University of California at Berkeley
College of Engineering
Mechanical Engineering Department

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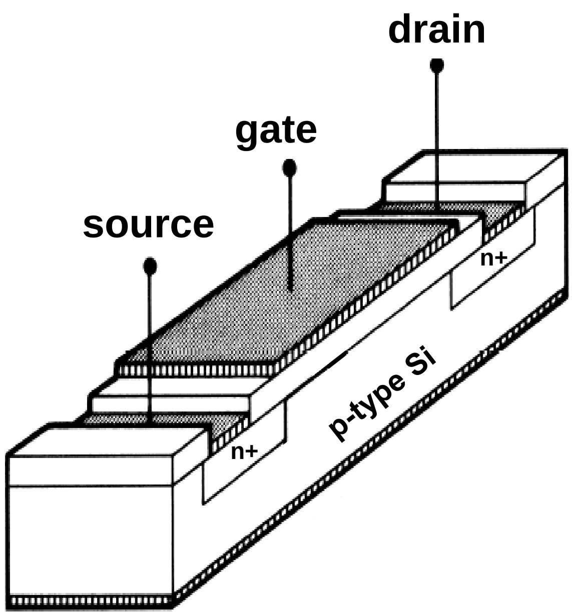
Problem Set #2

Problem 1 (MOSFET)

a. Sketch the 3D view model of an n-channel MOSFET (can be the same as the one we have discussed in class and the same figure). Please clearly mark all regions such as n and p doped regions, terminals …
b. Explain the principal operation of the n-channel MOSFET. Is the charge through the channel transported by holes or electrons?
c. Explain modes of operation of a MOSFET, including graphic illustrations.

a) **5 points**



b) **5 points**

As the gate voltage (V_G) is increased, holes are repelled away from the substrate surface. The surface is depleted of mobile carriers. The charge density within the depletion region is determined by the dopant ion density. As V_G increases above the threshold voltage (V_{TH}), a layer of conduction electrons forms at the substrate surface (under the gate oxide). Therefore, the electrons at the inversion layer can flow between the heavily doped (i.e. highly conductive) source and drain regions if there is a potential difference between them.

c) <u>10 points</u>

The operation of a MOSFET can be separated into three different modes, depending on the voltages at the terminals. The three operational modes are explained below **(based on a basic threshold model of N-MOSFET with a long channel)** :

Let $V_{GS} = V_{gate} - V_{source}$, $V_{DS} = V_{drain} - V_{source}$

i) Sub threshold mode [V_{GS} < V_{TH}]

The MOSFET is turned off, and there is no current flow between the source and the drain because the channel of inversion layer is not formed.

ii) Linear region mode, triode mode [V_{GS} > V_{TH} & V_{DS} < (V_{GS} - V_{TH})]

The MOSFET is turned on, and a channel between the source and the drain is created by the inversion of layer under the gate oxide. It allow current to flow between the drain and the source. Also, the current flow is controlled by the gate voltage relative to both the source and drain voltages since the channel is not pinched off. The current flow in the channel can be described as:

$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_{TH}) - \frac{V_{DS}}{2}\right]V_{DS}$$

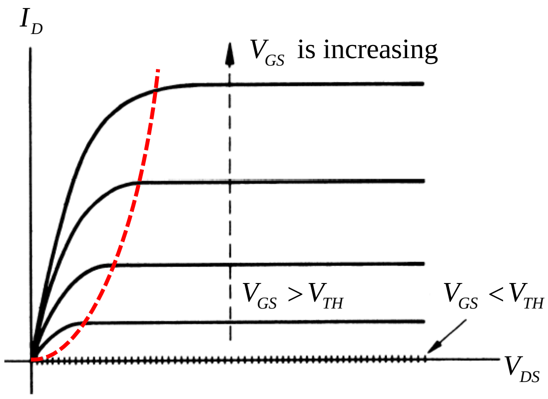
where μ_n is the electron effective mobility, W is the gate width, L is the gate length and C_{ox} is the gate oxide capacitance per unit area.

