Physics 364, Fall 2014, Lab #12 **Name:** ____________

(transistors I: emitter follower)

Monday, October 13 (section 401); Tuesday, October 14 (section 402)

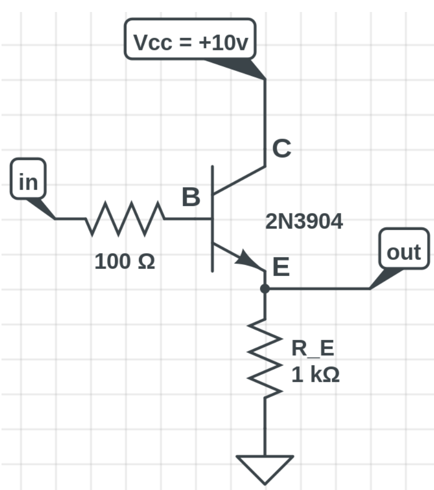
Course materials and schedule are at `positron.hep.upenn.edu/p364`

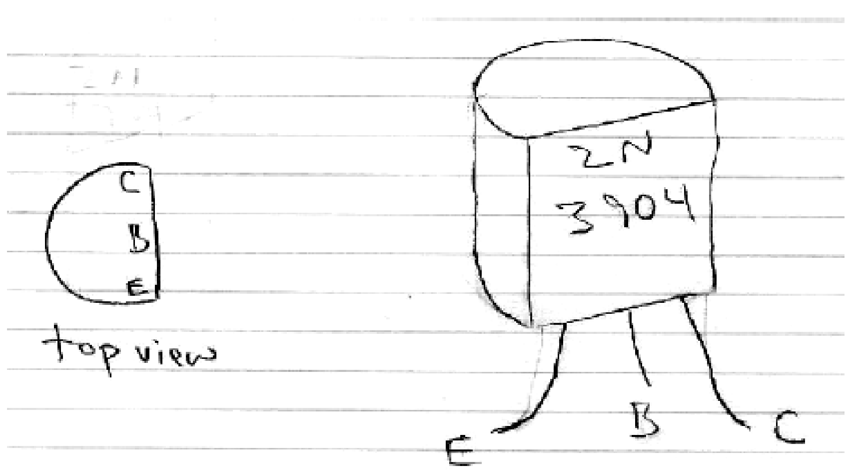
Today's is the first of four labs covering Bipolar Junction Transistors. Today, we will study the "emitter follower," which is roughly analogous to the opamp follower. Eggleston calls this circuit the "common collector amplifier." Like the opamp follower, the emitter follower has a voltage gain of 1 and an input resistance that is much larger than its output resistance. By the end of the lab, your emitter follower will be gradually morphing into something that is starting to act like a common-emitter amplifier, which we will study in more detail next time.

Part 1 **Start Time:** ____________

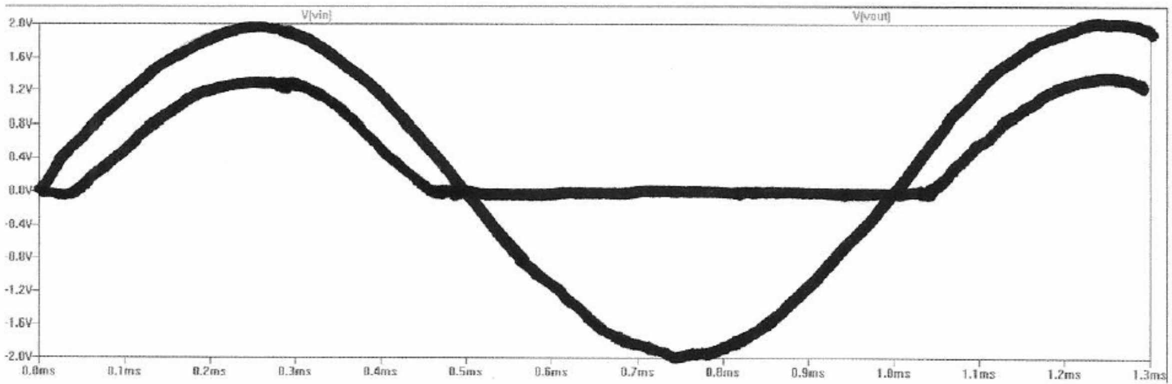
no-frills emitter follower (time estimate: 75 minutes)

