INTRODUCTION TO THE TWO TERMINAL MOS TRANSISTOR

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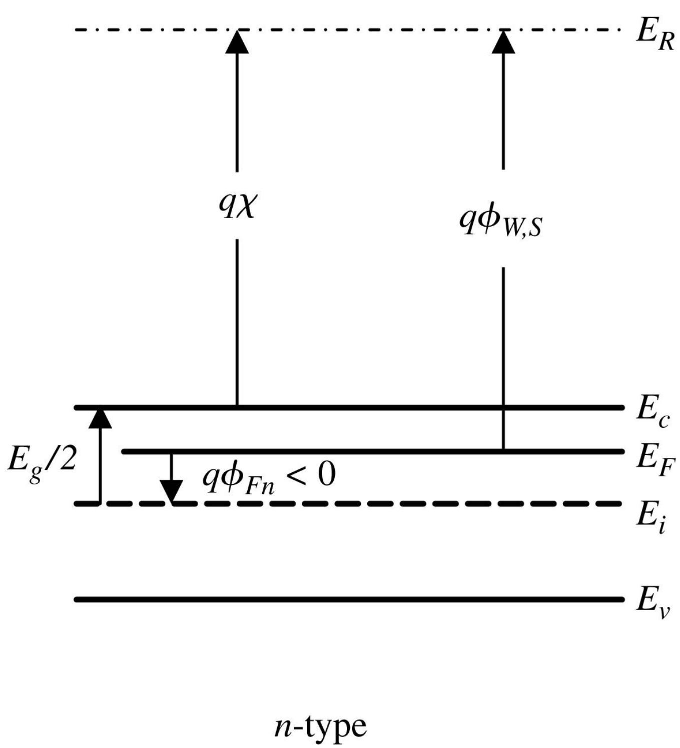
Announcements

- If you do not have your password or forgot it, I would prefer you to stop by.
- I have posted some YouTube videos on my channel that are sometimes helpful for things like labels
  - https://www.youtube.com/user/jlstine
  - The best option is getting experience with the tools and ask questions when you encounter something or have a question.
  - Remember to document your problem on slack (e.g., screenshots)
  - We hope to give out an assignment soon with Magic; however, if you wanted to try the inverter tutorial (walk through), it might be useful.
    - http://stineje.github.io

Motivation

- MOS devices are essential elements in every system that is out there now.
- This is because CMOS is so dominant in its use as well as its ease in use.
- However, there are over 200+ complicated model parameters for a given MOS device and understanding their impact means you need to need to know the basics.
- Each parameter is there it help describe an effect that is important for its MOS transistor characteristics.
- The only way to make sense out of its operation is to understand the phenomenon in the simple structure to understand the more complicated ones.

Electron affinity



$$\phi_{W,S} = \chi + \frac{E_g}{2 \cdot q} + \phi_F$$

$\boxed{q \cdot \chi = 4.05 \text{ eV for silicon}}$

Electron Affinity is the amount of energy released when an electron is added to a neutral atom or molecule to form a negative ion

Work Function

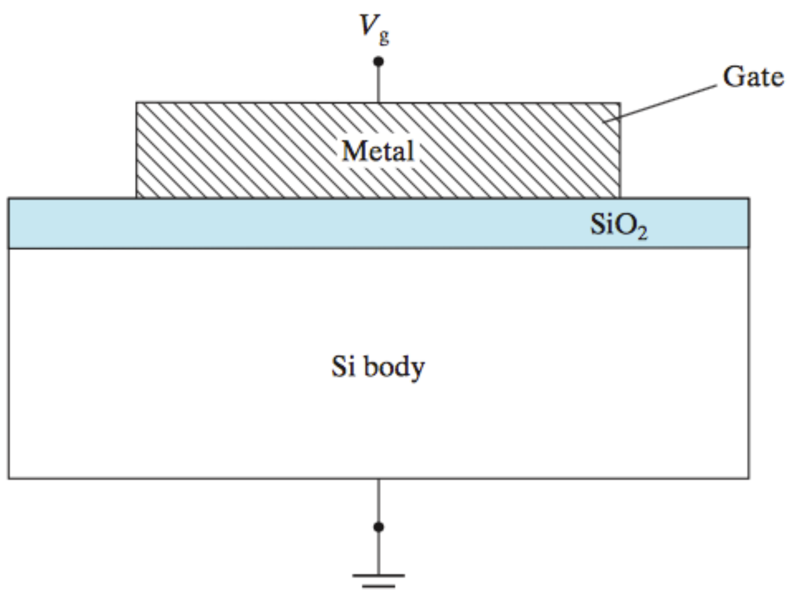
- Work function and work function potentials are not easy to measure.
  - Sometimes they are inconsistent compared to what they are published at.
- In the purest sense, a work function is the minimum thermodynamic work needed to remove an electron from a solid to a point in the vacuum immediately outside the surface.
- Can we calculate the contact potential of aluminum to a p-type semiconductor with a doping concentration of 10^{17} cm^{-3} at room temperature.
  - Assume the work function potential of aluminum is 4.1 V

$$\phi_{W,S} = \chi + \frac{E_g}{2 \cdot q} + \phi_F$$

$$\phi_F \approx +\phi_t \cdot \ln \frac{N_A}{n_i}$$

$$\boxed{\begin{aligned} \phi_{W,S} &= 4.05\ V + 0.56\ V + 0.42\ V = 5.3V \\ \phi_{Al,S} &= \phi_{W,S} - \phi_{W,Al} = 5.3\ V\ - 4.1\ V = 0.93\ V \end{aligned}}$$

Metal-Oxide-Semiconductor (M-O-S)

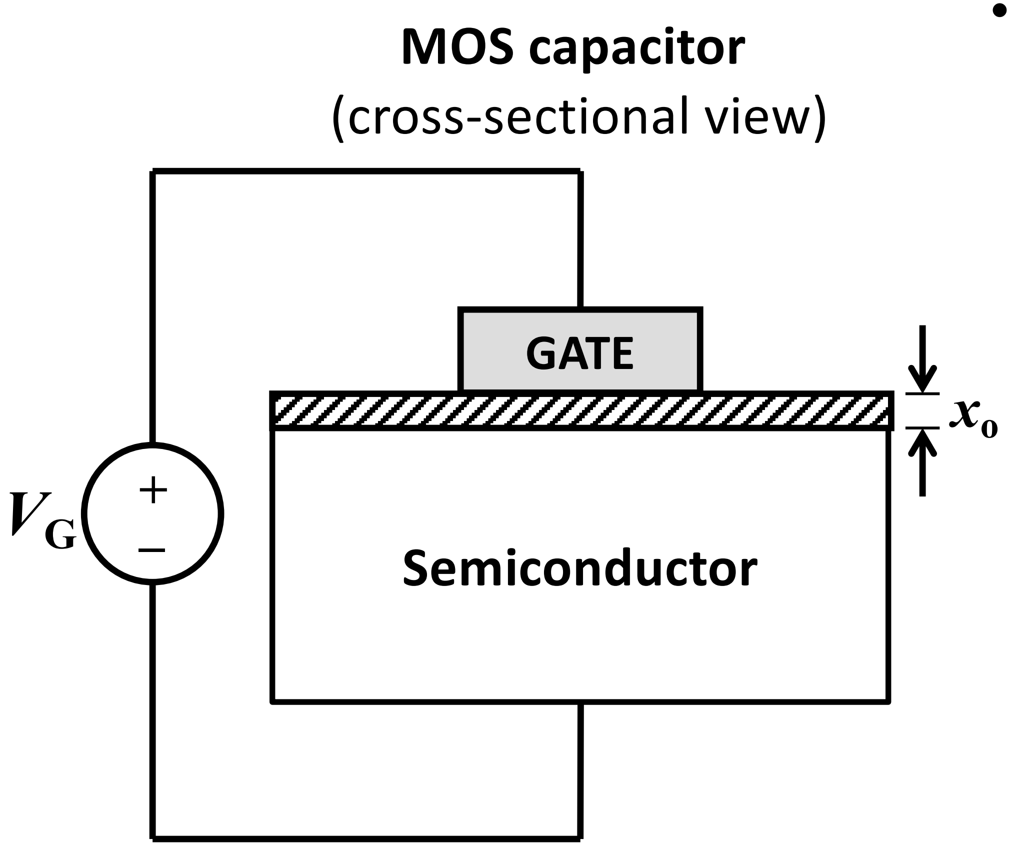


[Chenming Hu]

- Before 1970, the gate was made of metals, such as Al, however, 1970 heavily-doped polycrystalline silicon has been standard gate material because of its ability to withstand high temperature without reacting with Silicon Dioxide
  - MOS name stuck.
- Today processes are experimenting with putting metal back and replace SiO2 with more advanced dielectrics.

