EE532: Device Simulation Lab

Experiment No. 2

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Experiment Name: Design and Analysis of MOSCAP using SDE (command line mode), Sdevice in the SWB environment

1 MOS Capacitor

MOS Capacitor is known as heart of MOSFET.It is a two terminal device with metal on top, oxide in between and semiconductor in bottom.To understand the mos transistor it is very important to study the behaviour of moscap.

1.1 Design Parameters

Table 1: Design Parameters

Substrate	Silicon
Dopant	Boron
Doping	$5 \times 10^{16}/cm^3$
Doping type	constant profile placement
Area of substrate	100nm $\times$ 200nm
Oxide thickness	20nm
Gate metal	Aluminum
Metal thickness	40nm
Metal work-function	4.1eV

2 Physics Models

Table 2: Physics Models

Parameters	**Value/Type**
Band gap and Bandgap narrowing	Effective intrinsic density (no band gap narrowing)
mobility models	Mobility(Doping Dependence High Field Saturation
Temperature(K)	300
Traps	Fixed charge

3 Device Structure

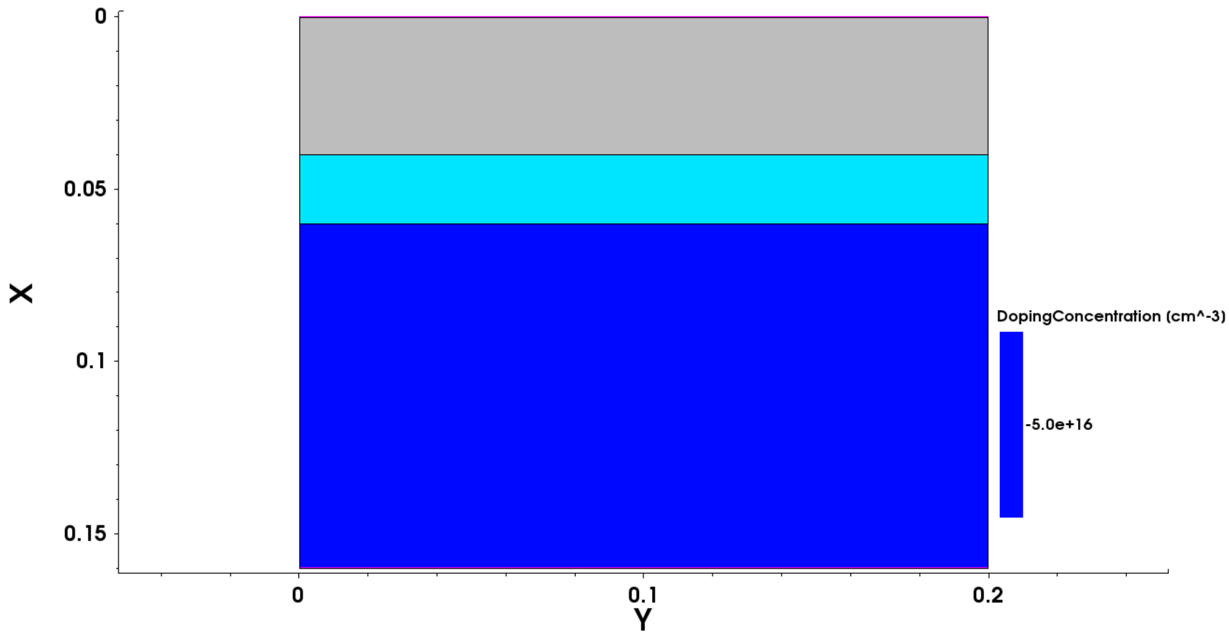

Figure 1: Doping profile without meshing

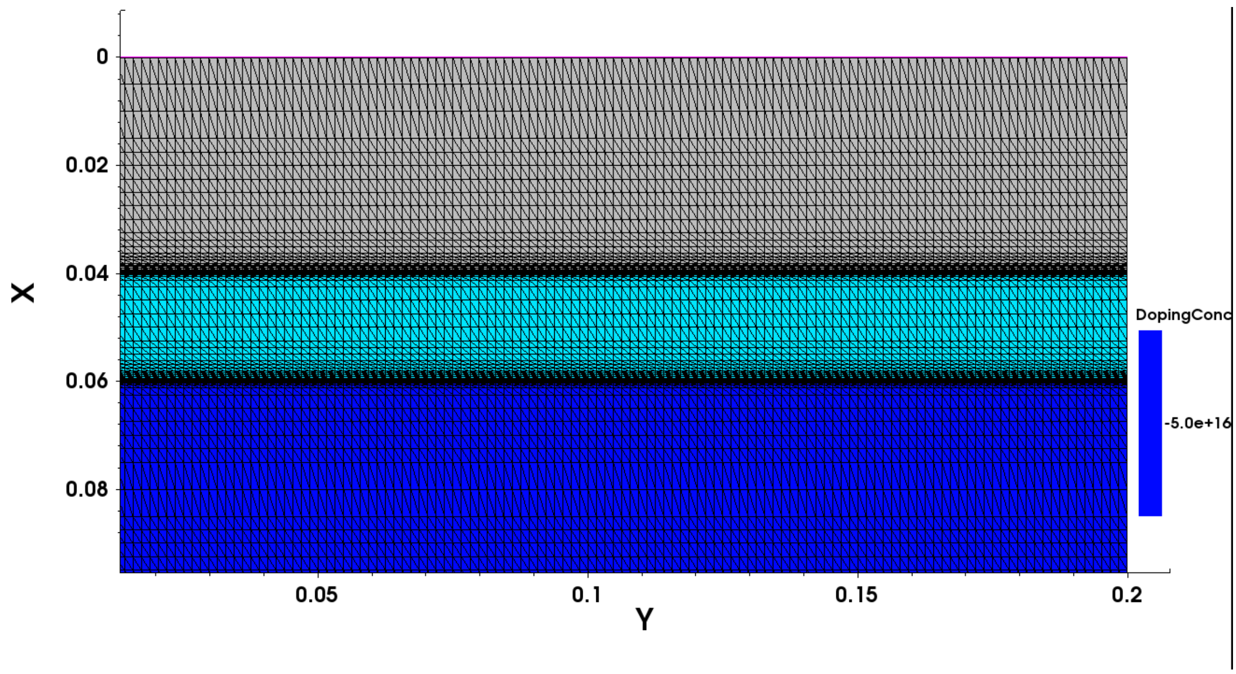

Figure 2: Doping profile with meshing

4 Analysis

Theoretical Calculations:

For flat band condition the fermi energy level of metal and semiconductor should be on same level.

$$WorkFunction = \chi + \frac{E_g}{2} + q\phi_F \tag{1}$$

where χ=Electron affinity of Silicon=4.05eV
E_g=band gap of silicon=1.12eV
N_a=doping of Substrate=5$\times 10^{16}/cm^3$
n_i=intrinsic carrier concentration of silicon=1.5$\times 10^{10}/cm^3$
ϕ_F=fermi potential=$\frac{kT}{q}\ln(\frac{N_A}{n_i})$

