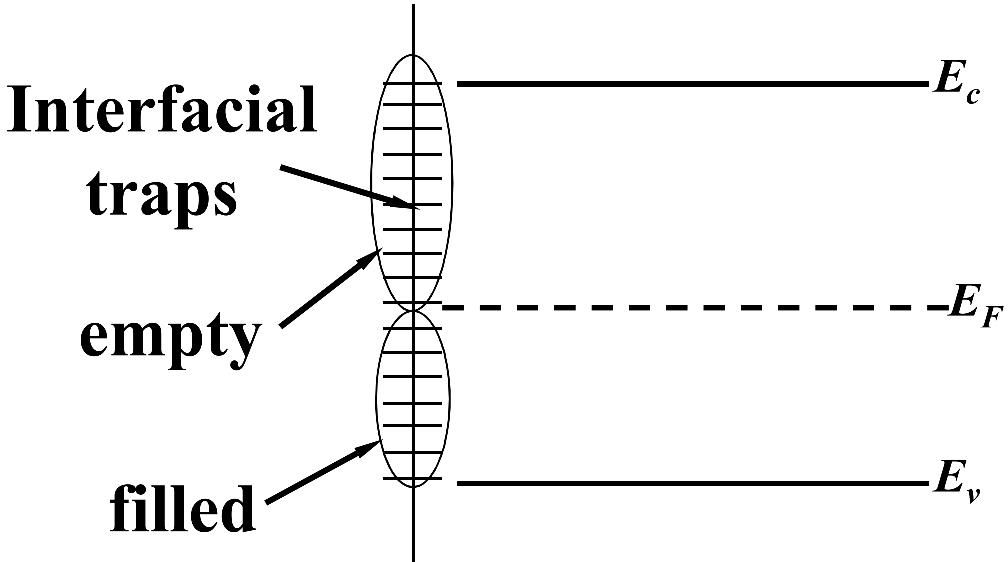
$$\Delta V_T = -\frac{\left(1.6\times10^{-19}\,C\right)\left(1\times10^{10}\,cm^{-2}\right)}{690\times10^{-9}\,F/cm^2} = 2.5\ \text{mV}$$

Interface Trapped Charge

1. Arises from allowed energy states in the forbidden gap of the Si, very close to Si-SiO_2 interface.
2. Physical origin unknown yet.
   → "dangling bond" (?)



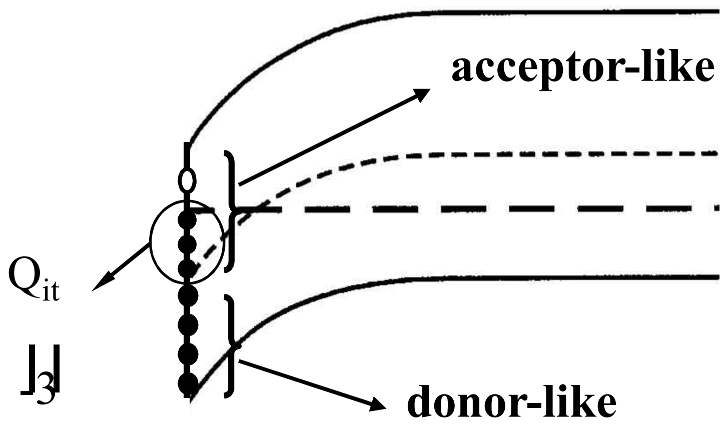
3. The surface state acts like a recombination center.
4. Function of V_{GB} → 가장 나쁜 charge.
5. Distributed throughout the entire band gap

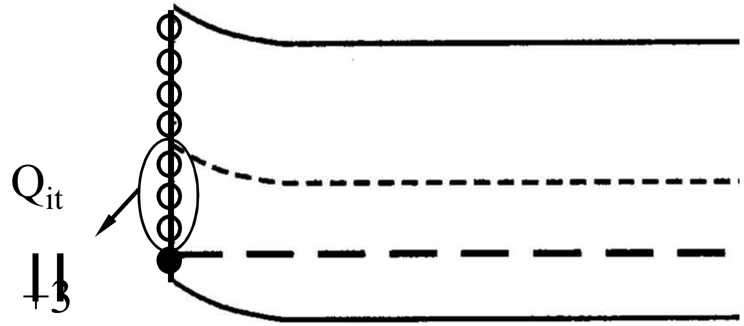


	Filled	Empty	
donor-like traps	"0"	"+"	below E_i
acceptor-like traps	"-"	"0"	above E_i