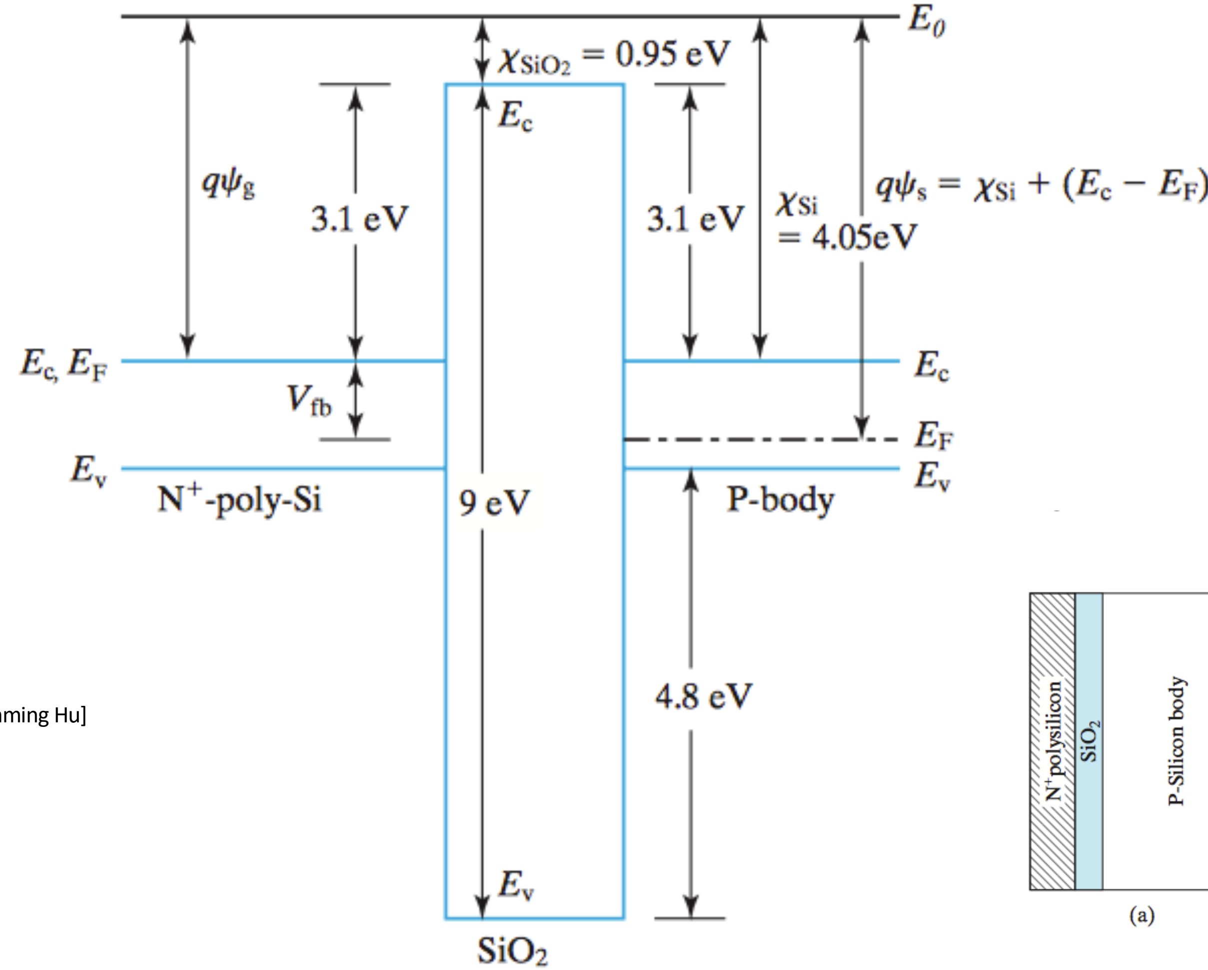
IMHO: Most critical understanding of MOS device comes from the MOS capacitor!!!

MOS Capacitor Structure



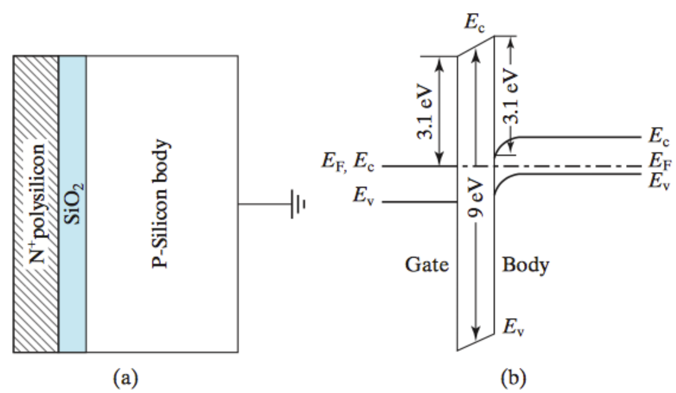
- MOS devices today employ:
  - degenerately doped polycrystalline Si ("poly-Si") film as the gate-electrode material
    - n^+-type for "n-channel" transistors
    - p^+-type, for "p-channel" transistors
  - SiO_2 as the gate dielectric
    - band gap = 9 eV
    - $\varepsilon = 3.9$
  - Si as the semiconductor material
    - p-type, for "n-channel" transistors
    - n-type, for "p-channel" transistors

MOS Equilibrium Band Diagram



Because of large energies of SiO_2, electrons and holes normally cannot pass through the gate dielectric.

[Chenming Hu]



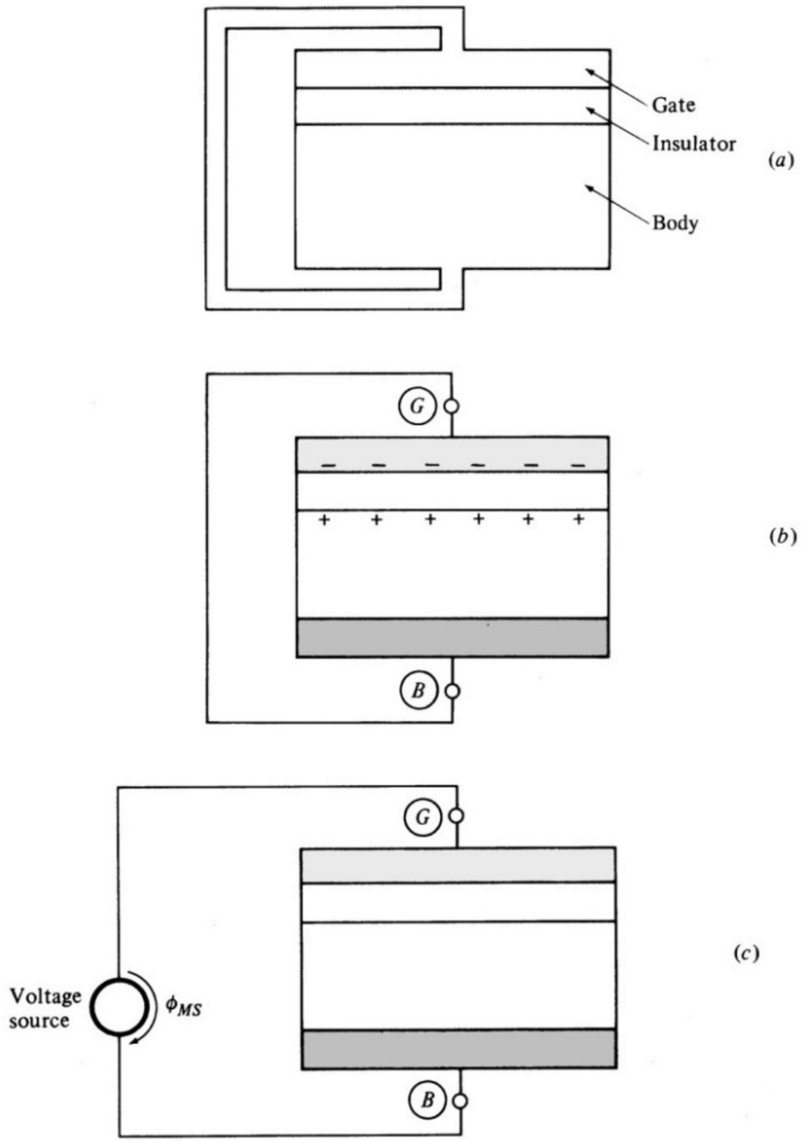
Mobile Charge Carriers in Semiconductors

- Two primary types of carrier action occur inside a semiconductor:
  - **Drift:** charged particle motion under the influence of an electric field.
  - **Diffusion:** particle motion due to concentration gradient or temperature gradient.
- Our goal for the coming week is to examine where current comes from in a MOS transistor and how that relates to its voltage across its Drain/Source.
  - Before we can do this well and since the models are so complex, we must understand the physics of the MOS capacitor.

