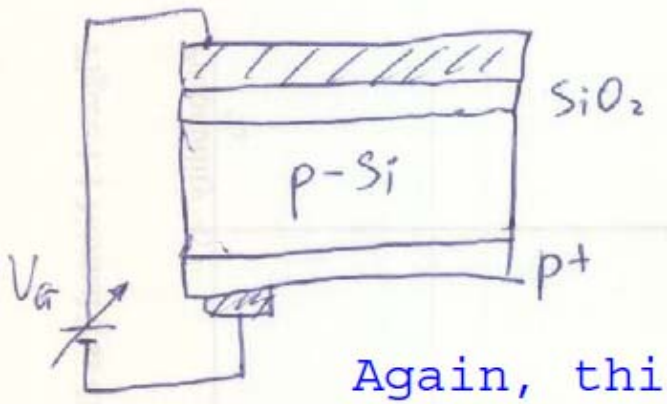
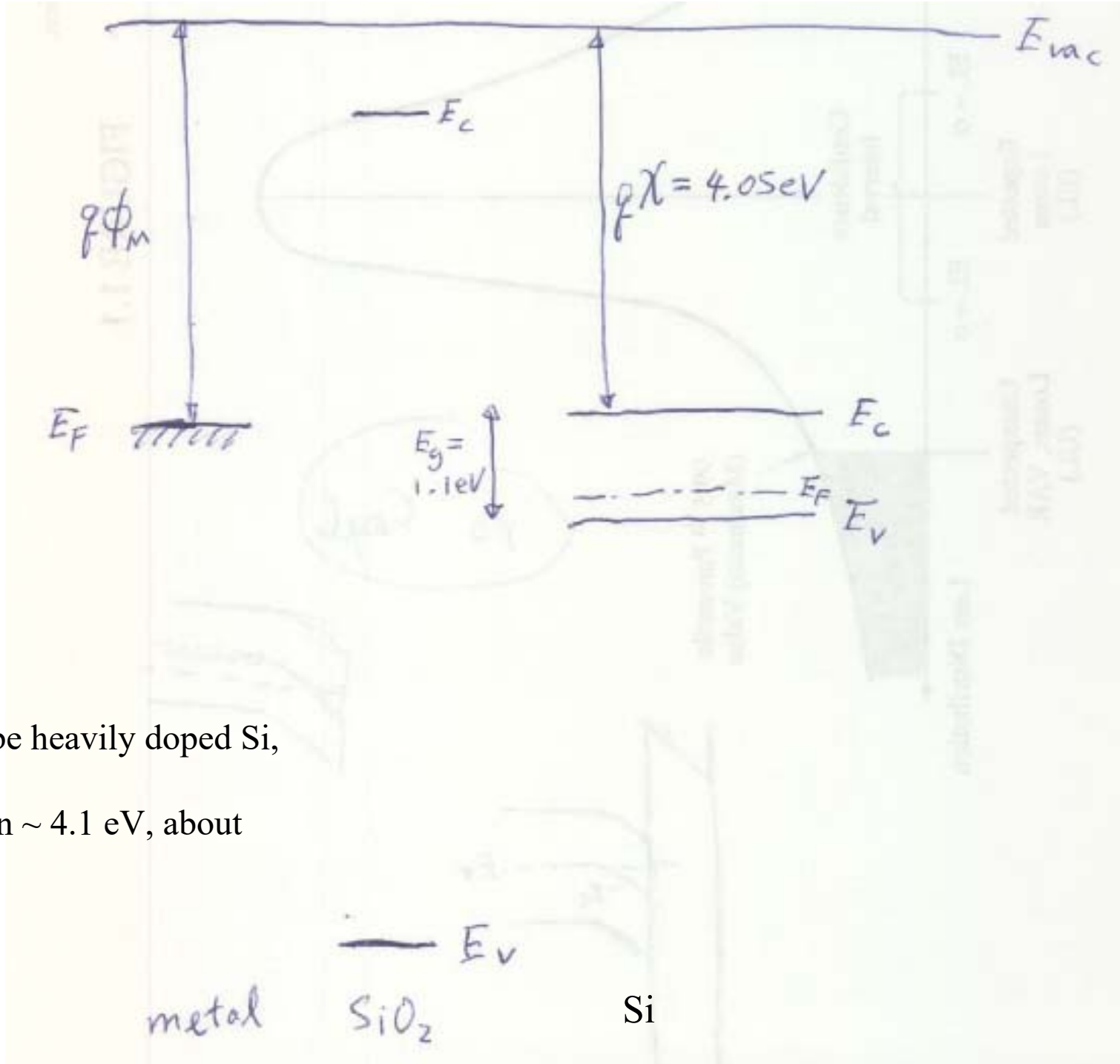
△ MOSFETs (or MISFETs to be general)