Build the (rather plain) emitter follower shown in the left figure below. The right figure below shows you how to identify the three terminals of the 2N3904 NPN transistor. The 100 Ω resistor at the base is not strictly necessary, but we'll include it (a) to reduce the chances of applying too large a reverse bias to the base→emitter junction (letting V_{BE} go more than a few volts below zero will cook the transistor), and (b) to make it easy for you to measure the base current I_B, by simply measuring the voltage drop across this resistor.

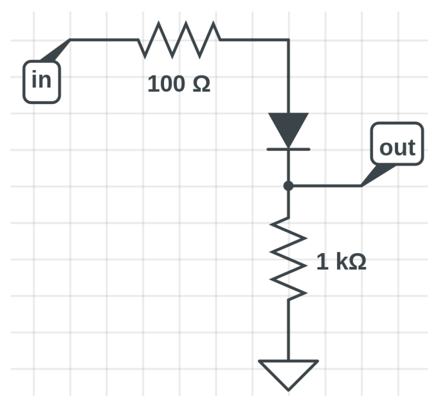




1.1 First check your connections by trying out your follower with a 4 V_{pp} sine wave input. The output should resemble the graph on page 9 of `reading07`, which we reproduce below.

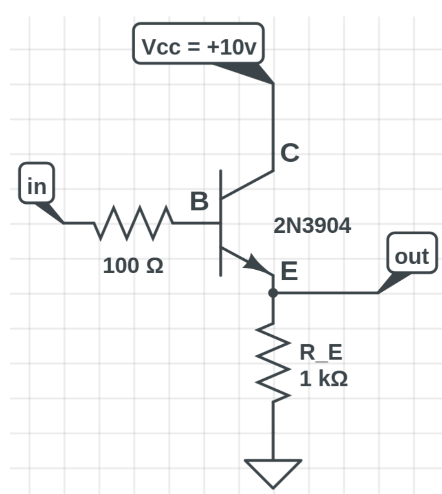


1.2 (*Nothing to build here.*) Recalling that the base-emitter junction behaves as a diode, make sure that you understand the features of the input and output by considering the diode circuit at right, which closely resembles a circuit you built in Lab 1. (The output of this circuit looks just like the above graph.) Do you understand (from the diode I-V curve) why V_{out} is a diode drop (about 0.7 V) below V_{in} and is clipped at 0 V when $V_{\text{in}} < 0$?

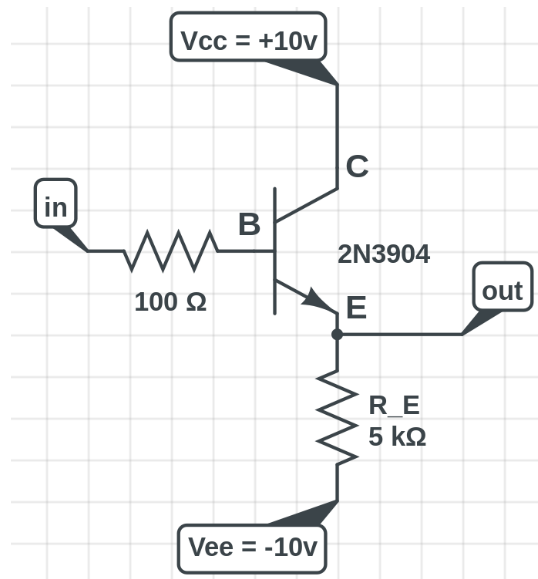


1.3 Now let's measure β for your transistor by recording voltages and inferring currents for several DC input voltages. Fill in a table like the one below. Just set V_{in} and measure V_B and V_E. You should be able to infer all of the other values. See whether I_E vs. V_{BE} and I_C/I_B follow your expectation. Probably the easiest way to supply V_{in} is to use the function generator's DC offset (channel 1), with the FG's smallest possible amplitude, which is 0.004 V_{pp}.

