Experiment-1

Bipolar Junction Transistor Characterization

Introduction

The objectives of this experiment are to observe the operating characteristics of bipolar junction transistors (BJTs). Methods for extracting device parameters for circuit design and simulation purposes are also presented.

Precautions

Bipolar junction transistors do not employ a fragile, thin gate oxide like MOSFETs do, and they are thus much more robust against electrostatic discharge (ESD) damage. Since all three leads of the BJT are interconnected by internal pn-junctions, small charges can bleed off through the leakage currents of these junctions, and static charges are soon dissipated internally. For these reasons, BJTs can usually be handled freely, and are rarely damaged by ESD. This makes them very pleasant to work with.

Procedure 1 BJT base lead and sex identification

Set-Up

Locate a type 2N3904 BJT from the parts kit. This should be a three lead device in a small plastic TO-92 package. Turn on a bench DMM and configure it to measure (two wire) resistance. Plug a black squeeze-hook test lead into the negative (−) banana jack of the meter and a red squeeze-hook test lead into the positive (+) banana jack of the meter. The objective of this procedure will be to determine which lead of the BJT is the base, and whether the BJT is an npn or pnp device using only the ohmmeter function of the DMM. Also locate a 1N4148 diode that will be used for reference.

Measurement-1

Measure the resistance of the 1N4148 diode with the DMM in both the forward and reverse bias directions. Note that the red lead from the (+) input of the DMM is the one which will have the more positive voltage for this type of test. Record these readings in your lab notebook, and note these readings as being “typical” for a forward and reverse biased pn-junction. You can then refer to these readings to determine the polarity of pn-junctions that exist within the BJT.

Recall that a BJT has pn-junctions between the base and both the emitter and collector terminals. Use the DMM in its ohmmeter setting to test pairs of leads on the BJT and therefore identify the base lead on the device. From the polarity which causes the base terminal to conduct, deduce whether the BJT is an npn or pnp device.

With the base lead identified, it stands to reason that the remaining leads must be the emitter and collector. A few measurements will next be made to examine if these two remaining leads can be distinguished by DMM measurements. First, use the DMM, again in its ohmmeter setting, to measure the resistance between emitter and collector with the base terminal open circuited. Try this with both polarities of the DMM leads. Next, use the DMM to measure the resistance between emitter and collector with the base now connected to the (−) lead of the DMM in addition to the other transistor lead that is already there. Again, try this in both polarity directions. Finally, use the DMM to measure the resistance between the emitter and collector with the base connected to the (+) lead of the DMM in addition to the other transistor lead that is already there. Again, try both polarity directions. You should end up with a total of six resistance measurements: 3 different base conditions (open, voltage low, voltage high) times 2 emitter/collector test voltage polarities.

Question-1

From your measurements above, summarize your findings about the given 2N3904 BJT in your notebook. Draw a picture of the device package and label the leads appropriately as E, B, C. (It is conventional to do this with a view of the device looking down on it with the leads pointing away from you, as if it were soldered into a printed circuit board. This is usually termed a component-side view, in reference to the component side of the circuit board.) Is it possible to distinguish the emitter lead from the collector lead using only an ohmmeter? Explain why or why not. Look up the data sheet for the the 2N3904 and compare your deductions with the manufacturer's specifications. The base terminal is normally thought of as the “control” terminal for the BJT, as it controls current flow from emitter to collector. With the base lead open circuited, is the BJT a “normally-on” or a “normally-off” device? Explain your answer in reference to the internal pn-junctions of the BJT and how they must be biased in order for conduction to occur.

Comment

Many DMMs have a separate function for pn-junction testing. On some meters this is an option on the resistance measurements. In this mode, often termed “diode test,” the DMM outputs a constant current of about 1 mA and it measures the voltage between the two leads without computing a resistance. The measured voltage is the turn-on voltage of the pn-junction for a 1 mA current, if the diode is forward biased. If the diode is reverse biased, then the DMM cannot force 1 mA of current into the diode and the voltage across the diode rises up to the upper range limit of the DMM, usually about 1.5 to 2.0 Volts. Some meters give an over-range indication in this case. Using the diode function of a DMM is another way to perform the above tests, and it gives more understandable information about the typical junction voltages of the BJT.

