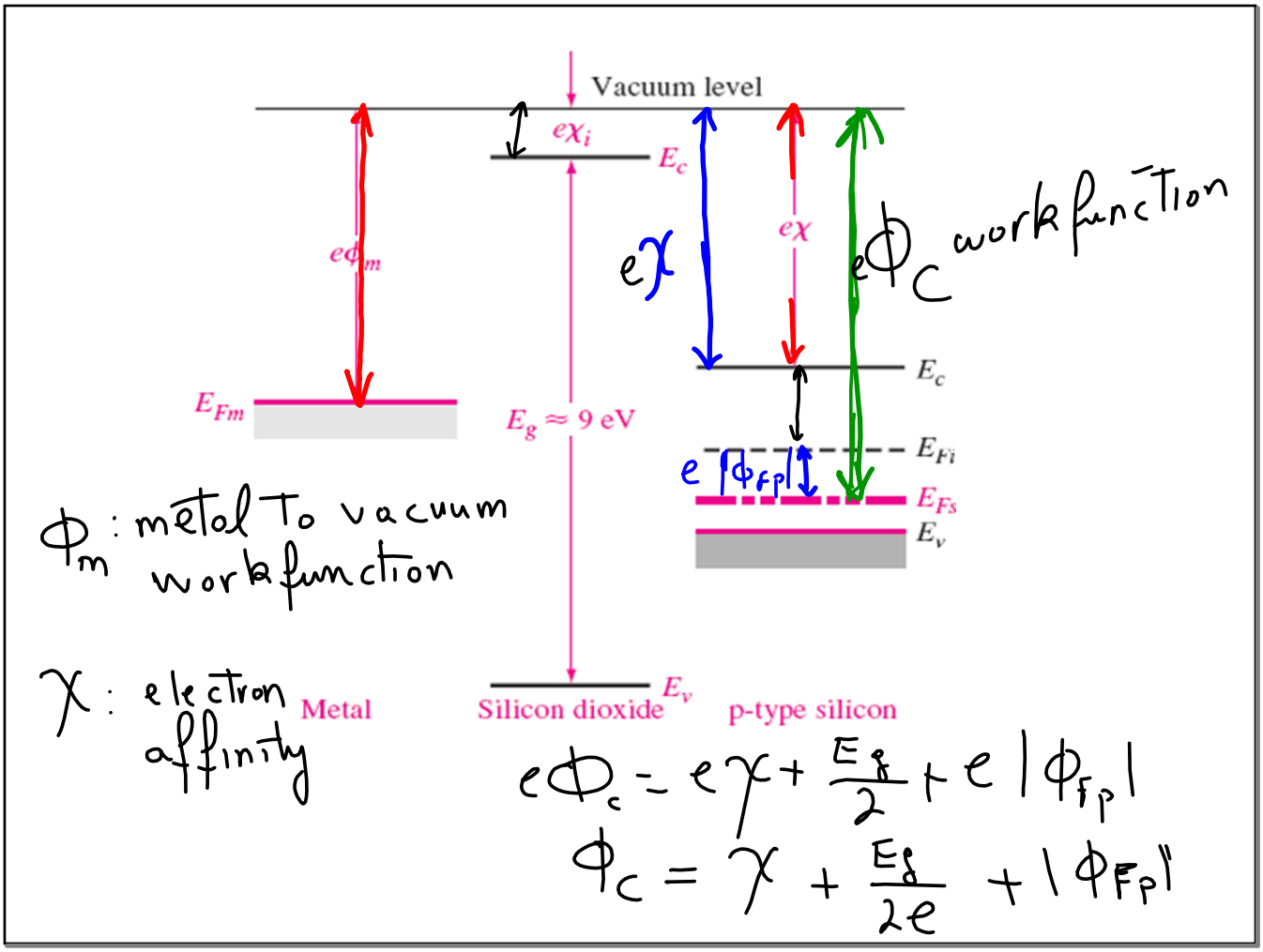

Vacuum level
$e\chi_i$
E_c
$e\phi_m$
E_{Fm}
$E_g \approx 9$ eV
E_v
Metal
Silicon dioxide
p-type silicon
$e\chi$
$e\chi$
$e\phi_c$ work function
E_c
E_{Fi}
$e|\phi_{Fp}|$
E_{Fs}
E_v
ϕ_m : metal To vacuum workfunction
χ : electron affinity
$e\phi_c = e\chi + \frac{E_g}{2} + e|\phi_{Fp}|$
$\phi_c = \chi + \frac{E_g}{2e} + |\phi_{Fp}|$