Two-Terminal MOS Structure

- The gate is made from a certain material and not necessarily the same as the substrate.
- A metal is used to contact the gate material and format the gate terminal or G
  - G = gate terminal
- The body is contacted through a back metal late and this metal forms the basis of the body terminal
  - B = body terminal

MOS Capacitor



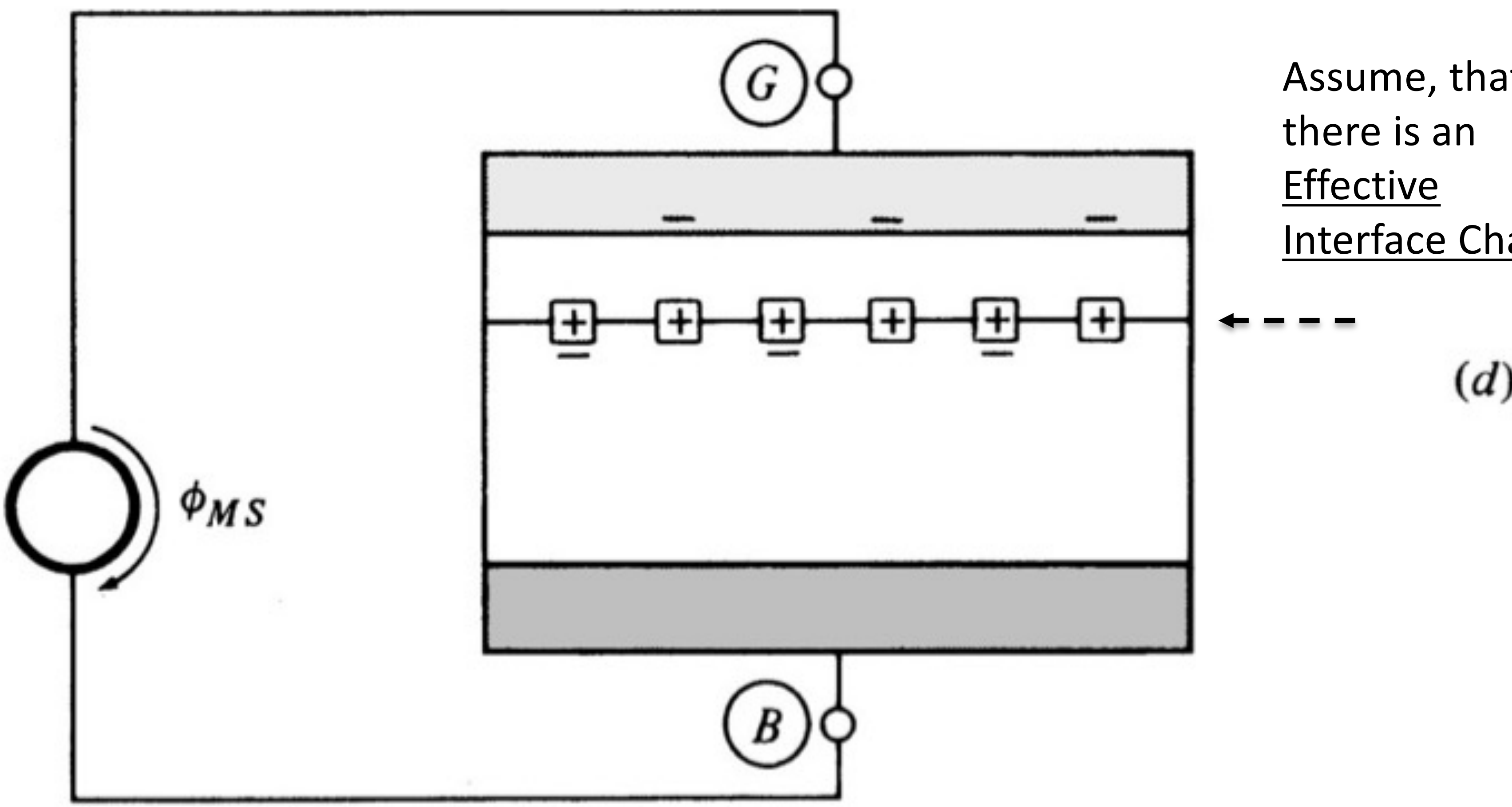
Initially, assume Gate and Body are made out of the same material

Historically, the S stood for semiconductor substrate and M for metal gate

$$\phi_{MS} = \phi_{W,M} - \phi_{W,S}$$

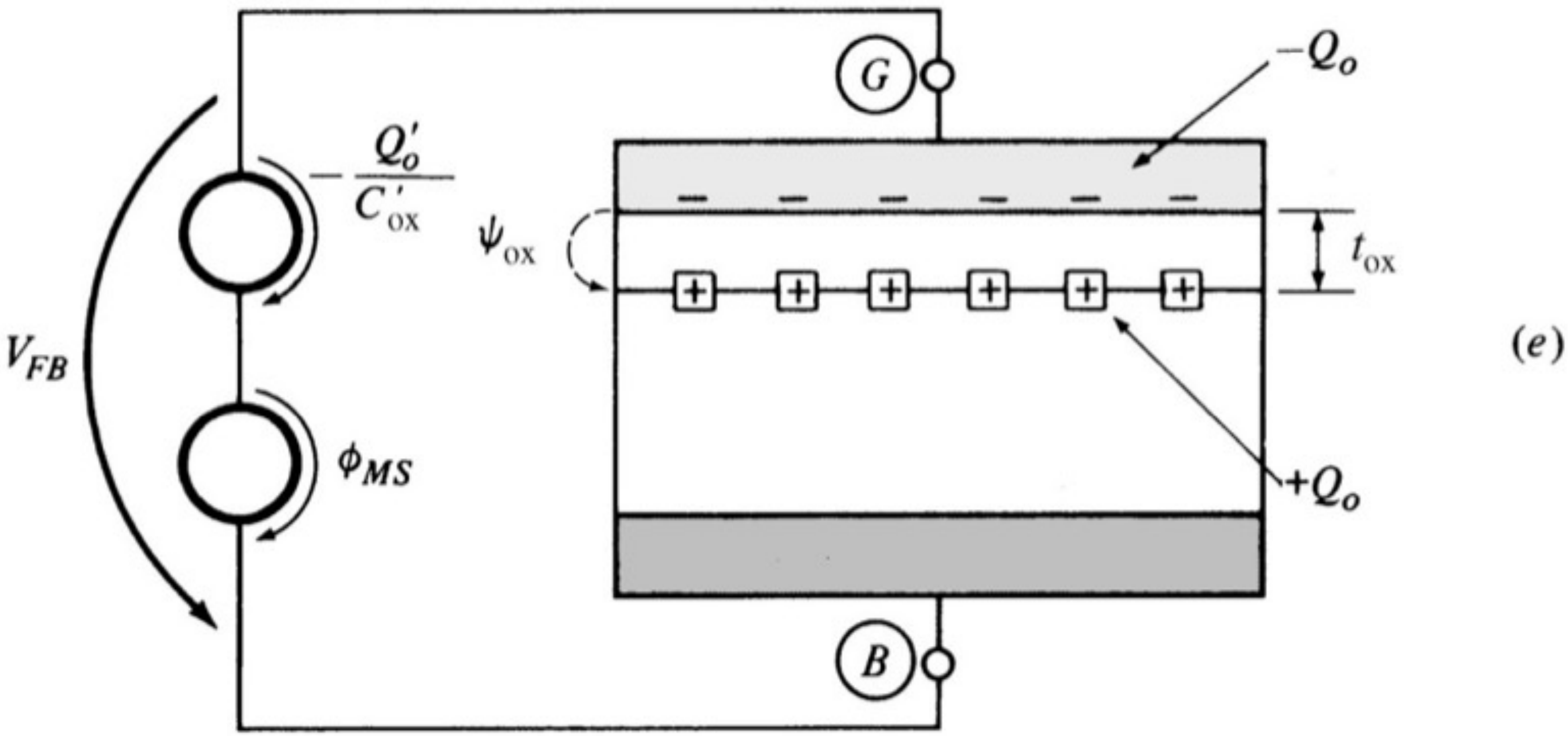
Added to contact potentials and make the substrate neutral

Initial Effective Charge, Q_0



Assume, that there is an <u>Effective Interface Charge</u>

Add bias : make substrate neutral



"Flatband Voltage"

$$V_{FB} = \phi_{MS} - \frac{Q'_0}{C'_{ox}} \qquad C'_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

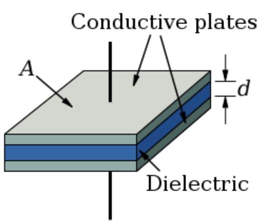
Admiral Ackbar™ : Non-ideal!

- An oxide field charge exists very close to the oxide-semiconductor interface due to the mechanisms of oxide formation.
- A so-called oxide trapped charge can exist throughout the oxide, but usually close to either of its interfaces to the body or the gate.
  - Also, can be acquired through radiation (space), photoemission, or the injection of high-energy carries from the body.
- A mobile ionic charge can exist within the oxide due to contamination by alkali ions introduced by the environment during fabrication.
- An interface trap charge (also called fast surface-state charge) exists at the oxide semiconductor interface.

[npr.org]

Capacitance

- Capacitance is essential to most devices and it's the charge that builds up on a device.
- Capacitance is essential to understanding CMOS as its inherently everywhere on the device.
  - Silicon Dioxide is an insulator!
- The main element we study is the Farad named after Michael Faraday.
  - Interestingly, the reciprocal of Farad is electrical **elastance**.



