

ELEC 131 - Electronic Circuits I

MOS Capacitor - Java Applet

Lab

Objectives:

Upon completion of this laboratory students should be able to:

- 1) Identify the three regions of operation of the MOS capacitor
 - 2) Draw the electric field and charge distribution for A MOS capacitor in depletion, accumulation, inversion, flatband, or at threshold.
 - 3) Understand the terms flatband and threshold voltage and be able to calculate them.
 - 4) Plot the gate charge and capacitance versus applied voltage.
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Procedure:

1) Visit the first link titled "Equilibrium Band Diagrams for MOS capacitors" at (<http://jas2.eng.buffalo.edu/applets/education/mos/mosCap/equiBand10.html>) This applet let you vary the gate material, substrate doping, oxide, thickness, and charge trapped at the oxide-semiconductor interface due to fabrication (Q_{ox}). The first graph shows the charge distribution the second graph shows the energy diagram with electron energy on the y-axis.

a) First set the Q_{ox} to zero (to keep life simple). Set the gate material to p-type Poly-Si ($M=p+poly$). Make sure the substrate doping is at 10^{15} , $t_{ox}= 100\text{\AA}$, and nmos is selected (**Note that although numbers on the plots may change the results are not accurate unless you re-execute the applet by pushing the separate or equilibrium buttons.**)

a) Hit the Separate button so the materials are not connected. Take a look at the bottom graph of electron energy vs position. Hit the "form junction" button to move the materials together (this is not yet in equilibrium, and could never exist except to help visual what is going on when you bring two materials together). The pink line represents the fermi energy of the electrons on the semiconductor side (Fermi energy = E_f), while the top of the gray rectangle represents the fermi energy on the metal side (or Poly-Si side. To reach equilibrium, these lines must be at the same energy.

More about the Energy diagram..

The energy (or voltage) between E_c and E_v is always 1.14 eV because this is a silicon, and that is the energy required to excite an electron away from its silicon atom to roam the crystal. E_i is defined as the center between E_c and E_v and is therefore 0.557 eV from each. The Energy $E_i - E_f = \phi_p = (Kt/q) \ln(N_a/n_i) = .31$ eV in this case.

c) Find the difference in average energy between the semiconductor and P+-poly material (hint: the P+ poly is like a very very heavily doped P-type Si, therefore the E_f line is coincident with the E_v line which is located .557 eV below E_i). Draw the energy band diagram as it appears with the values labeled

$$E_{f \text{ semiconductor}} - E_{f \text{ p+poly-si}} = \underline{\hspace{2cm}}$$

d) In this instance since the energy of electrons is higher in the semiconductor, therefore to reach equilibrium, electrons will transfer to the metal side! (The result should be electrons on the metal side (negative charge) and less electrons (or more holes) on the semiconductor side. Click the Equilibrium button to see.

e) Sketch the charge distribution and record the magnitudes of the charges at equilibrium.

a) From the charge distribution, sketch the Electric Field and potential across the junction. Find the total potential across the junction. (Give values!) Remember that the ratio of permittivities of Si to SiO₂ is ~3:1

Maximum E-field = _____ Total potential difference = ϕ = _____

g) Compare the potential difference you found in part g to that in part d. They should be the same! Also verify that the potential difference(ϕ), $\phi=Q/C_{ox}$

h) Label your graphs in part g "Accumulation". Notice that the charge on the semiconductor (holes) is the same type as the major carrier (p-type) so these extra charges "accumulate at the surface".

2. Click the **Separate** button. Change the metal material to n+ Poly-Si. Click the **form junction** button.

a) Notice that the top of the grey line for N+-Poly Si lines up with the E_c layer in the semiconductor because n+-Poly Si is like very very heavily doped n-type Si. Calculate the difference in average energy between the semiconductor and N+-poly material. (again distance between E_c and E_i = .557 eV).

$E_{f \text{ semiconductor}} - E_{f \text{ n+poly-si}} =$ _____

b) Based on where the fermi levels are, which way are the electrons going to move to reach equilibrium?

c) Check your answer by clicking the Equilibrate button.

d) Hey how come this one looks so much different?? Sketch the charge distribution and record the magnitudes.

- e) From the charge distribution, sketch the Electric Field and potential across the junction. (give values!) Remember that the ratio of permittivities of Si to SiO₂ is ~3:1.