$$\phi_F = 0.389V \tag{2}$$

$$WorkFunction = 4.05 + 0.56 + 0.389 = 4.99eV \tag{3}$$

4.1 Plot energy band diagram for various regions

4.1.1 Flatband

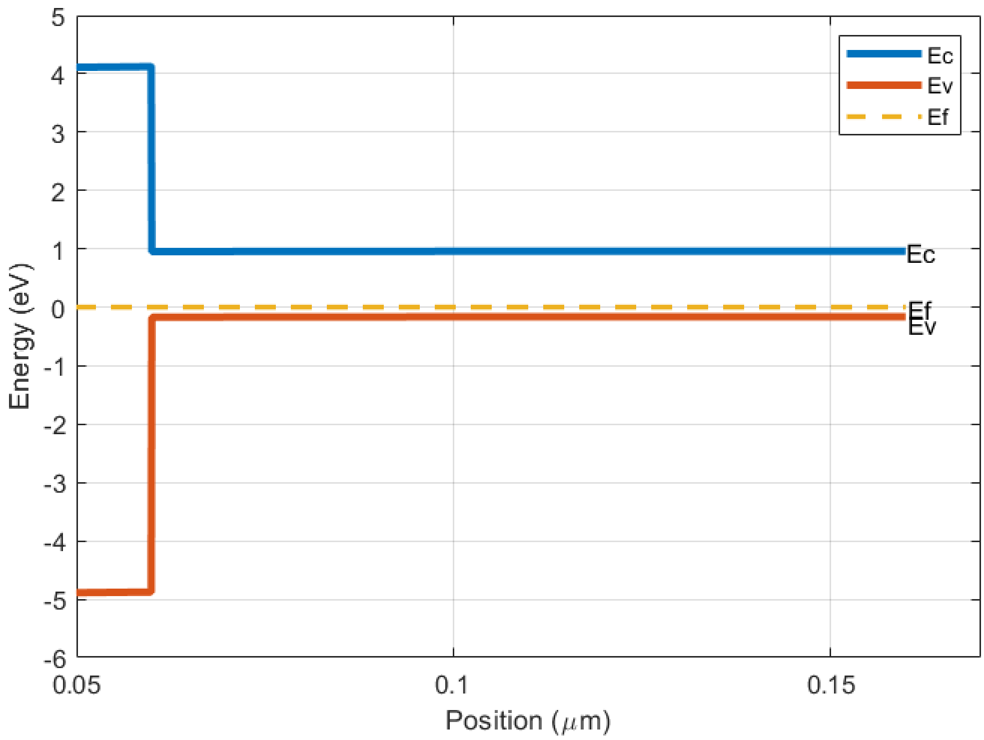

Figure 3: Energy band diagram at flatband condition

To make the band flat, we have given the work function of metal equal to 5eV.Here the moscap is in equilibrium condition.Voltage applied at the gate terminal is 0V.

4.1.2 Accumulation

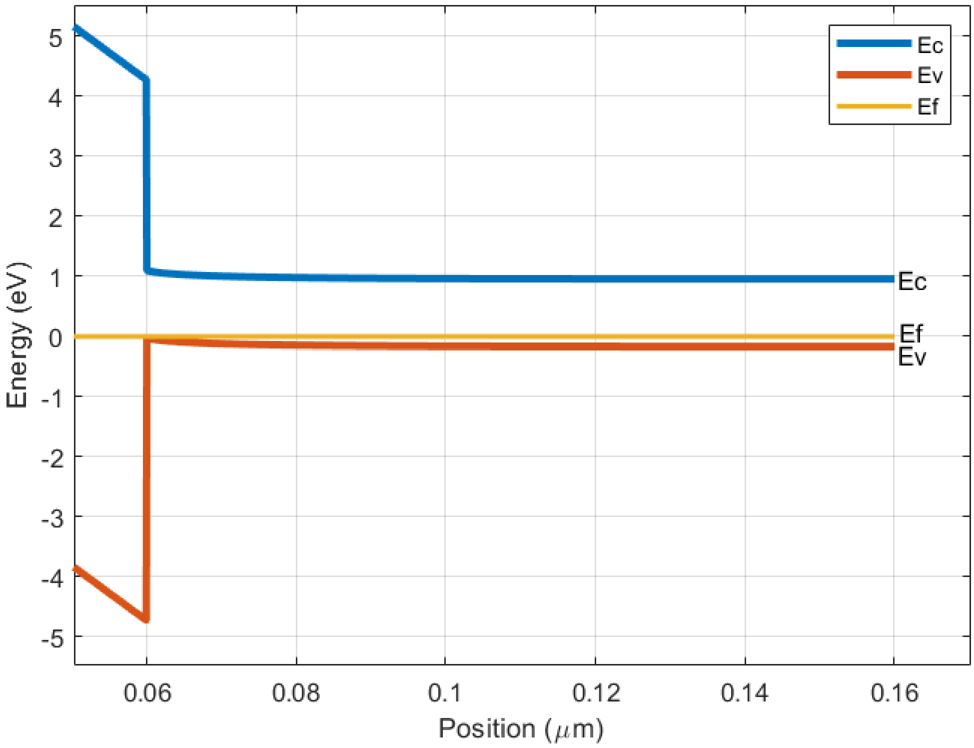

Figure 4: Energy band diagram at accumulation

Here we have applied gate voltage Vg=-2V.With the negative bias at the metal, the holes of the substrate will be accumulated near the oxide-silicon interface. This change can be observed from the band diagram as near the interface the gap between fermi level(Ef) and valence band(Ev) reduces which shows increase in the concentration of holes near interface.