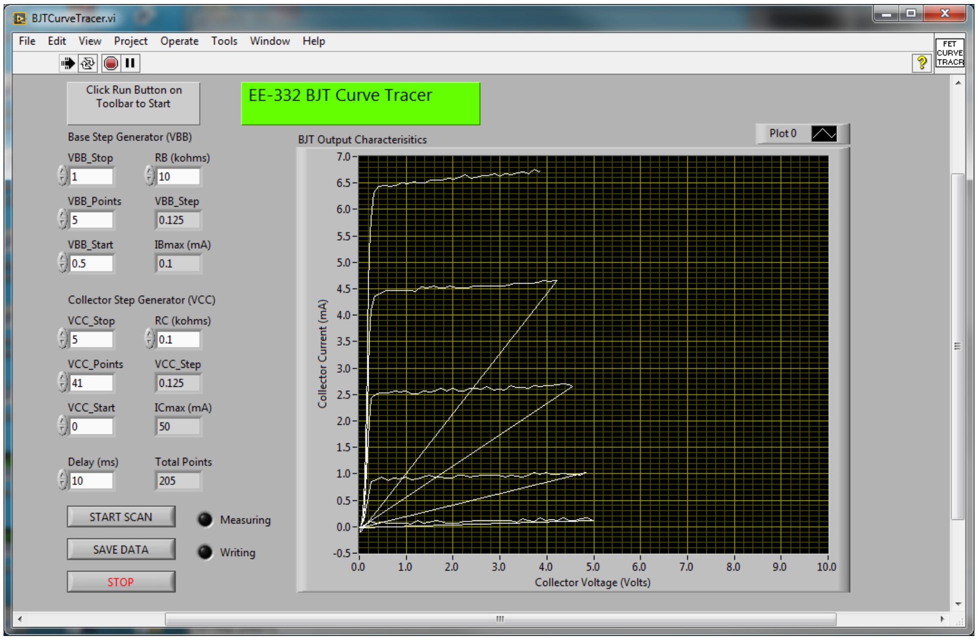
Procedure 2 Measurement of a BJT using a LabVIEW curve tracer

Comment

The objective of this procedure is to measure and record the current-voltage (I-V) characteristics of a BJT. For this, automatic computer-controlled instrumentation using LabVIEW and a data acquisition (DAQ) card will be used. Automatic measurements such as these are commonplace in the industrial environment, since they eliminate much of the possible variations that result from different human operators of the instruments. Automatic sequencing of measurements is also much faster than what a human could accomplish. This procedure will also provide some more experience with LabVIEW and computer-controlled electronic instrumentation.

Set-Up

First, copy the LabVIEW VI files to a directory on your laboratory computer. Then, launch LabVIEW and open the VI named BJTCurveTracer.vi. This is the main VI that will be used for this procedure, but it uses two other sub-VIs, named BJTStepGenerator.vi and BJTMeasurement.vi which must be in the same directory as the BJTCurveTracer.vi. Once you have the BJTCurveTracer.vi open, the front panel should appear as shown in Fig. E1.2a below:



Base Step Generator (VBB)

VBB_Stop 1
RB (kohms) 10
VBB_Points 5
VBB_Step 0.125
VBB_Start 0.5
IBmax (mA) 0.1

Collector Step Generator (VCC)

VCC_Stop 5
RC (kohms) 0.1
VCC_Points 41
VCC_Step 0.125
VCC_Start 0
ICmax (mA) 50

Delay (ms) 10
Total Points 205

Figure E1.2a

Similar to the diode curve tracer of Experiment-0, this BJT curve tracer also operates by scanning an excitation voltage that is applied across a series connection of the device under test (DUT) and a current sampling resistor. The voltages across both the DUT and current sampling resistor are measured by the DAQ hardware, and from this, a current-voltage (I-V) point is measured for the device. However, for the BJT curve tracer, there are now <u>two</u> excitation voltages, VBB and VCC, which are applied to the base and collector circuits, respectively, while the emitter of the BJT is kept grounded. In order to scan through all of the combinations of possible V_{BE} and V_{CE} values, the VCC scan is nested within the VBB scan. For each value of VBB, all of the VCC values are scanned in sequence, giving a total number of measurement points which is the product of the number of VBB and VCC points. As can be seen from the output characteristics shown in Fig. E1.2a, for each VBB value, the VCC values scan outward from the origin to their final value, and then the next VBB value is used to scan outward again. This creates the straight retrace lines that are shown in Fig. E1.2a, coming out radially from the origin. These are merely an artifact of the scanning sequence, and do not affect the measured data.

