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HOMEBREWER No. 5

GENERAL PURPOSE

NPN TRANSISTORS

Plastic Encapsulated

СВЕ

Metal Can Transistor

The

TO-92

TO-18

Bottom

View

SOT-23

Transistor

Surface Mount

Transistor

2N2222

2N3904

2N4401 **MPS2222**

MPS3904

MMBT2222LT1

MMBT3904LT1

MMBT4401LT1

Paul Harden, NA5N

The Handyman's Guide to -UNDERSTANDING TRANSISTOR DATA SHEETS & SPECIFICATIONS

Introduction

The most common bipolar junction transistors (BJT) used by hobbyists and ORPers are the 2N2222, 2N3904 and 2N4401. These NPN transistors have similar characteristics, and perform well at HF frequencies.

This tutorial explains how to "read" the data sheets on these devices and understand the specifications – which will enable vou to interpret data sheets for other devices as well.

The manufacturer's data sheets contains information in the following general categories:

- 1. Maximum (Breakdown) Ratings
- 2. "On" Characteristics
- 3. Small Signal Characteristics
- 4. Switching Characteristics

1. Maximum (Breakdown) Ratings

The maximum ratings are provided to ensure that the voltages and currents applied do not damage or cause excessive heating to the device. The maximum ratings fo the 2N2222, 2N3904 and 2N4401are shown in Table 1 The voltages, currents and power dissipation listed should not be exceeded to prevent damage to the device.

VCEO is the maximum collectoremitter voltage and VCBO is the maximum collector-base voltage. Fortunately, these breakdown voltages are well above the typical 12v used in most QRP applications.

This is not the case with VEBO, the maximum emitter-base voltage, typically 5-6v. If exceeded, this can cause a physical breakdown of the base junction, destroying the

Table 1 – MAXIMUM (BREAKDOWN) RATINGS									
	2N 2222	2N 2222A	2N 3904	2N 4401	MMBT 3904				
Collector–Emitter	Vceo	30v	40v	40v	40v	40v			
Collector-Base	Vсво	60v	75v	60v	60v	60v			
Emitter–Base	Vebo	5v	6v	6v	6v	6v			
Max. Coll. Current	lc	600mA	600mA	200mA	600mA	200mA			
Power dissipation	Pd	625mW	625mW	625mW	625mW	225mW			

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- MAXIMUM (BREAKDOWN) RATINGS									
	2N 2N 2N 2N MMBT 2222 2222A 3904 4401 3904								
	VCEO	30v	40v	40v	40v	40v			
	Vсво	60v	75v	60v	60v	60v			
	Vebo	5v	6v	6v	6v	6v			
:	lc	600mA	600mA	200mA	600mA	200mA			
	Pd	625mW	625mW	625mW	625mW	225mW			
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transistor. In a circuit, the biasing scheme sets the baseemitter voltage, VBE, to be safely below VEBO. However, in large-signal applications, VBE must include the DC base bias and the peak voltage of the signal to ensure VEBO will not be exceeded.

Collector Current, Ic(max), is the other maximum rating to be closely followed. Collector current exceeding lc(max) can damage the transistor, due to excessive current through the device, initiating thermal runaway – destroying the collector-emitter junction. The destruction of a transistor

in this manner is technically called catastrophic substrate failure for good reason!

Most QRP circuits are usually biased for well below lc(max). Vbe(max) and Ic(max) are generally a concern only in largesignal applications, such as RF drivers, PA stages, and some oscillator circuits.

2. ON CHARACTERISTICS

These specifications define the DC performance of the device while it is forward biased (Vbe \geq 0.7v), causing collector current to flow, or "on." The DC

Characteristics in **Table 2** are not absolute design values, but rather test values as measured by the manufacturer. This is why the data is listed with the test conditions, such as "Ic=1mA. VCE=10v."

