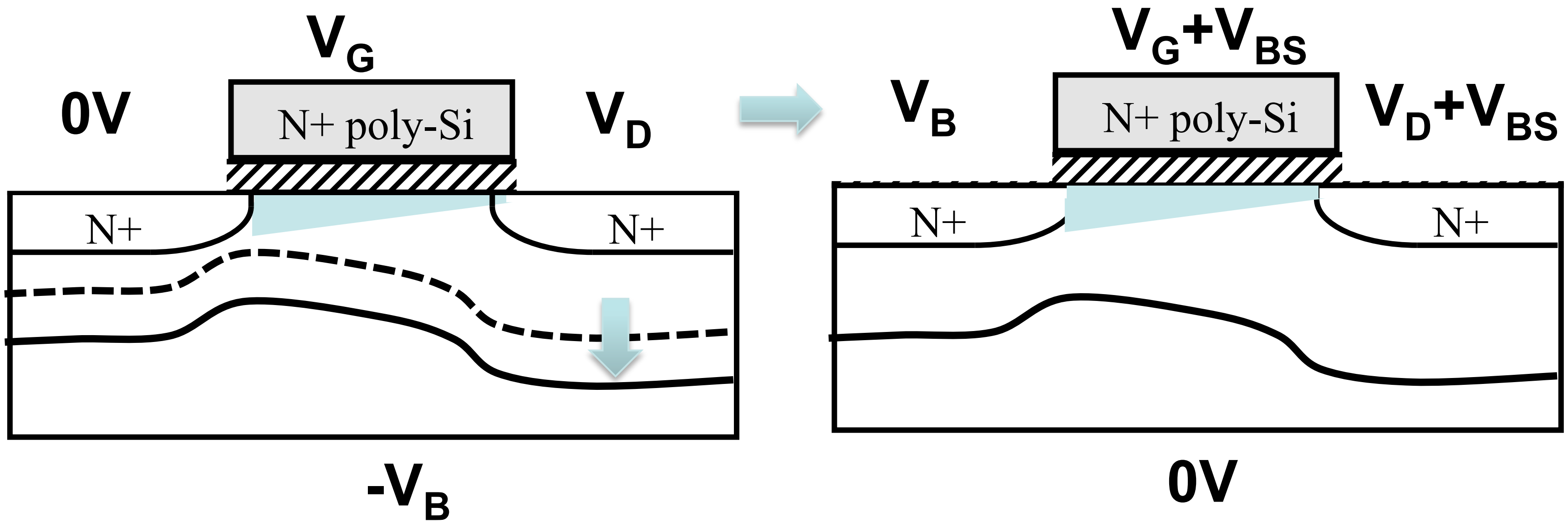
Body Effect (Non-zero Substrate Bias)



$$Q(y) = C_{OX}\left[V_{GS} + V_{BS} - V_{FB} - 2\phi_F - V(y)\right]$$
$$-\sqrt{2q\varepsilon_{si}N_A(2\phi_F + V(y))}$$

Follow the same steps, integrate from V_B (L=0) to V_B+V_D ($L=L_{eff}$)

Body Effect (Non-zero Substrate Bias)

$$I_D = \mu_{eff} C_{OX} \frac{W}{L} * [(V_G - V_{FB} - 2\phi_F - \frac{V_{DS}}{2})V_{DS}$$

$$- \frac{2\sqrt{2\varepsilon_{si} q N_A}}{3C_{OX}} \{(2\phi_F + V_{BS} + V_{DS})^{3/2} - (2\phi_F + V_{BS})^{3/2}\}]$$

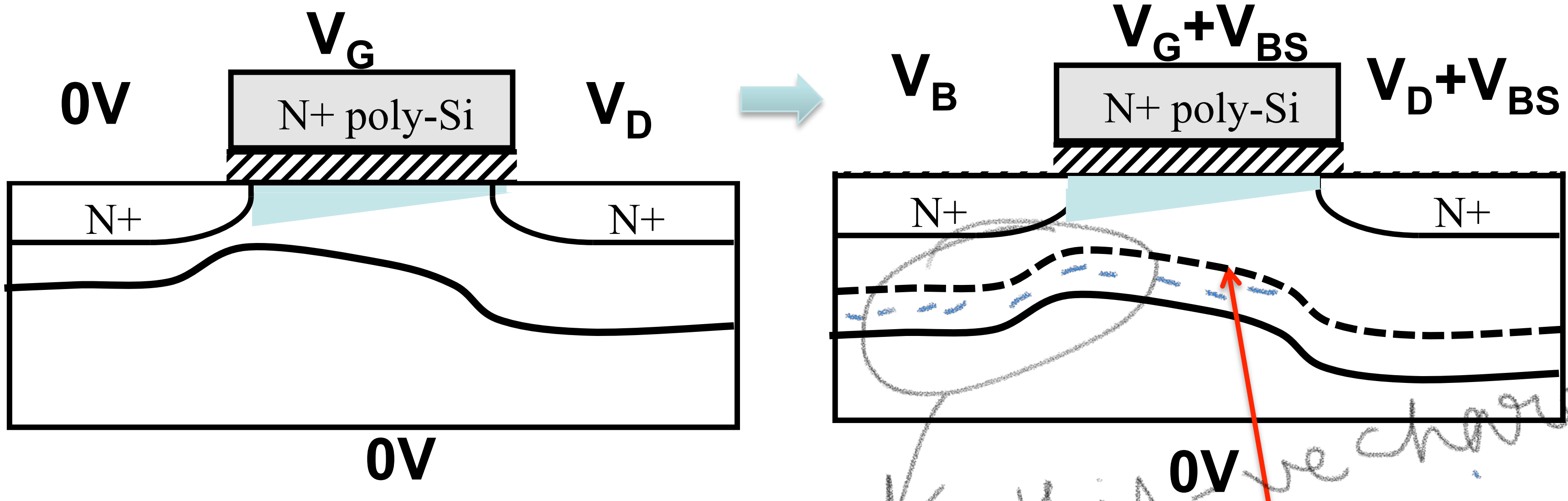
$$I_D = \mu_{eff} C_{OX} \frac{W}{L_{eff}} [V_{GS} - V_T] V_{DS}$$ **For small V_D**

$$V_T = V_{FB} + 2\phi_F + \frac{\sqrt{2\varepsilon_{si} q N_A (2\phi_F + V_{BS})}}{C_{OX}}$$ **Increase in V_T**

