MOS Capacitors

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Announcements

- Welcome to the second half of EE105!
- Professor Muller will be lecturing

- Midterm 1 handed back today
- Mean = 71.8 /100
- Median = 76/100
- Standard Dev = 16.9

- Midterm 2 on Thursday, March 23 in lecture
- DOWNLOAD NEW HW
- Attend discussion sessions! They are helpful for homework, exam reviews and topics not covered in lecture.

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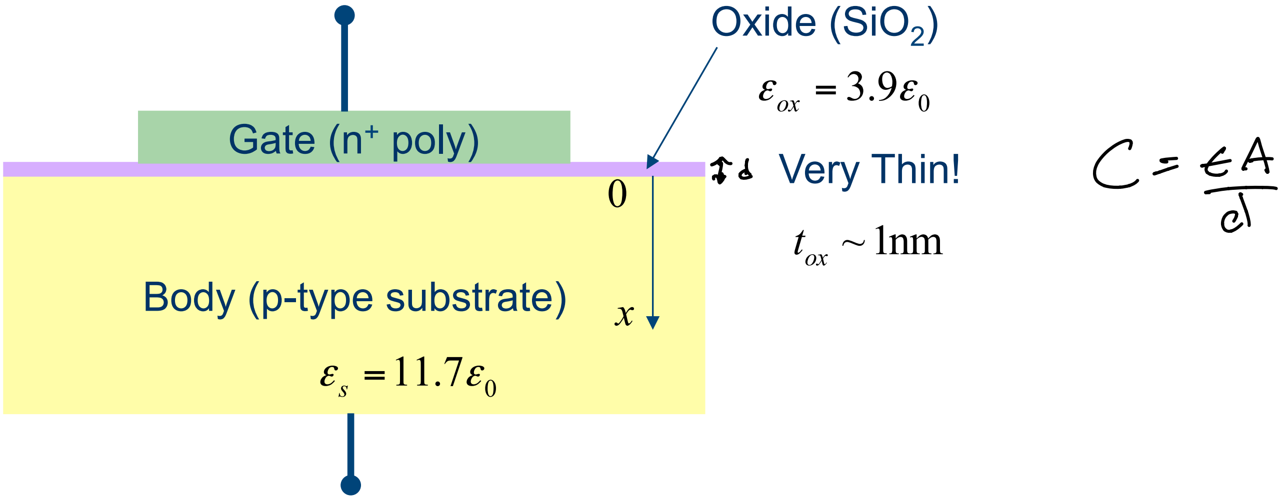
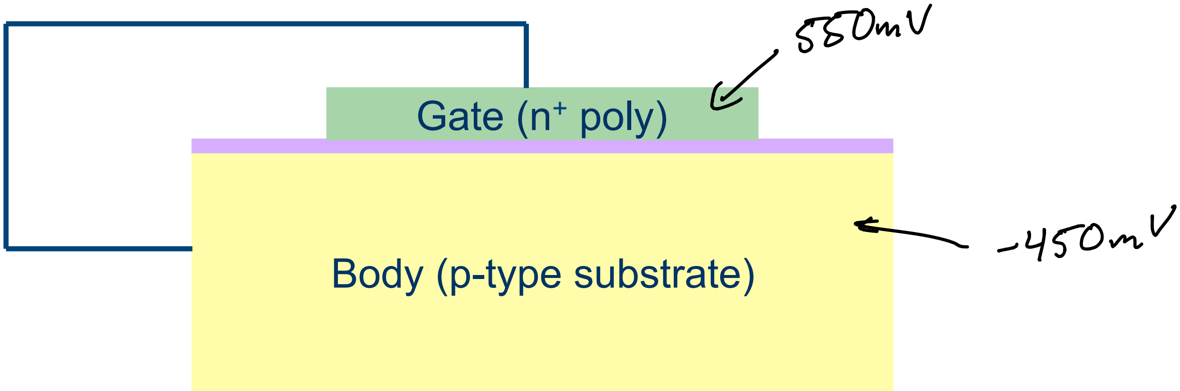
MOS Capacitor



- MOS = Metal Oxide Semiconductor
- Sandwich of conductors separated by an insulator
- "Metal" is more commonly a heavily doped polysilicon (poly-Si) layer n^+ or p^+ layer
  - *Was metal (e.g. Al) until ~1970 but changed to poly-Si due to high temperature processing. After 2008, metal gates have been reintroduced! Learn more about MOS process technology in EE130 & EE143*
- NMOS → p-type substrate, PMOS → n-type substrate

