XMUT204 Electronic Design

Demo 6 – BJT Circuit Simulation in LTspice

A. Introduction

This exercise is about SPICE Modelling of a BJT in LTspice from given manufacturer datasheet. BJT bipolar transistors require a certain number of parameters to get a good model. The syntax for the NPN type of this model is:

```
.model ModelNameNPN (par1=a par2=b………parn=x)
```

For PNP case:

```
.model ModelNamePNP (par1=a par2=b … parn=x)
```

Where `par1, par2, … parn` are the parameters that allow to model equations of the BJT.

B. Spice Parameters of BJT Model

The main parameters for a reasonable modelling of the behaviour of the component are summarized in the following table:

Parameters	Description	Units	Default Value
`IS`	Transport saturation current	A	1e-16
`XTI`	IS temperature effect exponent	no unit dimension	3.0
`EG`	Bandgap voltage (barrier height)	eV	1.11
`VAF`	Forward Early voltage	V	Infinite
`BF`	Ideal maximum forward beta	no unit dimension	100
`ISE`	Base-emitter leakage saturation current	A	0
`NE`	Base-emitter leakage emission coefficient	no unit dimension	1.5
`IKF`	Corner for forward-beta high-current roll-off	A	Infinite
`NK`	High-current roll-off coefficient	no unit dimension	0.5
`XTB`	Forward and reverse beta temperature coefficient	no unit dimension	0
`BR`	Ideal maximum reverse beta	no unit dimension	1.0
`ISC`	Base-collector leakage saturation current	A	0
`NC`	Base-collector leakage emission coefficient	no unit dimension	2.0
`IKR`	Corner for reverse-beta high-current roll-off	A	Infinite

RC	Collector ohmic resistance	Ohm	0
CJC	Base-collector zero-bias p-n capacitance	F	0
MJC	Base-collector p-n grading factor	no unit dimension	0.33
VJC	Base-collector built-in potential	V	0.75
FC	Forward-bias depletion capacitor coefficient	no unit dimension	0.5
CJE	Base-emitter zero-bias p-n capacitance	F	0
MJE	Base-emitter p-n grading factor	no unit dimension	0.33
VJE	Base-emitter built-in potential	V	0.75
TR	Ideal reverse transit time	sec	1e-8
TF	Ideal forward transit time	sec	0
ITF	Transit time dependency on Ic	A	0
XTF	Transit time bias dependence coefficient	no unit dimension	0
VTF	Transit time dependency on Vbc	V	Infinite
RB	Zero-bias (maximum) base resistance	Ohm	0

All these parameters are used by SPICE to represent the different functions that govern behaviour of the device in different situations. For example, base current in DC is calculated as:

`Ib = Junction surface *(Ibe1/BF + Ibe2 + Ibc1/BR + Ibc2),`

Where BF and BR are known parameters,

`Ibe1 = Direct Diffusion Current = IS*(e^(Vbe/(NF*Vt)) – 1)`

`Ibe2 = Base Emitter Current = ISE*(e^(Vbe/(NE*Vt)) – 1)`

`Ibc1 = Inverse Diffusion Current = IS*(e^(Vbe/(NR*Vt)) – 1)`

`Ibc2 = Base Collector Current = ISC*(e^(Vbe/(NC*Vt)) – 1)`

Similarly, there are functions for the collector current, for the determination of the base-emitter capacitance, base-collector capacitance, and features that investigate the influence of temperature for different parameters.

In this case, we will model a BJT transistor, NPN type, the BC548A, from datasheet info. Unlike the diode in which we could obtain different data directly from datasheet and from semi-empirical rules, we have few data that can be used directly, most of the parameters have to be extracted from datasheet graphs through the use of Spice Model Editor tools.

C. Modelling of a BJT Transistor from its Datasheet

We begin with the parameters that can be set to their default values without significant influence on the modelling. Assume: IS temperature effect exponent, bandgap voltage (barrier height), forward and reverse beta temperature coefficient, ideal reverse transit time and forward-bias depletion capacitor coefficient as default values.

`XTI=3,EG=1.11 eV,XTB=0,TR=10ns, FC=0.5`.

See below first pages of the datasheet for BC548A (see Appendix – Datasheet of BC548 BJT transistor).

The only information we can use directly is essentially the maximum value of `fT` at 300 Mhz, which allows us to estimate ideal forward transit time:

`TF=1/(6.28*300*10^6)=530ps`.

See other parameters obtained from the graphs of the datasheet.

Observe the evolution of `Vbe(sat)/Ic`, with respect to the ratio `Ic/Ib=10`, in the following voltage vs. collector current chart in the datasheet.

BC546, B BC547, A, B, C BC548, A, B, C

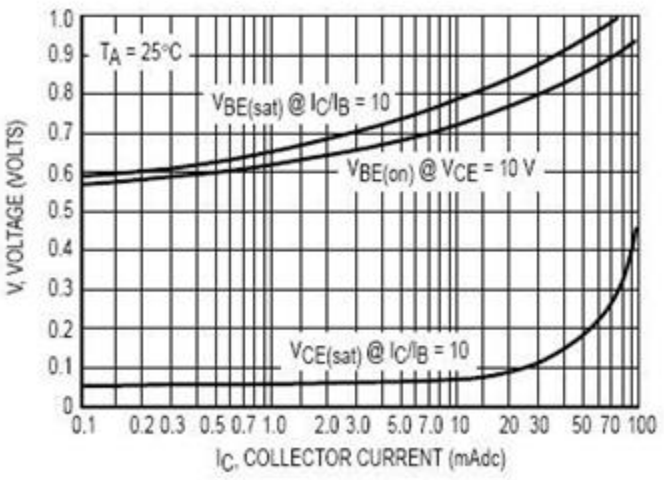


Figure 2. "Saturation" and "On" Voltages

From this first curve we find IS and RB. We obtain IS=8.172 fA and RB=32.751, then we set these values and continue.