[Wiki]

$$C = \varepsilon \cdot \frac{A}{d}$$

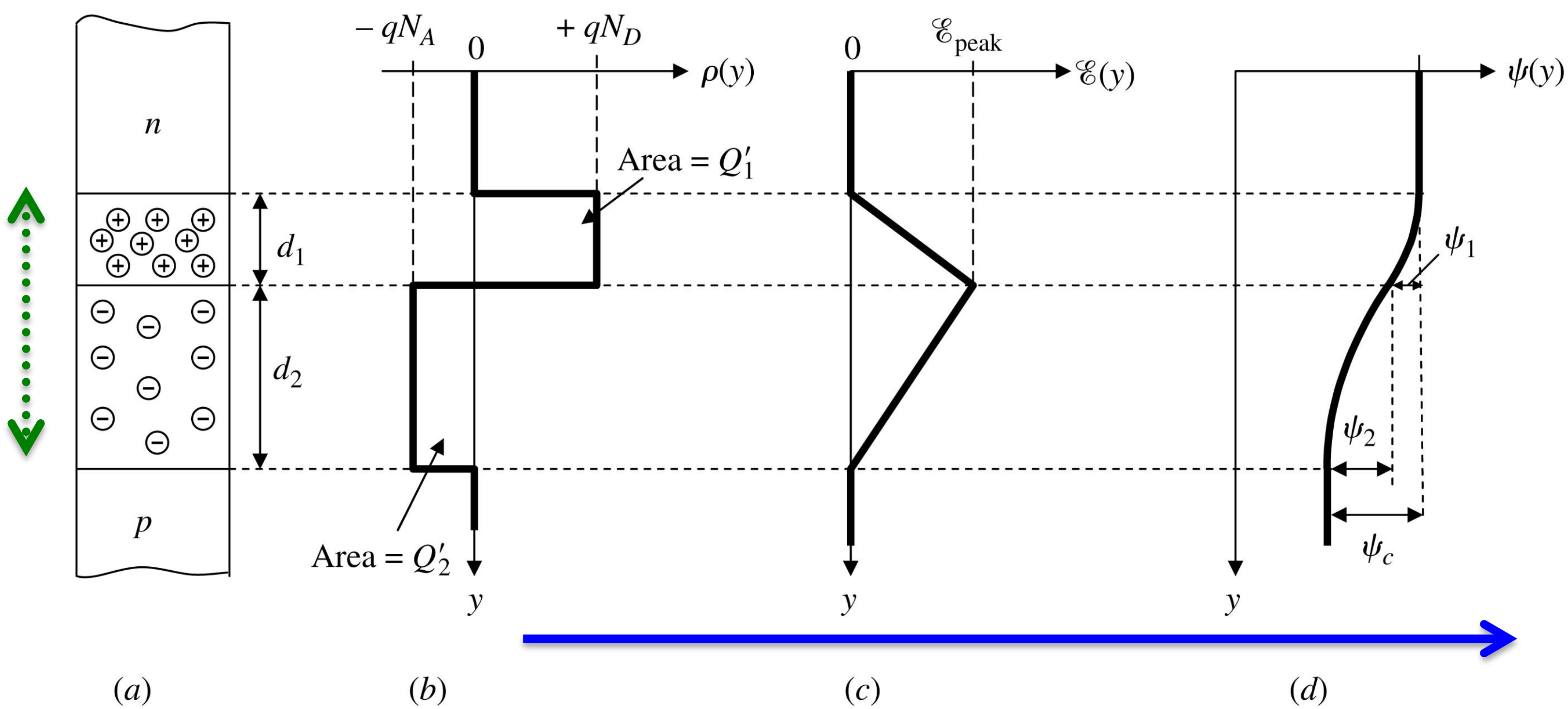
$$I(t) = C \cdot \frac{dV(t)}{dt}$$

Parallel Plate Capacitance

Voltage/Current Relationship

Depletion Region

- The depletion region acts an insulating region within a conductive, doped semiconductor material where the mobile carriers have been diffused away or have been forced away by an Electric Field.
  - Any material of different charges will incur a depletion region.



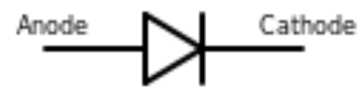
$$C = \frac{Q}{V}$$

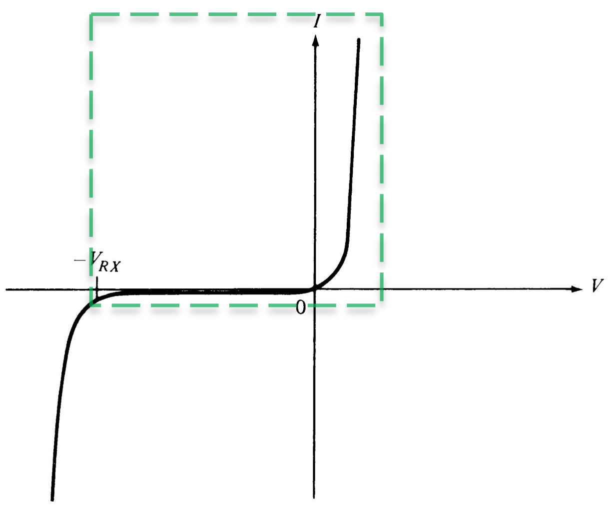
Reverse-based pn junction

William Bradford Shockley

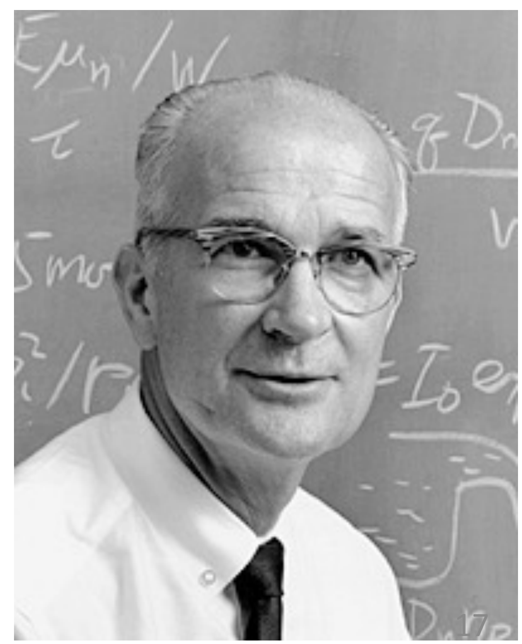
- He was an American Physicist and inventor and co-invented the transistor.
- The diode equation of a pn junction and its relations for current was named for him.

(1.5.2) $$I = I_0 \cdot \left(e^{V/\eta \cdot \phi_T} - 1\right)$$





Current is a function of drift, diffusion, and thermal recombination-generation (R-G)



MOS Capacitor

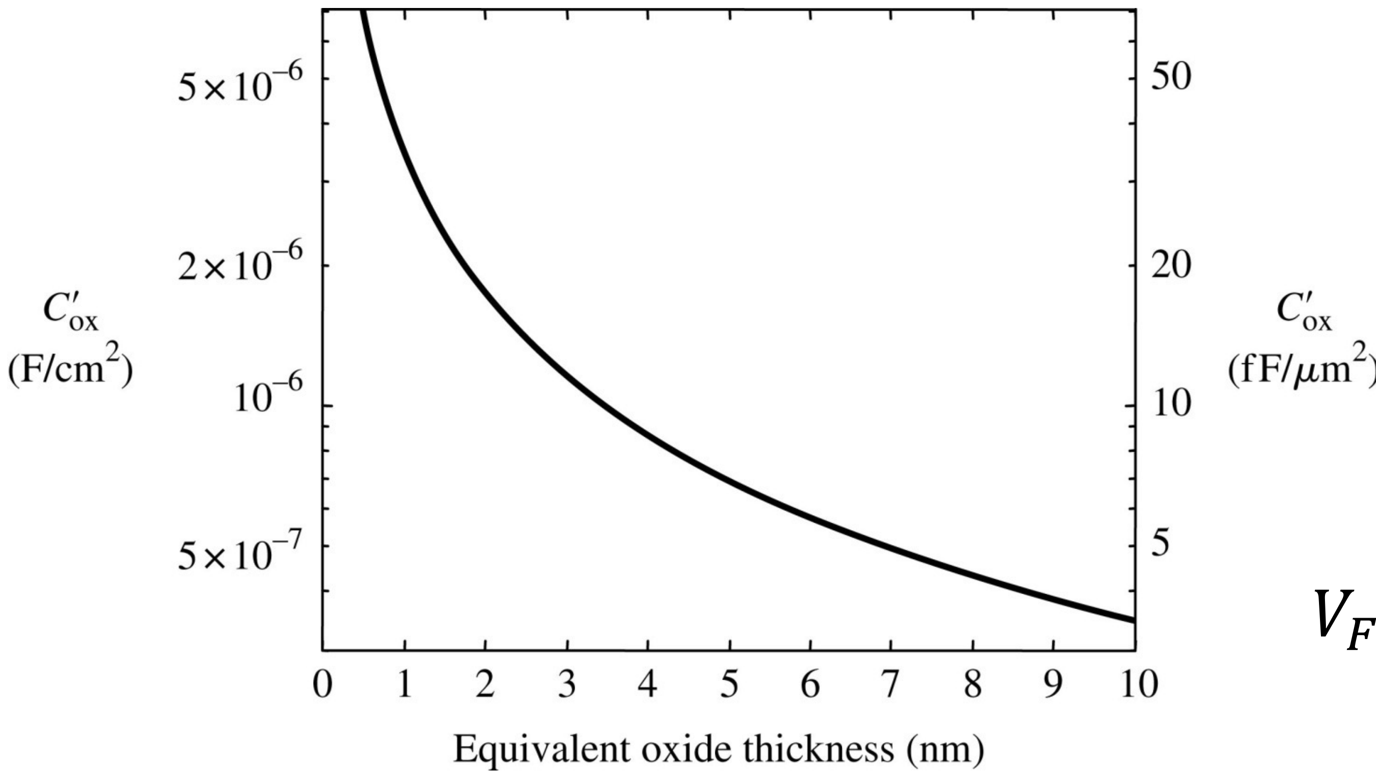


FIGURE 2.3
Capacitance per unit area vs. equivalent oxide thickness (EOT). For a SiO_2 ("oxide") insulator, EOT is the actual insulator thickness; for an insulator with permittivity ϵ_{ins} and thickness t_{ins}, EOT is $(\epsilon_{ox}/\epsilon_{ins})\,t_{ins}$.

