Fall 2008

EE 612: Nanoscale Transistors

HW6 SOLUTION

MOSFET Mobility

A long channel MOSFET is often used to "measure" the effective mobility of carriers in the inversion layer. A long channel device minimizes the influence of the parasitic series resistance and short channel effects. It may also provide a gate capacitance big enough to do a CV curve on. For this exercise, you will use the MOSFET simulation tool on nanoHUB.org (also available in the ABACUS suite of tools). You will treat the simulator like a "black box" and just use the IV characteristics it computes as you would use measured IV characteristics. For the last problem, you will also need the CV characteristics.

Important note: You will need to write some Matlab scripts for this assignment. Be sure to turn them in as part of the solution.

For this problem, you should specify a MOSFET as follow (approximately the 45 nm technology node).

$N_A = 2.7 \times 10^{18}$ cm^{-3} for the bulk doping
$EOT = 1.1$ nm
$Q_F = 0.0$
$T = 300$K
$V_{DD} = 1.0$V
Assume an n$^+$ polysilicon gate
Select "Gaussian S/D doping density"
Specify a channel length of 1 micron.
(Note that the "45nm technology node" is designed for MOSFETs with channel lengths as short as about 45nm, but longer test devices are frequently better for characterization. That is why we use a 1 micron long channel length.)

1) Determine the effective mobility by plotting the transfer characteristic, I_D vs. V_{GS} at $V_{DS} = 0.05$V and finding the mobility from the expression:

$$I_D = \mu_{eff} C_{ox} \left(\frac{W}{L} \right) (V_{GS} - V_T) V_{DS} \; .$$

To do this, you will have to download the file of the I_D vs. V_G data and write a Matlab script to extract μ_{eff} . Plot the resulting μ_{eff} vs. V_G .

2) There is another way to determine the mobility. Determine the "field-effect" mobility from

$$\mu_{FE} = \frac{L}{WC_{ox}V_{DS}}\left(\left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}}\right)$$

and plot it vs. V_G. Compare the field-effect to the effective mobility. Why are they different?

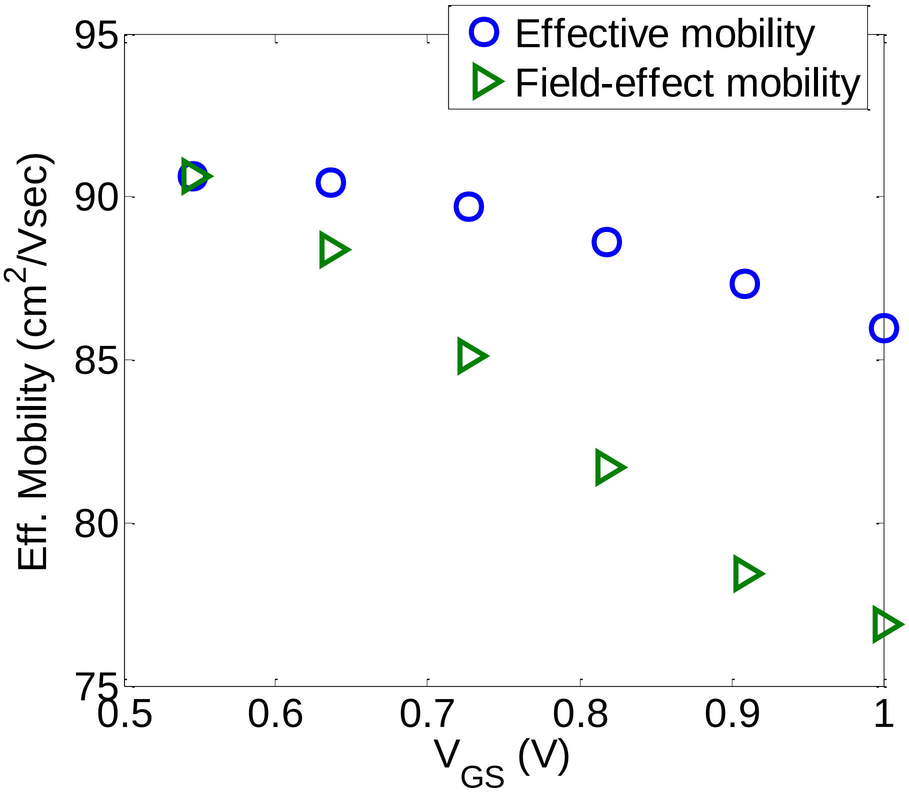
3) As discussed in your text book, when plotted vs. effective normal electric field (not vs. gate voltage or electric field at the oxide-silicon interface), plots of mobility vs. effective normal field display a "universal" characteristic. Plot the effective mobility, μ_{eff} , from part 1) vs. effective normal electric field and compare the results to those in Fig. 3.13 on p. 133 of the textbook by Taur and Ning.