The LabVIEW VI is designed to use a National Instruments NI-USB-6009 DAQ. All four differential analog inputs and both analog outputs are used to implement the BJT curve tracer. All of these terminals are on the analog connector block of the DAQ, pins 1-16. The overall connections are shown in the schematic of Fig. E1.2b, with the pin numbers shown for each terminal.

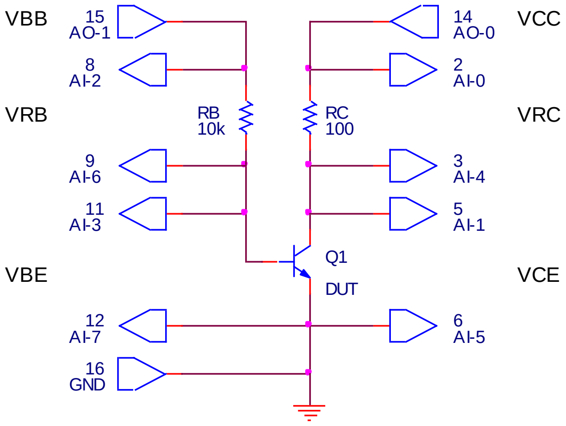


Figure E1.2b

The excitation voltage VCC is taken from the analog output channel-0 (AO-0) which uses pin #14 for AO-0 and pin #16 for the analog output ground (GND). Note that all of the pins labeled GND on the DAQ are equivalent (pins #1, 4, 7, 10, 13, and 16). The VCC voltage is applied across the series connection of a collector current sensing resistor RC = 100 Ω, and the collector-emitter leads of the device under test (DUT). Thus, VCC = VRC + VCE. Similarly, the excitation voltage VBB is taken from the analog output channel-1 (AO-1) which uses pin #15 for AO-1 and pin #16 for GND. The voltage is applied across the series connection of a base current sensing resistor RB = 10 kΩ, and base-emitter leads of the DUT. Thus, VBB = VRB + VBE.

Each of the four analog inputs uses a differential mode connection, so that the measured voltage is the difference between the voltages on each pair of analog input leads. VRC is measured using analog input channel-0 (AI-0), which takes the difference between AI-0 (pin #2) and AI-4 (pin #3). VCE is measured using analog input channel-1 (AI-1), which takes the difference between AI-1 (pin #5) and AI-5 (pin #6). VRB is measured using analog input channel-2 (AI-2), which takes the difference between AI-2 (pin #8) and AI-6 (pin #9). VBE is measured using analog input channel-3 (AI-3), which takes the difference between AI-3 (pin #11) and AI-7 (pin #12). Finally, the analog ground (GND) on pin #16 is connected to the emitter of the DUT. Any of the other GND pins could also work for this.

The best approach to constructing the circuit of Fig. E1.2b is to place as many as possible of the connections on the DAQ analog connector block itself, along with the current sensing resistors RC and RB, and then take the DUT connections off of the connector block to a solderless breadboard using three longer jumper wires. This will reduce the number of wires that need to go between the DAQ and the solderless breadboard, and also make it easier to switch around the DUT connections for different devices. Figure E1.2c shows one way of making these connections. The base circuit uses the green wire; the collector circuit uses the red wire, and the grounded emitter uses the black wire. These connections now effectively make the NI-USB-6009 into a three-terminal BJT curve tracer.

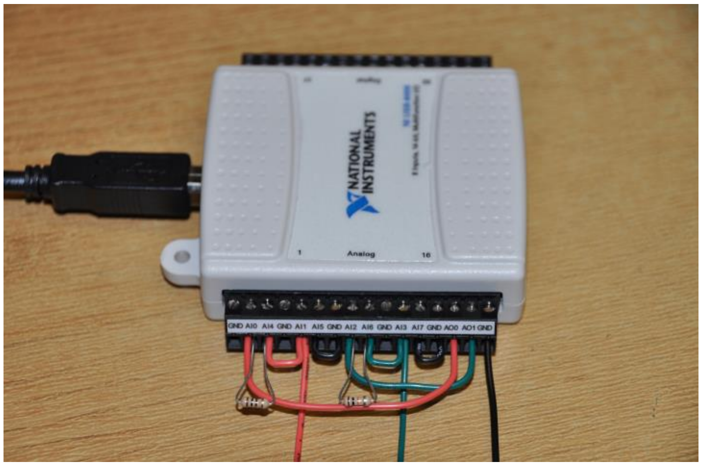


Figure E1.2c

Next, locate the 2N3904 npn BJT that was used in Procedure 1, and insert it into the solderless breadboard. Connect the emitter (black), base (green), and collector (red) leads from the DAQ analog connector block to the 2N3904 BJT as shown in Fig. E1.2d. The device is now ready to measure.

