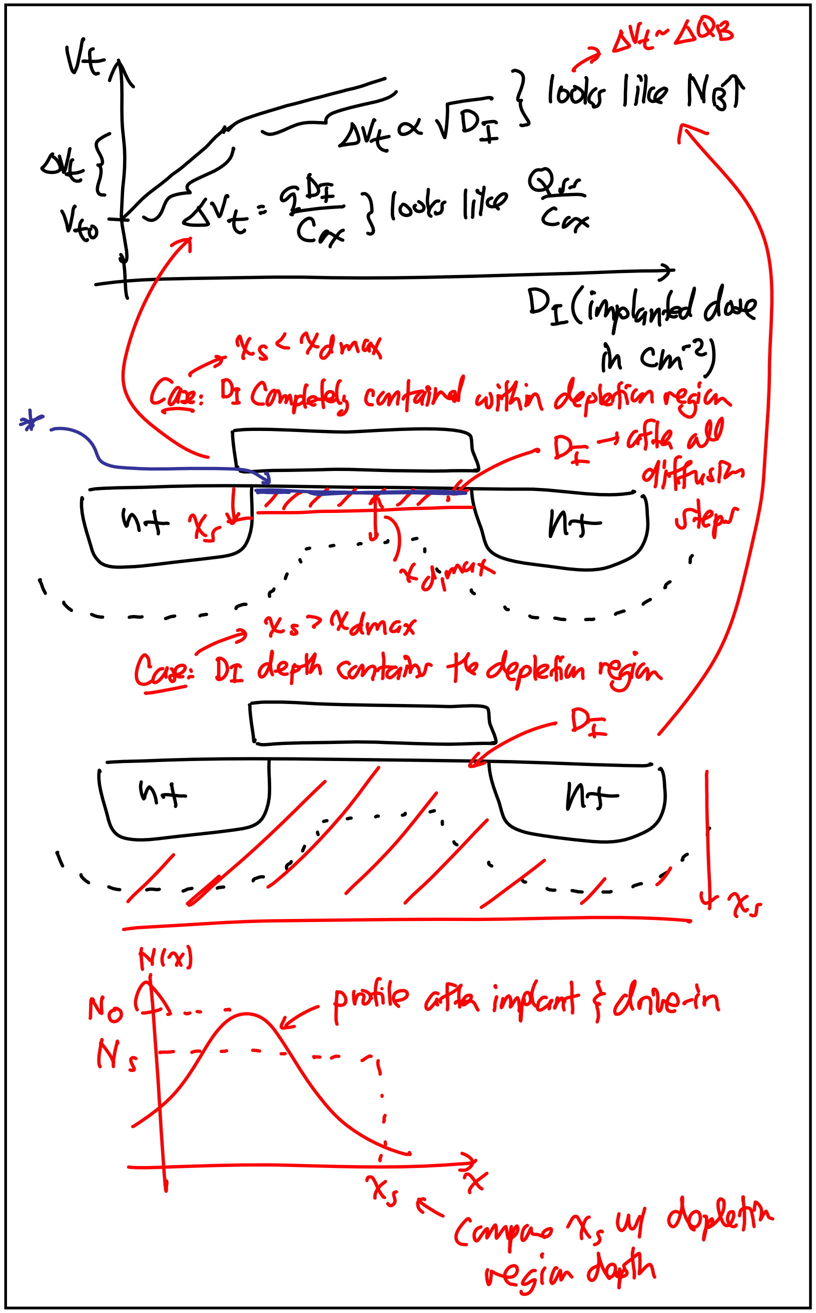
Lecture 26: Device Characterization

- **Announcements**:
- HW#10 due this coming Friday, April 30, at 5 p.m., in the EE143 drop box
- Lab 2 Report will be due Wednesday, May 12 (during Finals week), 7 p.m. – this is a change to give you more time to work on this report
- ---------------------------------------
- **Lecture Topics**:
  - Threshold Implant
    - Threshold voltage
    - Needed ΔV_t
    - V_t Implant Cases
  - Review of MOS Device Modeling
  - Device Characterization
    - Practical problems and solutions
    - Extraction of parameters
  - Yield
    - Poisson model
    - Price model
    - General models
    - Burn-in and reliability
- ---------------------------------------
- **Last Time**:

Question: How is V_t best adjusted?
What factors most impact V_t?

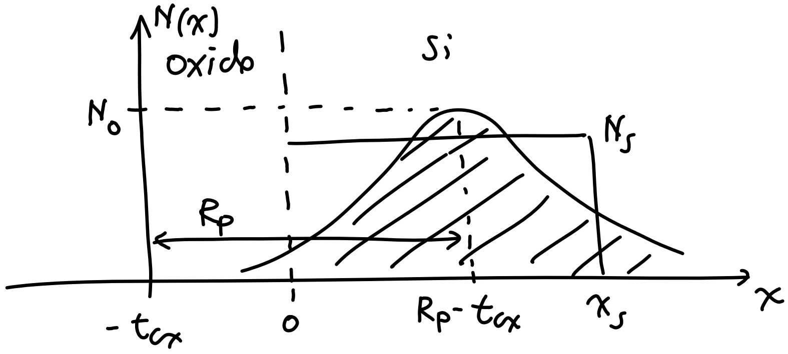
$$\boxed{V_t = \phi_{ms} - \psi_s - \frac{Q_{ss}}{C_{ox}} - \frac{Q_B}{C_{ox}}}$$