4) One of the errors in measuring effective mobility is the assumption that $Q_I = C_{ox}(V_{GS} - V_T)$, which is not accurate near threshold and well above threshold where polysilicon depletion and the inversion layer capacitance reduce the gate capacitance. Careful experimentalists measure the gate capacitance and then compute the gate charge from $Q_I(V_G) = \int_0^{V_G} C_G(V)dV$. It's even easier for you, because the MOSFET simulation tool produces an output file of $Q_G(V_G)$. Note: This is the total charge on the gate, not just the inversion charge. You will need to use "Surface charge vs. Vg" data to re-extract effective mobility.

Remove the assumption that $Q_I = C_{ox}(V_{GS} - V_T)$, re-measure μ_{eff} and plot the new μ_{eff} vs. effective normal field. Compare the results to those obtained in part 3).

Prob. 1 and 2) Solution

1) Comparison

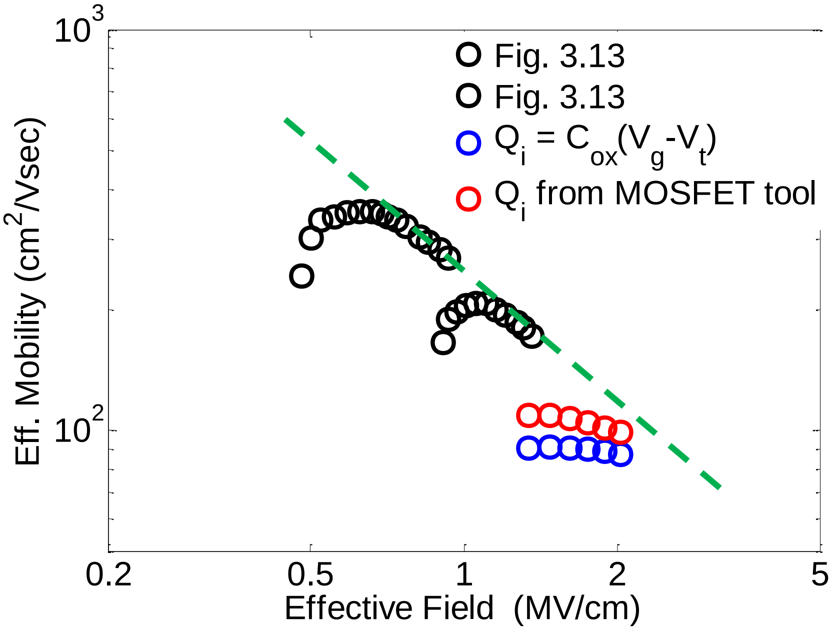


The field effective mobility is generally lower than the effective mobility. This difference is because the above expression of field effect mobility assumes that effective mobility does not depend on the gate bias. The correct expression can be written as,

$$\mu_{FE} = \frac{L}{WC_{ox}V_{DS}\left(1+\frac{(V_{GS}-V_T)}{\mu_{eff}}\frac{\partial\mu_{eff}}{\partial V_{GS}}\right)}\left(\left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}}\right)$$

Prob. 3 and 4) Solution

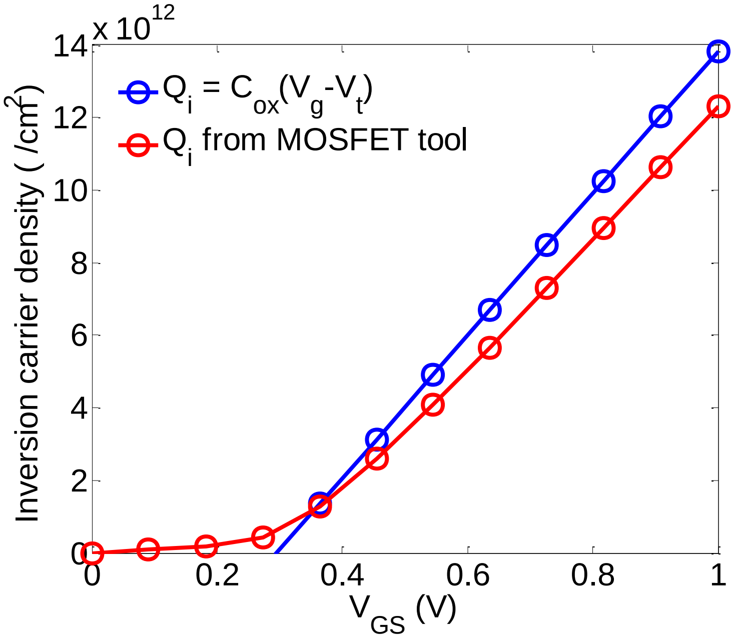
2) Effective mobility by two different approaches for Qinv extraction and comparison with universal mobility curve.



Mobility we obtained is little bit less than what we expect from universal mobility curve (dash line).