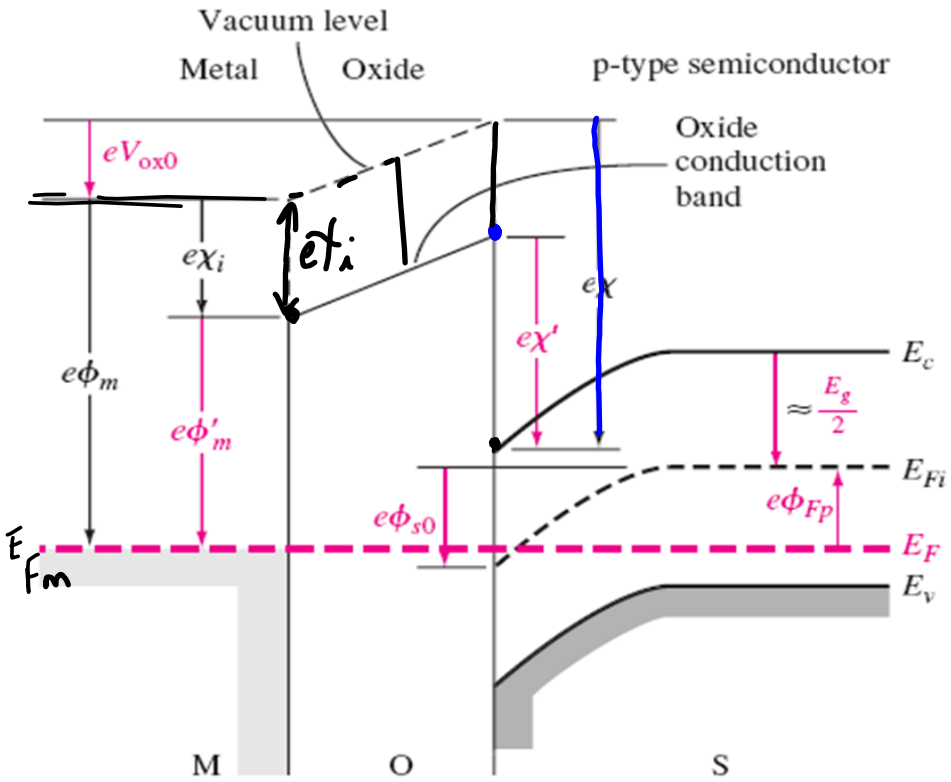
Φ_{ms} : workfunction difference

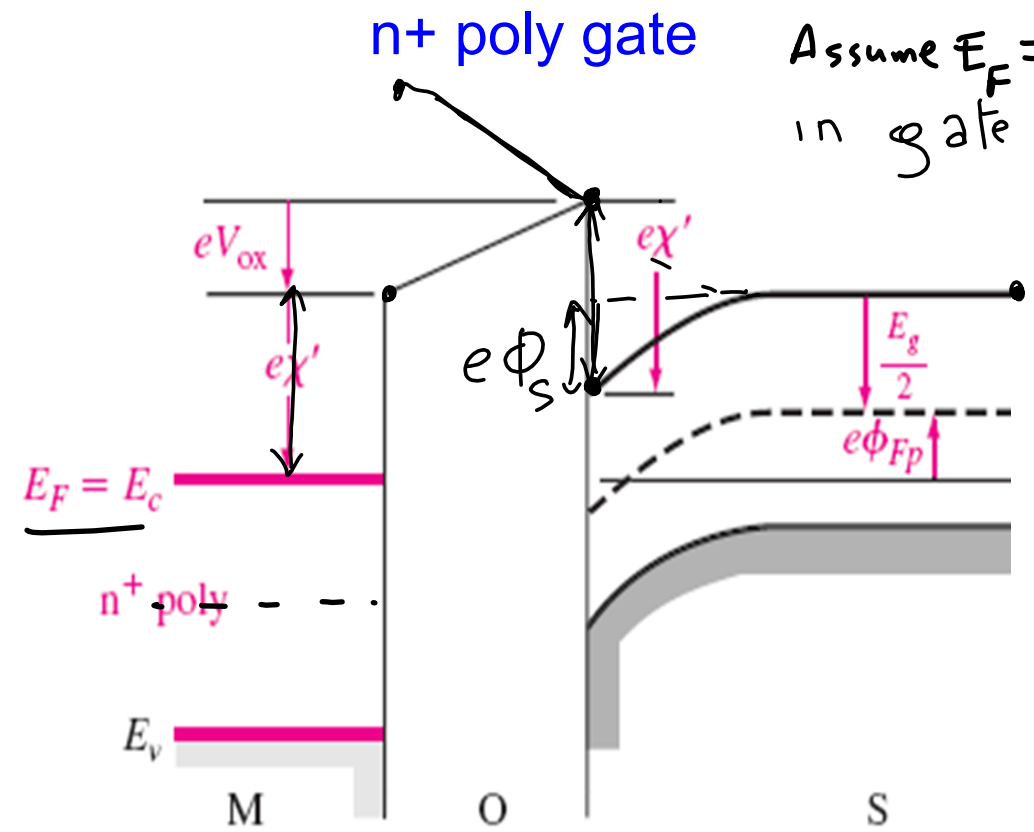
$$\Phi_{ms} = \Phi_m - \Phi_c$$

$$\Phi_{ms} = \Phi_m - \left(\chi + \frac{E_g}{2e} + |\phi_{Fp}|\right)$$

$$\Phi_{ms} = \Phi_m - \chi_i - \left(\chi - \chi_i + \frac{E_g}{2e} + |\phi_{Fp}|\right)$$