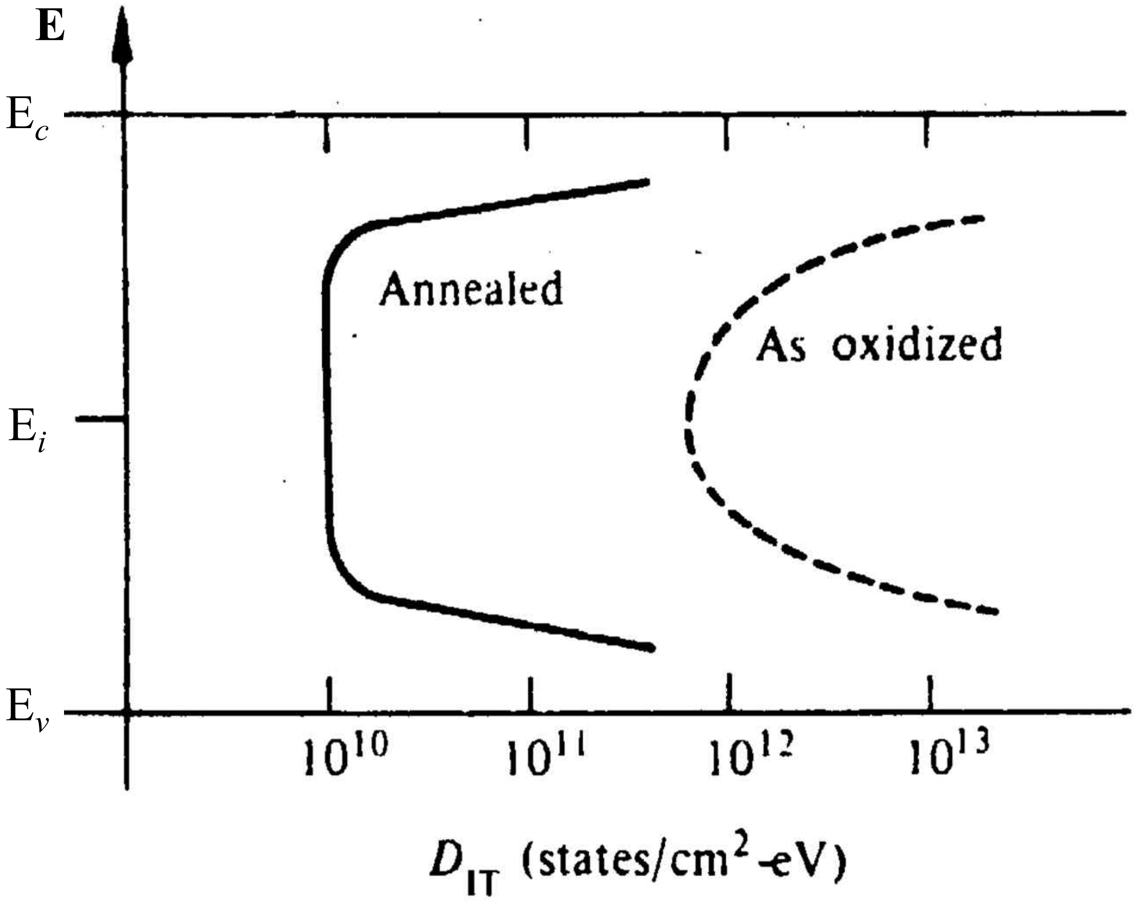
- inversion :
mostly filled

- accumulation :
mostly empty





6. Distribution of trap level vs. energy

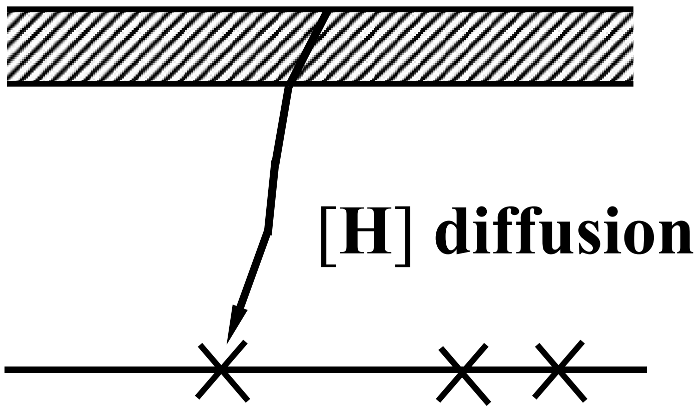


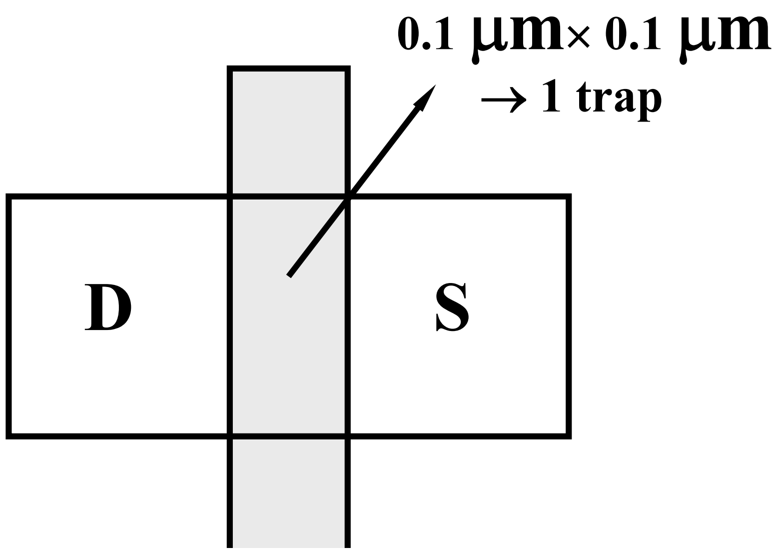
N_{it}
(#/cm^2)

7. (111

8. Annealing with hydrogen at relatively low temperature (≤ 500 °C) minimize D_{it}.

10^{10} traps/cm^2 → 100 traps/μm^2





Oxide Trapped Charge Q_{ot}

- Due to holes and electrons trapped in the bulk of oxide.

Effect of Oxide Charge on V_T

$$\Delta V_T = -\frac{Q_{tot}}{C_{ox}} \quad \text{(If } Q_{tot} \text{ at the interface)}$$

