PURDUE UNIVERSITY

NCN

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ECE606: Solid State Devices
Lecture 32: MOS Electrostatics

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Outline

1. **Background**
2. Band diagram in equilibrium and with bias
3. Qualitative Q-V characteristics of MOS capacitor
4. Conclusion

REF: Chapters 15-18 from SDF

Outline of the Course

Device-specific system design ← Application specific device operation ← Physical Principle of device Operation ← Foundation in Physics

- TFT for Displays
- CMOS-based Circuits for mP
- LASERS for Disk Drives
- MEMS for Read heads

EE606

- Resistors (5 wk)
- Diodes (3 wk)
- Bipolar (3 wk)
- **MOSFETs (3 wks)**

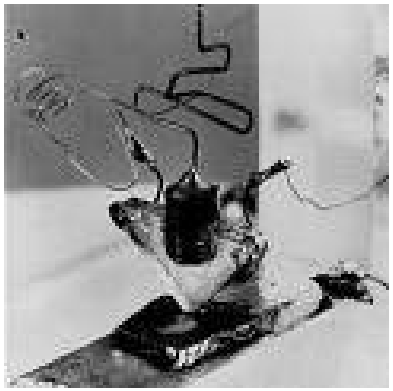
Quantum Mechanics + Statistical Mechanics ↓ Transport Equations

Scaling of MOSFETs

Vacuum Tubes

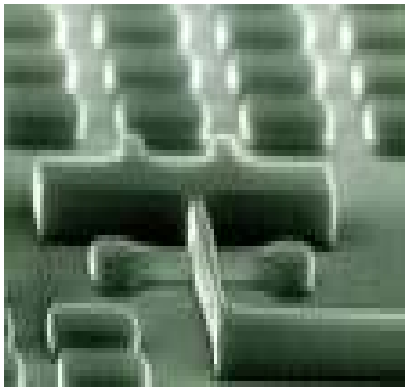
1906-1950s

Bipolar



1947-1980s

MOSFET



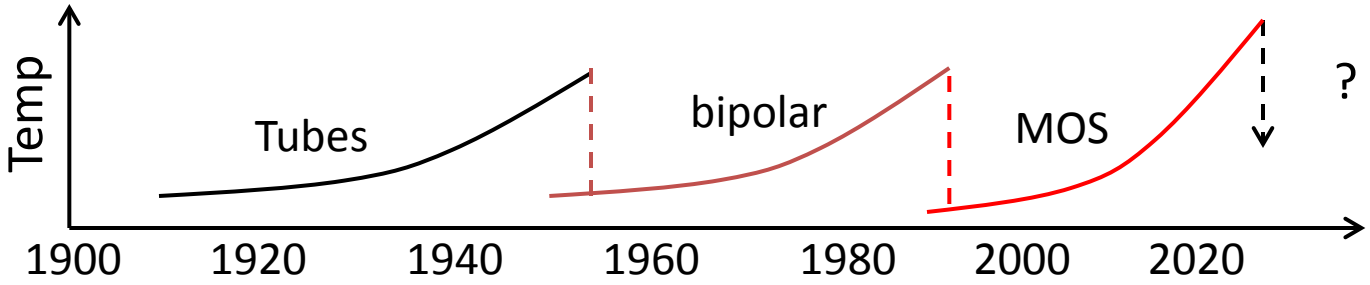
1960-until now

Now ??

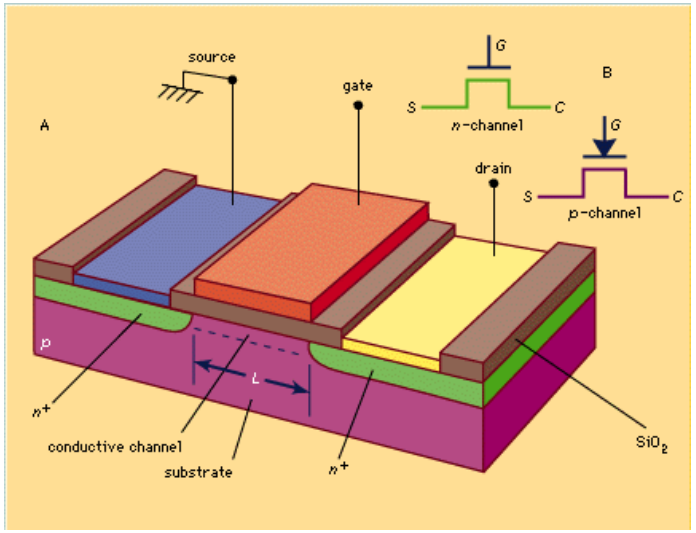
Spintronics

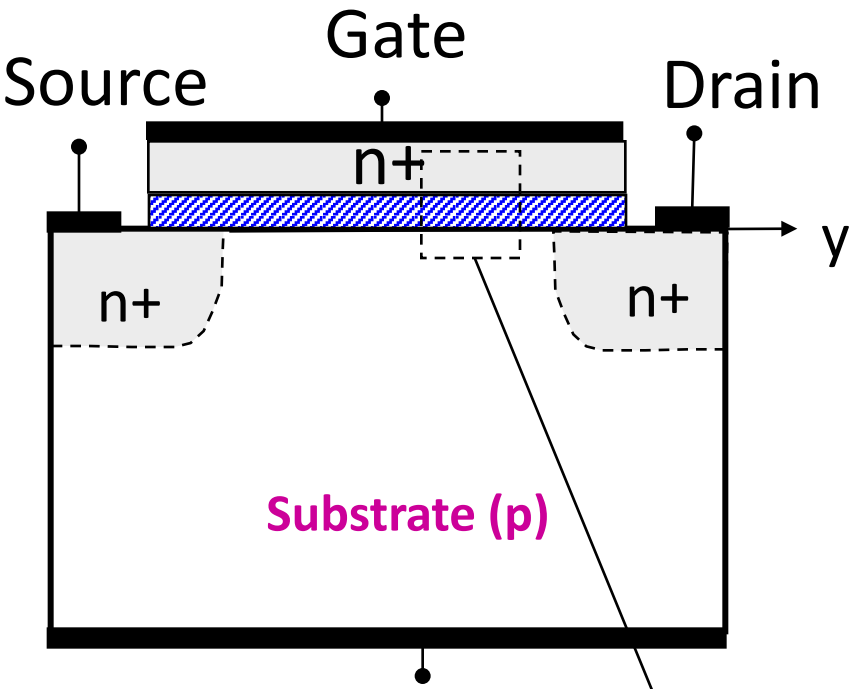
Bio Sensors

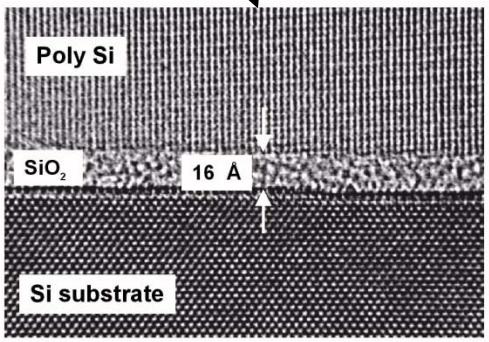
Displays ….



Basic Configuration of a MOSFET

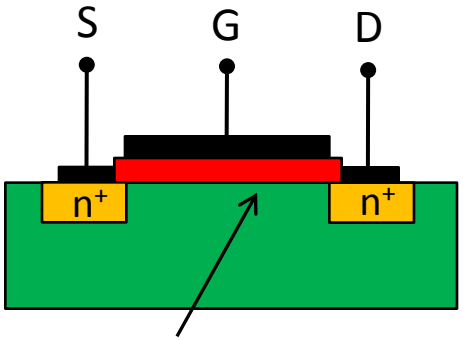






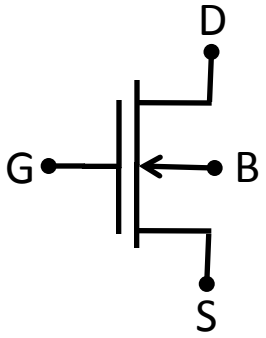
Almost like a lateral bipolar transistor!

