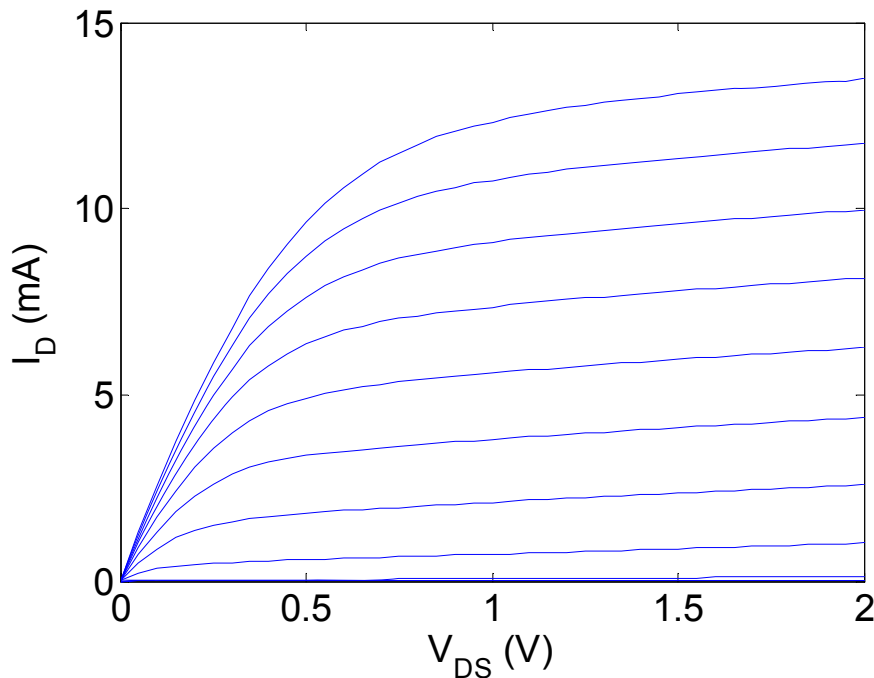


6.720 Device Characterization Project 2 - Solutions

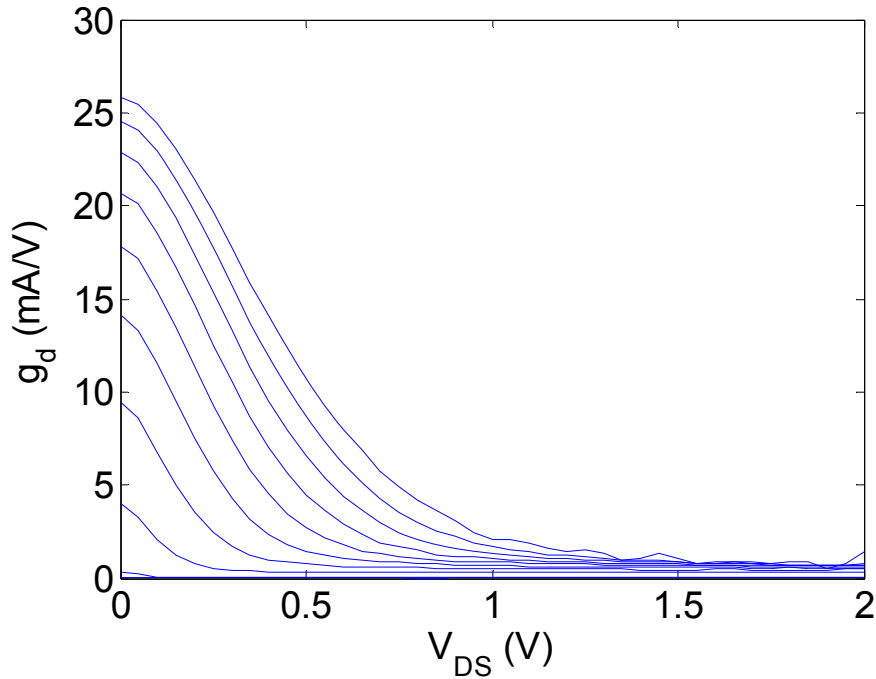
Jungwoo Joh

1-2) Output Characteristics

Graph 1 shows measured output characteristics, and graph 2 shows the corresponding output conductance. Here, V_{GS} is stepped up from 0 to 2 V in 0.2 V step. Notice that I_D increase not in quadratic but in linear with V_{GS} in saturation region, for example $V_{DS}=2$ V. This will be shown better in transfer characteristics. One of the reasons can be velocity saturation as the device is a short MOSFET.