Threshold Voltage Equation

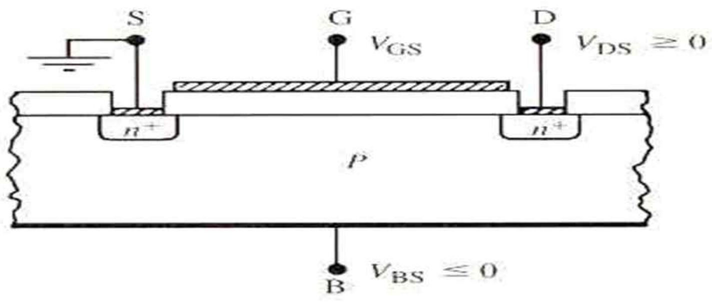
- Flat band voltage $\equiv V_{FB} \equiv$ $$\phi_{ms} - \frac{Q_{tot}}{C_{ox}}$$

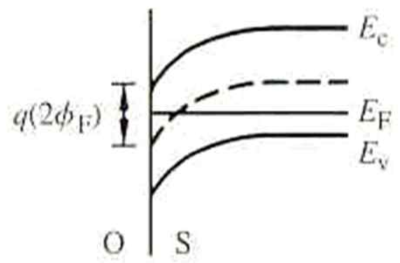
$$V_T = V_{FB} + 2\phi_F + \frac{\sqrt{4K_s\,\varepsilon_0\,q\,N_A\,\phi_F}}{C_{ox}} \qquad \sim 0.6\text{ V}$$

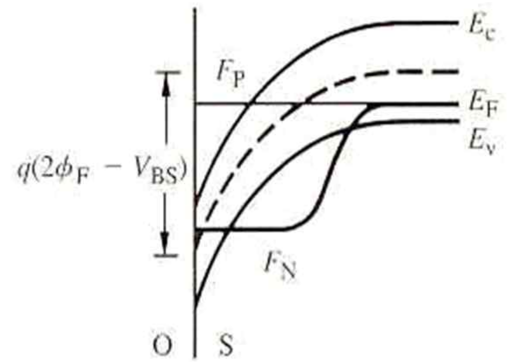
potential drop in Si (the $2\phi_F$ term) **potential drop in oxide** (the $\frac{\sqrt{4K_s\varepsilon_0 q N_A \phi_F}}{C_{ox}}$ term)

Back Biasing

- Body effect: Reverse biasing the back contact relative to the source → V_T change