HFE is the measured DC current gain of the transistor (see *Rule of thumb for HFE*). It is used for biasing the device in the linear region – primarily class A. Most data sheets provide HFE at two different collector currents, usually 1 and 10mA. Since most QRP circuits are biased for Ic <5mA (to conserve battery drain), HFE at Ic=1mA is typically used.

HFE also varies from transistor-to-transistor. This is why the data sheets list both HFE (min) and HFE (max). The manufacturer tested a large batch of 2N2222s and determined that hfe ranged from 50 (HFE min) to 150 (HFE max) at Ic=1mA, as shown on the data sheets (Table 2). Statistically, most transistors will fall between 50 and 150, or about HFE=100. This is why most design guides will recommend using a value of HFE=100 for bias calculations. Since the 2N3904 has a higher DC current gain, often HFE=150 is recommended for that device.

HFE min. and max, at Ic=1 and 10mA, can be plotted on a logarithmic graph (lines 1 and 2 on **Fig. 1**). The average

- Rule of thumb for VEBO: VEBO(max) or Vbe(max) for most general purpose BJTs is 5-6v – the maximum emitter-base voltage. Don't forget to include the peak voltage of the AC signal!
- Rule of thumb for lc(max): There isn't one! The only safe way to know the maximum Ic for a transistor is to consult the data sheets.

Table 2 – DC "ON" CHARACTERISTICS									
		2N 2222	2N 2222A	2N 3904	2N 4401	MMBT 3904			
DC Current Gain, HFI	Ξ								
Ic= 0.1mA, VCE=10v	HFE Min.	35	35	40	20	40			
Ic=1.0 mA, VcE=10v	HFE Min. HFE Max.	50 150	50 150	70 200	40 —	70 200			
Ic= 10 mA, Vce=10v	HFE Min. HFE Max.	75 225	75 250	100 300	80 —	100 300			
Collector-Emitter Sat Ic= 150mA, IB= 15mA	tage, Vc i 0.4vdc	=(sat) 0.3vdc	0.3vdc†	0.4vdc	0.2vdc†				
Base-Emitter Saturation Voltage, VBE(sat)Ic= 150mA, IB= 15mAVBE(sat)1.3vdc1.2vdc0.85vdc0.95vdc.85v						.85vdc†			
† Ic=50mA, Iв=5mA on 2N3904									

0.1 0.2 0.3 0.5



Rule of thumb for <u>HFE</u>:

Conventions used in electronic literature:

5

10

2 3

1

Collector Current, Ic (mA)

3

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value, HFE typ., can then be drawn (line 3, Fig. 1). This gives you HFE (typ) for various collector currents.

The value used for HFE is not critical. Using HFE=100, or even the conservative value of 50, will work 99% of the time. Therefore, one scarcely needs the data sheets for the DC characteristics, as the typical HFE = 100 at Ic=1mA is valid for most general purpose NPN transistors. Fig. 2 shows Ib vs. Ic for HFE at 50 and 100.

Saturation voltages, VCE(sat) and VBE(sat), defines the transistor behavior outside the linear operating region, that is, in the saturated region. This is of interest when operating the transistor as a saturated switch. The keying transistor in a transmitter, forming the +12v transmit voltage on key-down, is an example of a saturated switch.

3. SMALL SIGNAL CHARACTERISTICS

The small-signal characteristics describe the AC performance of the device. There is no standardized industry definition of smallsignal (vs. large-signal), but is generally defined where the AC signal is small compared to the DC bias voltage. That is, the signal levels are well within the linear operating region of the transistor.

The small signal characteristics include:

- 1) gain bandwidth product (Ft)
- 2) the AC current gain (hfe)
- 3) input and output impedances (hie and hoe)
- 4) input and output capacitances (Cibo and Cobo)
- 5) the noise figure (NF).

The small signal parameters are the most important to understand, as they describe the transistor's behavior at audio and RF frequencies, and used in the circuit design equations. These parameters vary greatly from one

transistor type to another, such that making assumptions (as we did with DC HFE =~100) can be risky. The data sheets must be used. The small-signal characteristics for Ft and hfe, from the data sheets, are shown in Table 3

Gain Bandwidth Product, or Ft, is defined as the frequency at which the AC current gain, hfe, equals 1 (0dB). See Fig. 3 (next page). This is the maximum frequency the device produces gain as an amplifier or oscillator.

On RF transistor data sheets, Ft is not always given. Instead, the power gain, Gp (or Gpe for common emitter power gain) is tested at a specific frequency. Ft can be derived from this information as shown in **Table 4**. Equations *x* and *Gp(mag)* convert the power gain, in dB, to unitless magnitude, as is hfe.

Rule of thumb for <u>HFE</u>:

Most general purpose NPN transistors have a DC HFE = 100 (typ) and thus used in most biasing equations for DC and low frequencies.



Table 3 – SMALL SIGNAL CHARACTERISTICS – Part 1								
		2N 2222	2N 2222A	2N 3904	2N 4401	MMBT 3904		
Gain Bandwidth Prod.	Ft (MHz).	250	300	300	250	300		
Small Signal Current Gain, hfe								
Ic=1.0 mA, Vce=10v†	hfe Min. hfe Max.	50 300	50 300	100 400	40 500	100 400		
Estimated	hfe Typ.	150	150	200	225	200		
Ic= 10 mA, Vce=10v †	HFE Min.	75 375	75 375	—	—	—		
† Measured at 1 KHz		515	515					

Table 4 – Calculating Ft from Gpe

$$x = \frac{\operatorname{Gp}(\operatorname{dB})}{10}$$
 Gp(ma

$$Gp(mag) = 10$$

Example:

The data sheet for the 2N5179 lists Gpe=15dB at 200MHz. Determine Ft.

$$x = \frac{15dB}{10} = 1.5$$
 Gp(mag)= $10^{1.5} = 32$
Ft = 200MHz $\sqrt{32} = 1130$ MHz

hfe is the **ac small-signal current gain**, and dependent on both frequency and the collector current. Hfe is also known as the *ac beta*. Ft and hfe work together to define the overall AC gain of the transistor at a specific frequency, as illustrated in **Fig. 3**.

hfeo is the low-frequency hfe, often very close to the DC HFE. The values for hfe shown in the data sheets are normally measured at 1KHz and Ic=1mA (sometimes @10mA). Hfeo is fairly constant from the audio frequencies to about 300 KHz.

<u>Beta cut-off frequency</u>, **f**, is the "3db point" of hfe, where hfe= 0.707hfeo, or f =Ft/hfeo. F is seldom listed on the data sheets.

 \mathbf{hfe} drops fairly linearly from f to Ft at 6dB/octave.

F , and the hfe vs. frequency plots, are seldom shown in the data books. This is why learning to interpret the data sheets is important to determine the actual gain (hfe) a transistor will provide at a specific frequency.

Design Example: Constructing an Hfe vs. Frequency Plot

Let's figure out what he will be for a 2N2222 on the 40M band, using both graphical and equational methods. It's really easy.

From **Table 3**, hfe=50 (min) to 300 (max). Let's pick hfe=150 as the average. Since hfe is measured at 1KHz, this is also **hfeo**. Draw a line on a chart to represent hfeo=150 (line #1, **Fig. 4**).

Calculate f and hfe @f as follows: (Ft=250MHz, 2N2222)

f = Ft/hfeo = 250MHz 150 = 1.7 MHz

hfe@f = .707hfeo = 0.707 x 150 = 106

Draw a dot at hfe@f on the chart (hfe=106 @ 1.7 MHz)

Or ... calculate hfe at the desired frequency, fo, such as 7MHz

hfe@fo = Ft/fo = 250MHz 7MHz = 36

Draw a line between f (or fo) and Ft (line #2, **Fig. 4**) to complete the hfe vs. frequency plot of the 2N2222 at Ic=1mA.

Therefore, at 7 MHz

ac gain is hfe = 36

How much signal gain will the 2N2222 provide at 144 MHz?

hfe = Ft/fo = 250MHz 144MHz = 1.7, or almost unity!

This is why general purpose transistors (Ft <400MHz) are not used at VHF for lack of useful gain above ~50 MHz.

Hfe vs. Ic. Hfe is also a function of Ic as shown in **Fig. 5**. This data sheet chart is used to adjust hfe at Ic other than 1mA, where hfe is measured. For designing battery powered circuits, Ic=1mA is recommended. Firstly, data sheet values can be used directly, saving additional calculations, since most parameters are listed for Ic=1mA. Secondly, these transistors have ample gains at Ic=1mA or less. The additional gain at a higher Ic may not justify





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the increase in battery drain. I.e., two amplifiers at Ic=1mA will yield far more gain than one amplifier at Ic=2mA.

Table 6 shows he at differentfrequencies for the 2N2222.

Table 5 lists the remaining small-
signal characteristics.

Input impedance, hie, is the resistive element of the baseemitter junction, and varies with Ic. It is used for input impedance calculations, and not particularly

useful in itself without considering Cibo.

Input capacitance, Cibo, is the capacitance across the baseemitter junction. For the 2N2222, Cibo(max)=30pF. The reactance (Xc) of Cibo is in parallel with hie (Xc||hie) – causing the equivalent input impedance, Zin, to be frequency dependent as shown in **Table 6**. As can be seen, Xc(Cibo) dictates the input impedance of the transistor, *not hie*. Cibo is thus important in estimating Zin at any given frequency. In selecting a transistor for RF, the smaller the value of Cibo, the better. In this case, the input *impedance* is called Zin, since it includes the frequency dependent *reactance* components.

Input resistance, Rin, for the common-emitter transistor, can also be estimated using hfe and emitter current, le, as follows:

Rin = re(hfe+1) where, re = 26 le(mA) (le lc)

The results of Rin from the above are also shown in **Table 6** for comparison. This method is generally preferred since he and le are known with greater accuracy than is hie and Cibo. In this case, the input *impedance* is called Rin, since it only includes resistive components (no *reactance* components).

The differences between the two methods, while close, demonstrates the difficulty in determining with certainty the input impedance of a transistor.

Output Admittance, hoe, represents the output resistance of the transistor by taking the reciprocal of the admittance. For example, at hoe(typ)=10umhos, Rout = 1/hoe = 1/10umhos = 100K. Like hie, hoe is not particularly useful by itself.

Output Resistance, Ro, is approximately the parallel equivalent of hoe and the collector load resistance, Rc, or Ro = Rc||hoe. See **Fig. 6**. Since Rc tends to be in the 1–5K range, and hoe 20–100K , Rc will dominate the output resistance of the transistor. As a result, output impedance is usually estimated by: Zo Rc. Note that the output impedance is set primarily by circuit values (Rc), and not by the transistor's small-signal parameters.

Table 5 - SMALL SIGNAL CHARACTERISTICS - Part 2								
		2N 2222	2N 2222A	2N 3904	2N 4401	MMBT 3904		
Input capacitance ‡ Output capacitance ‡	Cibo (max) Cobo (max)	30pF 8pF	25pF 8pF	8pF 4pF	30pF 7pF	8pF 4pF		
Input Impedance, typ. †	hie (min) hie (max)	2K 8K	2K 8K	1K 10K	1K 15K	1K 10K		
Output Admittance †	hoe (min) hoe (max)	5* 35*	5* 35*	1* 40*	1* 30*	1* 40*		
Noise Figure †	NF (max)	4dB	4dB	5dB	4.5dB	4dB		
† Measured at 1 KHz	‡ Measure	d at 1 Mł	Hz * m	nhos				

Table 6 – 2N2222 Input Impedances

based hfeo=	l on 150	based hfe and	on I re	base Xc(Cibc	d on)) hie ↓		
Freq	hfe	Rin		Xc(Cibo)	Zin		
3.5	71	1872		1516	1150		
7.0	36	962		758	658		
10.1	25	676		525	475		
14.0	18	494		379	352		
21.0	12	312		253	241		
28.0	9	234		190	183		
50.0	5	130		106	104		
144	2	52		37	36		
Rin=re(hfe+1)				Zin(eq) =	Xc hie		
where,				where,			
re=26/le(mA)				Cibo = 30pF			
=26 @1mA				hie = 5k	(

Fig. 6 – Input/Output Impedances basic amplifier configuration



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Cobo is the **output capacitance**, and is in parallel with the output resistance. However, Cobo is <10pF in most general purpose NPN transistors and has little effect at HF. This parameter is important in RF transistors operating in the VHF/UHF spectrum, where the shunting effect becomes a significant component of the output impedance. Obviously, the lower the value of Cobo, the better.

Noise Figure, NF, is defined as the ratio of the input to the output noise, neither of which is easily measurable by the amateur. The transistor will add noise, then be amplified by the hfe of the device just as the signal is, forming signal plus noise output, or S+N. The excess in the S+N to signal power is due to the noise figure (NF) of the device.

For the QRPer, the NF of the transistor is not highly important on HF. See **Table 7**. Select a transistor with a low NF for the audio stage(s), however, as this is where it will be the most evident.

Transconductance, gm, is another parameter provided on some data sheets. If not provided, gm can be estimated by: $gm = .038 \times le(mA)$.

4. SWITCHING CHARACTERISTICS

The Switching Characteristics define the operating limits of the transistor when used in pulsed, digital logic, or switching applications. QRP switching circuits include T-R switching, CW keying and band switching circuits using transistors. These are really large-signal characteristics, since the transistor is being driven from cut-off to saturation in most switching applications.

Fig. 7 illustrates the switching characteristics terms:

td, delay time is the time from the input L–H transition until the output begins to respond.

tr, rise time is the time it takes the output to go from 10% to 90% output voltage.

ts, **storage time** is the time from the input H–L transition until the output responds. This is usually the longest delay. **tf**, **fall time** is the time it takes the output to go from 90% to 10% output voltage.

These switching times, in the tens of nanoseconds, are thousands of times faster than the requirements for QRP applications, and seldom a design criteria when selecting a transistor. It is presented here for completeness only.

This tutorial should allow one to interpret the transistor data sheets, whether the complete data sheets from the manufacturer, or the abbreviated listings, such as found in the NTE Cross-Reference or in the ARRL Handbook. Many manufacturer's provide complete data sheets online. Understanding transistor specifications is essential in designing your own circuits, or identifying those "ham fest special" transistors and their suitability for your next project. Biasing transistors using these specs will be presented in a future *Handyman's* tutorial.

Table 7 – HF vs VHF Noise Figures

At HF – antenna and atmospheric noise is in the 20–30dB range, far exceeding the 10-12dB NF of a typical HF receiver. In other words, more noise is introduced to the receiver by the antenna and band conditions than the NF of the stages can introduce. For HF receiver applications, a NF of 4-6dB per transistor is sufficient. This is not the case at VHF.

At VHF/UHF – antenna and atmospheric noise is very low, often less than 10dB of noise power, making the overall system noise a function of the receiver, and the NF of the individual stages. At VHF/UHF, the NF of the transistors becomes very important, with transistors being selected with NF's in the 1.5dB to 2dB range not uncommon.

Table 8 – SWITCHING CHARACTERISTICS									
		2N 2222	2N 2222A	2N 3904	2N 4401	MMBT 3904			
Delay time	td	10ns	10ns	35ns	15ns	35ns			
Rise time	tr	25ns	25ns	35ns	20ns	35ns			
Storage time	ts	225ns	225ns	200ns	225ns	200ns			
all time	tf	60ns	60ns	50ns	30ns	50ns			