4.1.3 Depletion

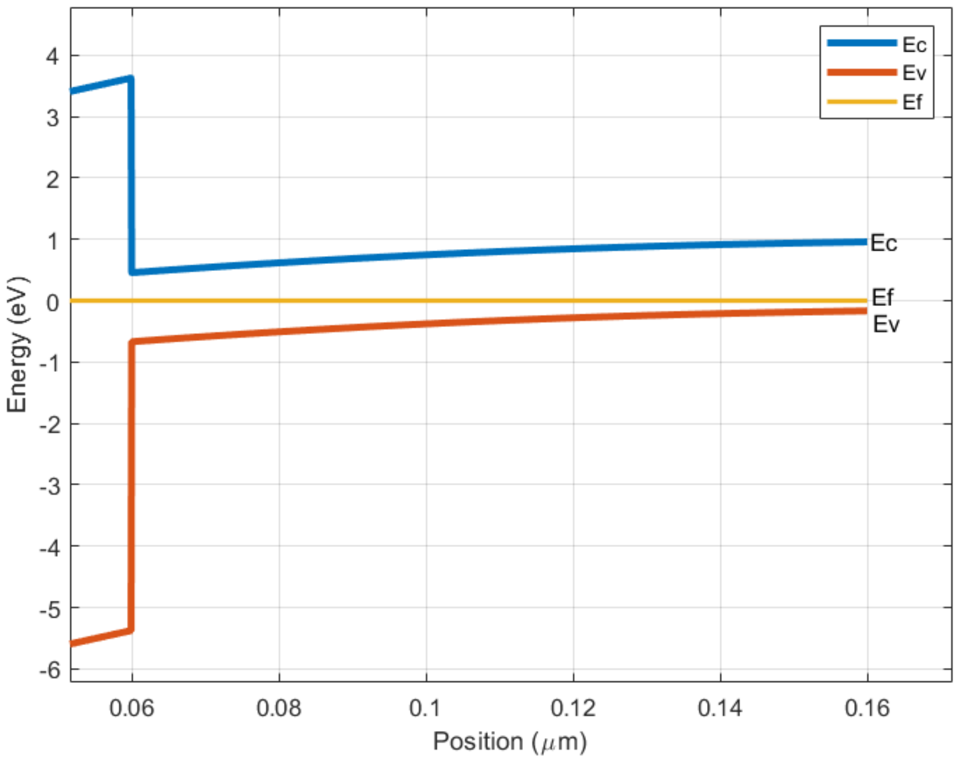

Figure 5: Energy band diagram at depletion

Now we have reverse the polarity and applied positive potential at the gate (Vg=1V). With the positive voltage at gate terminal, holes near the oxide-silicon interface will move away from interface and depletion region will be created. The concentration of majority carrier holes reduces near the interface which can be verified from the band diagram as the gap between the fermi level(Ef) and valence band(Ev) increases.

4.1.4 Inversion

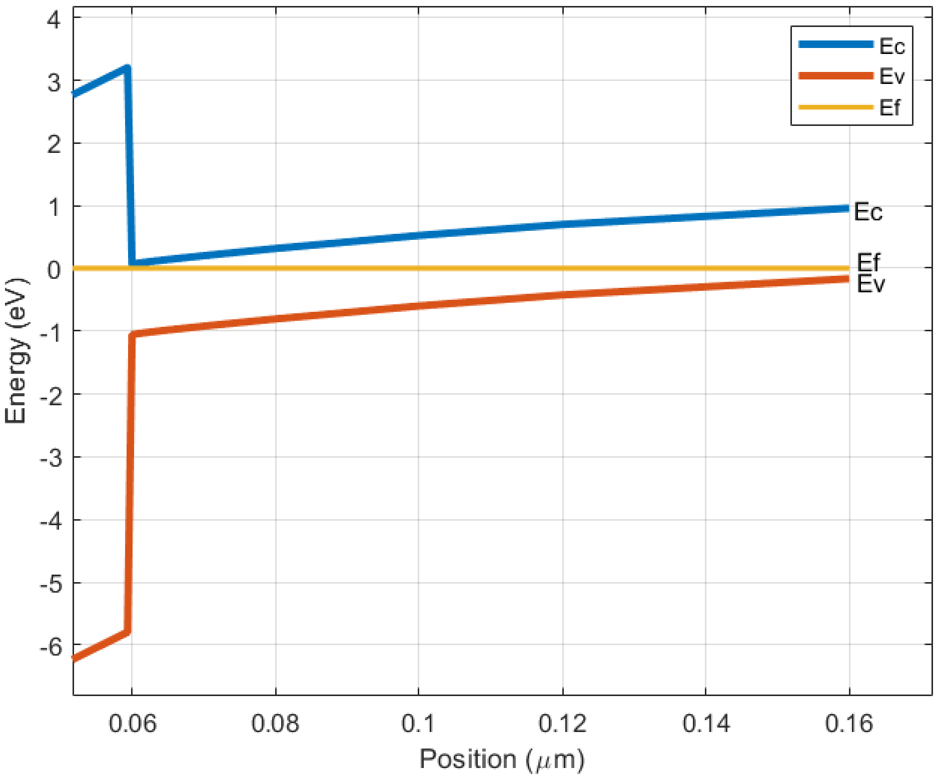

Figure 6: Energy band diagram at inversion

Threshold Voltage Calculation:

$$V_G = V_{TH} = 2\phi_F + \frac{\epsilon_s}{\epsilon_o} x_o \sqrt{\frac{2qN_A \times 2\phi_F}{\epsilon_s \epsilon_o}} \tag{4}$$

where, ϵ_s=permittivity of silicon=11.8ϵ_o
ϵ_o=permittivity of SiO_2=3.9ϵ_o
x_o=thickness of oxide
On solving the above equation we get, V_{TH}=1.47V

Here we have increased the voltage further, Vg=2V.As the voltage is greater than the threshold voltage then the substrate near the interface has been inverted from p-type to n-type.This can also be verifed from the band diagram that the fermi level near the interface is closer to conduction band rather than valence band as it is in the case of p-type.

4.2 Plot C-V curve at three different frequencies in single plot

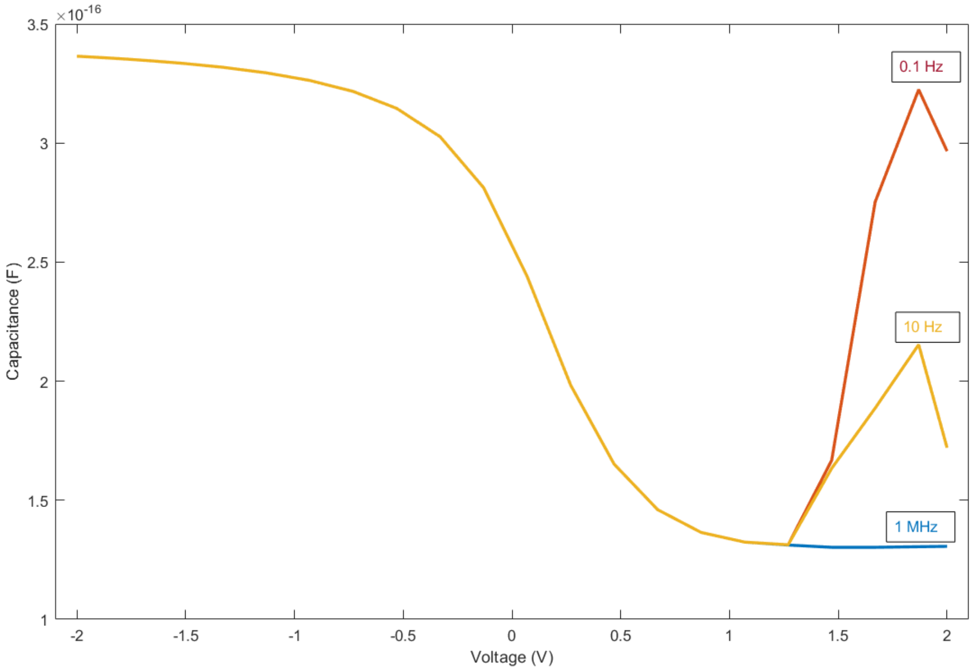

Figure 7: C-V curve at different frequencies

In the accumulation region, the moscap acts as capacitor whose capacitance is given by:

$$C_{ox} = \frac{\epsilon_{ox}}{x_o} = 0.172\mu F/cm^2 \tag{5}$$

Now as we increase the voltage then depletion region starts creating near the interface due to which depletion charges will also be formed and now the total capacitance will be the parallel combination of oxide capacitance and depletion capacitance and the overall capacitance value is reduced which can verified from the plot.
At the onset of inversion, depletion width will be maximum and its value is given by:

$$x_{dmax} = \sqrt{\frac{2\epsilon_s \times 2\phi_F}{qN_A}} = 0.1425\mu m \tag{6}$$

$$C_{dep.min} = \frac{\epsilon_s}{x_{dmax}} = 0.732nF/cm^2 \tag{7}$$

$$C_{min} = \frac{C_{ox} \times C_{dep.min}}{C_{ox} + C_{dep.min}} = 0.729nF/cm^2 \tag{8}$$

The capacitance will minimum at the depletion-inversion transition.Now for the low frequency if we increase the voltage then inversion layer of electron will be created near the interface which will act as shield and the overall capacitance will be again equal to C_{ox}.

