

Fall 2008

EE 612: Nanoscale Transistors

HW9 SOLUTION

“On becoming a true technology designer”

I first ran the default simulation and looked at the plot: “Surface charge vs. V_g ”

The vertical axis is labeled: “Exposed charge plus carriers”

“Exposed charge” must be what we call “depletion charge”

“carriers” must be electrons for an N-MOSFET

The units are C/cm², but this is obviously wrong from the numerical values. It must be “Exposed charge plus carriers” divided by q

Since the charge of interest in a MOSFET is the charge under the gate, and the units are per cm², this must be the total charge under the gate divided by the gate area.

In a MOSFET, the charge under the gate will not be uniform. Under low V_{ds} , it will be nearly uniform, so let me concentrate on the low V_{ds} region. (The high V_{ds} region will be very complicated.)

I am a little worried, however, because there will be some extra electron charge near the two ends of the device because of the S/D junctions. So let's use a little longer gate, so that this effect is not too large.

After some trial and error, I settled on the following parameters...

Channel Length = 250 nm (because the problem involves the charge under the gate, I wanted to spread the gate out a bit and reduce the edge effects).

Channel Nodes = 50 to get some more resolution in the longer channel

|Substrate Doping = $1e+18$ to make the substrate uniformly doped to removed any complications due to non-uniform channel doping

V_g Maximum = 0.5 V so that we don't get too much inversion layer charge, which would swamp everything else

Vd Bias Maximum = 0.05 – no need to compute 2 Vd's

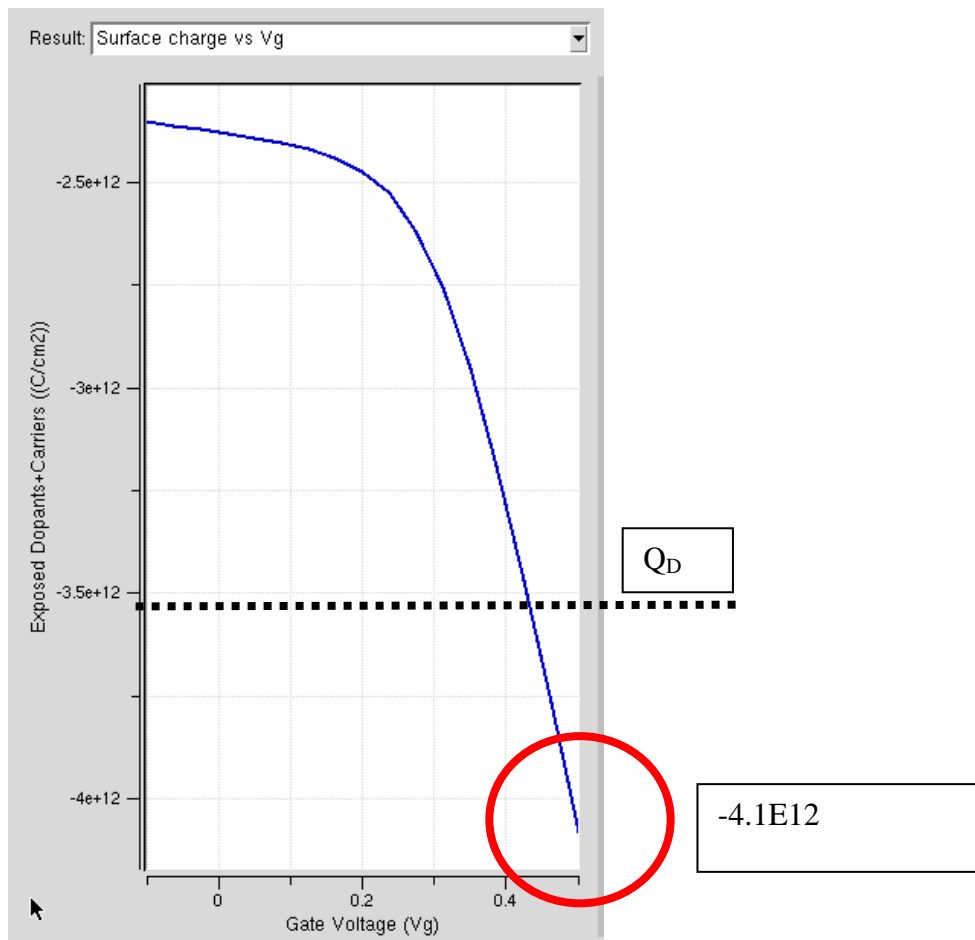
Number of curves = 1

Where to Plot 1-D Plots Along Depth? 175 nm – so that we produce a plot right down the middle of the gate

Let's first compute the expected depletion layer charge:

$$Q_{DM} = \sqrt{2q\epsilon_{Si}N_A(2\psi_B)} = 5.7 \times 10^{-7} C / cm^2 = q \times 3.5 \times 10^{12} / cm^2$$

Then let's do the simulation....