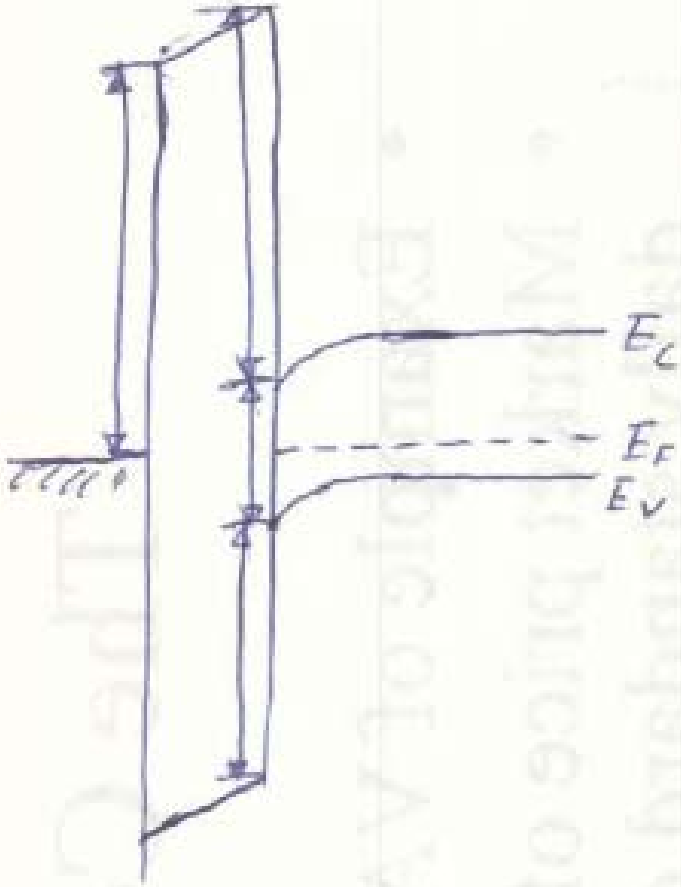


To understand MOSFETs, we must first understand MOS capacitors.

Again, this course is about the big picture



The gate could be heavily doped Si, or a true metal.
Al work function ~ 4.1 eV, about mid gap.



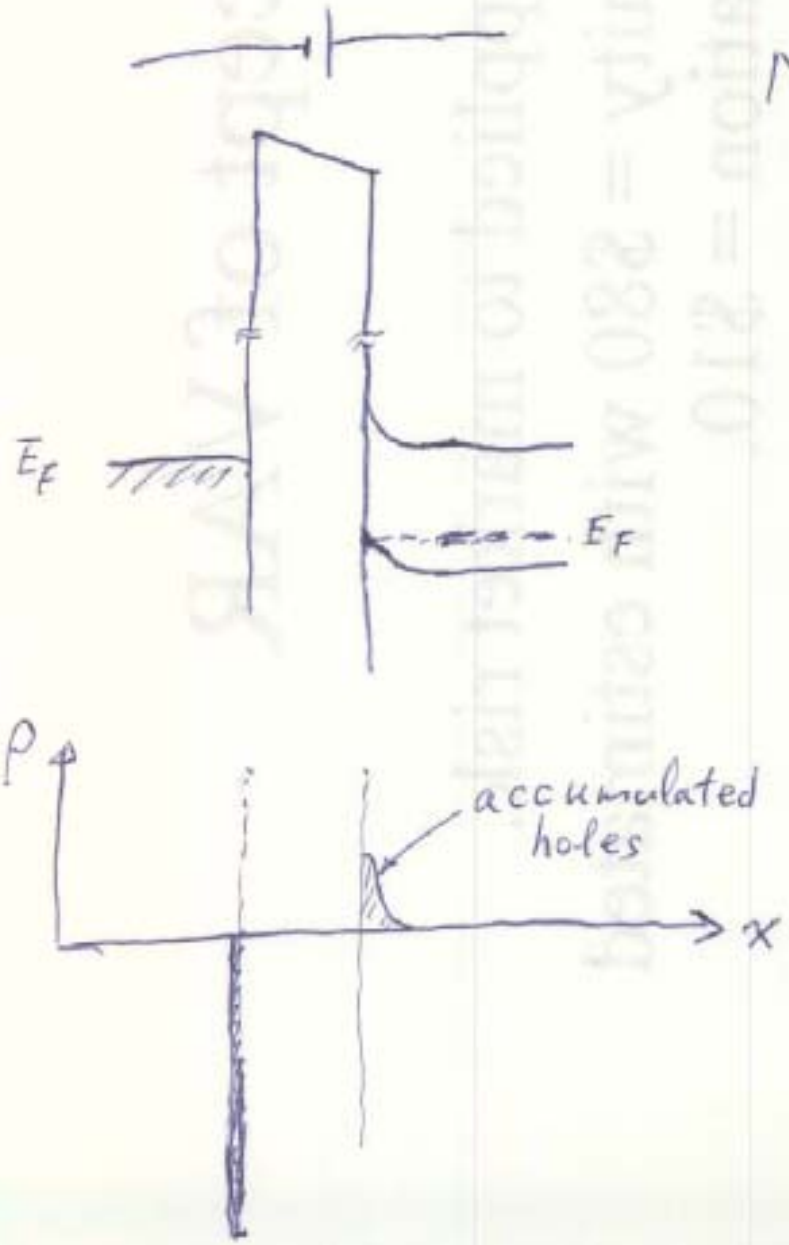
Equil.: E_F's line up.

- Energy differences indicated by doubled-headed arrows remain unchanged.

(Ignoring surface states)

Band (potential) profiles are linear in SiO_2 (Why?)

Band bending in Si (Why?)