If V_{BS}=0, inversion occurs when $\phi_s=2\phi_F$

If V_{BS}<0, inversion layer carriers migrate laterally into the S/D. The inversion occurs when $\phi_s=2\phi_F+|V_{BS}|$. The maximum depletion width

$$W_T = \sqrt{\frac{2K_s\varepsilon_o\left(2\phi_F + |V_{BS}|\right)}{qN_A}}$$

- At threshold,

$$V_{GB} = V_{FB} + 2\phi_F + |V_{BS}| + \frac{\sqrt{2qK_s\varepsilon_o N_A\left(2\phi_F + |V_{BS}|\right)}}{C_{ox}}$$

$$\therefore \underset{V_T}{\underset{\shortparallel}{V_{GS}}} = V_{GB} + V_{BS} = V_{FB} + 2\phi_F + \frac{\sqrt{2qK_s\varepsilon_o N_A\left(2\phi_F + |V_{BS}|\right)}}{C_{ox}}$$

$$= V_T(V_{BS} = 0) + \underbrace{\frac{\sqrt{2qK_s\varepsilon_o N_A}}{C_{ox}}}_{Body\ Factor}\left(\sqrt{2\phi_F + |V_{BS}|} - \sqrt{2\phi_F}\right)$$

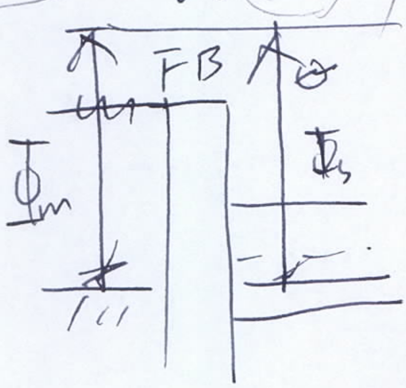
11/25/2010 Ch18

Non-Ideal MOS

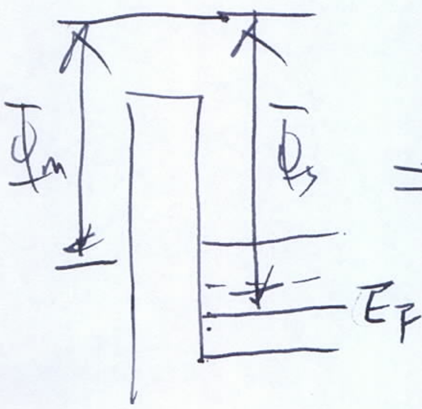
1. ϕ_{MS} : workfunction Difference.

$\phi_{MS} = \frac{1}{q}(\Phi_M - \Phi_S) =$ (energy)

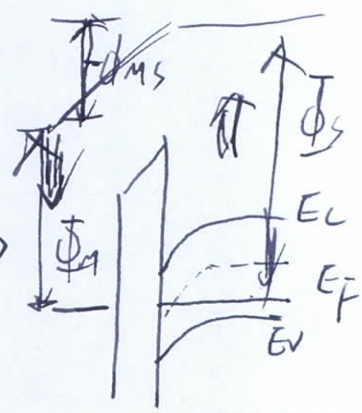
vs.



(1) when $\phi_{MS} = 0$

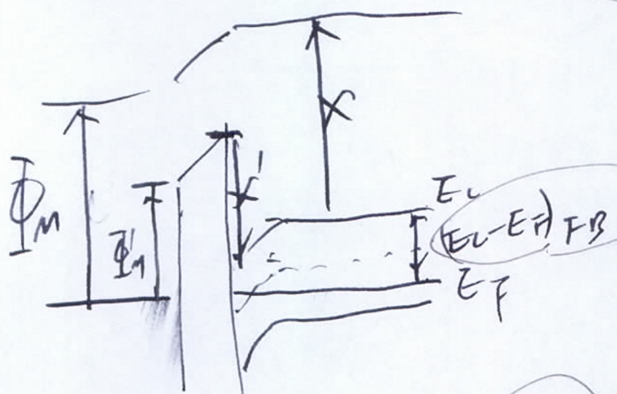


$\Phi_m < \Phi_s$



$\Delta V_T = +\phi_{MS}$ (이게 음수ー)

~~Required for FB.~~



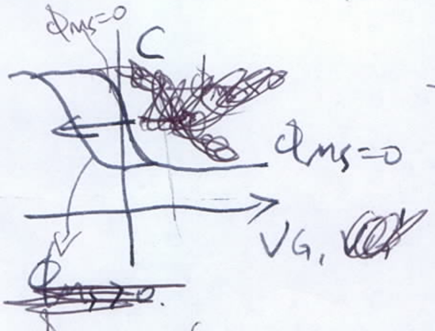
$$\Phi_M' + q\Delta\phi_{ox} = (E_C - E_F)_{FB} - q\phi_s + \chi'$$

$$V_{bi} = -(\phi_s + \Delta\phi_{ox}) = \phi_{MS}$$

(vacuum level이 굽어진 정도)

$$\therefore \phi_{MS} = \frac{1}{q}(\Phi_M - \Phi_S) = \frac{1}{q}\left(\Phi_M' - \chi' - (E_C - E_F)_{FB}\right)$$