Metal-Oxide-Semi Junction

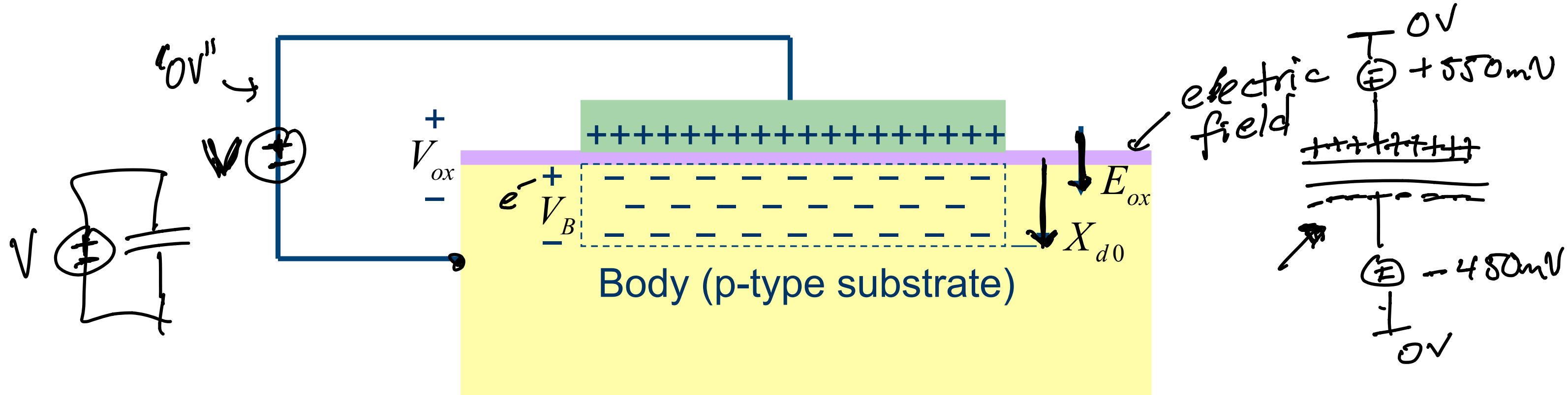


- Under thermal equilibrium, the n-type poly gate is at a higher potential than the p-type substrate

$$\phi_p = -\frac{kT}{q}\ln\frac{N_a}{n_i} \qquad \phi_{poly,n^+} = \frac{kT}{q}\ln\left(\frac{N_{d,poly}}{n_i}\right) \approx 550\text{mV}$$

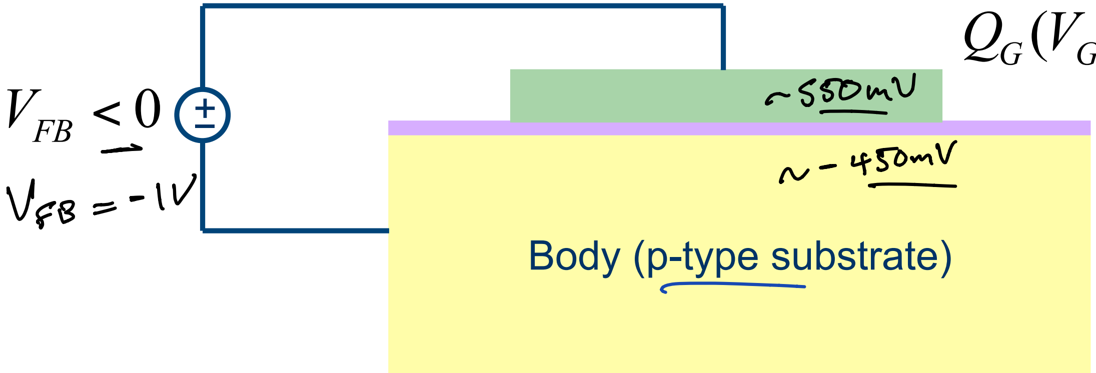
- No current can flow because of the insulator but this potential difference is accompanied with an electric field
- Fields terminate on charge!

Fields and Charge at Equilibrium

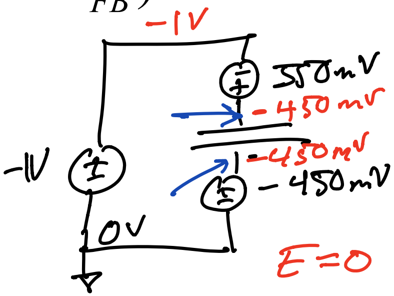


- At equilibrium there is an electric field from the gate to the body
- Need a positive charge on the gate, negative charge in substrate
- Since body is p-type, negative charges in the body come from a depletion region