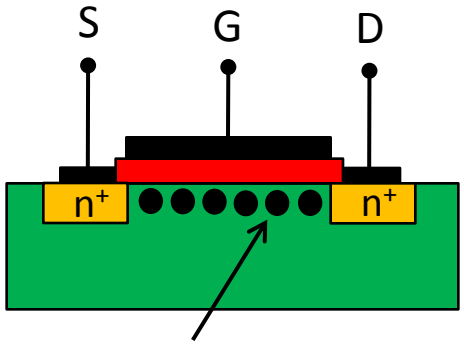
Symbols



No channel

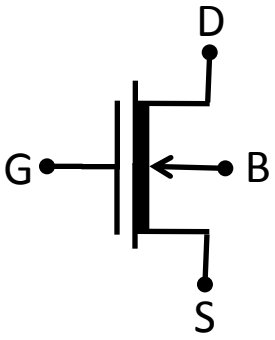
when $V_G = 0$



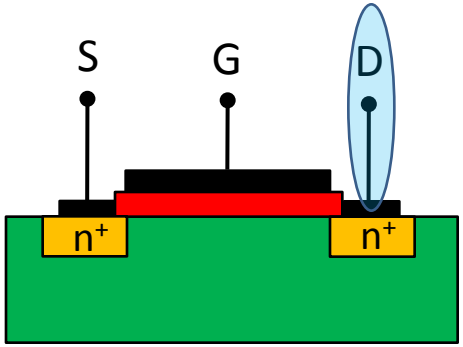


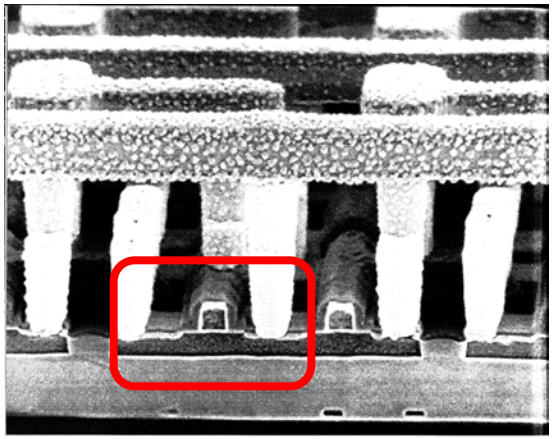
Channel

when $V_G = 0$

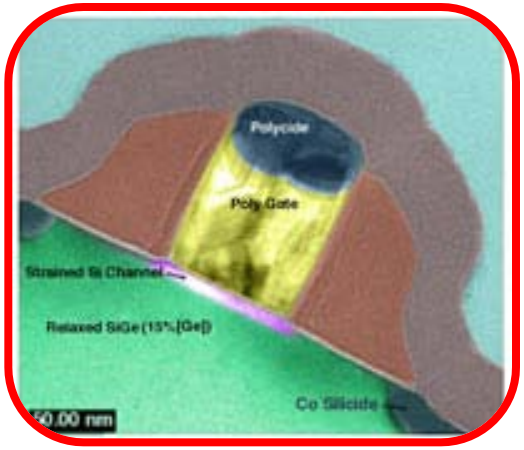


Background

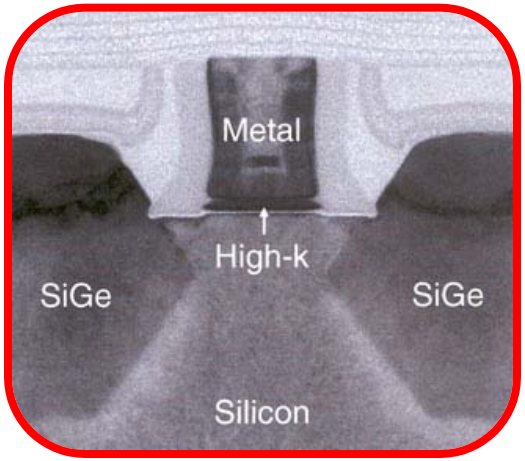




Strained MOSFET



High-k/metal gate MOSFET



Sources:
IBM J. Res. Dev.
Google Images
Intel website

Outline

1. Background
2. **Band diagram in equilibrium and with bias**
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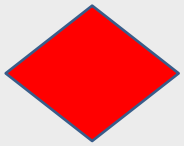
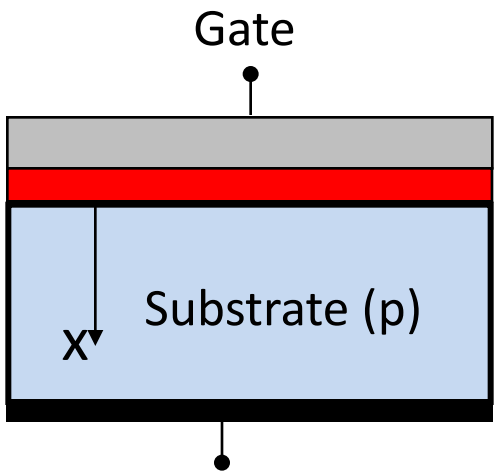
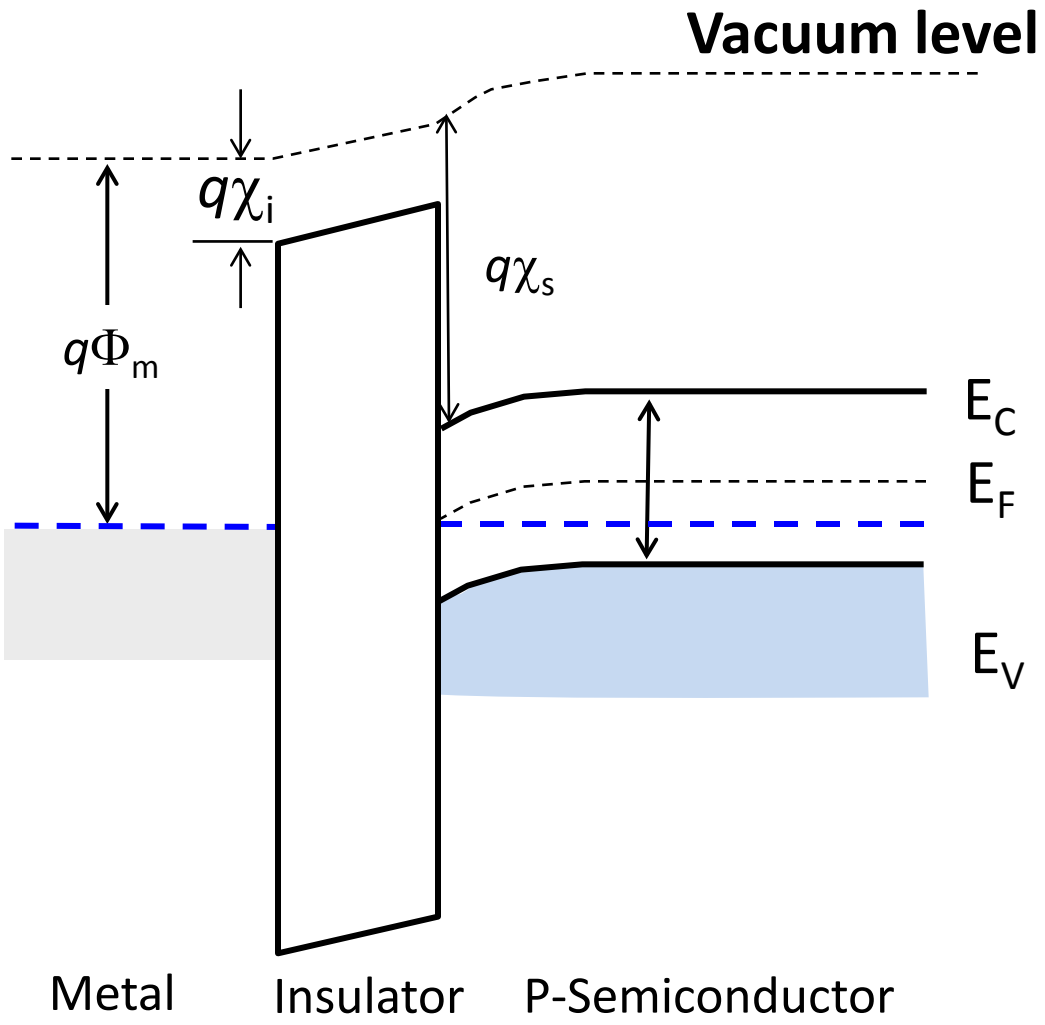
Topic Map