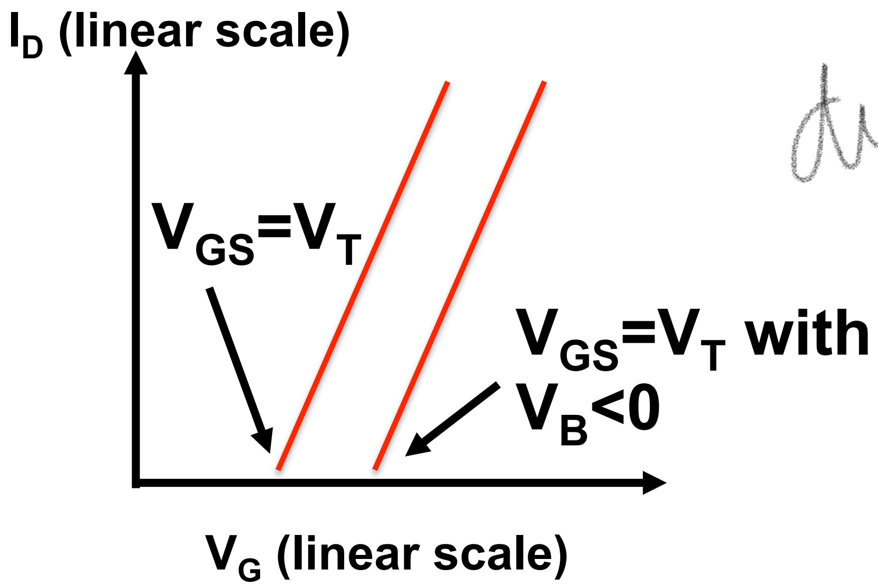
V_{BS} is +ve when -ve voltage is applied.

$$\frac{dV_T}{dV_{BS}} = \frac{\sqrt{\varepsilon_{si} q N_A / 2(2\phi_F + V_{BS})}}{C_{OX}}$$ **Depends on N_A**

Body Effect (Non-zero Substrate Bias)



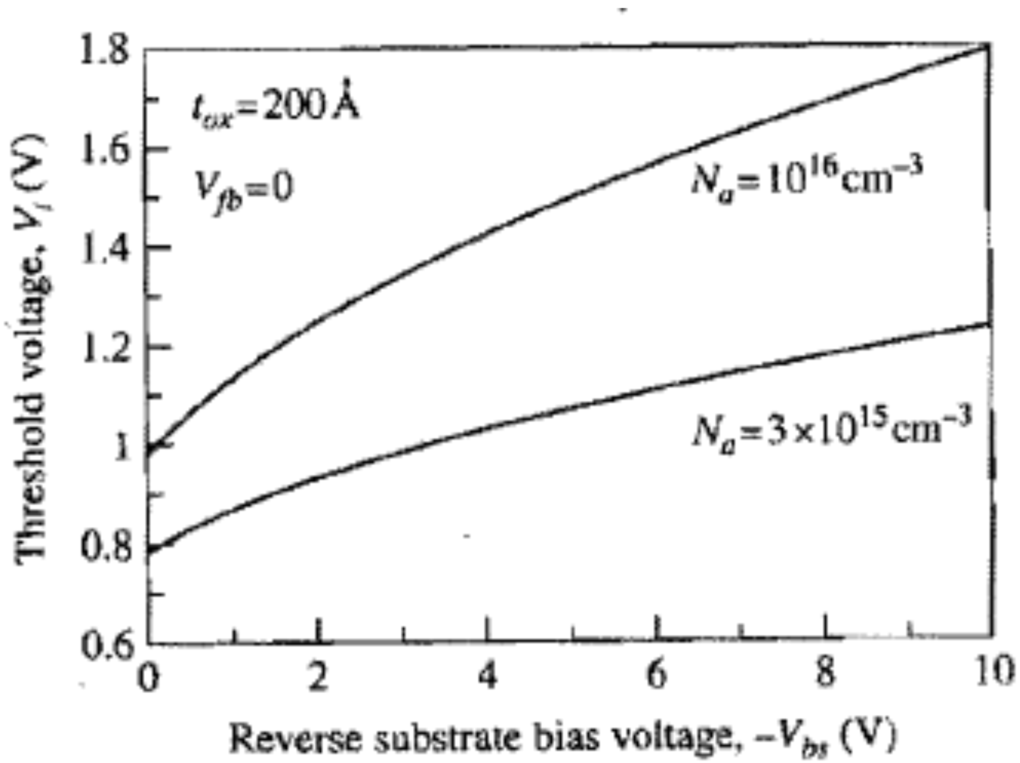
due to this we charge



Support extra depletion charge, need more gate charge → Increase in V_T

Impact of Reverse Body Bias on V_T

Higher sensitivity for higher channel doping



Ref: Taur and Ning

Impact of Temperature on V_T

For small V_D

$$I_D = \mu_{eff} C_{OX} \frac{W}{L_{eff}} \left[V_{GS} - V_T \right] V_{DS}$$

$$V_T = V_{FB} + 2\phi_F + \frac{\sqrt{2\varepsilon_{si} q N_A (2\phi_F)}}{C_{OX}}; \; V_{FB} = -\frac{E_G}{2q} - \phi_F$$

$$V_T = -\frac{E_G}{2q} + \phi_F + \frac{\sqrt{2\varepsilon_{si} q N_A (2\phi_F)}}{C_{OX}}$$

$$\frac{dV_T}{dT} = -\frac{1}{2q}\frac{dE_G}{dT} + \left(1 + \frac{\sqrt{\varepsilon_{si} q N_A / \phi_F}}{C_{OX}}\right)\frac{d\phi_F}{dT}$$

$$\frac{dV_T}{dT} = -\frac{1}{2q}\frac{dE_G}{dT} + (2m-1)\frac{d\phi_F}{dT}; \quad m = 1 + \frac{C_D}{C_{OX}}$$

Impact of Temperature on V_T

$$\phi_F = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right);\ n_i = \sqrt{N_C N_V}\,e^{-E_G/2kT}$$

$$\phi_F = \frac{E_G}{2q} - \frac{kT}{q}\ln\left(\frac{\sqrt{N_C N_V}}{N_A}\right)$$

$$\frac{d\phi_F}{dT} = \frac{1}{2q}\frac{dE_G}{dT} - \frac{k}{q}\ln\left(\frac{\sqrt{N_C N_V}}{N_A}\right) - \frac{kT}{q\sqrt{N_C N_V}}\frac{d\sqrt{N_C N_V}}{dT}$$

$$\frac{d\sqrt{N_C N_V}}{dT} = \frac{3}{2}\frac{\sqrt{N_C N_V}}{T};\ N_{C,V} = 2\left(\frac{2\pi m^* kT}{h^2}\right)^{3/2}$$

Impact of Temperature on V_T

$$\frac{dV_T}{dT} = -\frac{1}{2q}\frac{dE_G}{dT} + (2m-1)\frac{d\phi_F}{dT}$$

$$m = 1 + \frac{C_D}{C_{OX}}; \quad \frac{dE_G}{dT} = -2.7 * 10^{-4}\, eV / K$$

$$\frac{d\phi_F}{dT} = \frac{1}{2q}\frac{dE_G}{dT} - \frac{k}{q}\ln\left(\frac{\sqrt{N_C N_V}}{N_A}\right) - \frac{3}{2}\frac{k}{q}$$

$$\frac{dV_T}{dT} = \frac{m-1}{q}\frac{dE_G}{dT} - (2m-1)\frac{k}{q}\left[\ln\left(\frac{\sqrt{N_C N_V}}{N_A}\right) + \frac{3}{2}\right]$$

