Advanced Solid-State Devices

Atlas Simulation Assignments - MOS

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Part 2: MOS Capacitor

Assume that we are designing a MOS capacitor with substrate doping concentration of 1017 $Atom\ cm$3 of phosphorous and (a) aluminum gate and (b) polysilicon gate (choose reasonable properties).

1. Write MATLAB function(s) which gets oxide thickness, substrate doping and other parameters of a MOS capacitor and returns the threshold voltage for (a) Aluminum gate and (b) Polysilicon gate MOS capacitor.

Threshold voltage relations for metal gate MOS:

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n-channel MOS Threshold Voltage

$$V_T = V_{FB} + 2\phi_f + \frac{\sqrt{2\varepsilon_{si} N_A \left(2\phi_f + V_C - V_B\right)}}{C_{ox}} + \frac{qQ_i}{C_{ox}}$$

Doping

Oxide

Implant

Surface and oxide trapped charge

Substrate voltage

Local channel voltage

E_{GAP}

$$\phi_f = \frac{kT}{q} \ln\left(\frac{N_A}{n_i}\right) \qquad V_{FB} = 4.1 - \left(4.05 + \frac{1.1}{2} + \phi_f\right)$$

If no surface or oxide trapped charges.

Q_i is the implant dose in atoms per cm^2 and is positive for boron.

Flat band voltage relation for metal gate MOS :

$$V_{FB} = \Phi_{MS} = \Phi_M - \chi - \frac{E_g}{2q} - V_t \ln \frac{N_a}{n_i}$$

$$= 4.1 - 4.05 - 0.56 - 0.026 \times \ln \frac{10^{17}}{10^{10}} = -0.93\ \mathrm{V}$$

Threshold voltage relations for poly gate MOS (neglecting body effect) :

EXAMPLE 3-2 CONT. $V_{T0} = \Phi_{GC} - 2\varphi_{F(sub)} - \dfrac{Q_{B0}}{C_{ox}} - \dfrac{Q_{ox}}{C_{ox}}$

Q_{B0}:

$$Q_{B0} = -\sqrt{2qN_A\varepsilon_{Si}|2\phi_{F(sub)}|}$$

$$= -\sqrt{2(1.6\times10^{-19}\,C)(10^{16}\,cm^{-3})(1.06\times10^{-12}\,Fcm^{-1})\,|2\times0.35V|}$$

F = C/V

$$= -4.87\times10^{-8}\ C/cm^2$$

C_{ox}:

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{0.34\times10^{-12}\ Fcm^{-1}}{500\times10^{-8}\ cm} = 6.8\times10^{8}\ F/cm^2$$

Q_{ox}:

$$Q_{ox} = qN_{ox} = (1.6\times10^{-19}\,C)(4\times10^{10}\,cm^{-2}) = 6.4\times10^{-9}\ C/cm^2$$

$$\frac{Q_{B0}}{C_{ox}} = \frac{-4.87\times10^{8}\ C/cm^2}{6.8\times10^{8}\ F/cm^2} = -0.716\,V \qquad \frac{Q_{ox}}{C_{ox}} = \frac{6.4\times10^{-9}\ C/cm^2}{6.8\times10^{8}\ F/cm^2} = 0.094\,V$$

$$V_{T0} = -0.95V - (-0.70\,V) - (-0.72\,V) - (0.09\,V) = 0.38\,V$$

Flat band voltage relation for poly gate MOS :

EXAMPLE 3.2 Calculate the threshold voltage V_{T0} at $V_{BS} = 0$, fo[r] a polysilicon gate n-channel MOS transistor with the following parameters:

- substrate doping density $N_A = 10^{16}\ cm^{-3}$,
- polysilicon doping density $N_D = 2 \times 10^{20}\ cm^{-3}$,
- gate oxide thickness $t_{ox} = 500$ Angstroms,
- oxide-interface fixed charge density $N_{ox} = 4 \times 10^{10}\ cm^{-2}$.

$$\rightarrow\ V_{T0} = \Phi_{GC} - 2\varphi_{F(sub)} - \frac{Q_{B0}}{C_{ox}} - \frac{Q_{ox}}{C_{ox}}\ \leftarrow$$

$\varphi_{F(sub)}$, Φ_{GC}: $\Phi_{GC} = \varphi_{F(sub)} - \varphi_{F(gate)}$

$$\varphi_{F(sub)} = \frac{kT}{q}\ln\frac{n_i}{N_A} = 0.026V\ln\frac{1.45\times10^{10}}{10^{16}} = -0.35V$$

$$\varphi_{F(gate)} = \frac{kT}{q}\ln\frac{N_D}{n_i} = 0.026V\ln\frac{2\times10^{20}}{1.45\times10^{10}} = 0.60V$$

$$\Phi_{GC} = \varphi_{F(sub)} - \varphi_{F(gate)} = -0.35\ V - 0.60\ V = -0.95\ V$$

Writing matlab code to calculate Vthreshold (Vsourse-bulk = 0) :

```
% Constants
KT_q = 25e-3;
q = 1.6e-19;
epsilon0 = 8.85e-14;
epsilon_si = 11.9 * epsilon0;
ni = 1e10;
Eg = 1.12;
ElectronAffinity = 4.05;
Vsoursebulk = 0;
epsilon_ox = 3.9;
Phi_M = 4.1;

%asking for metal or poly gate?
gate_type = input('Enter the gate type (1 for Metal, 2 for Polysilicon): ');


Nacceptor = input('Enter the acceptor concentration (Nacceptor) in cm^-3: ');
tox = input('Enter the oxide thickness (tox) in cm: ');

%calculating the parameters using the relations provided in the report
Phi_f = (KT_q) * log(Nacceptor / ni);
Cox = (epsilon_ox * epsilon0) / tox;

if gate_type == 1

    Vflatband = Phi_M - ElectronAffinity - (Eg / (2)) - Phi_f;
    Vthreshold = Vflatband + 2 * Phi_f + sqrt(2 * q * epsilon_si * Nacceptor * (2 * Phi_f + Vsoursebulk)) / Cox;
else

    Ndonor = input('Enter the donor concentration (Ndonor) in cm^-3: ');
    Phi_gate = (KT_q) * log(Ndonor / ni);
    Phi_sub = (KT_q) * log(ni / Nacceptor);
    Vflatband = Phi_sub - Phi_gate;
    Vthreshold = Vflatband - 2 * Phi_sub + sqrt(2 * q * epsilon_si * Nacceptor * (2 * Phi_f + Vsoursebulk)) / Cox;
end


fprintf('The threshold voltage (Vthreshold) is: %.4f V\n', Vthreshold);

```

Testing the Matlab code for the example on slide #4 (poly gate):

```
>> Calculate_Threshold_Voltage
Enter the gate type (1 for Metal, 2 for Polysilicon): 2
Enter the acceptor concentration (Nacceptor) in cm^-3: 1e16
Enter the oxide thickness (tox) in cm: 500e-8
Enter the donor concentration (Ndonor) in cm^-3: 1e20
The threshold voltage (Vthreshold) is: 0.4687 V
```

Testing the Matlab code for Na = 1e17 and tox = 20e-7 cm (metal gate):

```
Enter the gate type (1 for Metal, 2 for Polysilicon): 1
Enter the acceptor concentration (Nacceptor) in cm^-3: 1e17
Enter the oxide thickness (tox) in cm: 20e-7
The threshold voltage (Vthreshold) is: 0.8479 V
```

Part 2: MOS Capacitor

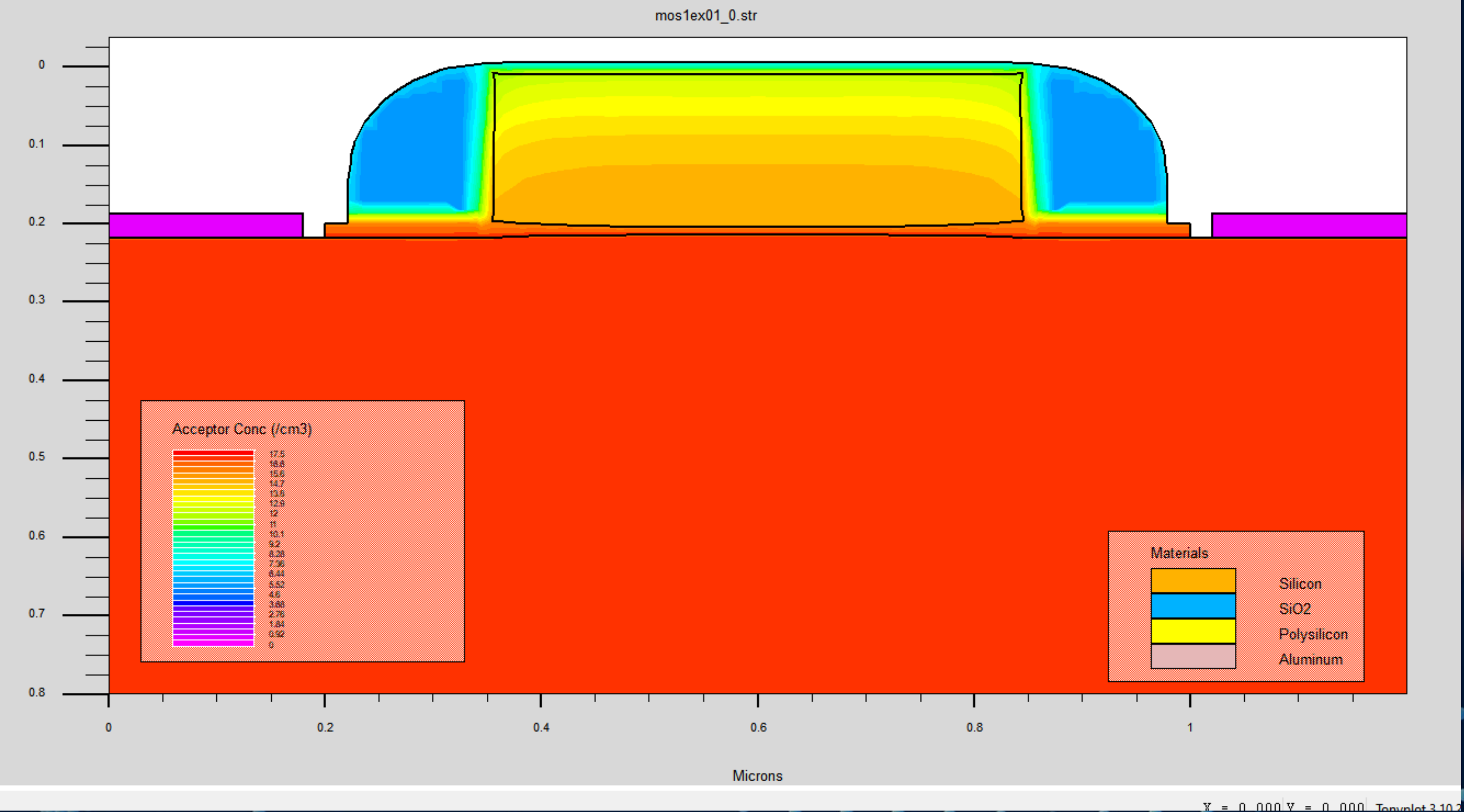
Assume that we are designing a MOS capacitor with substrate doping concentration of 1017 $Atom\ cm$3 of phosphorous and (a) aluminum gate and (b) polysilicon gate (choose reasonable properties).

1. Write MATLAB function(s) which gets oxide thickness, substrate doping and other parameters of a MOS capacitor and returns the threshold voltage for (a) Aluminum gate and (b) Polysilicon gate MOS capacitor.

