Tutorial Laboratory Experiment III: BJT Characterization

Appendix A. Report Template

Name: SAMPLE REPORT

Grading Rubric:

Data set completeness: _____

Error analysis thoroughness: _____

Procedure descriptions: _____

Accuracy: _____

Total Grade out of 20: _____

Grader comments:

Table 1. List of instruments and equipment used in experiment:

Instrument / Equipment	**Purpose**

1. Plot the I_C vs. V_{BE} characteristic of the SS9018 BJT. Use a fit of $ln(I_C)$ to V_{BE} to determine I_{sC}. The device case temperature was measured to be T = 293.45 K. $k_B = 8.625 \times 10^{-5}$ eV/K.

I_{sC}: ***0.19 fA***

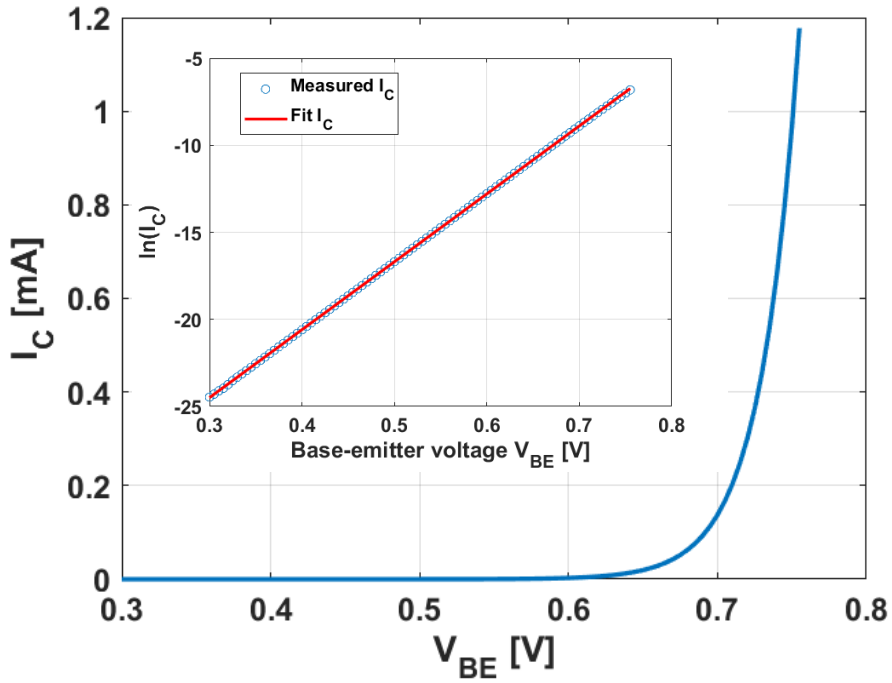

Figure 1. Plot of the BJT's I_C vs. V_{BE} characteristic. Inset shows the measured $ln(I_C)$ vs. V_{BE} and the linear fit.

The $ln(I_C)$ vs. V_{BE} measurement is pretty linear, with very small deviation. The analysis is pretty similar to the pn junction diode case:

$$ln(I_C) = ln(I_{sC}) + ln\left(e^{V_{BE}/\eta V_T}\right) = \frac{V_{BE}}{\eta V_T} + ln(I_{sC})$$

Thus, the slope of a linear fit is inversely proportional to ηV_T, and the y intercept is $ln(I_{sC})$. The device temperature is given as 293.45K, which corresponds to:

$$V_T = \frac{k_B T}{q} = 8.625 \times 10^{-5} \times 300 = 25.31\ mV$$

I used Matlab's *polyfit* command to fit the $ln(I_C)$-V_{BE} data.

***I_{sC}* = 1.902x10-16 A = 0.19 fA**

***n* = 1.013**

As the ideality factor is very close to 1, the measured external temperature and the BJT junction temperature must have been very close.

2. Plot the I_C vs. V_{CE} characteristics of the SS9018 BJT. What is the Early voltage, V_A? The Early voltage is found by doing a linear fit to I_C in the forward active region, and extrapolating to $I_C = 0$, i.e. finding the x-intercept. Give the average value for the 10 values calculated from the data set.

V_A: ***89.3 V***

Mean of 10 measurements is 89.3 V (minimum 88 V and maximum 90.2 V).

