ECE 304 Spring '05 Lab 1

Measuring transistor β_{DC}, Early voltage V_{AF}, and scale current I_S

Objective

When we design a circuit using bipolar transistors, we use idealized equations and an idealized transistor. PSPICE describes this ideal NPN transistor using the dot-model statement in Figure 1.

```
.model Qidealn NPN (Bf={B_F} Vaf={V_AF} Is={I_S})
```

FIGURE 1

PSPICE dot-model statement for the ideal bipolar transistor: β = Bf, Early voltage Vaf, and scale current Is; as shown by curly braces {}, these values are set using variables B_F, V_AF and I_S from a PARAMETER box

However, real circuits use real transistors. An example is the Q2N2222, approximated in PSPICE using the dot-model statement of Figure 2.

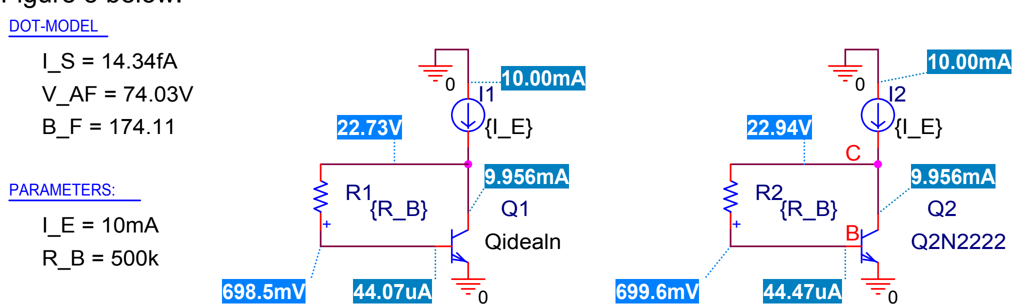
```
.model Q2N2222  NPN(Is=14.34f Xti=3 Eg=1.11 Vaf=74.03 Bf=255.9 Ne=1.307
+        Ise=14.34f Ikf=.2847 Xtb=1.5 Br=6.092 Nc=2 Isc=0 Ikr=0 Rc=1
+        Cjc=7.306p Mjc=.3416 Vjc=.75 Fc=.5 Cje=22.01p Mje=.377 Vje=.75
+        Tr=46.91n Tf=411.1p Itf=.6 Vtf=1.7 Xtf=3 Rb=10)
```

FIGURE 2

Dot-model statement of the Q2N2222 found by highlighting the device, right clicking, and selecting EDIT PSPICE MODEL

If we design using the ideal transistor, and build using, for example, the Q2N2222, can we expect the built circuit to behave anything like the designed circuit? To have hope of success, our ideal transistor should have parameter values selected to match the Q2N2222 as closely as possible. In this lab we will determine the values of Bf, Vaf and Is that make an ideal transistor approximate the Q2N2222.

We compare the PSPICE results for a Q2N2222 with an ideal transistor using the setup of Figure 3 below.



.model Qidealn NPN (Bf={B_F} Vaf={V_AF} Is={I_S})

FIGURE 3

Circuits for comparison of ideal transistor with shown dot-model statement with the Q2N2222; parameters I_S and V_{AF} are taken from the Q2N2222 dot-model statement, and $\beta_{DC}(V_{CB}=0V)$ is taken from β_{DC} for the Q2N2222 in the PSPICE output file for this value of I_E

The results of the comparison are shown in Figure 4. It is clear that the two curves agree closely as to value and slope. That is, the ideal transistor with the appropriate values of parameters B_F and V_{AF} closely approximates the V_{CB} dependence of the DC β of the Q2N2222.[1]

[1] However, in the ideal transistor, the DC beta and AC beta values are the same, and $\beta_{DC}(V_{CB}=0V)$ = Bf. Also β_{DC} is independent of current. In the Q2N2222, these simplifications are not so.

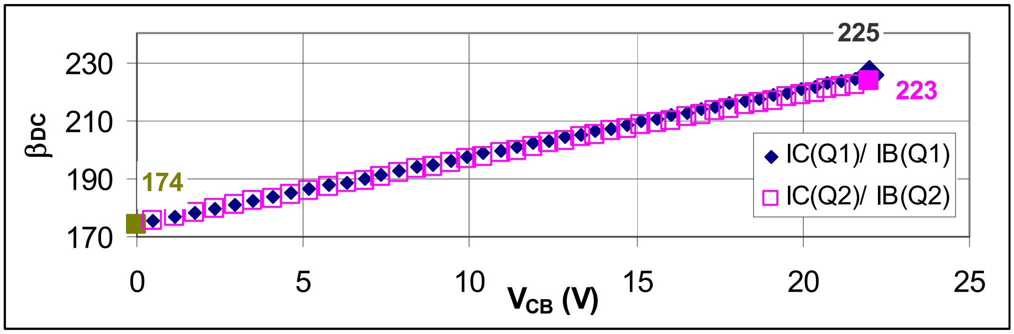


FIGURE 4

Comparison of β_{DC} vs. V_{CB} for the ideal and the Q2N2222 transistors with I_E = 10 mA

Because β_{DC} depends on current in the Q2N2222 (but does not depend on current in the ideal transistor) the value of $\beta_{DC}(V_{CB} = 0V)$ used for Bf in the ideal transistor has to be set to agree with the PSPICE output file BetaDC for the Q2N2222 at V_{CB} = 0V and the appropriate current. (For example, we force fitted the point at V_{CB} = 0V in Figure 4). Agreement is not perfect in Figure 4 because the dot-model statement of the Q2N2222 is much more complicated than that for the ideal transistor, as shown above in Figure 2.