$q D_I$



Implant/Diffusion N_s, x_s Cases

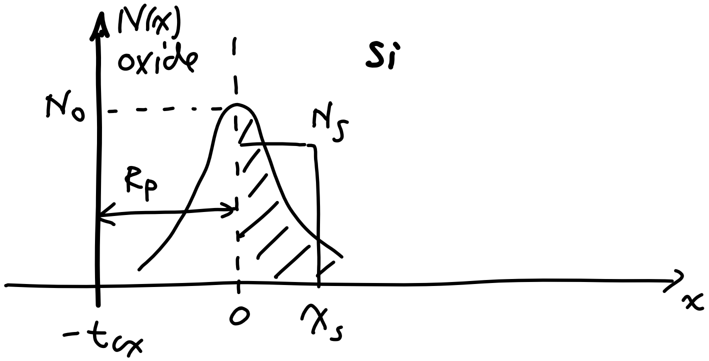
(a) Implant completely contained in Si -



$$N_0 = \frac{D_I/2}{\sqrt{\pi(Dt)}} \Rightarrow N_s = \frac{1}{2}N_0$$

$$Q = D_I \Rightarrow x_s = \frac{D_I}{N_s}$$

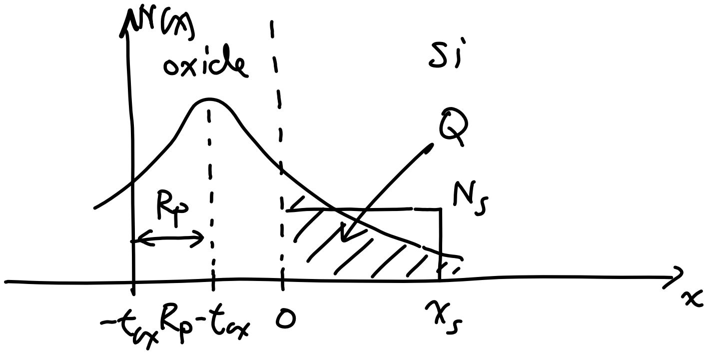
(b) Half of Implant in Si/Half in Oxide -



$$N_0 = \frac{D_I/2}{\sqrt{\pi(Dt)}} \Rightarrow N_s = \frac{1}{2}N_0$$

$$Q = D_I/2 \Rightarrow x_s = \frac{D_I/2}{N_s}$$

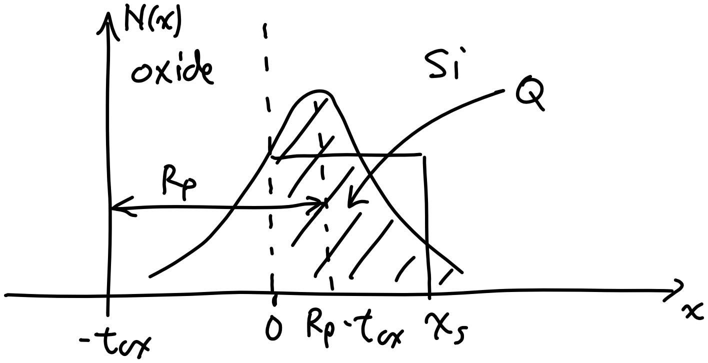
(c) Less Than Half of Implant in Si -



$$N_0 = \frac{D_I/2}{\sqrt{\pi(Dt)}} \exp\left[-\frac{(t_{ox}-R_p)^2}{(2\sqrt{Dt})^2}\right] \Rightarrow N_s = \frac{1}{2}N_0$$

$$x_s = \frac{Q}{N_s}$$

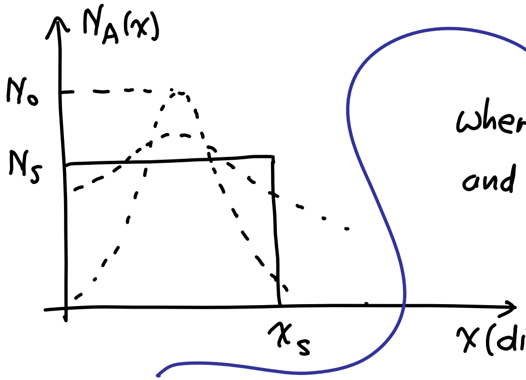
(d) More Than Half of Implant in Si -



$$N_0 = \frac{D_I/2}{\sqrt{\pi(Dt)}} \Rightarrow N_s = \frac{1}{2}N_0 \qquad x_s = \frac{Q}{N_s}$$

V_t Implant Design Procedure

Several cases → to distinguish between cases, approx. the threshold implant by a step function:



where $N_s = \frac{1}{2} N_o$

and $N_s x_s = Q' \propto D_I$

↑ want this

total dose in the Si

This just turns out to be a good approx.

↳ actual value can be determined experimentally

*

Case ①: δ function of (−) charge (ionized B acceptors) @ the Si-SiO₂ interface

↳ (i.e., $x_s = 0$)

$$\left.\right\} \boxed{\Delta V_t = -\frac{qD_I}{C_{ox}}} \propto D_I$$

⇒ equivalent to a reduction of fixed oxide charge Q_{ss} by qD_I:

$$V_t = V_{FB} - 2\phi_f - \frac{Q_B}{C_{ox}} - \frac{Q_{ss}}{C_{ox}} - \frac{qD_I}{C_{ox}}$$

← (−)

(−) (−) (+)

$\Delta V_t = (+)$ $\Delta V_t = (+)$ $\Delta V_t = (-)$

$\Delta V_t = (+)$ ⇒ what we need!

Case ②: x_s = finite < $x_{d,test}$

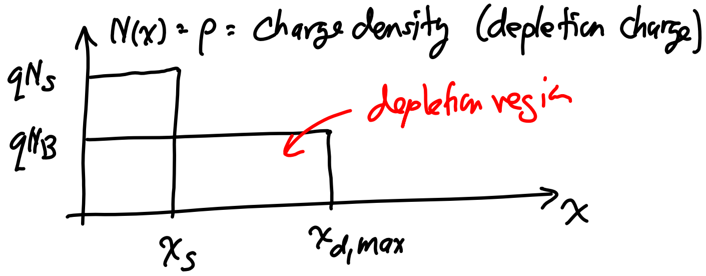
where $x_{d,test} = \sqrt{\frac{2\epsilon_s}{q}\frac{1}{N_s}(2\phi_{f,test})}$

not N_B!

where $\phi_{f,test} = V_T \ln\left(\frac{N_s}{n_i}\right)$

Note that those are just test conditions!