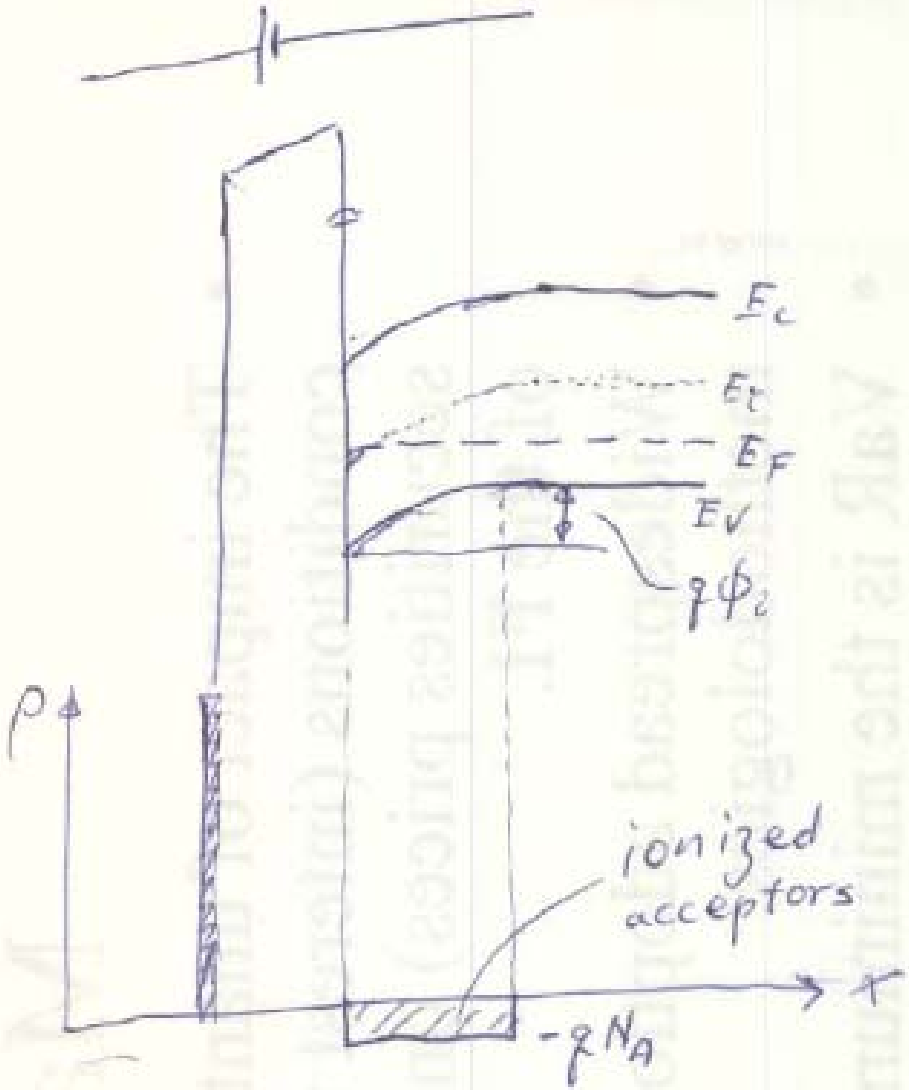


Now, apply a negative V_G

The surface (SiO_2-Si interface) is more p than the bulk.

— Accumulation

This band bending is different from that in depletion



Positive gate bias.

Near the interface, less p than the bulk.

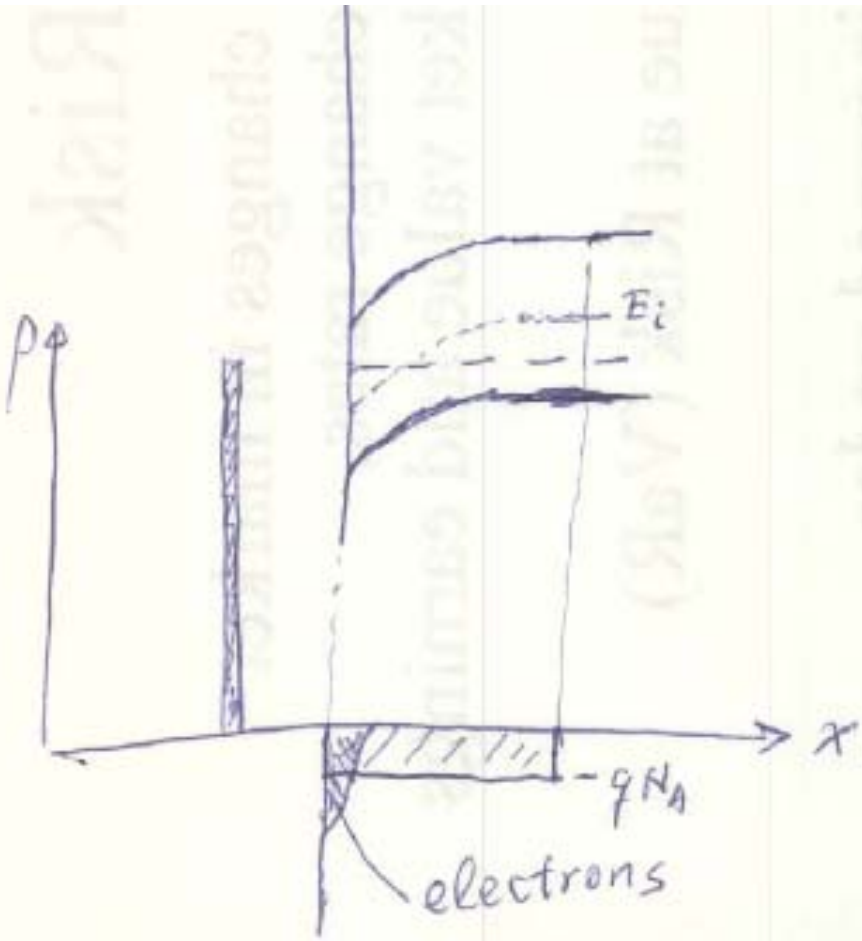
— depletion

Depletion approx.

$$x_d = \sqrt{\frac{2\varepsilon_0\varepsilon_r\phi_i}{qN_A}}$$

The depletion region charge $Q_d = qN_A x_d$

(per cross-section area)



Inversion

Increase the positive V_G.

