**Lecture 25**: $V_t$ Implant
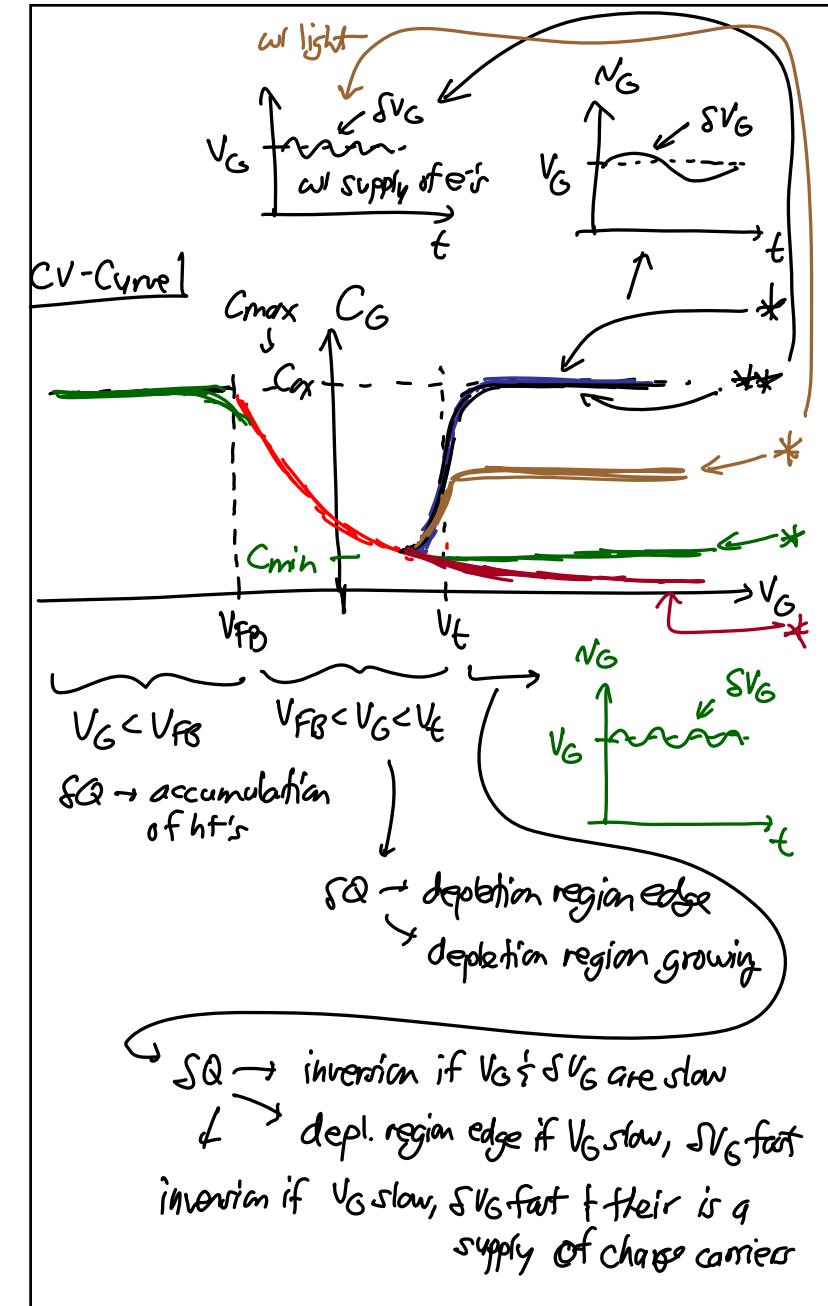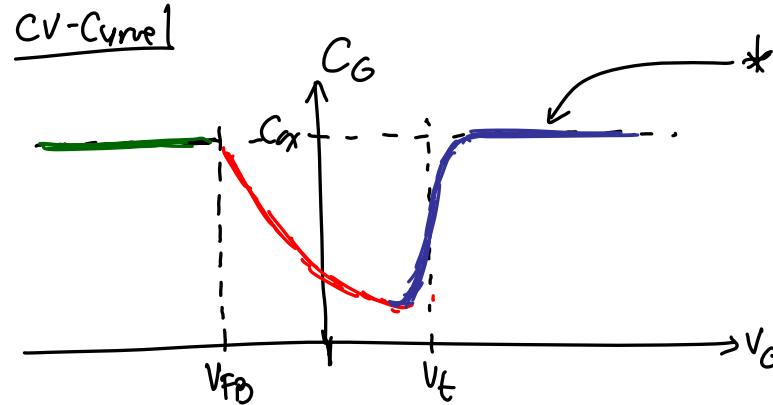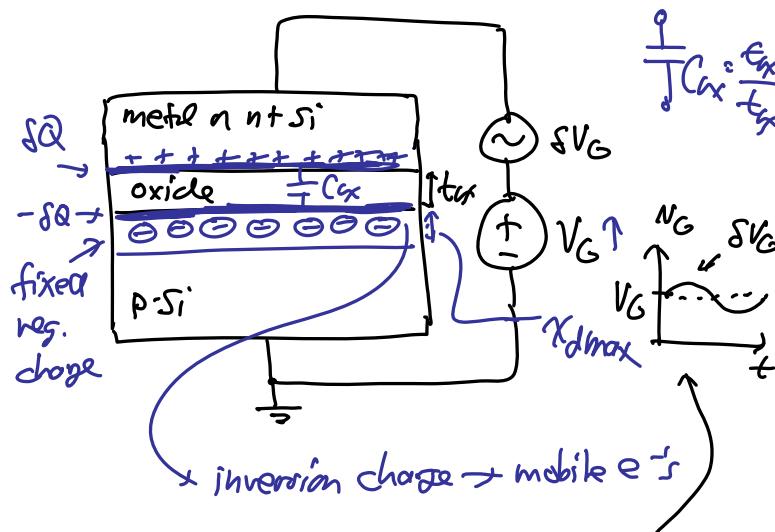
- **Announcements**:
- Congratulations on turning in your Lab 1 Report
- Lab 2 Report will be due Friday, Dec. 12 (during the RRR week), 7 p.m.
- HW#11 due Tuesday, next week, at 8 a.m.
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- **Lecture Topics**:
  - ↳ MOS CV
  - ↳ Extracting gate oxide thickness, $x_{ox}$
  - ↳ Extracting substrate concentration, $N_A$
  - ↳ Problems when measuring CV Curves
  - ↳ MOS CV problems & solutions
  - ↳ Threshold Implant
    - — Threshold voltage
    - — Needed $\Delta V_t$
    - — $V_t$ Implant Cases
- ----------------------------------------
- **Last Time**:





$V_G < V_{FB}$  $V_{FB} < V_G < V_t$

$\delta Q \to$ accumulation of ht's

$\delta Q \to$ depletion region edge
↳ depletion region growing

$\delta Q \to$ inversion if $V_G$ & $\delta V_G$ are slow
↳ depl. region edge if $V_G$ slow, $\delta V_G$ fast
inversion if $V_G$ slow, $\delta V_G$ fast + their is a supply of charge carriers

**Left panel:**

Case: $V_G > V_t$

$\frac{1}{C_{ox}} = \frac{\varepsilon_{ox}}{t_{ox}}$

metal or n+ Si

oxide — $C_{ox}$, $t_{ox}$

$\delta Q$

$-\delta Q$ fixed neg. charge

p-Si

$\delta V_G$

$V_G \uparrow$

$N_G$ $\delta V_G$

$V_G$ ... $t$

$x_{dmax}$

→ inversion charge → mobile e⁻'s

Case: $V_G \uparrow$ slowly, $\delta V_G$ varies slowly, i.e., at low frequency → slow enough for the inversion layer to form

*

Case: $V_G \uparrow$ slowly, $\delta V_G$ varies fast, i.e., high frequency.

→ inversion layer Q cannot vary fast enough

→ $\delta Q$ to support $\delta V_G$ does not occur at the inversion layer at the Si-SiO₂ interface, but rather @ the depletion region edge!

**Right panel:**

*

$\delta Q$

metal or n+ Si

$+ + + + + + + + +$

oxide

$\ominus \ominus \ominus \ominus \ominus$   $x_{ox}$

inversion charge

$-\delta Q$

p-Si

$\delta V_G$ $\longrightarrow$ $t$

$V_G$

$V_G$

$V_t$ $\longrightarrow$ $t$

$\begin{cases} \frac{1}{C_{ox}} = \frac{\varepsilon_{ox}}{x_{ox}} \\ \frac{1}{C_{Dmin}} = \frac{\varepsilon_{Si}}{x_{dmax}} \end{cases}$

$C_{min}$

$x_{dmax}$ (max depl. layer thickness)