To summarize, in this lab we:

1. Learn how to measure values for Bf, Vaf and Is,
2. Learn a bit about the current mirror as an approximation to an ideal current source,
3. Learn a bit about the variability of device parameters,
4. Learn that circuit design is necessarily approximate because our models aren't perfect, and
5. Learn how to use some features of EXCEL and PSPICE

Basic idea for finding parameter values

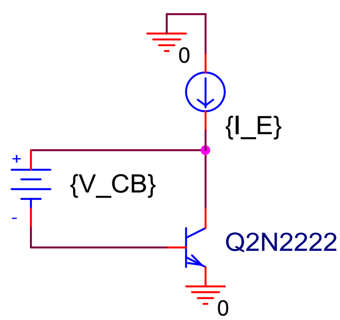


FIGURE 5

Idealized circuit for measuring DC beta and Early voltage

Figure 5 shows the basic idea behind the measurement of β_{DC} and V_{AF}. A known emitter current I_E is driven into the transistor and a known collector-to-base voltage V_{CB} is applied. The value of β_{DC} is then

EQ. 1

$$\beta_{DC} = \frac{I_E}{I_B} - 1.$$

The value of β_{DC} is plotted against V_{CB} and fitted to the formula of EQ. 2 below:

EQ. 2

$$\beta_{DC} = \beta_{DC}(V_{CB} = 0)\left(1 + \frac{V_{CB}}{V_{AF}}\right).$$

The slope and intercept of the plot determine β_{DC} at V_{CB} = 0V and the value of the Early voltage V_{AF}. To implement EQ. 1 we need the value of the base current I_B. Therefore, we modify the circuit as shown in Figure 6, and determine the base current from the known value of resistor R_B and the measured collector and base voltages as given in EQ. 3 below.

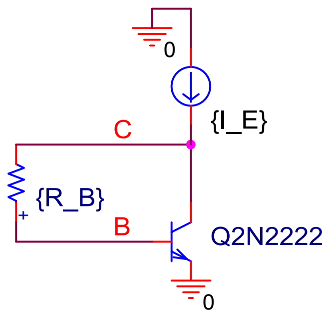


FIGURE 6

Circuit of Figure 5 modified to allow measurement of base current

EQ. 3

$$I_B = \frac{V_C - V_B}{R_B} .$$

Implementation of current source I_E

To apply a known current I_E as shown in Figure 3 we build an approximate current source using the circuit of Figure 7.

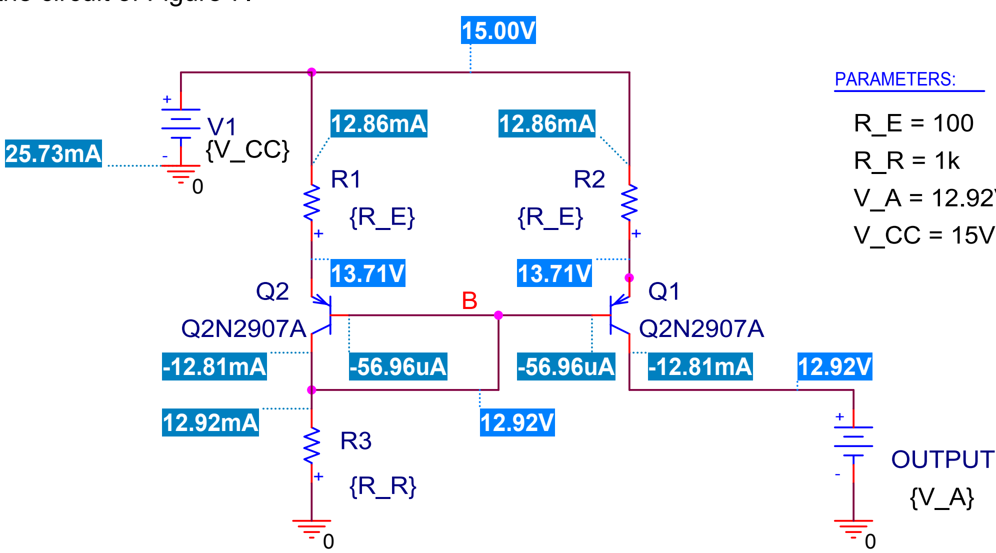


FIGURE 7

Circuit for a current mirror approximating an ideal current source

The applied bias V_A in Figure 7 has been chosen to equal the base voltage of the two transistors, making the bias conditions identical for both transistors. Because both transistors have the same dot-model statements (we say they are *matched*), they draw the same collector currents. We can plot the input current vs. V_A for this circuit to compare it with an ideal current source.