In the next graph, we must report the so-called output admittance (h parameters vs. collector current) from the datasheet.

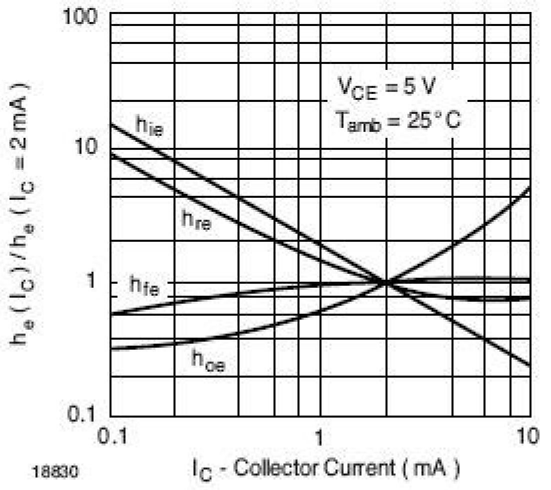


Figure 8. Relative h-Parameters vs. Collector Current

Now we get: VAF=139.172

Set the value found and continue with the next normalised current gain vs. collector current graph from the datasheet: `hfe` versus the collector current (Ic).

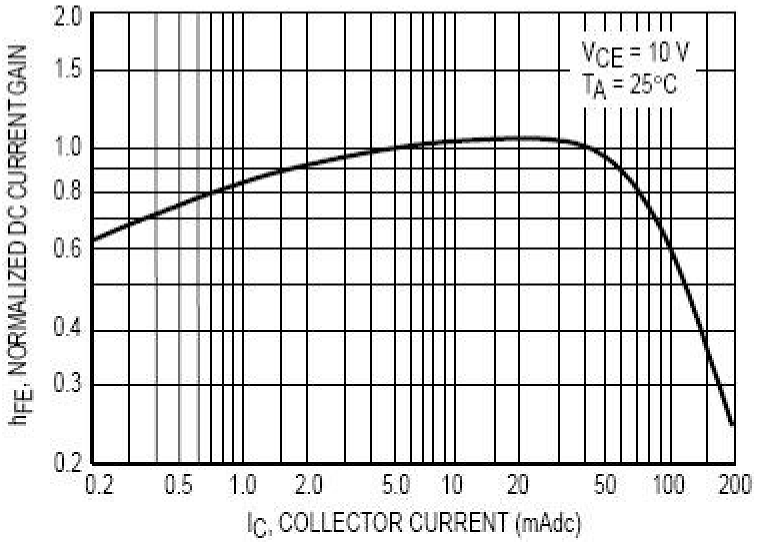


Figure 1. Normalized DC Current Gain

From this curve, we can extract: ideal maximum forward beta, corner for forward-beta high-current roll-off, base-emitter leakage saturation current, base-emitter leakage emission coefficient, and high-current roll-off coefficient.

`BF=212.95, IKF=208.44mA, ISE=65.20fA, NE=1.37, NK=0.839.`

And get from the plot the values for: ideal maximum reverse beta, corner for reverse-beta high-current roll-off, base-collector leakage saturation current, base-collector leakage emission coefficient, and collector ohmic resistance.

`BR=0.608, IKR=2.152, ISC=13.68fA, NC=1.80, and RC=0.86Ohm.`

Fix the data and see capacitance vs. reverse voltage graph from the datasheet. Adjust the values of the data.

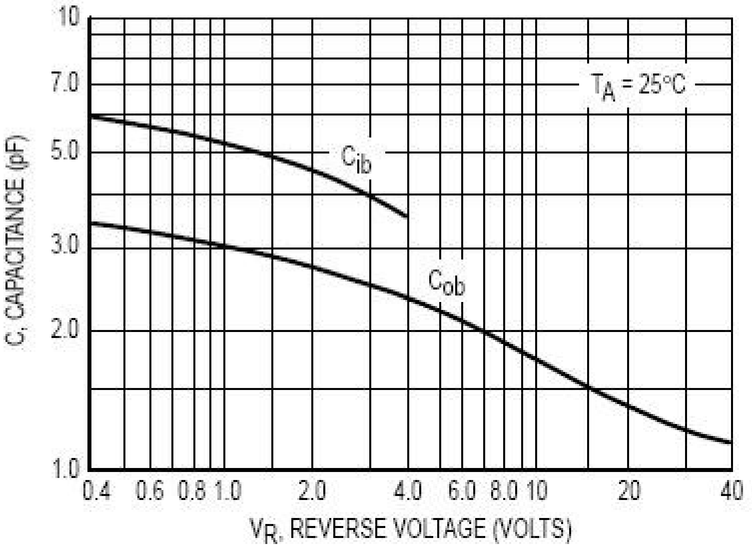


Figure 5. Capacitances

Input `Cob` data and get the curve.

Extracted data are: base-collector zero-bias p-n capacitance, base-collector built-in potential and base-collector p-n grading factor.

`CJC=3.968pF, VJC=0.833V, MJC=0.316`

Input data for `Cib` and we get.

From which we derive: base-emitter zero-bias p-n capacitance, base-emitter built-in potential, and base-emitter p-n grading factor.