$x_{dmax} = \sqrt{\frac{2\varepsilon_{Si}}{q}\frac{1}{N_A} 2|\phi_f|}$

~0.3V
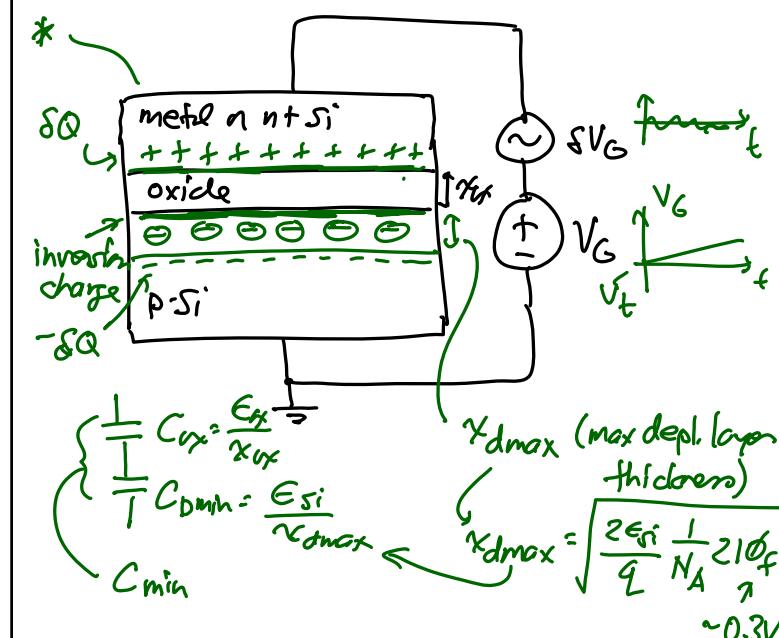
HF CV curve

→ Special Case: If there is a supply of e⁻'s nearby

** → then, inversion layer can steal the e⁻'s & support a fast $\delta V_G$

$V_G$

n+

n+

no matter how fast the $\delta V_G$

p-Si

← supply of e⁻'s
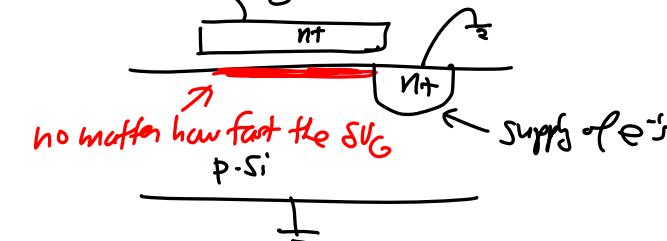
Another way to generate e⁻'s: light! $\longrightarrow$ *

Case: $V_G \uparrow$ fast, $\delta V_G$ varies fast (e.g., high freq.)

↳ now, $V_G \uparrow$ fast → too fast for the inversion layer to even form! (assuming no n+ junction & no light)

$+\delta Q$

metal or n+ Si
$+ + + + + + + +$
oxide
$\ominus \ominus \ominus \ominus \ominus \ominus \ominus$
p-Si
$-\delta Q$

$\dfrac{1}{\top} C_{ox} = \dfrac{\epsilon_{ox}}{x_{ox}}$

$\top C_D = \dfrac{\epsilon_{si}}{x_d(V_G)}$

$\delta V_G$

$V_G \rightarrow$

$x_d(V_G) > x_{dmax}$ (depl. region keeps getting bigger)

↳ thir drops below $C_{Dmin}$
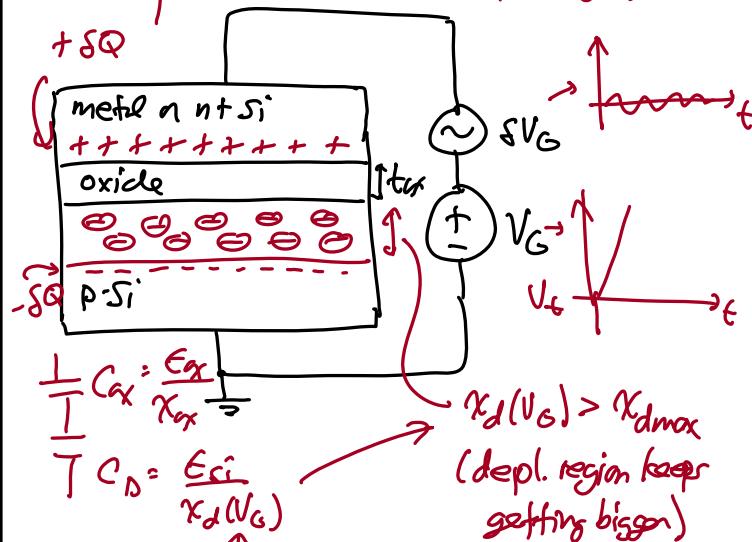
Practical CV
↳ using CV curves