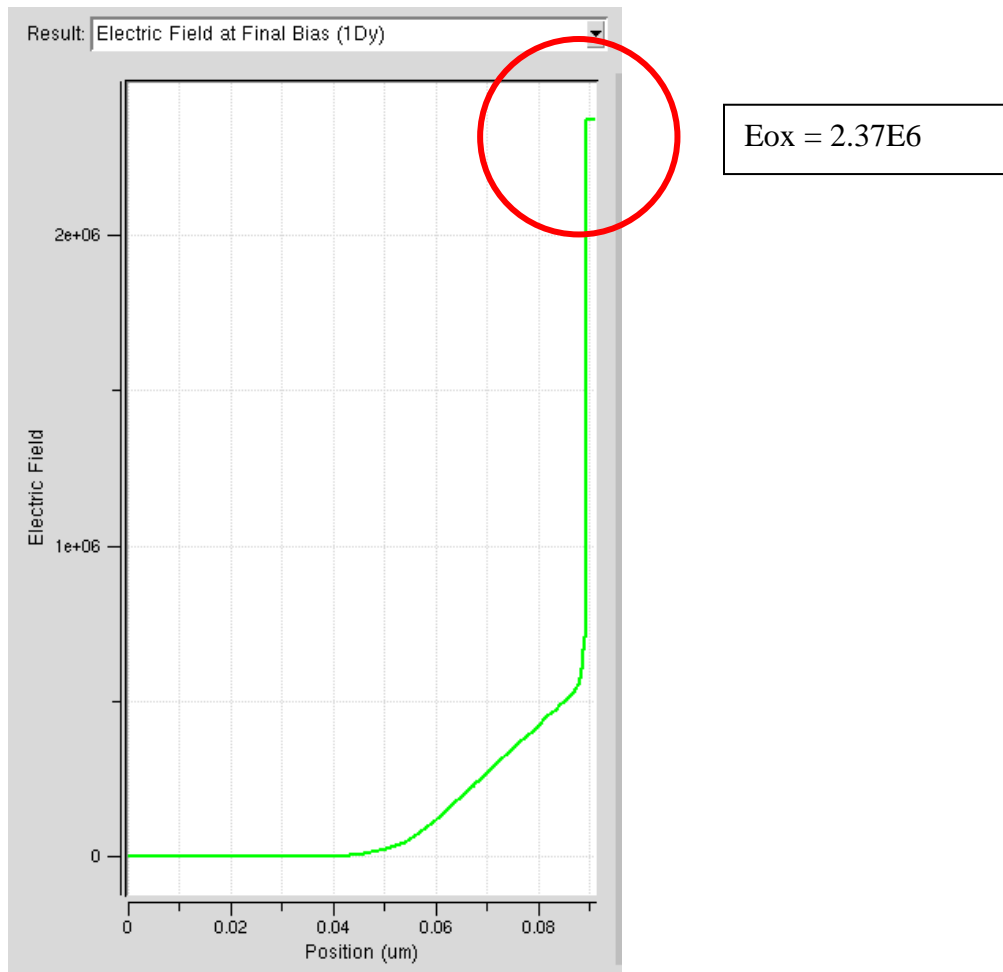


It is clear that there is no indication of the depletion charge on this plot, so it must not be plotting “exposed charge.”

We know that the simulation has to obey physics. Gauss’s Law relates the electric field in the oxide to the total charge in the semiconductor.

$$Q_{Si} = \epsilon_{ox} E_{ox}$$

So let’s look at the 1D plot vs. depth down the middle of the gate.
“Electric field at final bias (1Dy)”



We see the zero field in the bulk, the linearly increasing field in the depletion layer, and the constant field in the oxide. (Note that $y = 0$ is at the bottom of the device in the figure on the tool page and that $y = 91 \text{ nm}$ (0.091 um) is at the top of the oxide). It would have been helpful to have the on the figure of the device on the tool page, but we can figure it out anyway.