(bulk에서 $(E_C - E_F)$)



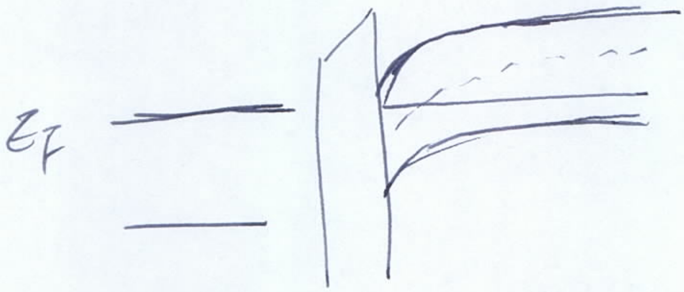
– ΔV_G for the same C or ϕ_s

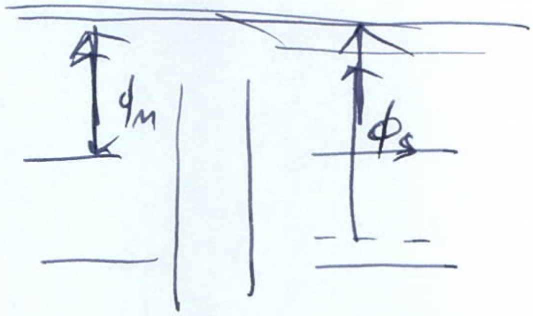
$= \phi_{MS}$

$\phi_{MS} < 0$ ($V_G=0$에서 이미 inversion이 일어났을 수도)

교재 Table 18.1 과 그림 18.3. → mostly $\phi_{MS} < 0$ 함

If Metal = heavily doped polysilicon





$$\phi_{MS} = -E_g/2 - \phi_F$$

$$= -\frac{E_g}{2} - \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right) \approx -900\,mV$$

~560mV ~ 330mV

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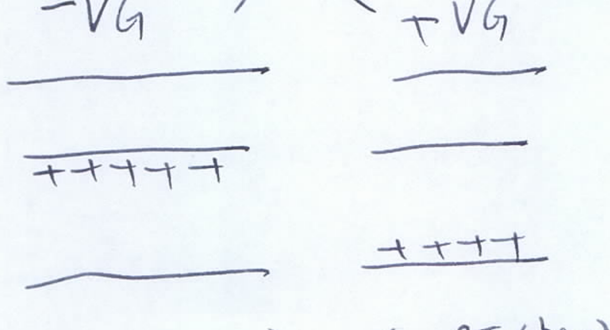
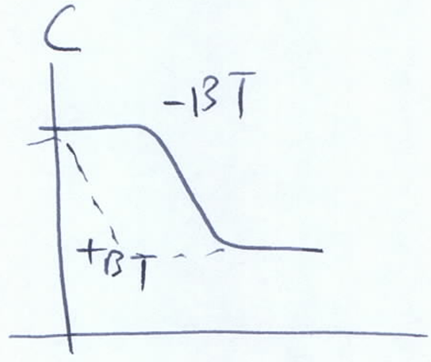
2. Mobile oxide charges

K^+, Na^+ ions – moving around

both at High T





$$\Delta V_T = -\frac{1}{K_o\epsilon_0}\int_0^{x_0} x\,\rho_{ox}(x)\,dx$$

p 651 & 652

부분적분 이용

부분적분

$$\int f'(x)\, g(x)\, dx = \int \left(f(x)\, g(x)\right)' dx - \int f(x)\, g'(x)\, dx$$

$$= f(x)\, g(x) - \int f(x)\, g'(x)\, dx$$

$$\int_0^{x_0} \int_x^{x_0} \rho_{ox}(x')\, dx'\, dx$$

(18.6 으로부터) (x=0 일때)

$$\left[\varepsilon_{ox}(0) - \varepsilon_{ox}(x_0)\right] k_0 \cdot \epsilon_0$$

$k_0 \epsilon_0 \varepsilon_{ox}$

$\varepsilon_{ox}(x_0)$?