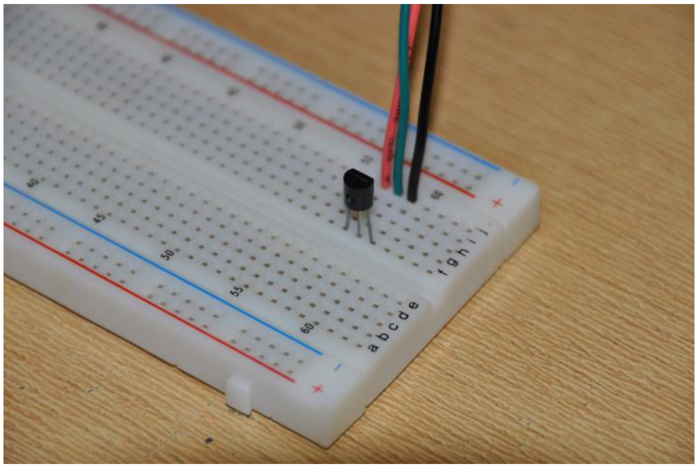


Figure E1.2d

Measurement-2 Start the LabVIEW BJTCurveTracer.vi by clicking on the Run button on the toolbar. Use the index finger pointer to input the scan parameters as follows. Input the current sensing resistor values as RB = 10 kΩ and RC = 0.1 kΩ. Set the Delay = 10 (ms). Set the VBB scan to start at 0.5 V, stop at 1.0 V, and use 5 points, giving +0.125 V/step. Set the VCC scan to start at 0.0 V, stop at +5.0 V, and use 41 points, giving +0.125 V/step. There should be a total of 205 measurement points. After all of the scan parameters have been entered, click on the START SCAN button. The red Measuring LED should glow while the data is being taken. After all of the data points have been collected, the resulting output characteristics will appear on the graph, similar to that shown in Fig. E1.2a.

To store the results in a spreadsheet file, click on the SAVE DATA button, and a dialog box will open, allowing you to specify the filename of the Excel .xls file and its location. Enter a filename like Experiment_1_Procedure_2 _2N3904.xls, and click on OK. The spreadsheet file will be written, and the red Writing LED will extinguish. After the data has been saved to a spreadsheet file, halt the running VI by clicking on the red STOP button.

Open up the spreadsheet file that was just written and examine the contents. There should be 8 columns of data, with a measurement point on each row. The columns are, reading left to right: {VBB, VCC, VRC, VCE, VRB, VBE, IC, & IB}. You might wish to insert a column header row to indicate this for future reference, since the LabVIEW VI does not insert these column labels. The first two columns are just the two excitation voltages VBB and VCC which were sent to the DAQ analog output channels. The next four columns are the analog input channel measurements, {VRC, VCE, VRB, & VBE}. The last two columns are the collector and base currents which are computed as IC = VRC/RC and IB = VRB/RB.

The front panel I-V graph plots the collector current I_C versus the collector-emitter voltage V_{CE}. Since the emitter is grounded in the measurements, V_C =

V_{CE}. All of the measurement points are plotted as one long chain of (x,y) data, so this introduces the four straight retrace lines back to the origin where V_{CC} changes from its maximum to its minimum values as the value of V_{BB} is incremented. Each of the five main curves shown on the graph correspond to fixed values of V_{BB}. Since the base-emitter voltage of the BJT is relatively constant, these five curves also represent the output characteristics of the BJT for relatively constant base current, I_B. Commercial curve tracers usually plot the output characteristics versus stepped values of I_B rather than V_{BB}, so this is the more common way to usually view the data.

Question-2 The DC forward current gain of the BJT is denoted by β_F and is the ratio of the collector to base currents: $\beta_F = I_C/I_B$. This is perhaps the single most important parameter for characterization of the BJT. β_F depends upon many factors and can be measured at many different points on the characteristic curves. In circuit design β_F gets used as a constant proportionality factor of collector to base current flow, and thus it should be measured at points on the characteristic curves where the collector current is actually proportional to the base current. Examining the characteristic curves which were just recorded, you should observe a region to the right of the saturation knee where the collector current flattens out, becoming nearly independent of V_{CE}, and where the vertical distance between successive base current sweeps is approximately constant. Measuring β_F anywhere within this region should yield values which are more or less constant over that whole region. Determine β_F for this set of characteristic curves for the 2N3904 BJT by creating a new column in the Excel spreadsheet which divides the IC column by the IB column. You should get a value in the range of 100 to 300 for those points where the value of VC is greater than the saturation knee. From your measured data, suggest a suitable value of common-emitter forward current gain β_F that characterizes the 2N3904 BJT.