→ enough electrons to screen the $\mathcal{E}$ field

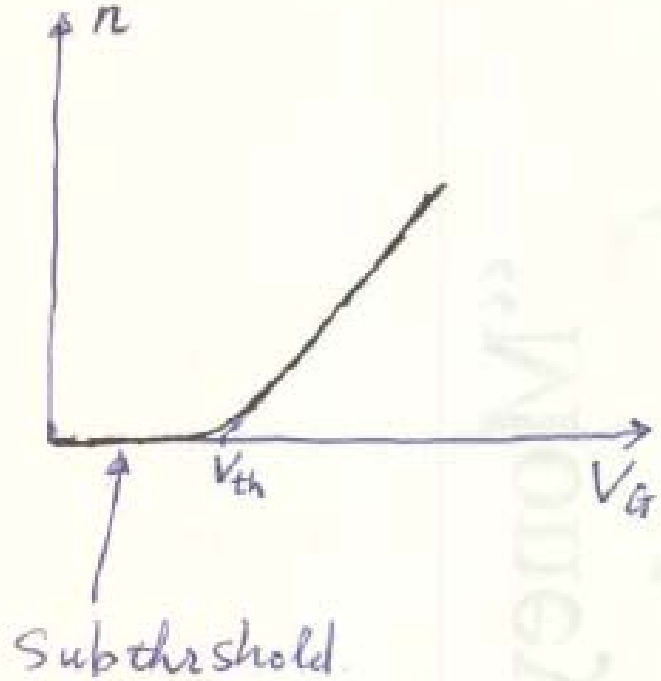
→ x_d can no longer widen

→ $x_{d\,max}$

$$Q_{d\,max} = qN_A\, x_{d\,max}$$

The V_G corresponding to x_d is V_{th}, after which

After $x_{d\max}$ is reached

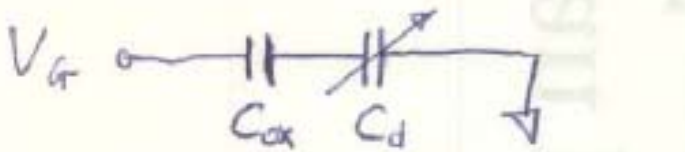


$$qn = C_{ox}(V_G - V_{th})$$

Every volt of increase in V_G is used to induce more e's.

Of course, V_{th} is <u>NOT</u> well defined

Subthreshold. ΔV_G is used to widen x_d. adding few e's.



The total MOS cap

$$\frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_d}$$

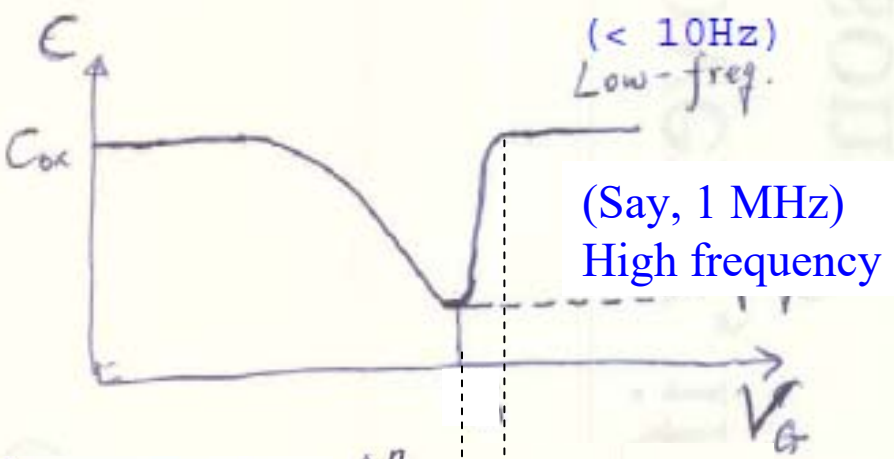
$$C_{ox} = \frac{\varepsilon_0 \varepsilon_r}{d}$$ — the ε_r of SiO_2, $\varepsilon_r = 3.9$

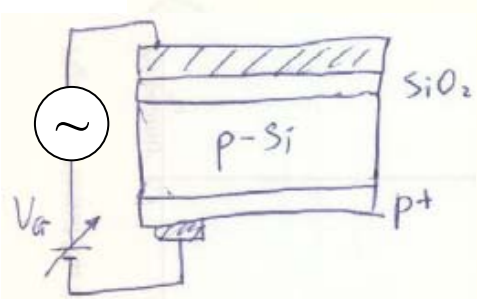
$$C_d = \frac{\varepsilon_0 \varepsilon_{r\,Si}}{x_d}$$ only when x_d is being modulated

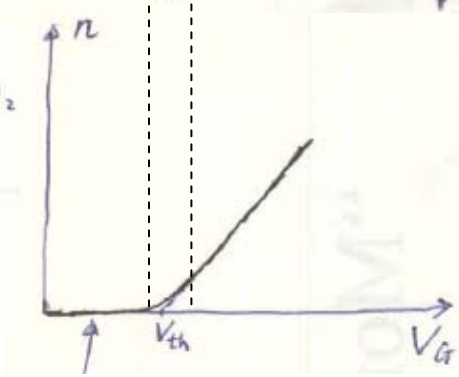
When $V_G > V_{th}$, (low-freq.)

$C_d = \infty$, i.e. $\frac{1}{C_d} = 0$

$\Rightarrow C = C_{ox}$

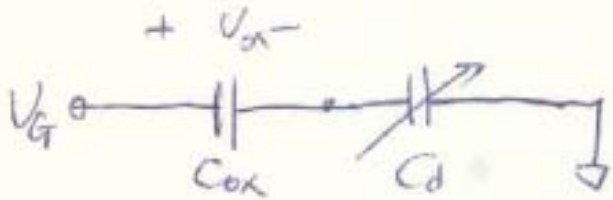






High frequency curve assuming no S/D, but only a body contact.
What if there is a S contact?