`CJE=6.808pF, VJE=1.319 V, MJE=0.477.`

Check on Fixed to set the data. We have already estimated `TF=530ps`. Then, we can enter this value and fix it.

Remain to be determined are parameters such as transit time dependency on Ic `(ITF)`, transit time bias dependence coefficient `(XTF)`, and transit time dependency on Vbc (`VTF)`.

If we input data couples of values from the current gain to bandwidth graphic from the datasheet.

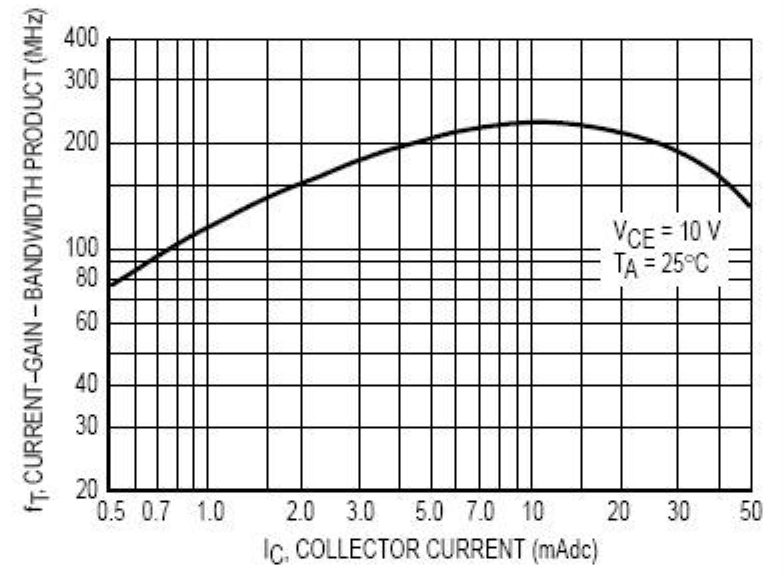


Figure 6. Current–Gain – Bandwidth Product

Set `XTF`, `VTF`, `ITF` to their default values `(10, 10, 1)`, we will see that the curve starts to match datasheet curve.

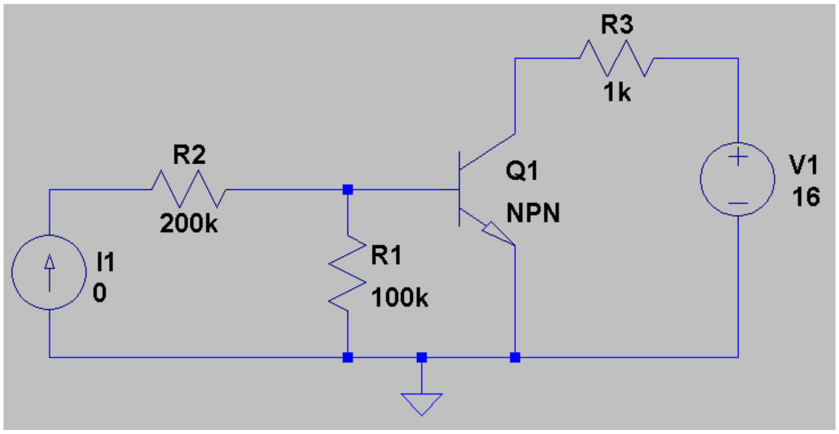
With a few attempts, we can have a good correspondence with the curve of the gain with the following values: `TF=670ps, XTF=150, VTF=10, ITF1=1.`

Finally, the model BC548A has the following expression:

```
.model BC548A NPN( Is=8.172f Xti=3 Eg=1.11 Vaf=139.172 Bf=212.95

+ Ise=62.50f Ne=1.37 Ikf=208.44m Nk=.839 Xtb=0 Br=0.608 Isc=13.68f

+ Nc=1.80 Ikr=2.152 Rc=.86 Cjc=3.968p Mjc=.316 Vjc=.833 Fc=.5

+ Cje=6.808p Mje=.477 Vje=1.319 Tr=10n Tf=670p Itf=1 Xtf=150

+ Vtf=10)
```

D. Testing of the Customised BJT Transistor

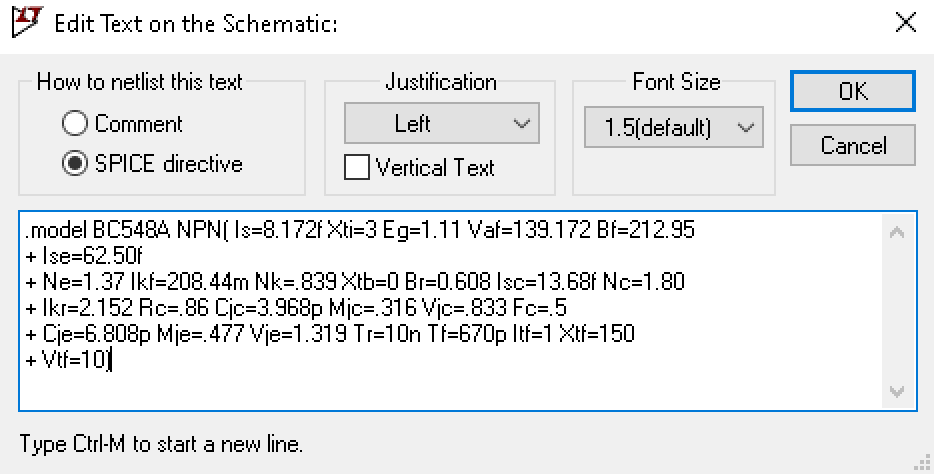
For testing the customised BJT transistor create the schematic of the circuit given below in LTspice.