	Equilibrium	DC	Small signal	Large Signal	Circuits
Diode					
Schottky					
BJT/HBT					
MOS					

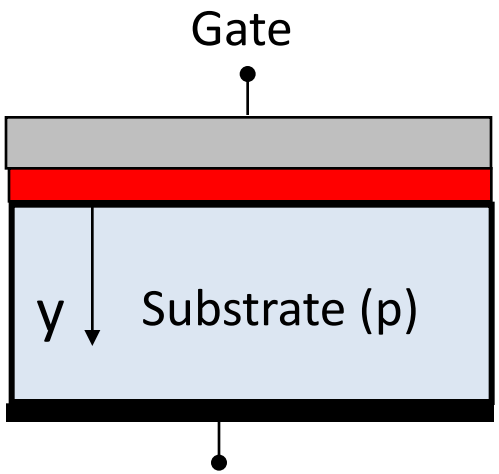
Electrostatics of MOS Capacitor in Equilibrium

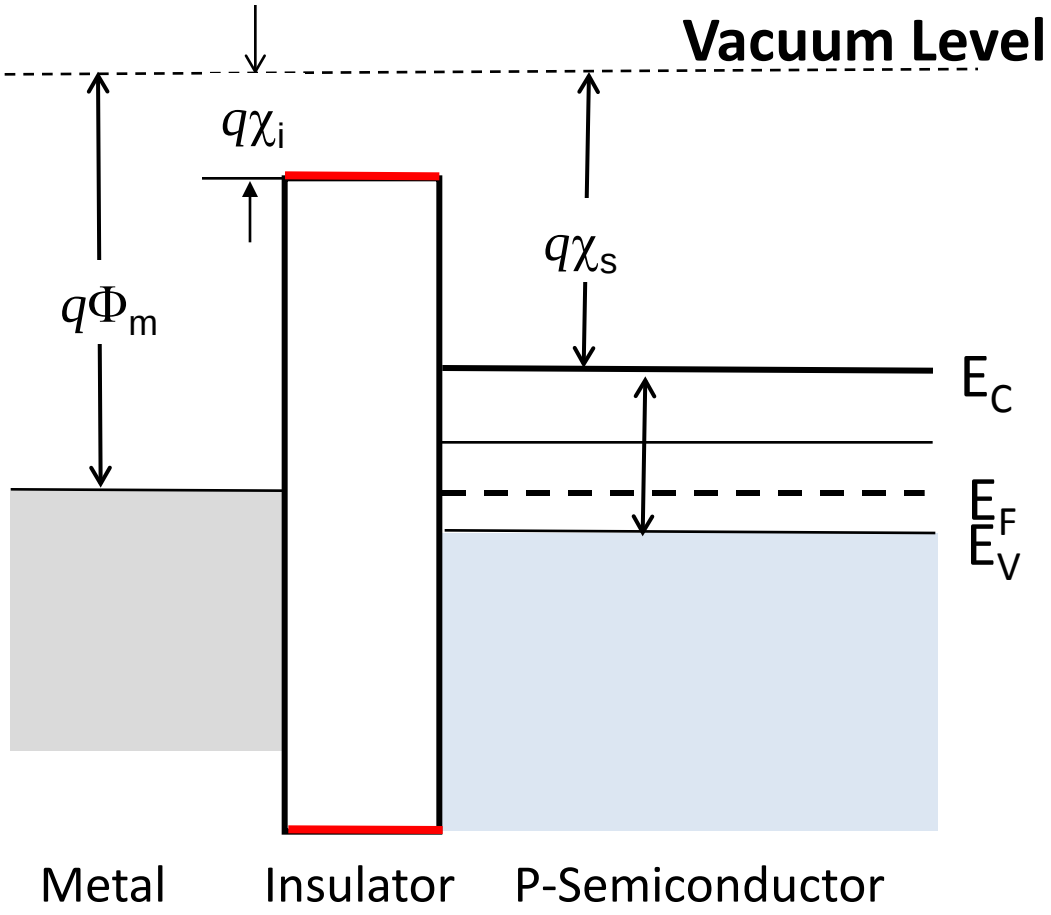


Schottky barrier with an interposed dielectric

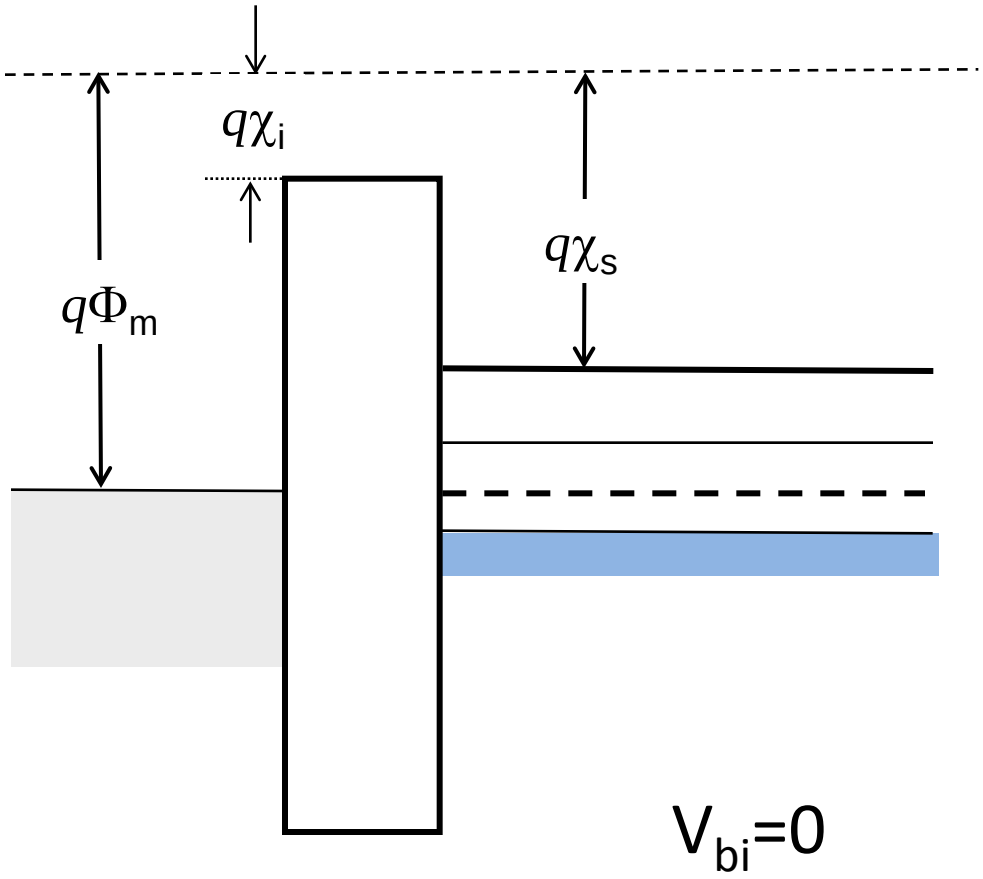