2. Using simulation, verify your function’s output for the MOS given above.

Verifying the results of the polygate in slide #6 using atlas silvaco MOS example #1:

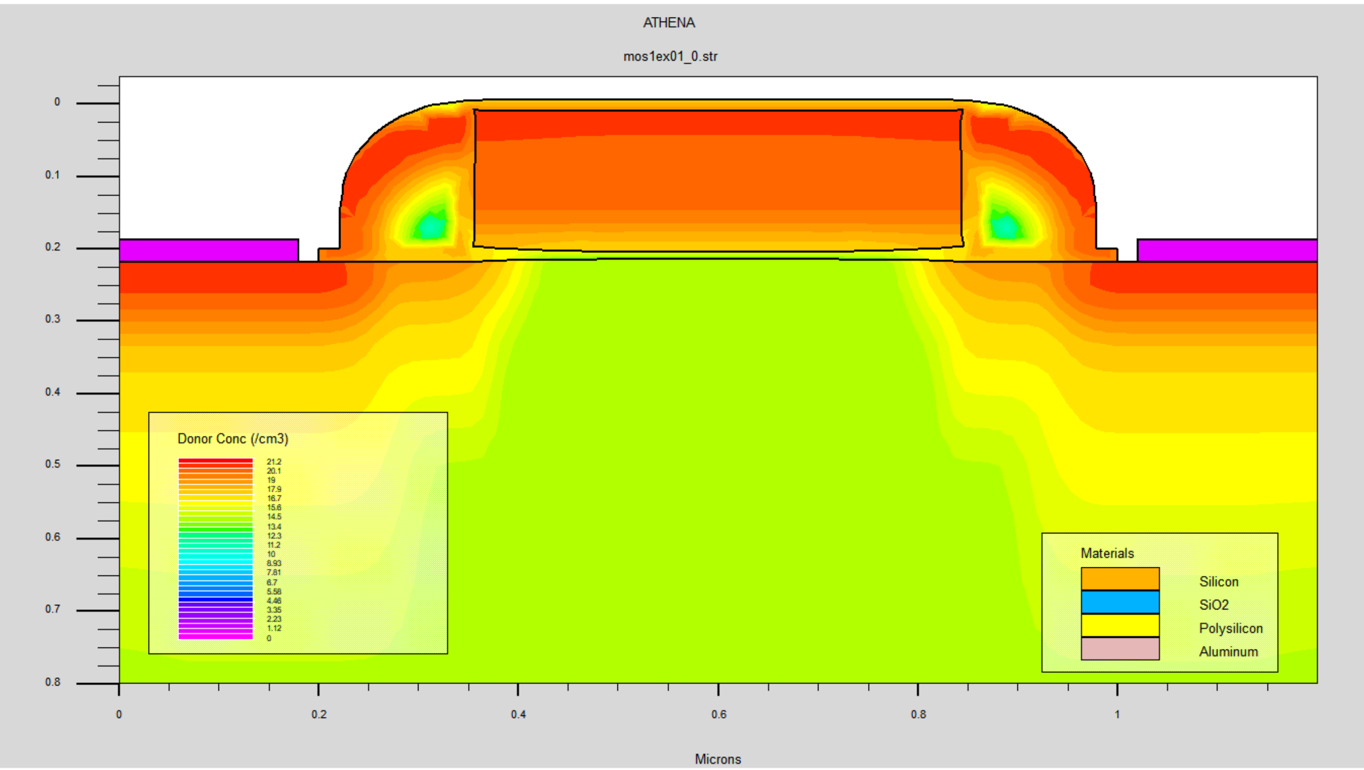
Acceptor Conc.



Depositing polysilicongate with 1e20 donor dopings like the matlab example.

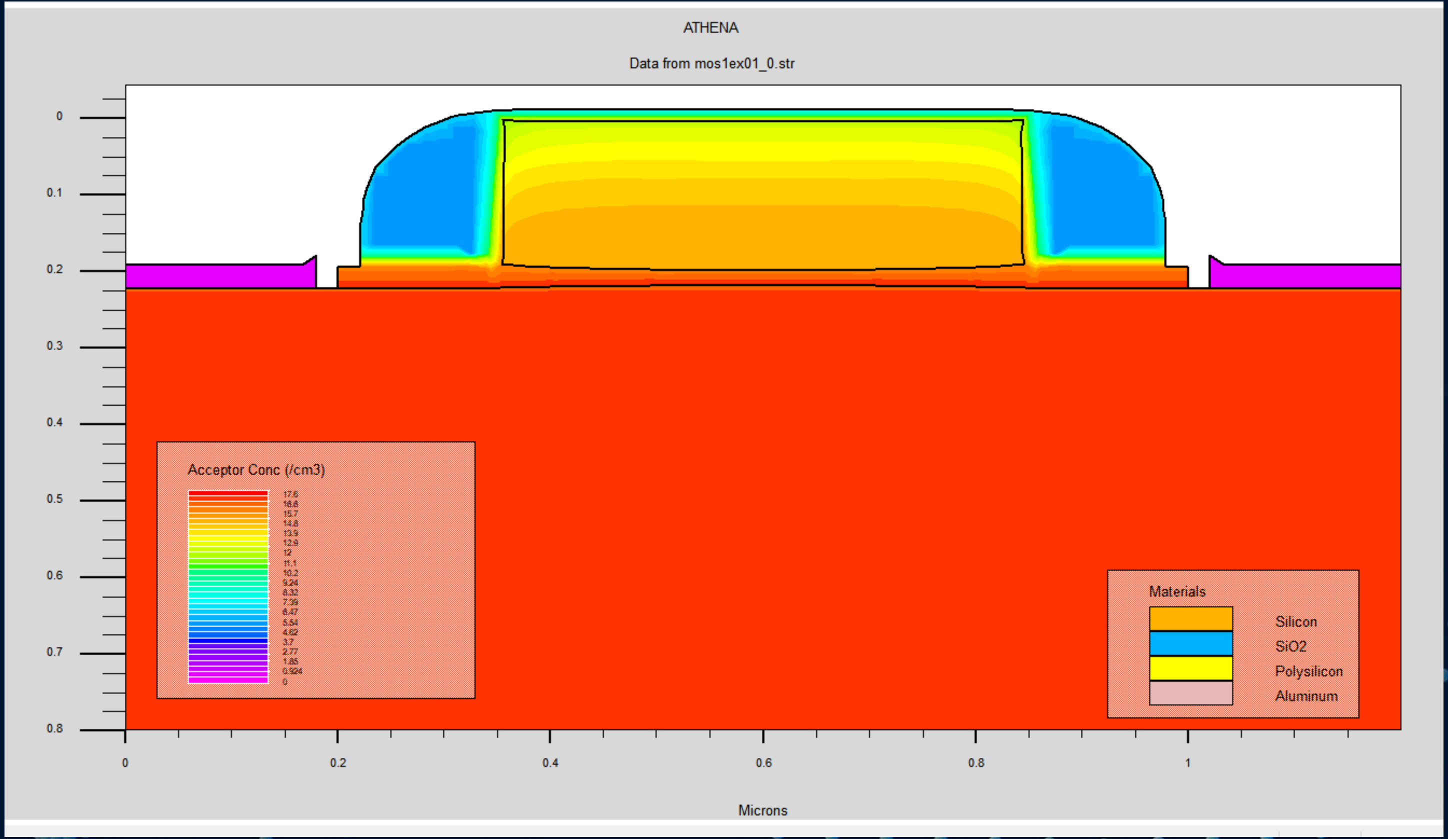
```
# Deposit polysilicon gate with uniform doping
depo poly thick=0.2 divi=10
doping uniform n.type conc=1e20
```

Donor Conc.:



Initializing the silicon with a boron concentration of 1e16 using the init command:

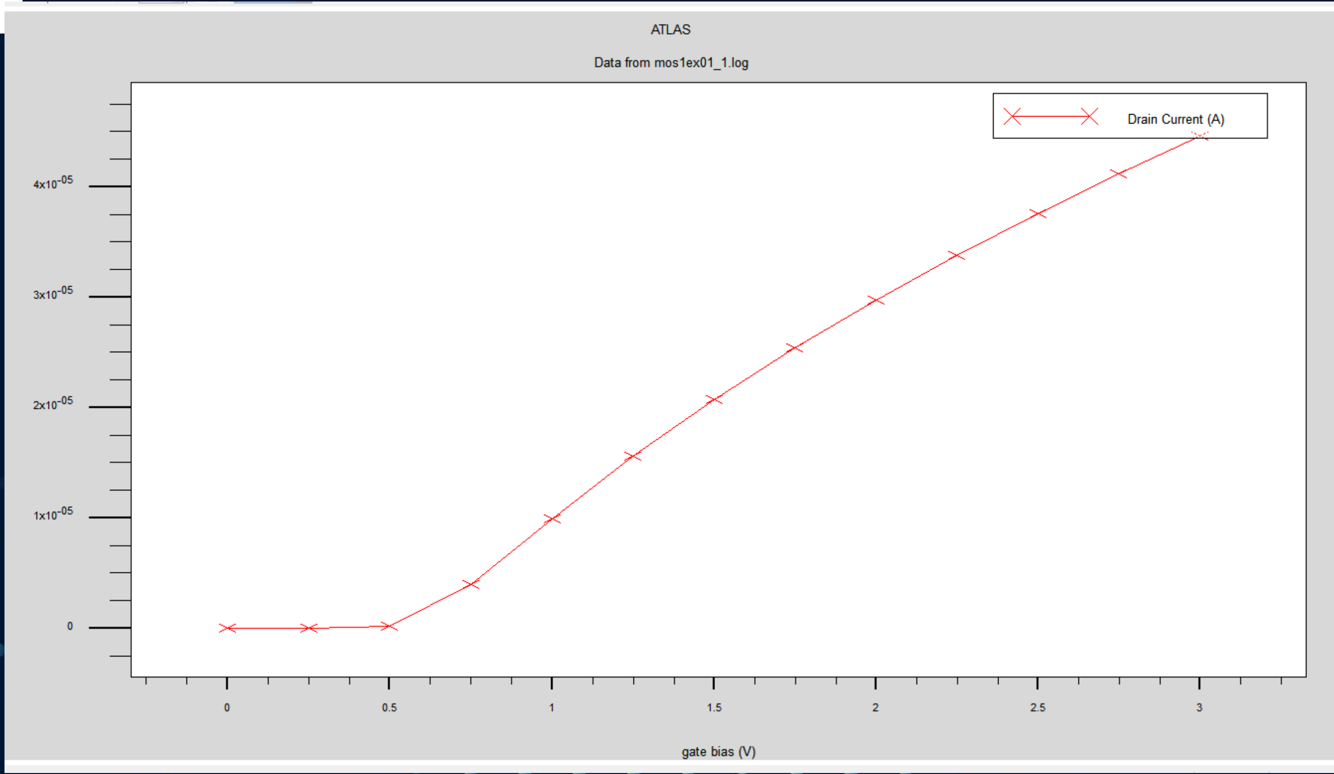
Boron Conc.:



Plotting drain current vs gate voltage to find the Threshold voltage (sweeping on Vgate_bias):

```
# Bias the drain
solve vdrain=0.1

# Ramp the gate
log outf=moslex01_1.log master
solve vgate=0 vstep=0.25 vfinal=3.0 name=gate
save outf=moslex01_1.str
```



As we can see the threshold voltage is around 0.5 v verifying the Matlab results.