Create a Spice directive that include the device definition of the customised BJT transistor as shown below.

```
.model BC548A NPN( Is=8.172f Xti=3 Eg=1.11 Vaf=139.172 Bf=212.95

+ Ise=62.50f Ne=1.37 Ikf=208.44m Nk=.839 Xtb=0 Br=0.608 Isc=13.68f

+ Nc=1.80 Ikr=2.152 Rc=.86 Cjc=3.968p Mjc=.316 Vjc=.833 Fc=.5

+ Cje=6.808p Mje=.477 Vje=1.319 Tr=10n Tf=670p Itf=1 Xtf=150

+ Vtf=10)
```

Edit the model description as given above in the Spice directive window.



How to netlist this text: ○ Comment ● SPICE directive

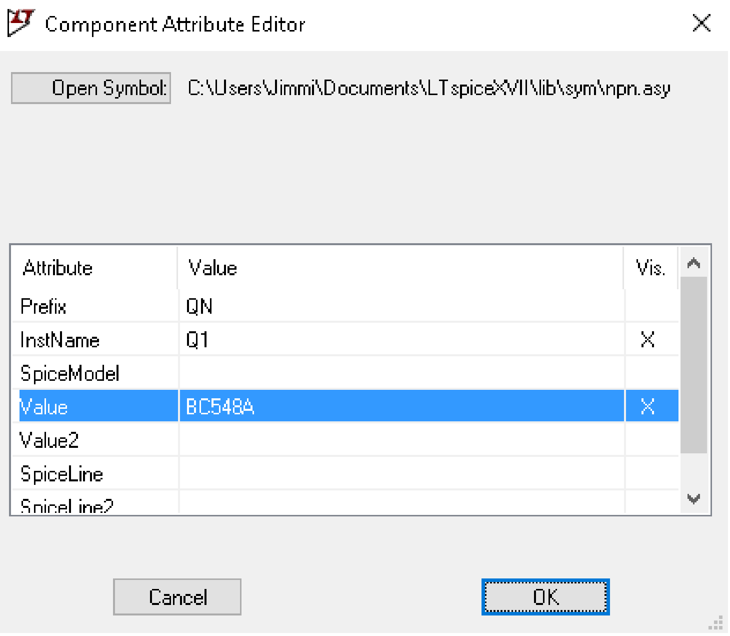
Justification: Left ☐ Vertical Text

Font Size: 1.5(default)

```
.model BC548A NPN( Is=8.172f Xti=3 Eg=1.11 Vaf=139.172 Bf=212.95
+ Ise=62.50f
+ Ne=1.37 Ikf=208.44m Nk=.839 Xtb=0 Br=0.608 Isc=13.68f Nc=1.80
+ Ikr=2.152 Rc=.86 Cjc=3.968p Mjc=.316 Vjc=.833 Fc=.5
+ Cje=6.808p Mje=.477 Vje=1.319 Tr=10n Tf=670p Itf=1 Xtf=150
+ Vtf=10)
```

Type Ctrl-M to start a new line.

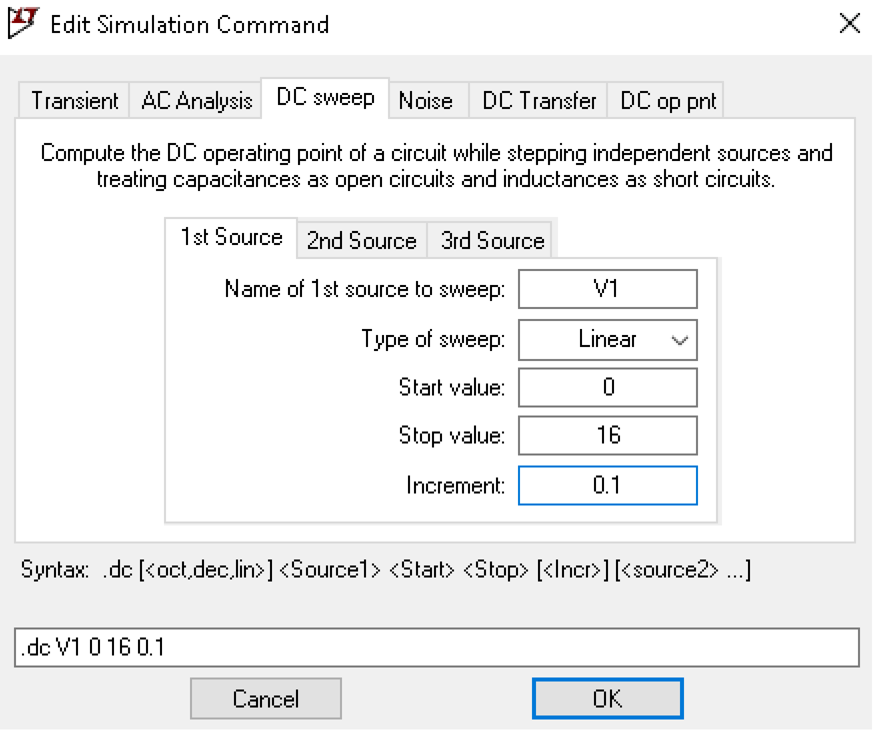
Assign the NPN transistor in the circuit for this customised BJT transistor.