No units are given for the electric field in the oxide, E_{ox} , but let’s assume that the units are V/cm, because nothing else would make sense.

Now we can compute $Q_{Si} = \epsilon_{ox} E_{ox} = 8.2 \times 10^6 C/cm^2 = 5.1 \times 10^{12} /cm^2$

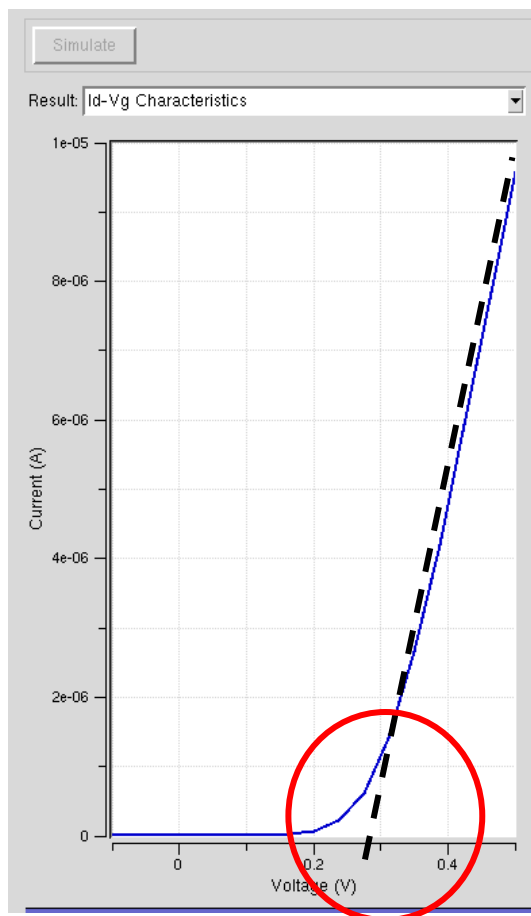
We should compare this with the “Total exposed charge (depletion charge) plus carriers” in the first plot. At $V_g = 0.5V$, that number was $4.1E12$, so the number in the first plot is something less than the sum of the depletion and inversion charge. What is it?

Maybe it is the inversion charge?

Recall that: $Q_i = -C_{ox} (V_G - V_T)$

$$C_{ox} = \frac{\epsilon_{ox}}{T_{ox}} = 1.73 \times 10^{-6} F/cm^2$$

From the I_d vs. V_g plot....



$V_t \sim 0.28V$

Using this value of V_t , we find

$$|Q_i| = -C_{ox} (V_G - V_T) = 3.8 \times 10^{-7} \text{ C/cm}^2 = q \times 2.37 \times 10^{12} / \text{cm}^2$$