$$\int_x^{x_0} \rho_{ox}(x')\, dx' = g(x)$$

$x = f(x)$

$-\rho_{ox}(x) = g'(x)$

$$x \left[\int_0^{x_0} \rho_{ox}(x')\, dx'\right] + \int_0^{x_0} (x \cdot \rho_{ox})\, dx$$

$$= \int_0^{x_0} x \rho\, dx$$

$$x\left(\varepsilon_{ox}^{(0)} - \varepsilon_{ox}(x_0)\right) k_0 \epsilon_0 + \int_0^{x_0} x \rho\, dx$$

$$\therefore\ \Delta\phi_{ox} = x_0\, \varepsilon_{ox}(x_0) - \frac{1}{k_0 \epsilon_0}\left[x\left(\varepsilon_{ox} - \varepsilon_{ox}(x_0)\right) k_0 \epsilon_0 + \int_0^{x_0} x \rho\, dx\right]$$

$$= \int_0^{x_0} x \rho\, dx$$

위는 극단적인 두경우 ($^{+}$charge 가 Top 고 Bottom이었으니까) 에 대해서 Delta Function을 이용하여 표시하였다
(annotations above: Top → $-BT$, Bottom → $+BT$)

$$\Delta V_G \begin{pmatrix} \text{Mobile ions} \\ \text{after } +BT \end{pmatrix} = -\frac{1}{K_0 \epsilon_0} \int_0^{x_0} x \, Q_M \, \delta(x_0) \, dx$$

$$= -\frac{x_0}{K_0 \epsilon_0} Q_M = -\frac{Q_M}{C_0}$$

$$\Delta V_G (-BT) = -\frac{1}{K_0 \epsilon_0} \int_0^{x_0} x \, Q_M \, \delta(0) \, dx = 0.$$

절대치 $\sim -10\text{V}$

$Q_M \sim 2\times10^{12}\ \text{cm}^{-2} \times q$

1.6×10^{-19}

$\frac{3.9\times\epsilon_0}{10^{-5}}$ (3.45×10^{-14})

$C_0 = ~~690\text{nF}~~/\text{cm}^2$ for ~~SiO2~~ oxide $0.1\,\mu\text{m}$ thick

$$\frac{~~2\times10^{12}\times1.6\times10^{-19}~~}{~~690\times10^{-9}~~}$$

$= ~~\frac{3.2}{690}\times10^{2}~~$

$=$

Solution: phosphorus Gettering.

Use PSG → this binds Mobile ions
thin layer of PSG at top.
Not to move around;
under control!

3. ~~Fixed oxide charge~~

~~Nature:~~

3 Fixed oxide charge

associated w/ structure at Si-SiO2 interface

111 > 110 > 110

~10^{10} cm^{-2}

$$\Delta V_T = -\frac{Q_f}{C_{ox}} = -q\frac{N_f}{C_{ox}}$$

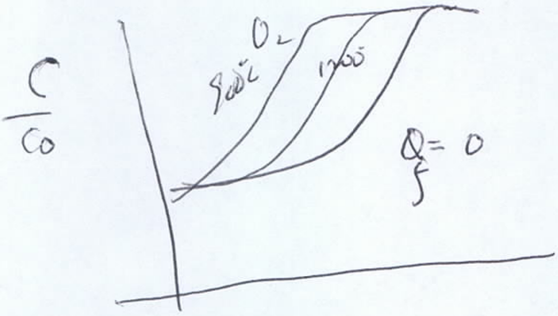
$50\,\text{Å}$, $C_{ox} = 690\,\text{nF/cm}^2$

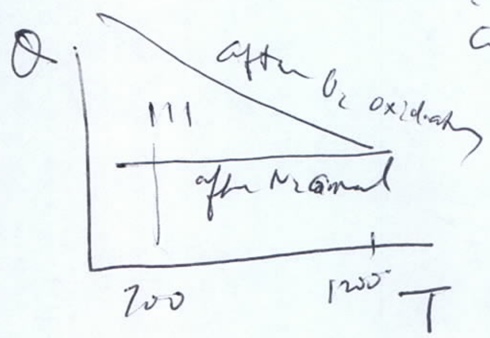
$\Delta V_T \doteq 2.5\,\text{mV}$

↑ maybe due to oxidizing reaction at the Si-SiO2 interface

due to excess ionic silicon broken away from the silicon lattice, and is waiting to react in the vicinity of Si-SiO2 interface when the oxidation process is abruptly terminated

solution. N_2 anneal at High Temp. → removes excess reaction components, SiOx, x<2, Si