$$\Phi_{ms} = \Phi_m' - \left(\chi' + \frac{E_g}{2e} + |\Phi_{Fp}|\right)$$

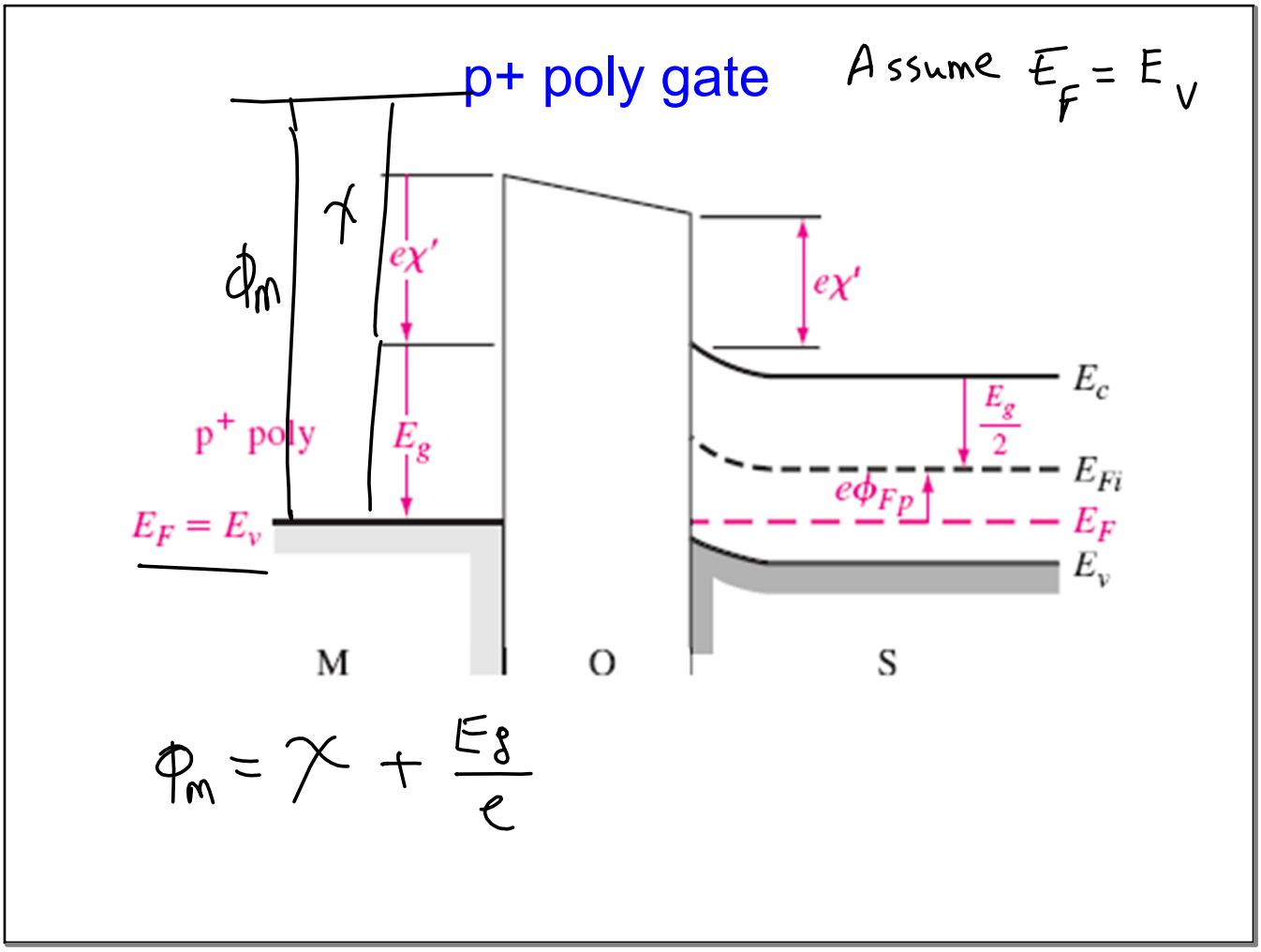

Vacuum level
Metal
Oxide
p-type semiconductor
Oxide conduction band
eV_{ox0}
$e\chi_i$
$e\phi_m$
$e\phi'_m$
$e\chi'$
$e\chi$
E_c
$\approx \frac{E_g}{2}$
E_{Fi}
$e\phi_{Fp}$
$e\phi_{s0}$
E_F
E_v
E_{Fm}
M
O
S



since $E_F = E_c \Rightarrow \phi_m = \chi$

$$\phi_{ms} = \cancel{\phi_m} - \left(\cancel{\chi} + \frac{E_g}{2e} + |\phi_{Fp}|\right)$$