Flat Band Voltage, $V_{GB} = V_{FB}$



$$Q_G(V_{GB} = V_{FB}) = 0$$

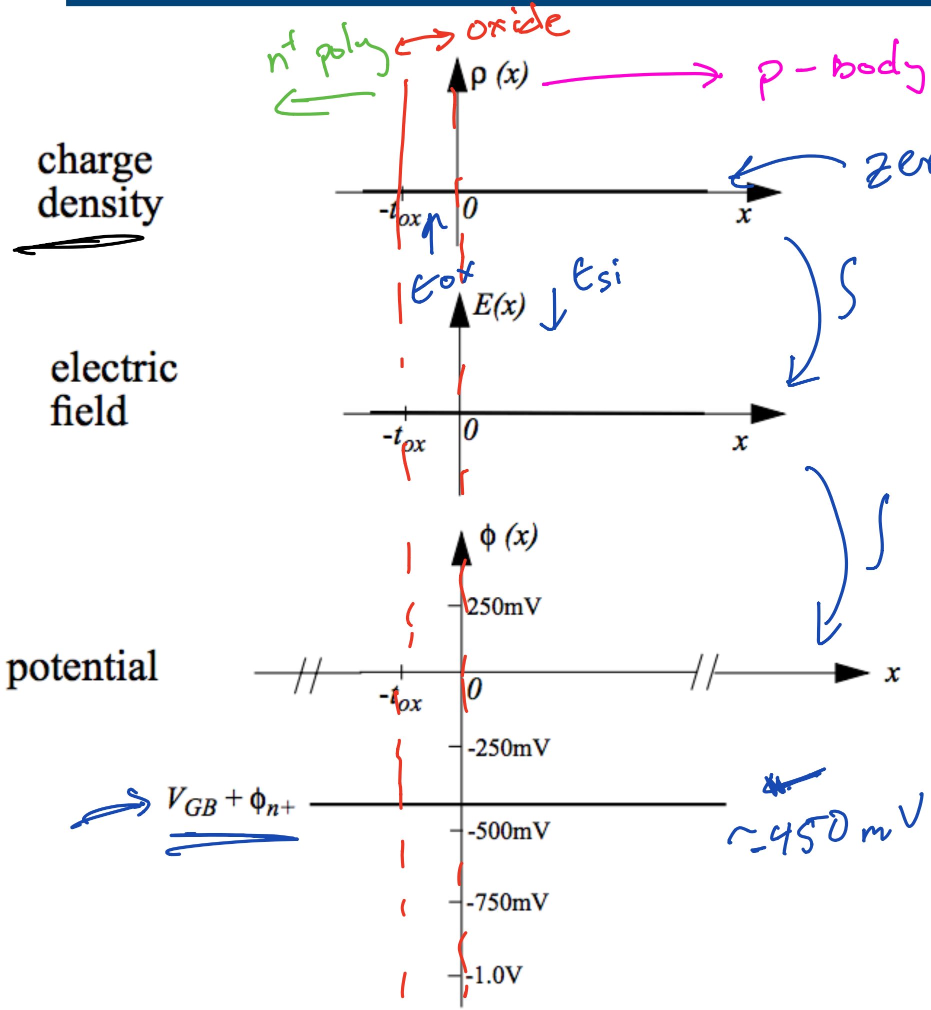


- If we apply a bias, we can compensate for this built-in potential

$$V_{FB} = -(\phi_{n^+} - \phi_p)$$

- In this case the charge on the gate goes to zero and the depletion region disappears
- In solid-state physics lingo, the energy bands are "flat" under this condition

Flat Band Voltage, $V_{GB} = V_{FB}$

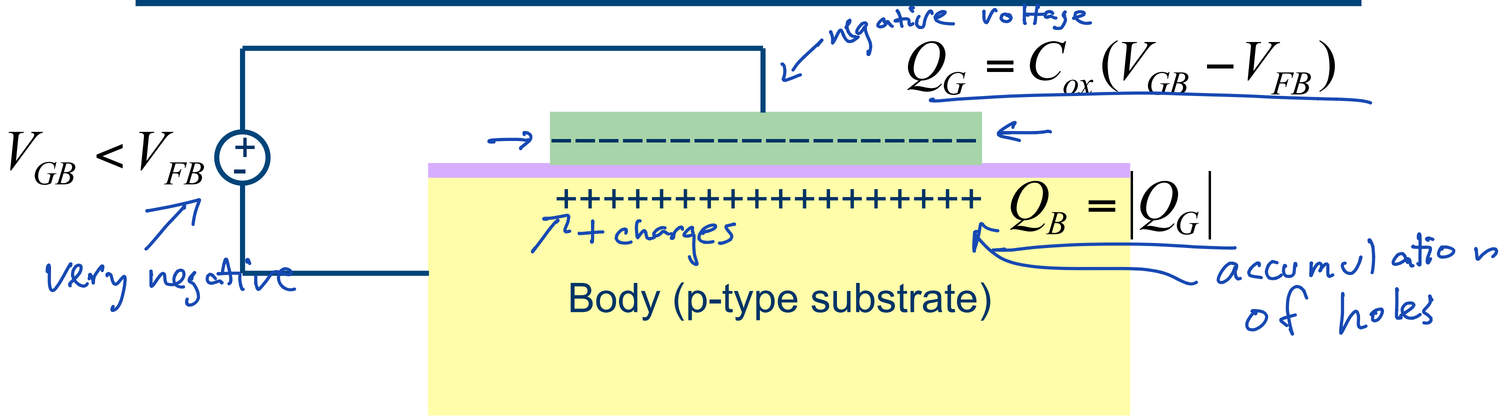


$$\frac{dE}{dx} = \frac{\rho}{k\epsilon_0} \qquad E = \int \frac{\rho}{k\epsilon_0} dx$$