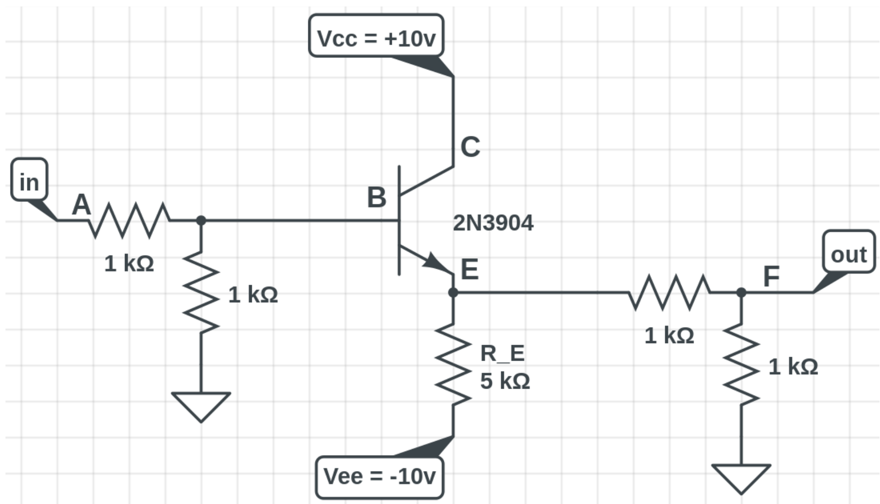
V_{in}	V_B	$V_{\text{in}} - V_B$	I_B	V_E	V_{BE}	I_E	I_C	I_C/I_B
−2 V								
−1 V								
0 V								
+1 V								
+2 V								
+3 V								
+4 V								
+5 V								

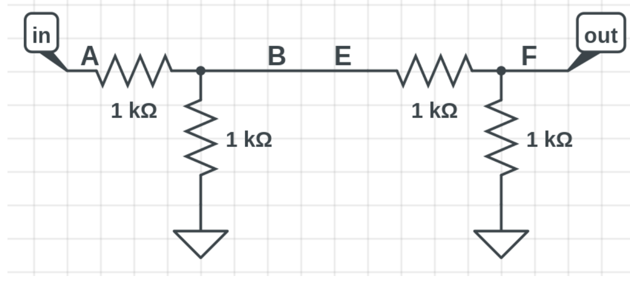


1.4 Now move "V_{EE}" (beneath R_E) from 0 V (ground) to −10 V, so that we can follow a bipolar signal. (You might also want to replace the 1 kΩ resistor with 5 kΩ, to keep your transistor from getting too warm. Can you see why (if V_{in} is 0 V on average) a small value of R_E makes the transistor dissipate enough power to warm it up?) Now remove the 100 Ω resistor from the base, just to assure yourself that it isn't doing anything important. Check, of course, that you can now follow a bipolar signal!



1.5 Let's build and try out our favorite (most dreaded?) "voltage divider loads voltage divider" circuit, as shown below — though this time we'll change the resistances to keep the math even simpler than usual. What do you see at points A, B, E, and F? (I didn't want to confuse anyone by writing A, B, C, D.) What would you expect from your opamp follower? What would you expect with no follower at all, e.g. by imagining (don't bother to build) the small figure at the bottom of the page?