Part 2: MOS Capacitor

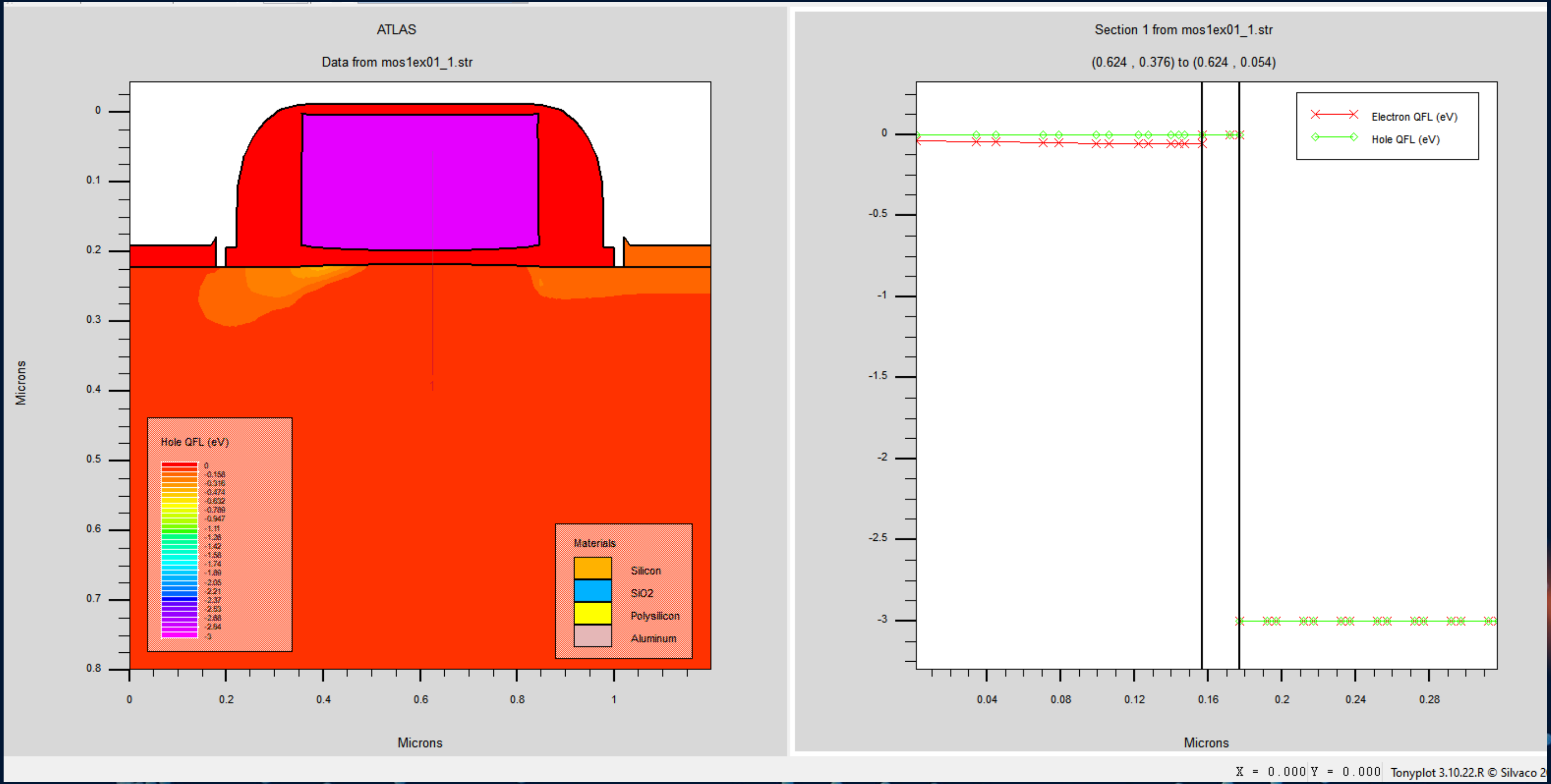
Assume that we are designing a MOS capacitor with substrate doping concentration of 1017 $Atom\ cm$3 of phosphorous and (a) aluminum gate and (b) polysilicon gate (choose reasonable properties).

1. Write MATLAB function(s) which gets oxide thickness, substrate doping and other parameters of a MOS capacitor and returns the threshold voltage for (a) Aluminum gate and (b) Polysilicon gate MOS capacitor.

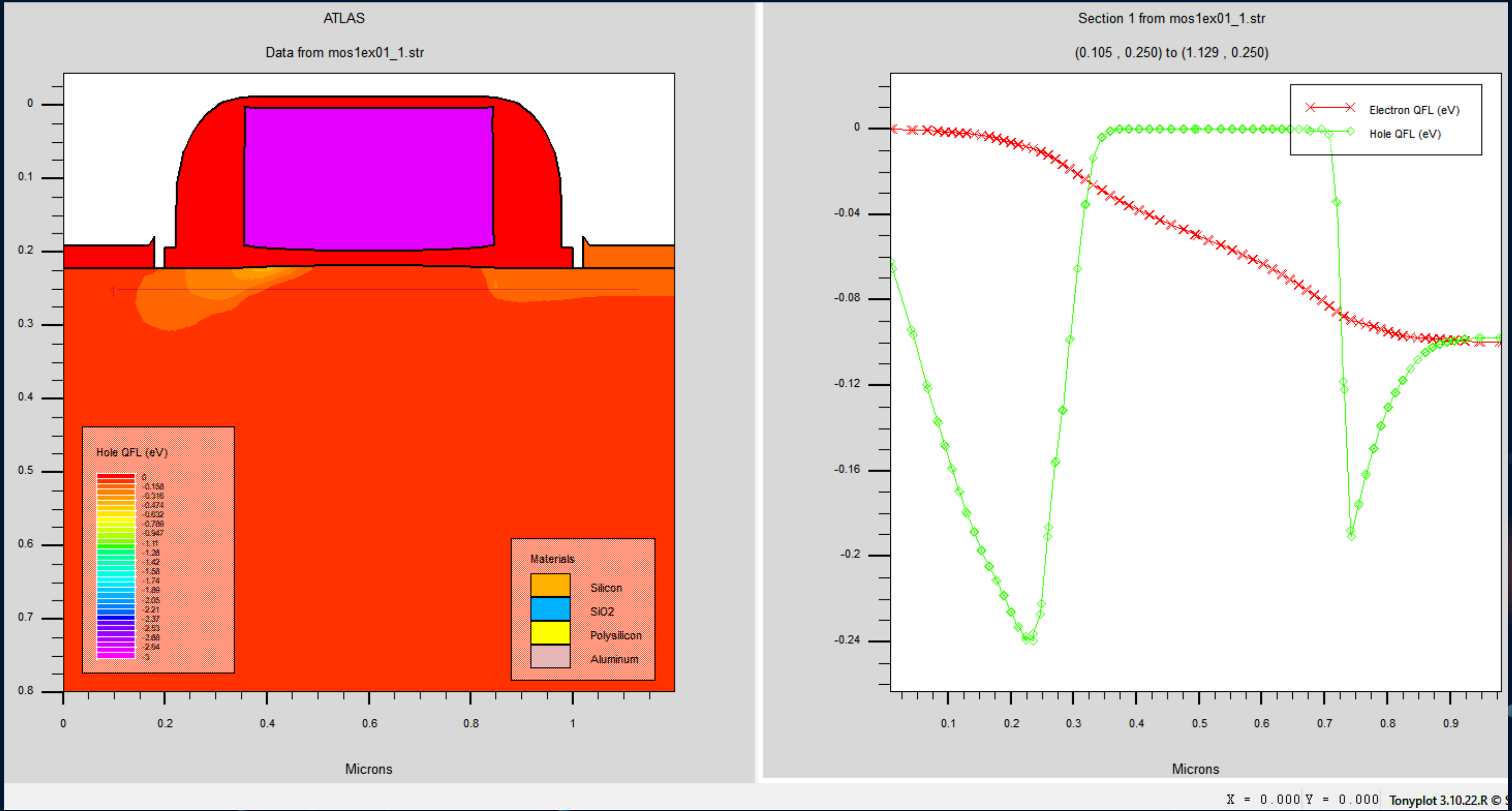
2. Using simulation, verify your function’s output for the MOS given above.

3. For different biases (zero bias, flat-band bias, fully depletion and inversion) simulate and extract the quasi-fermi level and valance/conduction bands.

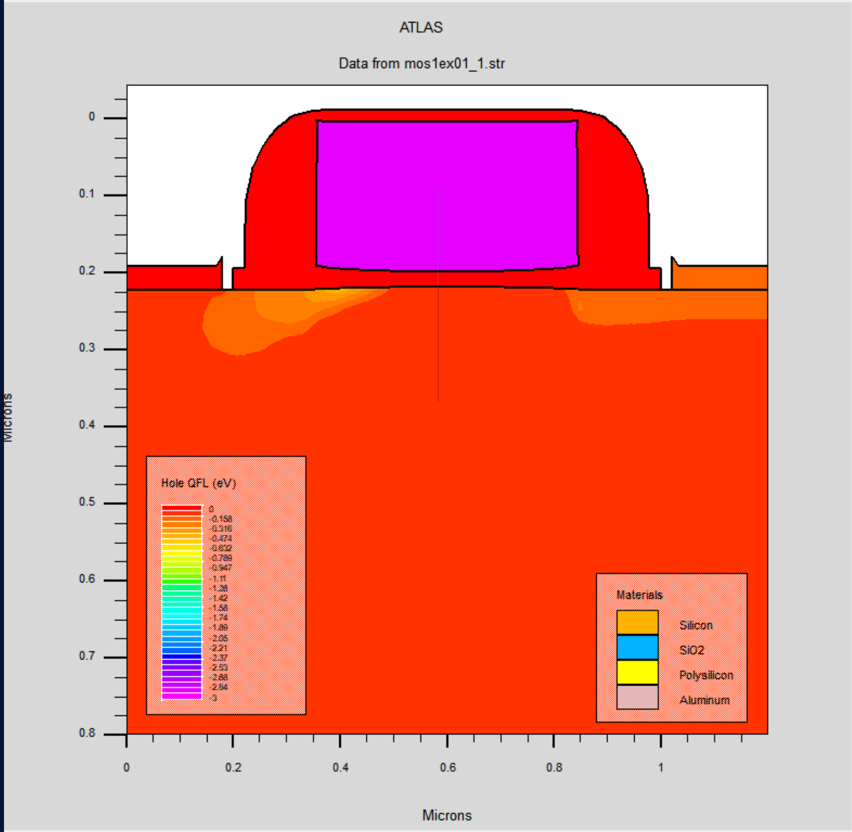
Zero bias: Hole and Electron quasi fermi levels (vertical cutline)

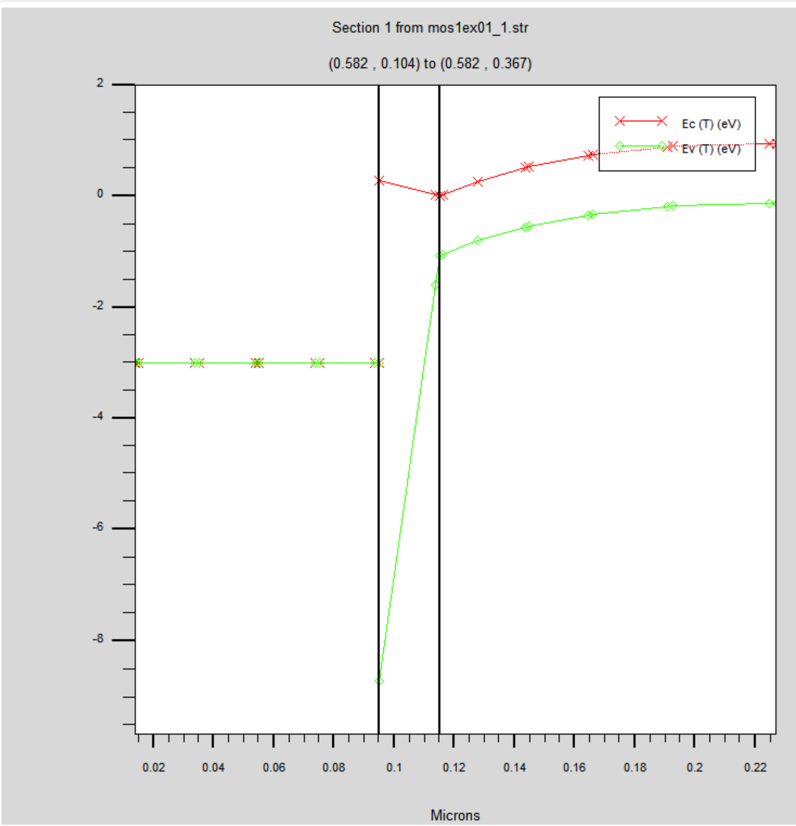


Zero bias: Hole and Electron quasi fermi levels (horizontal cutline)