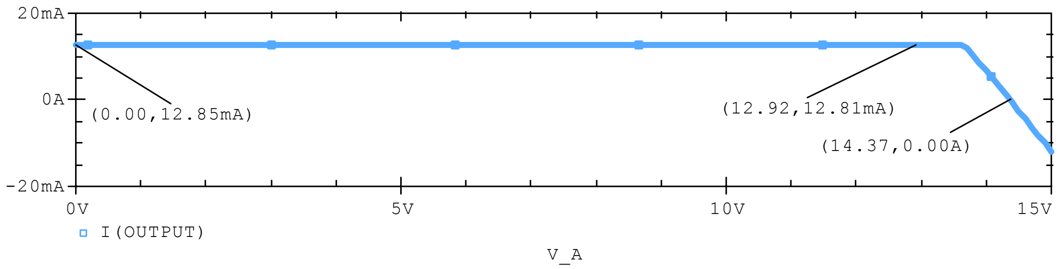


FIGURE 8

I-V behavior of the current mirror of Figure 7

Examining the *I-V* behavior of Figure 7, the current is nearly constant for V_A below about V_B = 12.92V. As V_A goes above this value, the current drops rapidly, because the transistor Q1 saturates, leaving the active mode. Thus, the circuit of Figure 7 is a pretty good approximation to an ideal current source delivering 12.81mA - 12.85 mA for voltages below about $V_A = V_B$ = 12.92V. The current level delivered by the mirror is adjusted using the resistor R_R, as is suggested because the current in R_R is $I_R = V_B/R_R$ and is nearly the same as the output current.

Calibration of the mirror

We cannot assume that both transistors in the mirror will be matched in the lab circuit, so we do a calibration run to find what current we actually get for a given bias condition. For example, suppose the two transistors have different scale currents I_S as shown in the dot-model statements of Figure 9 below.

```
.model Q2N2907A_IS1 PNP(Is={I_S1} Xti=3 Eg=1.11 Vaf=115.7 Bf=231.7 Ne=1.829
+         Ise=54.81f Ikf=1.079 Xtb=1.5 Br=3.563 Nc=2 Isc=0 Ikr=0 Rc=.715
+         Cjc=14.76p Mjc=.5383 Vjc=.75 Fc=.5 Cje=19.82p Mje=.3357 Vje=.75
+         Tr=111.3n Tf=603.7p Itf=.65 Vtf=5 Xtf=1.7 Rb=10)

.model Q2N2907A_IS2 PNP(Is={I_S2} Xti=3 Eg=1.11 Vaf=115.7 Bf=231.7 Ne=1.829
+                 Ise=54.81f Ikf=1.079 Xtb=1.5 Br=3.563 Nc=2 Isc=0 Ikr=0 Rc=.715
+                 Cjc=14.76p Mjc=.5383 Vjc=.75 Fc=.5 Cje=19.82p Mje=.3357 Vje=.75
+                 Tr=111.3n Tf=603.7p Itf=.65 Vtf=5 Xtf=1.7 Rb=10)
```

FIGURE 9

Dot-model statements for the Q2N2907A with the scale currents made a parameter I_{S1} or I_{S2}

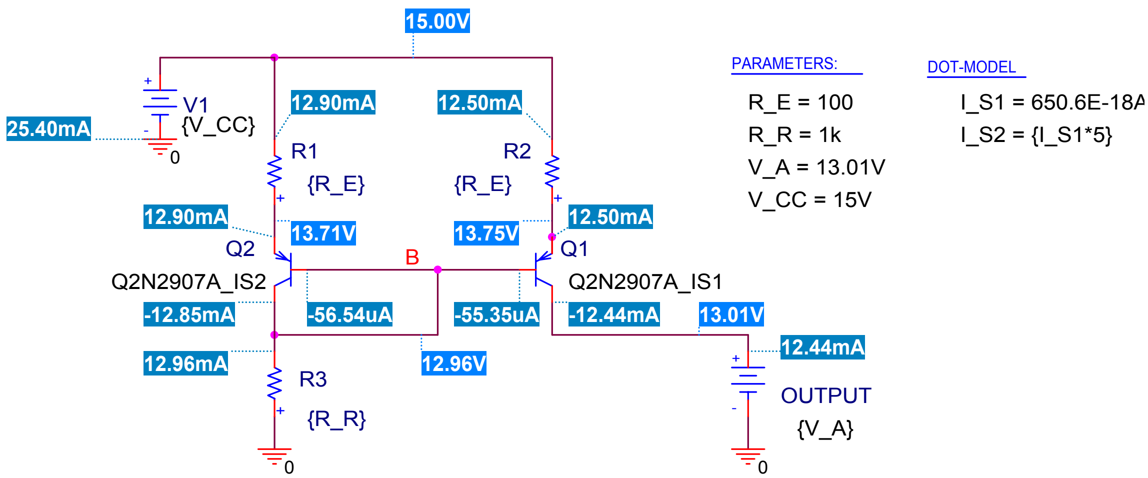


FIGURE 10

Current mirror with mismatched transistors: $I_{S2} = 5I_{S1}$

Figure 10 shows the current mirror with mismatched transistors: the currents in the two transistors are not the same, and the output current differs quite a bit from the current in R_R. We run an *I-V* curve like Figure 8 so we can determine exactly what current is provided to our test Q2N2222. An example is shown in Figure 11. Using this plot we can find exactly what current is delivered if we know the voltage V_A.