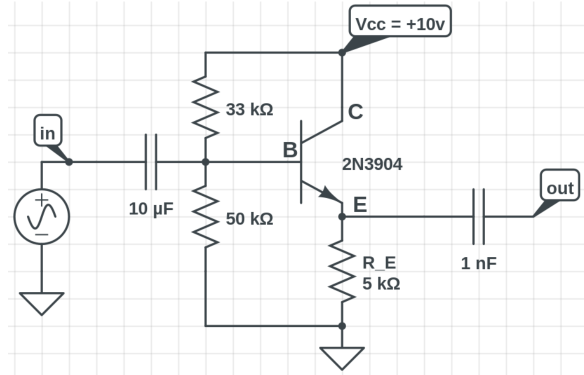


Part 2 **Start Time:** ____________

AC-coupled emitter follower

(time estimate: 45 minutes)

Now build the AC-coupled follower from page 12 of `reading07` (shown at right). We've updated the resistor values to match what we have in the lab, and we've chosen capacitor values that make it easier for you to measure $f_{3\text{dB}}$ separately at the input and output stages. In real life, both caps would be closer to 1 μF.



2.1 Does the follower follow? At what amplitude V_{in} does V_{out} begin to show clipping? Look at V_E when V_{out} is clipping, to understand what is happening.

2.2 What are $f_{3\text{dB}}$ for the input and output filters? First estimate what you expect for each filter, and then measure. To calculate $f_{3\text{dB}}$ for the output filter, you need to assume some value for the load resistance — for example the input resistance of your scope probe.

2.3 What are the quiescent (i.e. DC) values of V_B, V_E, V_{BE}, I_E, and I_C? (Most of these you can infer by measuring V_B and V_E.)

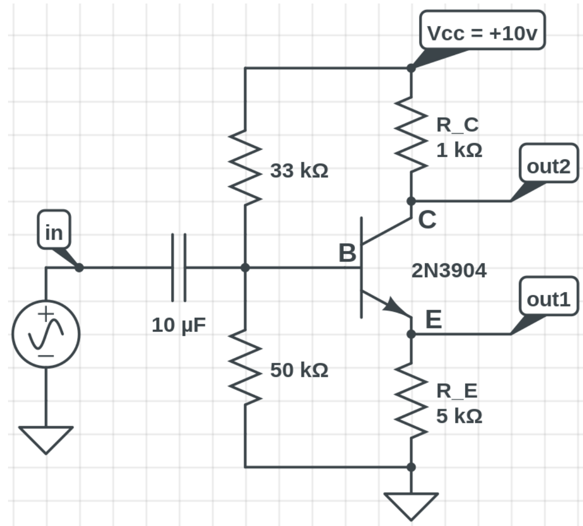
2.4 What is the quiescent current through the biasing network (the voltage divider to the left of the base)? What quiescent I_B do you estimate from your measured β from Part 1? An equivalent way of saying that the voltage divider is not too heavily loaded (does not droop) is to say that the current drawn by the base is much less than the current that flows through the two resistors of the voltage divider.

Don't take apart your follower yet!

Part 3 **Start Time:** ________________

morphing toward a common-emitter amplifier (time estimate: 60 minutes)

3.1 First make a minor modification to your emitter follower from Part 2: add a 1 kΩ resistor in place of the direct connection from the collector to +10 V. Also, remove the output capacitor.



Drive your circuit with a 2 V_{pp} sine wave and look at what's happening at both emitter and collector. What are the DC levels at the emitter and collector? Why? (This is really important to understand! So work through it!) What are the signal amplitudes (and relative signs)? Why? To see the DC levels, it may help to turn off the input signal for a moment.

3.2 Now replace the 5 kΩ emitter resistor with 2 kΩ. Draw the new schematic here. What is the largest signal you can apply to the input before one of the outputs clips? Which one clips first? Why? What is happening when it clips? Predict, then measure the quiescent voltage, V_B, at the base. (Quiescent means in the absence of any AC signal.) Now predict, then measure V_E. What is I_E? Now predict, then measure V_C.