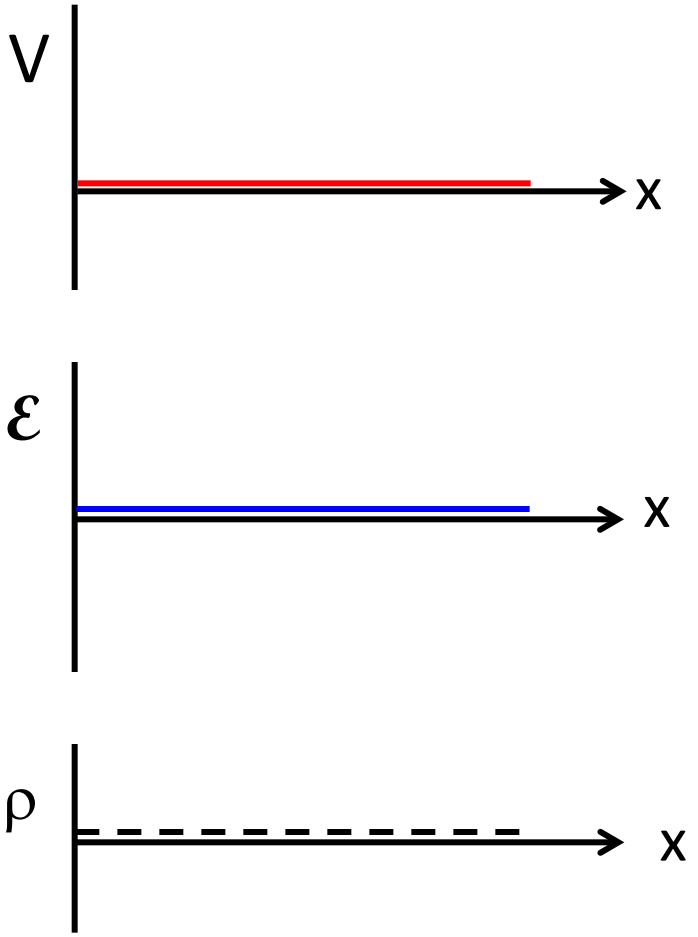
Idealized MOS Capacitor



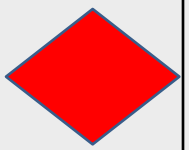


Potential, Field, Charges

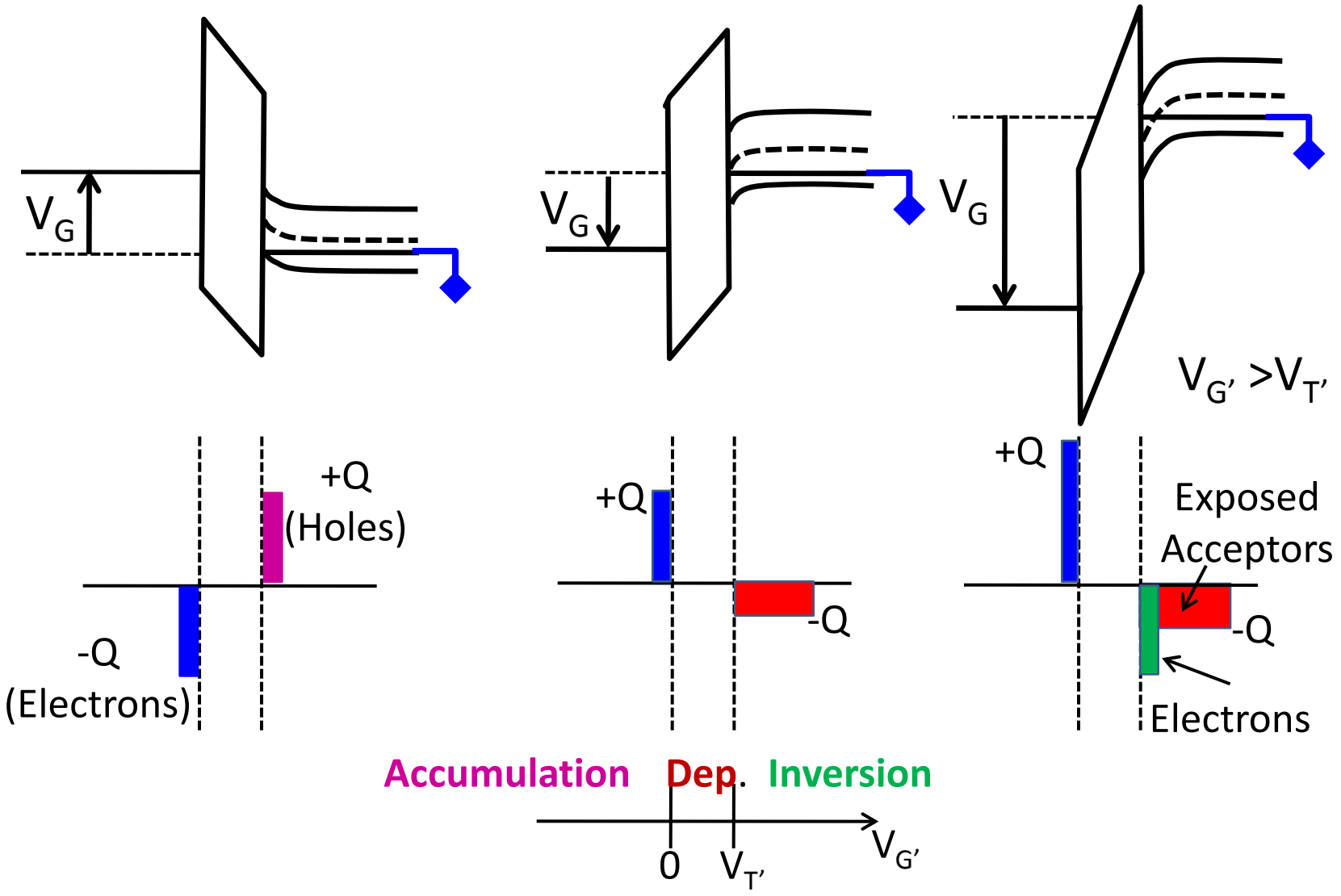




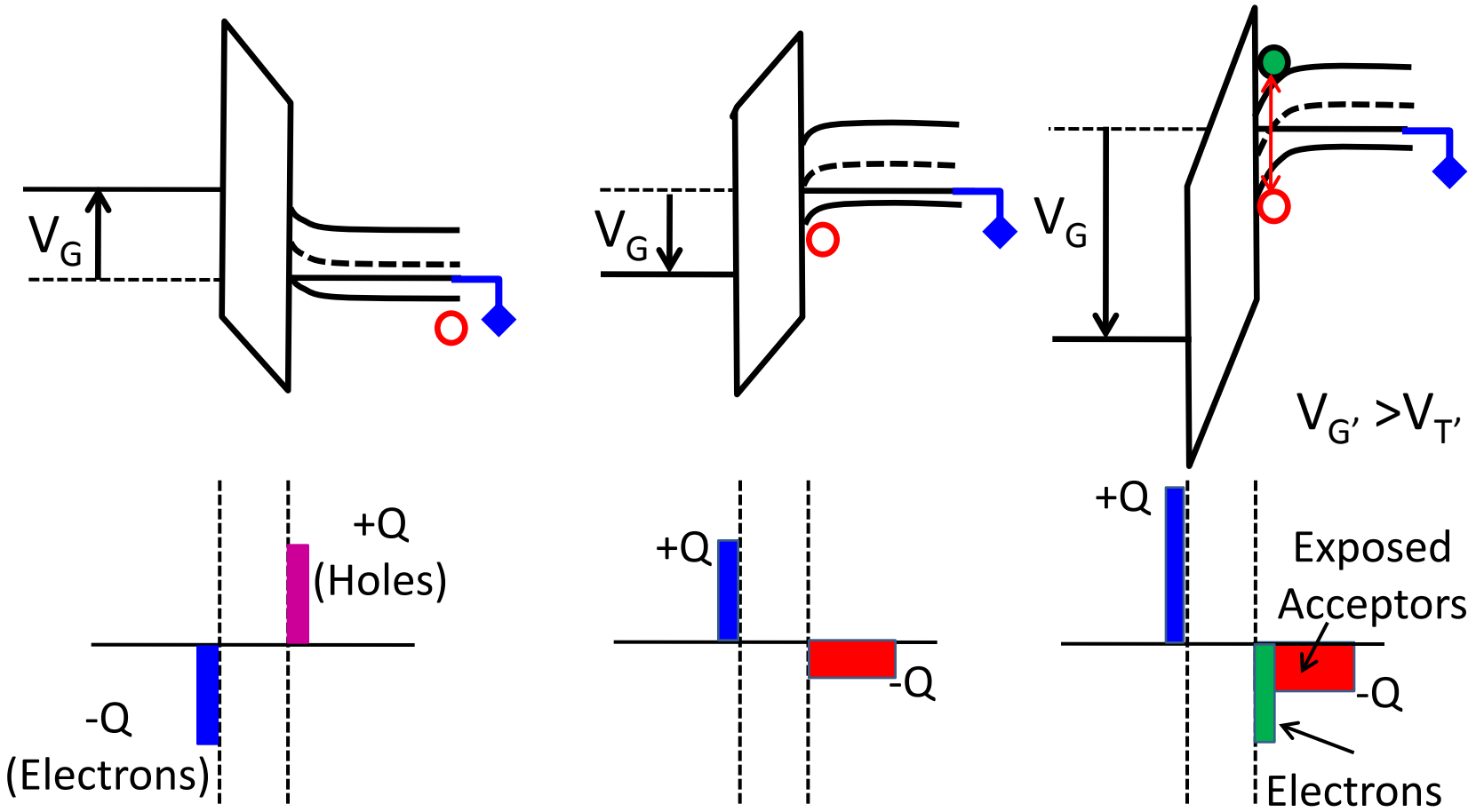
Topic Map

	Equilibrium	**DC**	Small signal	Large Signal	Circuits
Diode					
Schottky					
BJT/HBT					
MOSCAP					