C:\Users\Jimmi\Documents\LTspiceXVII\lib\sym\npn.asy

Attribute	Value	Vis.
Prefix	QN	
InstName	Q1	X
SpiceModel		
Value	BC548A	X
Value2		
SpiceLine		
SpiceLine2		

Test the circuit with the customised BJT transistor by plotting the current to voltage curve characteristics of the given BJT transistor. To achieve this, click run and swap to the DC Sweep tab and edit the voltage source V1 in the circuit in the 1st Source tab as seen in the figure below.



Compute the DC operating point of a circuit while stepping independent sources and treating capacitances as open circuits and inductances as short circuits.

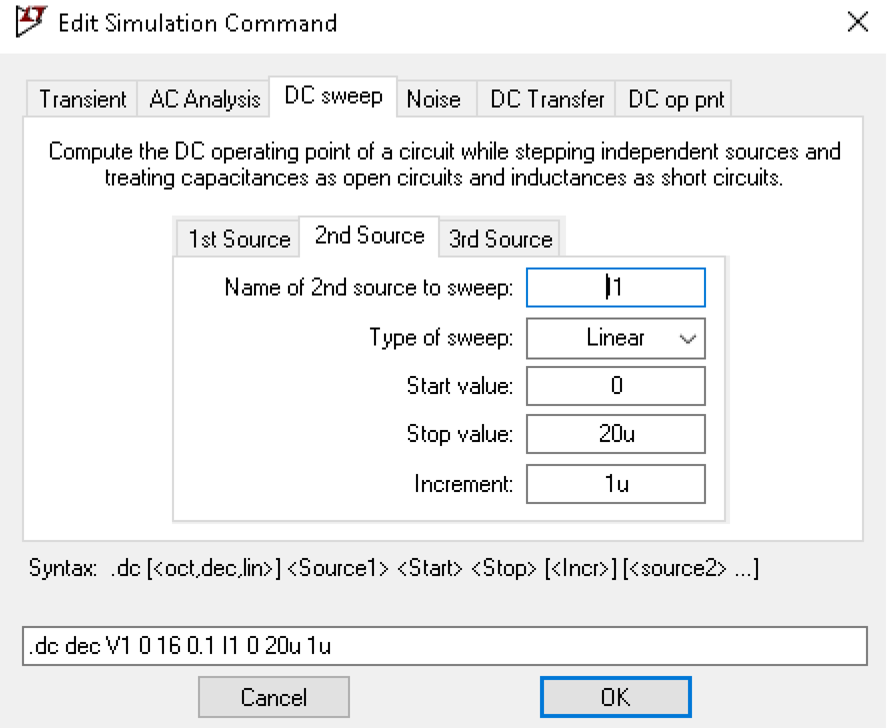
Name of 1st source to sweep: V1
Type of sweep: Linear
Start value: 0
Stop value: 16
Increment: 0.1

Syntax: .dc [<oct,dec,lin>] <Source1> <Start> <Stop> [<Incr>] [<source2> ...]

```
.dc V1 0 16 0.1
```

The V1 is the voltage source that we sweep. We are using linear interpolation starting at 0 V and ending at 16 V (can be any number of preference), and the increment is each 0.1 V. This will create a smooth linear input voltage rise.

Then, click the 2nd Source tab to edit the values for the current source I1.



Compute the DC operating point of a circuit while stepping independent sources and treating capacitances as open circuits and inductances as short circuits.

Name of 2nd source to sweep: I1

Type of sweep: Linear

Start value: 0

Stop value: 20u

Increment: 1u

Syntax: .dc [<oct,dec,lin>] <Source1> <Start> <Stop> [<Incr>] [<source2> ...]

```
.dc dec V1 0 16 0.1 I1 0 20u 1u
```

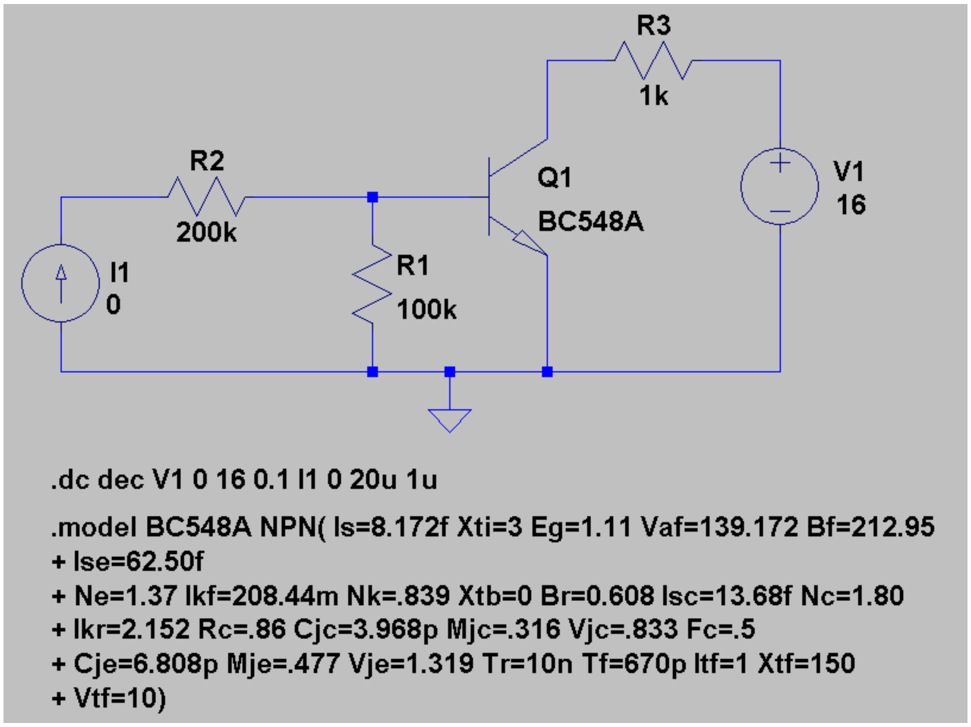
The second source is stepped in significant stages with linear interpolation.