3.3 Modify the biasing network (the voltage divider to the left of the base) so that the quiescent current through the collector is about 1 mA. To do that, figure out where the emitter should rest, then the base. If you want the ultimate flexibility in fine-tuning your biasing network, you could replace the two biasing resistors with a single 100 kΩ potentiometer, such that $R_1 + R_2 = 100$ kΩ, and $R_2/(R_1 + R_2)$ gives you the desired V_B — do you see how? Once you're done fiddling, draw your new schematic diagram, and then remeasure the quiescent values of V_B, V_E, and V_C. Now what is the largest signal that you can apply to the input without clipping? What is happening when one of the outputs clips?

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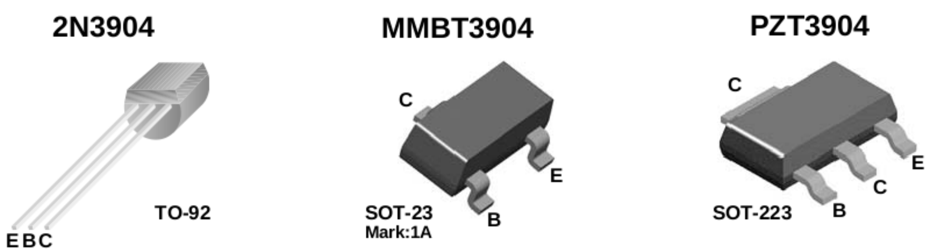
FAIRCHILD SEMICONDUCTOR®

October 2011

2N3904 / MMBT3904 / PZT3904
NPN General Purpose Amplifier

Features

- This device is designed as a general purpose amplifier and switch.
- The useful dynamic range extends to 100 mA as a switch and to 100 MHz as an amplifier.



Absolute Maximum Ratings* T_a = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	60	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current - Continuous	200	mA
T_J, T_{stg}	Operating and Storage Junction Temperature Range	-55 to +150	°C

* These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

NOTES:

1) These ratings are based on a maximum junction temperature of 150 degrees C.

2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

Thermal Characteristics T_a = 25°C unless otherwise noted

Symbol	Parameter	Max.			Units
		2N3904	***MMBT3904**	****PZT3904**	
P_D	Total Device Dissipation Derate above 25°C	625 5.0	350 2.8	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal Resistance, Junction to Case	83.3			°C/W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	200	357	125	°C/W

* Device mounted on FR-4 PCB 1.6" X 1.6" X 0.06".

** Device mounted on FR-4 PCB 36 mm X 18 mm X 1.5 mm; mounting pad for the collector lead min. 6 cm^2.

Electrical Characteristics T_a = 25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Max.	Units
OFF CHARACTERISTICS					
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage	I_C = 1.0mA, I_B = 0	40		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10μA, I_E = 0	60		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10μA, I_C = 0	6.0		V
I_{BL}	Base Cutoff Current	V_{CE} = 30V, V_{EB} = 3V		50	nA
I_{CEX}	Collector Cutoff Current	V_{CE} = 30V, V_{EB} = 3V		50	nA
ON CHARACTERISTICS*					
h_{FE}	DC Current Gain	I_C = 0.1mA, V_{CE} = 1.0V I_C = 1.0mA, V_{CE} = 1.0V I_C = 10mA, V_{CE} = 1.0V I_C = 50mA, V_{CE} = 1.0V I_C = 100mA, V_{CE} = 1.0V	40 70 100 60 30	 300	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10mA, I_B = 1.0mA I_C = 50mA, I_B = 5.0mA		0.2 0.3	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10mA, I_B = 1.0mA I_C = 50mA, I_B = 5.0mA	0.65	0.85 0.95	V V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	I_C = 10mA, V_{CE} = 20V, f = 100MHz	300		MHz
C_{obo}	Output Capacitance	V_{CB} = 5.0V, I_E = 0, f = 1.0MHz		4.0	pF
C_{ibo}	Input Capacitance	V_{EB} = 0.5V, I_C = 0, f = 1.0MHz		8.0	pF
NF	Noise Figure	I_C = 100μA, V_{CE} = 5.0V, R_S = 1.0kΩ, f = 10Hz to 15.7kHz		5.0	dB
SWITCHING CHARACTERISTICS					
t_d	Delay Time	V_{CC} = 3.0V, V_{BE} = 0.5V I_C = 10mA, I_{B1} = 1.0mA		35	ns
t_r	Rise Time			35	ns
t_s	Storage Time	V_{CC} = 3.0V, I_C = 10mA, I_{B1} = I_{B2} = 1.0mA		200	ns
t_f	Fall Time			50	ns