Below the saturation knee, the value of I_C/I_B will be less than its maximum value of β_F, and this is termed the forced-β, or $\beta_{forced} = I_C/I_B < \beta_F$, in the saturation region of operation. Within the saturation region, $V_{CE} = V_{CE,sat}$, and this will typically be a small voltage in the range of 0.1 to 0.2 Volts. From the Excel spreadsheet, make a plot of $V_{CE,sat}$ versus I_C/I_B. You will need to include only those data points which fall within the saturation region. One convenient way to do this is to first sort the data into two ranges; those points which correspond to saturated, and those which correspond to forward-active operation of the BJT; and then plot just those points in the saturation region. From your plotted data, suggest a suitable value of saturation voltage $V_{CE,sat}$ that characterizes the 2N3904 BJT.

Procedure 3 Dependence of β_F on collector current level

This procedure is a continuation of Procedure 2. The objective is to measure the value of β_F over a wider range of currents than was done in Procedure 2.

Set-Up

If it is not already done, set up the NI-USB-6009 DAQ and wire up its analog connector block as described in Procedure 2 to create the BJT curve tracer front end circuit of Figs. E1.2b and E1.2c, using RB = 10 kΩ and RC = 100 Ω. Insert a 2N3904 npn BJT into the solderless breadboard and connect it to the curve tracer front end circuit as shown in Fig. E1.2d. Since we are expecting a β_F value of around a few hundred, RB is selected to be about one hundred times the size of RC.

If it is not already running, launch LabVIEW and open the BJTCurveTracer.vi. Click on the Run button to start the VI. Set up the base step generator to scan from 1.0 V to 2.0 V in 5 points, giving a step size of 0.25 V/step. Set up the collector step generator to scan from 0.0 V to +5.0 V in 41 points, giving a step size of 0.125 V/step. Set the delay time to 5 ms or greater. This should give 205 total points. These are the same settings as in Procedure 2, except that the base step generator is set up to run up to higher values of base current and thus produce higher collector currents.

Measurement-3

Click on the START SCAN button and wait for the VI to complete the measurements and display the resulting I_C versus V_{CE} characteristics. The displayed I_C current levels should be higher than those measured previously. Once a suitable set of I-V curves has been obtained, click on the SAVE DATA button to store these measurements into an Excel spreadsheet.

Next, the transistor characteristics at a much reduced current level will be measured. Since a β_F value of around 100-200 is still anticipated, the value of RB should still remain about 100 times the value of RC. However, to measure lower current levels, both RB and RC should be increased in the same proportion. Change the present values of these resistors on the curve tracer front end circuit to be RB = 100 kΩ and RC = 1.0 kΩ. Change the base step generator to scan from 1.0 V to 3.0 V in 5 points, giving 0.5 V/step. Leave the collector step generator at its present setting to scan from 0.0 V to +5.0 V in 41 points, giving 0.125 V/step. Click the START SCAN button to begin the measurement sequence. The recorded data should show current levels approximately a factor of 10 less than those before. Click on the SAVE DATA button to store these measurements in a (different) Excel spreadsheet. Click on the STOP button to halt the VI.

Question-3

From the two Excel spreadsheets that were produced, combine the measurements into one by copying and pasting the data. Because the BJTCurveTracer.vi will not send sufficient significant figures to the spreadsheet for small values of IB, both the base and collector currents should be recomputed within the spreadsheet using the formulas IB = VRB/RB and IC = VRC/RC, noting that there were two sets of RB and RC values used to gather the overall data. Next, compute the value of $\beta_F = I_C/I_B$ for each measurement point and observe the general trend of the data as a function of the collector current level. Create a plot of β_F versus I_C for those points corresponding to a forward-active operating point of $V_{CE} = 3.0$ Volts. Comment on the dependence of β_F on I_C, and from your plot, estimate the value of I_C which yields the maximum value of β_F.