$$\boxed{\phi_{ms} = -\left(\frac{E_g}{2e} + |\phi_{Fp}|\right)}$$


p+ poly gate
Assume $E_F = E_V$
ϕ_m
χ
$e\chi'$
$e\chi'$
E_c
$\frac{E_g}{2}$
E_{Fi}
$e\phi_{Fp}$
E_F
E_v
p+ poly
E_g
$E_F = E_v$
M
O
S
$\phi_m = \chi + \frac{E_g}{e}$

$$\Phi_{ms} = \Phi_m - \left(\chi + \frac{E_g}{2e} + |\phi_{Fp}|\right)$$

$$\Phi_{ms} = \chi + \frac{E_g}{e} - \left(\chi + \frac{E_g}{2e} + |\phi_{Fp}|\right)$$

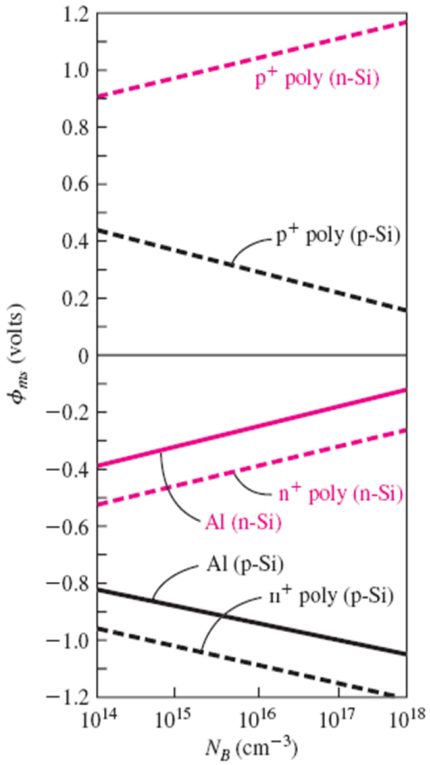
$$\Phi_{ms} = \frac{E_g}{2e} - |\phi_{Fp}|$$