$$E = -\frac{\partial \phi}{dx} \qquad \phi = -\int E\,dx$$

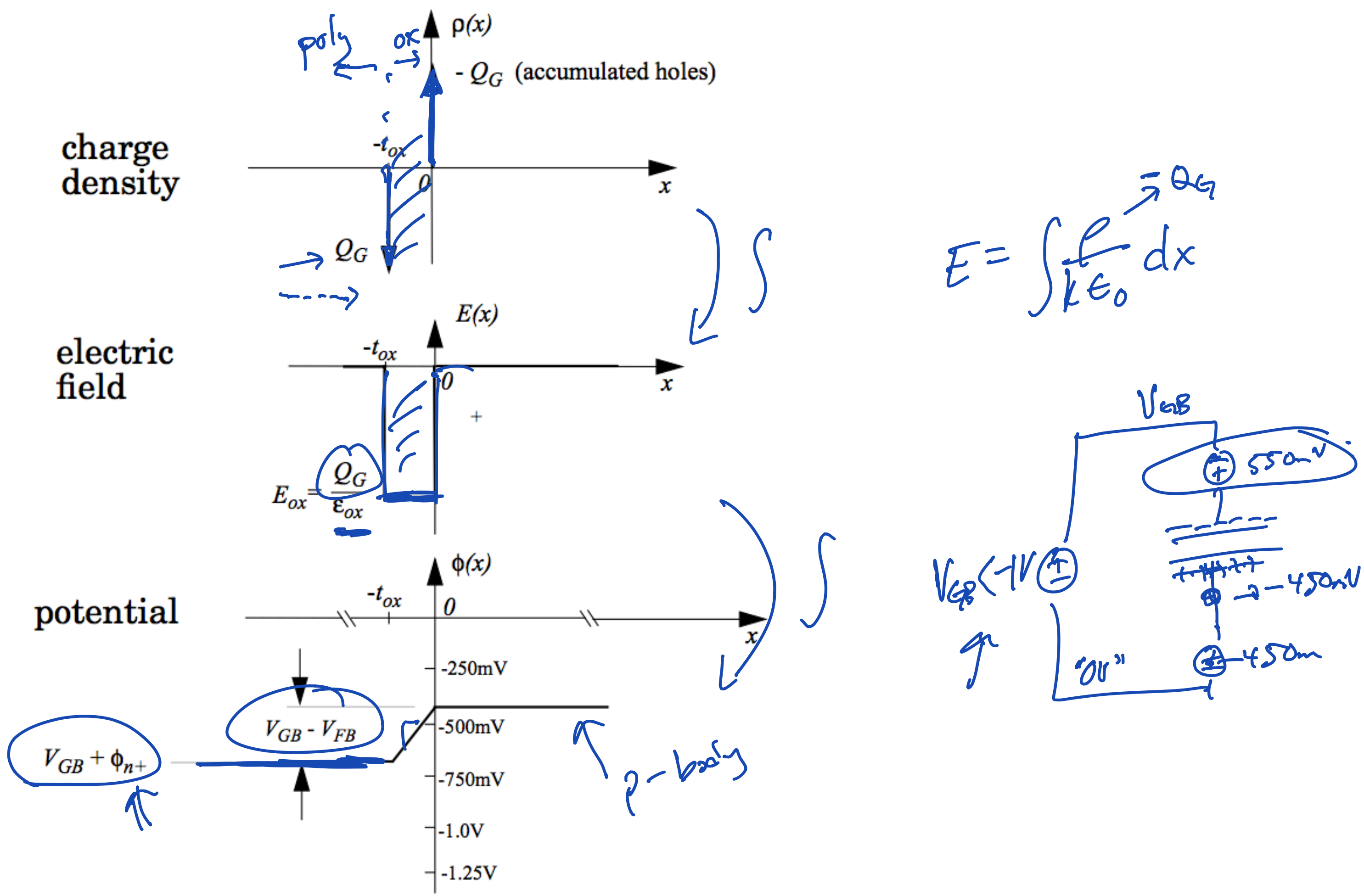
$+C$

Accumulation, $V_{GB} < V_{FB}$

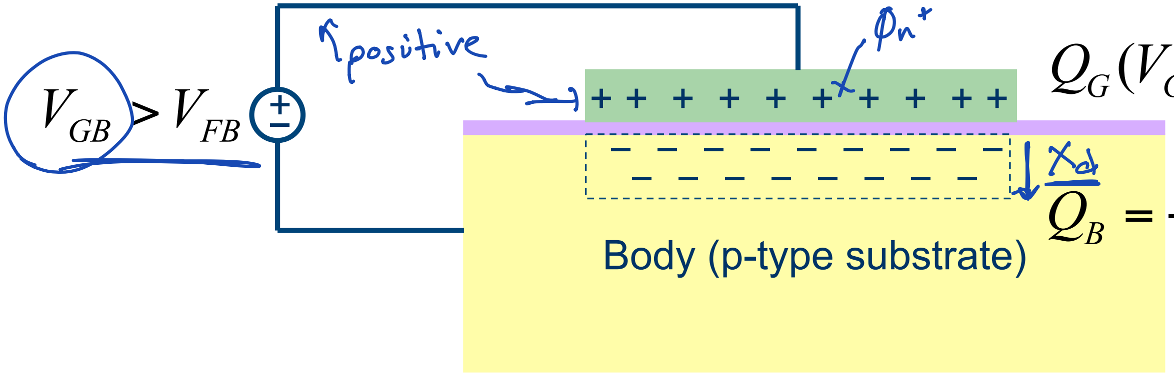


- If we further decrease the potential beyond the "flat-band" condition, we essentially have a parallel plate capacitor
- Plenty of holes and electrons are available to charge up the plates
- Negative bias attracts holes under gate

Accumulation, $V_{GB} < V_{FB}$



Depletion, $V_{GB} > V_{FB}$



$$Q_G(V_{GB}) = -Q_B$$

$$Q_B = -qN_a X_d(V_{GB})$$

- Similar to equilibrium, the potential in the gate is higher than the body
- Body charge is made up of the depletion region ions
- Potential drop across the body and depletion region