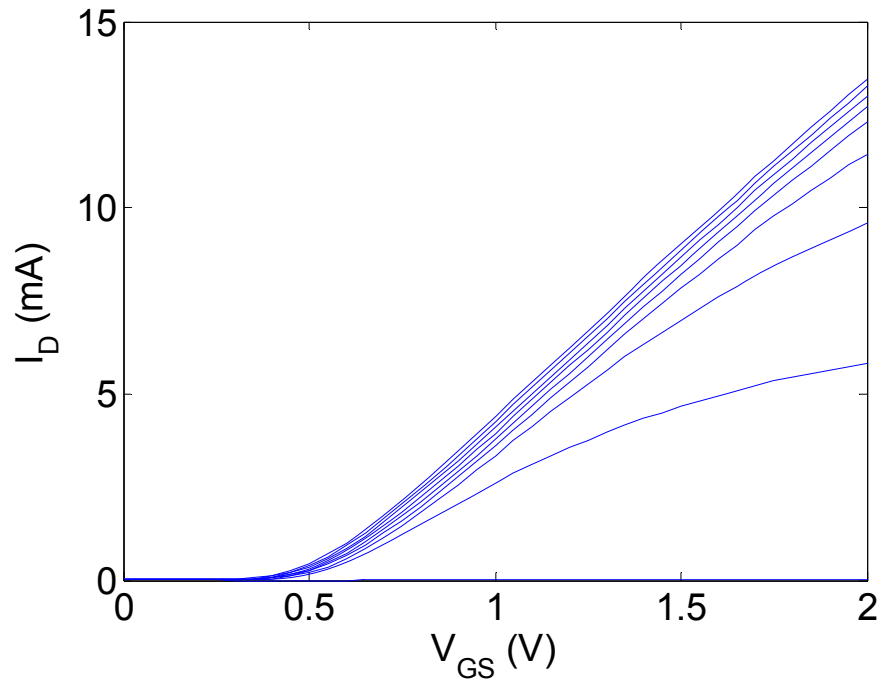
Graph 1. Output Characteristics. $V_{GS}=0\sim 2$ V in 0.2 V step.



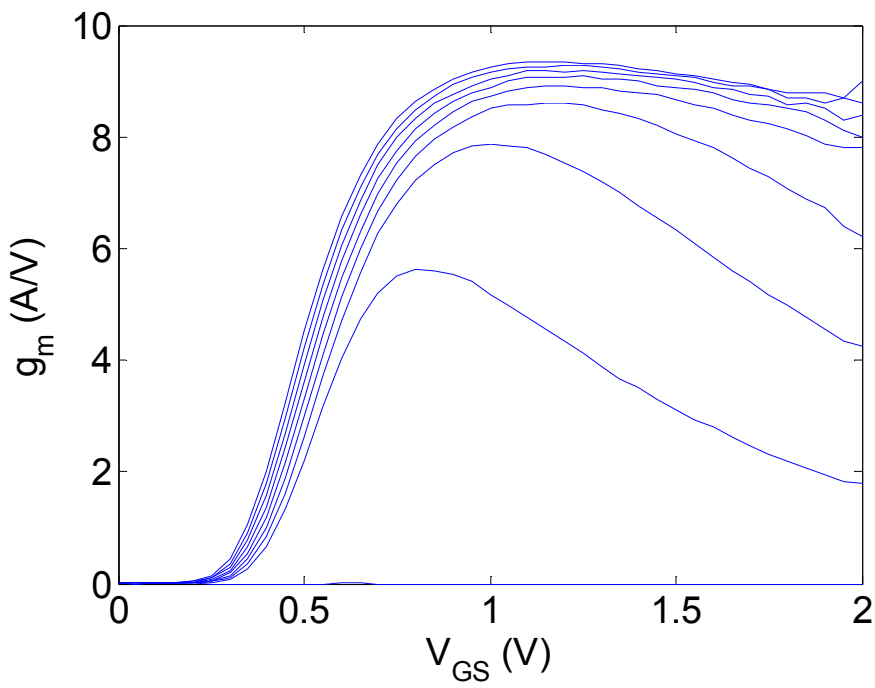
Graph 2. Output conductance. $V_{GS}=0\sim 2$ V in 0.2 V step.

3-4) Transfer Characteristics

Graph 3 shows measured transfer characteristics, and graph 4 shows the corresponding transconductance. Here, V_{DS} is stepped up from 0 to 2 V in 0.25 V step. First, It can be seen that the threshold voltage is around 0.3~0.4 V, where the device turns on. As mentioned earlier, it can be clearly seen that I_D increases linearly with V_{GS} in the saturation region (for example, at $V_{DS}=2$ V). This can be also seen in transconductance in the saturation region. As it can be seen, transconductance in the saturation region is not linear with V_{GS} , but almost constant, which is a signature of velocity saturation. In the linear region (for example at $V_{DS}=0.25$ V), I_D does not increase linearly with V_{GS} at high V_{GS} . This may be due to increased surface scattering and mobility degradation in high vertical electric field. In addition, at high current, voltage drop in parasitic source resistance can result in transconductance decrease as one can see in graph 4.