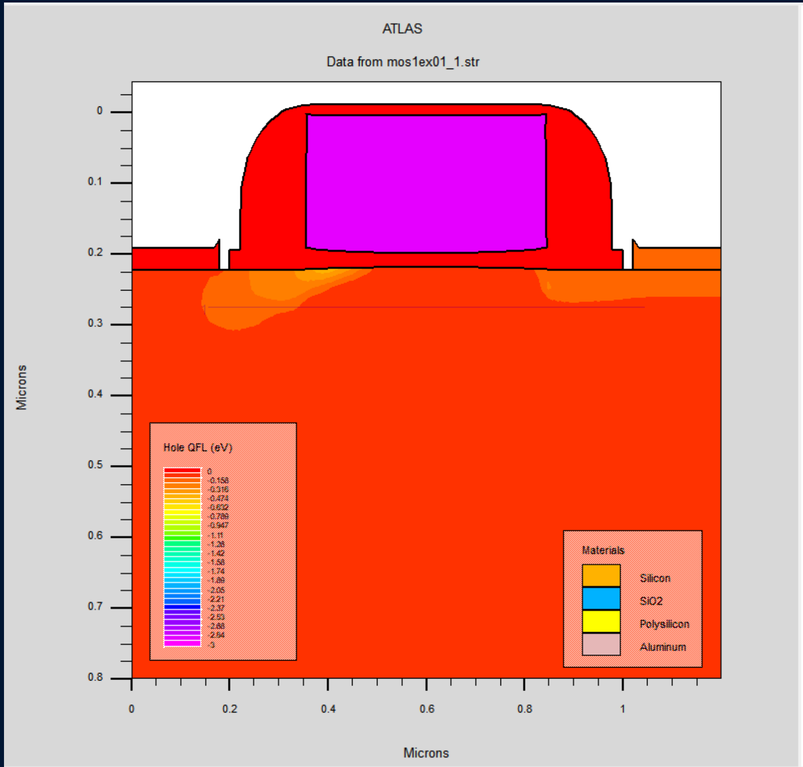


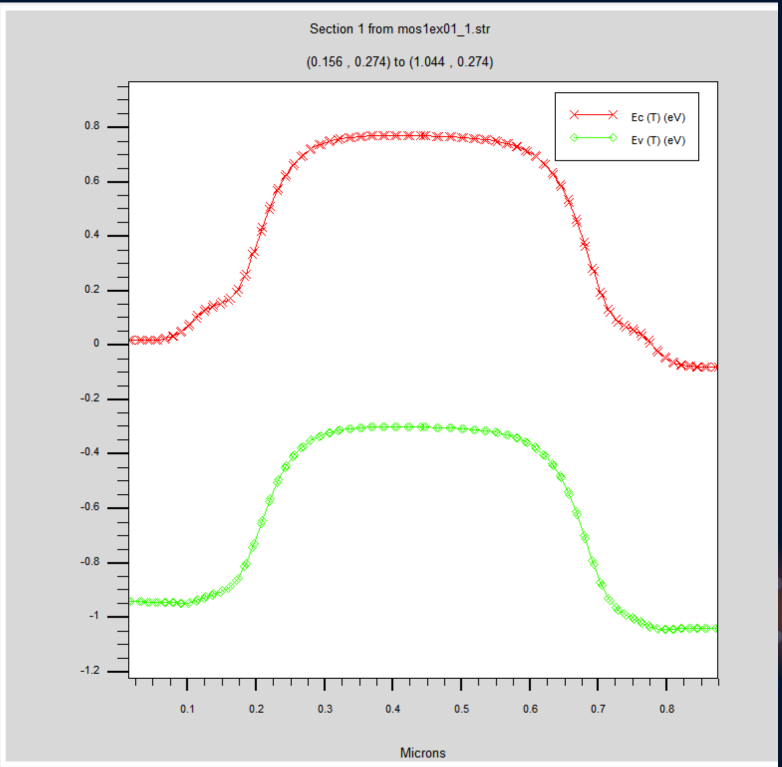
Zero bias: Ec and Ev (vertical cutline)



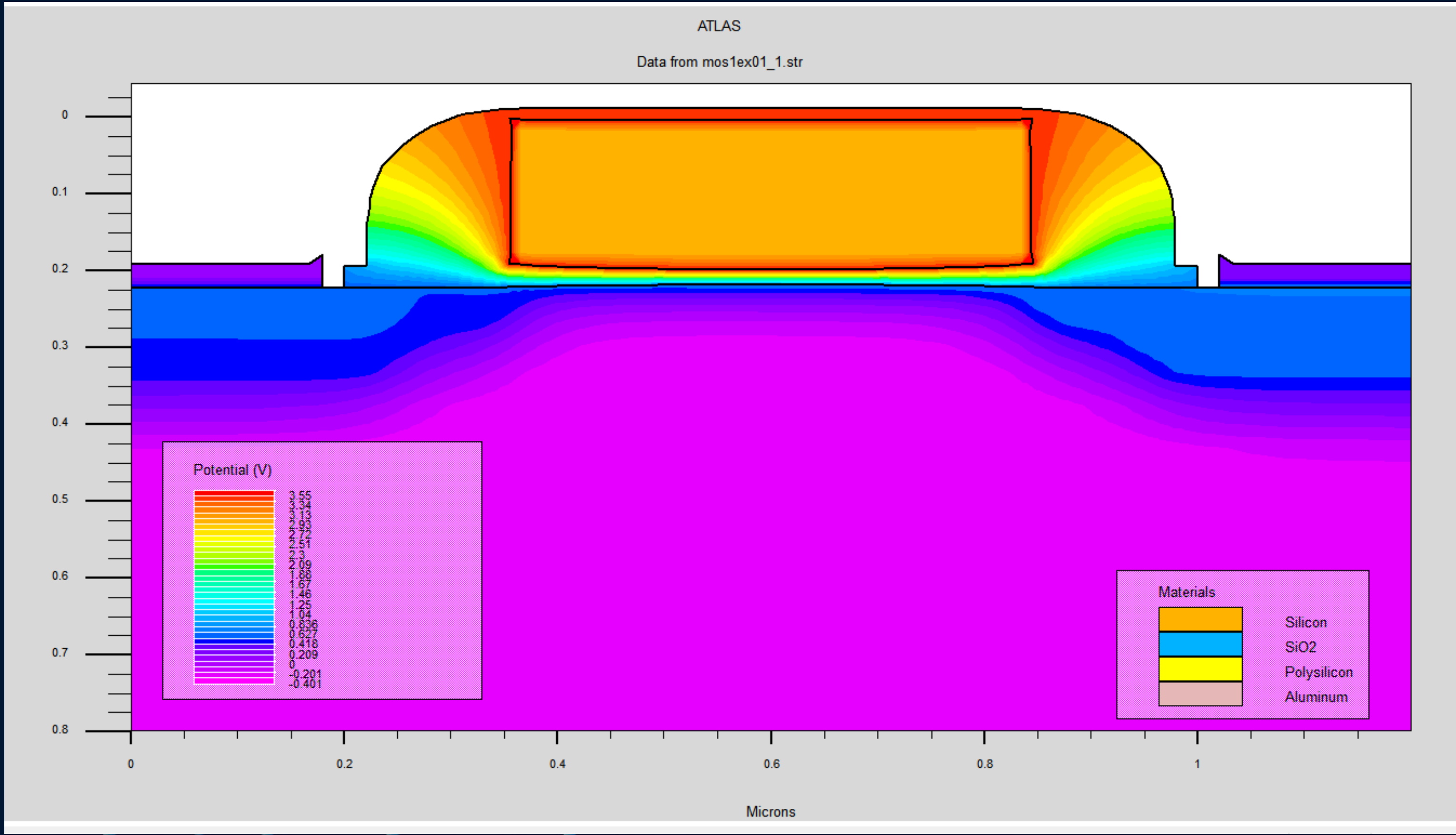


Zero bias: Ec and Ev (horizontal cutline)