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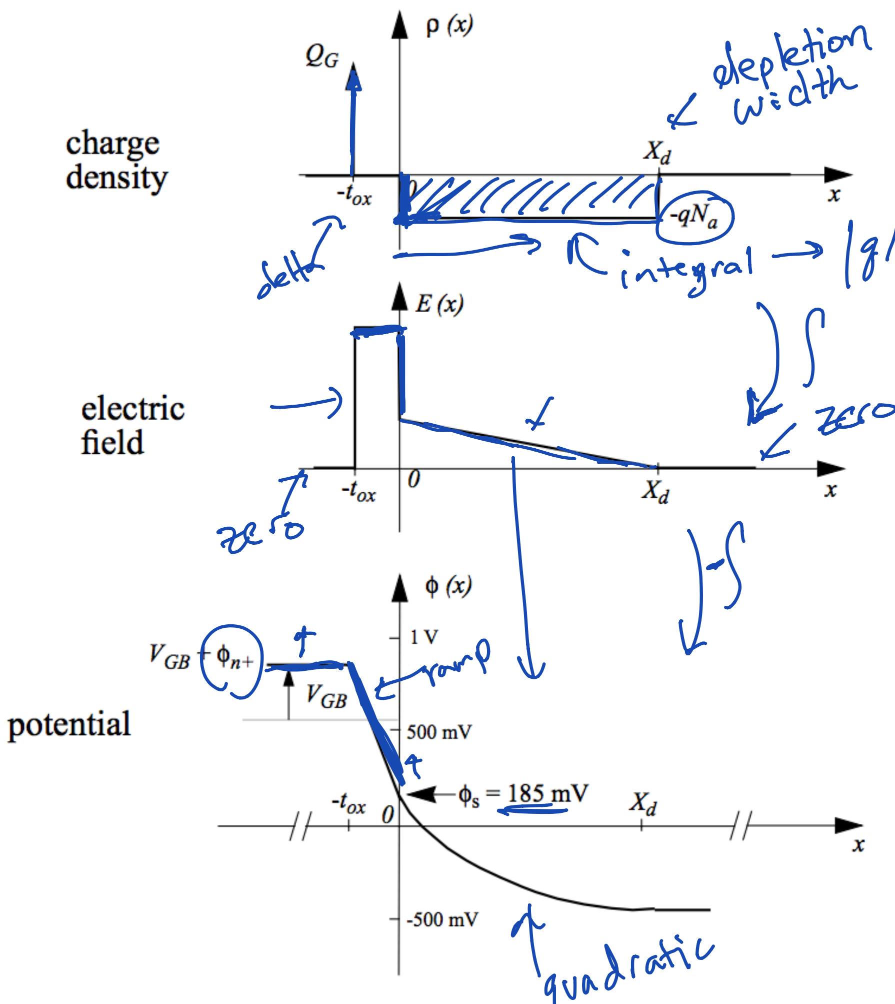
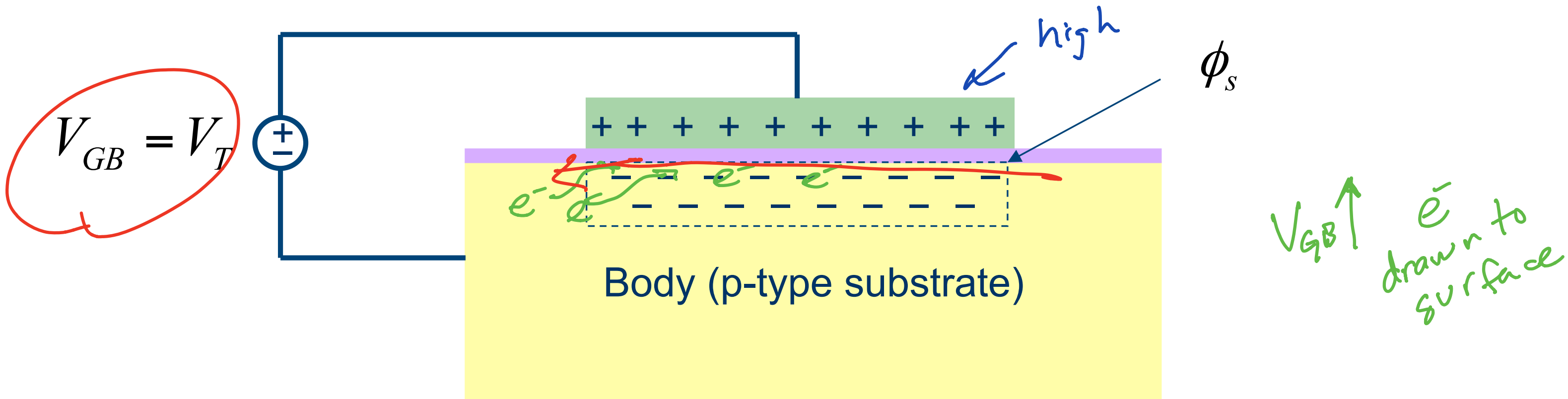
Depletion, $V_{GB} > V_{FB}$



ϕ_S = surface potential

Inversion, $V_{GB} > V_T$



- As we further increase the gate voltage, eventually the surface potential increases to a point where the electron density at the surface equals the background ion density

$$n_s = n_i e^{\frac{q\phi_s}{kT}} = N_a \longrightarrow \phi_s = -\phi_p$$

- At this point, the depletion region stops growing and the extra charge is provided by the inversion charge at surface
- "Inversion" meaning that the surface is effectively n-type