Electrostatics under Bias

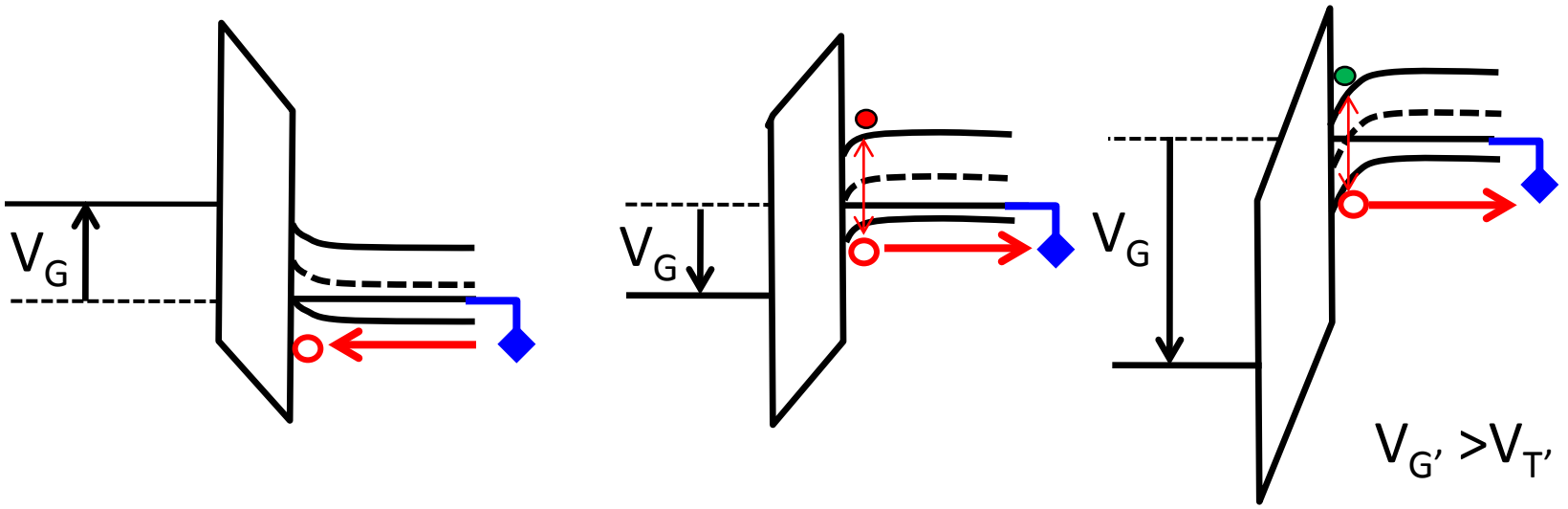


Where do charges come from?



- Integrate charge to find potential.

Response Time



Dielectric Relaxation

$$\tau = \frac{\sigma}{\kappa_s \varepsilon_0}$$

SRH Recombination-Generation

$$R = \frac{np - n_i^2}{\tau_n (p + p_1) + \tau_p (n + n_1)} \rightarrow \frac{-n_i}{\tau_n + \tau_p}$$

Ref. Lecture no. 15

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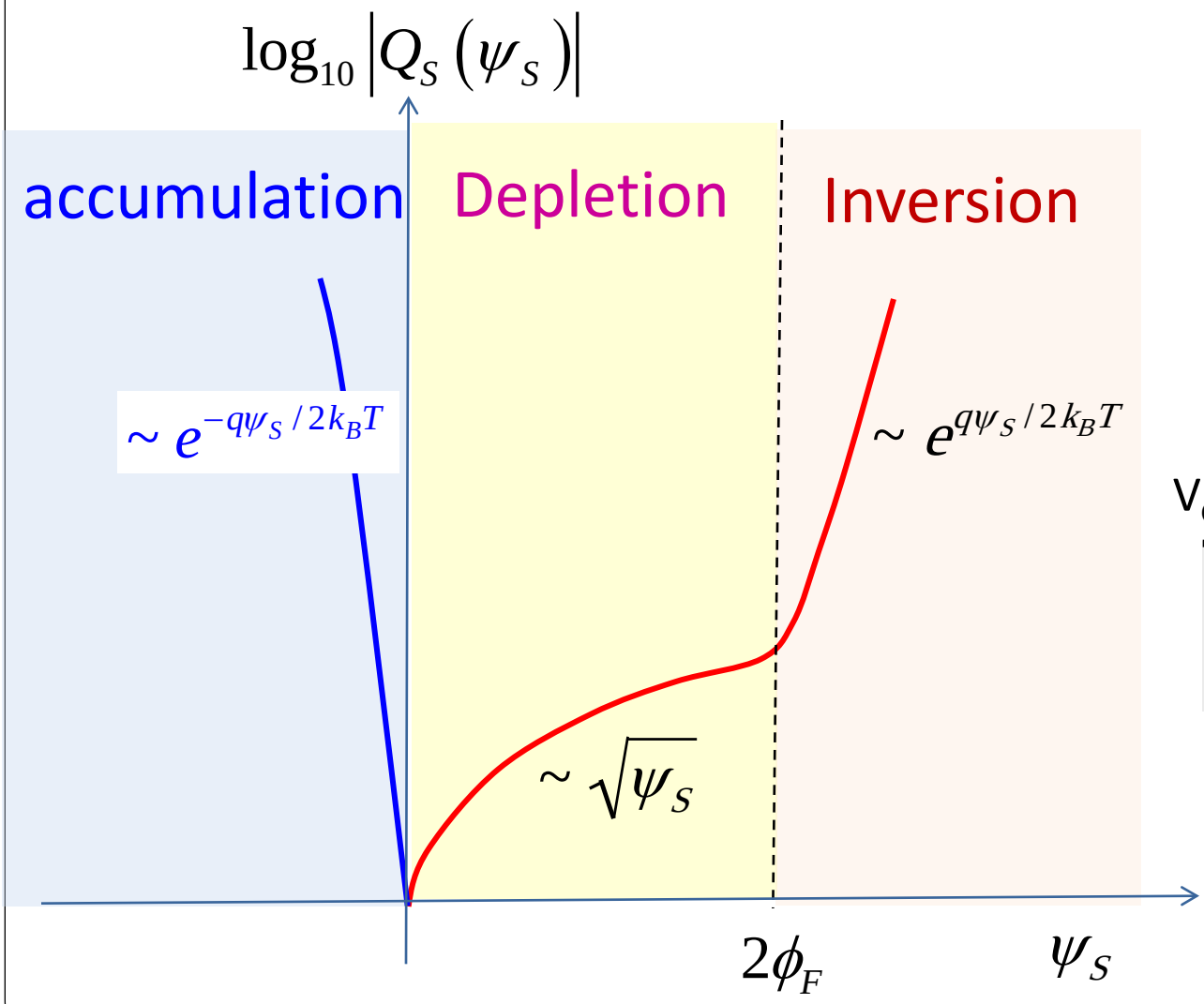
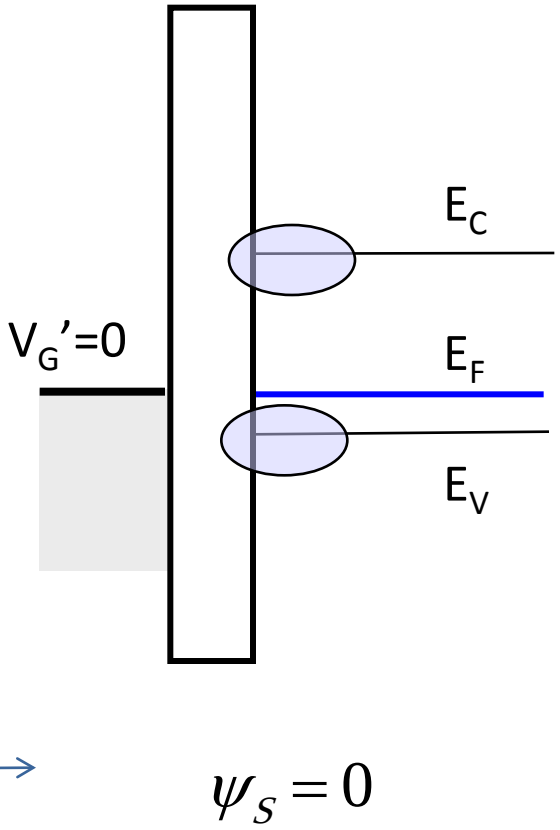
Charges and Surface Potential