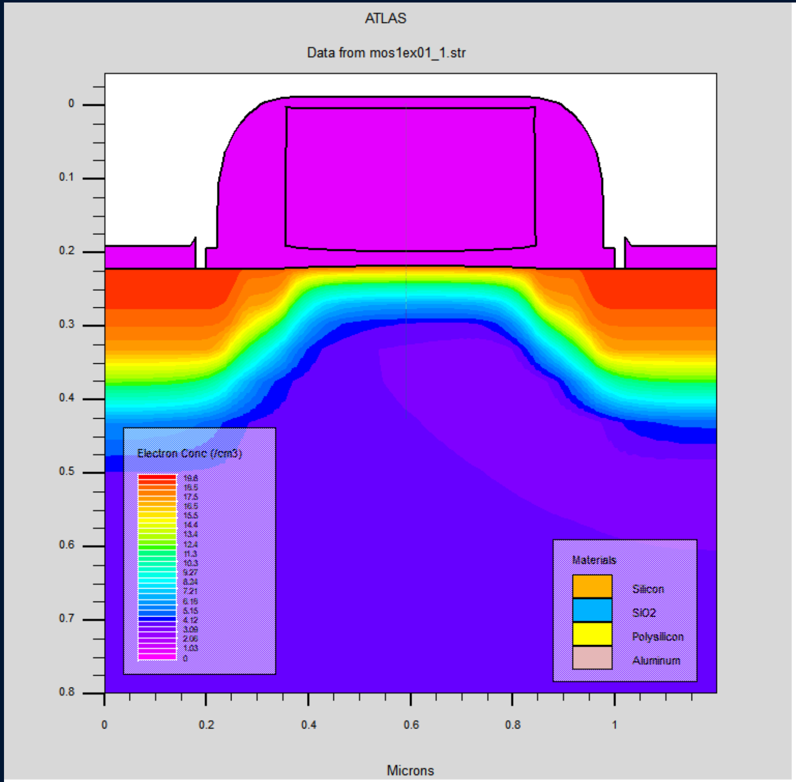


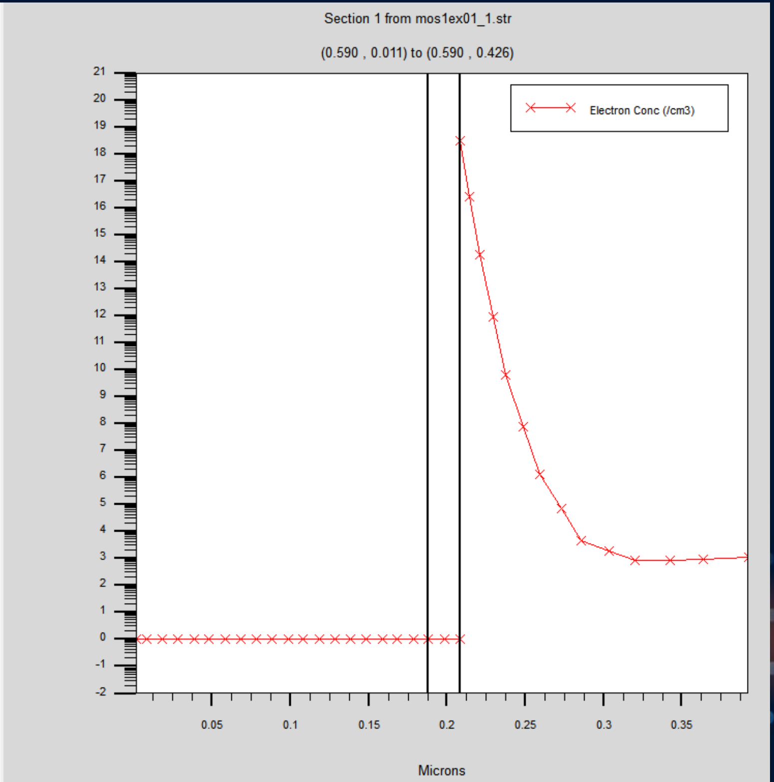


3.5v bias to the gate: potential



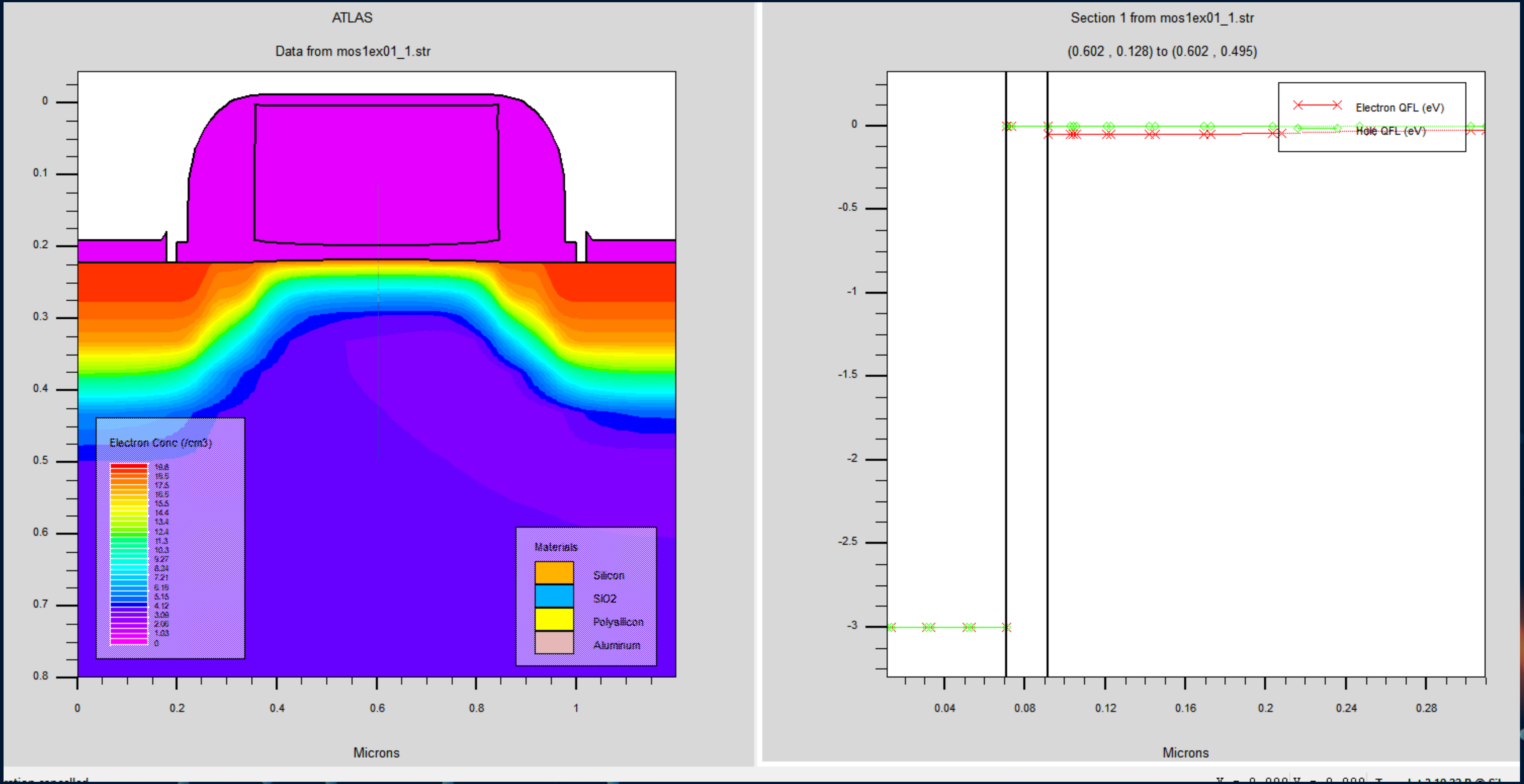
3.5v bias to the gate: electron conc.



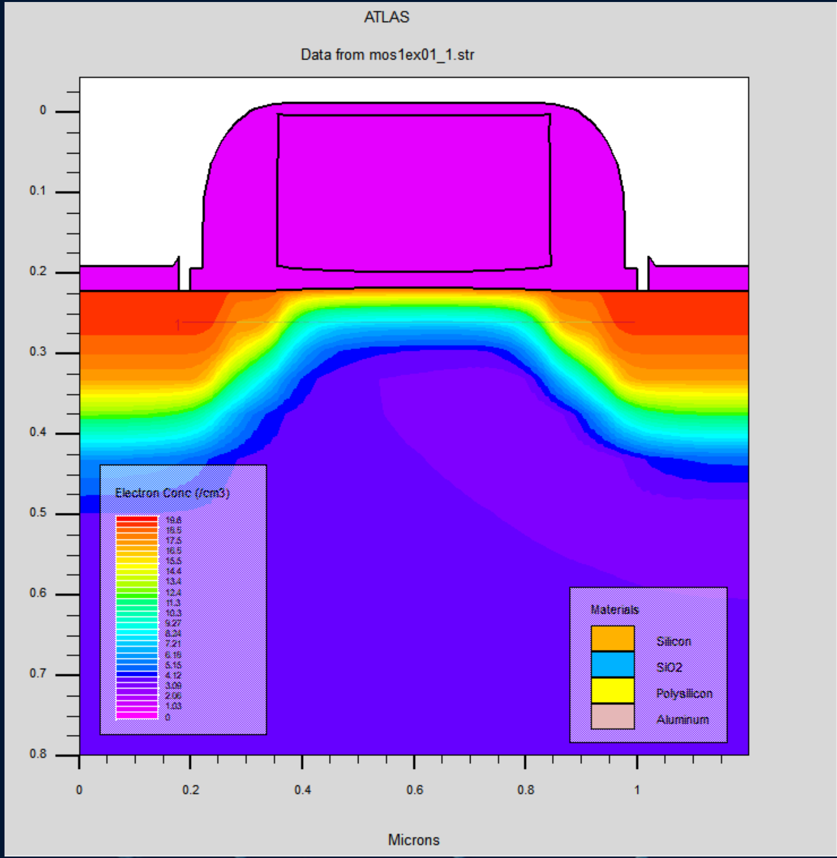


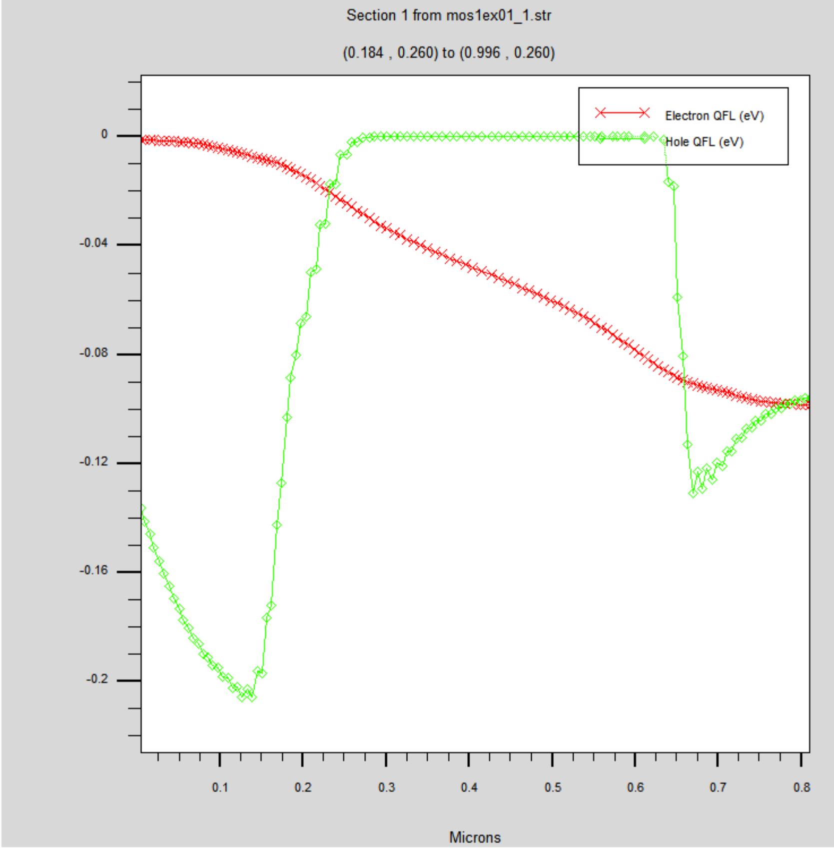
As we can see we are in the invesion region because we have electrons forming in the channel

3.5v bias to the gate: Inversion region e-h QFL (vertical cutline)