① Determine $x_{ox}$: (Gate Oxide Thickness)

$\leftarrow C_{max}$ ← HF CV Curve

$C_{min}$ → $V_G$

$C_{max} = A \times C_{ox} = A \times \dfrac{\epsilon_{ox}}{x_{ox}}$ ← solve for $x_{ox}$

↑ area   ↑ known   ↓ Known
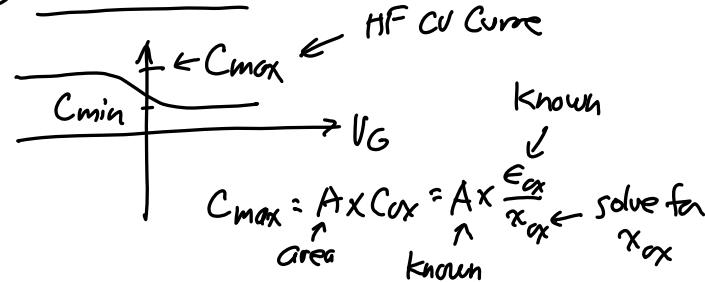
② Determine $N_A$: (substrate doping conc.)

$C_{max}$ $AC_{Dmin}$ $= C_{min}$

$\dfrac{1}{C_{min}} = \dfrac{1}{C_{max}} + \dfrac{1}{AC_{Dmin}}$

where $C_{Dmin} = \dfrac{\epsilon_{si}}{x_{dmax}} = \dfrac{\epsilon_{si}}{\sqrt{\dfrac{2\epsilon_{si}}{q} \dfrac{1}{N_A} (2\phi_d)}}$

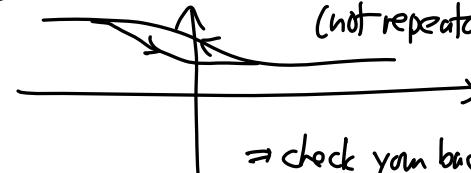↳ solve for $N_A$

③ Determine $V_{FB}$: (flatband voltage)

$\dfrac{1}{C_{FB}} = \dfrac{1}{C_{max}} + \dfrac{1}{A \dfrac{\epsilon_{si}}{L_D}}$

$\left( L_D = \text{Debye length} = \sqrt{\dfrac{2\epsilon_{si}}{q} \dfrac{1}{N_A} \left(\dfrac{kT}{q}\right)} \right)$
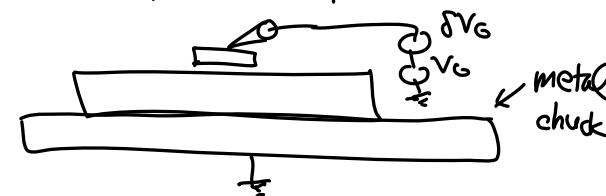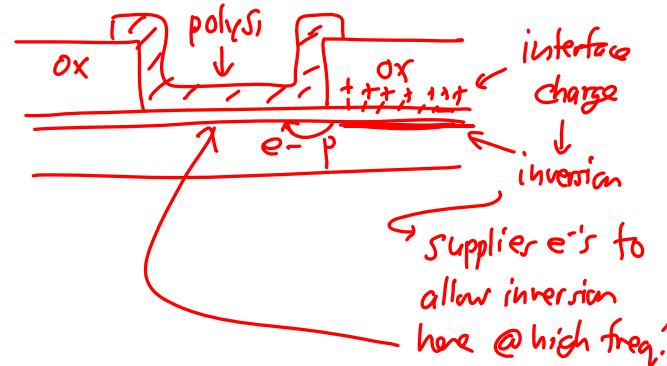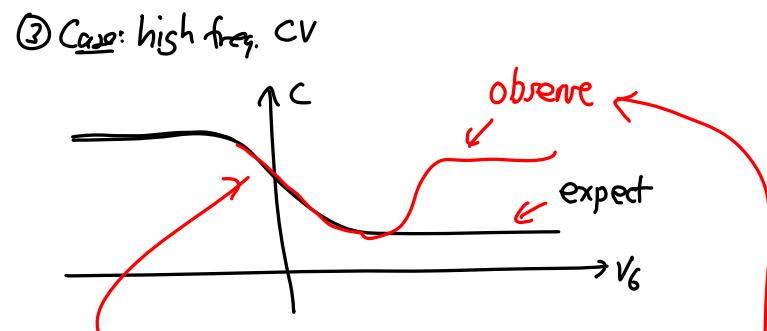
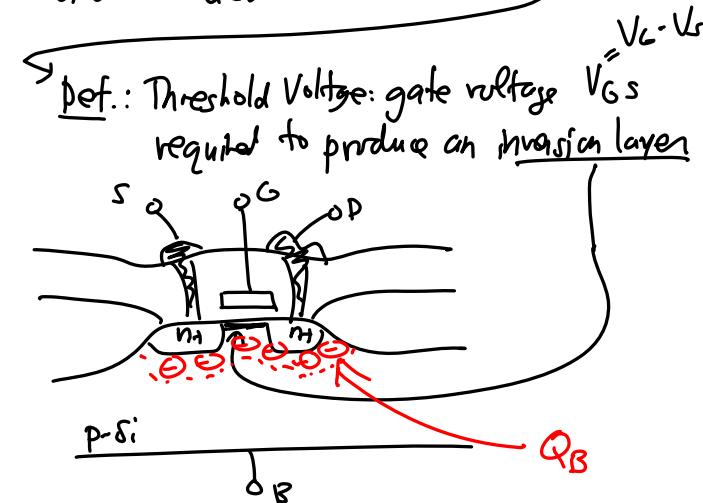↳ then get $V_{FB}$...