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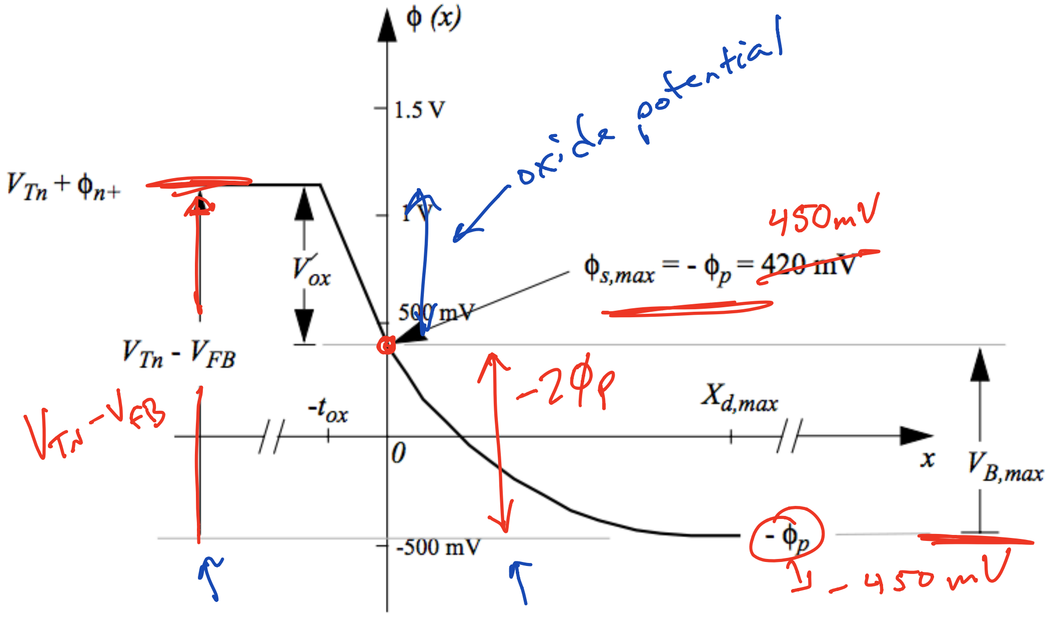
Inversion, $V_{GB} > V_T$

threshold voltage

$$\phi_{s,\,max} = -\phi_p$$



Threshold Voltage

- The threshold voltage is defined as the gate-body voltage that causes the surface to change from p-type to n-type
- For this condition, the surface potential has to equal the negative of the p-type potential
- We can derive that this voltage is equal to:

oxide potential

$$V_{Tn} = V_{FB} - 2\phi_p + \frac{1}{C_{ox}}\sqrt{2q\varepsilon_s N_a(-2\phi_p)}$$

in depletion

$q N_a X_d$

$V_{TN} - V_{FB} = 2\phi_p$

$\phi_{ox} = E_{ox} t_{ox} = \frac{-Q}{C_{ox}}$

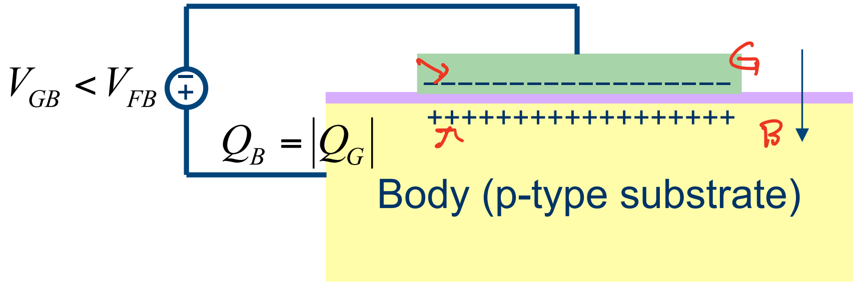
$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$

$Q_{ox} \rightarrow q N X_d = \sqrt{q N_a 2 \epsilon_s \phi_s}$

Recap Accumulation: $V_{GB} < V_{FB}$

≈1V

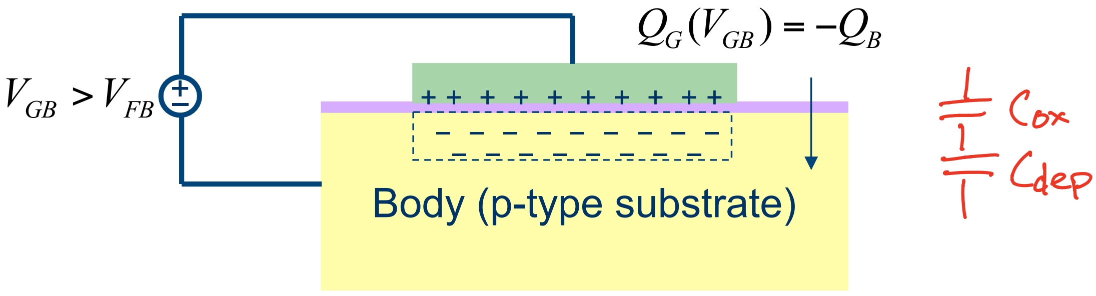
$$Q_G = C_{ox}(V_{GB} - V_{FB})$$



- Essentially a parallel plate capacitor
- Capacitance is determined by oxide thickness