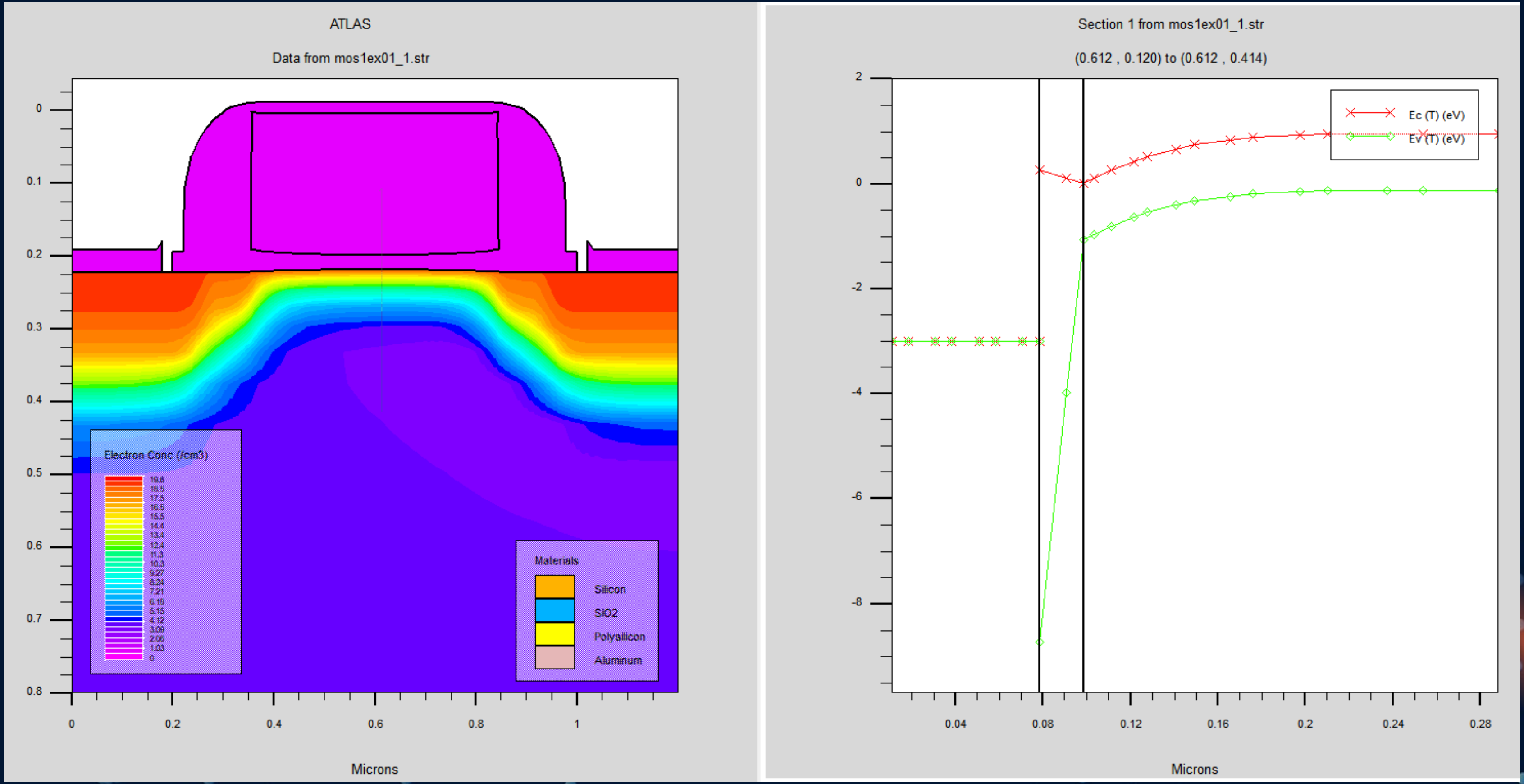


3.5v bias to the gate: Inversion region e-h QFL (horizontal cutline)

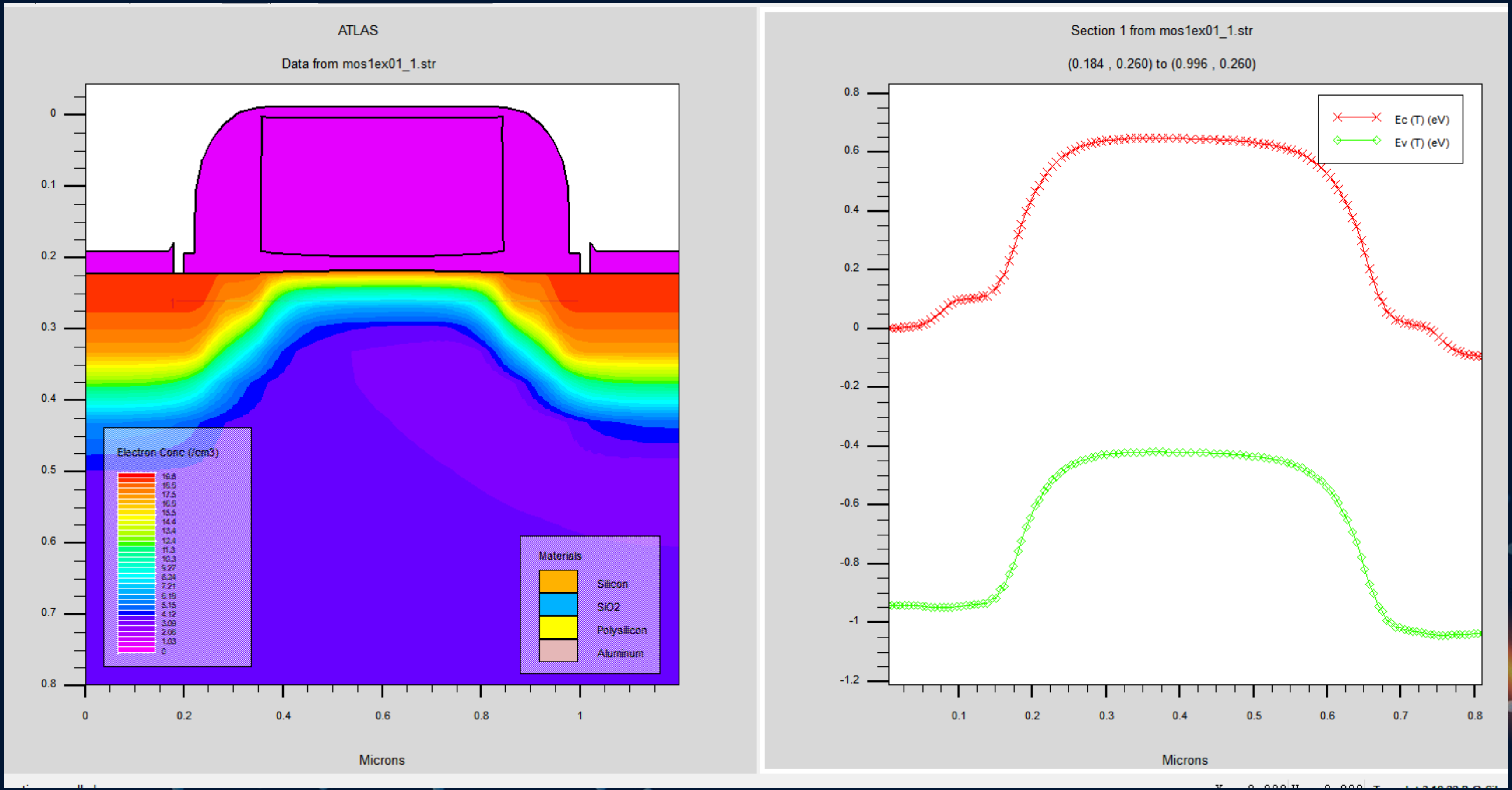




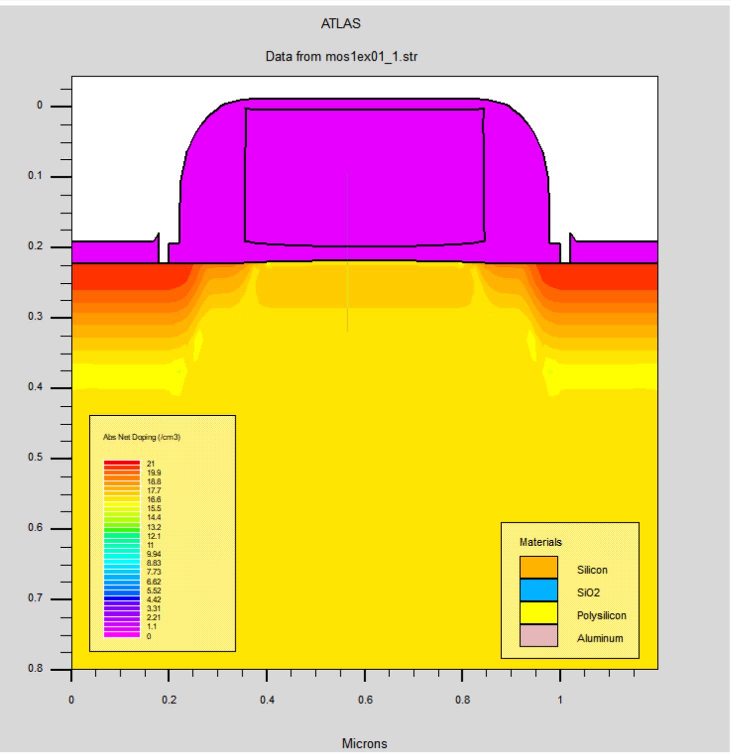
3.5v bias to the gate: Inversion region Ec and Ev (vertical cutline)

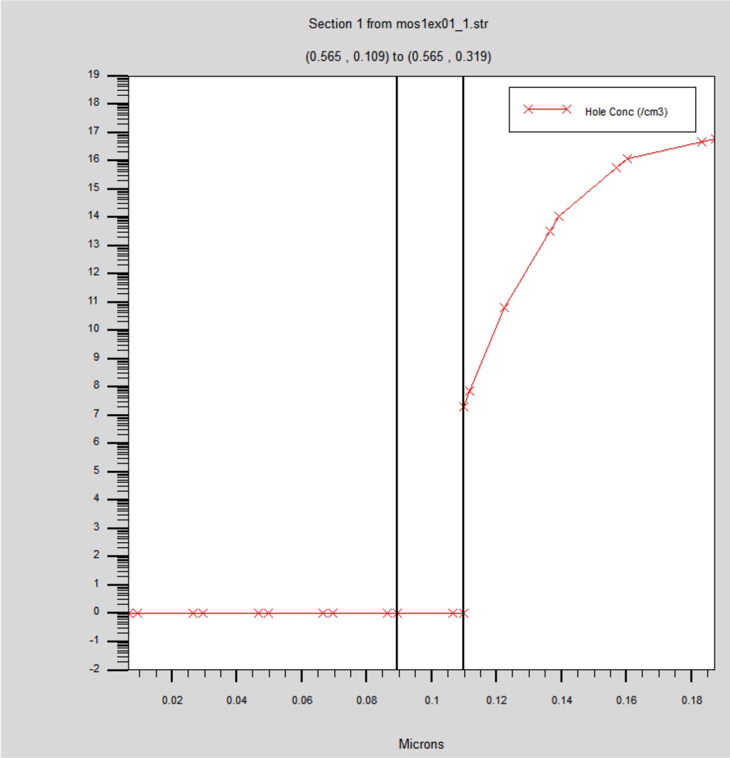


3.5v bias to the gate: Inversion region Ec and Ev (horizontal cutline)



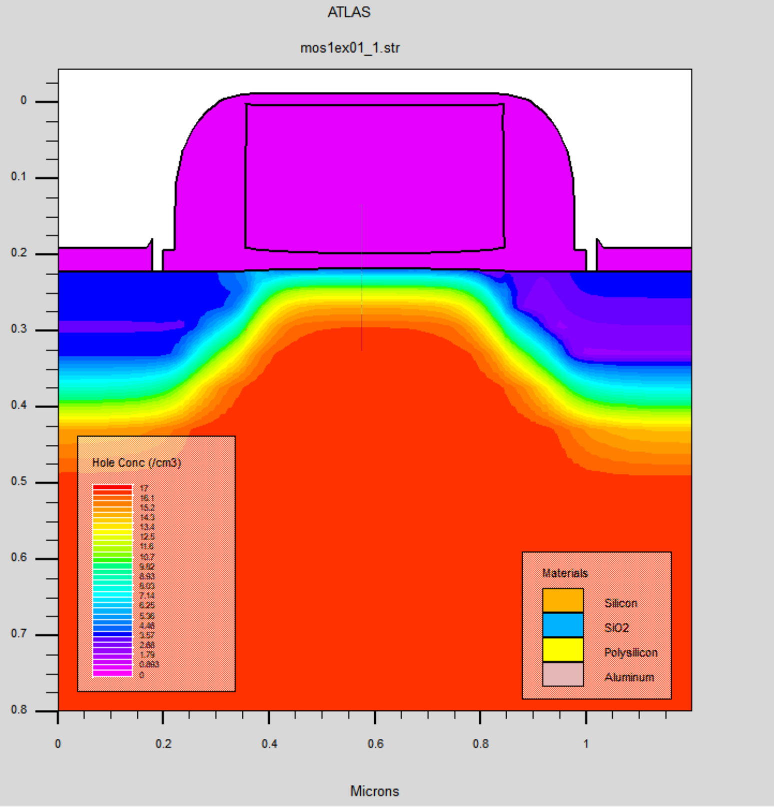
Finding the full depletion bias point: 1.1V bias?