$$C'_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

$$V_{FB} = \phi_{MS} - \frac{Q'_0}{C'_{ox}}$$

C-V measurement

[Keysight]

- An AC impedance meter, sometimes called an LCR meter (for inductance [L], capacitance [C], resistance [R]), measures complex impedances with an auto balanced bridge maintaining AC virtual ground at the sense side of the capacitor.
  - Meters of this type typically have a frequency range of 1kHz to 10MHz.
- Obtaining basic AC impedance parameters means measuring the amplitude of the impedance
- Also, useful for determining gate oxide thickness.

Two common AC impedance models: 1.) the parallel model and 2.) the series model.

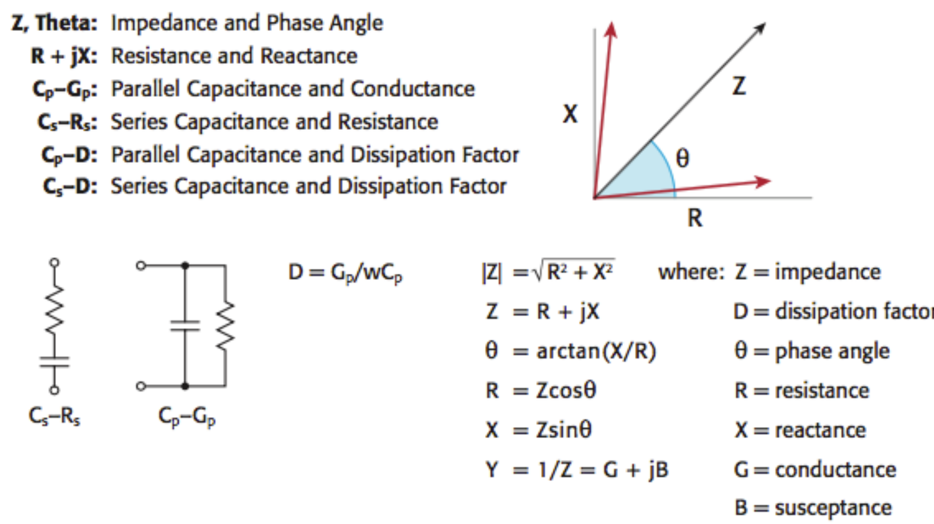


Figure 2. Basic AC impedance parameters

[Textronix]

Problem (Example 2.2)

- Calculate the flatband Voltage for a p-type body with $N_A = 10^{18}$ cm^{-3}, a SiO_2 insulator with a thickness t_{ox} = 2 nm , and an n-type polysilicon gate with $N_D = 10^{20}$ cm^{-3}. The interface charge Q_0' is 10^{-8} C/cm^2.

$$\phi_{MS} = -0.560 - 0.476 = -1.036\,V$$

$$C'_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

$$\epsilon_{ox} = k_{ox} \cdot \epsilon_0$$

$$k_{ox} = 3.9$$

$$C'_{ox} = 1.73\times10^{-6}\ {}^{F}/_{cm^2}$$

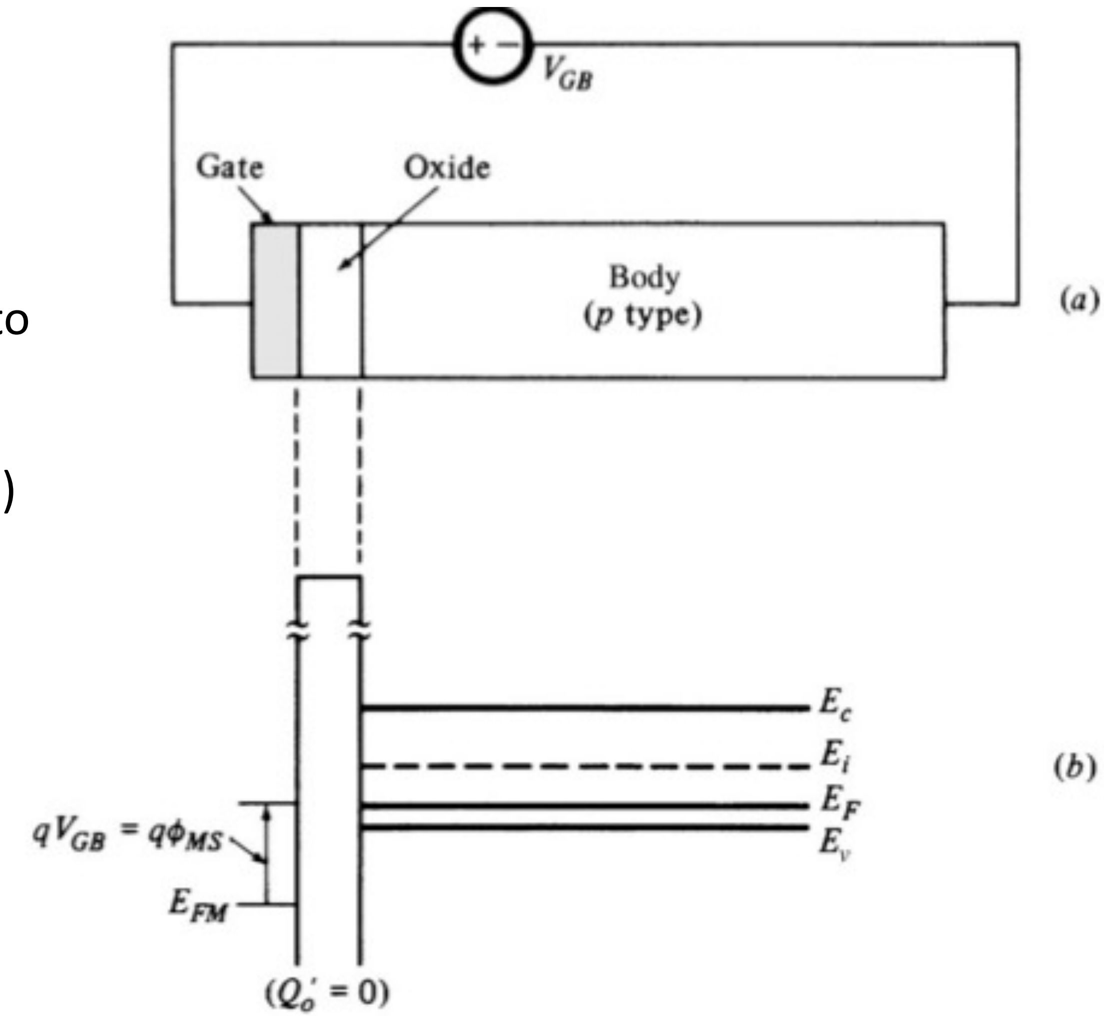
$$\frac{-Q'_0}{C'_{ox}} = -.006\,V$$

$$V_{FB} = -1.036 - 0.006 = -1.042\,V$$

Same experiment with pn junction

Remember from pn junction that the potential is related to the conduction band edge!

(Assume $\phi_{MS} > 0$, $Q_0' > 0$)



Apply full throttle captain!

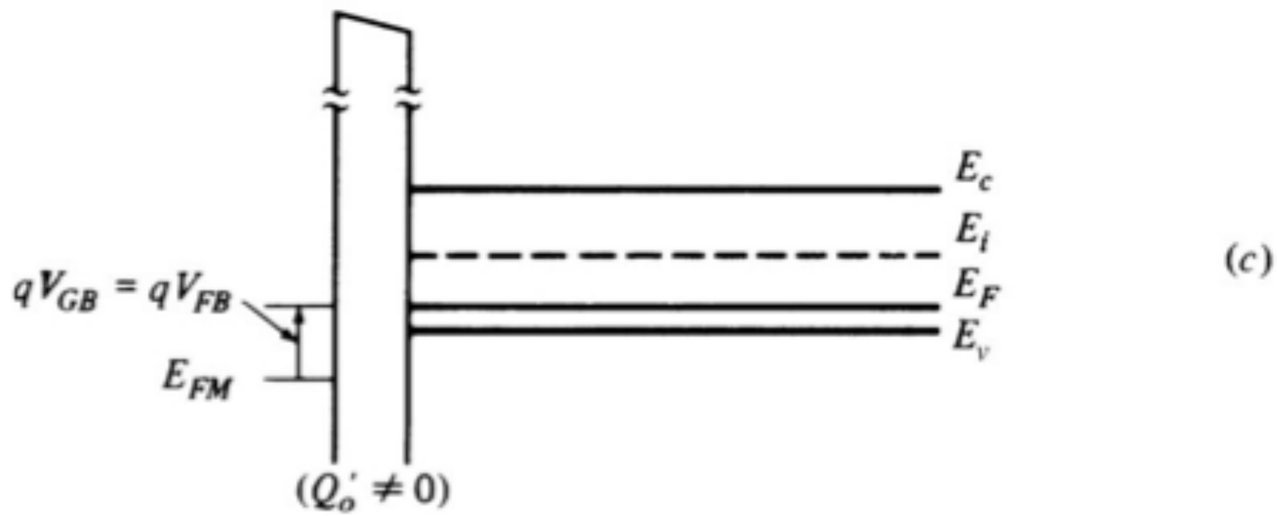


FIGURE 2.3
Capacitance per unit area vs. equivalent oxide thickness (EOT). For a SiO_2 ("oxide") insulator, EOT is the actual insulator thickness; for an insulator with permittivity ϵ_{ins} and thickness t_{ins}, EOT is $(\epsilon_{ox}/\epsilon_{ins})t_{ins}$.

With general externally applied bias

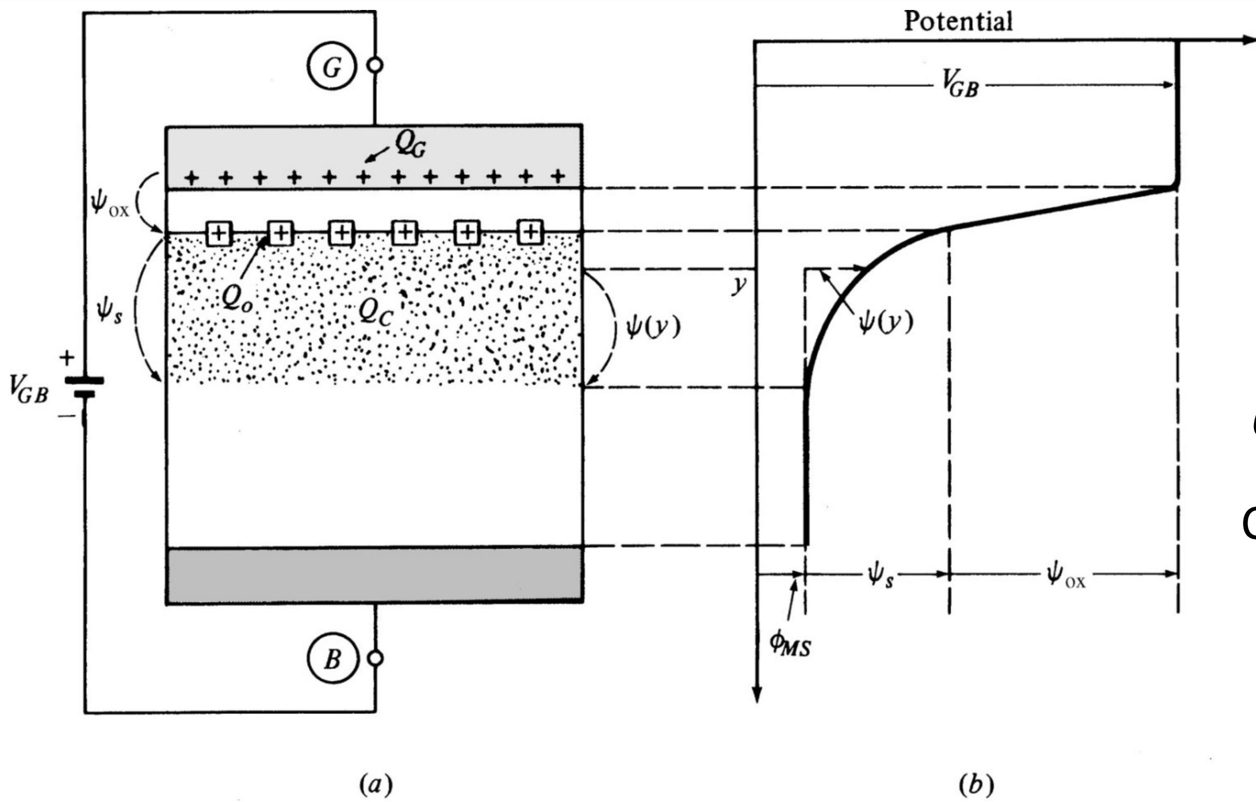


FIGURE 2.5 *(a)* A *p*-body, two-terminal MOS structure under general gate-body bias; *(b)* potential distribution, assuming the gate, the body-metal contact, and the external wires are all made of the same material. The special case of $\psi_s > 0$ has been assumed in drawing this plot.

For semiconductor to be neutral!

$$Q'_G + Q'_0 + Q'_C = 0$$

Charge Balance Eqn.

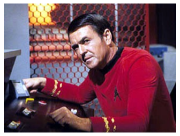
$$\Delta Q'_G + \Delta Q'_C = 0$$

Q_c : Charge across bulk
Q_0 : interface charges
Q_g : gate charges

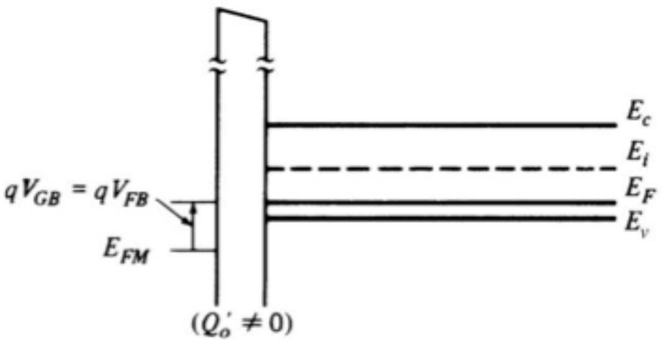
$$V_{GB} = \psi_{ox} + \psi_S + \phi_{MS}$$

Potential Balance or KVL

$$\Delta V_{GB} = \Delta\psi_{ox} + \Delta\psi_S$$

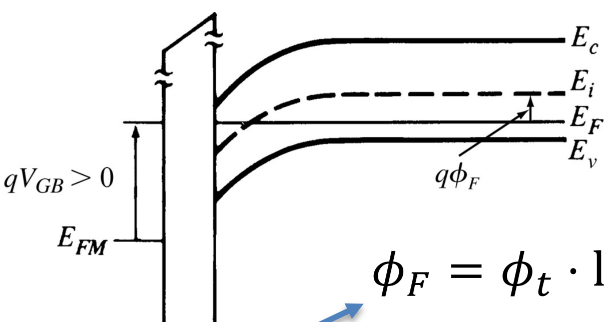


Too much engine captain!!!

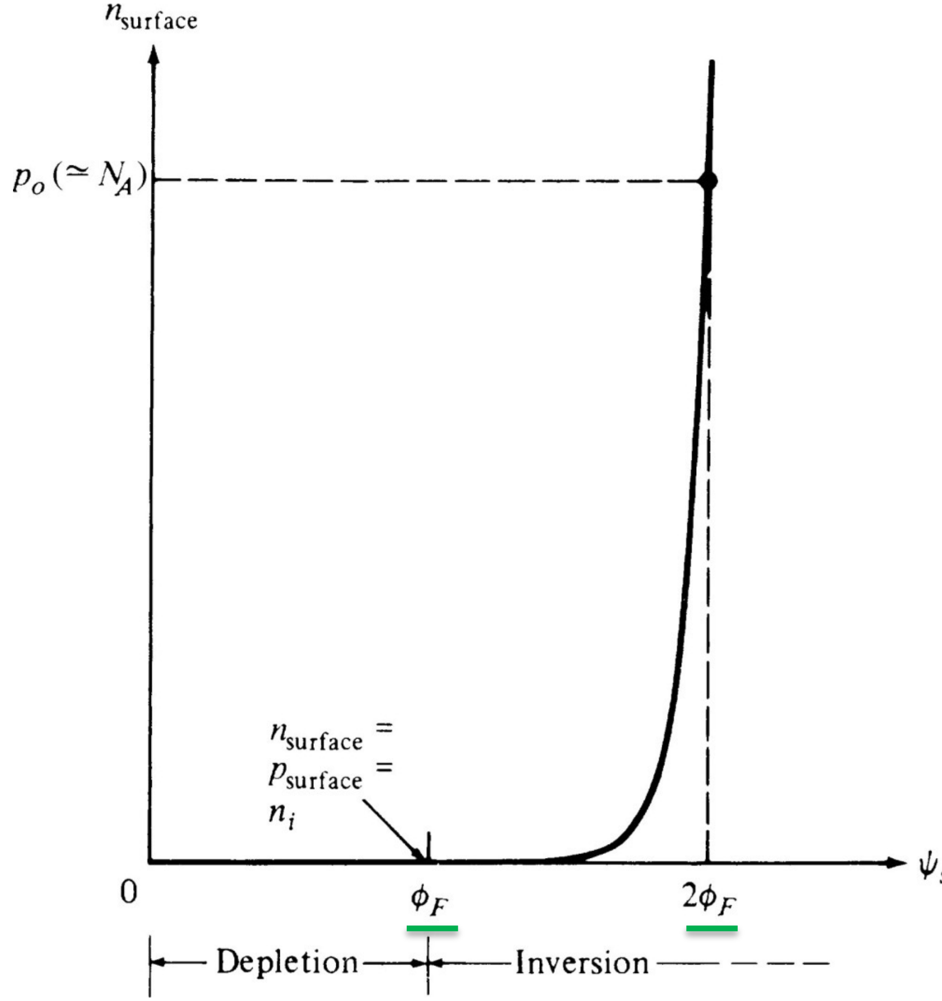


(c)