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

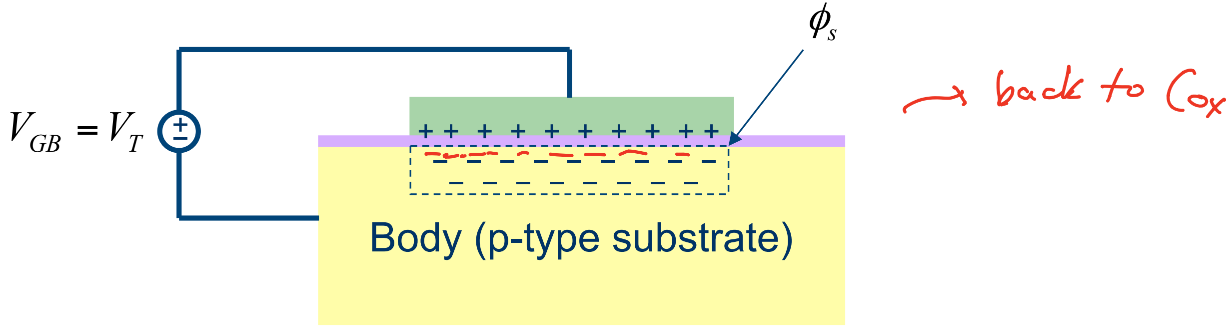
Recap Depletion: $V_{FB} < V_{GB} < V_T$



$$Q_B = -qN_a X_d(V_{GB})$$

- Positive charge on gate terminates on negative charges in depletion region
- Potential drop across the oxide and depletion region
- Charge has a square-root dependence on applied bias

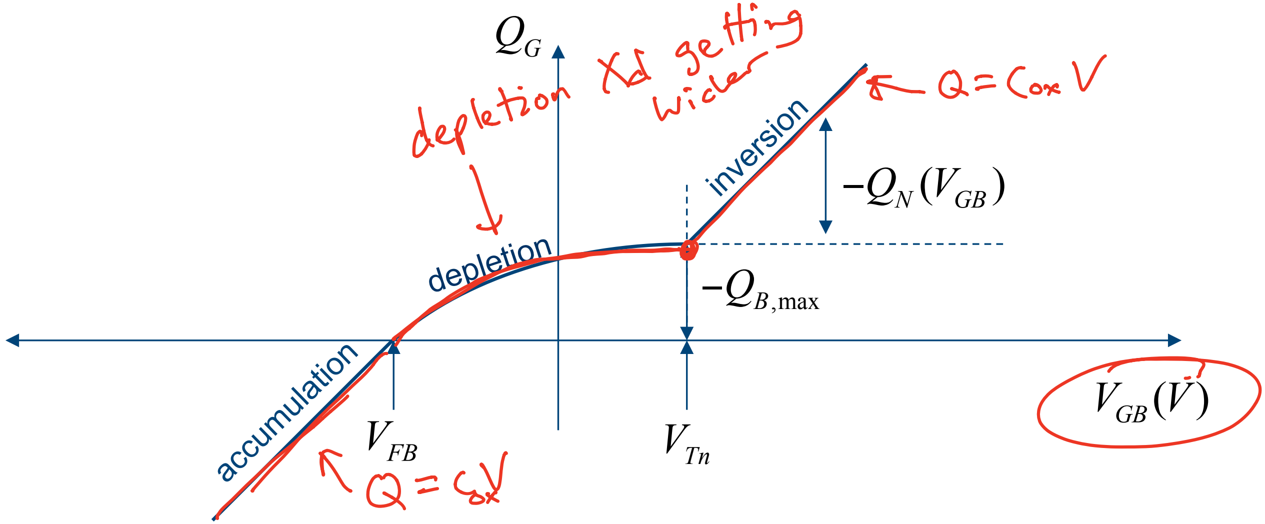
Recap Inversion: $V_{GB} > V_T$



$$n_s = n_i e^{\frac{q\phi_s}{kT}} = N_a$$

- The surface potential increases to a point where the electron density at the surface equals the background ion density
- At this point, the depletion region stops growing and the extra charge is provided by the inversion charge (electrons) at the surface

Q-V Curve for MOS Capacitor



- In accumulation, the charge is simply proportional to the applies gate-body bias
- In inversion, the same is true
- In depletion, the charge grows slower since the voltage is applied over a depletion region