If true, then all the implanted dose is within the depletion region w/ $x_{d,max}$ in the N_B-doped area: i.e.,



$$\boxed{\Delta V_t = -\frac{qD_I}{C_{ox}}} \propto D_I \text{ (still)}$$

Case ③: $x_s < x_{d,test}$

⇒ depletion region completely contained within the implanted x_s region

$$V_t = V_{FB} + |\psi_s| + \frac{\sqrt{2q\epsilon_s N_s}}{C_{ox}}\underbrace{\left(|\psi_s| + V_{SB}\right)^{1/2}}_{\text{this term }\Delta\text{'s the most!}}$$

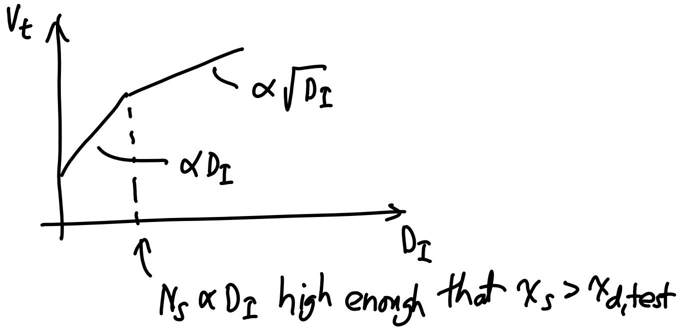
$$|\psi_s| = 2\left|\frac{kT}{q}\ln\frac{n_i}{N_s}\right|$$

Thus, for $N_s >> N_B$:

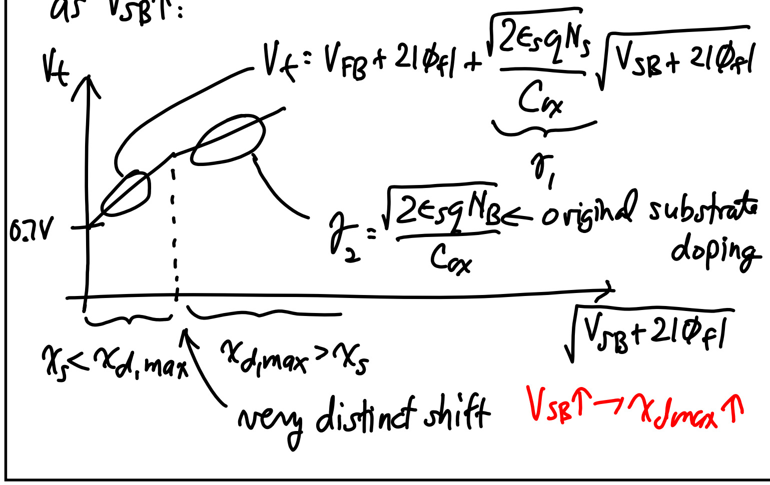
$$\Delta V_t = \frac{\sqrt{2q\epsilon_s N_s}}{C_{ox}}\left(|\phi_s| + V_{SB}\right)^{1/2} \propto \sqrt{N_s} \Rightarrow \Delta V_t \propto \sqrt{D_I}$$

$$\left[N_s \approx \frac{1}{2}N_o = \frac{1}{2}\frac{D_I/2}{\sqrt{\pi(Dt)}} \Rightarrow N_s \propto D_I\right]$$

and



When x_s passes through $x_{d,max}$ (or vice versa) → can see a distinct change in body effect parameter γ as $V_{SB}\uparrow$:



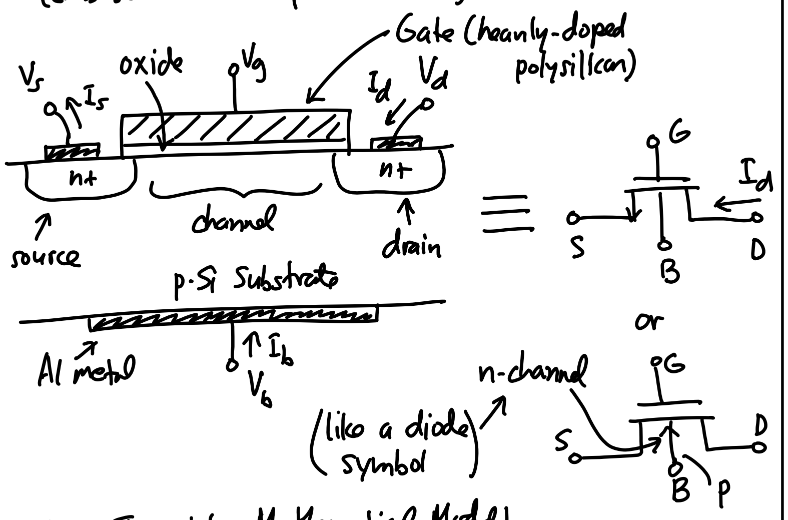
$$V_t = V_{FB} + 2|\phi_F| + \underbrace{\frac{\sqrt{2\epsilon_s q N_s}}{C_{ox}}}_{\gamma_1}\sqrt{V_{SB} + 2|\phi_F|}$$

$$\gamma_2 = \frac{\sqrt{2\epsilon_s q N_B}}{C_{ox}} \leftarrow \text{original substrate doping}$$

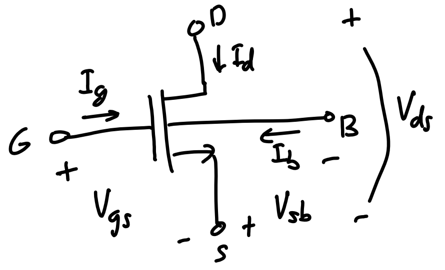
$V_{SB}\uparrow \rightarrow x_{dmax}\uparrow$

MOS Device Model Summary

(cross-section view of NMOS device)



NMOS Transistor Mathematical Model



① Cut-Off Region: ($V_{gs} \le V_t$)