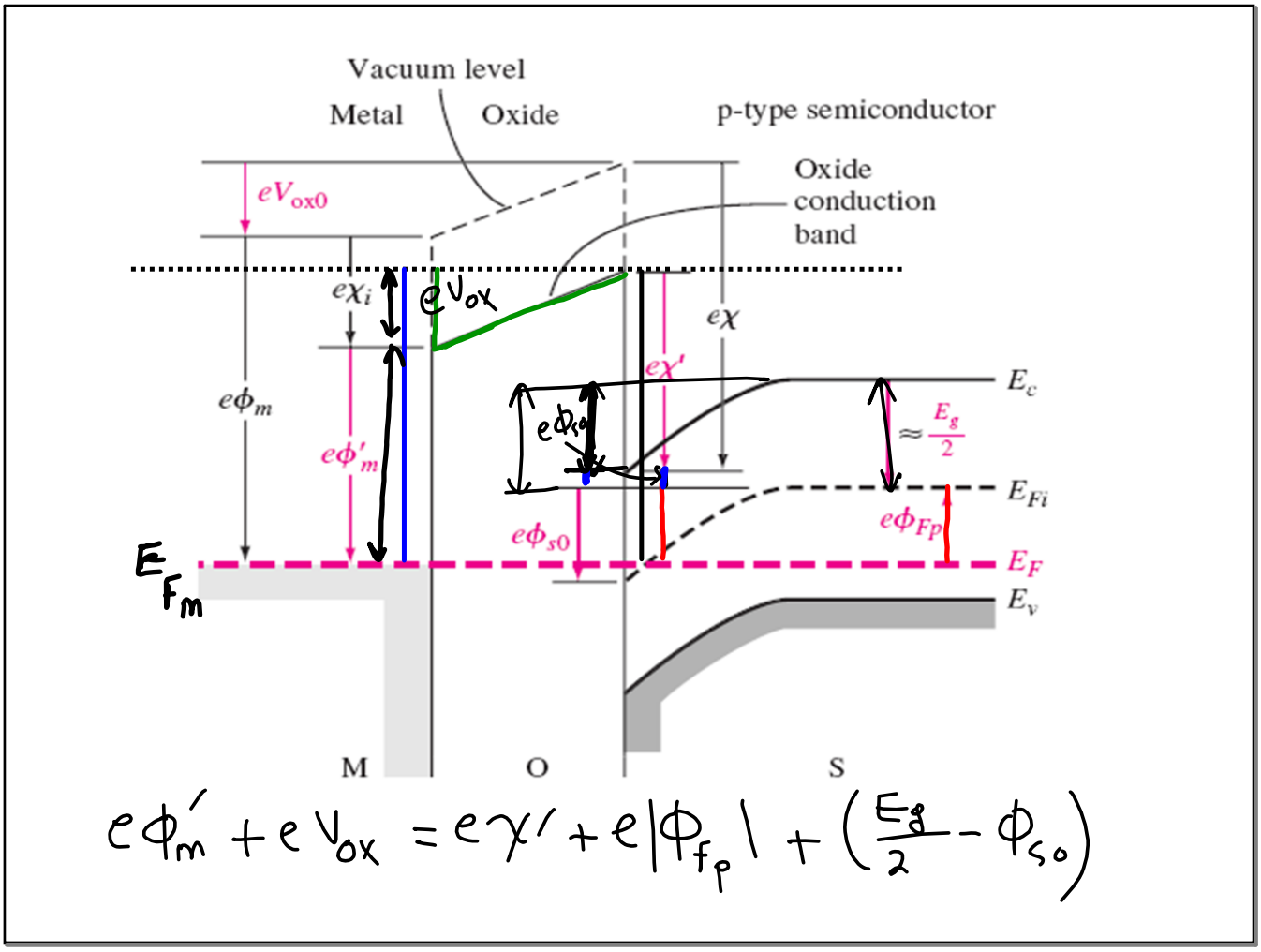
p^+ poly

p-type Silicon	n-type Silicon
Aluminum gate:	Aluminum gate:
$\phi_{ms} = \left[\phi'_m - \left(\chi' + \frac{E_g}{2e} + \lvert\phi_{Fp}\rvert\right)\right]$	$\phi_{ms} = \left[\phi'_m - \left(\chi' + \frac{E_g}{2e} - \phi_{Fn}\right)\right]$
n^+ polysilicon gate:	n^+ polysilicon gate:
$\phi_{ms} = -\left(\frac{E_g}{2e} + \lvert\phi_{Fp}\rvert\right)$	$\phi_{ms} = -\left(\frac{E_g}{2e} - \phi_{Fn}\right)$
p^+ polysilicon gate:	p^+ polysilicon gate
$\phi_{ms} = \left(\frac{E_g}{2e} - \lvert\phi_{Fp}\rvert\right)$	$\phi_{ms} = \left(\frac{E_g}{2e} + \phi_{Fn}\right)$

since φ_{Fp} is negative, $\left|\varphi_{Fp}\right| = -\varphi_{Fp} \Rightarrow$