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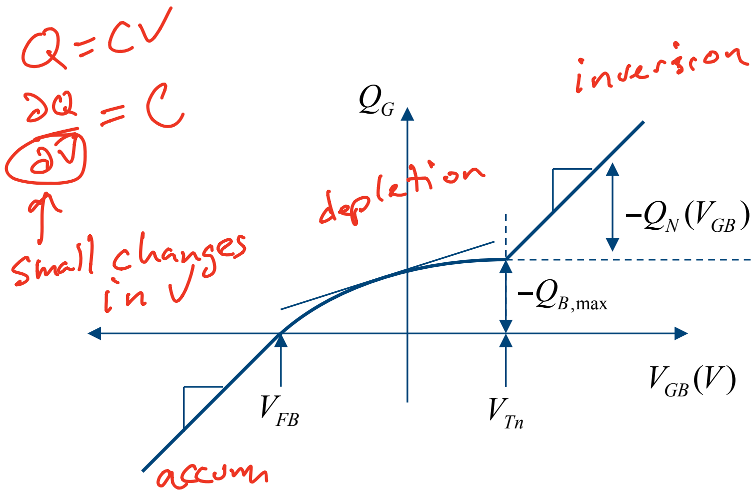
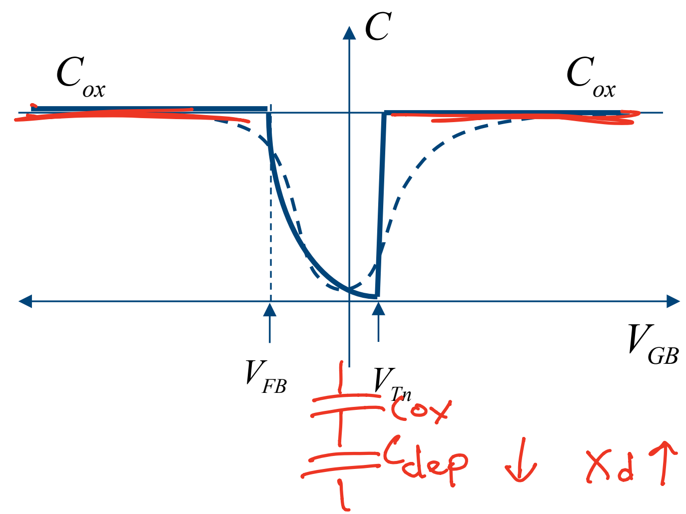
MOS CV Curve

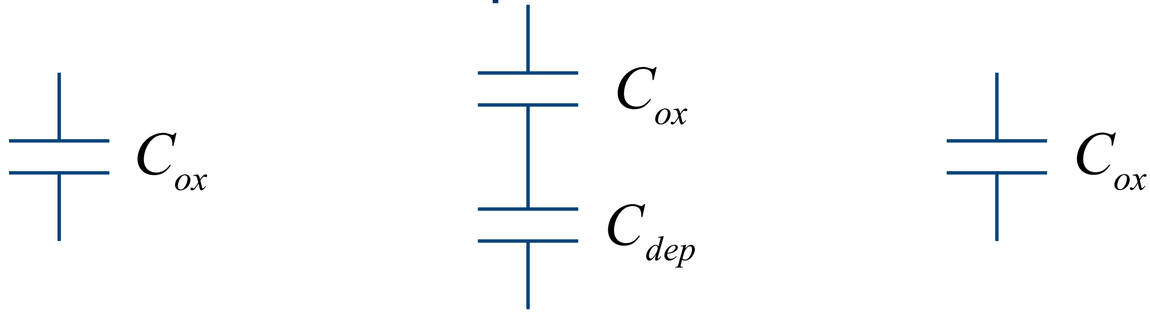




- Small-signal capacitance is slope of Q-V curve
- Capacitance is constant in accumulation and inversion
- Capacitance in the depletion region is smallest
- Capacitance is non-linear in depletion

C-V Curve Equivalent Circuits

Accumulation **Depletion** **Inversion**



$$C_{dep} = \frac{\varepsilon_s}{x_{dep}} \qquad C_{tot} = \frac{C_{dep} C_{ox}}{C_{dep} + C_{ox}} = \frac{C_{ox}}{1 + \frac{C_{dep}}{C_{ox}}} = \frac{C_{ox}}{1 + \frac{\varepsilon_s}{\varepsilon_{ox}} \frac{t_{ox}}{x_{dep}}}$$

- In accumulation mode the capacitance is just due to the voltage drop across t_{ox}
- In depletion region, the voltage drop is across the oxide and the depletion region
- In inversion the incremental charge comes from the inversion layer (depletion region stops growing).

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Numerical Example

- MOS Capacitor with p-type substrate:

$$t_{ox} = 20\text{nm} \qquad N_a = 5\times10^{16}\,\text{cm}^{-3}$$

- Calculate flat-band:

$$V_{FB} = -(\phi_{n^+} - \phi_p) = -(550 - (-402)) = -0.95\text{V}$$

- Calculate threshold voltage:

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.45\times10^{-13}\,\text{F/cm}}{2\times10^{-6}\,\text{cm}}$$

$$V_{Tn} = V_{FB} - 2\phi_p + \frac{1}{C_{ox}}\sqrt{2q\varepsilon_s N_a(-2\phi_p)}$$

$$V_{Tn} = -.95 - 2(-0.4) + \frac{\sqrt{2\times1.6\times10^{-19}\times1.04\times10^{-12}\times5\times10^{16}\times2\times0.4}}{C_{ox}} = 0.52\text{V}$$

Num Example: Electric Field in Oxide

- Apply a gate-to-body voltage:

$$V_{GB} = -2.5 < V_{FB}$$

- Device is in accumulation
- The entire voltage drop is across the oxide:

$$E_{ox} = \frac{V_{ox}}{t_{ox}} = \frac{V_{GB} + \phi_{n^+} - \phi_p}{t_{ox}} = \frac{-2.5 + 0.55 - (-0.4)}{2 \times 10^{-6}} = -8 \times 10^5 \, \frac{\text{V}}{\text{cm}}$$

- The charge in the substrate (body) consist of holes:

$$Q_B = -C_{ox}(V_{GB} - V_{FB}) = 2.67 \times 10^{-7} \, \text{C/cm}^2$$