$I_g = I_b = 0$; $I_d = 0$

② Linear (or Triode) Region: $(V_{gs}-V_{tn} \geq V_{ds} \geq 0)$

$$I_g = I_b = 0;\quad I_d = \mu_n C_{ox}\frac{W}{L}\left(V_{gs}-V_{tn}-\frac{V_{ds}}{2}\right)V_{ds}$$

$$= k_n\left(V_{gs}-V_{tn}-\frac{V_{ds}}{2}\right)V_{ds}$$

③ Saturation Region: $(V_{ds} \geq V_{gs}-V_{tn} \geq 0)$

$$I_g = I_b = 0;\quad I_d = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{gs}-V_{tn})^2(1+\lambda V_{ds})$$

$$= \frac{1}{2}k_n(V_{gs}-V_{tn})^2(1+\lambda V_{ds})$$

where:

$\mu_n \triangleq$ e⁻ mobility in the channel

$C_{ox} \triangleq$ gate oxide capacitance per unit area

$k_n = k_n'\frac{W}{L} = \mu_n C_{ox}\frac{W}{L}$

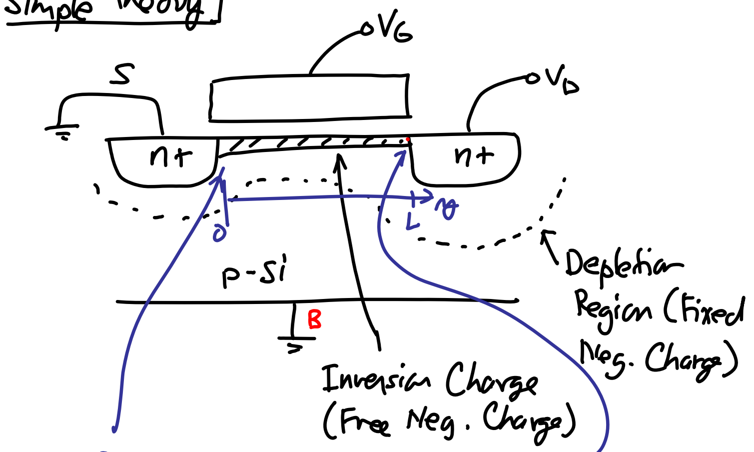
$I_g = I_b = 0$ for all regions (at least for dc)

$$V_{tn} = f(V_{SB}) = V_{to} + \gamma\left(\sqrt{V_{SB}+2|\Phi_F|} - \sqrt{2|\Phi_F|}\right)$$

Body Factor → $\gamma = \frac{1}{C_{ox}}\sqrt{2q\epsilon_s N_{sub}}$ ← substrate doping conc.

MOS FET IV Curves

Simple Theory:

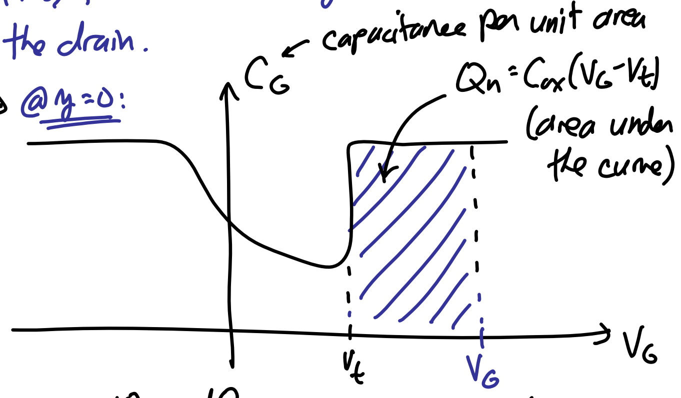


$Q_n(y=0) = C_{ox}(V_G - V_t)$

$Q_n(y=L) = C_{ox}(V_G - V_D - V_t)$

Thus, the inversion charge thins down towards the drain.

@y=0:



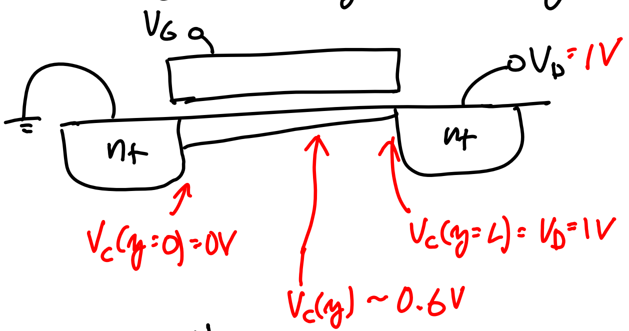
$C_G = \frac{dQ}{dV} = \frac{dQ_n}{dV}$ ← when inversion charge can keep up w/ the frequency

$$Q_n = \int dQ_n = \int_{V_t}^{V_G} C_G\, dV = C_{ox}(V_G - V_t) \quad @\ \underline{\underline{y = 0}}$$

For y = somewhere between 0 & L:

$$Q_n = \int_{V_t}^{V_G - V_c(y)} C_G\, dV = C_{ox}\left(V_G - V_c(y) - V_t\right)$$

$V_c(y)$ ↑ channel voltage @ location y



Get Drain Current

⇒ I_D must be the same @ every channel location (by current continuity)

⇒ Thus:

$$I_D = I_D(y) = W Q_n(y)\, v(y)$$

width → W

carrier velocity, i.e., velocity of Q_n → $v(y)$

$$v(y) = \mu_n \cdot E_y(y) = \mu_n \cdot \frac{dV_c(y)}{dy}$$

μ_n: mobility

$E_y(y)$: channel directed electric field @ y

$$I_D(y) = W \mu_n Q_n(y)\, dE_y(y)$$
$$= W \mu_n C_{ox}\left(V_G - V_c(y) - V_t\right) \cdot \frac{dV_c(y)}{dy}$$