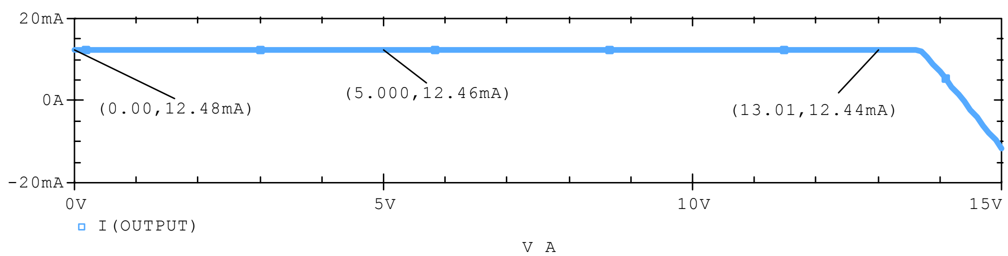


FIGURE 11

Calibration run for the mirror in Figure 10

Fitting procedure

We first build a mirror like Figure 10, and make an *I-V* calibration run. Then we hook up the Q2N2222 as shown in Figure 3, using the mirror in place of the current source to provide I_E. Then we measure V_C, V_B, R_B and determine the value of I_E for various V_{CB} values, and put this data into an EXCEL spreadsheet. We make a best fit to this plot using the TRENDLINE feature of EXCEL, as explained next.

DATA ENTRY

The data is entered on the spreadsheet as shown in Figure 12 below. Measured data is outlined with boldface column headings. R_B is unnecessarily repeated.

O9 = =I_E/I_B-1

B_DC Determination

Row	R_B	V_C	R_B	V_B	V_CB	I_B	V_C	I_E	B_dc
4							Calibration Curve		
6	1.00E+04	1.413277	1.00E+04	0.712457	0.700819	7.01E-05	1.413277	0.012851	182.3738
7	2.00E+04	2.101271	2.00E+04	0.712201	1.38907	6.95E-05	2.101271	0.012851	184.0294
8	3.00E+04	2.777362	3.00E+04	0.711952	2.06541	6.88E-05	2.777362	0.012851	185.6558
9	4.00E+04	3.442151	4.00E+04	0.711709	2.730442	6.83E-05	3.442151	0.01285	187.2544
10	5.00E+04	4.096191	5.00E+04	0.711472	3.384718	6.77E-05	4.096191	0.01285	188.8266
11	6.00E+04	4.739991	6.00E+04	0.711241	4.02875	6.71E-05	4.739991	0.01285	190.3737
12	70000	5.374022	70000	0.711016	4.663006	6.66E-05	5.374022	0.01285	191.8968
13	80000	5.998716	80000	0.710795	5.287921	6.61E-05	5.998716	0.012849	193.3969
14	90000	6.61448	90000	0.710579	5.9039	6.56E-05	6.61448	0.012849	194.8752
15	100000	7.221685	100000	0.710368	6.511317	6.51E-05	7.221685	0.012849	196.3325

FIGURE 12

Data entered on spreadsheet and calculation made of I_B, I_E, V_{CB} and β_{DC}

FITTING THE DATA

A plot is made of β_{DC} vs. V_{CB} as shown in Figure 13.

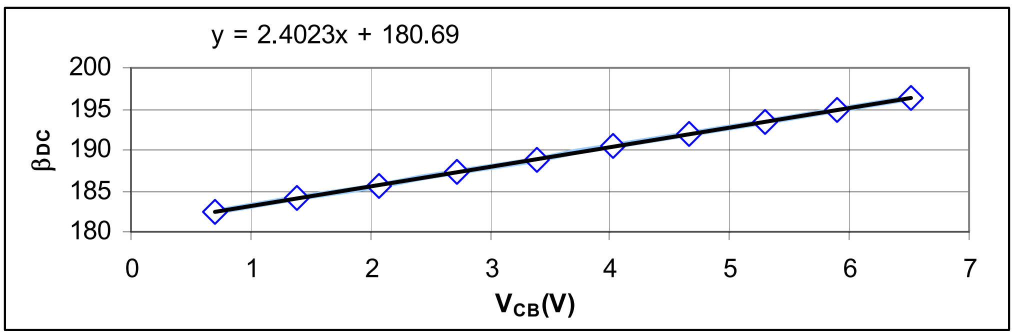


FIGURE 13

Plot of calculated results from spreadsheet with TRENDLINE formula at top

A TRENDLINE is found by right clicking on the curve and selecting ADD TRENDLINE, as shown in Figure 14.