Inversion



(d)



$$\phi_F = \phi_t \cdot \ln\frac{N_A}{n_i}$$

$$\frac{n_i^2}{N_A} \longrightarrow n_0$$

$$\frac{n_{surface}}{n_0} = e^{\psi_s/\phi_t} \longrightarrow n_{surface} = N_A \cdot e^{(\psi_S - 2\cdot\phi_F)/\phi_t}$$

Also, for n-type semiconductor

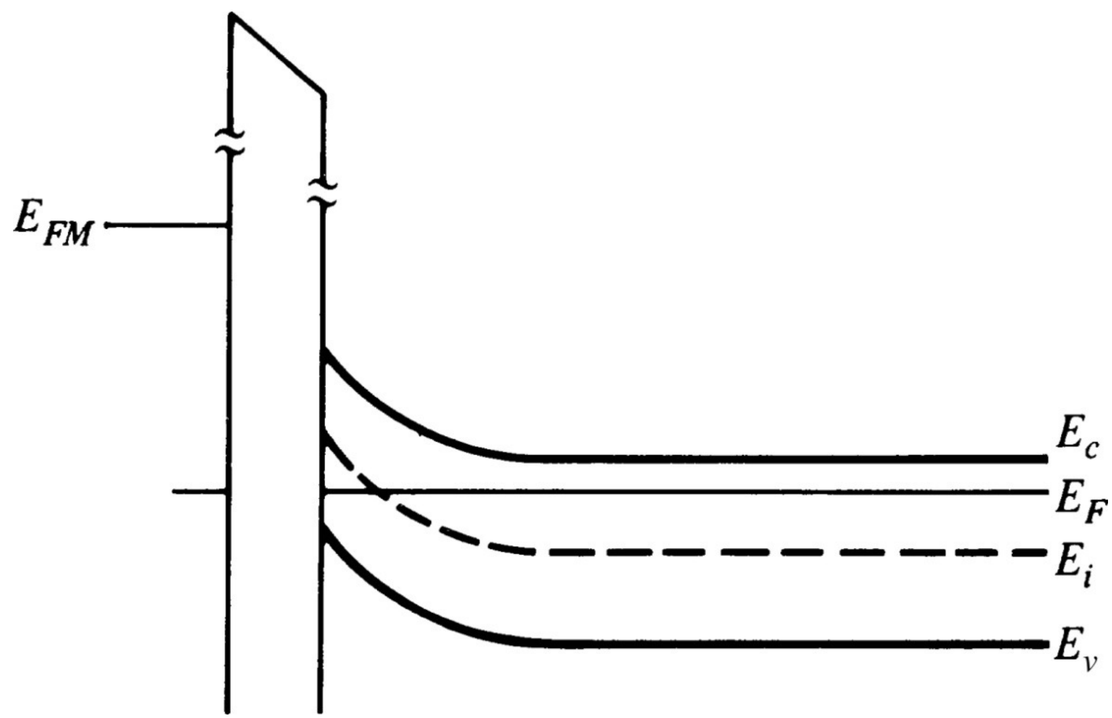


FIGURE 2.9 Energy band diagram for a two-terminal MOS structure with an *n*-type body in inversion.

MOS Devices

- MOS devices are key to the operation of CMOS, and they are integral to current integrated circuits today in many applications.
- We will examine this MOS device very closely over the next two weeks.
- Understanding this process requires solving complex non-linear equations, so we need some mechanism to help with this.
  - We will use MATLAB, but you are welcome to use any other method to accomplish the same feature.
  - Some good tools to try are:
    - C [MINPACK (set of libraries built to help solve these operations quickly in C – interestingly, BLAS and LINPACK/EISPACK are what drove Cleve Moler to make MATLAB).]
    - Python – check out http://numpy.org
    - You are on your own if you use your own tool mainly because I do not have time to debug other programs (but don't let me stop you if you like a specific program).

MATLAB

- I am not trying to promote programs or tell you which programs you should use, but you need to learn how to use programs to solve scientific problems.
- MATLAB in my opinion is the best program to do this – this is especially true with the plethora of tools boxes.
  - OSU provides MATLAB for free to all CEAT students.
  - https://ceat-its.okstate.edu/matlab_simulink
- MATLAB is extremely expensive in industry, so I wish there were options for other programs to promote competition.
  - There are some free open-source programs that do a good job at mimicking what MATLAB is doing.
  - https://opensource.com/alternatives/matlab

Finding Roots

- Most of you have not had me in previous classes and that's okay.
- You need to learn how to find roots of an equation, especially in this class since homework will eventually have equations you have solve for specific roots.
  - That is, if you have an equation for pressure that is $p(x) = \ln(x^2)$ and you want to find where the pressure is 0.7, how do you solve this?
- The simplest way around this is to estimate of the root of the equation $f(x)=0$ or to make a plot of the function and observe where it crosses the x-axis.
  - That is $g(z) = p(x) – 0.7$
  - What you are doing here is creating a "new" function that is the error between what you want (the answer) and your desired value.

Creating functions in MATLAB

- You can easily create functions in MATLAB with a powerful addition to its program.
- f(x) = ln(x^2) can be written as f = @(x) log(x^2)
- For example, you can type:

```
g = @(x) log(x^2)
g(3.23)
ans = 2.3450
```

MATLAB’s `fzero` Function

- MATLAB’s `fzero` provides the best qualities of both bracketing methods and open methods.
  - Using an initial guess:
    `x = fzero(function, x0)`
    `[x, fx] = fzero(function, x0)`
    - *`function`* is a function handle to the function being evaluated
    - *`x0`* is the initial guess
    - *`x`* is the location of the root
    - *`fx`* is the function evaluated at that root
  - Using an initial bracket:
    `x = fzero(function, [x0 x1])`
    `[x, fx] = fzero(function, [x0 x1])`
    - As above, except *`x0`* and *`x1`* are guesses that *must* bracket a sign change