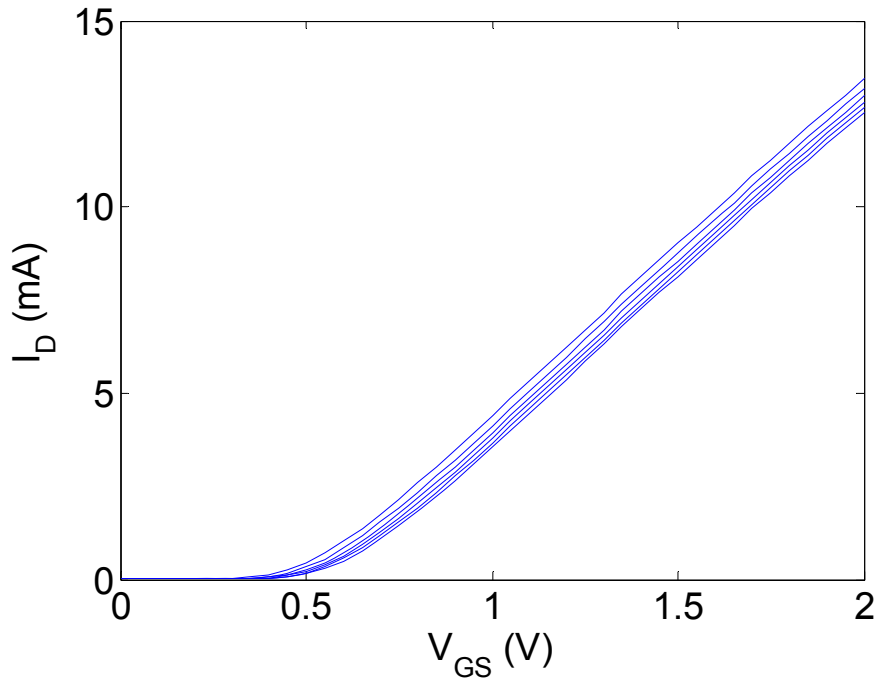
Graph 3. Transfer characteristics. $V_{DS}=0\sim 2$ V in 0.25 V step.



Graph 4. Transconductance. $V_{DS}=0\sim 2$ V in 0.25 V step

5) Backgate Characteristics

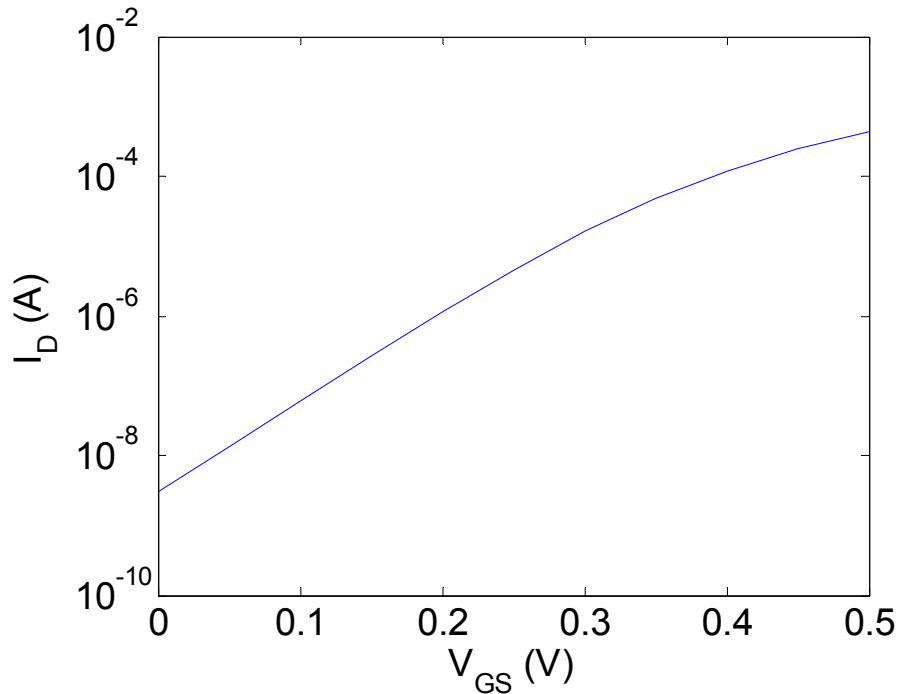
Graph 5 shows backgate characteristics at $V_{DS}=2$ V with $V_{BS}=0\sim-2$ V in -0.4 V step. As it can be seen, the threshold voltage shifts positive as reverse bias is applied to the body.



Graph 5. Backgate characteristics. $V_{BS}=0\sim-2$ V in -0.4 V step (left to right)

6) Subthreshold Characteristics

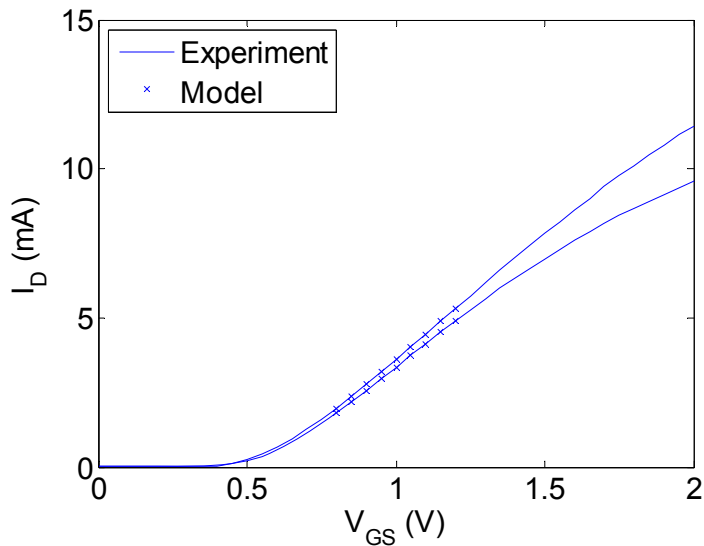
Graph 6 shows subthreshold characteristics at $V_{DS}=2$ V. Notice the device turns on at around $V_{GS}=0.3$ V, where I_D curve starts to deviate from exponential behavior.