Same expressions for n-type and p-type with the substitution of φ_{Fp} by φ_{Fn}


1.2
1.0
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
ϕ_{ms} (volts)
p^+ poly (n-Si)
p^+ poly (p-Si)
n^+ poly (n-Si)
Al (n-Si)
Al (p-Si)
n^+ poly (p-Si)
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
N_B (cm^{-3})



$$e\phi'_m + eV_{ox} = e\chi' + e|\phi_{fp}| + \left(\frac{E_g}{2} - \phi_{s0}\right)$$

$$e\phi_m' + eV_{oxo} = e\chi' + e|\phi_{fp}| + \left(\frac{E_g}{2} - e\phi_{so}\right)$$

$$\phi_m' + V_{oxo} = \chi' + |\phi_{Fp}| + \frac{E_g}{2e} - \phi_{so}$$

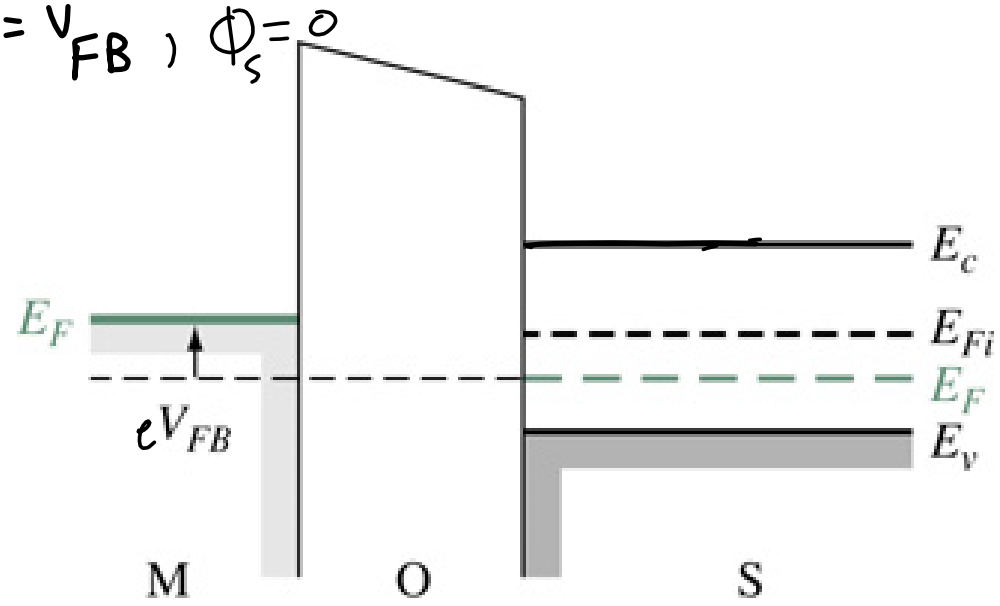
$$V_{oxo} + \phi_{so} = -\phi_m' + \chi' + |\phi_{Fp}| + \frac{E_g}{2e}$$

$$V_{oxo} + \phi_{so} = -\underbrace{\left[\phi_m' - \chi' - |\phi_{Fp}| - \frac{E_g}{2e}\right]}_{\phi_{ms}}$$