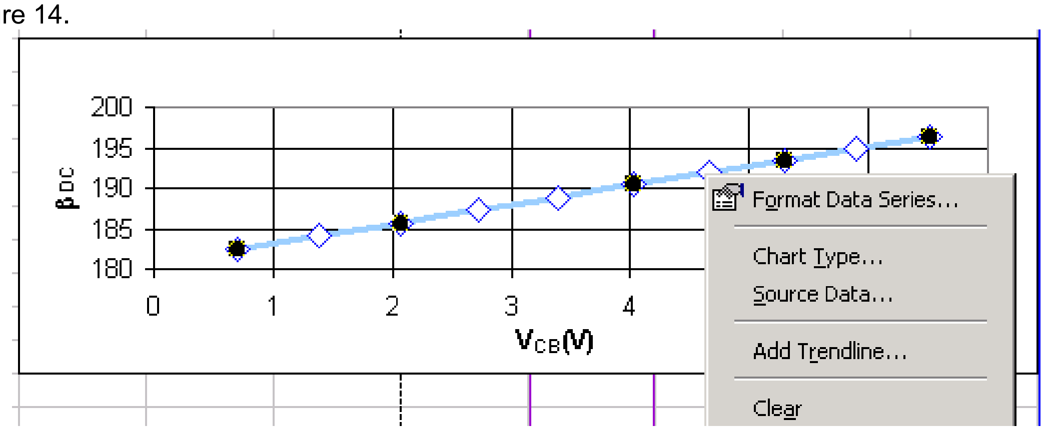


FIGURE 14

Adding a TRENDLINE

We also select the LINEAR type, as shown in Figure 15, and choosing the OPTIONS tab we elect to DISPLAY EQUATION on the chart, as shown in Figure 16.

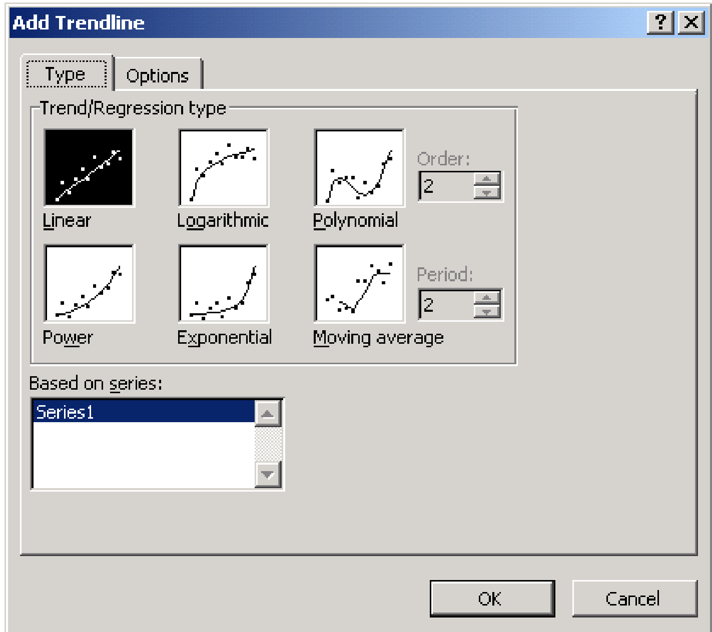


FIGURE 15

Choosing the LINEAR trend line

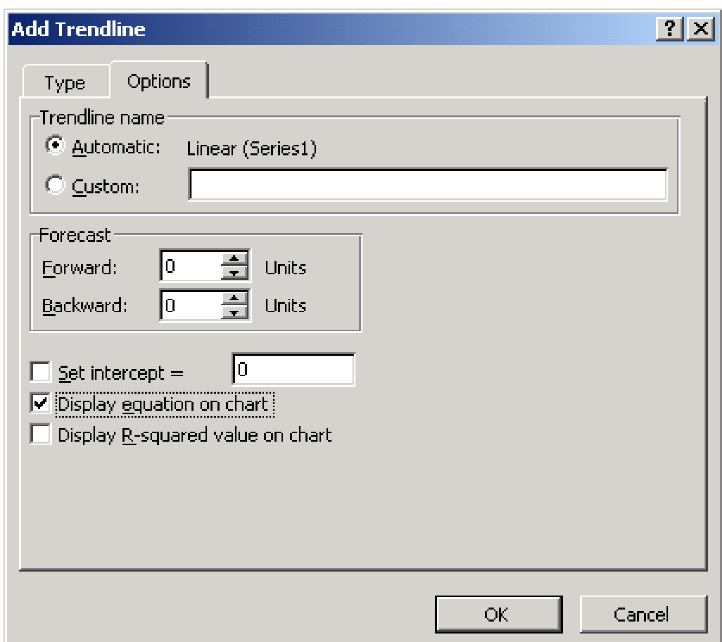


FIGURE 16

Choosing to DISPLAY EQUATION on chart

With the slope and intercept from the trend line equation in the form $y = mx + b$ we find the value of $\beta_{DC}(V_{CB} = 0V)$ and V_{AF} using the equations

EQ. 4

$$\beta_{DC}(V_{CB} = 0V) = b \text{ and } V_{AF} = b/m.$$

Figure 17 shows the results.

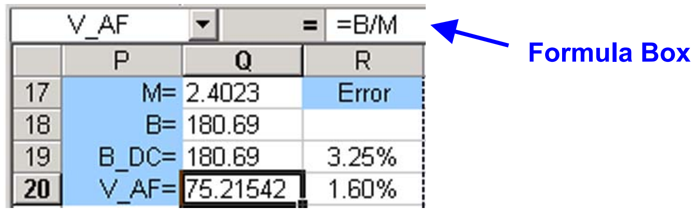


FIGURE 17

Calculation of β_{DC} and V_{AF}; the formula box shows EQ. 4

To obtain a formula in the formula box in Figure 17, we must name the variables M and B by highlighting P17:Q20 and using the menu INSERT/NAME/CREATE. See Figure 18 below.