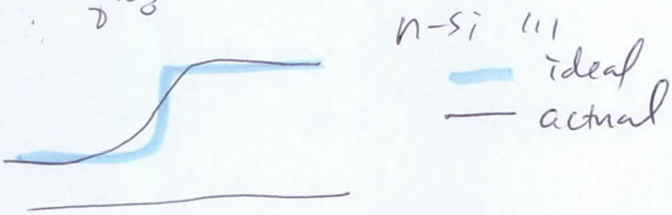


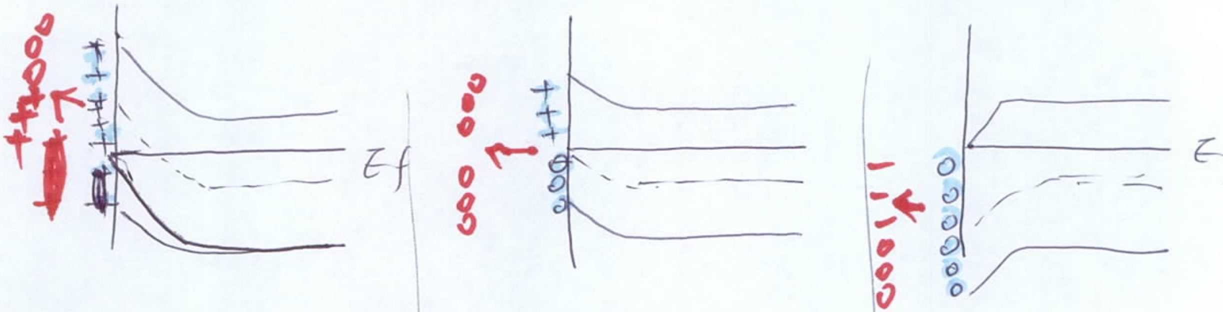
4. Interface Trapped charge

origin ~ dangling bond at Si-SiO2 interface

act like recomb. centers (distributed throughout bandgap)

fn of VG





Inversion — depletion — Accumulation

VG<0 — VG>0

state 들이 (filled 0 charge / Empty + charge)

① Donor-like 라고 가정하면

⇒ 많은 VG 변화 — 약간의 변화 — 변화가 없어야 함

⟶ 이는 실제 Data 와 맞지 않음

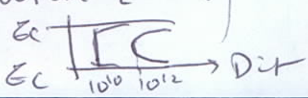
② Modify Model

Ei 아래는 Donor-like

Ei 위는 Acceptor-like (filled − charge / Empty 0 charge) → 실제 Acceptor 와는 다른 것임! Model 이므로 Data 에 맞으면 됨.

⇒ 약간의 VG 변화 (−) 방향 — 별 변화 없음 — 약간의 (+) 방향 변화

위 Data 를 설명하면 | Solution 은 H_2 anneal (passivation)



overall

~~ΔV~~

$$V_T = V_{FB} + \sout{2\phi_F + \phi_s}\ V_T'$$

$V_{FB} = \phi_{ms} - \frac{Q_{tot}}{C_{ox}}$ ← all oxide charges

where $V_T' = 2\phi_F + \Delta\phi_{ox}$

$\Delta\phi_{ox} = \frac{K_s x_o}{K_o}\sqrt{\frac{4qN_A}{K_s\epsilon_0}\phi_F}$ for n-ch,

$-\frac{K_s x_o}{K_o}\sqrt{\frac{4qN_D}{K_s\epsilon_0}(-\phi_F)}$ for p-ch

---

Back Biasy

$V_{BS} < 0$ This makes it harder to ~~in~~ reach inversion by $(-V_{BS})$

So now $2\phi_F$ is replaced by $(2\phi_F - V_{BS})$

V_T adjust by Implatum

Boron implatation ~~Q~~ charge introduced Q_I

then $\Delta V_G = -\frac{Q_I}{C_o}$ (Donor는 반대)

12/7 Ch18 Non ideal MOS 마무리 정리.
+ Ch19 Modern FET

~~[illegible]~~

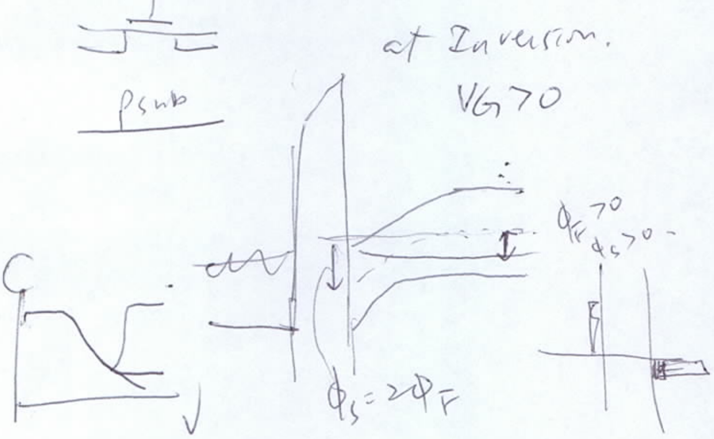
12/9 마무리 Lecture + Q/A.

12/14 반도체 Fab Tour

12/16 시험.