`fzero` Options

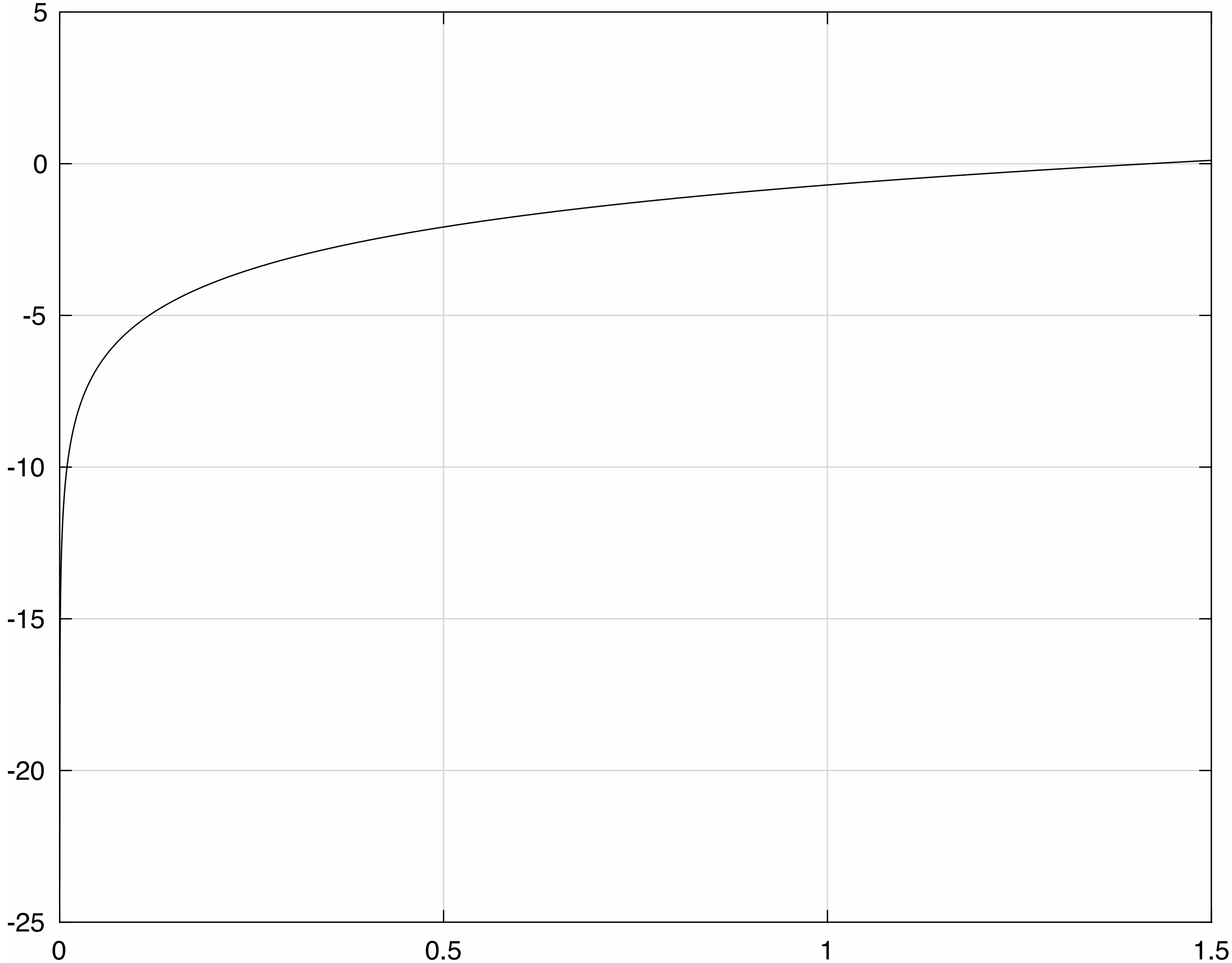
- Options may be passed to fzero as a third input argument - the options are a data structure created by the `optimset` command
- *options* = optimset('*par*$_1$', *val*$_1$, '*par*$_2$', *val*$_2$, …)
  - *par*$_n$ is the name of the parameter to be set
  - *val*$_n$ is the value to which to set that parameter
  - The parameters commonly used with `fzero` are:
    - `display`: when set to 'iter' displays a detailed record of all the iterations
    - `TolFun`: A positive scalar that sets a termination tolerance on x.

`fzero` Example

- `options = optimset('Display','iter','TolFun',1e-8)`
- Sets options to display each iteration of root finding process
- `[x, fx] = fzero(@(x) log(x^2)-0.7, 0.1, options)`
- `g = @(x) log(x^2)-0.7;`
- `[x, fx] = fzero(g, 0.1, options)`

  – Uses fzero to find roots of $f(x)=log(x^2)$ starting with an initial guess of x=0.1.
- MATLAB reports `x=1.41907, fx=-1.11022e-16` after 46 function counts

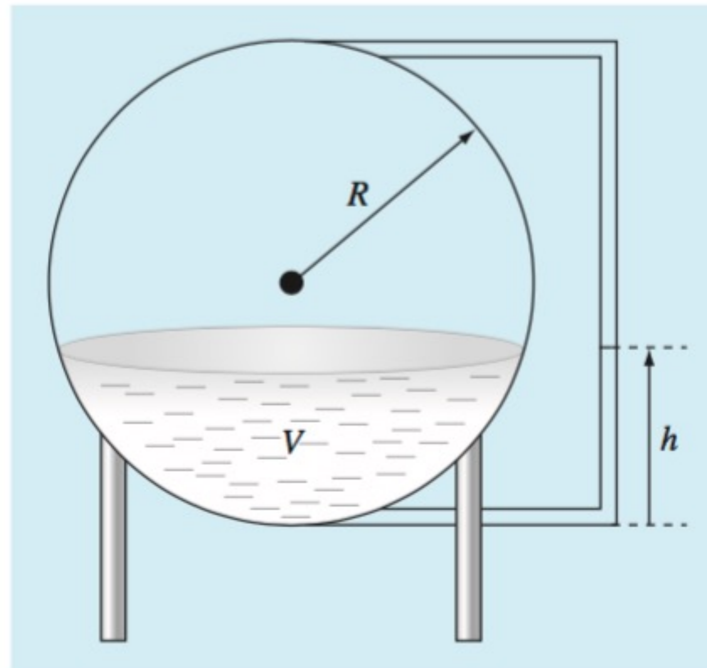
Plot of log(x.^2 – 0.7)



Example

- V =volume [m^3] = 30 m^3
- h = depth of water in tank [m] = ?
- R = tank radius [m] = 3 m

$$V = \pi \cdot h^2 \cdot \frac{(3 \cdot R - h)}{3}$$

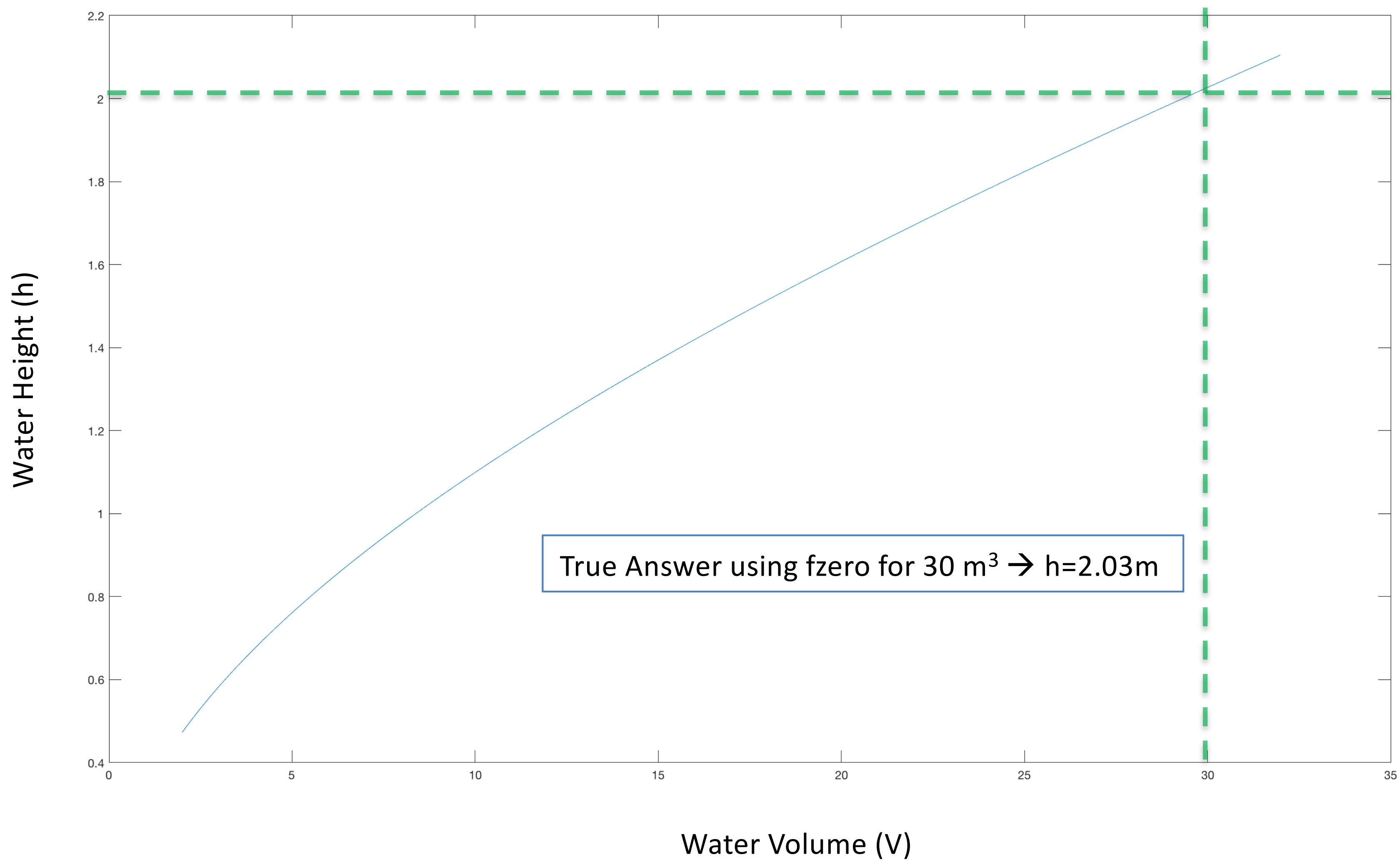


Show a plot of height vs. Volume you purchase! For this problem, you have to assume you cannot solve for `h` given `V`, `R`

MATLAB code

```
clear
clc
% Radius
R = 3
% Equation
V = @(h) pi * h.^2 .* ((3*R-h)/3);
% Initial/Final Values
InitialV = 2;
FinalV = 32;
% Initialize y
y = [];
for x = InitialV:.1:FinalV
    y = [y fzero(@(h) V(h) - x, 1)];
end
```

Plot of water available based on size of vessel



Summary

- Learned the introduction of MOS devices through the MOS Capacitor.
- The MOS Capacitor is a very important in understanding the operation of the MOS device.
- We will go through in detail items in Chapter 2 and follow on the sections closely based on our tentative schedule.