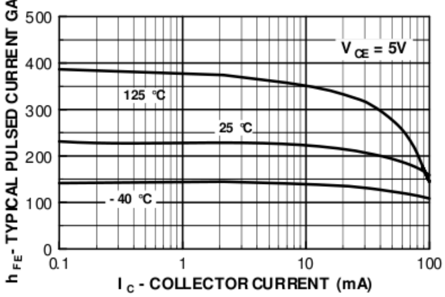
* Pulse Test: Pulse Width ≤ 300μs, Duty Cycle ≤ 2.0%

Ordering Information

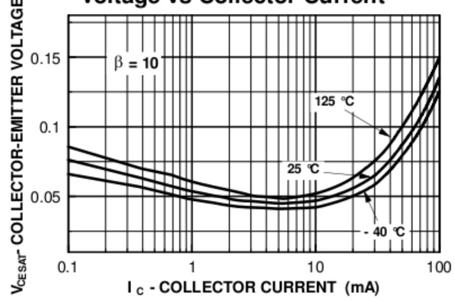
Part Number	Marking	Package	Packing Method	Pack Qty
2N3904BU	2N3904	TO-92	BULK	10000
2N3904TA	2N3904	TO-92	AMMO	2000
2N3904TAR	2N3904	TO-92	AMMO	2000
2N3904TF	2N3904	TO-92	TAPE REEL	2000
2N3904TFR	2N3904	TO-92	TAPE REEL	2000
MMBT3904	1A	SOT-23	TAPE REEL	3000
MMBT3904_D87Z	1A	SOT-23	TAPE REEL	10000
PZT3904	3904	SOT-223	TAPE REEL	2500

Typical Performance Characteristics

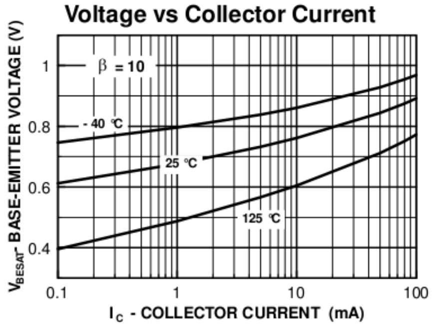
Typical Pulsed Current Gain vs Collector Current



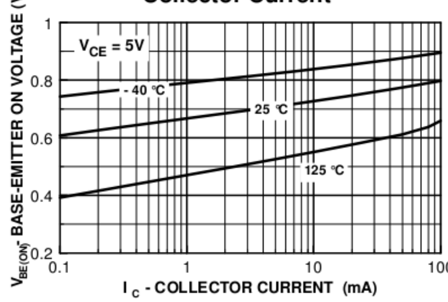
Collector-Emitter Saturation Voltage vs Collector Current



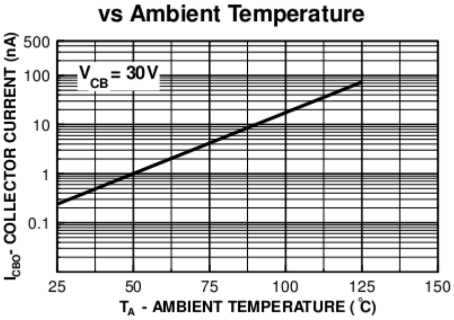
Base-Emitter Saturation Voltage vs Collector Current