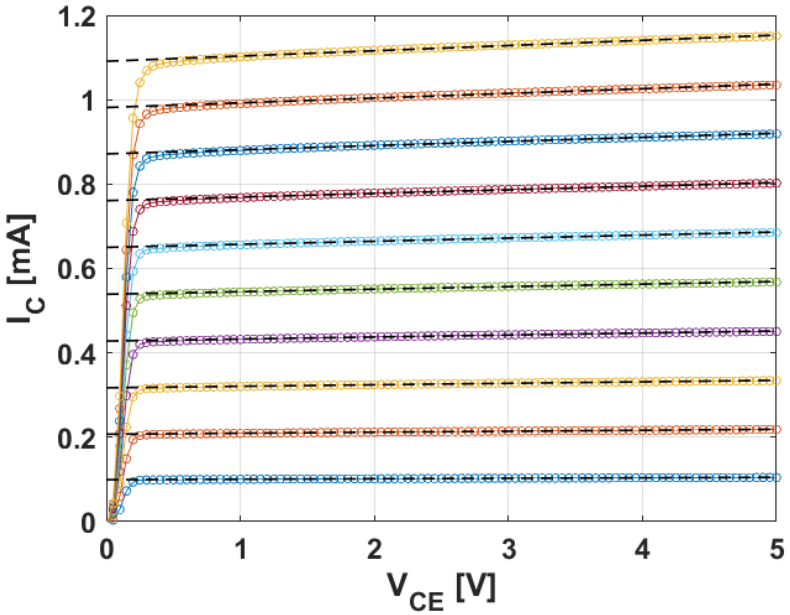

Figure 2. Plot of the BJT's I_C vs. V_{CE} characteristic.

See the attached *ss9108Vce.m* file for the analyses for questions 2 and 3. I used Matlab's *ployfit* command to find linear fits to the I_C vs. V_{CE} curves above V_{CE} = 0.7 V (chosen because V_{BC} = 0 V). The *x*-axis intercept of the fit is by definition the Early voltage. See the figure below for the Early voltages calculates for each of the 10 base current values from 1 μA to 10 μA. The calculated V_A values range from 88 V to 90.2 V. The average value is 89.3 V.

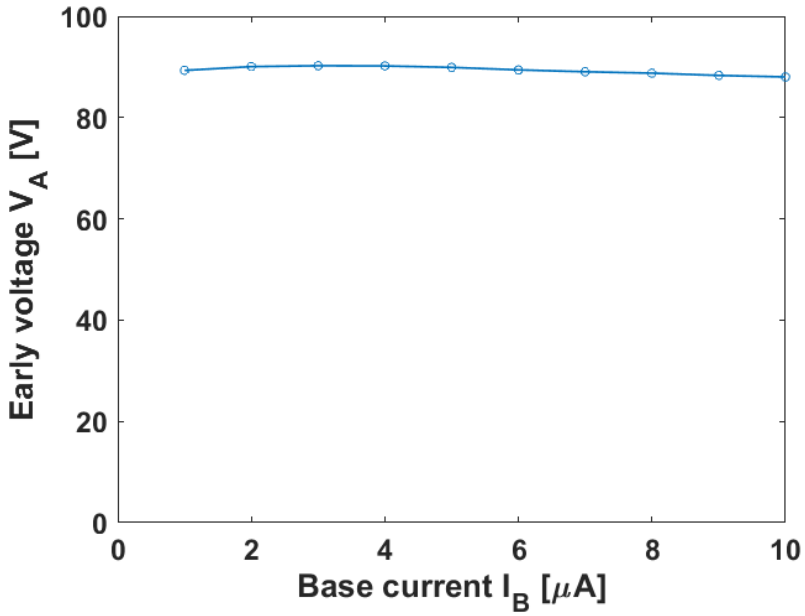

Figure 3. Plot of calculated Early voltage vs. applied base current.

3. Using the collector current at the forward active-saturation boundary, determine the common emitter current gain from the I_C vs. V_{CE} characteristics. Give the average value for the 10 values calculated from the data set.

h_{FE}: ***106.1***

Mean of 10 measurements is 106.1 (minimum 98.9 and maximum 108.5).