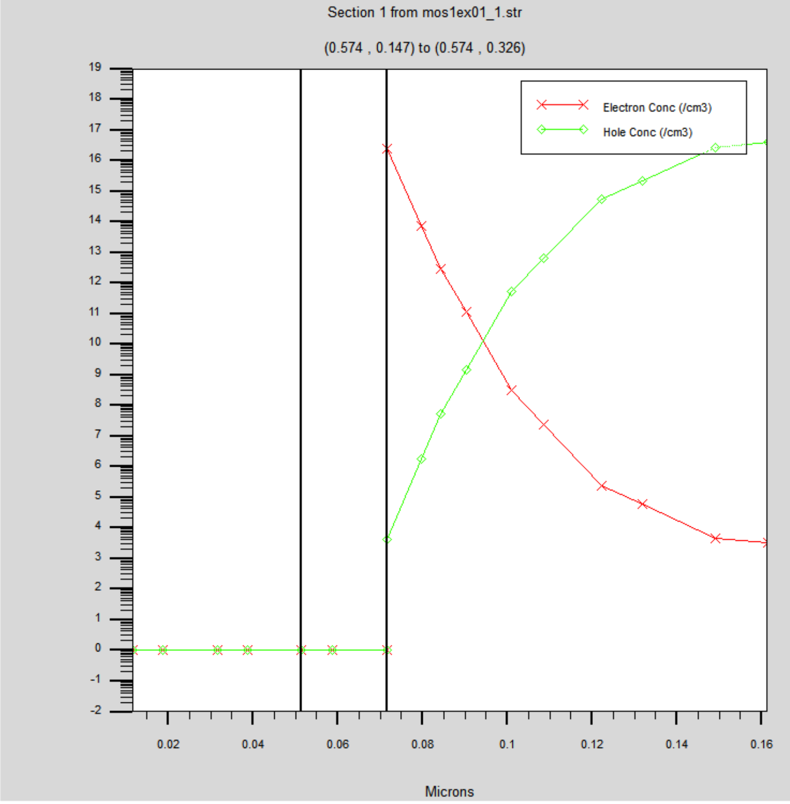




This is a NMOS, so in the full depletion region, there should be no holes in the proximity of oxide but as we can see with 1.1v bias there are 1e7 holes left.

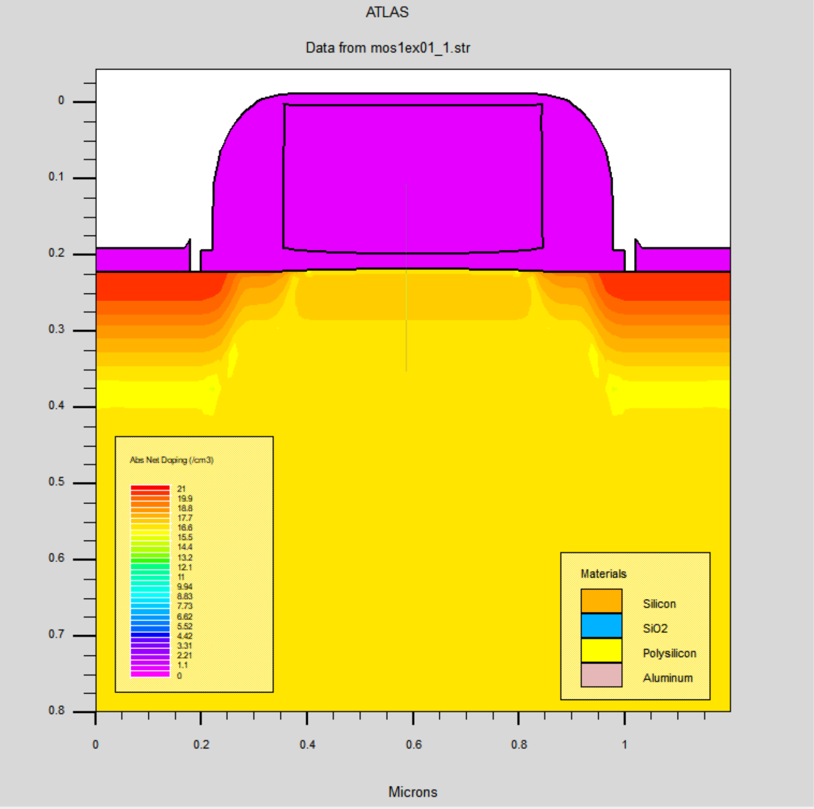
Finding the full depletion bias point: 1.6V bias?

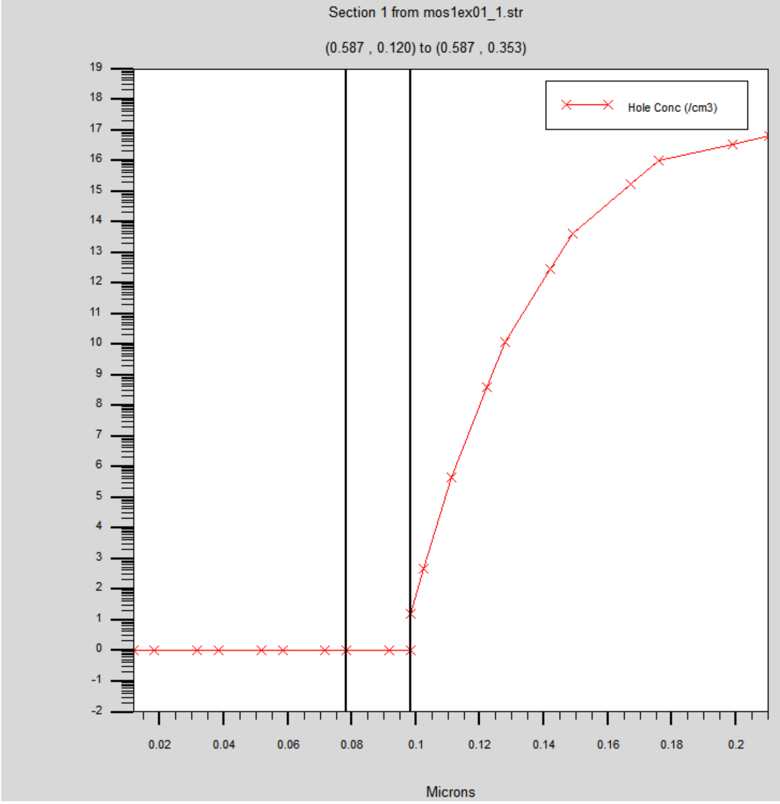




This is a NMOS, so in the full depletion region, there should be no holes in the proximity of oxide but as we can see with 1.6v bias there are 1e3 holes left.