Comment

At low values of collector current, generation-recombination processes in the base-emitter juction produce additional base current which is not associated with a proportional collector current. Hence, at low current levels, the current gain falls. At high values of collector current, series resistance and high-level injection phenomenon become important, and both cause the current gain to fall off in this region. All BJTs have a designed “sweet spot” where they deliver maximum current gain. Usually, other operational parameters such as frequency response, power efficiency, and minimum noise production are also optimized around this region. It is certainly possible to use a BJT outside of this region of optimal current gain, but one must suffer degradation in all of these parameters when doing so. The manufacturer’s data sheets provide very detailed information about how all of these parameters vary with collector current level. A little effort expended in matching these performance curves to a given design will lead to much better circuit performance.

Procedure 4 Measurement of BJT reverse characteristics

Comment The objectives of this procedure are to measure the I-V output characteristics of a BJT in the reverse-active region of operation.

Set-Up If it is not already done, set up the NI-USB-6009 DAQ and wire up its analog connector block as described in Procedure 2 to create the BJT curve tracer front end circuit of Figs. E1.2b and E1.2c, using RB = 10 kΩ and RC = 100 Ω. Insert a 2N3904 npn BJT into the solderless breadboard and connect it to the curve tracer front end circuit as shown in Fig. E1.2d.

Now, reverse the BJT in the solderless breadboard so as to swap the emitter and collector leads. The collector lead should now be grounded, and emitter lead should be connected to RC, and the base should remain where it was originally, connected to RB. This can be simply accomplished by just removing the BJT, rotating it 180 degrees and re-inserting it into the solderless breadboard.

If it is not already running, launch LabVIEW and open the BJTCurveTracer.vi. Click on the Run button to start the VI. Set up the base step generator to scan from 0.5 V to 1.0 V in 5 points, giving a step size of 0.125 V/step. Set up the collector step generator to scan from 0.0 V to +5.0 V in 41 points, giving a step size of 0.125 V/step. Set the delay time to 5 ms or greater. This should give 205 total points. These are the same settings as in Procedure 2.

Measurement-4 Click on the START SCAN button to begin the measurement sequence. After the measurements are complete, the resulting I-V characteristics will look quite different from those in Procedure 2. First, all five base voltage curves will appear to lie almost on top of one another, and second, the the resulting I-V curves should be very noisy appearing and rather indistinct. This is because the resulting collector current level is very low and the front end circuit is not producing very much voltage drop across the collector current sampling resistor RC to compute an accurate current.

Fix this problem by changing RC to a value of 1.0 kΩ on the front end circuit. Be sure to also change the value of RC on the curve tracer front panel. Click on the START SCAN button again to remeasure the transistor. The resulting I-V curves should be less noisy, but still rather small in magnitude (much less than 1 mA anywhere). Because the β_R is so small, the base current will need to be increased to produce a reasonable set of I-V curves.

Fix this problem by changing RB to a value of 1.0 kΩ on the front end circuit. Be sure to also change the value of RB on the curve tracer front panel. Click on the START SCAN button again to remeasure the transistor. The resulting

I-V curves should now appear reasonably noise-free and significant in magnitude to provide good data.

Click on the SAVE DATA button to record the measurement data to an Excel spreadsheet. Choose a new filename so as to not overwrite any existing measurements. Click the STOP button to halt the VI.

Question-4 Using the Excel spreadsheet, calculate the value of $\beta_R = I_E/I_B$ for each of the measurement points. Note that with the transistor reversed in the solderless breadboard, the recorded value of I_C will, in effect, be I_E. What is the typical range of values for β_R? Does the value of β_R vary significantly with I_E?

From your results above, discuss in your notebook the interchangeability of the emitter and collector leads of a BJT. While a BJT consists most simply of just two back-to-back pn-junctions, explain why the conduction from collector to emitter has such a large difference in current gain with different directions of flow. What is asymmetrical about the BJT structure to cause this?

Procedure 5 Measurement of BJT turn-on voltage and ideality factor

Comment

The turn-on voltage of the base-emitter junction is denoted by $V_{BE,on}$ or V_{γ}, and is usually approximated as a constant 0.6 to 0.7 Volts for quick circuit analysis. However, this voltage is not really constant, and varies logarithmically with the base current. The measurements of this procedure are to determine the parameters for an ideal diode equation which models the base-emitter junction characteristics.

Set-Up

If it is not already done, set up the NI-USB-6009 DAQ and wire up its analog connector block as described in Procedure 2 to create the BJT curve tracer front end circuit of Figs. E1.2b and E1.2c, using RB = 10 kΩ and RC = 100 Ω. Insert a 2N3904 npn BJT into the solderless breadboard and connect it to the curve tracer front end circuit as shown in Fig. E1.2d.