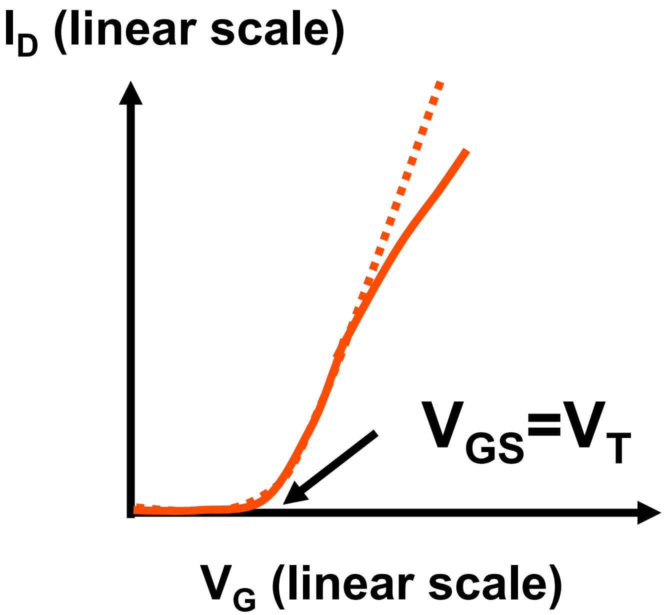
V_T reduces at higher T

Recap: Transfer I-V, Linear Region

Drain current deviates from linearity for high V_{GS} (>V_T)

$$I_D = \mu_{eff} C_{OX} \frac{W}{L_{eff}} \left[V_{GS} - V_T \right] V_{DS}$$

Degradation of mobility at high transverse field, deviation of curve from linear dependence



Low-field mobility

$$\mu_{eff} = \frac{\mu_0}{1+\alpha(V_{GS}-V_T)}$$

$$\mu_{eff} = \frac{\mu_0}{1+\alpha(V_{GS}-V_T)+\beta(V_{GS}-V_T)^2}$$

Effective Mobility

$$\mu_{eff} = \frac{\int_0^{X_I} \mu n(x)\, dx}{\int_0^{X_I} n(x)\, dx}$$

Effective or average mobility in the channel, show universality

Define effective electric field (average transverse electric field), E_{eff} in the channel (Gauss law):

$$E_{eff} = \frac{1}{\varepsilon_{si}}\left(|Q_D| + \frac{1}{2}|Q_{INV}|\right)$$

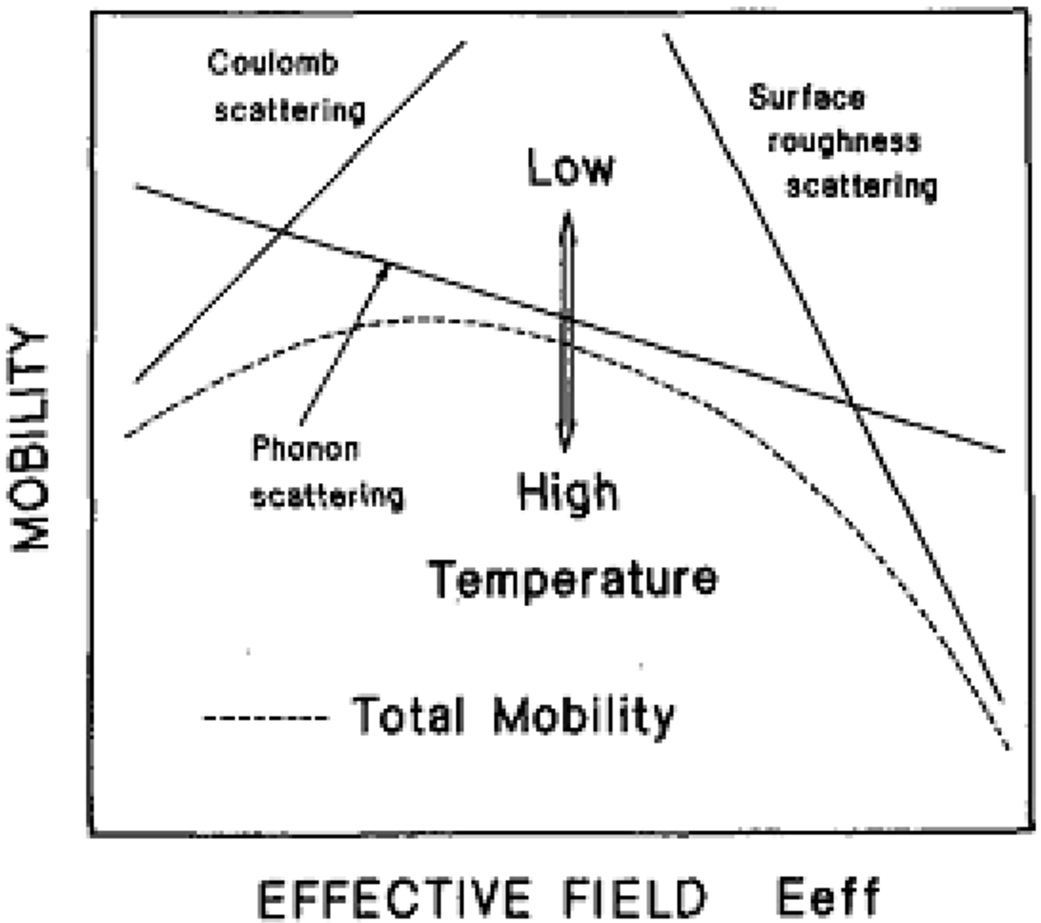
Holds good for NMOS (electrons)

$$E_{eff} = \frac{1}{\varepsilon_{si}}\left(|Q_D| + \frac{1}{3}|Q_{INV}|\right)$$