Problems w/ CV

① → drifts around (not repeatable)

⇒ check your backside contact

$\delta V_G$
$V_G$
← metal chuck

② 

C

observe

expect

→ $V_G$

⇒ bad Si-SiO₂ : lots of surface states
  ↳ not enough sintering!

③ Case: high freq. CV

C

observe

expect

→ $V_G$

Why?
⇒ light?
⇒ field inversion

polySi

ox          ox
      interface charge

e⁻  p        inversion

→ supplies e⁻'s to allow inversion here @ high freq.

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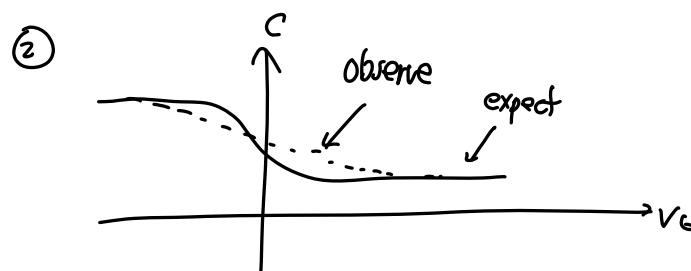
**Threshold Implant**

⇒ implant to tailor/adjust the threshold voltage $V_t$ of an MOS device

Def.: Threshold Voltage: gate voltage $V_{GS}$
  $= V_G - V_S$
  required to produce an inversion layer

S          G          D

$n+$        $n+$

$Q_B$

p-Si

B

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

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

, where → same as VFB

$\emptyset_{ms}$ = work function difference [in V]
  between gate material and bulk Si

$\psi_s$ = surface potential in Si @ onset of
  strong inversion        → $|\emptyset_f| \sim 0.3V$
  $= 2\emptyset_f$ for uniformly doped substrate

$Q_{ss}$ = oxide charge per unit area @ the oxide-Si interface $[C/cm^2]$

$Q_B$ = charge stored in the depletion region (at the onset of inversion)

$$|Q_B| = \sqrt{2q\epsilon_{si}N_B(2|\phi_f| + |V_{SB}|)} \quad [C/cm^2]$$

conc. in bulk     reverse bias

$$x_{dmax} = \sqrt{\frac{2\epsilon_s}{q}\frac{1}{N_B}(2|\phi_f| + |V_{SB}|)}$$

$C_{ox}$ = gate oxide capacitance per unit area $[F/cm^2]$

Case: $V_{SB} = 0$

$$V_t(V_{SB}=0) = V_{t0} = \phi_{ms} - 2\phi_f - \frac{Q_{ss}}{C_{ox}} - \frac{Q_{B0}}{C_{ox}}$$

$$|Q_{B0}| = \sqrt{2q\epsilon_s N_B(2|\phi_f|)}$$

Then:

$$V_t = \phi_{ms} - 2\phi_f - \frac{Q_{ss}}{C_{ox}} - \frac{Q_B}{C_{ox}}$$

$$= \underbrace{\phi_{ms} - 2\phi_f - \frac{Q_{ss}}{C_{ox}} - \frac{Q_{B0}}{C_{ox}}}_{V_{t0}} - \frac{Q_B - Q_{B0}}{C_{ox}}$$