Begin with 0 A and end with somewhere around 20 uA (can be more or less, depends on transistor choice and beta value, that is why experimentation works best with this method).

Use an increment value of 1 uA steps or anything beneath 20 uA. Click OK.

```
.dc dec V1 0 16 0.1 I1 0 20u 1u
```

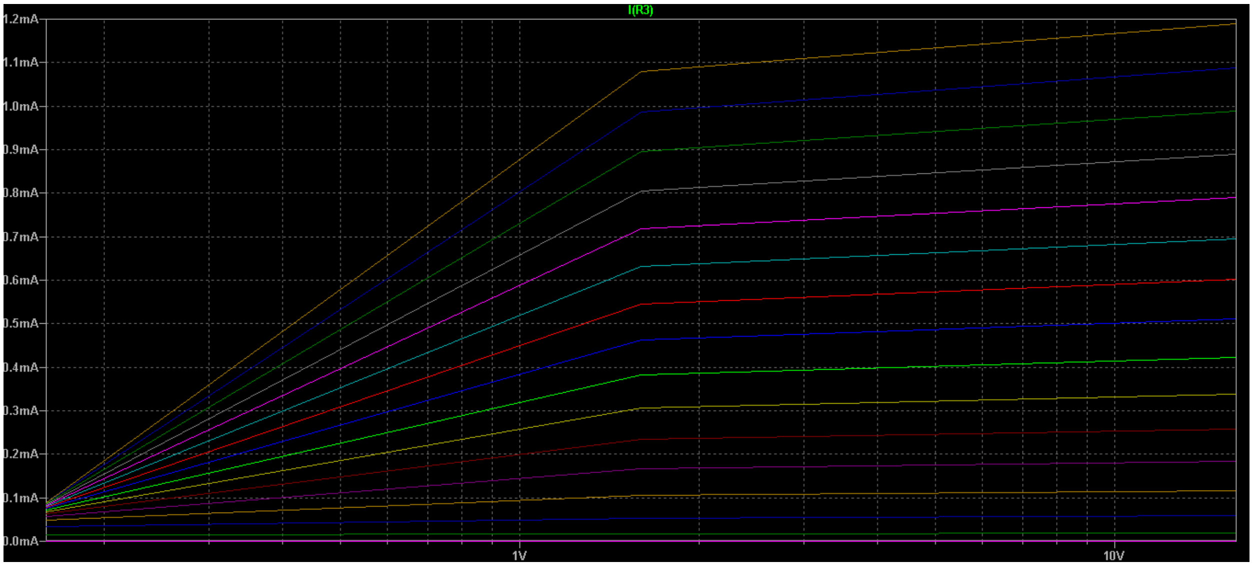
The final schematic of the customised BJT transistor circuit is shown in the following figure.



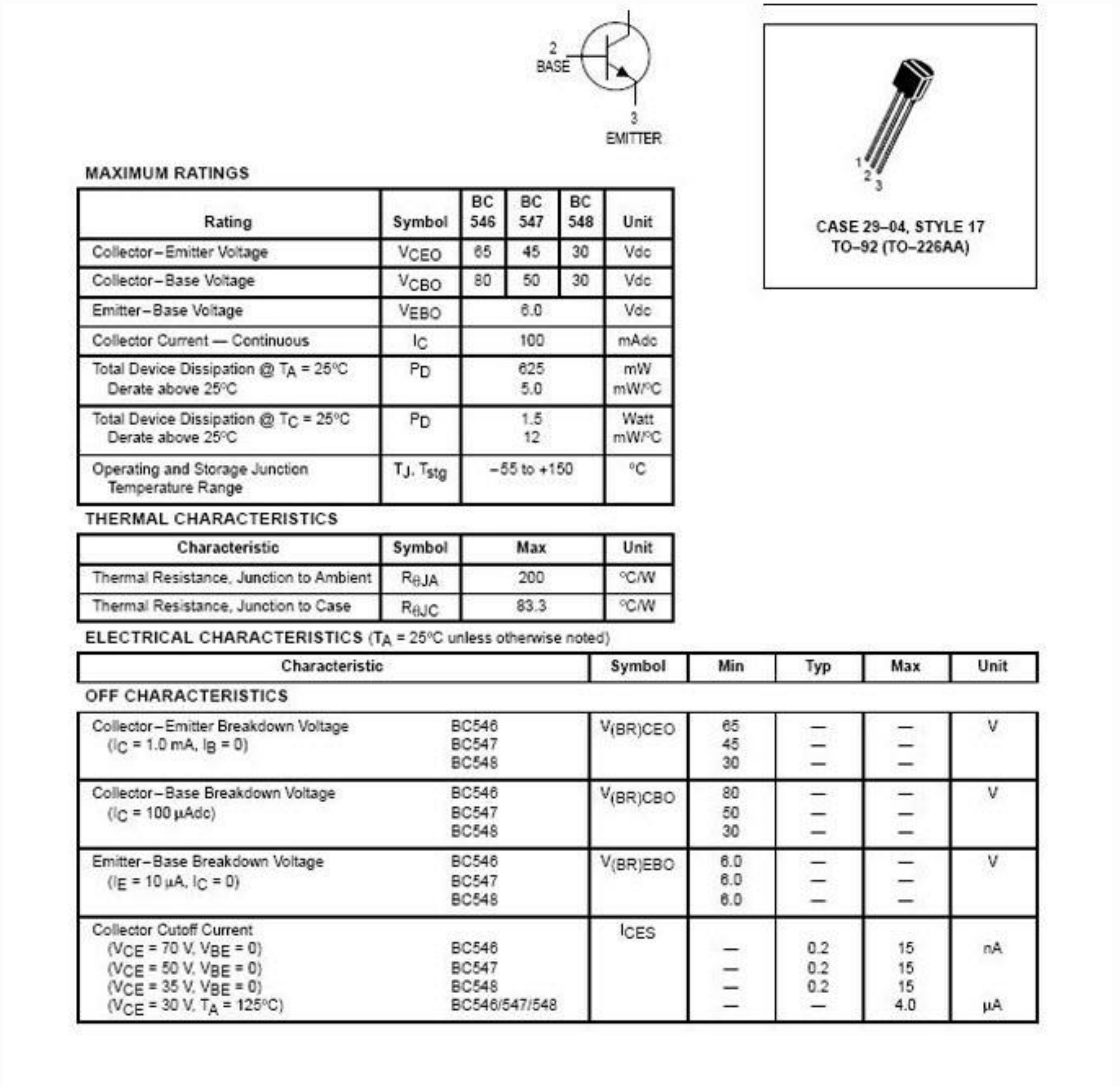
```
.dc dec V1 0 16 0.1 I1 0 20u 1u
.model BC548A NPN( Is=8.172f Xti=3 Eg=1.11 Vaf=139.172 Bf=212.95
+ Ise=62.50f
+ Ne=1.37 Ikf=208.44m Nk=.839 Xtb=0 Br=0.608 Isc=13.68f Nc=1.80
+ Ikr=2.152 Rc=.86 Cjc=3.968p Mjc=.316 Vjc=.833 Fc=.5
+ Cje=6.808p Mje=.477 Vje=1.319 Tr=10n Tf=670p Itf=1 Xtf=150
+ Vtf=10)
```

