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DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

EEE416/4060 HIGH SPEED ELECTRONIC DEVICES
Problem Sheet 2

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1. An n-channel Si MOSFET has an oxide thickness of 10 nm, a gate length of 150 nm, a gate width of 1µm and a p-type channel doping of 5 x 10^{16} cm^{-3}. The channel electron mobility for this structure is $0.06 m^2 V^{-1} s^{-1}$.
For a gate voltage of 3 V calculate the following

(note: you may assume $n_i\{Si) = 1.5 \times 10^{10}$ cm^{-3} , $\varepsilon_r(Si) = 12$, $\varepsilon_r (SiO_2) = 3.9$ and the flat band voltage for this structure is 0.3 V)

(i) The oxide gate capacitance per unit area, C_{ox}

(ii) The inversion voltage, V_B

(iii) The threshold voltage, V_T

(iv) The Transconductance, g_m

(v) The saturation current, I_D

(vi) The cut-off frequency, f_T

The oxide gate capacitance per unit area, C_{ox}

(i) $C_{ox*,}\mathrm{OT}AL = \varepsilon A/d$ $\quad C_{ox}(per\ m^2) = \varepsilon.d = 3.9\ x\ 8.85E{-}12 / 1E{-}8 = 3.45E{-}3\ Fm^{-2}$

The inversion voltage, V_B

$(ii) V_B = -kT/q.\ln(N_A/N_i) = -0.026\ln(5E16/1.5E10) = -0.39V$

(iii) The threshold voltage, V_T

$V_T = -|V_{FB}| + 2|V_B| + (2q\varepsilon_S N_A\ |2V_B|\ )^{1/2}/Cox$

$2q\varepsilon_s N_A .2V_B$ = 2 x1.6E-19x(12x8.85E-12)x5E22x (2 x 0.39) = 1.325E-6

SQRT(3.976E-7)=1.151E-3

So $V_T = -0.3+0.78+0.334=0.814V$

(Note ε_s means permittivity of the semiconductor, not the oxide)

(iv) The Transconductance, g_m

$g_m = Z\mu C_{ox}/L\ .(V_{GS}-V_T)\ .\ Z\mu Cox/L = 1.38E{-}3$ $\quad V_{GS}$ = 3.0V. $\quad (V_{GS} - V_T)$=2.185V.

Therefore g_m = 3.01E-3S

(v) The saturation current, I_D $ID = Z\mu C_{ox}/2L\ .(V_{GS}-V_T)^2$ = 6.9E-4. 2.185^2 =3.29mA

(vi) The cut-off frequency, f_T

$f_T = \mu/2\pi L^2 . (V_{GS} - V_T)$ = 927GHz

2. If trapped charge equivalent to 5 x 10^{15}m^{-3} electrons m^{-3} appears in the gate oxide of the device in 1 above, calculate the new V_T ,g_m , and I_D .

The important thing to realise is that trapped charge causes an increase in V_T – transistor now has to receive a higher voltage to overcome this extra charge.

The amount of this increase is $|Q_{ss} / C_{ox}|$.
Q_{ss} in this case is just = n.q = 5E15x 1.6E-19C so $|Q_{ss} / C_{ox}|$ = 0.23V

New V_T = 0.814 + 0.23 = 1.044 . New (V_{GS} - V_T) = 1.956V
New $g_m = Z\mu C/L$ (1.956)= 2.70E-3
New $I_D = Z\mu C_{ox}/2L\ (VGS - VT)2$= 6.9E-4. (1.956)^2 = 2.64mA

3. Calculate f_T for the device of question 1 above but using saturation velocity rather than the low field mobility value . Comment on the difference.

The cut of frequency using mobility approximation is $f_T = \mu 2\pi / L^2 . (V_{GS} - V_T)$ - from before.
This is voltage dependent. The expression is fine at low voltages but eventually the mobility will saturate. Then the carrier velocity will become constant (independent of the voltage)

$V_{Sat} = distance/\ time = L/\tau$
$f_T = 1/2\pi\tau$. Therefore $f_T = V_{Sat}/2\pi L$ = $1E{-5}/\ 2\pi.1.5E{-7}$= 106GHz

This is a far more sensible value than the 927GHZ value calculated from the mobility (which would be an all time device record). In reality all high speed devices tend to have f_T limited by the saturation velocity regime.

4. An n-channel MOSFET displays a drain current of 50μA and 80μA ~at V_{GS} = 1.5 V and 2.5 V respectively when V_{DS}= 0.1 V (i.e. in the linear region). Calculate the equivalent electron channel mobility for a device with a gate length and width of 0.2μm and 1 mm respectively. Assume that C_{OX} = 1x10^6 Fm^{-2} . How does your value compare with the quoted mobility for Si at room temperature?

In the linear region of a MOSFET $I_D = Z\mu C_{ox}/L.[V_{GS} - V_T)$- $V_{DS}/2].V_{DS}$
Considering the difference between 2 currents:
$I_D(1) - I_D(2) = I_D(2.5V) - I_D(1.5V)$ = 30μA = $Z\mu Cox/L[2.5-1.5].0.1$ *(Note the V_T and $V_{DS}/2$ terms cancel!)*

Rearranging gives:
$\mu = 30\mu A.L/\ (Z[1].0.1)$ = $30E{-6}x\ 0.2E{-6}/(1E{-3}x\ 0.1x\ 1E{-6})$ =$0.06m^2V^{-1}s^{-1}$

This is the same value as given before, which gives some reassurance. But the book value for Si is 0.15 m^{2}V^{-1}s^{-1} (note more usually written as $1500cm^2V^{-1}s^{-1}$). Our calculated value is about half of this one. The reason is that the electrons are not in pure bulk silicon. In the MOSFET there will be some scattering from interfaces such as the gate Si/SiO_2 interface . This lowers the mobility.