Because we want to measure only the base-emitter junction characteristics, remove the wire from the base of the BJT and short the base to the collector with a short jumper wire on the solderless breadboard.

If it is not already running, launch LabVIEW and open the BJTCurveTracer.vi. Click on the Run button to start the VI. Set up the base step generator to scan from 0.0 V to 0.0 V in 1 point, giving a step size of “NaN” (Not a Number). This will keep the base step generator output at 0.0 Volts and it will not scan over any base voltage values. Set up the collector step generator to scan from 0.0 V to +5.0 V in 51 points, giving a step size of 0.1 V/step. This will sequence the measurement of 51 pairs of (V_{BE},I_C) values. Since the base and emitter are shorted together, both terminals are driven with the same curve tracer excitation voltage. Set the delay time to 5 ms or greater.

Measurement-5

Click on the START SCAN button and wait for the VI to complete the measurements and display the resulting I_C versus V_{CE} characteristics. This should produce a current-voltage characteristic very similar to a regular pn-junction. Click on the SAVE DATA button and record the measured data in an Excel spreadsheet. Click on the STOP button to halt the VI.

Question-5

Using the Excel spreadsheet, create a new column which is the logarithm base 10 of the measured collector current. Use the “LOG10” function in Excel to do this, and do this only for those measurement points whose collector current is non-zero. Now create a plot of LOG10(IC) versus VB. This should produce a nearly straight line. The vertical axis is the logarithm of the collector current, relative to a value of 1 mA. That is, a value of “0” on the log scale corresponds to 1 mA, a value of “−1” on the log scale corresponds to 0.1 mA, and so on. The slope and y-intercept of this curve characterize the base-emitter junction characteristic.

Use the LINEST function in Excel to create a best-fit (least squares estimate) of the straight line going through these data points. Note that the LINEST function is an array function. After typing it in, you should select two adjacent cells in a row to hold the values of slope and y-intercept that it will return. To do this, after entering the formula into a cell, press F2 to edit the cell, then press CNTL+SHIFT+ENTER to make this an array formula. For more details, see the help window in Excel.

The first element of the calculated array should be a value of around 15-16. This is the slope of the straight line in decades/Volt. The reciprocal of this should be a value of around 60-70 mV/decade, which is the product of kT/q times the ideality factor η for the transistor. At a temperature of 300 K, the value of $V_T = kT/q$ is about 57 mV. Divide the calculated reciprocal slope by 57 mV to find the ideality factor η for the transistor.

The second element of the calculated array should have a value of around -10 to -11. This is the y-intercept of the straight line. Since the logarithm values are relative to a value of 1 mA, a value of -10 would correspond to a saturation current of $I_S = 10^{-13}$ Amperes. Determine the value of the saturation current for the 2N3904 npn BJT.

Finally, from the original measurement data that plotted I_C versus $V_{CE} = V_{BE}$, determine a reasonable value of $V_{BE,on}$ which characterizes the 2N3904 BJT for milliampere current levels.

Procedure 6 Measurement of BJT output conductance

Comment

The characteristic output curves for a BJT are not exactly horizontal in the forward-active region of operation. The slight slope that the curves exhibit in this region is their output conductance. If the BJT behaved like an ideal current source, the output current would not be a function of V_{CE}, and the curves would be truly horizontal. This slight increase in I_C as a function of V_{CE} in the forward-active region can be represented by a small conductance in parallel with the ideal current source in the BJT model.

Set-Up

If it is not already done, set up the NI-USB-6009 DAQ and wire up its analog connector block as described in Procedure 2 to create the BJT curve tracer front end circuit of Figs. E1.2b and E1.2c, using RB = 10 kΩ and RC = 100 Ω. Insert a 2N3904 npn BJT into the solderless breadboard and connect it to the curve tracer front end circuit as shown in Fig. E1.2d.

If it is not already running, launch LabVIEW and open the BJTCurveTracer.vi. Click on the Run button to start the VI. Set up the base step generator to scan from 0.5 V to 1.0 V in 5 points, giving a step size of 0.125 V/step. Set up the collector step generator to scan from 0.0 V to +5.0 V in 41 points, giving a step size of 0.125 V/step. Set the delay time to 5 ms or greater. This should give 205 total points. These are the same settings as in Procedure 2.

Measurement-6

Click on the START SCAN button and wait for the VI to complete the measurements and display the resulting I_C versus V_{CE} characteristics. If the characterisitics appear reasonable, click the SAVE DATA button to record the measurements to an Excel spreadsheet.