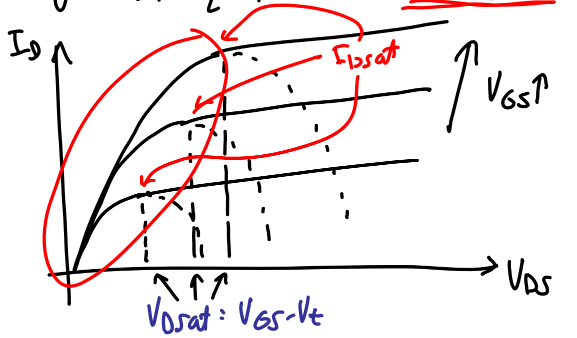
$$\therefore \int_0^L I_D\, dy = W \mu_n C_{ox} \underbrace{\int_{V_S}^{V_D} \left(V_G - V_c(y) - V_t\right) dV_c(y)}$$

$$\left.(V_G - V_t)V_c - \tfrac{1}{2}V_c^2\right|_{V_S}^{V_D}$$
$$= (V_G - V_t)V_D - \tfrac{1}{2}V_D^2 - (V_G - V_t)V_S + \tfrac{1}{2}V_S^2$$
$$= (V_G - V_t)V_{DS} - \tfrac{1}{2}(V_D + V_S)(V_D - V_S)$$
$$= \left(V_G - V_t - \tfrac{1}{2}V_D - \tfrac{1}{2}V_S\right)V_{DS}$$
$$= \left(V_G - V_S - V_t - \tfrac{1}{2}V_D + \tfrac{1}{2}V_S\right)V_{DS}$$
$$= (V_{GS} - V_t)V_{DS} - \tfrac{1}{2}V_{DS}^2$$

$$I_D L = W \mu_n C_{ox}\left[(V_{GS} - V_t)V_{DS} - \tfrac{1}{2}V_{DS}^2\right]$$

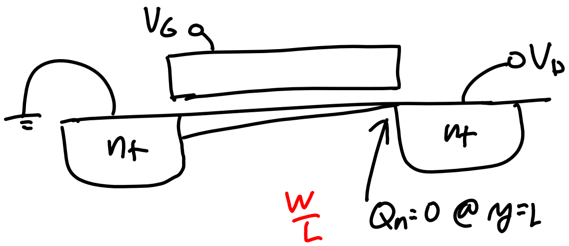
$$\therefore \boxed{I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_t)V_{DS} - \tfrac{1}{2}V_{DS}^2\right]}$$

↳ This is the classic linear (or triode) region I_D equation for $\underline{V_{DS} < V_{GS} - V_t}$!



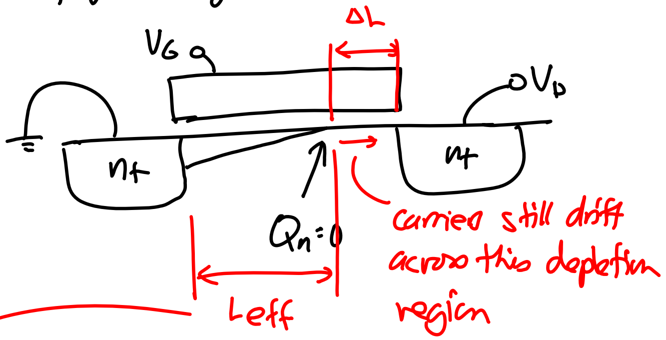
When $V_{DS} = V_{GS} - V_t = V_{Dsat} \rightarrow Q_n = C_{ox}(V_G - V_D - V_t) = 0$

↳ get this:



and $I_D = I_{Dsat} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_t)^2$

When $V_{DS} > V_{GS} - V_t$, then $V_c(y) = V_{GS} - V_t$ @ a y between $y = 0$ & $y = L$: ⇒ get:



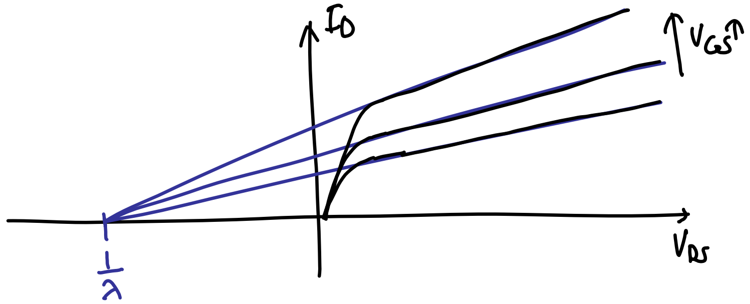
Now, the effective channel length is

$L_{eff} = L - \Delta L \longrightarrow I_D$ will rise

For $V_{DS} > V_{GS} - V_t$ (i.e., $V_{DS} > V_{Dsat}$):

$$\boxed{I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_t)^2(1+\underset{\approx}{\lambda} V_{DS})}$$

where λ models the "channel length modulation" phenomenon & can be measured from:



The above models "long-channel" devices.

For more advanced "short-channel" devices, the models must be adjusted.

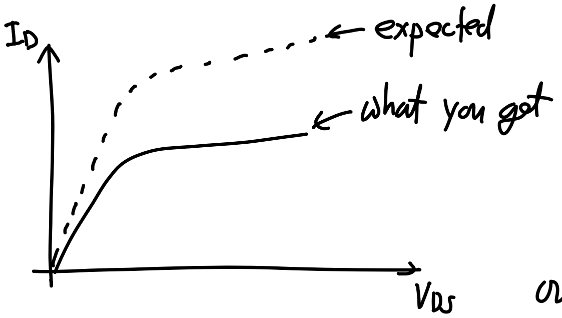
↳ topics covered in EE 231 & EE 141

↓ move on to talk about:

$\boxed{\text{Device Characterization}}$ (i.e., what you're doing in your lab right now)

Potential Problems During Measurement

(a)



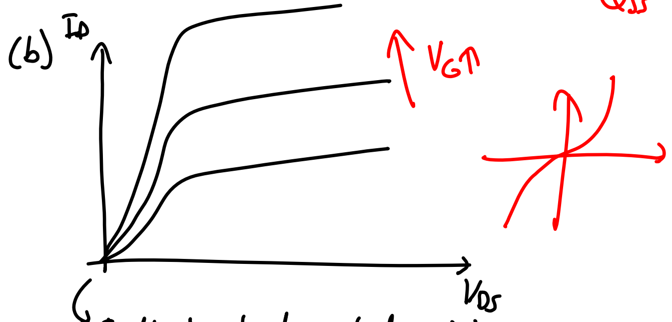
over ↷

⇒ can be caused by:

① Series resistance → check probe contact

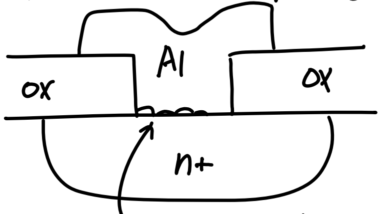
② Excessive surface states → check CV curve & subthreshold slope — Q_{ss}

(b)



Indicates bad contact resistance.