Maximum E-field = _____ Total potential difference = ϕ = _____

- f) Compare the potential difference you found in part 2e to that in part 2a. They should be the same!
- g) Now why does this look so different than the last case? Run the Equilibrate again and notice how the depletion region forms before the excess electrons at the surface starts to accumulate. Basically as the electrons arrive they start to compensate the Na dopant forming Na⁻ (exactly like at a p-n junction!). This continues until the concentration of electrons at the surface is the same as the hole concentration in the bulk substrate (=Na). Any additional electrons then accumulates at the surface.
- h) Label the charge, Electric Field, and potential plots as "Inversion". This term means that the surface of the semiconductor has changed types (*inverted* from p-type to n-type in this case)

3. Click the **Separate** button. Now change the doping of the substrate to $2e^{16}$ (leave other parameters the same, n+poly-gate). Click the **form junction** button.

- a) As before, calculate the difference in average energy between the semiconductor and N+ poly material. It should only have changed slightly from part 2 above since the potential varies as the natural log of the doping.

$$E_{f \text{ semiconductor}} - E_{f \text{ n+poly-si}} = \underline{\hspace{2cm}}$$

Based on where the fermi levels are, which way are the electrons going to move to reach equilibrium?

- b) Check your answer by clicking the Equilibrate button.
- c) Hey this one is different too?? Sketch the charge distribution and record the magnitudes.

- d) From the charge distribution, sketch the Electric Field and potential across the junction. (give values!) Remember that the ratio of permittivities of Si to SiO₂ is ~3:1.

$$\text{Maximum E-field} = \underline{\hspace{2cm}} \quad \text{Total potential difference} = \phi = \underline{\hspace{2cm}}$$

- e) Compare the potential difference you found in part 3d to that in part 3a. They should be the same!
 - f) Label these plot "Depletion" . In this case since the doping was higher, charge balance was reached before the surface concentration of electrons was equal to the concentration of holes in the bulk p-type Si. The surface has not yet reached "inversion" it is still "depleted"
4. Now run the second java applet on the list, " Equilibrium Band Diagram for MOS Capacitor showing potential across the junction " at <http://jas2.eng.buffalo.edu/applets/education/mos/mosCap/equiPot10.html>. Run the same three scenarios as in part 1,2 and 3 to quickly check your sketches and values. Note that the potential graph is off the scale, so you will have to rely on your analysis..
5. Now run the Third applet, "MOS Capacitor Energy Diagram " <http://jas2.eng.buffalo.edu/applets/education/mos/mosCap/biasBand10.html>. This applet allows you to apply an external voltage to the MOS structure as well as examine equilibrium. The purpose of this exercise is to understand the terms "Flatband voltage" and "Threshold voltage".

Flatband Voltage

A) For the same set up as in Part 1 (p+ - Poly-gate, $Q_{ox}=0$, nmos, $t_{ox}=100 \text{ \AA}$, and doping = $1e^{15}$), First hit the equilibrium button - you see exactly what you did in section 1. Now hit the "Flatband" button. This finds the applied voltage that results in the energy band diagram (at the bottom) to be totally flat. Record this value and comment on how it relates to the potential across the structure found in part 1d and g?

V flatband (p+poly gate with $N=1e^{16}$) = _____

B) repeat part A to find the flatband voltage for the depletion and inversion conditions in part 2 and 3.

V flatband (n+poly gate with $N=1e^{16}$) = _____

V flatband (n+poly gate with $N=2e^{16}$) = _____

Threshold Voltage

6. With the same applet, for the same set up as in Part 1 (p+ - Poly-gate, $Q_{ox}=0$, nmos, $t_{ox}=100 \text{ \AA}$, and doping = $1e^{15}$), hit the "Threshold" button. This finds the applied voltage that results in the surface concentration of electrons at the oxide-semiconductor interface equal to the concentration of holes in the bulk. This condition is reached when $E_f - E_i$ at the surface = $E_i - E_f = \phi_p$ in the bulk p-type si. Look closely at the bottom graph to see that this is true. Any further voltage should result in excess electrons piling up at the oxide-semiconductor surface called accumulation.

A) Record the Threshold voltage for all three cases.

V threshold (p+poly gate with $N=1e^{16}$) = _____

V threshold (n+poly gate with $N=1e^{16}$) = _____

V threshold (n+poly gate with $N=2e^{16}$) = _____

B) To verify that additional voltage would result in excess electrons piling up a the oxide-semiconductor surface, Click the V_{gb} button to increase the voltage beyond threshold. Record what happens.

C) Verify the the three threshold voltage above with hand analysis using the threshold voltage eq...