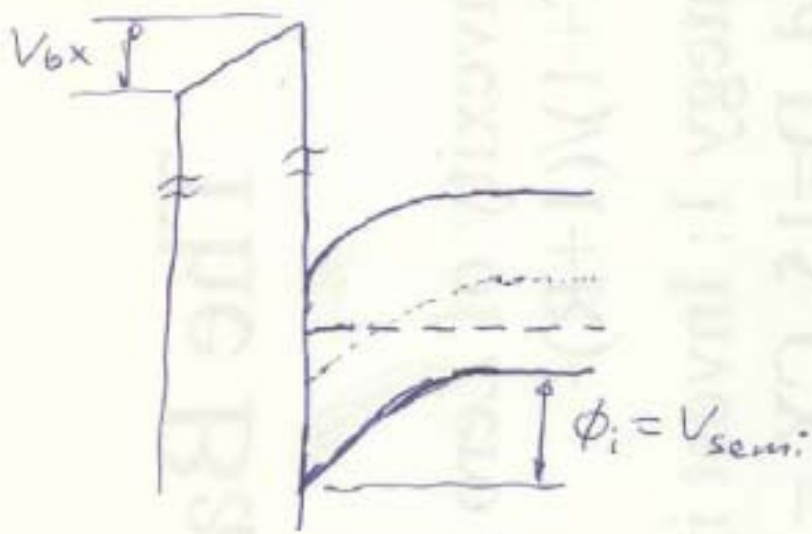
Why did the industry go back to metal gates?



Voltage division

$$\phi_i = \frac{C_{ox}}{C_{ox} + C_d} V_G$$

Voltage division between the dielectric and the semiconductor



In the depletion regime (i.e. sub-threshold) while x_d being widened, n does increase, since E_F moves.

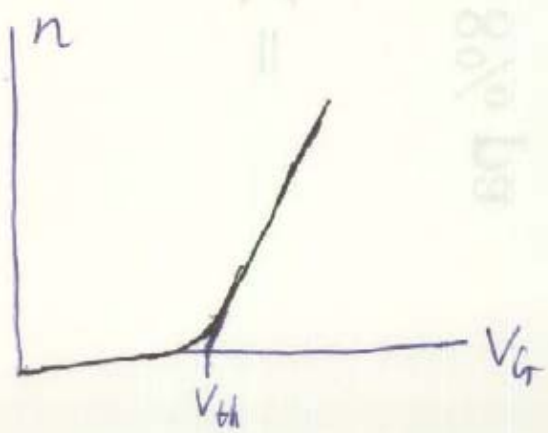
$$n \propto e^{\frac{q\phi_i}{kT}}$$

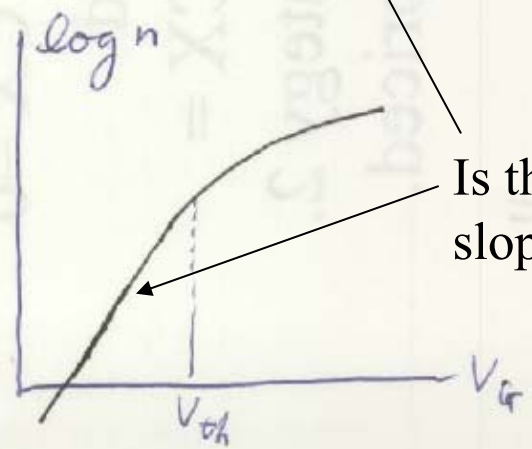
$$n \propto e^{\frac{q\phi_i}{kT}}$$

$$\frac{q\phi_i}{kT} = \frac{qV_G}{kT} \cdot \frac{C_{ox}}{C_{ox}+C_d} = \frac{qV_G}{\frac{C_{ox}+C_d}{C_{ox}}\,kT}$$

$$= \frac{qV_G}{\left(1+\frac{C_d}{C_{ox}}\right)kT} \equiv \frac{qV_G}{\xi kT}$$

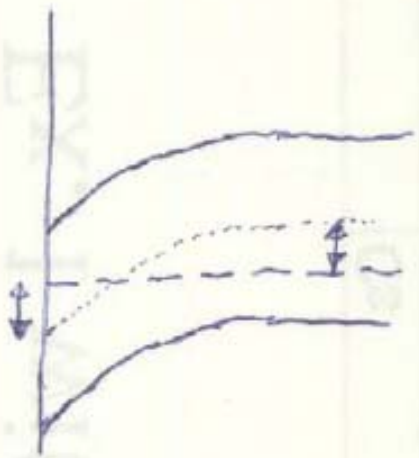
$$\xi = 1 + \frac{C_d}{C_{ox}} > 1$$





Is there a way to make this slope steeper?

Again, V_{th} is <u>NOT</u> well defined.

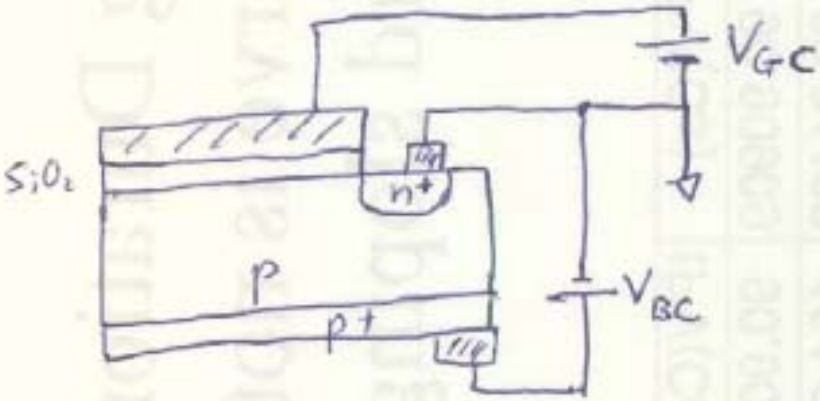


Common definition of V_{th}:

The V_G that makes the surface to be n as much as the bulk is p.