For PMOS (holes), en empirical form is used

Effective Mobility vs. Effective Field

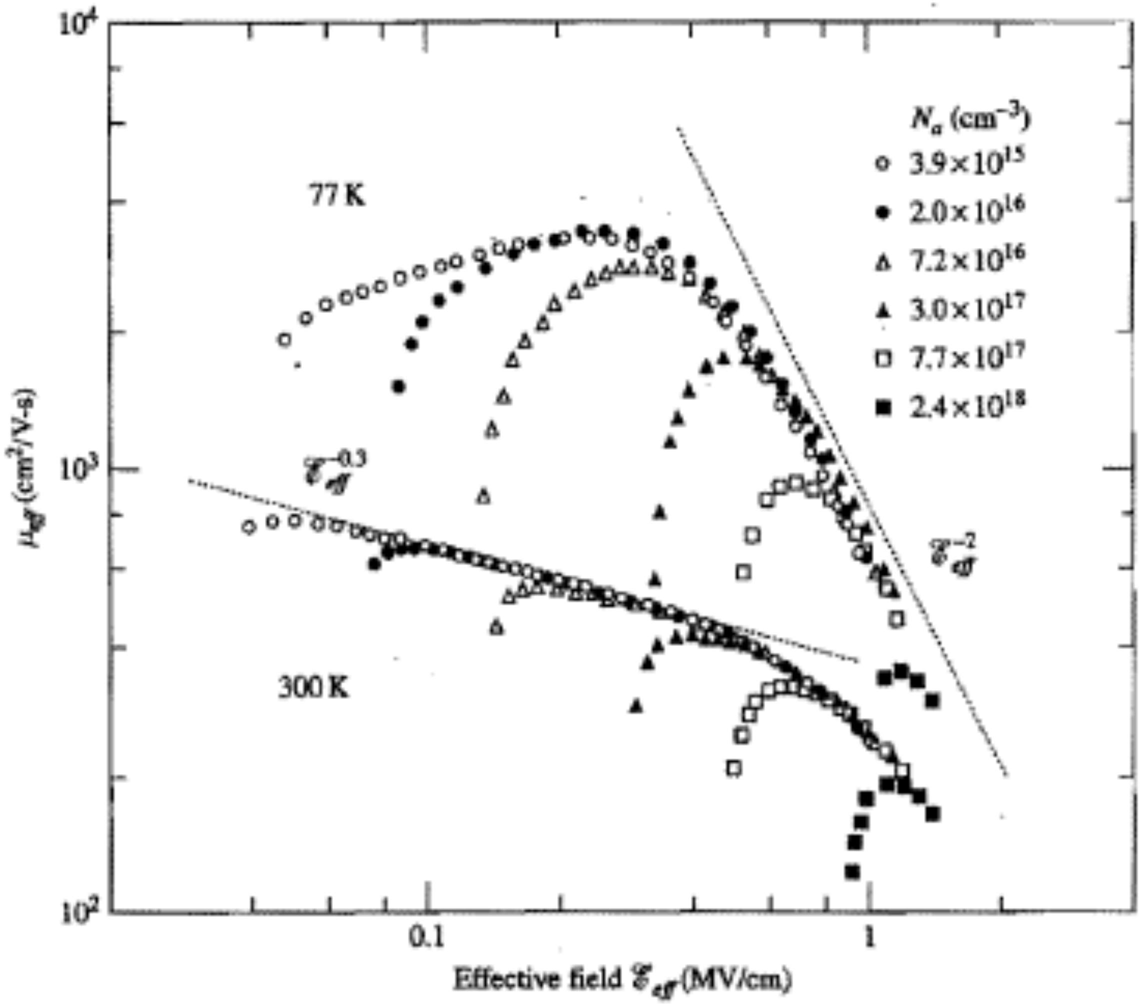
Different mechanisms responsible for mobility



Ref: Taur and Ning

Effective Mobility – Electrons in NMOSFET

For electrons in n-MOSFET



Ref: Taur and Ning

Universal slope, fall off due to Coulomb scattering

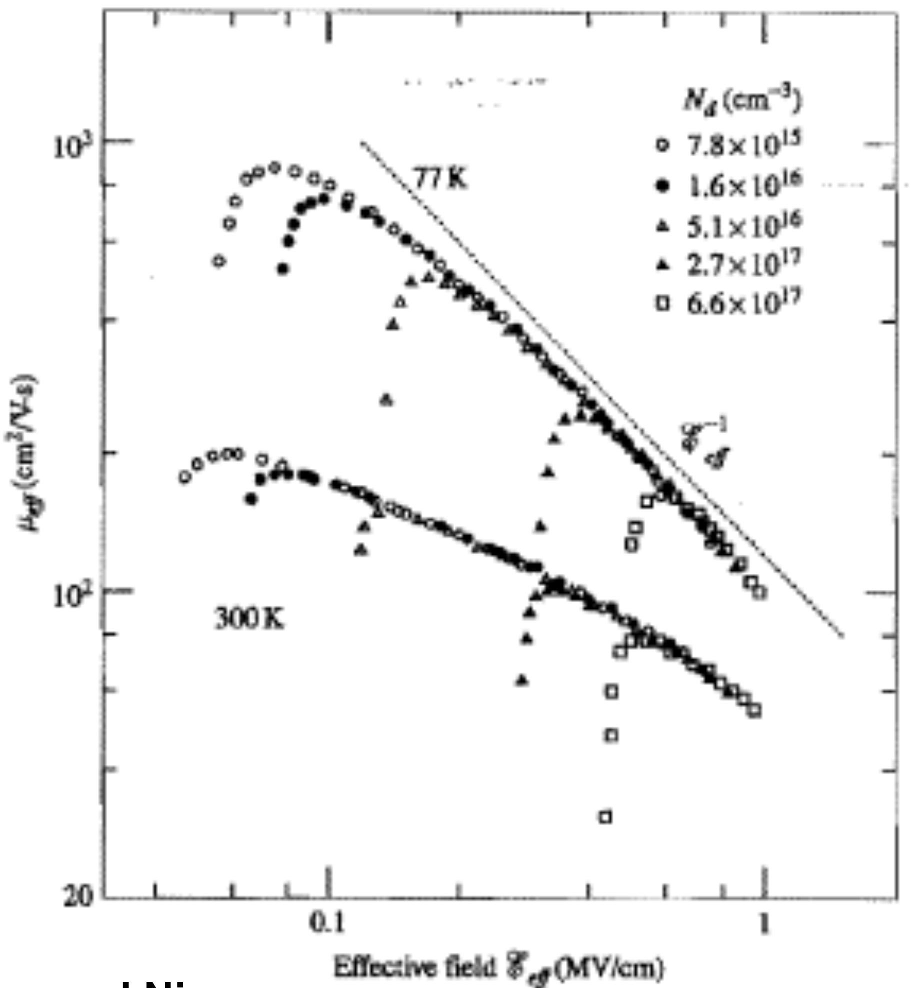
Higher phonon scattering at higher T

Universal empirical relation (different doping)

$$\mu_{eff} = AE_{eff}^{-n}$$

Effective Mobility – Holes in PMOSFET

For holes in p-MOSFET



Ref: Taur and Ning

Universal slope, fall off due to Coulomb scattering

Higher phonon scattering at higher T

Universal empirical relation (different doping)

$$\mu_{eff} = AE_{eff}^{-n}$$

Effective Field (Empirical Formula)

$$E_{eff} = \frac{1}{\varepsilon_{si}}(|Q_D| + \frac{1}{2}|Q_{INV}|)$$

$$|Q_D| = \sqrt{4\varepsilon_{si} q N_A \phi_F} = C_{OX}(V_T - V_{FB} - 2\phi_F)$$