Solution of $Q_S(\psi_S)$

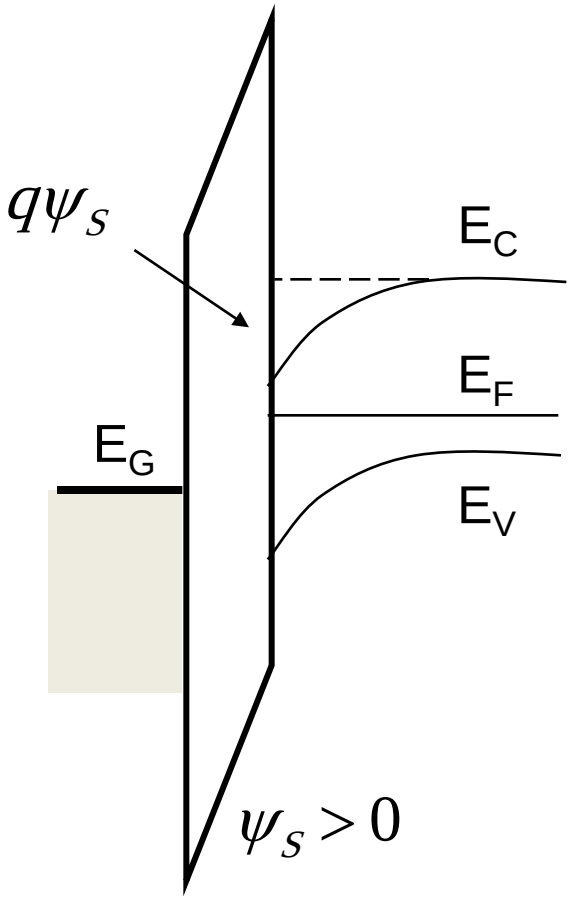
$$\nabla \bullet \vec{D} = \rho$$

$$\nabla \bullet \left(\vec{J}_n / -q \right) = (G - R)$$

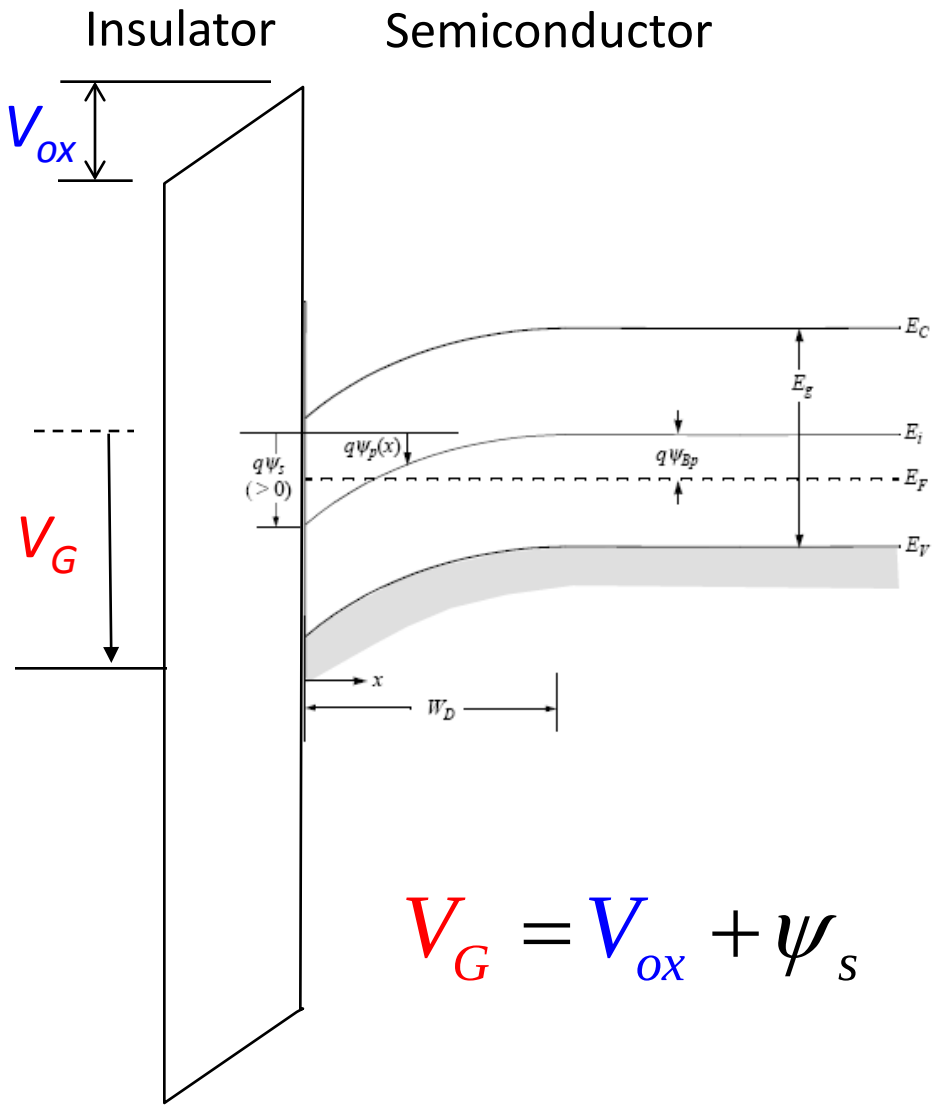
$$\nabla \bullet \left(\vec{J}_p / \ q \right) = (G - R)$$

Poisson equation

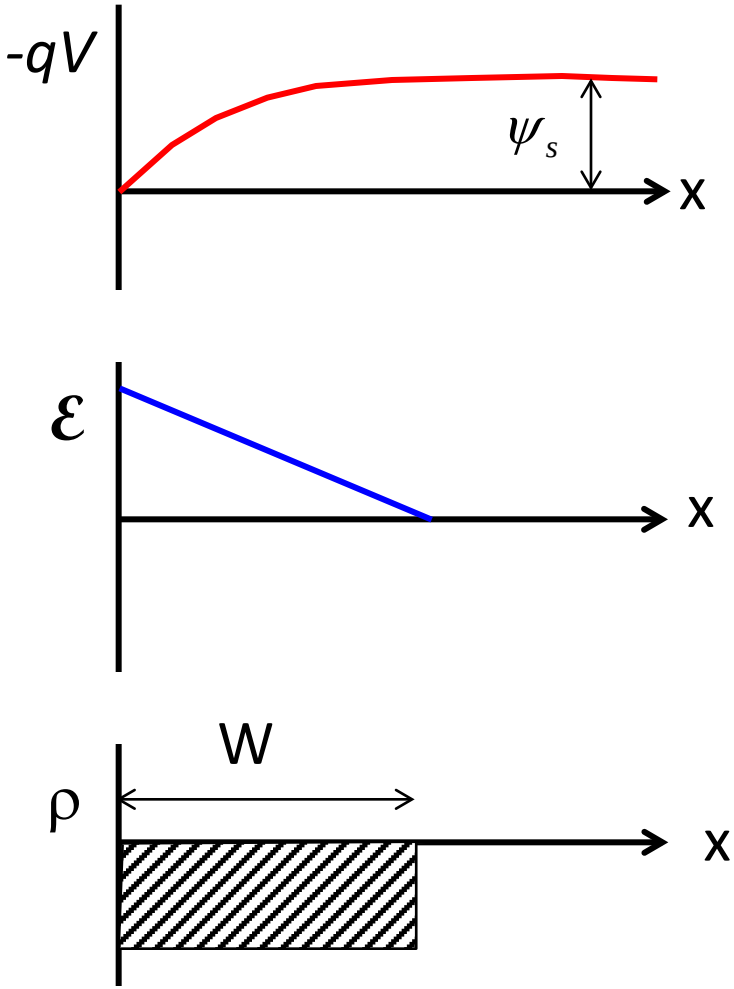
$$\frac{d^2\psi}{dx^2} = \frac{-q}{\kappa_{Si}\varepsilon_0}\left[p_0(x) - n_0(x) + N_D^+ - N_A^- \right]$$