In order to determine h_{FE}, we need to know I_{C0}, the collector current without the Early effect. One possibility is to use the collector current at V_{CE} = 0.7 V. Another is to make an attempt to determine I_{C0} by comparing the measured and fit I_C vs. V_{CE} curves. I chose the latter approach in the attached analysis script, and (arbitrarily) chose 98% of the fit value as my threshold for determining IC0, scanning from V_{CE} = 0 V to 5 V.

The common emitter current gain definition is:

$$h_{FEnominal} = \beta_{nominal} = \frac{I_{C0}}{I_B}$$

Compare this with the h_{FE} value given in the SS9018's datasheet, which measure the common emitter current gain for a fixed V_{CE} = 5 V. This value thus includes the Early effect.

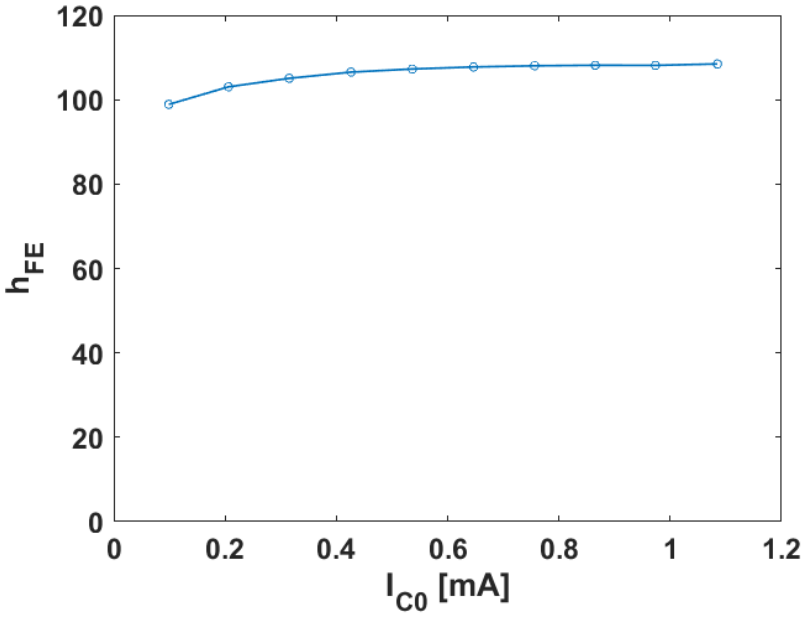

Figure 4. Plot of calculated h_{FE} vs. nominal collector current.

```
% SS9018 NPN BJT Analysis - IC vs. VBE
clear;
close all;
m = csvread('SS9018vbe.csv',1,0);
% VBE, IB, IC;
VBEx = m(:,1);
IBx = m(:,2);
ICx = m(:,3);

lnIc = log(ICx);
p = polyfit(VBEx,lnIc,1);
% p(1) is 1/nV_T
% p(2) is ln(Is)
% dimension is 1,2
kB = 8.625e-5; % V/K
T = 293.5; % K
VT = kB*T;
Isc = exp(p(2))
n = 1/(p(1)*VT)

lnIcFit = polyval(p,VBEx);
figure;
h = axes;
plot(VBEx,log(ICx),'o');
hold on
plot(VBEx,lnIcFit,'LineWidth',2,'Color','r');
legend('Measured I_C','Fit I_C');
xlabel('Base-emitter voltage V_{BE}
[V]','FontName','Arial','FontSize',16,'FontWeight','Bold');
ylabel('ln(I_C)','FontName','Arial','FontSize',16,'FontWeight','Bold')
;
set(h,'FontName','Arial','FontSize',14,'FontWeight','Bold');
xlim([0.3 0.8]);
grid on


Icfit = exp(lnIcFit);
figure;
h = axes;
plot(VBEx,1000*Icfit,'LineWidth',2)
xlabel('V_{BE}
[V]','FontName','Arial','FontSize',16,'FontWeight','Bold');
ylabel('I_C
[mA]','FontName','Arial','FontSize',16,'FontWeight','Bold')
set(h,'FontName','Arial','FontSize',14,'FontWeight','Bold');
grid on
xlim([0.3 0.8]);
set(h,'XTick',[0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8]);

beta = ICx./IBx;
figure; plot(beta)
```

```
% SS9018 NPN BJT Analysis -  IC vs. VCE
clear;
close all;
m = csvread('SS9018vce.csv',1,0);
VCE = m(:,1);
IC = m(:,2:11);
IB = 1e-6*(1:1:10);

number_of_measurements = length(IB);

pVa = zeros(number_of_measurements,2);
maxindVce = length(VCE);
indFitStart = 1;
% Vce,sat should be < 0.3V, can choose Vce>0.5V for determining V_A
% Sample report: chose VCE >= 0.7 V
while VCE(indFitStart) < 0.7
    indFitStart = indFitStart + 1;
end