$$\boxed{V_{oxo} + \phi_{so} = -\phi_{ms}}$$

Flat Band Voltage V_{FB}

$V_G = V_{FB}$, $\phi_s = 0$



$$V_G = \Delta V_{ox} + \Delta \phi_s$$

$$V_G = (V_{ox} - V_{oxo}) + (\phi_s - \phi_{so})$$

$$V_G = V_{ox} + \phi_s - (V_{oxo} + \phi_{so})$$

ϕ_{ms}

$$\boxed{V_G = V_{ox} + \phi_s + \phi_{ms}}$$

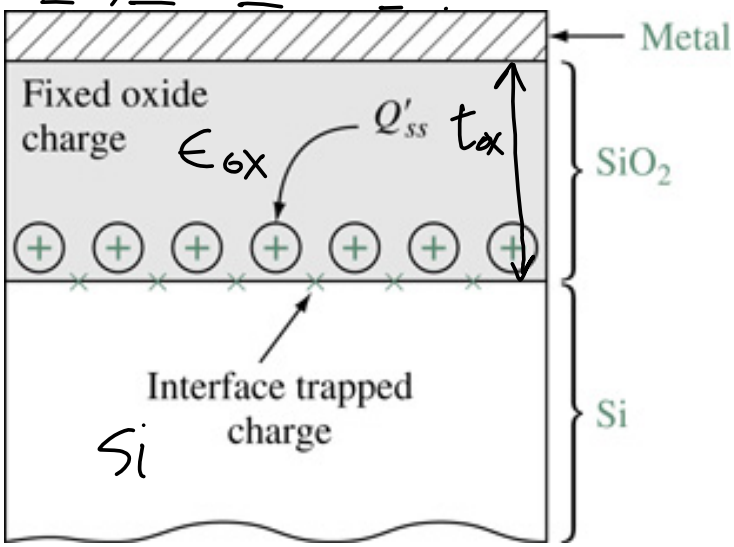
Oxide charge

Q'_{ss}: fixed oxide charge $\frac{coul}{cm^2}$

$-Q'_{ss} = C_{ox} V_{ox}$

$V_{ox} = -\frac{Q'_{ss}}{C_{ox}}$

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



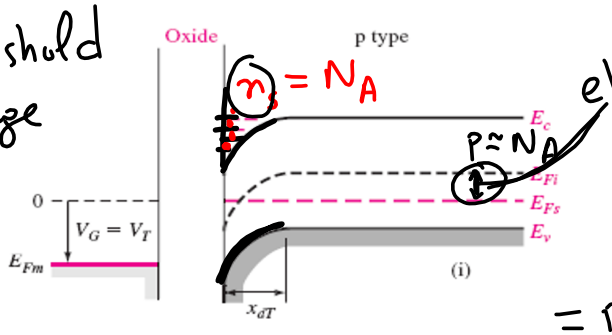
At flat band, $V_G \equiv V_{FB}$, $\phi_s = 0$

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

$$V_{FB} = -\frac{Q'_{ss}}{C_{ox}} + \phi_{ms}$$

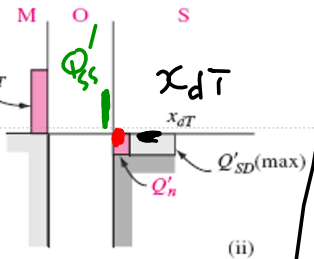
$V_G = V_T$: threshold voltage

$\phi_s = 2|\phi_{Fp}|$



$\frac{E_{Fs} - E_{Fi}}{kT} = n_i e = N_A$

$\phi_{SD}(max) = -e N_A x_{dT}$



$\phi_s = 2|\phi_{Fp}|$ ---(1)

$V_G = V_T$: Threshold voltage

At threshold voltage, the electron density at the surface is equal to the hole density in the bulk region.

$\phi'_{mT} + \phi'_{ss} \simeq |\phi'_{SD}(max)| + |\phi'_n| \Rightarrow \phi'_{mT} \simeq |\phi'_{SD}(max)| - \phi'_{ss}$