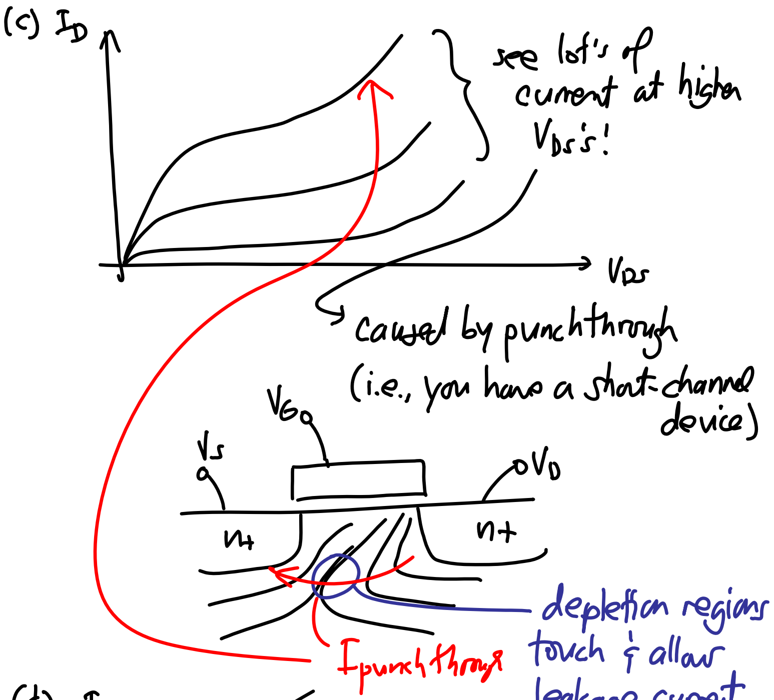
Contact holes didn't open right:



Some residual oxide left.

Can be fixed by sending a lot of current through the contact and "burning through"!

(c)

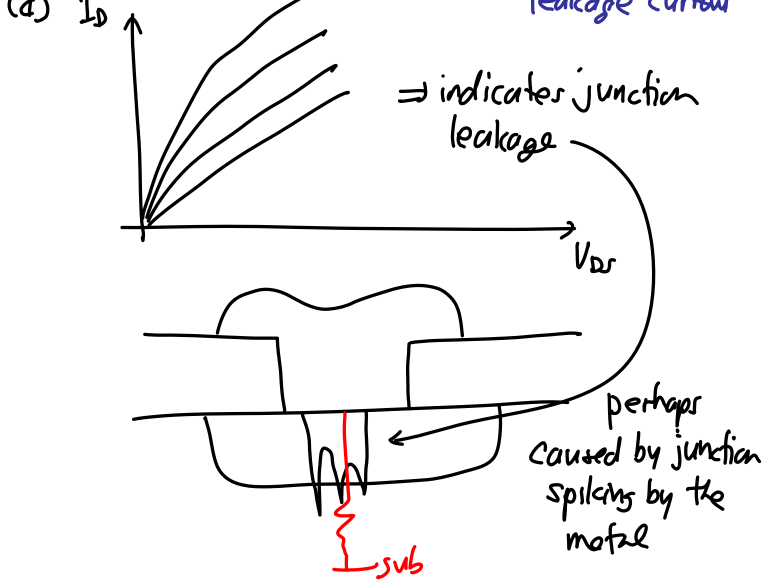


see lots of current at higher V_{DS}'s!

caused by punchthrough (i.e., you have a short-channel device)

depletion regions touch & allow leakage current

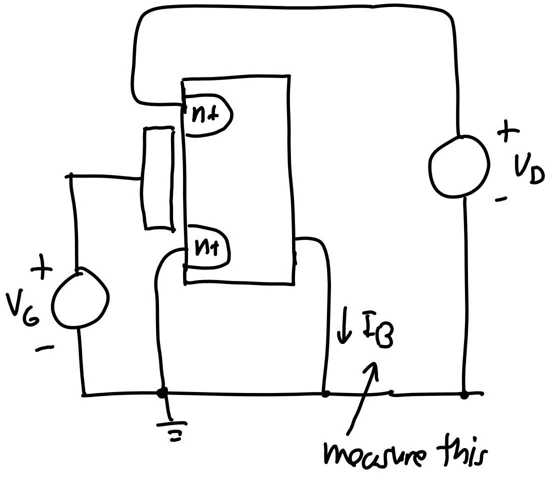
(d)



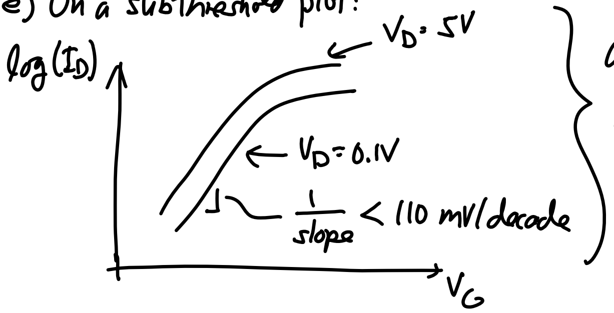
⇒ indicates junction leakage

perhaps caused by junction spiking by the metal

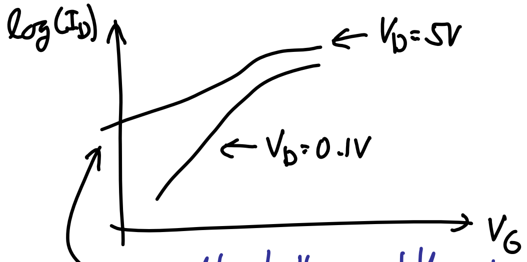
To check for this, can hook up as follows:



(e) On a subthreshold plot:

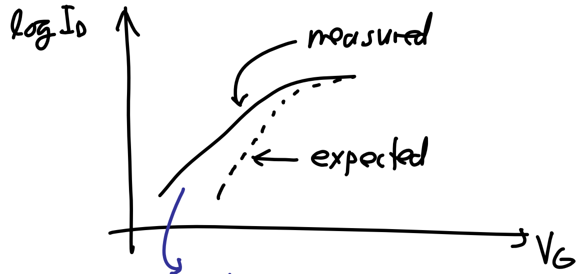


What one expects!



caused by bulk punchthrough (your channel is too short)

What if you got this?



probably caused by poor Si-SiO_2 interface

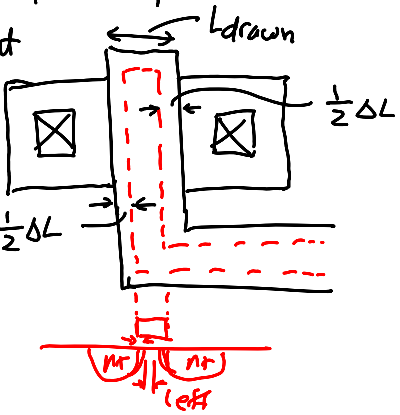
Did you do an adequate forming gas anneal?

Quantitative Device Characterization

→ How can we measure the following:

(a) ΔL ← gate length deviation
(b) ΔW ← gate width deviation
(c) μ ← mobility
(d) γ ← body effect parameter

(a) ΔL measurement

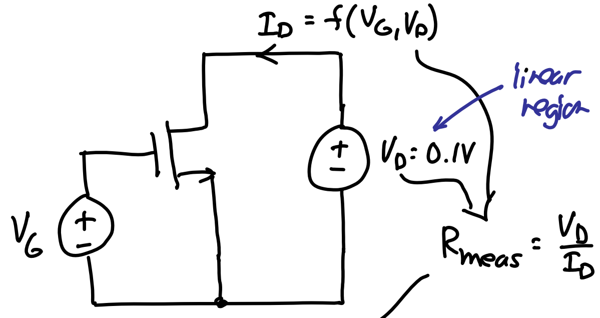


ΔL is due to:

① Lithography
② Poly gate etch undercut
③ Lateral diffusion of S/D junctions

$L_{eff} = L_{drawn} - \Delta L$

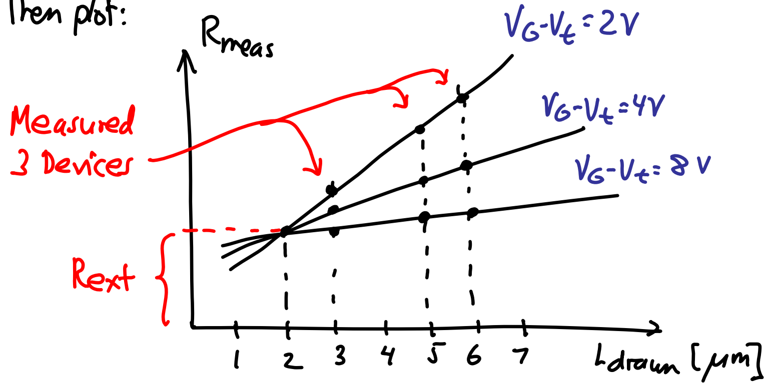
⇒ How does one measure ΔL?



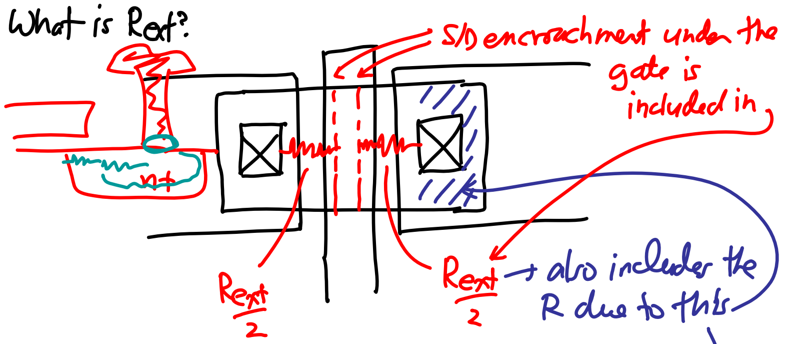
$R_{meas} = \frac{V_D}{I_D}$

Measure R_{meas} for several devices w/ the same W_{drawn} & different L_{drawn}.

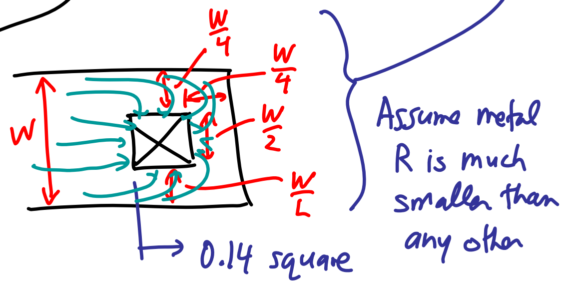
Then plot:



What is R_{ext}?



Need to eliminate R_{ext} from R_{meas} to find the actual MOS channel resistance R_c.



$I_D = \mu C_{ox}\frac{W}{\underset{\nwarrow L_{eff}}{L}}\left[(V_{GS}-V_t)V_{DS} - \frac{1}{2}\cancel{V_{DS}^2}\right]$

$[V_{DS} = 0.1V = small] \Rightarrow I_D \approx \mu C_{ox}\frac{W}{L}(V_{GS}-V_t)V_{DS}$

↳ This includes R_c only; no R_{ext}.

$R_c \triangleq$ channel resistance

$$= \frac{V_{DS}}{I_D} = \frac{\cancel{V_{DS}}}{\mu C_{ox}\frac{W}{L}(V_{GS}-V_t)\cancel{V_{DS}}} = \frac{\overset{L_{drawn}-\Delta L}{\overset{\parallel}{L_{eff}}}}{\mu C_{ox} W (V_{GS}-V_t)}$$

∴ $\boxed{R_c = \frac{L_{drawn} - \Delta L}{\mu W C_{ox}(V_{GS} - V_t)}}$

and

$$\boxed{R_{meas} = R_c + R_{ext} = \frac{L_{drawn} - \Delta L}{\mu W C_{ox}(V_{GS} - V_t)} + R_{ext}}$$

Can solve for ΔL!