for ind = 1:1:number_of_measurements
    pVa(ind,:) =
polyfit(VCE(indFitStart:maxindVce),IC(indFitStart:maxindVce,ind),1);
end
% Ic = Ic0(1+Vce/VA) = p(1)Vce + p(2)
% so p(2) = Ic0 with an error, as VCEsat wasn't subtracted from above
- not
% yet determined
% and p(1) = Ic0/VA = 1/ro
% hence VA = p(2)/p(1)
Va = pVa(:,2)./pVa(:,1);
VAavg = sum(Va)/number_of_measurements

Ifit = 0*IC;
for ind = 1:1:number_of_measurements
    Ifit(:,ind) = polyval(pVa(ind,:),VCE);
end

figure;
h = axes;
plot(VCE,1000*IC,'Marker','o','MarkerSize',4)
xlabel('V_{CE}
[V]','FontName','Arial','FontSize',16,'FontWeight','Bold');
ylabel('I_C
[mA]','FontName','Arial','FontSize',16,'FontWeight','Bold')
set(h,'FontName','Arial','FontSize',14,'FontWeight','Bold');
%ylim([0 1.2e-3])
ylim([0 1.2])
grid on

figure;
h = axes;
plot(VCE,1000*IC,'Marker','o','MarkerSize',4)
hold on
```

```
plot(VCE,1000*Ifit,'LineWidth',1,'Color','k','LineStyle','--')
xlabel('V_{CE}
[V]','FontName','Arial','FontSize',16,'FontWeight','Bold');
ylabel('I_C
[mA]','FontName','Arial','FontSize',16,'FontWeight','Bold')
set(h,'FontName','Arial','FontSize',14,'FontWeight','Bold');
%ylim([0 1.2e-3])
ylim([0 1.2])
grid on


% Plot of Early Voltage data
figure;
h = axes;
plot(1e6*IB(1:number_of_measurements),Va,'LineWidth',1,'Marker','o','M
arkerSize',4)
ylim([0 100])
xlabel('Base current I_B [\muA]','FontSize',16,'FontWeight','Bold');
ylabel('Early voltage V_A [V]','FontSize',16,'FontWeight','Bold');
set(h,'FontName','Arial','FontSize',14,'FontWeight','Bold');

% Calculate beta, need IC0
Vcesat = zeros(number_of_measurements,1);
hFE = Vcesat;
IC0 = hFE;
for ind = 1:1:number_of_measurements
    ind2 = 1;
    % Find Vce,sat and therefore Ic0 by comparing measured with fit
IC. In
    % saturation regtion Imeasured < I fit. Chose the point where the
error
    % is 2% or less as Ic0 (arbitrarily)
    while IC(ind2,ind) < 0.98*Ifit(ind2,ind)
        ind2 = ind2+1;
    end
    Vcesat(ind) = VCE(ind2);
    hFE(ind) = IC(ind2+1,ind)/IB(ind);
    IC0(ind) = IC(ind2+1,ind);
end

%{
figure;
h = axes;
plot(IB(1:number_of_measurements),Vcesat)
title('Vcesat vs. Ib');
%}
figure;
h = axes;
plot(1000*IC0,hFE,'LineWidth',1,'Marker','o','MarkerSize',4)
xlabel('I_{C0}
[mA]','FontName','Arial','FontSize',16,'FontWeight','Bold');
ylabel('h_{FE}','FontName','Arial','FontSize',16,'FontWeight','Bold')
```

```
set(h,'FontName','Arial','FontSize',14,'FontWeight','Bold');
ylim([0 120])
%title('hFE vs. IchFE');
```