$$V_{ox} = \frac{Q'_{mT}}{C_{ox}} = \frac{|Q'_{SD(max)}| - Q'_{ss}}{C_{ox}}$$

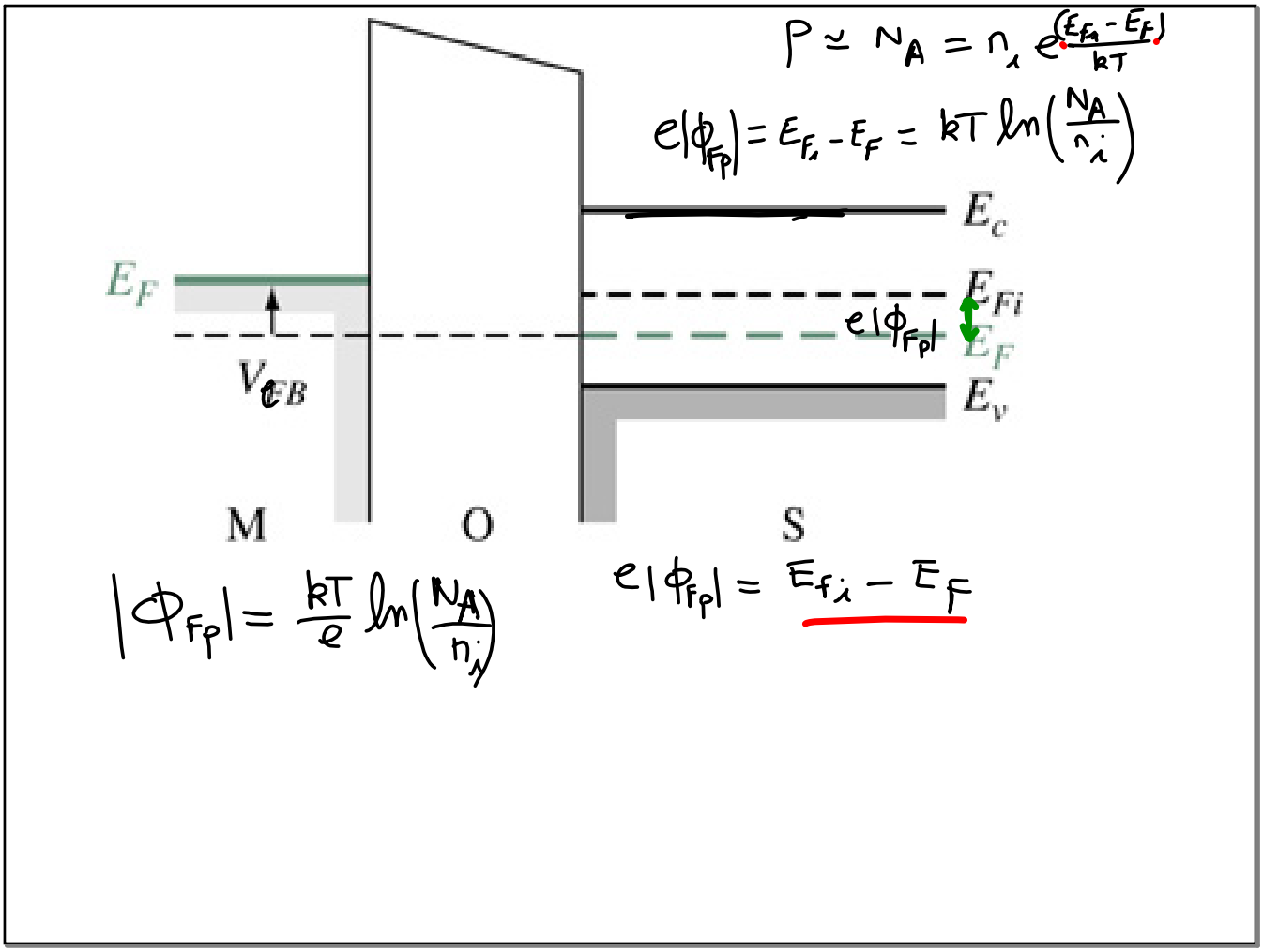
* $V_G = V_{ox} + \Phi_{ms} + \Phi_s$

At threshold, $V_G \equiv V_{TN}$, Φ_s

$$V_{TN} = \frac{|Q'_{SD(max)}| - Q'_{ss}}{C_{ox}} + \Phi_{ms} + 2|\Phi_{Fp}|$$

$$V_{TN} = \frac{|Q'_{SD(max)}|}{C_{ox}} + 2|\Phi_{Fp}| + \underbrace{\Phi_{ms} - \frac{Q'_{ss}}{C_{ox}}}_{V_{FB}}$$

$$V_{TN} = \frac{|\Phi'_{SD(max)}|}{C_{ox}} + V_{FB} + 2|\phi_{Fp}|$$


$p \simeq N_A = n_i e^{\frac{(E_{Fp} - E_F)}{kT}}$
$e|\phi_{Fp}| = E_{Fi} - E_F = kT \ln\left(\frac{N_A}{n_i}\right)$
E_c
E_{Fi}
E_F
E_v
$e|\phi_{Fp}|$
V_{FB}
M
O
S
$|\phi_{Fp}| = \frac{kT}{e} \ln\left(\frac{N_A}{n_i}\right)$
$e|\phi_{Fp}| = E_{Fi} - E_F$