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

$$\gamma = \frac{1}{C_{ox}}\sqrt{2q\epsilon_{si}N_B}$$

Signs in the $V_t$ Equation:

| Parameter | NMOS | PMOS |
|---|---|---|
| Substrate | p-type | n-type |
| $\phi_{ms}$: | | |
|   metal gate | − | − |
|   n+ Si gate | − | − |
|   p+ Si gate | + | + |
| $\phi_f$ | − | + |
| $Q_{B0}$ (a $Q_B$) | − | + |
| $Q_{ss}$ | + | + |
| $\gamma$ | − | + |
| $C_{ox}$ | + | + |

Parameters to Adjust:

① $\psi_s = 2\Phi_f$:    $\Phi_f = \frac{kT}{q}\ln\left(\frac{N_D}{n_i}\right)$ for n-substrate  ← n-doping conc.

intrinsic conc.    $\Phi_f = \frac{kT}{q}\ln\left(\frac{n_i}{N_A}\right)$ for p-substrate
↗ for undoped Si        ↗ p-doping conc.

These are logarithmic w/ doping conc.!
i.e., 10X increase in $N_B \rightarrow 2.3\frac{kT}{q} \sim 60\,mV$  } very small change

∴ $\Phi_f$ not a good way to adjust $V_t$

② $\Phi_{ms} = \Phi_{f(sub)} - \Phi_{f(gate)} \rightarrow$ ineffective for the same reason as

③ $|Q_B| = \sqrt{2q\epsilon_s N_B\,(2|\Phi_f| + |V_{SB}|)}$    ✳

can increase $|Q_B|$ w/ $N_B\uparrow$
(can set significant $\Delta V_t$ here)

…but if you must increase $|N_B|$ too much:
⟹ problems: ① lower carrier mobility, $\mu\downarrow$
② S/D capacitance ↑
③ lower junction breakdown voltage

✳ → Can also $\Delta V_{SB} \rightarrow \Delta V_t$
↳ impractical → many devices would need to have their own well
for much area!

④ $C_{ox}\downarrow$: but then lose drive

⑤ $\frac{Q_{ss}}{C_{ox}}$: $Q_{ss}$ due to oxide-Si interface charge

not controllable (easily)
↑ want to minimize

↳ but if we could introduce a controlled amount of $Q_{ss} \rightarrow$ best way to set $\Delta V_t$

Ex. Threshold implant for NMOS
↳ enhancement implant

$V_t = V_{FB} - 2\Phi_f - \frac{Q_B}{C_{ox}}$  } starting $V_t$ (before implant)
     (−)    (−)     (−)

← n+ polysi ($10^{20}\,cm^{-3}$)

p-Si: $10^{15} - 10^{16}\,cm^{-3}$

read this!

$\Delta V_t = 0.8V$

← $V_t = 0.7V$

← −0.1V

$\frac{|Q_B|}{C_{ox}} \approx 0.1 \rightarrow 0.2V$ (for $N_A = 10^{15}\,cm^{-3}$, $t_{ox} = 20\,nm$)

$2|\Phi_f| = 0.6V$

← −0.9V

$\Phi_{ms} = V_{FB} = \Phi_{f(sub)} - \Phi_{f(gate)} \approx -0.9V$

$V_t$

$\Delta V_t \propto \sqrt{D_I}$ } looks like $N_B \uparrow$

$\rightarrow \Delta V_t \sim \Delta Q_B$

$\Delta V_t$ {

$V_{to}$

$\Delta V_t = q \frac{D_I}{C_{ox}}$ } looks like $\frac{Q_{ss}}{C_{ox}}$

$D_I$ (implanted dose in $cm^{-2}$)

$\rightarrow x_s < x_{dmax}$

Case: $D_I$ Completely contained within depletion region

$D_I \rightarrow$ after all diffusion steps

n+  $x_s$

n+

$\rightarrow x_s > x_{dmax}$

Case: $D_I$ depth contains the depletion region

$D_I$

n+

n+

$\downarrow x_s$

$\log N(x)$

$N_0$

$\frac{1}{2} N_0 = N_s$

$\leftarrow$ profile after implant & drive-in

$x_s$  $x$

$\leftarrow$ Compare $x_s$ w/ depletion region depth