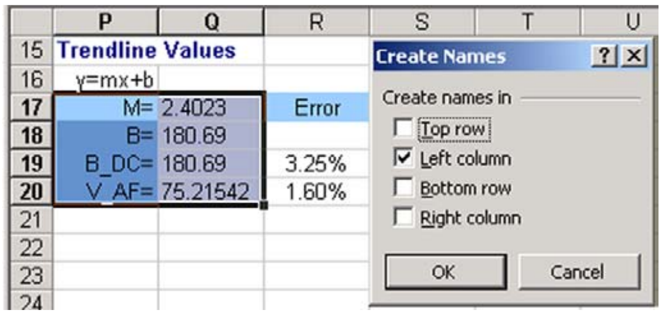


FIGURE 18

Naming variables to obtain formulas in the FORMULA BOX

Another example of this procedure is shown in the Appendix.

The values in Figure 17 can be compared to the PSPICE output file $\beta_{DC}(V_{CB}=0V) = 175$ and $V_{AF} = 74.03V$. Accuracy is as shown in Figure 17.

This procedure should be followed for three current levels near the values 100 μA, 1 mA and 10 mA, for two different Q2N2222 transistors. The results should be compared with each other and with the manufacturer's data sheet and the differences summarized.

Precautions

The temperature will change as the transistor heats up – allow the transistor to cool between data points.

Finding the scale current

The base voltage of the Q2N2222 is given by

EQ. 5

$$V_{BE} = V_{TH}\ell n\left(\frac{I_C(V_{CB}=0V)}{I_S}\right) = V_{TH}\ell n\left(\frac{I_E(V_{CB}=0V)}{I_S\left(1+\frac{1}{\beta(V_{CB}=0V, I_E)}\right)}\right),$$

where V_{TH} is the thermal voltage, 25.864mV at 27°C. Your transistor may be at a different temperature: for one thing, it heats when drawing current. In EQ. 5, I_S is the scale current. If there is no Early effect, the current does not depend on collector-base bias V_{CB}, but in our ideal transistor there is an Early effect and the current is given by EQ. 6 below. (The Q2N2222 uses a more complex equation, approximated by EQ. 6.[2])

[2] In the Q2N2222 the current is given by PSPICE as found on pp. 208-209 of the online manual PSpceRef.pdf accessed from your START menu under START/PROGRAMS/ORCAD FAMILY RELEASE 9.2 LITE EDITION/ON LINE MANUALS/PSPICE REFERENCE GUIDE/BIPOLAR TRANSISTOR

EQ. 6

$$I_C = I_C(V_{CB} = 0V)\left(1 + \frac{V_{CB}}{V_{AF}}\right).$$

Because I_C depends on V_{CB}, using a current corresponding to $V_{CB} > 0$ in EQ. 5 will lead to an incorrect V_{BE}. Also, note that in EQ. 5, the value of β varies with current level I_E; that is, $\beta = \beta(V_{CB}, I_E)$.

According to EQ. 5, a plot of base voltage of the Q2N2222 vs. $\ell n(I_E)$ will have a slope of V_{TH}, and by doing a best fit we can find the best value of I_S. If $\beta >> 1$, the error in neglecting variation of β with I_E when plotting will not have much effect upon the value obtained for I_S. Doing the fit with the largest and smallest β-value is a check on this particular error.

ENTERING THE DATA

An example worksheet for finding V_{TH} and I_S is shown in Figure 19 below. The measured data is for the case $V_{CB} = 0$ V, or $R_B = 0\ \Omega$.

	B	C	D	E	F	G	H	I	J	K	L	M
6							Calculated	Calculated	Calculated	Percent		Percent
7	**Fitted Values**			R_R	I_E	V_B	V_TH_Q3	I_S_Q3	V_BE	Error	Trendline	Error
8	V_TH	0.025868		100	0.0697	0.766	0.026100	9.7221E-15	0.7587046	0.89	0.762844	0.35
9	I_S	1.2678E-14		215	0.0441	0.750	0.025978	1.1193E-14	0.7468559	0.42	0.750023	0.00
10	B_DC	162.6		464	0.0245	0.732	0.025882	1.2458E-14	0.7316679	0.05	0.733589	0.21
11	B_DC(min)	148.9		1000	0.0124	0.713	0.025820	1.3320E-14	0.7140578	0.19	0.714534	0.25
12	B_DC(max)	176.3		2154	0.0059	0.692	0.025784	1.3806E-14	0.6947137	0.33	0.693602	0.17
13				4642	0.0026	0.671	0.025763	1.4061E-14	0.6738291	0.41	0.671004	0.01
14				10000	0.0011	0.648	0.025751	1.4186E-14	0.6508884	0.46	0.646181	0.27
15						Averages	0.025868	1.2678E-14	Total Error	2.74		1.26

