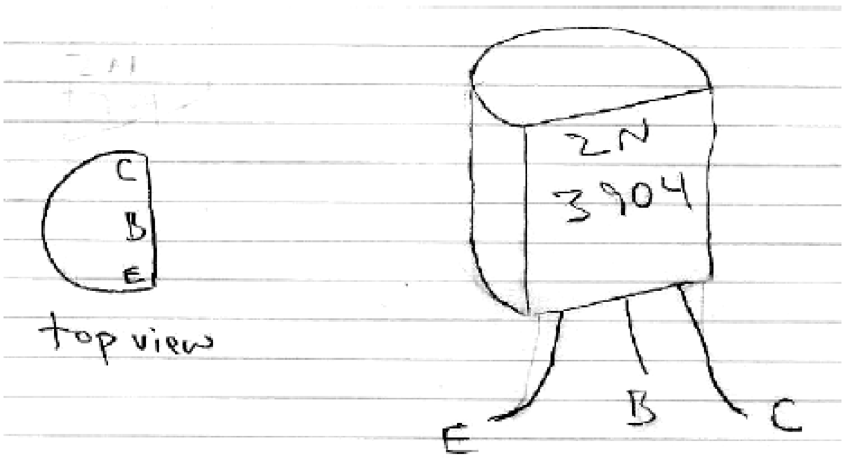
Physics 364, Fall 2014, Lab #13 **Name:** ____________________

(transistors II: common-emitter amplifier; current source; and switch)
Wednesday, October 15 (section 401); Thursday, October 16 (section 402)

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

Today's is the second of four labs covering Bipolar Junction Transistors. Today, we will study the *common-emitter amplifier,* which is roughly analogous to the opamp inverting amplifier. We'll then build a transistor-based *current source,* which will reappear in next week's differential amplifier. Finally (if you have time left at the end), we'll use a transistor as a simple on/off *switch,* which is a non-linear application of the transistor's useful property of permitting a very small current to control the flow of a much larger current.



Part 0 **Start Time:** ____________

finish up Lab 12 (time estimate: 30 minutes)

Start out by finishing up whatever you may have left to do (if anything) from Part 3 of Lab 12. That last part was intended as a segue between the emitter follower and the common-emitter amplifier, so it should connect nicely with the first topic from today's lab.

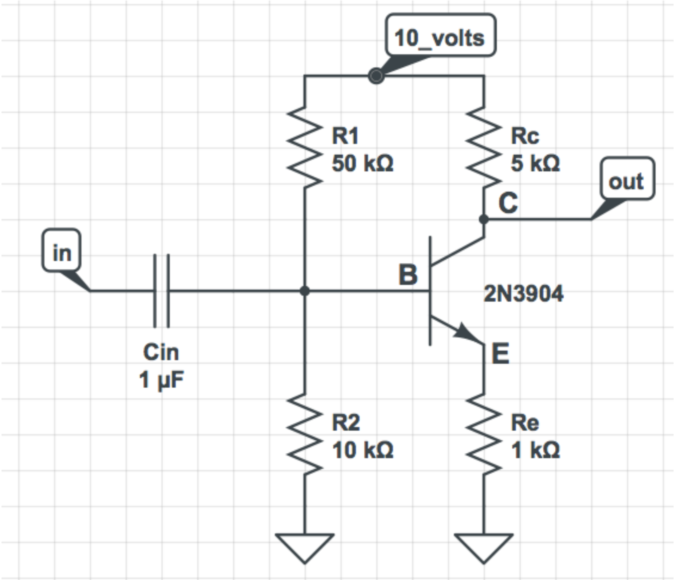
Part 1

Start Time: ________________

common-emitter amplifier

(time estimate: 75 minutes)

1.1 Build the common emitter amplifier shown below. Look at the quiescent state first. Predict, then measure V_B. Then predict, then measure V_E. Then predict, then measure V_C. Remember that V_E follows V_B (minus a diode drop), that $I_C \approx I_E$, and that $V_C = V_{CC} - I_C R_C$, where V_{CC} is the +10 V power supply above the collector. What do you expect the gain $\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}V_{\mathrm{in}}}$ to be? Now inject a 1 $\mathrm{V_{pp}}$ sine wave and check (both sign and magnitude).



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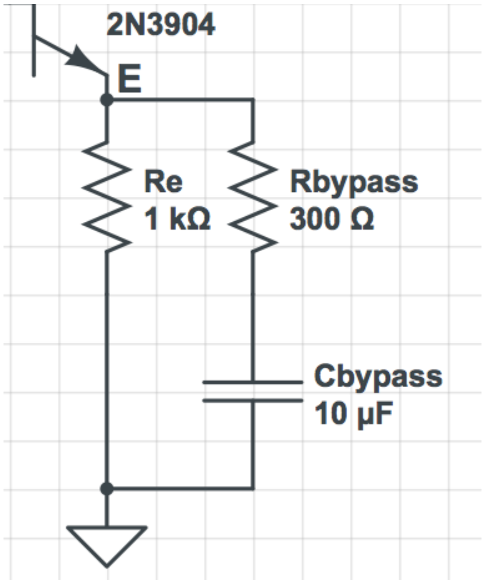
1.2 Now let's raise the AC gain somewhat. This is the same trick we used with the opamp-based microphone amplifier a week or so ago. In parallel with the 1 kΩ emitter resistor add a 300 Ω resistor in series with a 10 μF capacitor, as sketched below. What gain do you predict at signal frequencies (e.g. 1 kHz), where $|Z_{\text{cap}}| \ll 300\ \Omega$? Measure the AC gain. What do you expect for the largest signal you can amplify? Try it. (Be careful to observe the proper polarity on the 10 μF capacitor — the longer lead should be kept at higher potential than the shorter lead.)



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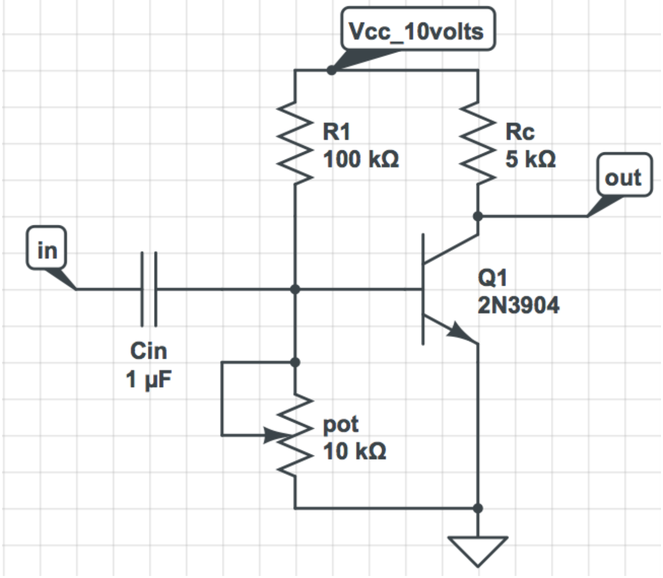
1.3 Now try the *grounded-emitter amplifier* (so called by Horowitz & Hill), to see its limitations. Build the circuit shown below. Use a 100 kΩ resistor and a 10 kΩ potentiometer for the bias network, so that you can easily move V_B around in the range of approximately 0–1 V. Aim for about 0.65 V, and adjust if you need to. (You can use the quiescent value of V_C to measure I_C, and adjust V_B to keep I_C around 1 mA — which puts the quiescent value of V_C around 5 V. I_C will creep upward as your transistor grows warmer, so you may need to readjust. If an emitter resistor R_E were present, it would provide a form of feedback to stabilize I_C: increasing I_C would increase V_E, hence decrease V_{BE}, hence pushing I_C back down. But the grounded-emitter amplifier lacks this feedback mechanism, so it is thermally unstable.) Drive the input with the largest **triangle** wave that doesn't cause the output to clip, probably around 50 $\mathrm{mV_{pp}}$. You should see the "barn roof" distortion illustrated on page 16 of `reading07`. Explain how this "barn roof" shape comes about.

(Before spending too much time on this part, be sure to budget at least 30 minutes or so for Part 2.)

Next, try a range of emitter resistors (or better yet, use a 1 kΩ potentiometer) to see at what point the distortion becomes less noticeable. Can you explain the appearing / disappearing distortion by considering $R_E + r_e$ (where $r_e = 25\text{ mV}/I_C$) at the signal peaks vs. valleys? Including the effect of r_e (the dynamic resistance of the base-emitter junction), the gain of this amplifier should be $-R_C/(R_E + \frac{25\ \Omega}{I_C})$, where I_C is measured in milliamps. The distortion should become negligible (i.e. the triangular shape should be faithfully reproduced) once the gain becomes relatively constant throughout each complete cycle of the triangle wave.



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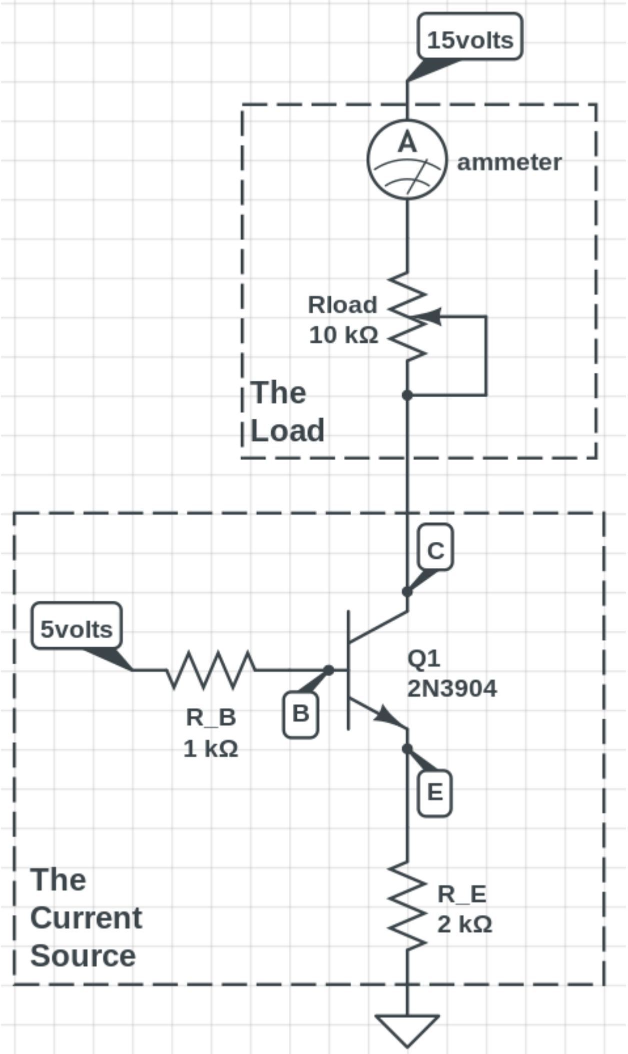
Part 2 **Start Time:** ________________

current source (time estimate: 30 minutes)

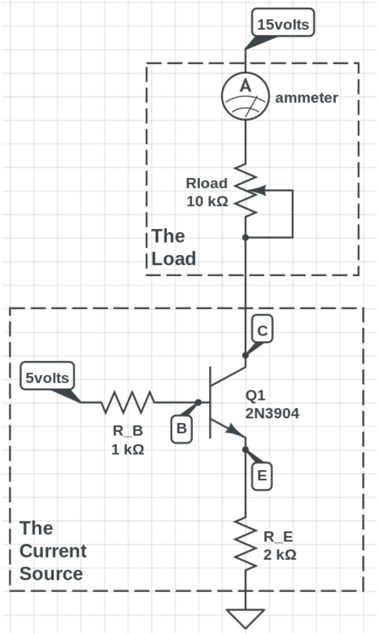
This circuit consists of two connected parts: a current source (bottom box) and a load (top box). The job of a current source is to provide a constant current, even if R_{load} varies. Whereas a voltage source "prefers" to drive an open circuit ($R_{\text{load}} = \infty$), a current source actually prefers to drive a short circuit ($R_{\text{load}} = 0$). So we'll start out with the easiest case, $R_{\text{load}} = 0$, and then gradually increase R_{load} until our current source fails to do its job. Before we do that, let's use what we know about transistors to analyze this current source. More precisely, this circuit is a *current sink,* because current flows down from the load into the transistor. (If instead we used a PNP transistor (described in next weekend's reading), we could put the load at lower potential than the current source — so then we'd really have a current source, not a sink.) We'll refer to this circuit as a current source anyway.



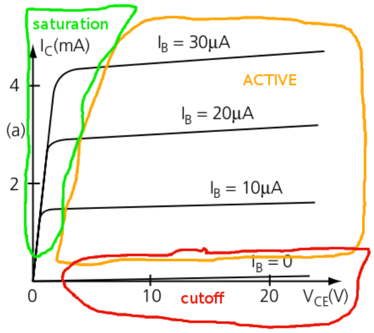
2.1 Let's analyze the current source from the previous page. On the assumption that the transistor is in active mode, and therefore $I_B = \frac{I_C}{\beta} \ll I_C$, what do you expect V_B to be? And therefore what do you expect V_E to be? Now, given the value of R_E below the emitter, what do you expect I_E to be? So then what current do you expect to flow at the collector (and in what direction)? By the way, the presence of the base resistor R_B makes no difference except in the extreme case in which the transistor goes into *saturation.*

Now ask yourself about the assumption that the transistor is in active mode. If V_{CE} becomes too small (e.g. a few tenths of a volt), the transistor enters saturation mode. What (approximately) is the minimum voltage at the collector to keep the transistor in active mode in this current source?

2.2 Now build and test the current source from the previous page, whose schematic we reproduce here. Is the supplied current consistent with your prediction? How large can you make R_{load} (how low can V_C go) before the transistor saturates, and the active-mode rules no longer apply?



2.3 For the range of R_{load} in which the transistor remains in active mode, see if there is a measureable slope $\frac{\mathrm{d}I_C}{\mathrm{d}V_C}$. A non-zero slope corresponds to a non-infinite R_{out} of the current source. An ideal current sources has $R_{\text{out}} = \infty$, which is the opposite of an ideal voltage source. My CircuitLab simulation shows $R_{\text{out}} \approx 2.5\ \mathrm{M}\Omega$, which is quite big. The reason $\frac{\mathrm{d}I_C}{\mathrm{d}V_C} \neq 0$ (and therefore $R_{\text{out}} \neq \infty$) is the nonzero slope of I_C vs. V_{CE} in the transistor curves shown below (from `reading07` page 8) — a phenomenon called the *Early Effect*. If you can see a slope at all, it will probably be just barely big enough to measure.



Part 3 Start Time: ______________

on/off switch (optional – if time)

(time estimate: 30 minutes)

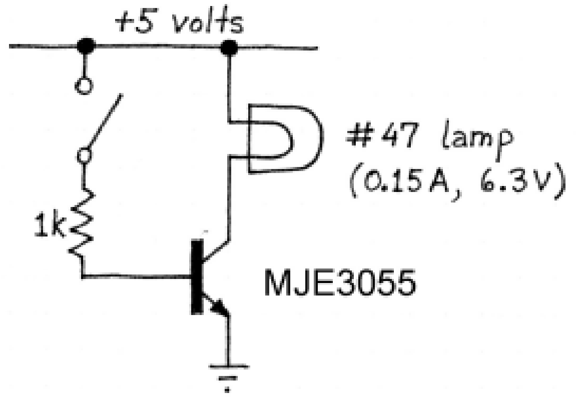
The key feature of a transistor is that it allows a small current (I_B) to control the flow of a much larger current (I_C). So far we have used this feature to make amplifiers whose output is proportional to the input, but larger — larger current in the case of the emitter follower, and larger voltage in the case of the common-emitter amplifier.

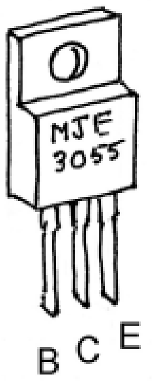
A transistor can also be used as an electrically controlled on/off switch, in which the presence of absence of a relatively small current (I_B) switches on or off the flow of a much larger current (I_C). When the switch is *off,* the transistor is in *cutoff* mode, where $I_C = 0$. When the switch is *on,* the transistor is in *saturation* mode, where V_{CE} is small (typically a few tenths of a volt above zero), $V_{BE} > 0$, and I_C is large. In this mode, $I_C \neq \beta I_B$. The motivation for using saturation mode is that the power $I_C V_{CE}$ dissipated in the transistor is small, even though a large current I_C flows through the load that the transistor is turning on/off (and hence through the collector).

Try buildling the transistor switch shown below. Use a high-power MJE3055 transistor from the back room: it can tolerate larger currents and can transfer heat to the surrounding air more effectively than the smaller 2N3904. **Notice the different pinout!** Use a pushbutton DPDT switch from the back room to switch the small current I_B on/off. (Or just use a wire if you're feeling lazy.)

Measure (or infer) I_B. Measure I_C and V_{CE}. Convince yourself that I_B, while significant, is still quite a bit smaller than I_C in saturation mode.

To convince yourself that I_C is no longer proportional to I_B in the saturated regime, try replacing the 1 kΩ resistor with 10 kΩ. The $\approx \times 10$ reduction in I_B should make only a very small difference in I_C. So "saturated" means that the transistor is as "on" as it can be: that further increases in I_B (the control knob) will not appreciably increase I_C (the flow that is being controlled). Saturation mode is like the fully-open state of a valve.





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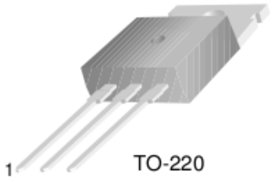
FAIRCHILD
SEMICONDUCTOR ™

MJE3055T

General Purpose and Switching Applications

- DC Current Gain Specified to I_C =10A
- High Current Gain-Bandwidth Product : f_T = 2MHz (Min.)



1.Base 2.Collector 3.Emitter

NPN Silicon Transistor

Absolute Maximum Ratings T_C=25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CBO}	Collector -Base Voltage	70	V
V_{CEO}	Collector-Emitter Voltage	60	V
V_{EBO}	Emitter-Base Voltage	5	V
I_C	Collector Current	10	A
I_B	Base Current	6	A
P_C	Collector Dissipation (T_C=25°C)	75	W
P_C	Collector Dissipation (T_a=25°C)	0.6	W
T_J	Junction Temperature	150	°C
T_{STG}	Storage Temperature	- 55 ~ 150	°C

Electrical Characteristics T_C=25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Max.	Units
BV_{CEO}	Collector-Emitter Breakdown Voltage	I_C = 200mA, I_B = 0	60		V
I_{CEO}	Collector Cut-off Current	V_{CE} = 30V, I_B = 0		700	μA
I_{CEX1} I_{CEX2}	Collector Cut-off Current	V_{CE} = 70V, V_{BE}(off) = -1.5V V_{CE} = 70V, V_{BE}(off) = -1.5V @ T_C = 150°C		1 5	mA mA
I_{EBO}	Emitter Cut-off Current	V_{EB} = 5V, I_C = 0		5	mA
h_{FE}	*DC Current Gain	V_{CE} = 4V, I_C = 4A V_{CE} = 4V, I_C = 10A	20 5	100	
V_{CE}(sat)	*Collector-Emitter Saturation Voltage	I_C = 4A, I_B = 0.4A I_C = 10A, I_B = 3.3A		1.1 8	V V
V_{BE} (on)	*Base-Emitter On Voltage	V_{CE} = 4V, I_C = 4A		1.8	V
f_T	Current Gain Bandwidth Product	V_{CE} = 10V, I_C = 500mA	2		MHz

* Pulse test: PW≤300μs, duty cycle≤2% Pulse

Typical Characteristics

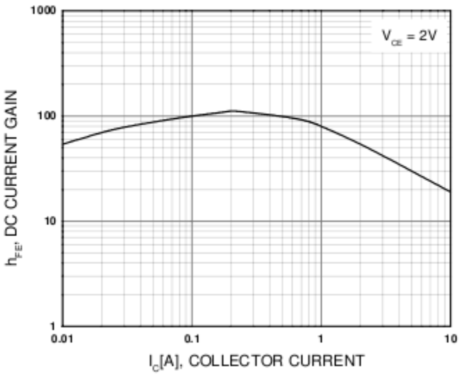


Figure 1. DC current Gain

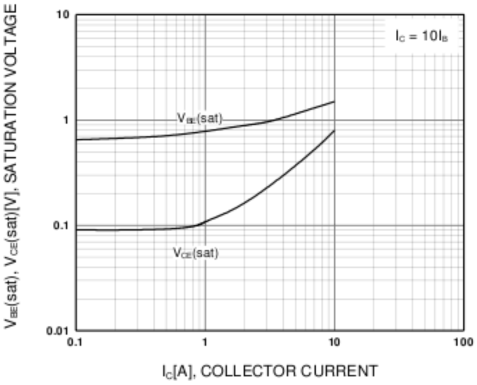


Figure 2. Base-Emitter Saturation Voltage
Collector-Emitter Saturation Voltage

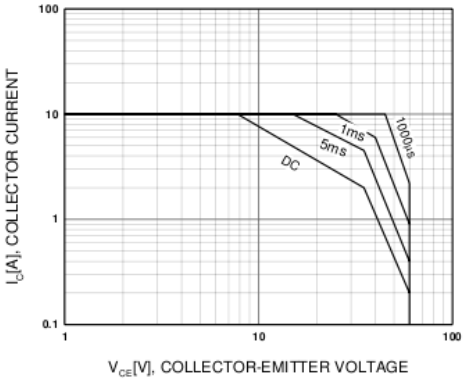


Figure 3. Safe Operating Area

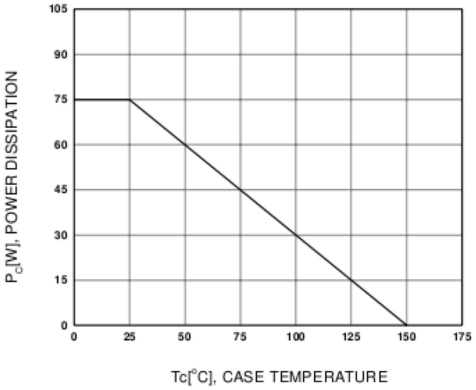


Figure 4. Power Derating

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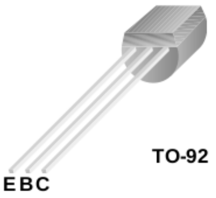
October 2011

2N3904 / MMBT3904 / PZT3904
NPN General Purpose Amplifier

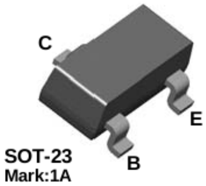
Features

- 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.

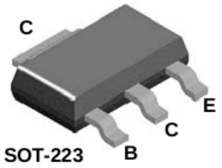
2N3904



MMBT3904



PZT3904



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	$I_C = 10\mu A, I_E = 0$	60		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	$I_E = 10\mu A, I_C = 0$	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	$I_C = 100\mu A, V_{CE} = 5.0V$, $R_S = 1.0k\Omega$, 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