Kind of arbitrary.

What if we add a contact to access the channel?



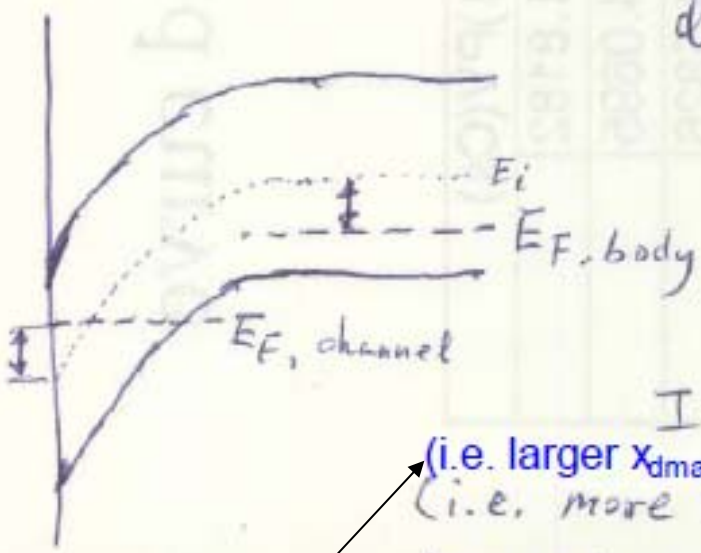
V_{GC}: G-to-Channel bias.

V_{BC}: Body-to-channel bias.

$V_{BC} < 0$.

Channel & Body NOT in Equil.

Channel & Body have different E_F's.



$E_{F,body} - E_{F,channel}$

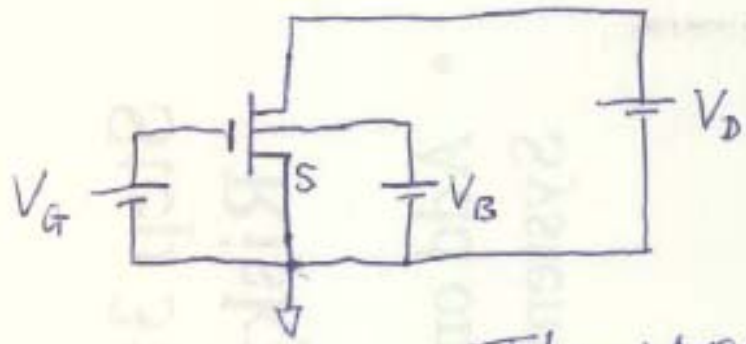
$= |V_{BC}|$

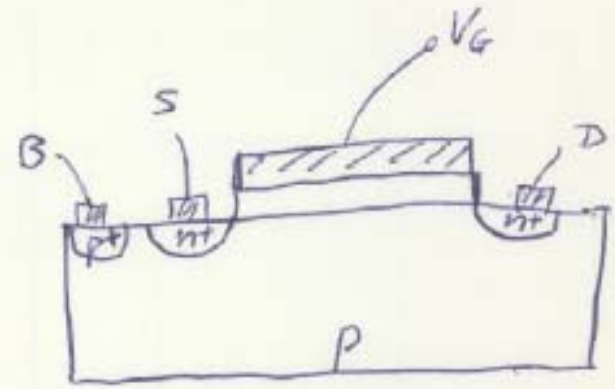
It now takes a larger V_{GC} (i.e. more band bending) to reach inversion. $\Rightarrow V_{th} \uparrow$: Body effect

(i.e. larger x_{dmax} --> larger Vox needed)

Use Gauss's law to think about this.

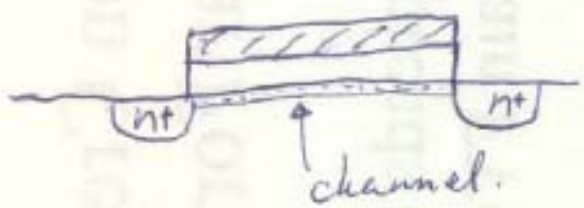
□ MOSFET IV





The MOSFET is a 4-termial device.

Body effect varies V_{th} (only!).

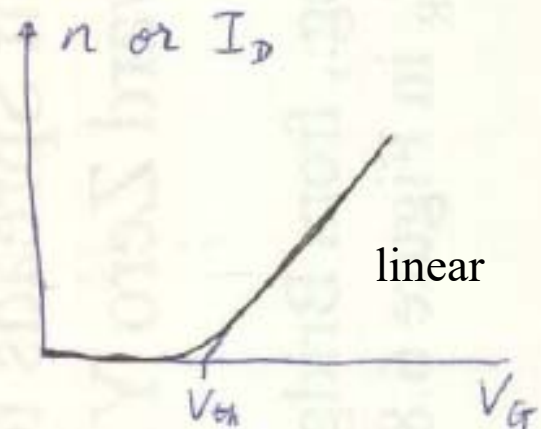


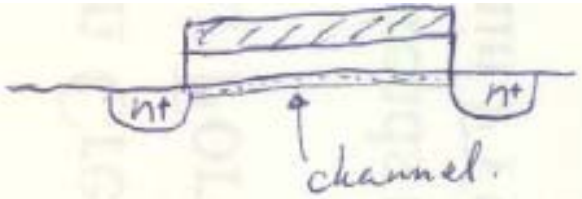
When V_D is very small, the channel is almost uniform from S to D.