FIGURE 19

Worksheet for finding V_{TH} and I_S; the TRENDLINE predictions also are shown

FITTING THE DATA

Measured data is in columns R_R, I_E and V_B. V_{BE} in Column J is calculated using EQ. 5 and the values of V_{TH}, I_S and β_{DC} in cells C8-C10. Then V_{TH}(Q3) is found by making the calculated V_{BE} of Column J agree with the measured value of V_{BE} in Column G. To find this value of V_{TH}(Q3), EXCEL tool GOAL SEEK is used. For example, we set the cursor in cell J8 and use the menu TOOLS/GOAL SEEK to obtain the GOAL SEEK menu in Figure 20. The SET CELL is V_{BE} and the VALUE is the measured V_B. The CHANGING CELL is the thermal voltage V_{TH}. Hitting OK, V_{TH} is changed to the value that makes $V_{BE} = V_B$. We copy this value and paste it into the column V_{TH}(Q3). This procedure is followed for all the entries. At the bottom of the V_{TH}(Q3) column, the average value of V_{TH}(Q3) is found using EXCEL function AVERAGE(). Then this value is copied into V_{TH}, cell C8.

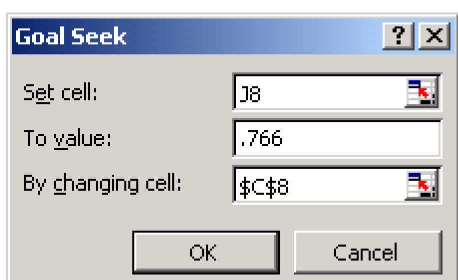


FIGURE 20

GOAL SEEK menu for finding the value of V_{TH} (cell C8) that makes V_{BE} (cell J8) equal V_B (value .766 V for Row 8)

After the average V_{TH} is found, the values of I_S(Q3) are found the same way, and the average value of I_S is pasted into cell C9. Because V_{BE} depends logarithmically on I_S, even a large change in I_S hardly affects the fit. Therefore, the value of I_S found by fitting is not very accurate.

ALTERNATIVE METHOD USING TRENDLINE

As a simpler alternative method, we might think to use the TRENDLINE feature of EXCEL as shown in Figure 21. Once the slope and intercept are found, they can be converted to values of V_{TH} and I_S, as shown in Figure 22.

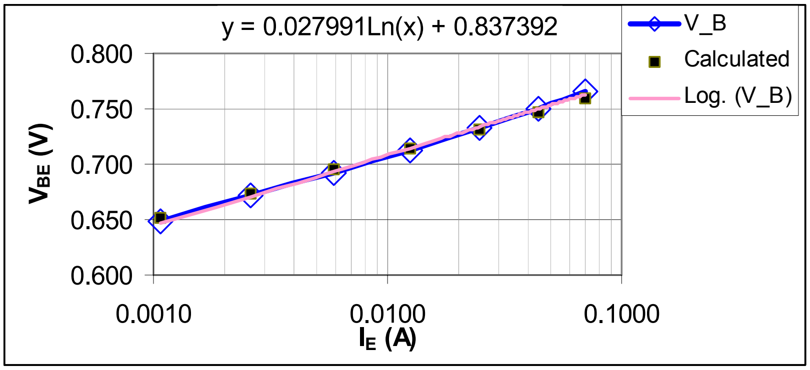


FIGURE 21

Using the TRENDLINE feature of EXCEL to find V_{TH} and I_S.

C22 = =EXP(-B/M)/(1+1/B_DC)

	B	C	D
17	**Trendline values**		
18	y=mx+b		
19	M	0.027991	
20	B	0.837392	
21	V_TH	0.027991	
22	I_S	1.01106E-13	

FIGURE 22

Converting the slope and intercept to V_{TH} and I_S.

The TRENDLINE approach gives a lower error of fitting (see Figure 19) than the more tedious approach using GOAL SEEK, but it does not give values as close to the true values. Therefore, the GOAL SEEK method, which fits V_{TH} first and I_S second, is preferred.

Prelab requirements

Decide what resistor values you will use in the lab. They should be standard values, but you will have to measure them to get accurate values.

Construct your spreadsheet using the standard resistor values you selected. Use one worksheet for I_S and V_{TH} determination, and a second worksheet for β_{DC} and V_{AF} determination. Both worksheets are in the *same* spreadsheet.

Make PSPICE simulations of the procedures you will follow to measure the transistor parameters and generate the plots you are going to use.

Test the spreadsheet using "imitation" data generated by PSPICE to see how close your fitting procedure comes to the values of the transistor parameters actually used in generating your "imitation" data.

Tabulate your actual values alongside the extracted values found using the fitting procedure.

In the lab

Here's a brief summary of the things to be done in the lab that are discussed in this document.

1. Do parameter measurements for two Q2N2222 transistors at three current levels, levels near 100μA, 1mA and 10mA. Put your data on worksheets like Figure 12 and Figure 19, and make graphs like Figure 13 and Figure 21 showing both your data and your fits.
2. Plot your β_{DC} vs. I_E for both devices and from PSPICE
3. Compare the results for all parameters with manufacturer's data sheets
4. Summarize the differences and discuss whether they are within the range of values suggested by the manufacturer

The temperature will change as the transistor heats up – allow the transistor to cool between data points. A heat sink for discrete Q2N2222's is available.

Appendix

Pasting PSPICE data into EXCEL

The PSPICE data from a PROBE plot are copied to the spreadsheet from PROBE by highlighting the curve label in the caption of the PROBE plot. Then use the PROBE toolbar EDIT/COPY to copy the curve. Next the cursor is placed on the worksheet and the EXCEL menu PASTE is selected. Remove the unnecessary spaces in the column headings.