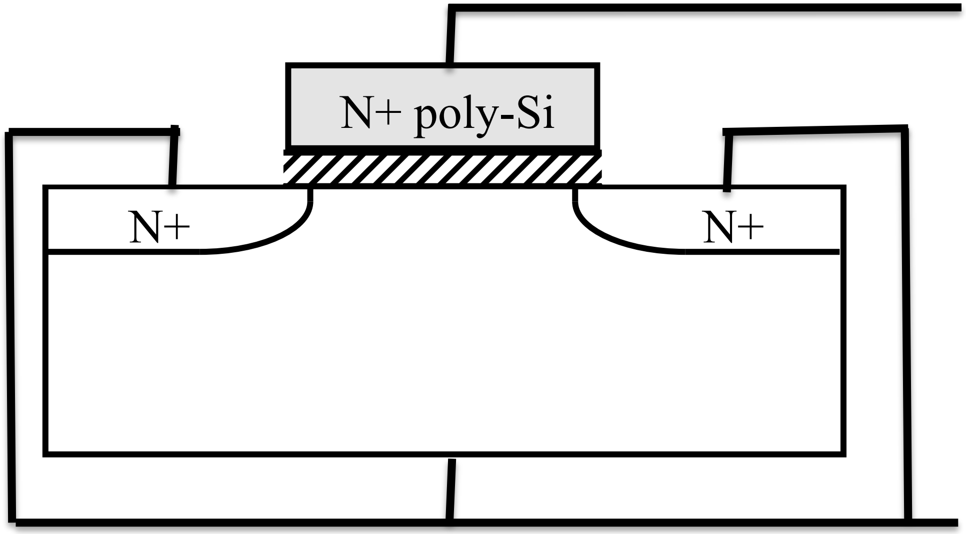
$$|Q_{INV}| = C_{OX}(V_G - V_T)$$

$$E_{eff} = \frac{V_T - V_{FB} - 2\phi_F}{3T_{OX}} + \frac{V_G - V_T}{6T_{OX}}$$

Alternative (better) E_{eff}: Obtain mobile charges by integrating split CV

CV in MOSFET (NMOS)

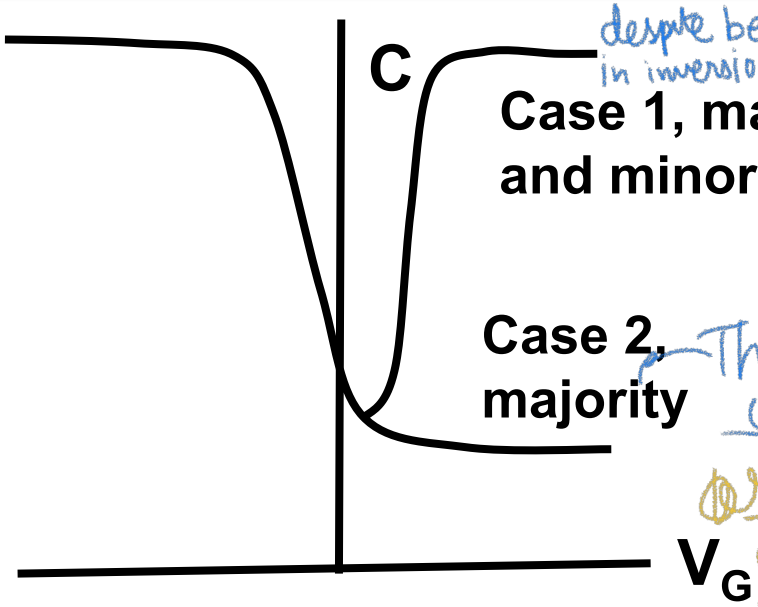
We do high CV measurement



Three combinations:

shorted

1) G and S, D, B
2) G and B
3) G and S, D → shorted

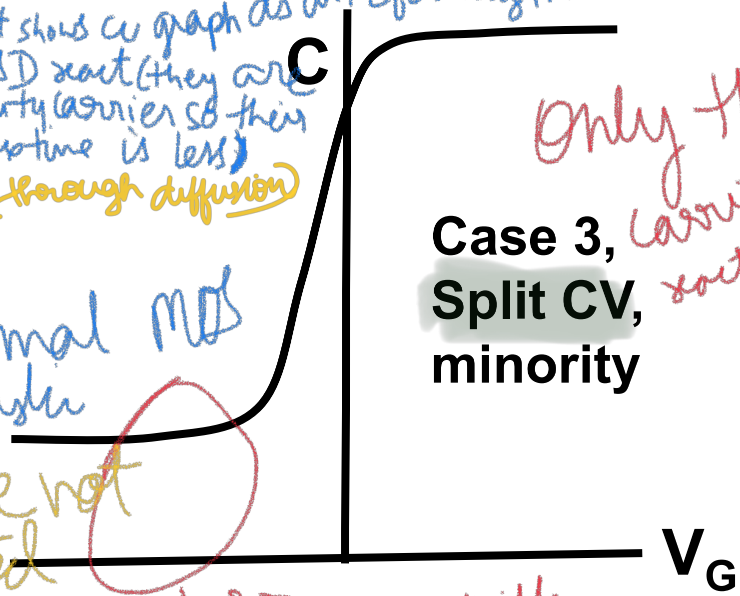


Case 1, majority and minority

despite being hfCV still it shows cv graph as an LfCV being in inversion ē from S & D react (they are majority carrier so their responsetime is less) (through diffusion)

Case 2, majority — This is normal MOS characteristic

as S & D are not connected so won't supply carrier

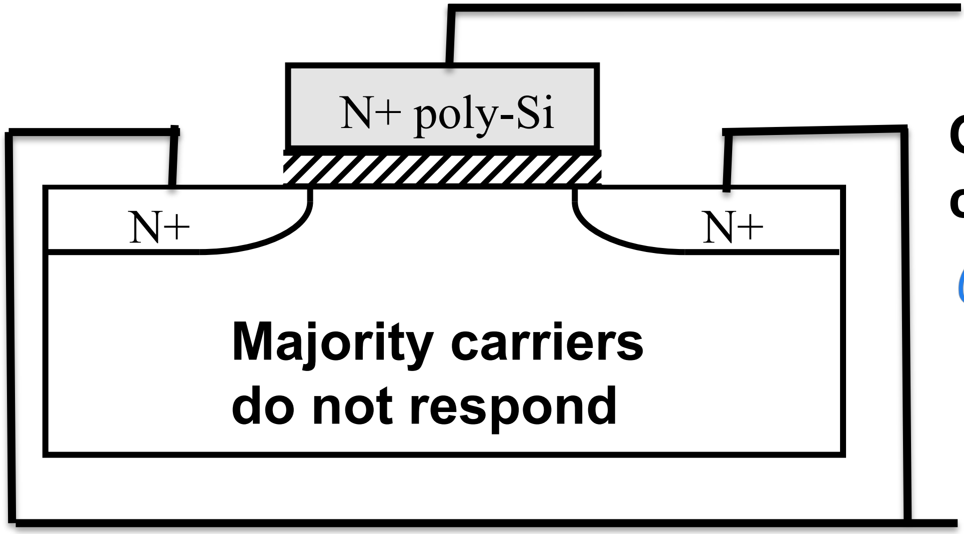


Case 3, Split CV, minority

Only the majority carrier in the S D react

→ This is negligible

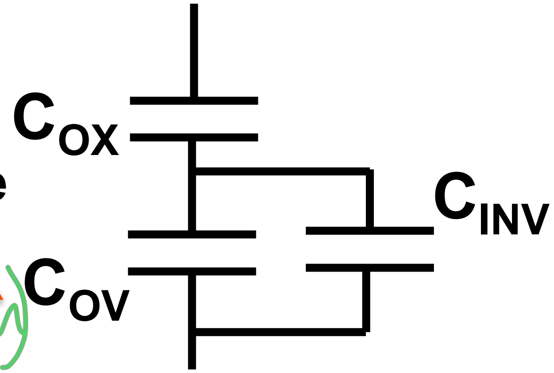
Split CV in MOSFET (NMOS)