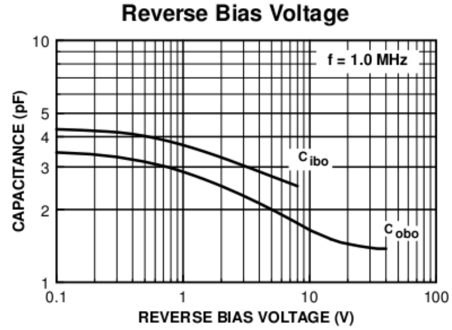
Base-Emitter ON Voltage vs Collector Current



Collector-Cutoff Current vs Ambient Temperature

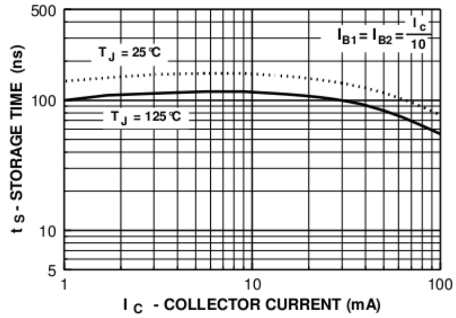


Capacitance vs Reverse Bias Voltage

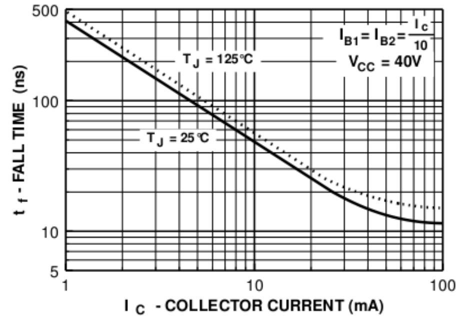


Typical Performance Characteristics (continued)

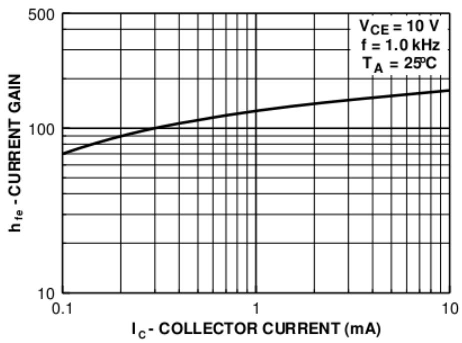
Storage Time vs Collector Current



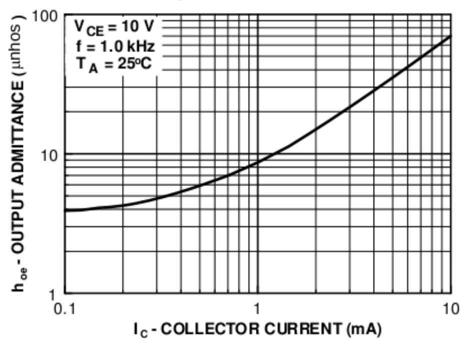
Fall Time vs Collector Current



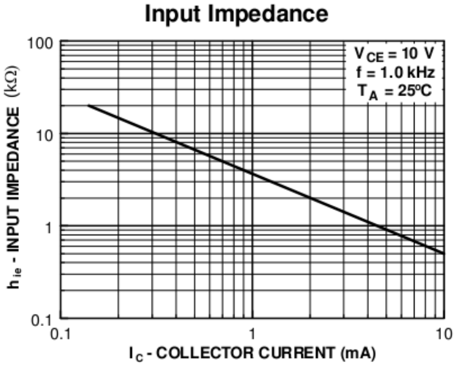
Current Gain



Output Admittance



Input Impedance



Voltage Feedback Ratio