(b) ΔW measurement

⇒ pick devices w/ different W_{drawn} but same L_{drawn}

⇒ but if W_{drawn} is changing, then R_{ext} isn't a constant → must suppress R_{ext} in order to use this equation

must use a device w/ a large L_{drawn} (~ 50μm)

[L_{drawn} = large] ⇒ $R_{meas} = R_c + \cancel{R_{ext}}$

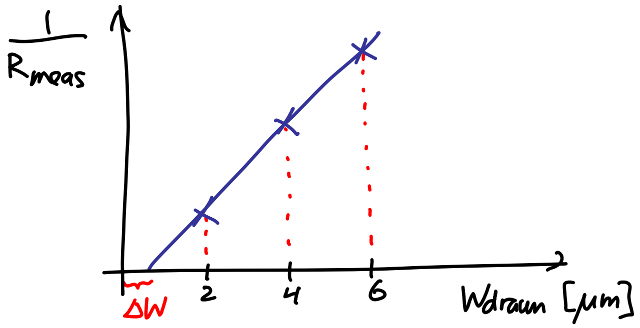
$$\therefore R_{meas} \approx \frac{L_{eff}}{W_{eff}\,\mu C_{ox}(V_{GS} - V_t)} \gg R_{ext}$$

$W_{eff} = W_{drawn} - \Delta W$

$$\frac{1}{R_{meas}} = K(W_{drawn} - \Delta W)$$

⇒ $\frac{1}{R_{meas}} = 0$ when $W_{drawn} = \Delta W$!

Thus:



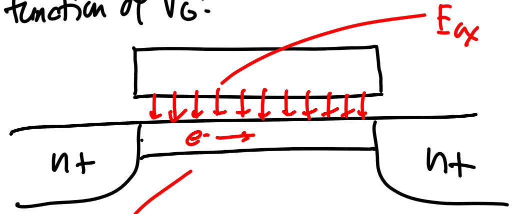
(c) $\mu(V_G)$ → mobility as a function of V_G

⇒ use large devices (e.g., W = 50μm, L = 50μm)

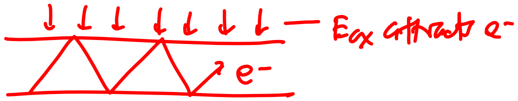
⇒ V_{DS} = small ≈ 0.1V : $I_D = \underset{?}{\mu} C_{ox}\frac{W}{L}(V_{GS} - V_t)V_{DS}$

$$\mu(V_G) = \frac{I_D}{\frac{W}{L}C_{ox}(V_{GS} - V_t)V_{DS}}$$

Why a function of V_G?

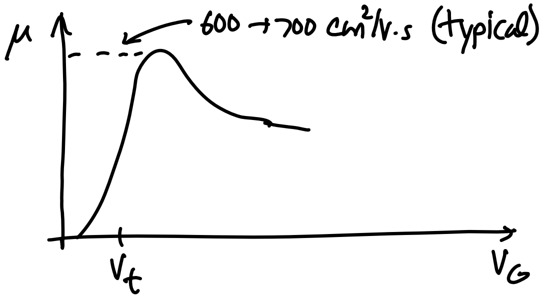


e- is attracted to the surface:



spends more time near the surface

more collisions w/ Si-SiO$_2$ interface → smaller mobility

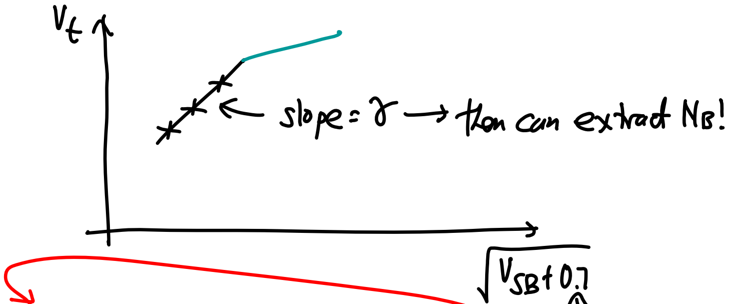


(d) γ ⇒ again, use large devices, e.g., W = 50 μm, L = 50 μm

$$V_t = V_{t0} + \gamma\left(\sqrt{2|\phi_f| + V_{SB}} - \sqrt{2|\phi_f|}\right)$$

$$\uparrow$$

$$= \frac{\sqrt{2\epsilon_s q N_B}}{C_{ox}} \quad \Big\}\ \text{for uniformly doped channel}$$

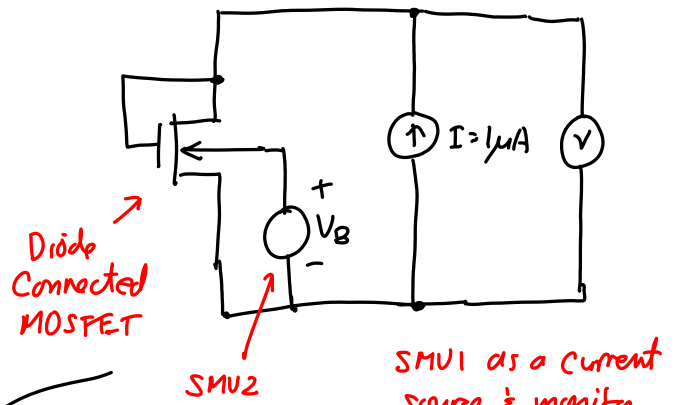


$2|\phi_f|$

Actually depends on N_B → choose a starting $|\phi_f|$ then iterate w/ N_B till convergence → then get ϕ_F & N_B …

How does one measure V_t?
↳ several methods …
(we'll discuss just one … you'll use another in your lab …)

Using the 4155 Semiconductor Parameter Analyzer:



SMU1 as a current source & monitor the voltage (~V_t)

Get: