Device Characterization Project 1

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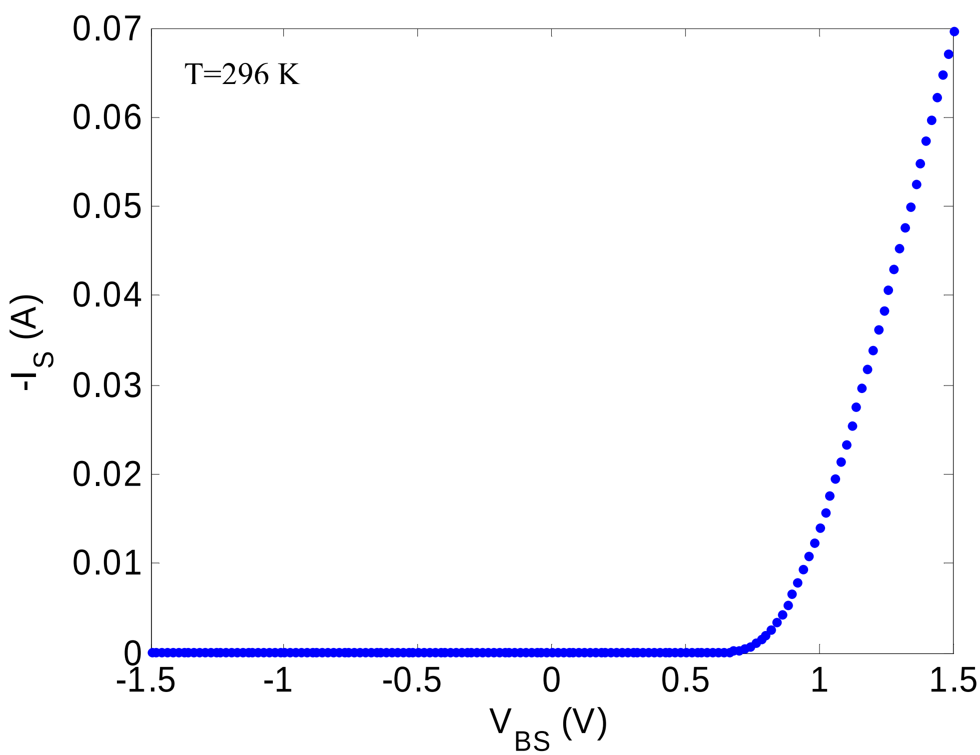
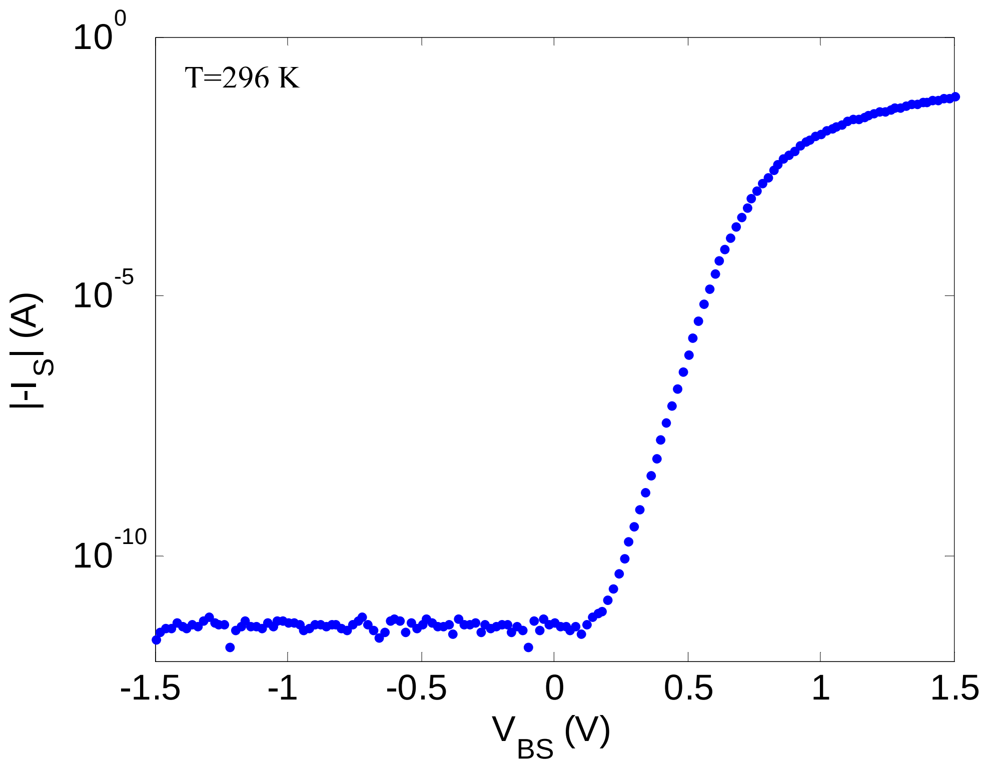
1) Obtain I-V characteristics

With source, drain, and gate grounded, V_{BS}=-1.5~1.5 V was applied. As the body is p-type and the source is n-type in an n-channel MOSFET, when V_{BS}>0 the source-body diode is in forward bias. However, as both body-source and body-drain diodes are simultaneously turned ON and OFF by applying V_{BS}(=V_{BD}), it is important to measure I_S instead of I_B. Another way to do it is to ground the gate and the drain and apply voltage to the source. In this case, I_B should be measured as I_S contains I_D component, which is different from what is done in this solution. As I_{sat} turns out to be smaller than the current precision of Agilent 4155, reverse bias leakage current does not show clearly in a log scale (see Graph 2).



Graph 1. I-V characteristics of body-source diode in linear scale.



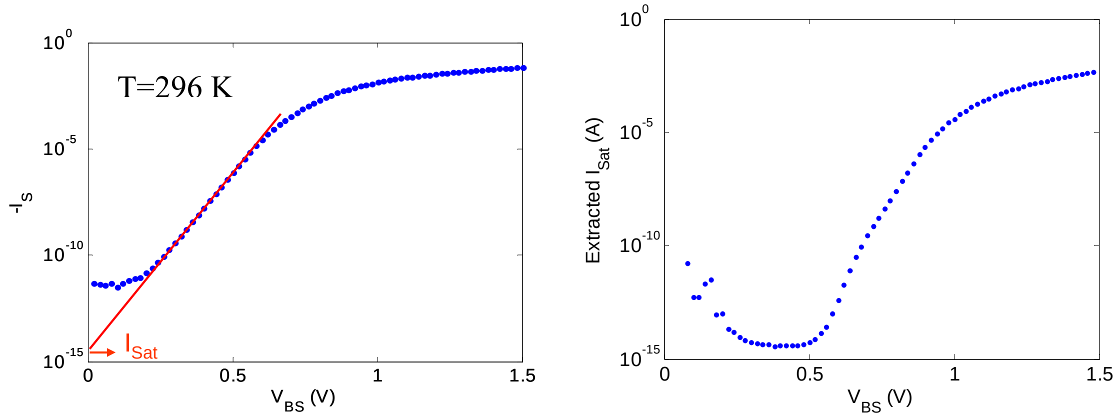
Graph 2. I-V characteristics of body-source diode in semi log scale.

2) Extract I_{Sat}

As reverse bias leakage current, which should be constant to $-I_{sat}$, is usually not ideal, it is inaccurate to extract I_{Sat} from the reverse bias region. It may seem to look constant in Graph 2, but this is due to the precision of the measurement instrument as mentioned. Therefore, we should extract I_{Sat} from the forward bias region. If we take logarithm of both sides of ideal diode equation (in case of $V >> kT/q$), we get:

$$\log I = \log I_{sat} + \frac{qV}{kT} \log e$$

Therefore, in the log I vs. V curve, the slope is (log e)/kT and y-intercept is log I_S. As shown in Graph A1, there is a region where the curve is almost linear: I_{BS} around V = 0.4 V. For this region, if we fit the data in a least-squares sense (I did it with Matlab. See the appendix for the details), we get **I_{Sat}=3.80x10^{-15} A**. As it can be seen in Graph A1, I_{Sat} is constant in $0.3 < V_{BS} < 0.5$ V. The inverse slope from the experimental data is 60.2 mV/dec, which is slightly bigger than the theoretical value kT/q/log e =58.8 mV/dec at 296 K (the measured temperature).

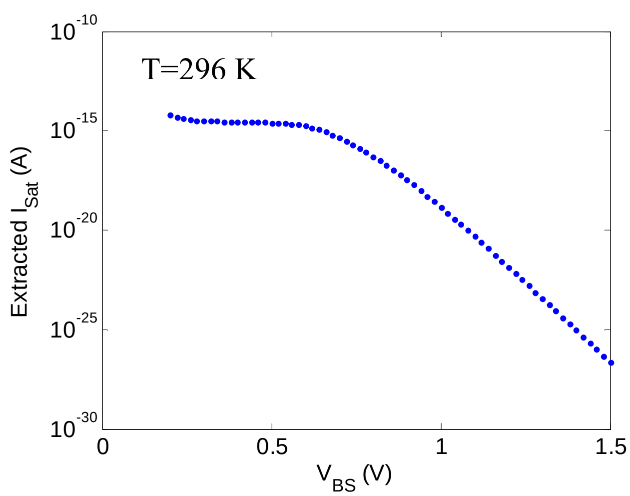


Graph A1. Extraction of I_{Sat} from different data point by finding y-intercept.

Another way to extract I_{Sat} is just from the ideal diode equation:

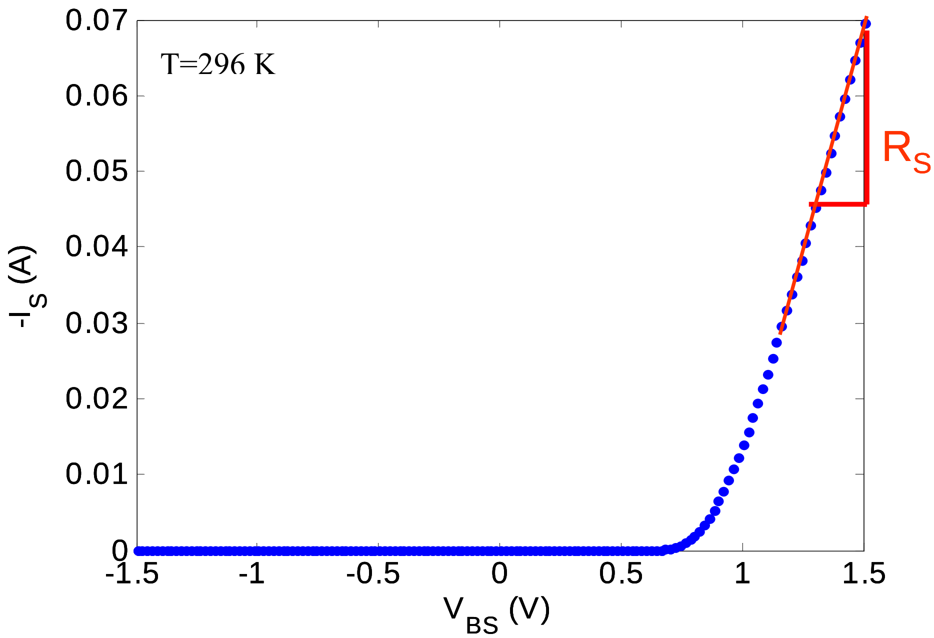
$$I_{Sat} = \frac{I}{(\exp(\frac{qV}{kT}) - 1)}$$

However, we should be careful when we choose the data point to get I_{Sat} because we have to select a data point where the diode behaves mostly as an ideal diode. I_{Sat} calculated from different data points is shown in Figure 2b. As it can be seen, I_{Sat} is fairly constant between $0.3<V_{BS}<0.5$ V, where the diode behaves most ideally. At V_{BS}=0.4 V, we get **$I_{Sat}=2.83\times10^{-15}$ A**, which is close to the value that we got before. Some of you have tried this method but used a value close to V_{BS}=0 or V_{BS}=1.5 V where the diode is not working ideally, so you got much bigger value.



Graph A2. Extracted I_{Sat} from different data points from the ideal diode equation.

3) Extract R_S



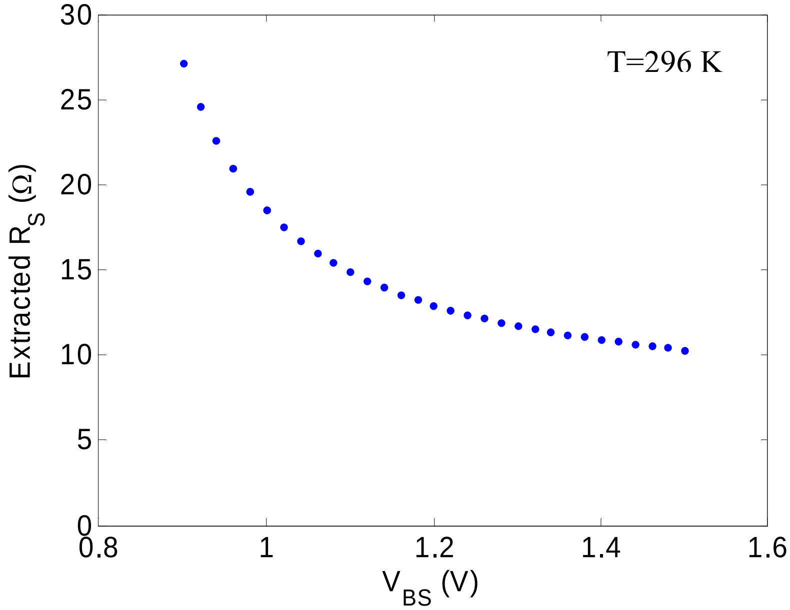
Graph A3. R_S extraction.

Because the voltage across the ideal diode increases exponentially with the current, while the voltage across the parasitic resistance increases linearly with the current, when V_{BS} is large enough we can assume that all the incremental voltage is applied to the series resistance. Around V_{BS}=1.5 V, if we fit the data into a line and get the slope (see Graph A3), we get R_S=8.03 Ω.

A more precise way is just to solve the 2nd order equation for R_S:

$$R_S = -\frac{1}{I}[\ln(\frac{I}{I_{Sat}}+1)\frac{kT}{q}-V]$$

R_S calculated from different data points is shown in Graph A4. As it can be seen, it becomes fairly constant at V_{BS}>1.4 V. At V_{BS}=1.5 V, we get R_S=10.3 Ω.



Graph A4. Extracted R_S from different data points.

4) Plot the ideal model, second order model, and the experimental data

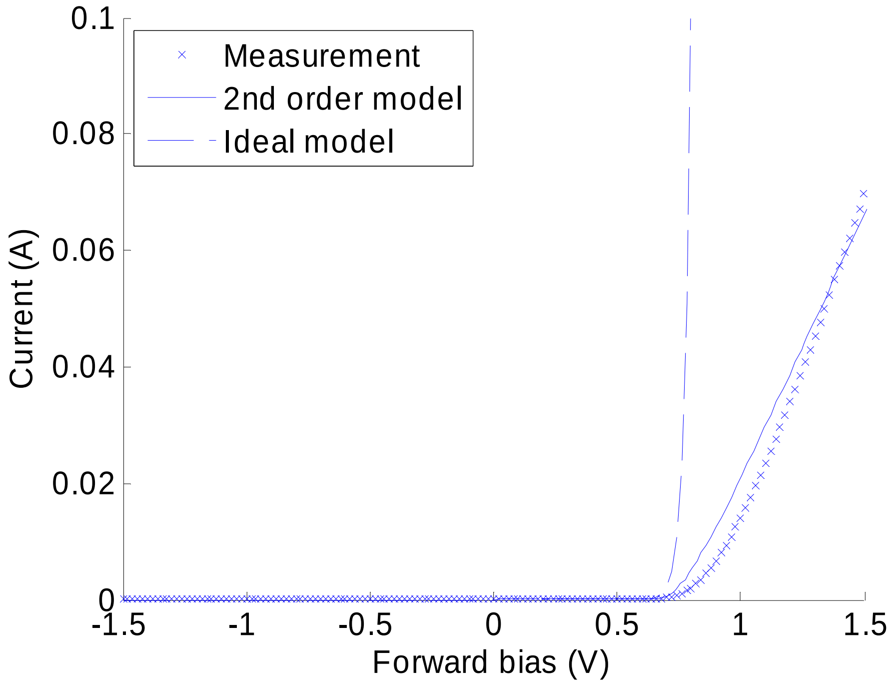


Figure 3. Linear I-V plot of theoretical models and experimental data

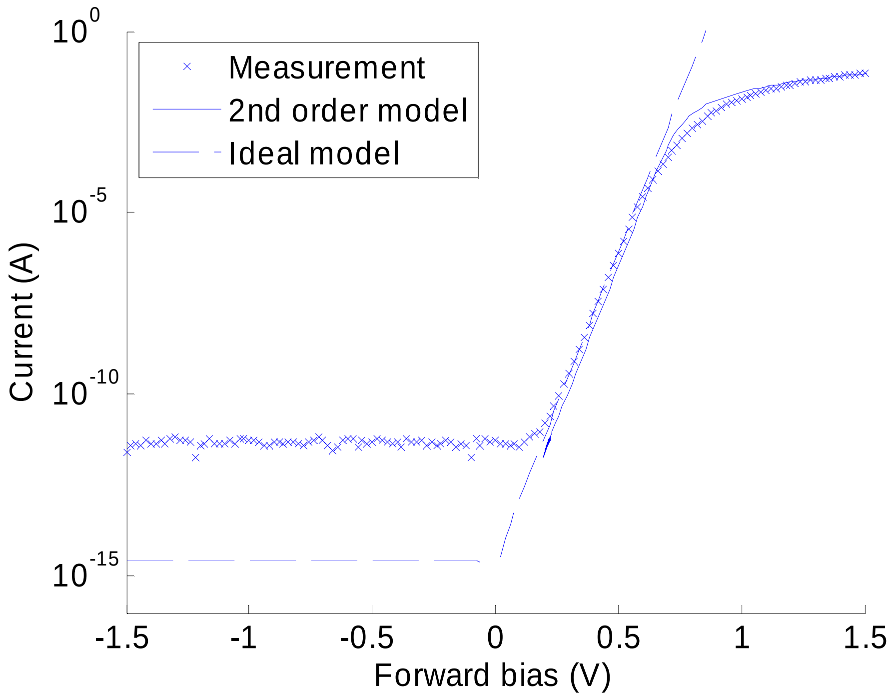


Figure 4. Semilog I-V plot of theoretical models and experimental data

Although the ideal model predicts the turn on voltage fairly well, the curve just skyrockets after turn-on due to no R_S. For those of you have gotten too big I_{Sat}, the turn-on voltage in the models should be much lower than the experimental value. Although the second order model fits quite well with the experimental data, there are still some discrepancies. First, as mentioned before, the slope in semilog plot is not ideal especially at low bias, and for this reason, we usually put "ideality factor" n in the diode equation:

$$I = I_{Sat}(\exp(\frac{qV}{nkT}) - 1)$$

One of this non-ideality is carrier recombination in space charge region. Also for high V_{BS}, n could approach 2 due to high-level injection. In fact, as can be seen in Figure 4, the experimental I-V curve starts to bend earlier than the 2nd order model after around V_{BS}=0.6 V.

Appendix: Matlab code

```
close all;
clear all;

k = 8.62e-5;    % eV/K
T = 296.472;    % K

data = csvread('Device_4.csv', 3, 0);
VBS = data(:, 1);
IB = data(:, 2);
ID = data(:, 3);
IG = data(:, 4);
IS = data(:, 5);
n = data(:, 6);     % dlogIs/dV
n2 = data(:, 7);    % dlogId/dV

% 1) Graph 1
plot(VBS, -IS, '.');
xlabel('V_{BS} (V)', 'fontsize', 14);
ylabel('-I_{S} (A)', 'fontsize', 14);
set(gca, 'fontsize', 14);

% 1) Graph 2
figure;
semilogy(VBS, abs(IS), '.');
xlabel('V_{BS} (V)', 'fontsize', 14);
ylabel('|-I_{S}| (A)', 'fontsize', 14);
set(gca, 'fontsize', 14);
ylim([1e-12 1]);

% 2)
for kk = 80:150
   p = polyfit(VBS(kk:kk+1), log10(abs(IS(kk:kk+1))), 1);

   n(kk) = 1/p(1);
   I_sat(kk) = 10^p(2);
end
I_sat0 = I_sat(95)  % around VBS=0.4 V

figure;   % Graph A1
semilogy (VBS(80:150), I_sat(80:150), '.');
xlabel('V_{BS} (V)', 'fontsize', 14);
ylabel('Extracted I_{Sat} (A)', 'fontsize', 14);
set(gca, 'fontsize', 14);
%I_sat = exp(log(abs(IS))-VBS/k/T);
%I_sat0 = I_sat(95)

%I_sat2 = -IS(95)/(exp(VBS(95)/k/T)-1)  % VBS=0.4 V
I_sat2 = -IS./(exp(VBS/k/T)-1);
I_sat20 = I_sat2(95)        % VBS=0.4 V
```

```
% Graph A2
figure;
semilogy (VBS(86:151), I_sat2(86:151), '.');
xlabel('V_{BS} (V)', 'fontsize', 14);
ylabel('Extracted I_{Sat} (A)', 'fontsize', 14);
set(gca, 'fontsize', 14);

% 3)

p = polyfit(VBS(146:151), -IS(146:151), 1); % around VBS=1.5 V

R = 1/p(1)
R2 = -(log(-IS/I_sat20 + 1)*k*T - VBS)./-IS;
R20 = R2(151)       % VBS=1.5 V

figure;
plot (VBS(120:151), R2(120:151), '.');
xlabel('V_{BS} (V)', 'fontsize', 14);
ylabel('Extracted R_S (\Omega)', 'fontsize', 14);
set(gca, 'fontsize', 14);

% 4)
V_2nd = k*T * (log(abs(IS)/I_sat20) + 1) + (-IS).*R20;
I_ideal = I_sat20 * (exp(VBS/k/T) - 1);

% Graph 3
figure;
hold on;
plot(VBS, -IS, 'x');
plot(V_2nd, -IS);
plot(VBS, I_ideal, '--');
ylim([0 0.1]);
xlim([-1.5 1.5]);
xlabel('Forward bias (V)', 'fontsize', 14);
ylabel('Current (A)', 'fontsize', 14);
legend('Measurement', '2nd order model', 'Ideal model', 'location', 'northwest');
set(gca, 'fontsize', 14);


% Graph 4
figure;
hold on;
plot(VBS, abs(IS), 'x');
plot(V_2nd, abs(IS));
plot(VBS, abs(I_ideal), '--');
ylim([1e-16 1]);
xlim([-1.5 1.5]);
xlabel('Forward bias (V)', 'fontsize', 14);
ylabel('Current (A)', 'fontsize', 14);
legend('Measurement', '2nd order model', 'Ideal model', 'location', 'northwest');
set(gca, 'fontsize', 14, 'yscale', 'log');
```