Using Visual Basic for Applications

Instead of repeating the sequence of operations to use GOAL SEEK for each row of the worksheet, you can use a MACRO based on VBA. For example, to set V_{TH} using the procedure outlined above, the macro in Figure 23 can be used.

```
Sub Set_VTH()
' Set_VTH Macro
' Macro recorded 1/5/2005 by John Brews
'
' Keyboard Shortcut: Ctrl+t
'
  Dim J As Integer

  For J = 1 To 7
    Range("V_BE").Cells(J).GoalSeek Goal:=Range("V_B").Cells(J).Value, _
      ChangingCell:=Range("V_TH")
    Range("V_TH").Select
    Selection.Copy
    Range("V_TH_Q3").Cells(J).Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
      False, Transpose:=False
    Range("V_BE").Cells(J + 1).Select
  Next J

  Range("H15").Select
  Selection.Copy
  Range("V_TH").Select
  Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False

End Sub
```

FIGURE 23

Macro to scan down the rows of the table in Figure 19 to adjust V_{TH} so that $V_{BE} = V_B$; the underscore _ at the end of lines is a line continuation symbol

For the macro to work, NAMED ranges have to be set up. For example, with the rows and columns highlighted as shown in Figure 24, the menu INSERT/NAME/CREATE is selected to obtain the CREATE NAMES menu in Figure 24. Click OK.

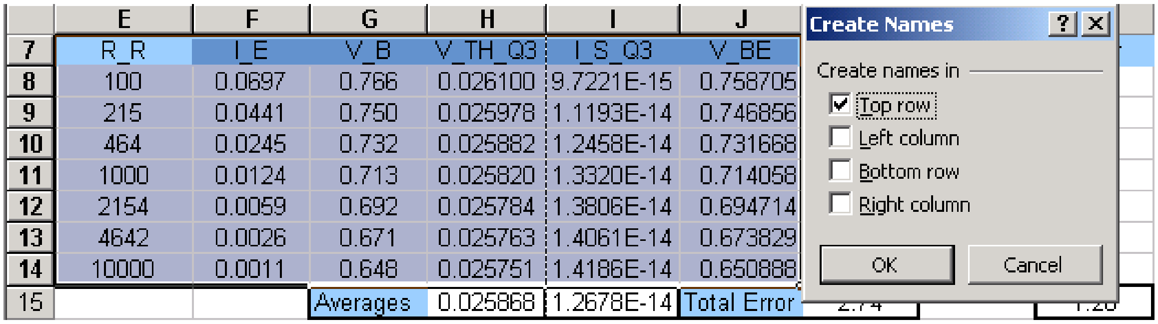


FIGURE 24

With the columns and their names highlighted, INSERT/NAME/CREATE names the columns: for example, column E8:E14 is named R_R

In the macro of Figure 23, the language Range("V_BE")• Cells(J) then refers to the J-th cell of column variable V_{BE}. The macro is easily invoked using the keyboard shortcut Ctrl+t. To set up the shortcut, use the menu TOOLS/MACRO/MACROS/OPTIONS to obtain the menus of Figure 25.

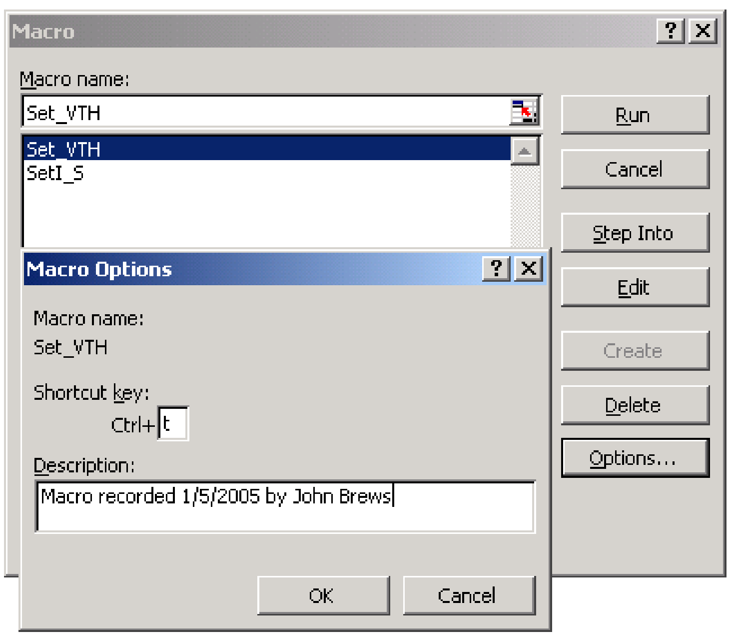


FIGURE 25

Setting up a keyboard shortcut Ctrl+t to run the macro

The macro is first recorded using the feature TOOLS/MACRO/RECORD NEW MACRO. The recording determines much of the language in the final macro. Then knowledge of VBA, which is a lot like BASIC, is used to introduce the names of ranges and the FOR-NEXT LOOP. It is not suggested that you learn how to use VBA. This example is intended to make you aware that this feature exists, and that it can be useful.