Mobility difference between part 3) and part 4) comes from inversion carrier density difference as shown in below. Cox(VgVt) overestimates inversion charge by about 15%.

3) Inversion carrier density difference by two methods.



Matlab code

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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Written by Changwook Jeong for HW6 assignment
% n type MOSFET
% L = 1000 nm, channel nodes = 100, W = 1um,
% Gaussian doping profile,
% peak channel doping = 2.7e18 /cm3, peak S/D doping = 2e20
% Tox=1.1nm, Vds=0.05
% Default value is used for other parameters.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;close all;clear;

% IV data from MOSFET tool
IV= [       0,       2.27946711e-11
        0.0909090909,       4.88437083e-10
         0.181818182,       1.12833983e-08
         0.272727273,       1.98865399e-07
         0.363636364,       1.03343472e-06
         0.454545455,       2.26296353e-06
         0.545454545,       3.56511616e-06
         0.636363636,       4.84786839e-06
         0.727272727,       6.08661426e-06
         0.818181818,       7.27609731e-06
         0.909090909,       8.41742701e-06
                   1,       9.51382199e-06
    ];  % in V, A

% Surface charge data

Ng =[                   0,       -5509362175000
        0.0909090909,       -5615609112500
         0.181818182,       -5694123775000
         0.272727273,       -5943216756250
         0.363636364,       -6801468562500
         0.454545455,       -8108995875000
         0.545454545,       -9599296687500
         0.636363636,      -11174983000000
         0.727272727,      -12798885562500
         0.818181818,      -14453561750000
         0.909090909,      -16129508625000
                   1,      -17820992687500 ];  % in Vg, #/cm2

% universal mobility curve from Takagi 1994

m1=[1.3588  171.8619
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```
1.3096  180.7714
1.2699  186.0684
1.209   194.3064
1.158   200
1.1092  207.3522
1.056   207.3522
1.0115  204.3794
0.96887 197.1326
0.93377 188.7749
0.91108 165.7681]; % MV/cm, cm2/V-sec,  mobility @ 300K, Nsub = 2.4e18

m2=[
0.48062 243.0495
0.50176 301.8329
0.52383 333.9387
0.55706 341.251
0.58876 348.7234
0.6261  351.2504
0.66173 351.2504
0.69084 346.2146
0.71241 341.251
0.73919 333.9387
0.7717  322.0981
0.82065 304.0201
0.85149 295.3652
0.89995 282.8427
0.93377 268.9025]; % MV/cm, cm2/V-sec, mobility @ 300K, Nsub = 7.7e17

% parameters
L = 1000e-9; W = 1000e-9; EOT=1.1e-9; eps0 = 8.85e-12; epsox = 3.9;
epssi = 11.9; Nsub = 2.7e18; ni = 1.45E10; Eg = 1.12; q = 1.602E-19;
kb = 8.61735E-5*q; T = 300;
psiB = (kb*T/q)*log(Nsub/ni); Vfb = - Eg/2 - psiB;
Cox = (epsox*eps0)/(EOT);
Vgs = IV(:,1); Id = IV(:,2); dl=length(IV); Vds=0.05;

% Vth calculation
gm = gradient(Id)./gradient(Vgs);
[AB, IX]=sort(gm(:),'descend');x =IX(1); s = AB(1);
Id_lin= @(vt) 1e6*(s*vt + Id(x)-s*Vgs(x));
[Vth, fval]=fsolve(Id_lin,0.1);

% prob 1) Effective mobility calculation: muEff
Qinv0 = Cox * (Vgs - Vth) /1e4;  %in col/cm2
muEff = Id./(Qinv0*Vds)/(W/L) ;  % in cm2/V-sec

% prob 2) Filed effect mobility calculation: muFe
muFe = L*gm./(Cox*Vds*W) * 1e4; % in cm2/V-sec

% prob 3) comparison with universal mobility from Takagi 1994
% Effective field calculation

Eeff = ((Vth-Vfb-2*psiB)/(3*EOT)...
    +(Vgs-Vth)/(6*EOT)) * 1e-8;  % in MV/cm, from Eqn 3.49
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```
% prob 4) muEff calculation using Qi from MOSFET tool(integration of CV)
Qi = -q * ( Ng(:,2)- Ng(1,2) ) ;   %in col/cm2
muEff_new = Id./(Qi*Vds)/(W/L) ;  % in cm2/V-sec

% plot
figure(1)
plot(Vgs,muEff,'o',Vgs,muFe,'>');
figure(2)
plot(Vgs,Qinv0/q,'o',Vgs,Qi/q,'>')
figure(3)
% Universal mobility curve
plot(m1(:,1),m1(:,2),'ok',m2(:,1),m2(:,2),'ok');
hold on
% plot beyond threshold voltage
plot(Eeff(6:11),muEff(6:11),'ob',Eeff(6:11),muEff_new(6:11),'or');
```