(Depletion) Potential, Field, Charges



$$V_G = V_{ox} + \psi_s$$



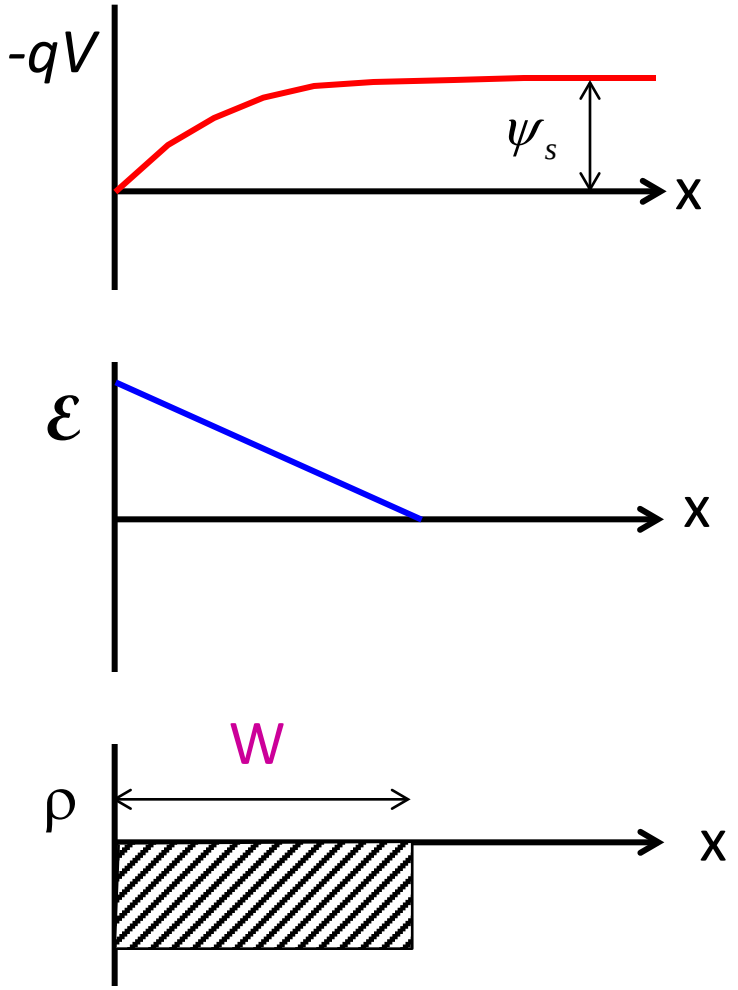
Surface Potential

(2) $$\psi_s = \frac{1}{2}\left(\frac{qN_A W}{\kappa_s \varepsilon_0}\right) W = \left(\frac{qN_A W^2}{2\kappa_s \varepsilon_0}\right)$$

(3) $$W = \sqrt{\frac{2\kappa_s \varepsilon_0 \, \psi_s}{qN_A}}$$

(1) $$\mathcal{E}(0^+) = -\frac{qN_A W}{\kappa_s \varepsilon_0}$$

(4) $$V_G = V_{ox} + \psi_s$$



Gate Voltage /Surface Potential in Depletion Region

$$V_G = \mathcal{E}_{ox}(0^-)x_0 + \left(\frac{qN_A W^2}{2\kappa_s \varepsilon_0}\right)$$

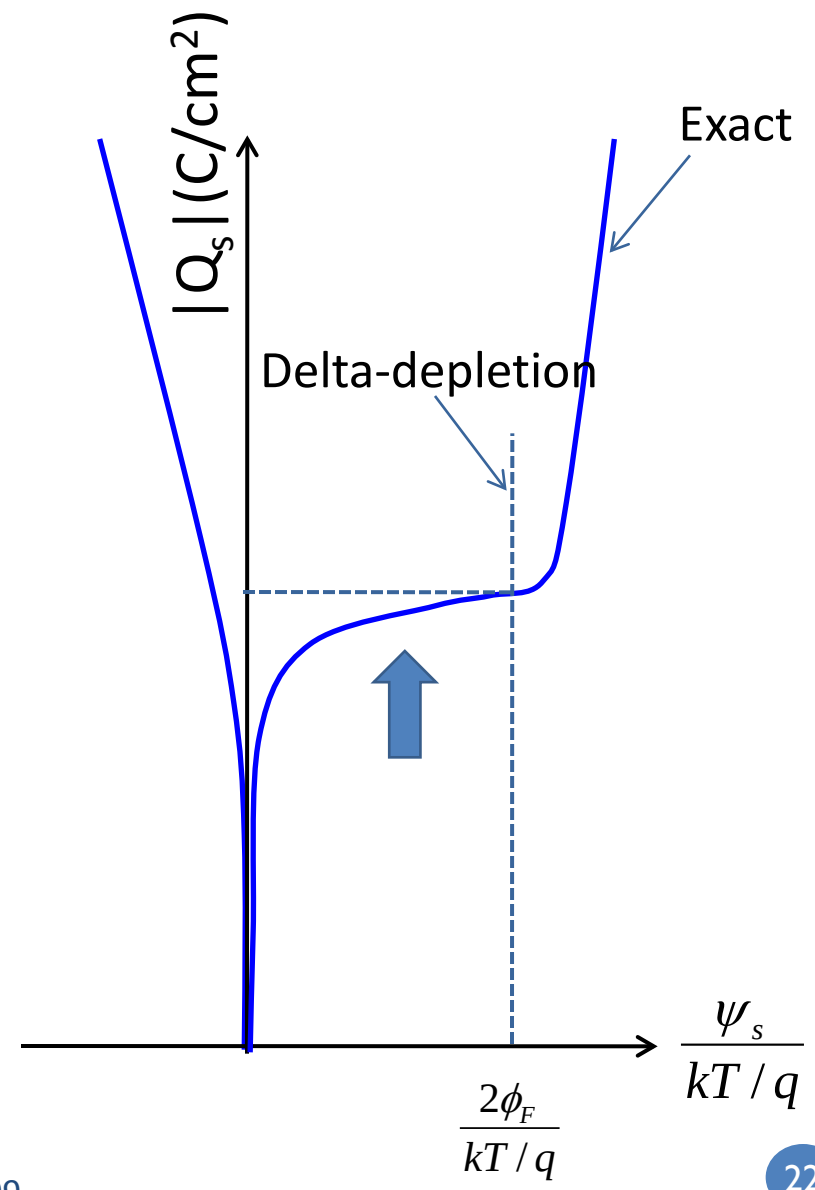
$$= \left[\frac{qN_A W}{\kappa_{ox}\varepsilon_0}\right] x_0 + \left(\frac{qN_A W^2}{2\kappa_s \varepsilon_0}\right)$$

$$= \frac{qN_A x_0}{\kappa_{ox}\varepsilon_0}\sqrt{\frac{2\kappa_{ox}\varepsilon_0}{qN_A}}\sqrt{\psi_s} + \psi_s$$

$$\equiv \mathcal{B}\sqrt{\psi_s} + \psi_s$$

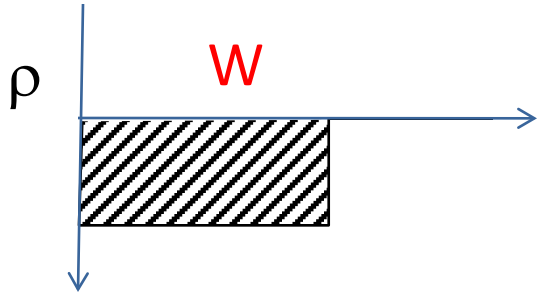
.....because $\psi_s = \left(\frac{qN_A W^2}{2\kappa_s \varepsilon_0}\right)$