In the case of high frequency, when we increase the voltage beyond V_{TH} then the change in ac voltage across the MOS capacitor changes rapidly but the changes in the inversion layer will not be able to respond as electrons are thermally generated at a particular rate.Due to this reason the effective capacitance will be equal to C_{min}.
For mid-frequency the characteristics will be between low and high frequency.

4.3 Plot C-V curve at three different concentrations in single plot

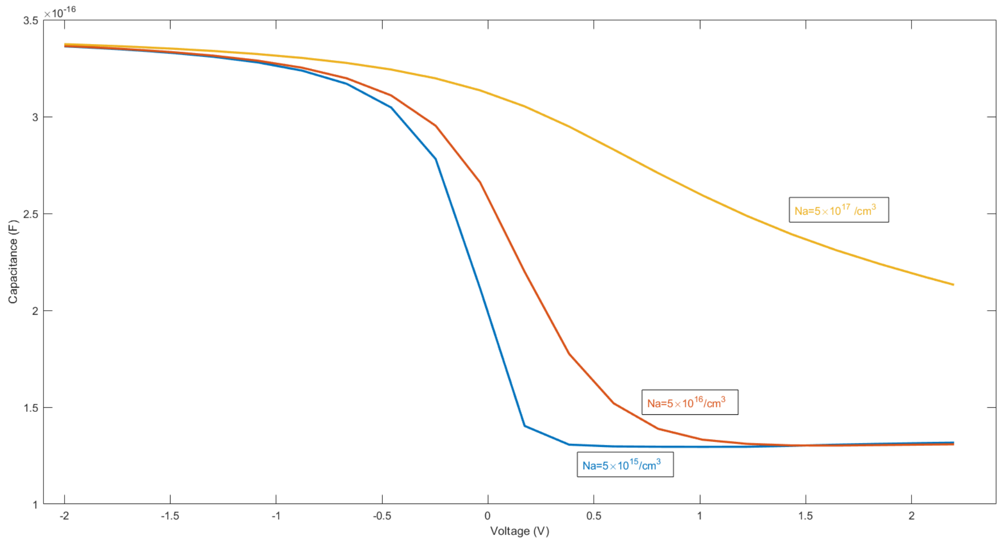

Figure 8: C-V curve at different doping concentration

$$V_G = V_{TH} = 2\phi_F + \frac{\epsilon_s}{\epsilon_o} x_o \sqrt{\frac{2qN_A \times 2\phi_F}{\epsilon_s \epsilon_o}} \tag{9}$$

From the above equation we can see that if we change the doping concentration of substrate then accordingly threshold voltage also changes.

Table 3: Doping Vs Threshold voltage

Doping	**Threshold voltages(V_{TH})**
N_A=5×$10^{15}/cm^3$	V_{TH} = 0.851V
N_A=5×$10^{16}/cm^3$	V_{TH} = 1.47V
N_A=5×$10^{17}/cm^3$	V_{TH} = 3.14V

Hence we can see that as doping concentration increases, threshold voltage also increases which can be verified from the plot.