For plotting the current to voltage curve characteristics of the customised BJT transistor, probe the current on the leg where the 1 kΩ line goes into the transistor (the collector). A special symbol (i.e. a magnifying glass symbol) will show up if one hovers over the leg.

The plot given in the figure below is the voltage-to-current characteristics of the customised BJT.



Appendix – BC548 BJT Transistor



2
BASE

3
EMITTER

CASE 29–04, STYLE 17
TO–92 (TO–226AA)

MAXIMUM RATINGS

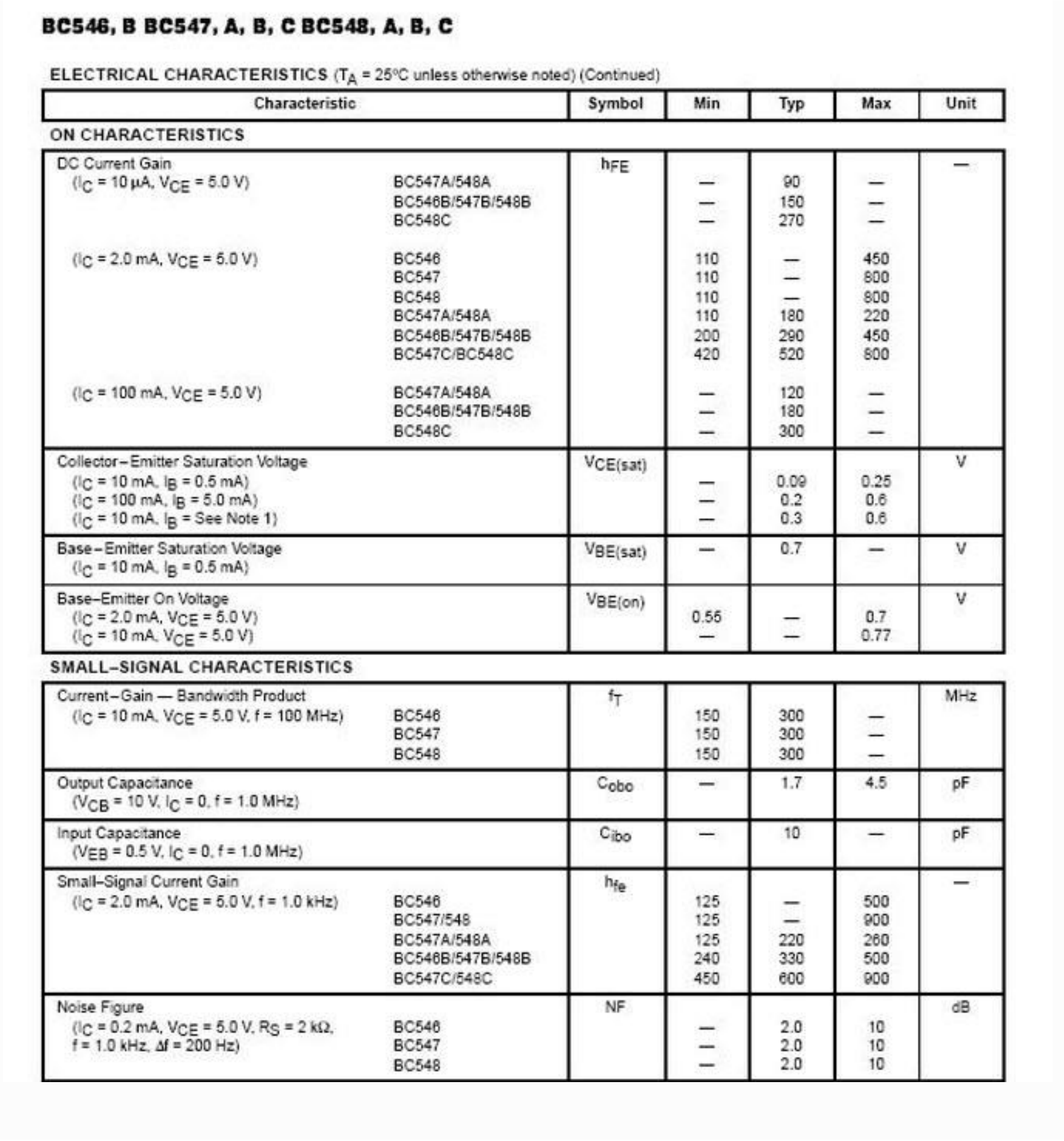
Rating	Symbol	BC 546	BC 547	BC 548	Unit
Collector–Emitter Voltage	V_{CEO}	65	45	30	Vdc
Collector–Base Voltage	V_{CBO}	80	50	30	Vdc
Emitter–Base Voltage	V_{EBO}	6.0			Vdc
Collector Current — Continuous	I_C	100			mAdc
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	625 5.0			mW mW/°C
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	1.5 12			Watt mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	–55 to +150			°C