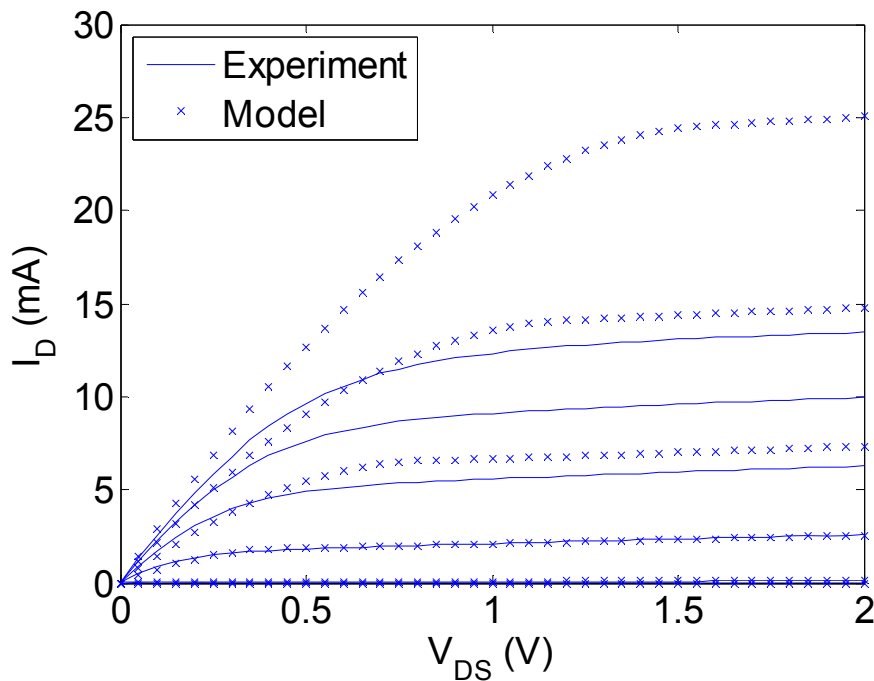
Graph 6. Subthreshold characteristics. $V_{DS}=2$ V.

7) As discussed earlier, measured data do not match well with the ideal MOSFET equation especially in the saturation region. Therefore, the best region to extract μC_{OX} and V_{th} is the linear region. This can be done best with I_D vs V_{GS} graph in the linear regime. Of course, we can extract those parameters with output characteristics curve, but as I_D is the 2nd order equation of V_{DS} , the fitting is more complicated, so it would be easier to fit I_D as a function of V_{GS} . In the transfer curve, the slope is $\mu C_{OX} \frac{W}{L} V_{DS}$, and the y-intercept is $-\mu C_{OX} \frac{W}{L} (\frac{V_{DS}}{2} + V_{th}) V_{DS}$, so we can extract μC_{OX} and V_{th} . With $V_{DS} = 0.25 \sim 0.5V$, I fit the data in $V_{GS} = 0.8 \sim 1.2V$ (notice here we can assume that the device is in the linear region), and an average value is taken. The extracted values are $\mu C_{OX} = 1.63e-4$ A/V², and $V_{th} = 0.35$ V. This is shown in Graph A1.

Graph 7 shows the measured and modeled output characteristics. The model coincides with data in the linear region and in the saturation region for small V_{GS} . However, as mentioned before, measured saturation current does not increase as $(V_{GS} - V_{th})^2$, so the model does not predict well the measured data for large V_{GS} .



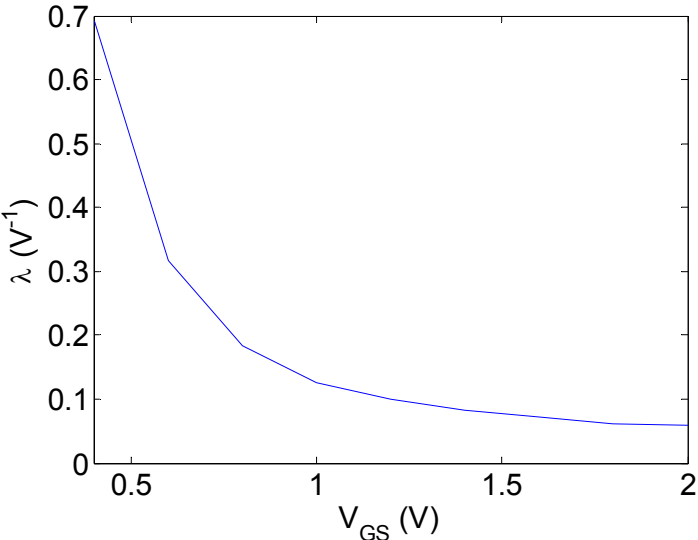
Graph A1. Measured and modeled transfer characteristics to extract V_{th} and μC_{ox} . $V_{DS}=0.25$ and 0.5 V.