$\sigma = q n \mu$

The channel is just a V_G-controlled resistor.

"transfer characteristics"

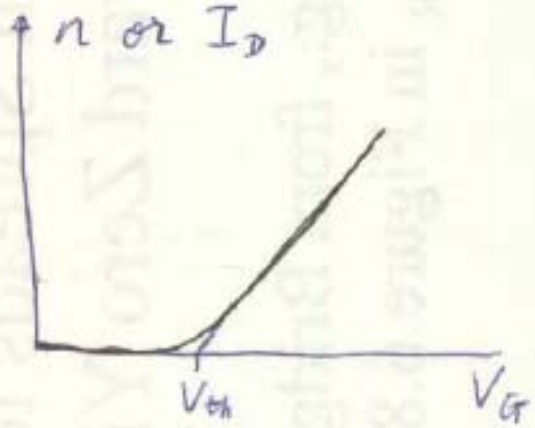




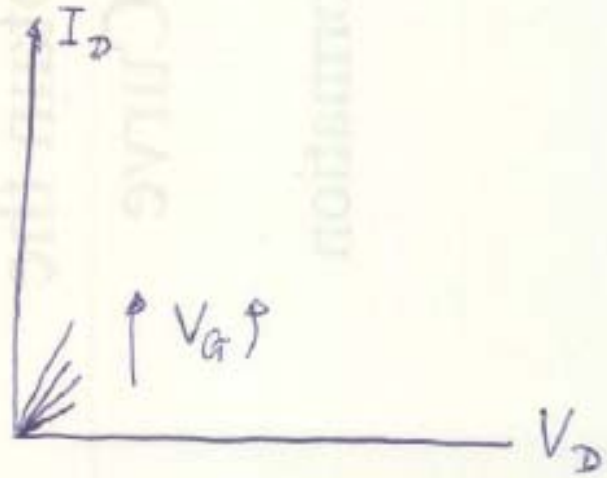
the channel is almost uniform from S to D.

$\sigma = q n \mu$

The channel is just a V_G-controlled resistor.

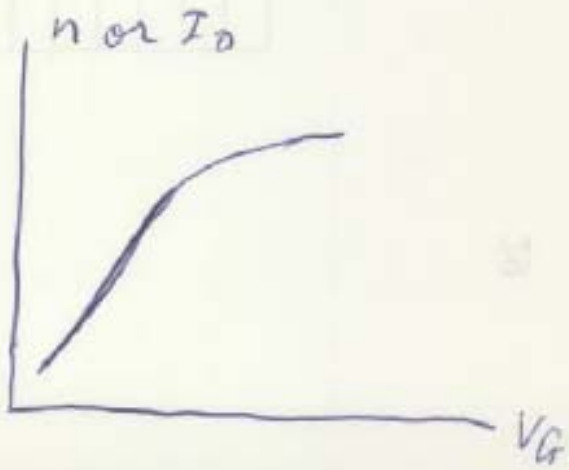


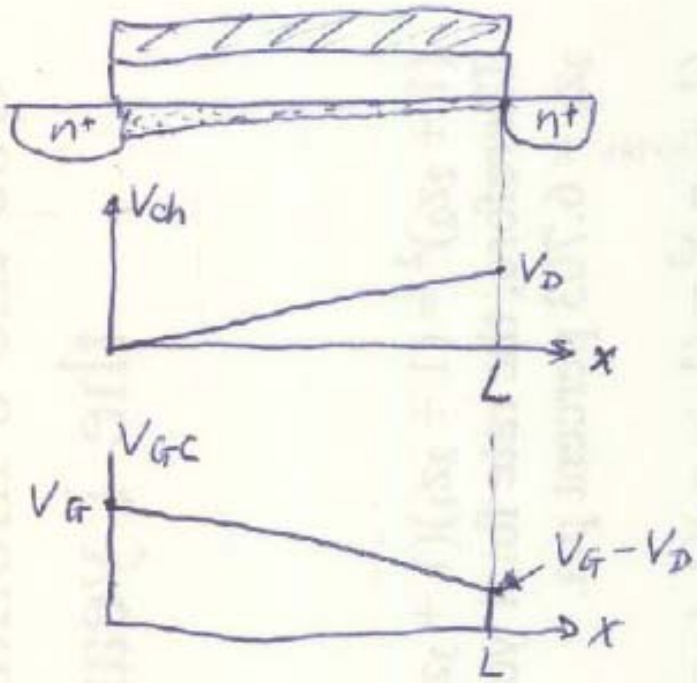
"Transfer" curve.



"Output" curves

Subthreshold.





At larger V_D:

$n(x) \downarrow$ as $x \to L$.

So, output curves bend down.

When $V_G - V_D = V_{th}$,

$n(x=L) = 0$.

"pinch-off"

when $V_G - V_D = V_{th}$,

$n(x=L) = 0$.

"pinch-off"

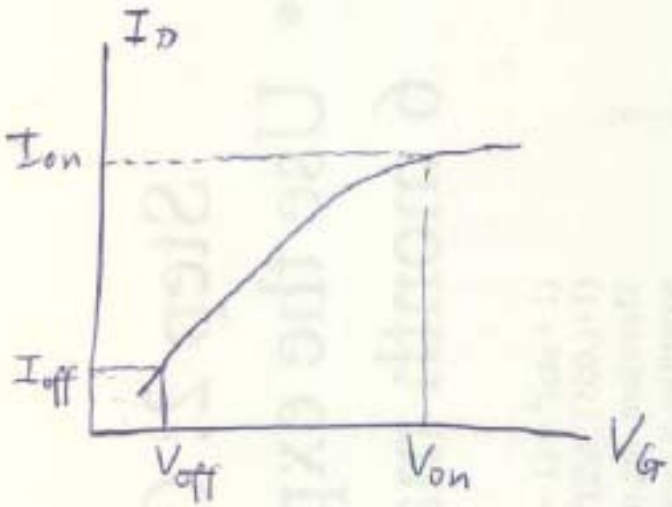
when $V_G - V_D > V_{th}$, I_D no longer ↑ with V_D.

"Saturation" regime.

$$I_D \propto (V_G - V_{th})^2$$

$$g_m = \frac{dI_D}{dV_G} = \mu C_{ox} \frac{W}{L} (V_G - V_{th})$$

☐ Comments on the sub-V_{th} regime.



$$I \propto e^{\frac{qV_G}{\xi kT}}$$

$$\xi = 1 + \frac{C_d}{C_{ox}}$$

Best limit: $\xi = 1$

$$\frac{d}{dV_G} \log I = \frac{1}{60} \text{ dec/mV}$$

— sub-V_{th} slope.

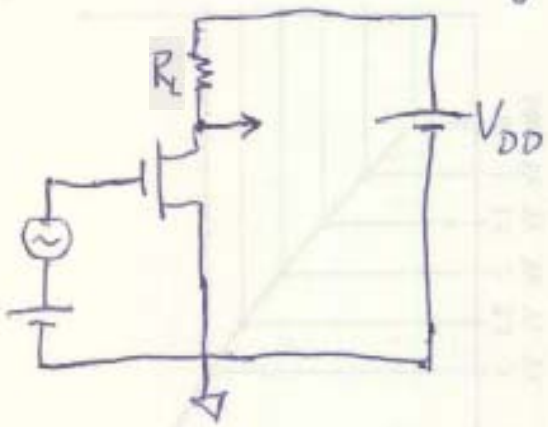
$$\frac{dV_G}{d(\log I)} = 60 \text{ mV/dec}$$

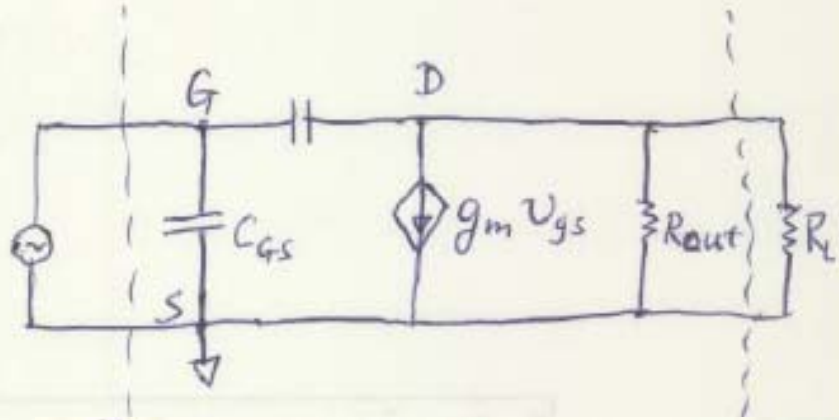
— sub-V_{th} swing.

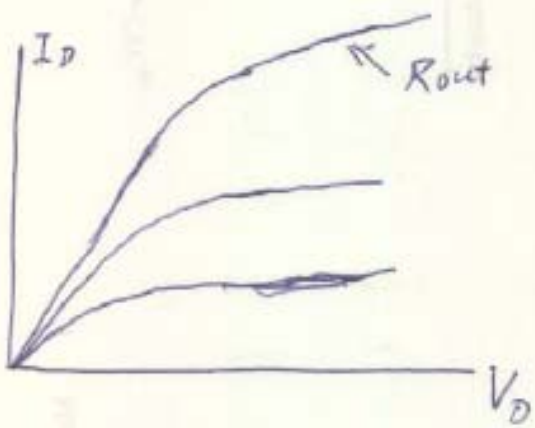
It's a hot research area to come up with new devices w/ swing < 60 mV/dec.

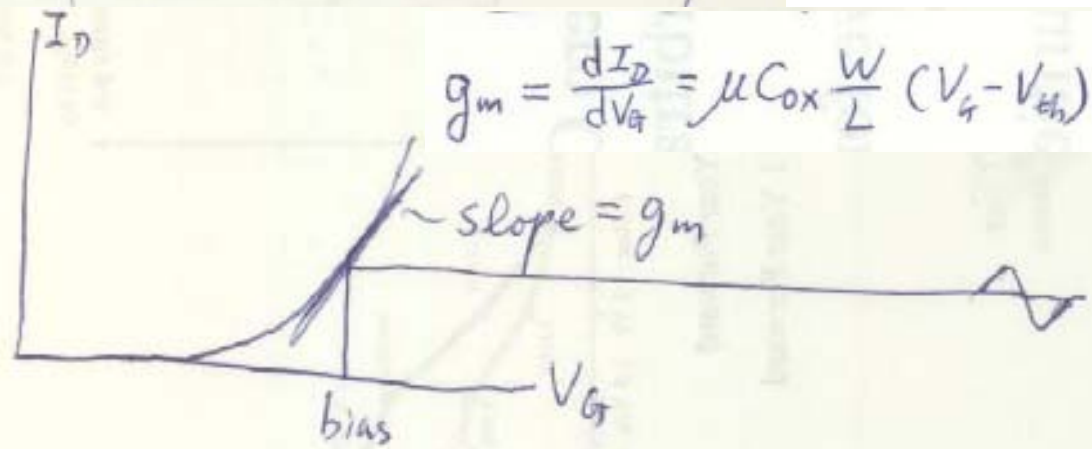
□ Small-signal equivalent ckt

Saturation regime used in amplifiers









Gain = $g_m R_L$