4.4 Show the impact of different metal work function (atleast three value) in single plot

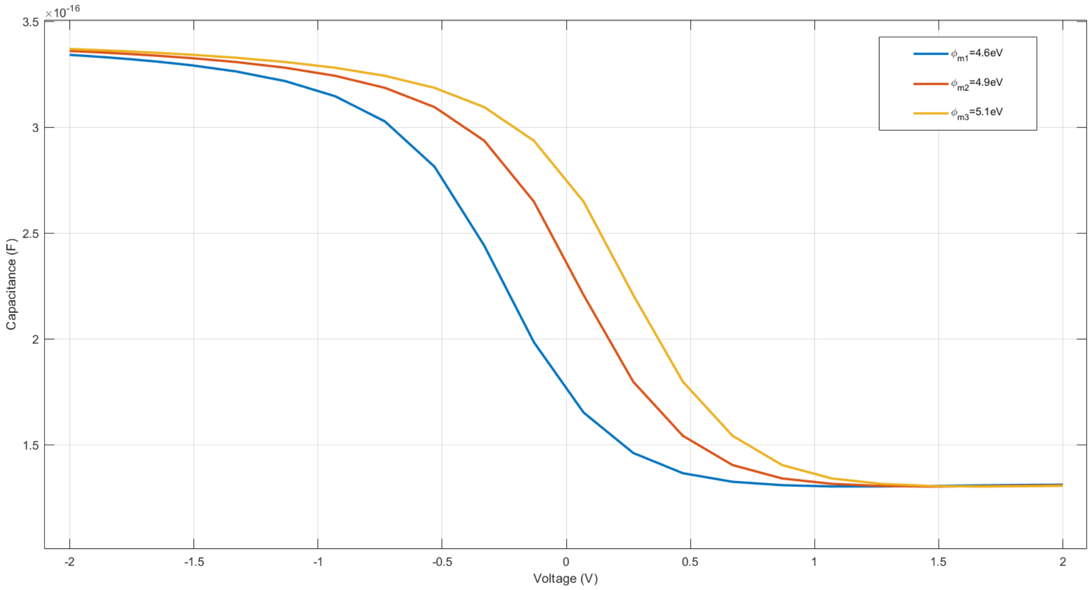

Figure 9: C-V curve at different work functions

$$V_G = V_{TH} = V_{FB} + 2\phi_F + \frac{\epsilon_s}{\epsilon_o} x_o \sqrt{\frac{2qN_A \times 2\phi_F}{\epsilon_s \epsilon_o}} \tag{10}$$

Here V_{FB}=ϕ_{ms}=difference in the work function of metal and substrate

Table 4: Work function Vs Threshold voltage

work function difference	**Threshold voltages(V_{TH})**
ϕ_{m1}=4.6eV	V_{TH} = 1.07V
ϕ_{m2} =4.9eV	V_{TH} = 1.37V
ϕ_{m3}=5.1eV	V_{TH} = 1.57V

From the table we can see that as work function difference values changes then the value of threshold voltage also changes and this can be verified from the plot.

4.5 Plot C-F curve of moscap in different region

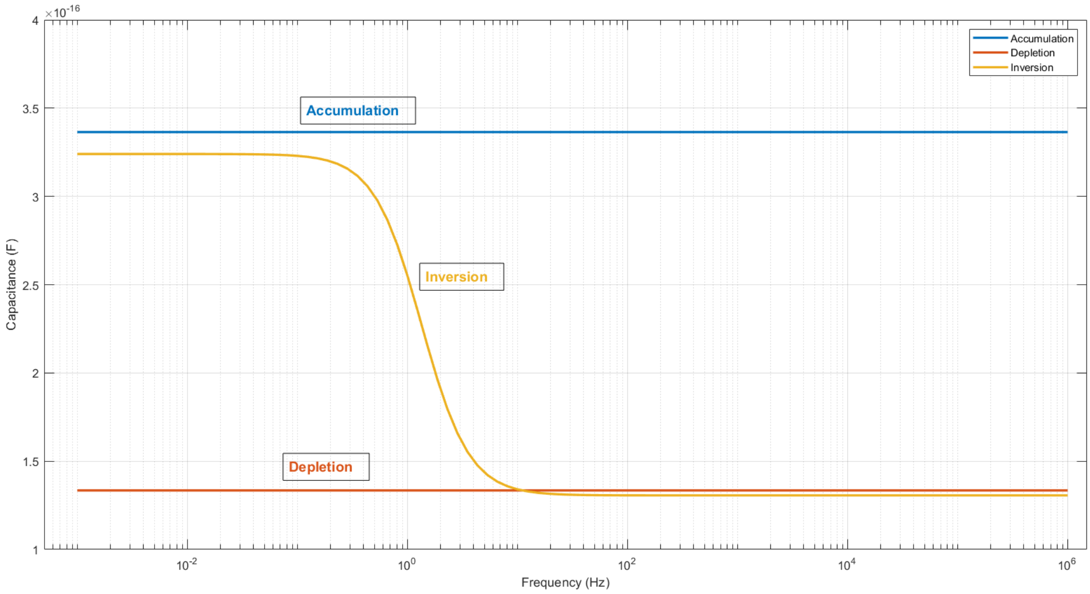

Figure 10: C-F curve in defferent region

As we have seen in the C-V curve at different frequency that in the accumulation region the capacitance is equal to oxide capacitance(C_{ox}) whose value remains constant with respect to frequency.