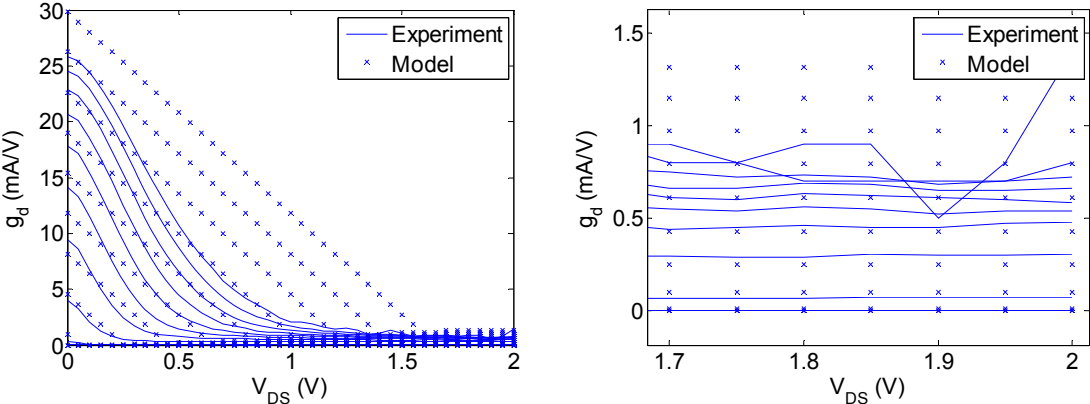
Graph 7. Measured and modeled output characteristics. $V_{GS}=0\sim 2$ V in 0.4 V step.

8) λ can be extracted from the slope of output characteristic curve in saturation region ($V_{DS}=1.8\sim 2$ V), which is essentially the same as averaging output conductance g_d in that region. λ is in fact not constant but dependent on V_{GS} as shown in graph A2. For $V_{GS}=1\sim 2$ V, the

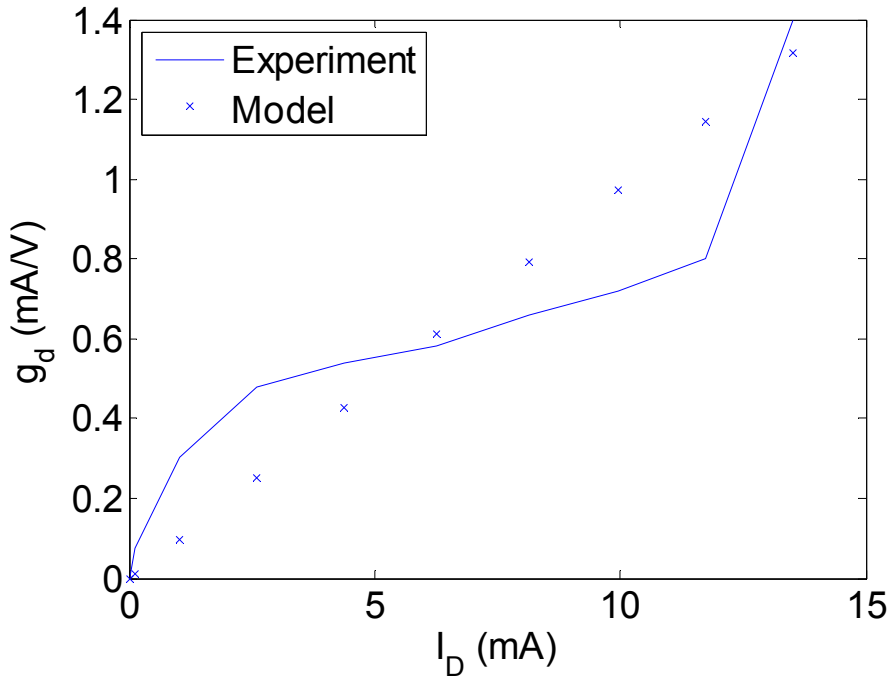
averaged λ is 0.1 V^{-1} . Also in this case, the measured output conductance in the saturation region is lower than the predicted value as shown in Graph 8. This is because in the model, conductance is proportional to $(V_{GS} - V_{th})^2$ in saturation region. Graph A3 shows measured and modeled output conductance as a function of the drain current at $V_{DS}=2 \text{ V}$.



Graph A2. λ as a function of V_{GS} .

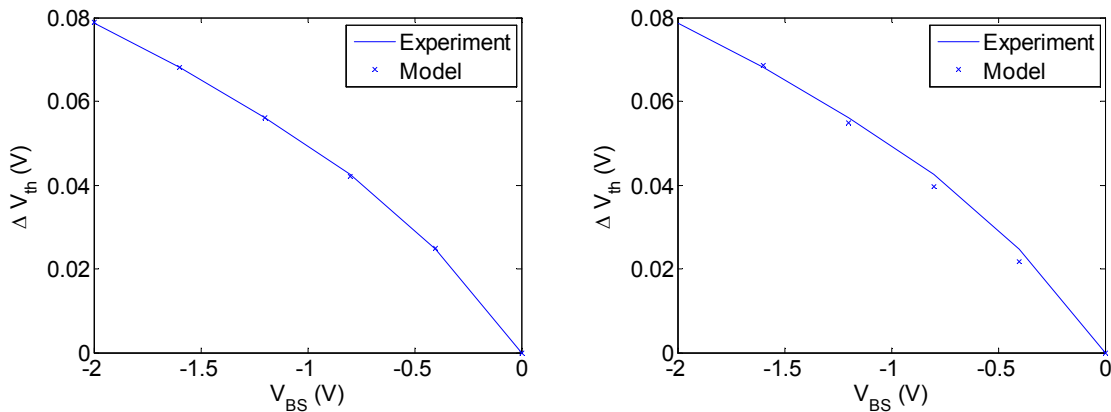


Graph 8. Measured and predicted output conductance. $V_{GS}=0\sim 2 \text{ V}$ in 0.4 V step (left: whole region, right: saturation region)



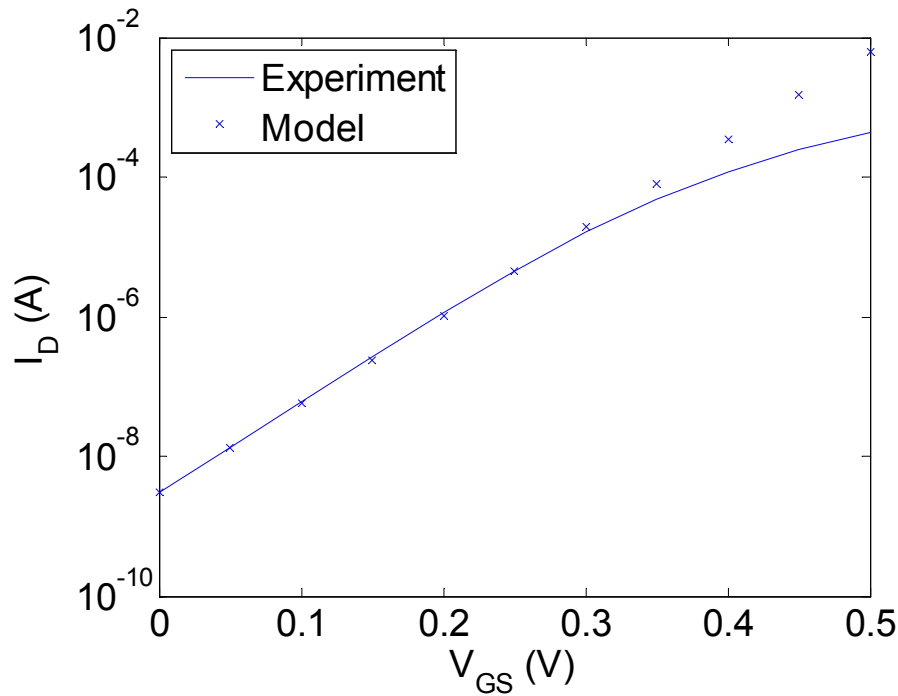
Graph A3. Measured and modeled output conductance as a function of I_D @ $V_{DS}=2$ V.

9) From the x-intercept of graph 5, ΔV_{th} for $-V_{BS} = 0, 0.4, 0.8, 1.2, 1.6, 2.0$ (V) can be extracted. From $\Delta V_{th} = \gamma\sqrt{\phi - V_{BS}} - \sqrt{\phi}$, the measured data was fit to get $\gamma=0.1$ V^{1/2} and $\phi_{sth}=0.6$ V. Although the best fit was $\gamma=0.08$ V^{1/2} and $\phi_{sth}=0.2$ V, this does not seem physical, so the fitting was re-done for $0.6 < \phi_{sth} < 1$ V. Graph 9 shows measured and modeled threshold voltage shift.



Graph 9. Measured and modeled change in V_{th} as a function of back bias V_{BS} . The left is the best fit, and the right is the fit with reasonable ϕ_{sth} .

10) The data at $V_{GS}=0\sim 0.25$ V in graph 6 are fit into the equation $\ln I_D = \ln I_{off} + \frac{qV_{GS}}{nkT}$, and from the slope and the y-intercept, $I_{off} = 3.11e-009$ A, $S=76$ mV/dec, and $n=1.33$ are extracted. The experimental and modeled curves are shown in graph 10.



Graph 10. Measured and modeled subthreshold characteristics at $V_{DS}=2$ V.