Overlap capacitance

due to ΔL

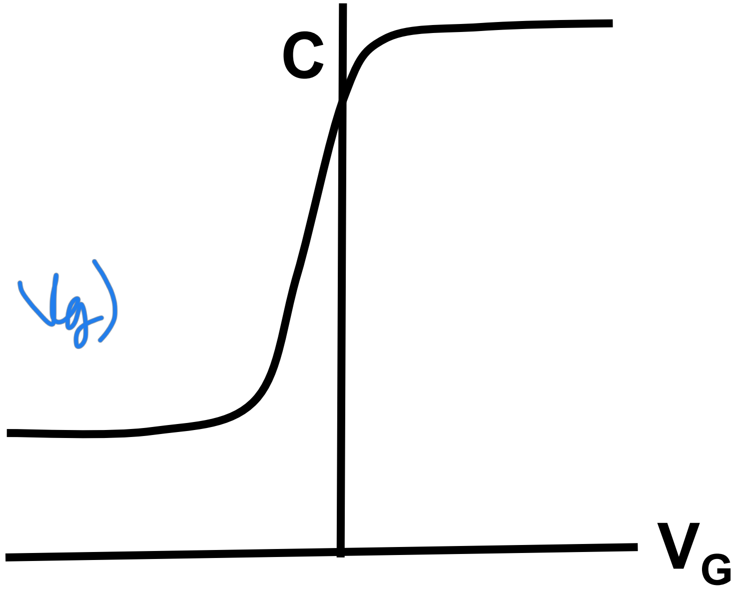
(in inversion)



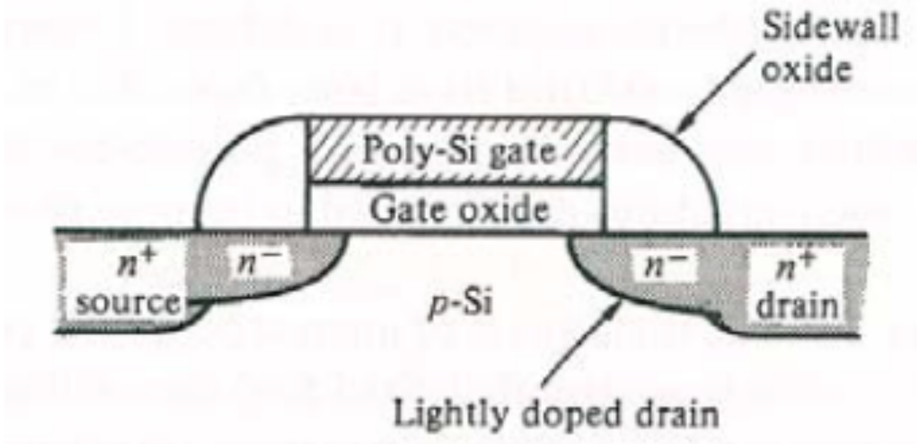
$$C_{INV}(V_G) = \left(\frac{1}{C} - \frac{1}{C_{OX}} \right)^{-1} - C_{OV}$$

measured (function of Vg)

$$Q_{INV} = \int_{V_{GACC}}^{V_{GINV}} C_{INV}(V_G)\, dV_G$$

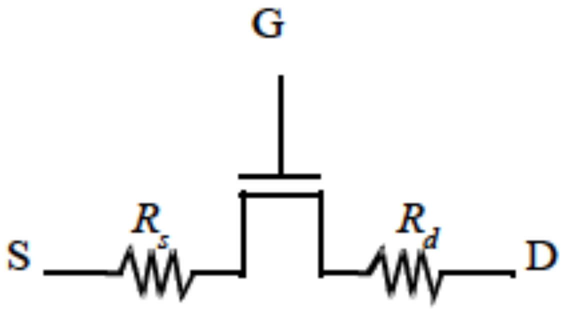


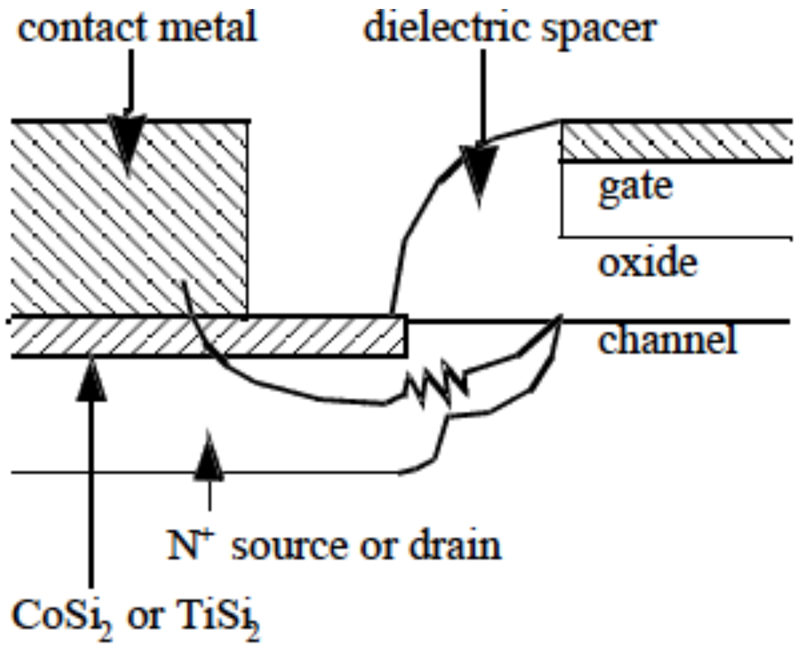
Parasitic S/D Resistance (Series Resistance)



Solution → Lightly doped S/D extension, improves SCE

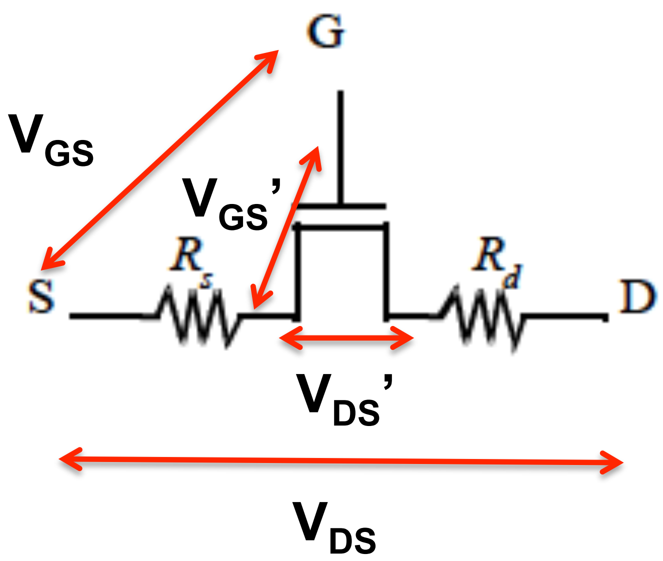
Cons → Increase in series resistance



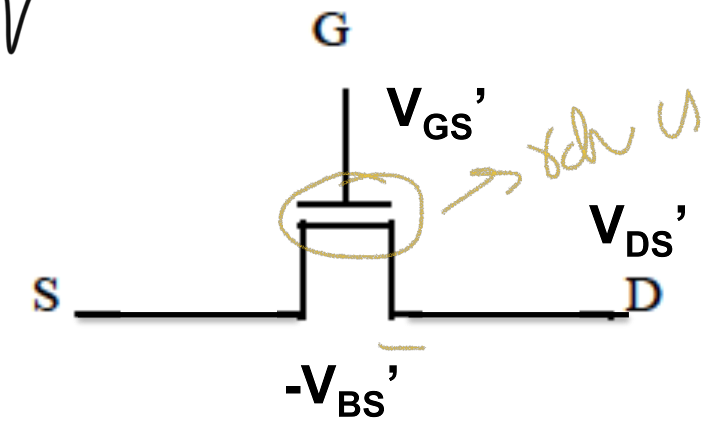


Ref: Taur and Ning

Series Resistance Effect



$R_S = R_D = R_{SD}/2$



→ Vch is present

Applied voltage V_{DS}, V_{GS}
Internal voltage V_{DS}', V_{GS}'
and V_{BS}' due to IR drop

$$V_{GS}' = V_{GS} - R_S I_D$$
$$V_{GS}' = V_{GS} - 0.5 R_{SD} I_D$$
$$V_{DS}' = V_{DS} - (R_S + R_D) I_D$$
$$V_{DS}' = V_{DS} - R_{SD} I_D$$
$$-V_{BS}' = 0.5 R_{SD} I_D$$

Series Resistance Effect

$$R_{ch} = \frac{V_{DS}'}{I_D} = \frac{L_{eff}}{\mu_{eff} C_{OX} W (V_G' - V_T' - m V_{DS}'/2)}$$

$$V_T' = V_{FB} + 2\phi_F + \frac{\sqrt{2\varepsilon_{si} q N_A (2\phi_F + V_{BS})}}{C_{OX}}$$

$$V_T' = V_{FB} + 2\phi_F + \frac{\sqrt{2\varepsilon_{si} q N_A (2\phi_F)}}{C_{OX}} (1 + \frac{V_{BS}}{2\phi_F})^{1/2}$$

$$V_T' = V_T + (m-1) V_{BS}; \quad m = 1 + \frac{\sqrt{\varepsilon_{si} q N_A / (4\phi_F)}}{C_{OX}}$$

Series Resistance Effect

resistance of channel of a actual mos

different from Rsd

$$R_{ch} = \frac{V_{DS}'}{I_D} = \frac{L_{eff}}{\mu_{eff} C_{OX} W (V_G' - V_T' - mV_{DS}'/2)}$$

$$V_G' = V_G - 0.5 R_{SD} I_D$$

$$V_D' = V_D - R_{SD} I_D$$

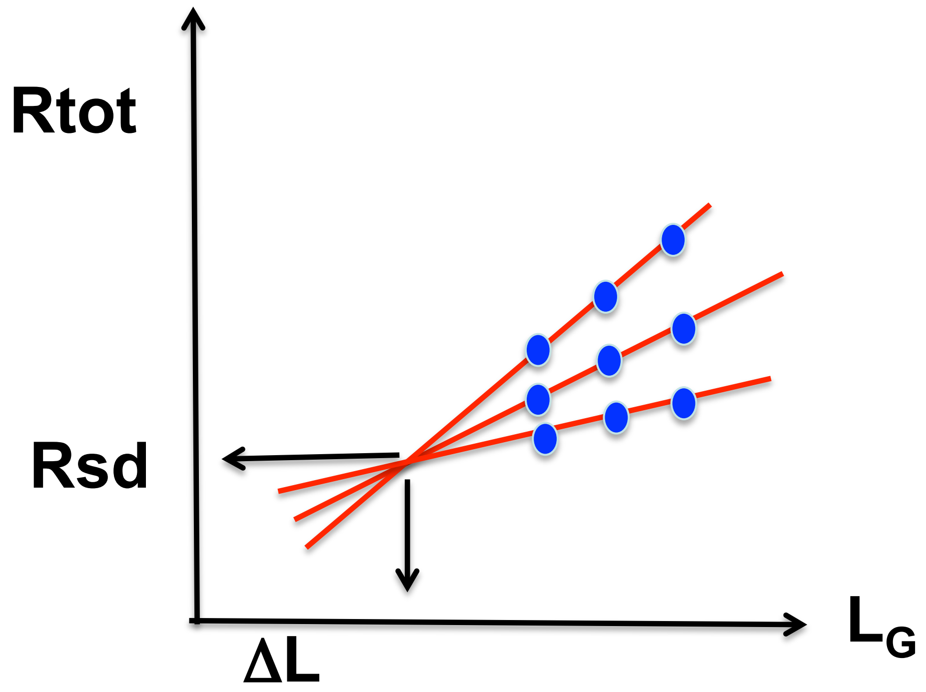
$$V_T' = V_T + 0.5(m-1) R_{SD} I_D$$

$$V_G' - V_T' - mV_{DS}'/2 = V_G - V_T - mV_{DS}/2$$

Series Resistance Effect

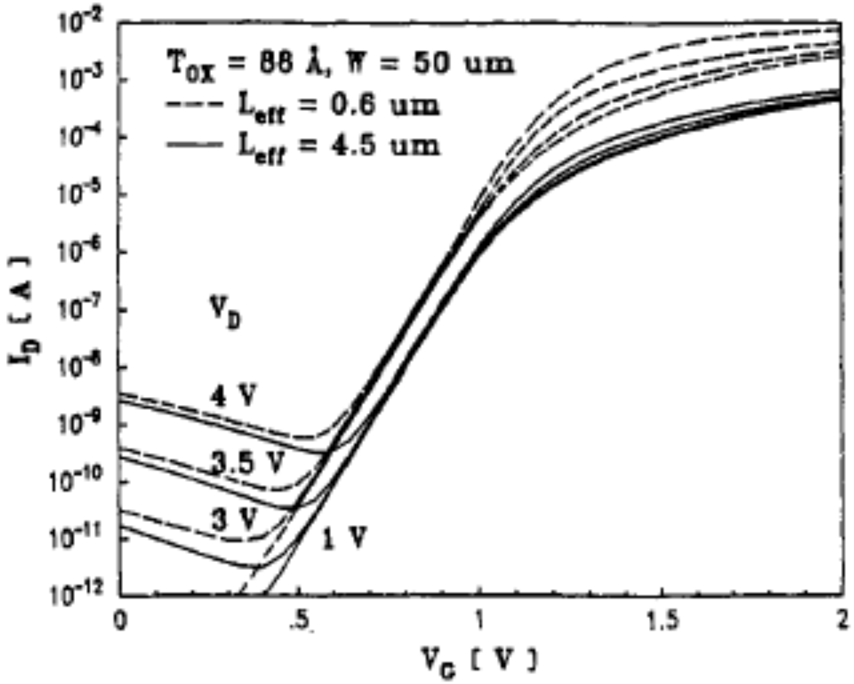
$$R_{tot} = \frac{V_{DS}}{I_D} = R_{sd} + R_{ch} = R_{sd} + \frac{\overset{L_{eff}}{L_G - \Delta L}}{\mu_{eff} C_{OX} W (V_G - V_T - m V_{DS}/2)}$$