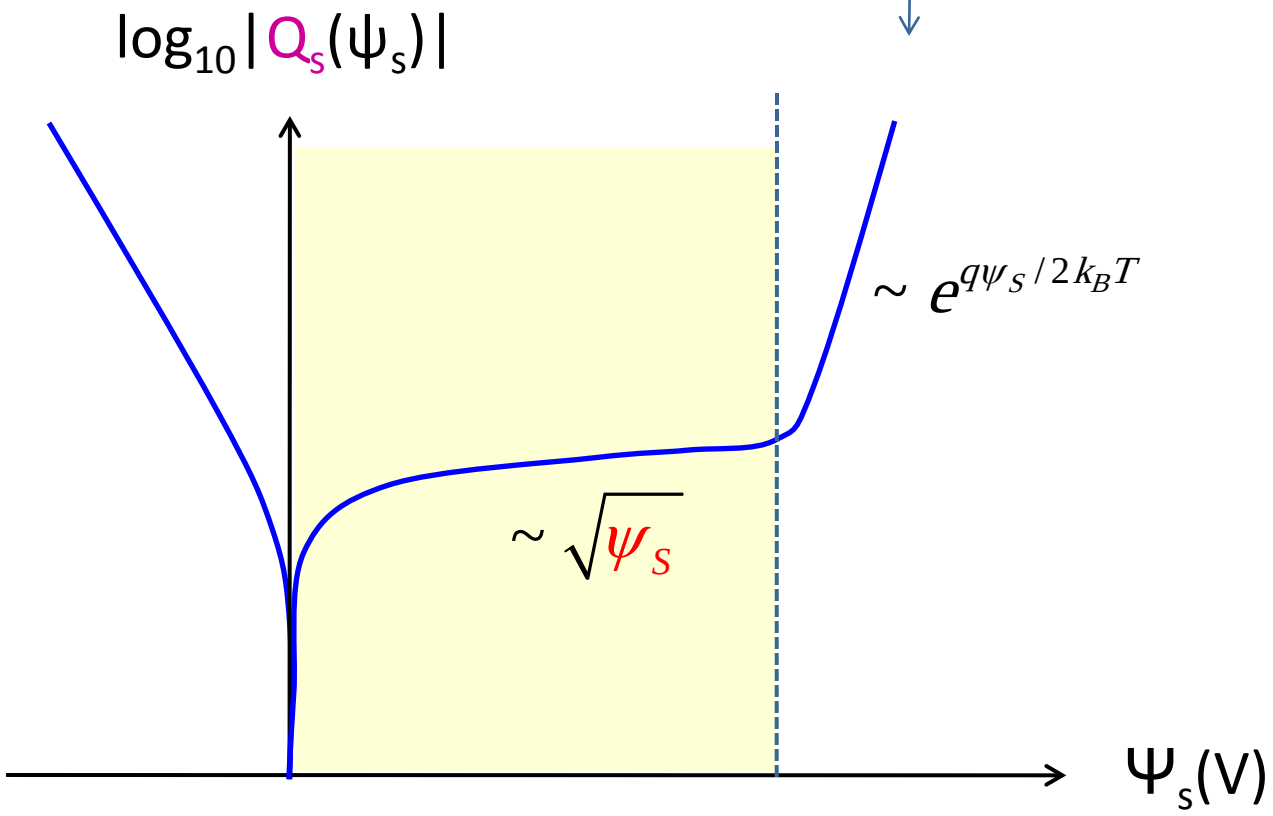
V_G known, determine ψ_S



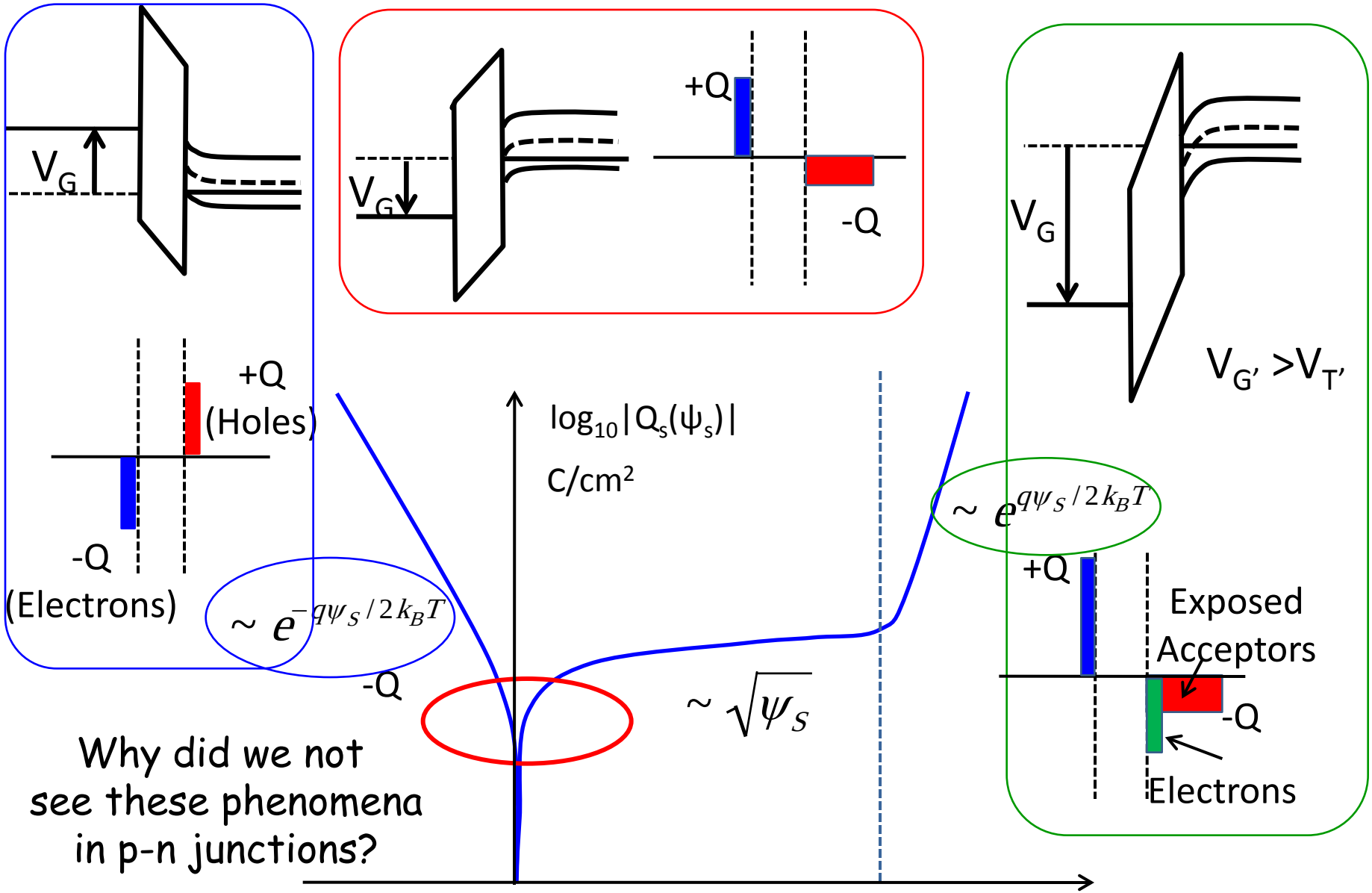
Gate Voltage and Depletion Charge

$$Q_S(\psi_S) = -qN_A W = \sqrt{2qN_A \kappa_{Si} \varepsilon_0 \psi_S}$$





Surface Potential and Induced Charge



Conclusion

MOSFET is the dominant electronic device now, not because it is superior to BJTs in terms of performance, but because it consumes far less power and allow denser integration.

MOSFET is an inherently 2D device. We separate out the vertical and horizontal components to qualitatively explore the mechanics of its operation.

We explored relation between gate voltage and induced charge for a MOS-C today. We will continue this discussion in the next class.