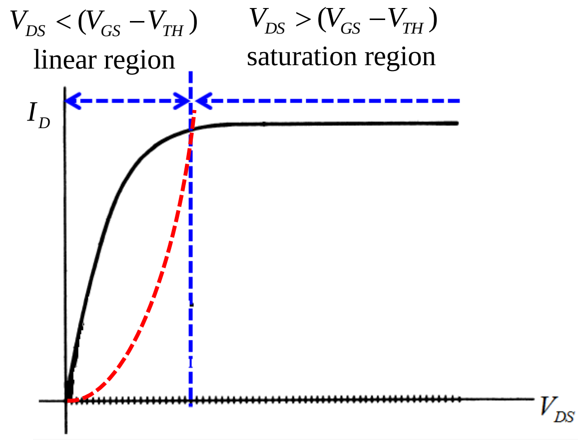
iii) Saturation mode, active mode [V_{GS} > V_{TH} & V_{DS} > (V_{GS} - V_{TH})]

The MOSFET is turned on, and a channel between the source and the drain is created by the inversion of layer under the gate oxide. However, the current flow between the drain and the source is not controlled by the source and drain voltage. When V_{DS} is increased to be equal to V_{GS} - V_{TH}, the inversion layer charge density at the drain end of the channel equals to zero (pinch-off). Then, the current is saturated because the voltage applied to across the inversion layer is always constant . The current flow in the channel can be described as:

$$I_D = I_{D,sat} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$$

In addition, the graphical illustrations on the above explanation are following.



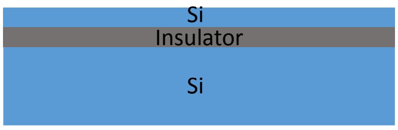


Problem 2 – **10 points**

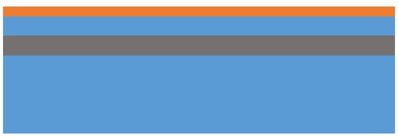
The student should show the ability to illustrate the process using **cross sectional view** figures.

Any angle of view is acceptable, but three general steps must be included:

1) Photolithography



Start with a SOI wafer



Spin coating a photoresist layer

Exposure and develop

2) Etching of Si

Etching of Si

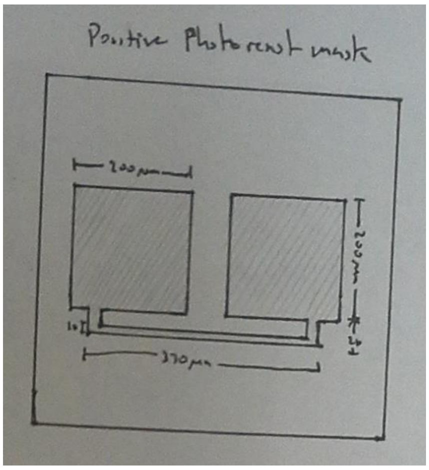
3) Removal of other parts

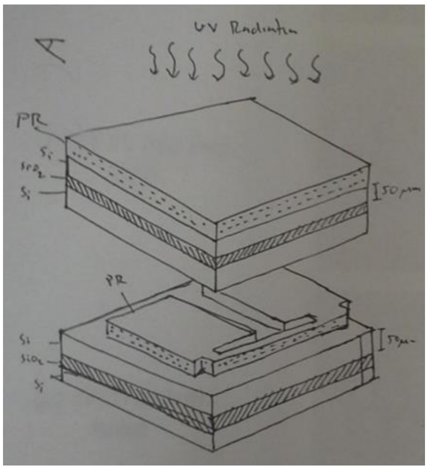
Removal of photoresist

Release of the structure

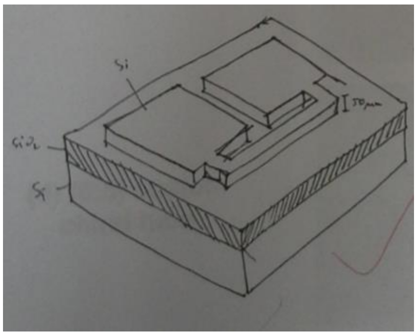
To help understand, here are some 3D drawings from a student’s homework:

Mask and photolithography process:





The Si structure after removel of photoresist:



Problem 3 – **10 points**

Each subset is **5 points** if the vector is correct and the student showed his/her efforts to make the tube. If the vector is incorrect, take -2 points.

The direction and the diameter how the grapheme sheet is rolled up are defined by the vector (n,m). For example, if you want to make a (5,2) nanotube, the sheet is rolled up so that the atom labeled (0,0) is overlapped on the atom labeled (5,2).

$$C_h = na_1 + ma_2$$