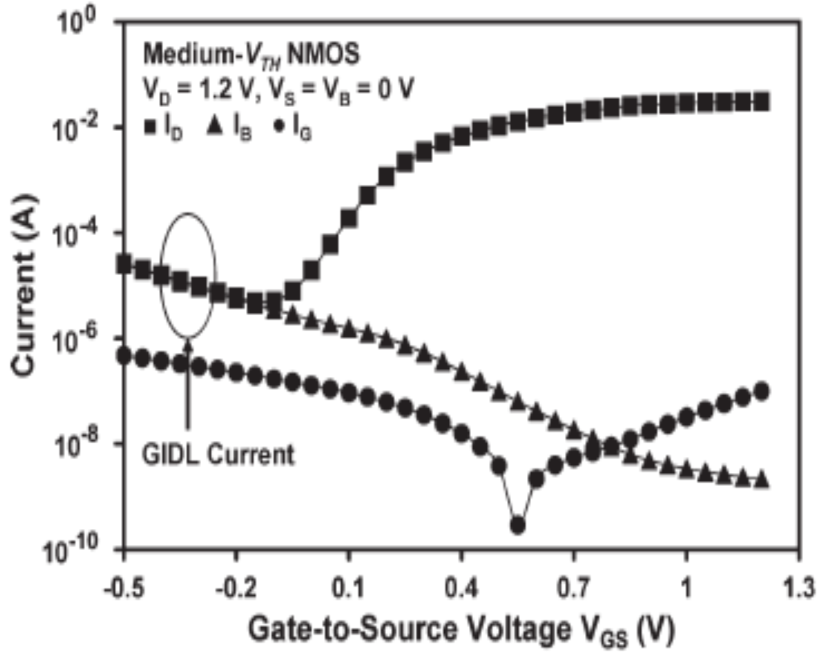
Rtot versus L_G gives a straight line, plot for several V_G



Measured data (symbols) at different V_G, fit and extrapolate

Gate Induced Drain Leakage (GIDL)





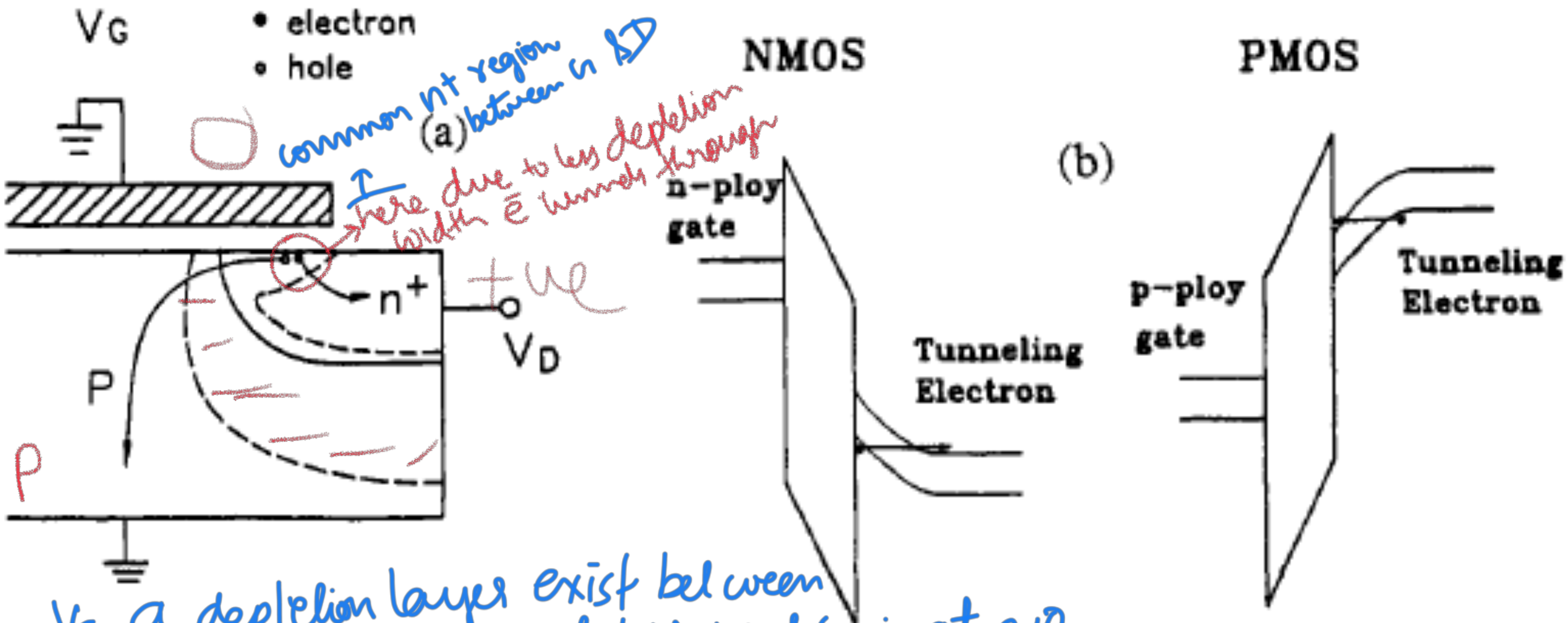
Transfer curves, high drain bias, show increase in current at V_G ~ 0V (left: long L, right: short L devices)

Ref: Chan, IEDM 1987 and Yuan, TED 2008

Gate Induced Drain Leakage (GIDL)

It increases I_D at very low V_g
body current also increases

High V_D and low V_G (~0), vertical field is negative (NMOS) and positive (PMOS), cause band-to-band tunneling (gate induced)



Due to low V_g a depletion layer exist between common (overlap) region of b/w G D. D is at high +ve & G is at ~0

Ref: Chan, IEDM 1987

Gate Induced Drain Leakage (GIDL)

$$E_{OX} = \frac{(V_D - V_G) - E_G / q}{T_{OX}}$$

$$E_S = \frac{(V_D - V_G) - E_G / q}{(\varepsilon_{Si} / \varepsilon_{ox})T_{OX}}$$

$$I_{GIDL} = A * E_S \exp(-B / E_S)$$

Oxide electric field to initiate GIDL, band bending should be more than bandgap

GIDL current (peak location) depends on field in semiconductor surface

Drain overlap region, $V_{FB} \sim 0$

Ref: Chan, IEDM 1987