Review

NMOS (on p-Si sub)



$V_T = V_{FB} + V_T'$

$V_{FB} = \phi_{MS} - \dfrac{Q_{tot}}{C_{ox}}$ (−)

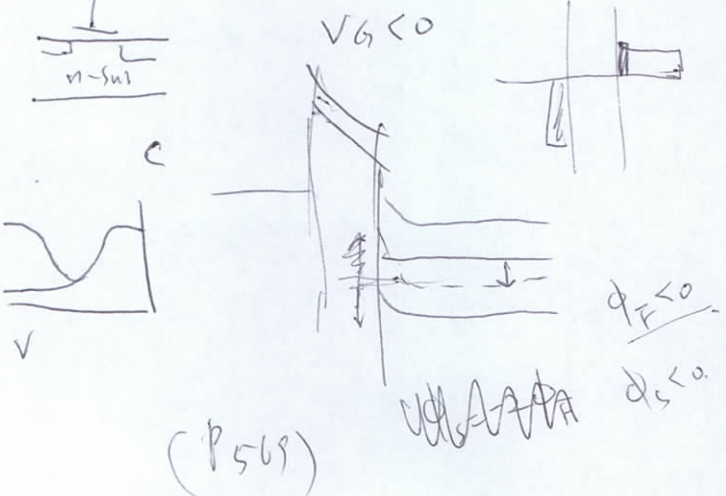
Q_{tot}: Fixed charge, mobile charge, interface trap charge

$V_T' = 2\phi_F + \Delta\phi_x$

(+) $\dfrac{K_S x_0}{K_0}\sqrt{\dfrac{4qN_A}{K_S\epsilon_0}\phi_F}$

$\phi_F = \dfrac{kT}{q}\ln(N_A/n_i)$

PMOS (on n-Si sub)



(P569)

$V_T = V_{FB} + V_T'$

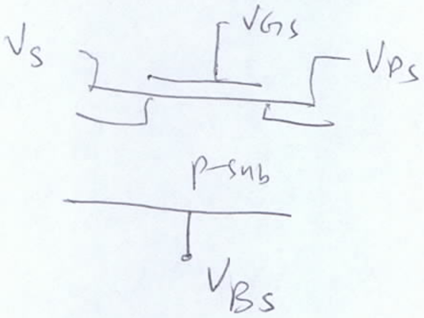
$V_{FB} = \phi_{MS} - \dfrac{Q_{tot}}{C_{ox}}$

(ϕ_{MS}: negative but less negative than in p-sub. P649)

$V_T' = 2\phi_F - \dfrac{K_S x_0}{K_0}\sqrt{\dfrac{4qN_D}{K_S\epsilon_0}(-\phi_F)}$ (−)

$\phi_F = -\dfrac{kT}{q}\ln\left(\dfrac{N_D}{n_i}\right)$

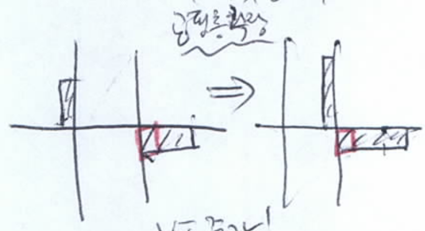
Back Biasing



NMOS

$V_{BS} < 0$

|VB| 증가하기 때문에 공핍층 확장



V_T 증가!

This makes it harder to reach inversion by $(-V_{BS})$

Also depletion region widens.

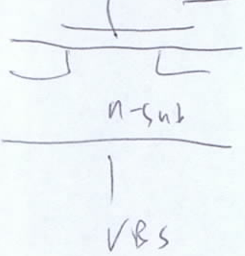
So now $2\phi_F$ is replaced by $(2\phi_F - V_{BS})$ — becomes more positive.

So $V_T = V_{FB} + V_T'$

$$V_{FB} = \phi_{MS} - \frac{Q_{tot}}{C_{ox}}$$

$$V'_{T(nMOS)} = (2\phi_F - V_{BS}) + \frac{K_S x_o}{K_o}\sqrt{\frac{2qN_A}{K_S\epsilon_0}(2\phi_F - V_{BS})}$$

PMOS



$V_{BS} > 0$

replaced by $(2\phi_F - V_{BS})$, becomes more negative

$$V_{FB} = \phi_{MS} - \frac{Q_{tot}}{C_{ox}}$$

$$V'_{T(pMOS)} = (2\phi_F - V_{BS}) - \frac{K_S x_o}{K_o}\sqrt{\frac{2qN_D}{K_S\epsilon_0}(-2\phi_F + V_{BS})}$$

V_T adjustment by I^2

Boron (holes) into NMOS

Positive charge introduced Q_I

$$\Delta V_T = -\frac{Q_I}{C_o}$$