$$C_{ox} = \frac{\epsilon_{ox}}{x_o} \tag{11}$$

For depletion region, the value of capacitance decreases as there is an additional depletion capacitance in parallel with oxide capacitance.This value does not changes with frequency.

$$C_{dep.min} = \frac{\epsilon_s}{x_{dmax}} \tag{12}$$

$$C_{min} = \frac{C_{ox} \times C_{dep.min}}{C_{ox} + C_{dep.min}} \tag{13}$$

In the inversion region as frequency changes, capacitances changes because inversion layer of electron is not formed near the interface at higher frequency due to their limitation of thermal generation rate.

4.6 Show the effect of fixed charge on the CV curve for at least three values of fixed charge

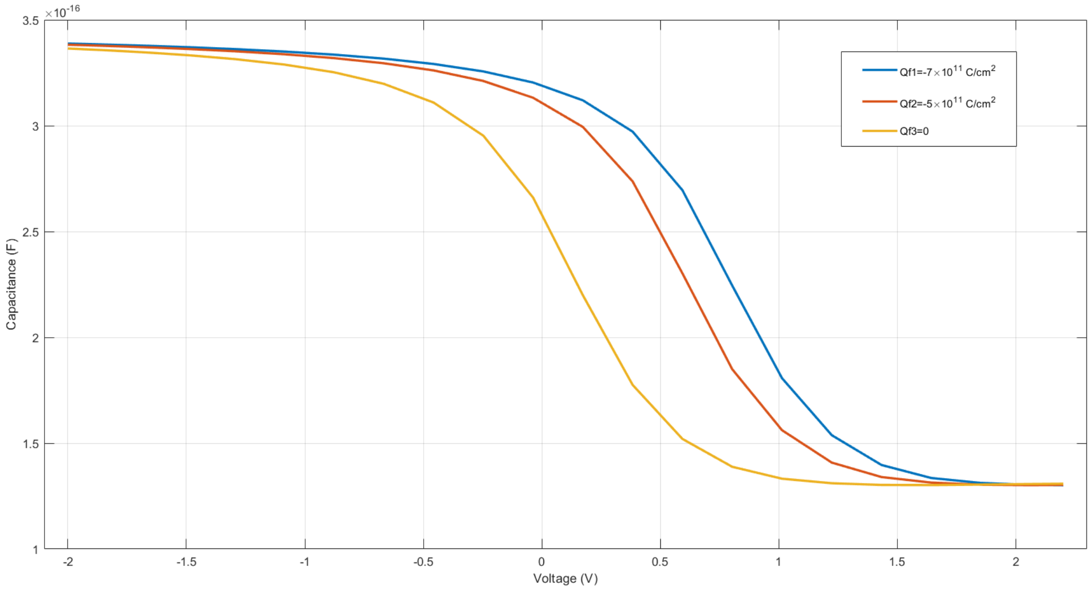

Figure 11: C-V curve at different values of fixed charges

The effect of fixed oxide charge can be seen from the equation:

$$V_G = V_{TH} = 2\phi_F + \frac{\epsilon_s}{\epsilon_o} x_o \sqrt{\frac{2qN_A \times 2\phi_F}{\epsilon_s \epsilon_o}} + \frac{-Q_f}{C_{ox}} \tag{14}$$

Table 5: Fixed charges Vs Threshold voltage

Fixed charges	**Threshold voltages(V_{TH})**
$Q_{f1} = -7 \times 10^{11} C/cm^2$	$V_{TH} = 2.12$V
$Q_{f2} = -5 \times 10^{11} C/cm^2$	$V_{TH} = 1.93$V
$Q_f = 0$	$V_{TH} = 1.47$V

As the value of fixed charge changes, the threshold voltage changes which can be verified from the plot.

5 Conclusion

In this experiment we have designed a MOS capacitor with certain specification on swb workbench using script command.First we have plotted the band diagram of moscap at different regions such as accumulation,flatband,depletion and inversion and observed the bending in the energy levels.We have plotted the C-V curve in different regions and observed how its value changes at low,mid and high frequency.After that we have varied the doping concentration of substrate and seen its effect on C-V curve.We have also varied the value of workfunction and observed that the threshold voltage varies accordingly.We have plotted C-F curve in different regions and varied the value of fixed charges and seen its effect on the value of threshold voltage.