Next, insert a 10 kΩ resistor in parallel with the emitter and collector terminals of the 2N3904 BJT under test. This will simulate additional output conductance to emphasize what the effects are on the output I-V characteristics of the transistor. Click on the START SCAN button again and wait for the VI to complete the measurements. The resulting output characteristics should show a much increased slope, corresponding to the addition of 0.1 mS of conductance between the collector and the emitter. If you wish, click the SAVE DATA button to record these new measurements to an Excel spreadsheet. Be use to use a new filename to avoid overwriting any existing measurements. Click the STOP button to halt the VI.

Question-6

From the Excel spreadsheet that recorded the BJT characteristics *without* the additional 10 kΩ resistor connected, use Excel to compute the slope of the five output curves in units of Ω^{-1} (or Mhos, Siemens, or S).

Unlike when the 10 kΩ resistor was connected, the value of the BJT output conductance will tend to increase in proportion to the collector current I_C. The output conductance is usually expressed as λI_{Csat}, where λ is a constant with units of V^{-1}. I_{Csat} is the saturated value of forward-active collector current, i.e. the current that would result in the absence of any output conductance, and which is usually measured close to the saturation knee of the output curve. Using Excel, find the best fit value of λ which allows the forward-active output curves to be well approximated by the relationship

$$I_C = I_{Csat} (1 + \lambda V_{CE}) .$$

Procedure 7 Temperature effects

Comment Temperature is an extremely important influence on bipolar transistor circuits. Like pn-junctions, BJTs have a very strong temperature dependence that must be appreciated to design successful circuits. This procedure gives some idea of how strong this temperature dependence can be.

Set-Up If it is not already done, set up the NI-USB-6009 DAQ and wire up its analog connector block as described in Procedure 2 to create the BJT curve tracer front end circuit of Figs. E1.2b and E1.2c, using RB = 10 kΩ and RC = 100 Ω. Insert a 2N3904 npn BJT into the solderless breadboard and connect it to the curve tracer front end circuit as shown in Fig. E1.2d.

If it is not already running, launch LabVIEW and open the BJTCurveTracer.vi. Click on the Run button to start the VI. Set up the base step generator to scan from 0.5 V to 1.0 V in 5 points, giving a step size of 0.125 V/step. Set up the collector step generator to scan from 0.0 V to +5.0 V in 41 points, giving a step size of 0.125 V/step. Set the delay time to 5 ms or greater. This should give 205 total points. These are the same settings as in Procedure 2.

Measurement-7 Click on the START SCAN button to record a reference set of characteristics at room temperature. Now for some fun… Take a hot soldering iron and use it to significantly heat up the device and then take another scan of the device characteristics. Alternatively, you can go the other direction. Use a can of freeze spray to significantly cool down the transistor and then take another scan of the device characteristics. Make a note in your lab notebook what the relative magnitude of either of these effects is. Click on the SAVE DATA button to store any of your measured data sets to an Excel spreadsheet.

Precautions Be careful not to burn yourself with the soldering iron. Similary, be careful not to blast yourself or your laboratory partners with the freeze spray.

Question-7 In your lab notebook, briefly discuss what is problematic about this temperature sensitivity for designing stable circuits. Also discuss how this temperature sensitivity could be useful for making a sensor.

Procedure 8 Measurement of a pnp BJT

Locate a 2N3906 pnp BJT and from the techniques above, obtain a set of characteristic curves using the LabVIEW and DAQ card curve tracer. Note that the base and collector step generators must be set up to scan over negative voltages in order to properly bias the pnp transistor. Record this set in an Excel spreadsheet, and note the primary differences from the 2N3904 npn BJT.

Note! The NI-USB-6009 DAQ cannot produce negative analog output voltages, so it will not be capable of performing this procedure. However, other DAQ models have this capability and could be used here if they are available.

Procedure 9 Measurement of a power BJT

Locate a TIP-29 npn power BJT and from the techniques shown previously, obtain a set of characteristic curves using the LabVIEW and DAQ card curve tracer. Record this set in an Excel spreadsheet, and note the primary differences from the 2N3904 npn BJT.

Procedure 10 Measurement of an array BJT

Locate a CA3046 npn BJT array and obtain a set of characteristic curves using the LabVIEW and DAQ card curve tracer. Record this set in an Excel spreadsheet, and note any differences from the 2N3904 npn BJT.