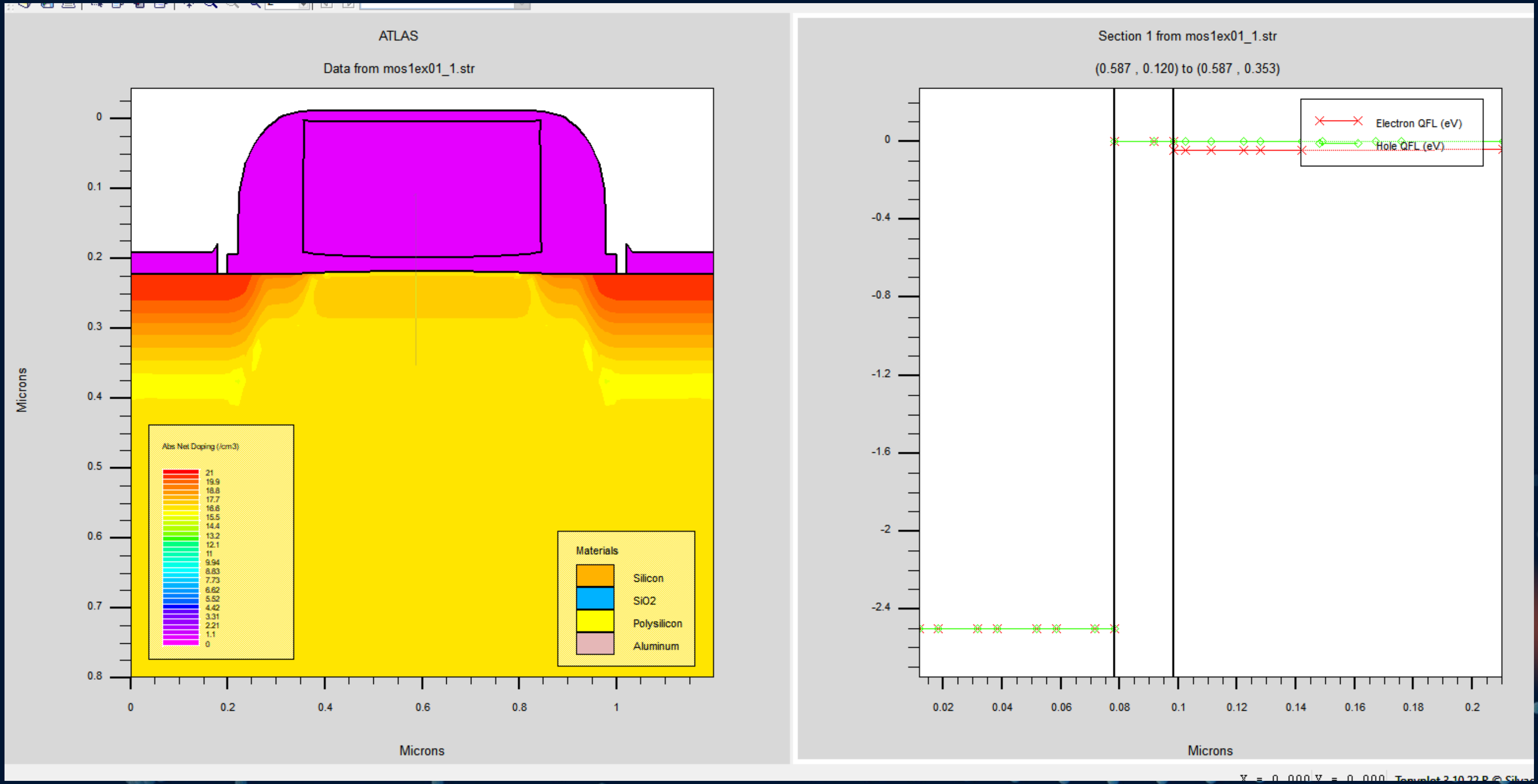
2v Gate Bias: Full depletion region



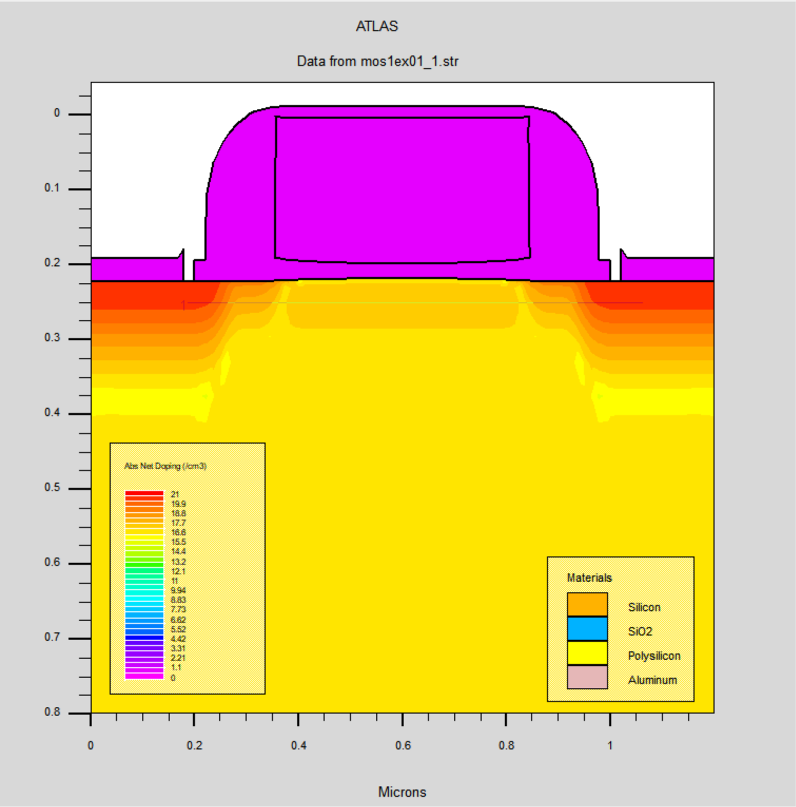


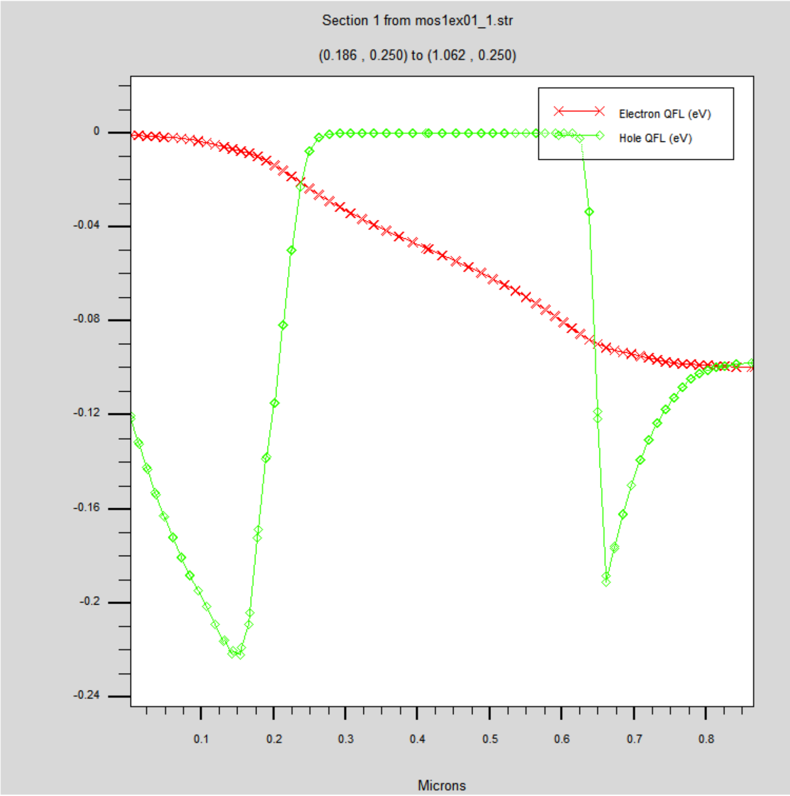
As we can see with 2v bias there are no holes left.

2v bias to the gate: Depletion region e-h QFL (vertical cutline)

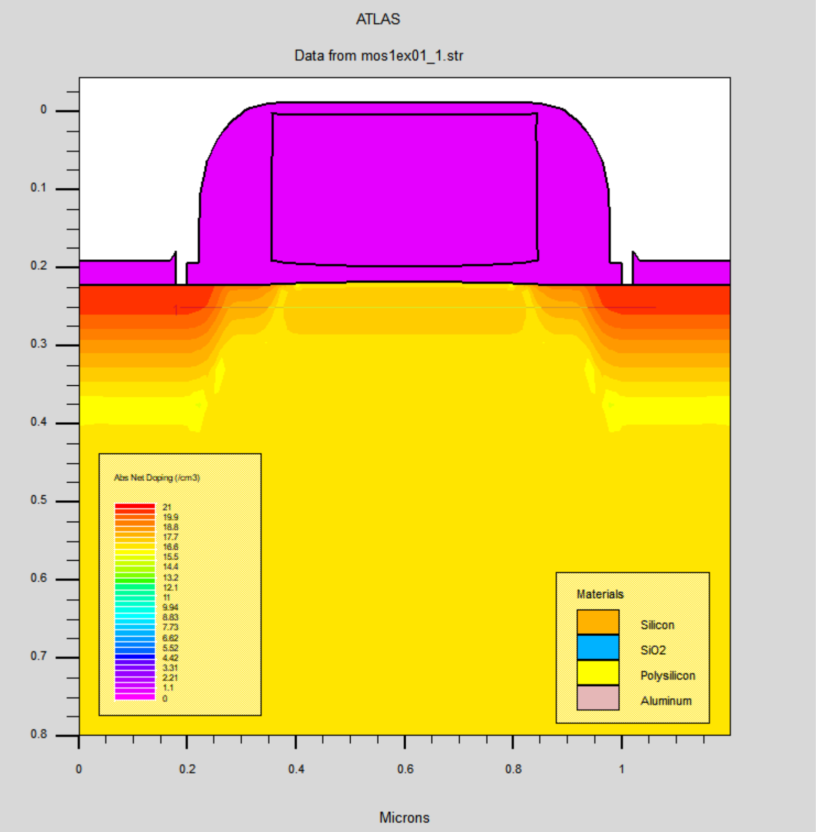


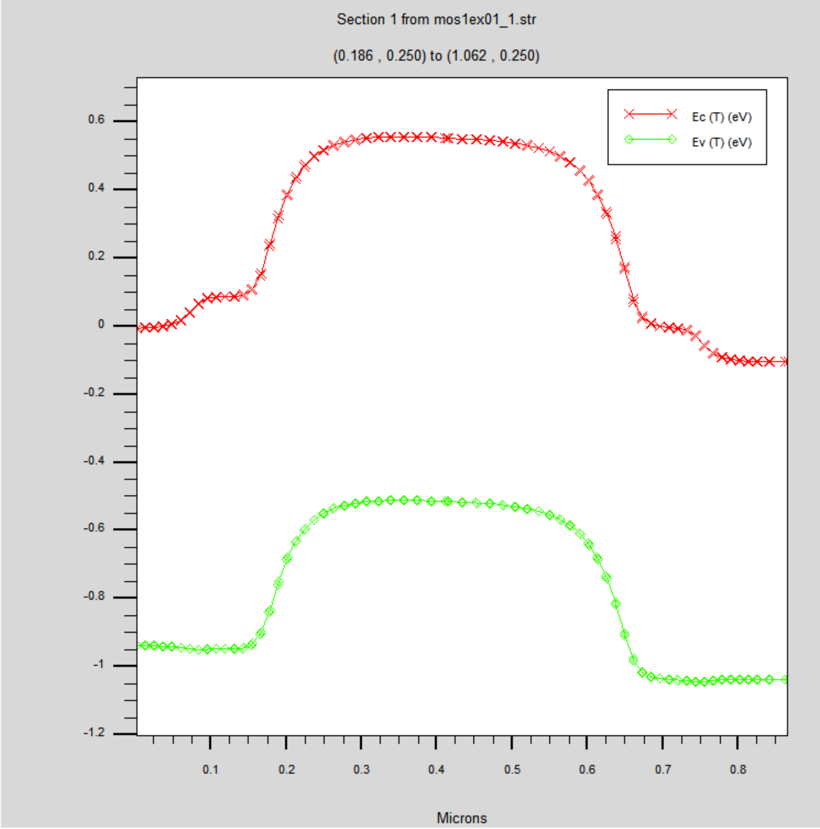
2v bias to the gate: Depletion region e-h QFL (horizontal cutline)



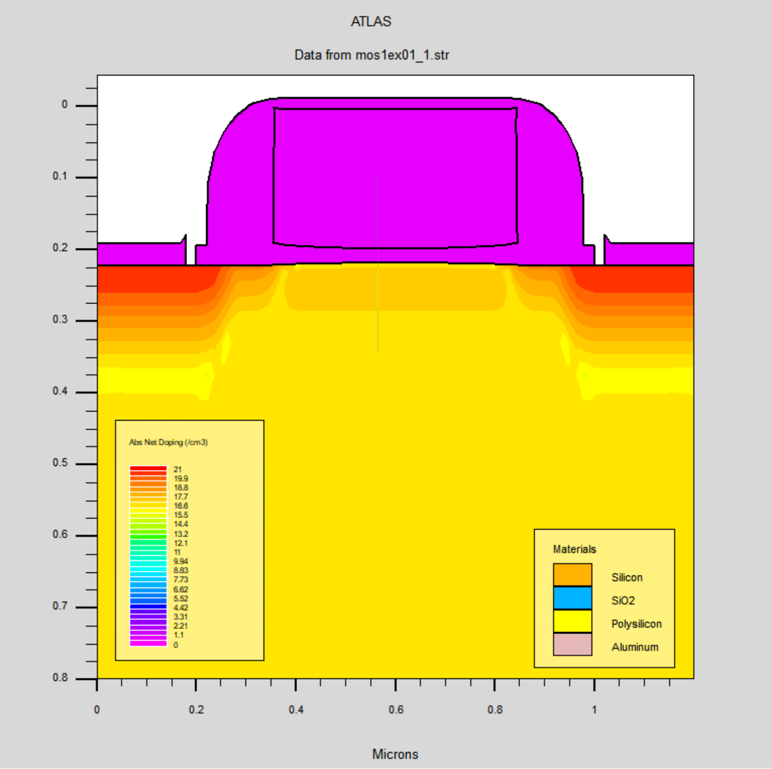


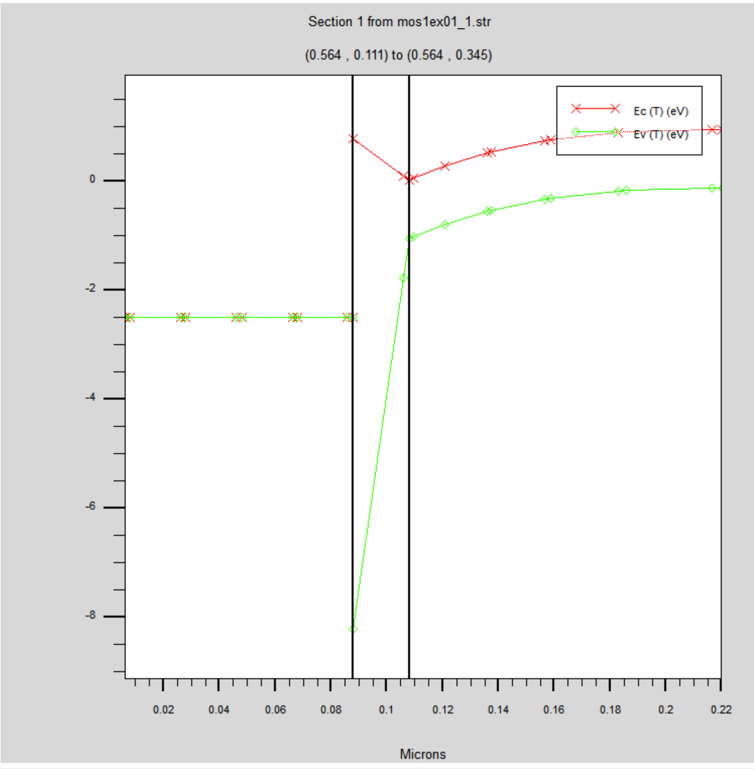
2v bias to the gate: Depletion region Ec and Ev (horizontal cutline)





2v bias to the gate: Depletion region Ec and Ev (vertical cutline)





References

1. ATLAS User's Manual
2. ATLAS provided examples (MOS)
3. Research Gate website forum