Appendix: Matlab code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% 6.720 Device characterization project 2
% by Jungwoo Joh
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;

L = 0.18e-4; % cm
W = 20e-4; % cm
q = 1.6e-19;
k = 8.62e-5; %eV/K

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% T(K)=, 296.546000
% VG, IG, VD, ID, GM
% V, A, V, A, A/V
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

T= 296.546000;
N = 41;

data2 = csvread('transfer.csv', 3, 0);

Vg = data2(1:N, 1);

% Problem 3, transfer characteristics (Graph 3)
figure (3);
figure (12);

for i = 0:8
    Id = data2(i*N + 1: (i + 1) * N, 4);
    Vd0(i+1) = data2(i*N + 1, 3);
    figure (3);
    plot(Vg, Id * 1000); % Id in mA
    hold on;

    fit1 = polyfit(Vg(17:25), Id(17:25), 1); % Vg=0.8~1.2V
    V_th_lin(i+1) = -fit1(2)/fit1(1) - Vd0(i+1)/2;
    u_Cox_lin(i+1) = fit1(1) * L / W / Vd0(i+1);

    if i == 2 || i == 3 % VDS=0.25, 0.5 V
        Id_model0 = u_Cox_lin(i+1) * W / L * (Vg-Vd0(i+1)/2-V_th_lin(i+1))*Vd0(i+1);
        figure (12);
        plot(Vg, Id * 1000); % Id in mA
        hold on;
        plot(Vg(17:25), Id_model0(17:25)*1000, 'x');
    end
end

figure (3);
%title('Transfer Characteristics (Graph 3)');
xlabel('V_G_S (V)', 'fontsize', 16);
ylabel('I_D (mA)', 'fontsize', 16);
set(gca, 'fontsize', 16);
ylim([0 15]);

figure (12);
%title('Transfer Characteristics (Graph A)');
```

```

xlabel('V_G_S (V)', 'fontsize', 16);
ylabel('I_D (mA)', 'fontsize', 16);
legend('Experiment', 'Model', 'location', 'northwest');
set(gca, 'fontsize', 16);
ylim([0 15]);

% Problem 7
u_Cox = mean(u_Cox_lin(2:3)) % VDS=0.25, 0.5 V
V_th = mean(V_th_lin(2:3)) % VDS=0.25, 0.5 V

% Problem 4, gm, (Graph 4)
figure (4);

for i = 0:8
    gm = data2(i*N + 1: (i + 1) * N, 5);
    plot(Vg, gm * 1000); % gm in mS
    hold on;
end
%title('Transconductance(Graph 4)');
xlabel('V_G_S (V)', 'fontsize', 16);
ylabel('g_m (A/V)', 'fontsize', 16);
set(gca, 'fontsize', 16);
ylim([0 10]);

% Problem 6 (Graph 6)
figure (6);

semilogy(Vg(1:11), Id(1:11)); % last Id is Id @ VDS=2 V
%title('Subthreshold Characteristics(Graph 6)');
xlabel('V_G_S (V)', 'fontsize', 16);
ylabel('I_D (A)', 'fontsize', 16);
set(gca, 'fontsize', 16);

% Problem 10
fit1 = polyfit(Vg(1:6), log10(Id(1:6)), 1); % VGS=0~0.25 V
S = 1/fit1(1)
loff = 10^(fit1(2))
n = S / (0.0259*T/300*log(10))

figure (10);
semilogy(Vg(1:11), Id(1:11));
hold on
semilogy(Vg(1:11), loff*exp(Vg(1:11)/0.0259/n), 'x');
%title('Subthreshold Characteristics 2(Graph 10)');
xlabel('V_G_S (V)', 'fontsize', 16);
ylabel('I_D (A)', 'fontsize', 16);
legend('Experiment', 'Model', 'location', 'northwest');
set(gca, 'fontsize', 16);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% T(K)=, 296.361000
% VD, ID, VG, IG, GD
% V, A, V, A, A/V
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

N = 41;

data = csvread('output.csv', 3, 0);

Vd = data(1:N, 1);

```

```

% Problem 1, Output characteristic (Graph 1)
figure (1);
figure (7);
ld_model = zeros(11, length(Vd));
for i = 0:10
    Id = data(i*N + 1: (i + 1) * N, 2);
    Vg0(i+1) = data(i*N + 1, 3);

    figure (1);
    plot(Vd, Id * 1000); % Id in mA
    hold on;

    fit1 = polyfit(Vd(37:41), Id(37:41), 1); % VDS=1.8~2 V
    %lambda(i+1) = fit1(1)/u_Cox/W*2*L/(Vg0(i+1)-V_th)^2;
    lambda(i+1) = fit1(1)/ld(37);

    if mod(i, 2) == 0
        figure (7); % Problem 7
        plot(Vd, Id * 1000); % Id in mA
        hold on;
        for j = 1:length(Vd)
            if Vg0(i+1) < V_th
                Id_model(i+1, j) = 0;
            else if (Vd(j) < Vg0(i+1) - V_th) % linear
                Id_model(i+1, j) = u_Cox * W / L * (Vg0(i+1)-Vd(j)/2-V_th)*Vd(j);
            else % saturation
                Id_model(i+1, j) = u_Cox * W / (2*L) * (Vg0(i+1)-V_th)^2 * (1 + lambda(i+1)*(Vd(j)-(Vg0(i+1)-V_th)));
            end
        end
        end
        plot(Vd, Id_model(i+1,:) * 1000, 'x'); % Id in mA
    end
end

figure (1);
%title('Output Characteristics(Graph 1)');
xlabel('V_D_S (V)', 'fontsize', 16);
ylabel('I_D (mA)', 'fontsize', 16);
set(gca, 'fontsize', 16);
ylim([0 15]);

figure (7);
%title('Output Characteristics(Graph 7)');
xlabel('V_D_S (V)', 'fontsize', 16);
ylabel('I_D (mA)', 'fontsize', 16);
set(gca, 'fontsize', 16);
ylim([0 30]);
legend('Experiment', 'Model', 'location', 'northwest');

figure (11);
plot (Vg0, lambda);
xlabel('V_G_S (V)', 'fontsize', 16);
ylabel('\lambda (V^{-1})', 'fontsize', 16);
set(gca, 'fontsize', 16);
xlim([0.4 2]);

% Problem 2, gd (Graph 2)
figure (2);
figure (8);

lambda0 = mean(lambda(5:11)) % Problem 8

```

```

for i = 0:10
    gd = data(i*N + 1: (i + 1) * N, 5);
    Id0(i+1) = data((i + 1) * N, 2);
    gd0(i+1) = data((i + 1) * N, 5);
    figure (2);
    plot(Vd, gd *1000); % gd in mS
    hold on;

    figure (8);
    plot(Vd, gd *1000); % gd in mS
    hold on;
    for j = 1:length(Vd)
        if Vg0(i+1) < V_th
            gd_model(i+1, j) = 0;
        else
            if (Vd(j) < Vg0(i+1) - V_th) % linear
                gd_model(i+1, j) = u_Cox * W / L * (-Vd(j) + Vg0(i+1) - V_th);
            else % saturation
                %gd_model(i+1, j) = u_Cox * W / (2*L) * (Vg0(i+1)-V_th)^2 * lambda0;
                gd_model(i+1, j) = Id0(i+1) * lambda0;
            end
        end
    end
    plot(Vd, gd_model(i+1,:) * 1000, 'x'); % gd in mS
    gd_model0(i+1) = gd_model(i+1, length(Vd));
end

figure (2);
%title('Output Conductance (Graph 2)');
xlabel('V_D_S (V)', 'fontsize', 16);
ylabel('g_d (mA/V)', 'fontsize', 16);
set(gca, 'fontsize', 16);
ylim([0 30]);

figure (8);
%title('Output Conductance (Graph 8)');
xlabel('V_D_S (V)', 'fontsize', 16);
ylabel('g_d (mA/V)', 'fontsize', 16);
set(gca, 'fontsize', 16);
legend('Experiment', 'Model', 'location', 'northeast');
ylim([0 30]);

figure (13);
plot (Id0 * 1000, gd0 * 1000);
hold on;
plot (Id0 * 1000, gd_model0 * 1000, 'x');
xlabel('I_D (mA)', 'fontsize', 16);
ylabel('g_d (mA/V)', 'fontsize', 16);
set(gca, 'fontsize', 16);
legend('Experiment', 'Model', 'location', 'northwest');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% T(K)=, 296.320000
% VG, IG, VB, IB, VD, ID, GM
% V, A, V, A, V, A, A/V
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

N = 41;

data3 = csvread('backgate.csv', 3, 0);

```

```

Vg = data3(1:N, 1);

% Problem 5
figure (5); % Graph 5
Vbs=[];

for i = 0:5
    Id = data3(i*N + 1: (i + 1) * N, 6);
    Vbs(i+1) = data3(i*N + 1, 3);
    plot(Vg, Id * 1000); % Id in mA
    fit1 = polyfit(Vg(19:23), Id(19:23), 1); % Vgs=0.9~1.1 V
    V_th_back(i+1) = -fit1(2)/fit1(1);
    hold on;
end
%title('Backgate Characteristics(Graph 5)');
xlabel('V_G_S (V)', 'fontsize', 16);
ylabel('I_D (mA)', 'fontsize', 16);
set(gca, 'fontsize', 16);
ylim([0 15]);

% Problem 9
del_Vth = V_th_back - V_th_back(1);

mymodel1 = fittype('g_fit*((phi_fit - x)^0.5 - phi_fit^0.5)');
opt1 = fitoptions(mymodel1);
opt1.Startpoint=[0.1 0.8];
opt1.Lower=[0 0.6];
opt1.Upper=[1 1];
[fit1,gof1] = fit(Vbs', del_Vth', mymodel1, opt1);

phi = fit1.phi_fit
gamma = fit1.g_fit
del_Vth_model = gamma*(sqrt(phi-Vbs) - sqrt(phi));

figure (9); % Graph 9
plot(Vbs, del_Vth);
hold on
plot(Vbs, del_Vth_model, 'x');
%title('Backgate Characteristics (Graph 9)');
xlabel('V_B_S (V)', 'fontsize', 16);
ylabel('\Delta V_t_h (V)', 'fontsize', 16);
legend('Experiment', 'Model');
set(gca, 'fontsize', 16);

```