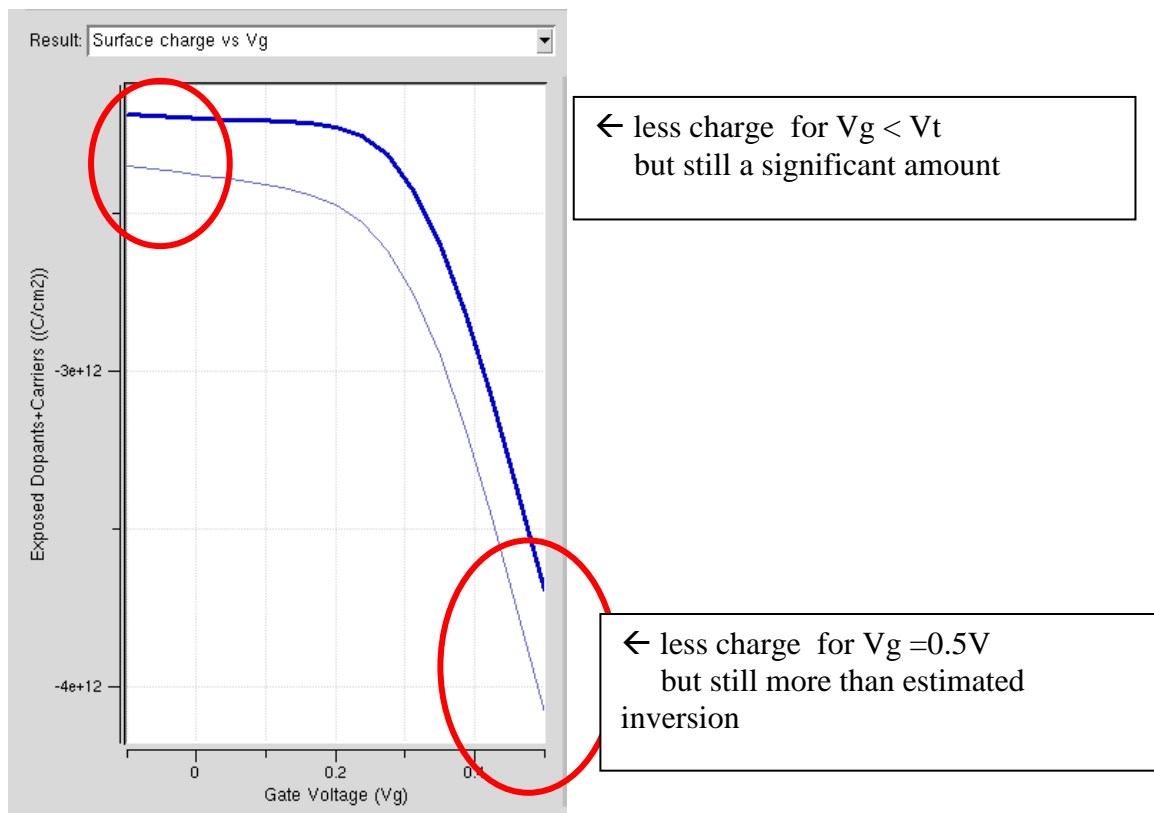
If we compare this to the first plot, we see that the “Exposed charge plus carriers” is more than the inversion charge we computed, but substantially less than the estimated inversion charge plus the estimated depletion charge ($5.9\text{E}12$)

If we use more rigorous form such as eqn (3.58) in the textbook, Q_i is $1.7\text{E}12$. Now, the sum of the depletion charge ($3.5\text{E}12$) and inversion charge ($1.7\text{E}12$) is more consistent with $Q_{si} = 5.1\text{E}12$ obtained from Gauss law.

It seems clear that this plot is not what it says it is.

For $V_g > V_t$, the quantity increases linearly with V_g , but it does not go to zero for $V_g < V_t$ as it should. It may be the inversion layer charge plus something extra. What could that extra charge be? We determined that it cannot be the depletion layer charge. Maybe it is some extra charge at the edges of the gate due to the source/drain regions. If that is the case, then if we make the gate much longer, this effect should get smaller and the plot should be closed to our estimated inversion layer charge.

Let's re-do the simulation with $L = 1000 \text{ nm}$



So the results depend the channel length, but it looks like we still don't have a long enough channel length to eliminate this edge effect.

Is it reasonable that the results could be so sensitive to electrons from the S/D region?

How many electrons per cm^2 are there in the S/D regions?

$$N_{SD} = 2N_D x_j = (2 \times 10^{20}) \times 21 \text{nm} = 8.4 \times 10^{15} / \text{cm}^2$$

The “extra” charge that we are trying to explain is $2.2\text{E}12 / \text{cm}^2$, which is only 0.03% of the charge in the source and drain. So it's not unreasonable to expect that a small amount of this charge spills into the channel, it can have a big effect and explain these results.

Now, we only explain $2.2\text{E}12 / \text{cm}^2$ at $V_g = 0\text{V}$. Using the Q_i obtained from eqn (3.48), estimated charges at $V_g = 0.5$ are $3.9\text{E}12 (= 1.7\text{E}12 + 2.2\text{E}12)$, which is closer to $4.1\text{E}12$ on the plot.

We could gain further confidence in this conclusion by plotting $n(x)$ vs. x from source to drain and we would see that some of the S/D electrons spill into the channel.

We would also lower the S/D doping to $2\text{E}19$ and we would see that the “extra” charge that we are trying to explain is reduced, which again tells us that it's an edge effect.

Final conclusion:

It appears that the quantity that is being plotted is the integral of the electron density from the source end of the channel to the drain end divided by the gate area. This is not the inversion layer density because of edge effects where the gate meets the heavily doped source and drain.

Comments:

1. You will get full credits if you do the followings:
 - 1) discuss that the numbers on the plot are not consistent with the analytical expressions in the sub-threshold and above threshold (30 pt)
 - 2) notice that there's difference between long and short channel and try to discuss that. (30 pt)