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Ambient	$R_{\theta JA}$	200	°C/W
Thermal Resistance, Junction to Case	$R_{\theta JC}$	83.3	°C/W

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic		Symbol	Min	Typ	Max	Unit
OFF CHARACTERISTICS						
Collector–Emitter Breakdown Voltage (I_C = 1.0 mA, I_B = 0)	BC546 BC547 BC548	$V_{(BR)CEO}$	65 45 30	— — —	— — —	V
Collector–Base Breakdown Voltage (I_C = 100 μAdc)	BC546 BC547 BC548	$V_{(BR)CBO}$	80 50 30	— — —	— — —	V
Emitter–Base Breakdown Voltage (I_E = 10 μA, I_C = 0)	BC546 BC547 BC548	$V_{(BR)EBO}$	6.0 6.0 6.0	— — —	— — —	V
Collector Cutoff Current (V_{CE} = 70 V, V_{BE} = 0) (V_{CE} = 50 V, V_{BE} = 0) (V_{CE} = 35 V, V_{BE} = 0) (V_{CE} = 30 V, T_A = 125°C)	 BC546 BC547 BC548 BC546/547/548	I_{CES}	 — — — —	 0.2 0.2 0.2 —	 15 15 15 4.0	 nA μA



BC546, B BC547, A, B, C BC548, A, B, C

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted) (Continued)

Characteristic		Symbol	Min	Typ	Max	Unit
ON CHARACTERISTICS						
DC Current Gain		h_{FE}				—
(I_C = 10 μA, V_{CE} = 5.0 V)	BC547A/548A		—	90	—	
	BC546B/547B/548B		—	150	—	
	BC548C		—	270	—	
(I_C = 2.0 mA, V_{CE} = 5.0 V)	BC546		110	—	450	
	BC547		110	—	800	
	BC548		110	—	800	
	BC547A/548A		110	180	220	
	BC546B/547B/548B		200	290	450	
	BC547C/BC548C		420	520	800	
(I_C = 100 mA, V_{CE} = 5.0 V)	BC547A/548A		—	120	—	
	BC546B/547B/548B		—	180	—	
	BC548C		—	300	—	
Collector–Emitter Saturation Voltage		$V_{CE(sat)}$				V
(I_C = 10 mA, I_B = 0.5 mA)			—	0.09	0.25	
(I_C = 100 mA, I_B = 5.0 mA)			—	0.2	0.6	
(I_C = 10 mA, I_B = See Note 1)			—	0.3	0.6	
Base–Emitter Saturation Voltage (I_C = 10 mA, I_B = 0.5 mA)		$V_{BE(sat)}$	—	0.7	—	V
Base–Emitter On Voltage		$V_{BE(on)}$				V
(I_C = 2.0 mA, V_{CE} = 5.0 V)			0.55	—	0.7	
(I_C = 10 mA, V_{CE} = 5.0 V)			—	—	0.77	
SMALL–SIGNAL CHARACTERISTICS						
Current–Gain — Bandwidth Product		f_T				MHz
(I_C = 10 mA, V_{CE} = 5.0 V, f = 100 MHz)	BC546		150	300	—	
	BC547		150	300	—	
	BC548		150	300	—	
Output Capacitance (V_{CB} = 10 V, I_C = 0, f = 1.0 MHz)		C_{obo}	—	1.7	4.5	pF
Input Capacitance (V_{EB} = 0.5 V, I_C = 0, f = 1.0 MHz)		C_{ibo}	—	10	—	pF
Small–Signal Current Gain		h_{fe}				—
(I_C = 2.0 mA, V_{CE} = 5.0 V, f = 1.0 kHz)	BC546		125	—	500	
	BC547/548		125	—	900	
	BC547A/548A		125	220	260	
	BC546B/547B/548B		240	330	500	
	BC547C/548C		450	600	900	
Noise Figure		NF				dB
(I_C = 0.2 mA, V_{CE} = 5.0 V, R_S = 2 kΩ, f = 1.0 kHz, Δf = 200 Hz)	BC546		—	2.0	10	
	BC547		—	2.0	10	
	BC548		—	2.0	10	