Fall 2008

EE 612: Nanoscale Transistors

HW5: DUE TUESDAY, SEPTEMBER 30

Ballistic FETs and V_T

1) For a p-MOSFET with $N_D = 2.7\times10^{18}$ cm^{-3}, a p$^+$ polysilicon gate with $(E_V - E_F) = 0.0$, an EOT_{elec} of 1.1nm, and charge at the oxide-Silicon interface of $Q_F / q = 5\times10^{10}$ cm^{-2}, compute the threshold voltage at $V_{SB} = 0, -0.5, +0.5$ V.

2) Assume that the off-current of a MOSFET at T = 27°C and V_{SB} = 0.0 is 0.1 μA/μm. Estimate the off current at T = 100°C. You should assume a MOSFET with the same parameters as given in problem 1).

3) As derived in Taur and Ning,

$$I_D = \mu_{eff} C_{ox}\left(\frac{W}{L}\right)(m-1)\left(\frac{k_B T}{q}\right)^2 e^{q(V_{GS}-V_T)/mk_BT}\left(1-e^{-qV_{DS}/k_BT}\right)$$

describes the I-V characteristic of a MOSFET in the subthreshold region. <u>Explain</u> how to modify this expression to describe the subthreshold region of a ballistic MOSFET. HINT: You should not try to derive the subthreshold characteristic of a ballistic MOSFET; you should just modify the above expression based on your understanding of the physics behind it.

4) Electrons moving in the x-y plane of a MOSFET channel have a +x-directed velocity of $\upsilon_x = \upsilon\cos\theta$ where $m^*\upsilon^2/2 = (E-\varepsilon_1)$, where ε_1 is the energy of the first subband (think of this like the bottom of the conduction band).

a) Show that at a given energy, the average +x-directed velocity, $\langle\upsilon_x\rangle = 2/\pi$.

b) Show by integrating over energy, that the overall average +x-directed velocity is

$$\langle\upsilon_x\rangle = \int_{\varepsilon_1}^{\infty}\frac{2}{\pi}\upsilon e^{-(E-E_F)/k_BT}dE \Big/ \int_{E_C}^{\infty} e^{-(E-E_F)/k_BT}dE = \sqrt{\frac{2k_BT}{\pi m^*}} \equiv \upsilon_T$$

(where Boltzman statistics has been assumed for carriers).

5) Assume Boltzmann statistics and compute the ballistic mobility for an L = 50nm MOSFET with silicon channel ($m^* = 0.19m_0$) vs. GaAs channel ($m^* = 0.063m_0$). Compare the two numbers and discuss the significance.

6) At T = 0K in a ballistic MOSFET, the density of inversion layer electrons with positive velocities is given by

$$n_S^+ = \frac{m^*}{2\pi\hbar^2}\left(E_F - \varepsilon_1\right),$$

where ε_1 is the energy of the first subband (think of this like the bottom of the conduction band). At T = 0K in the ballistic MOSFET, the average velocity of the electrons with positive velocities is

$$\tilde{\upsilon}_T = \frac{4}{3\pi}\upsilon_F = \frac{4}{3\pi}\sqrt{\frac{2\left(E_F - \varepsilon_1\right)}{m^*}}.$$

a) Use the two equations above to develop an expression for the on-current of a ballistic MOSFET in the fully degenerate limit.

b) Assume $n_S^+ = 10^{13}$ per cm^2 and $m^* = 0.19m_0$ (silicon) and compare the ballistic injection velocities under non-degenerate and fully degenerate conditions.

7) The transconductance of a MOSFET in the saturation region of operation is frequently used to estimate the velocity in the channel according to

$$\langle \upsilon \rangle = \frac{g_m}{C_{ox}}$$

a) Show that this expression gives the velocity at the top of the barrier for a ballistic MOSFET in the non-degenerate limit.

b) Show that under fully degenerate conditions (T = 0K), this expression does not give the velocity at the top of the barrier.

c) Compare a) and b) to the result from the complete velocity saturation model.

8) Explain in words (no more than three sentences) why the subthreshold current increases exponentially with gate voltage.