0.0.1 Bipolar Junction Transistor **Q**

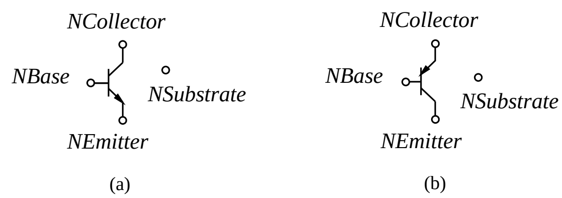

Figure 1: Q — bipolar junction transistor element: (a) NPN transistor; (b) PNP transistor.

Form:
`Q`*name NCollector NBase NEmitter* [*NSubstrate*] *ModelName* [*Area*] [`OFF`]
`+` [`IC=`*Vbe*, *Vce*]
where

NCollector is the collector node.

NBase is the base node.

NEmitter is the emitter node.

NSubstrate is the optional substrate node. If not specified, ground is used as the substrate node. If *NSubstrate* is a name as allowed in PSPICE) it must be enclosed in square brackets, e.g. `[`*NSubstrate*`]`, to distinguish it from *ModelName*.

ModelName is the model name.

Area is the area factor
If the area factor is omitted, a value of 1.0 is assumed. (Units: none; Optional; Default: 1; Symbol: *Area*)

`OFF` indicates an (optional) initial condition on the device for the `DC` analysis. If specified the `DC` operating point is calculated with the terminal voltages set to zero. Once convergence is obtained, the program continues to iterate to obtain the exact value of the terminal voltages. The OFF option is used to enforce the solution to correspond to a desired state if the circuit has more than one stable state.

`IC` is the optional initial condition specification using `IC=`V_{BE}, V_{CE} is intended for use with the `UIC` option on the `.TRAN` line, when a transient analysis is desired starting from other than the quiescent operating point. See the *.IC* line description for a better way to set transient initial conditions.

Example:

```
Q20 10 50 0 QFAST IC=0.65,15.0
Q5PUSH 10 29 14 200 MODEL1
```

Description:

NPN Model NPN Si Bipolar Transistor Model

PNP Model PNP Si Bipolar Transistor Model

LPNP Model PSPICE Only Lateral PNP Si Bipolar Transistor Model

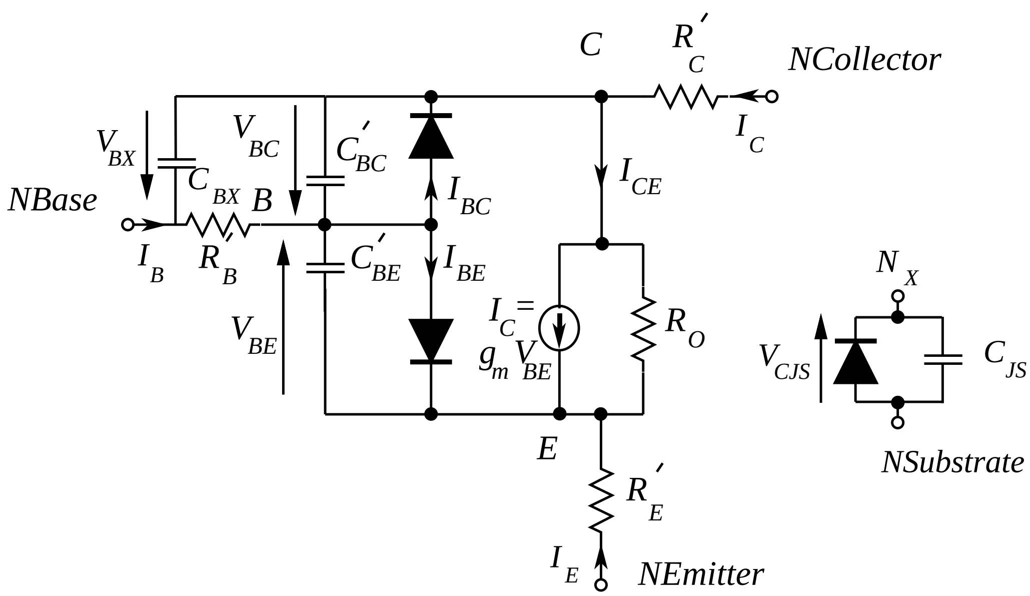

Figure 2: Schematic of the NPN bipolar junction transistor model. In the NPN and PNP models node N_X is connected to node C. In the LPNP model node N_X is connected to node B.

The NPN and PNP BJT models are identical but with the positive sense of currents and voltages opposite so that the model parameters are always positive. The LPNP model is used for a lateral PNP IC transistor structure. In the NPN and PNP models the node N_X in figure 2 is connected to node C — the internal collector node. In the LPNP model node N_X is connected to node B — the internal base node. Only the model type designated on the element line distinguishes which schematic is used.

The bipolar junction transistor model in SPICE is based on the charge control model of Gummel and Poon. Extensions in the SPICE implementation deal with effects at high bias levels. The model reduces to the simpler Ebers-Moll model with the omission of appropriate model parameters.

Standard Calculations

The physical constants used in the model evaluation are

k	Boltzmann's constant	$1.3806226\,10^{-23}$ J/K
q	electronic charge	$1.6021918\,10^{-19}$ C

Absolute temperatures (in kelvins, K) are used. The thermal voltage

$$V_{\mathrm{TH}}(T_{\mathrm{NOM}}) = \frac{kT_{\mathrm{NOM}}}{q}. \tag{1}$$

Temperature Dependence

Temperature effects are incorporated as follows where T and T_{NOM} are absolute temperatures in Kelvins (K).

$$V_{\mathrm{TH}} = \frac{kT}{q} \tag{2}$$

$$I_S(T) = I_S e^{\left(E_g(T)\frac{T}{T_{\mathrm{NOM}}} - E_G(T)\right)/V_{\mathrm{TH}}} + \left(\frac{T}{T_{\mathrm{NOM}}}\right)^{X_{TI}/N_F} \tag{3}$$

$$I_{SE}(T) = I_{SE} e^{\left(E_g(T)\frac{T}{T_{\mathrm{NOM}}} - E_G(T)\right)/V_{\mathrm{TH}}} + \left(\frac{T}{T_{\mathrm{NOM}}}\right)^{X_{TI}/N_E} \tag{4}$$

$$I_{SC}(T) = I_{SC} e^{\left(E_g(T)\frac{T}{T_{\mathrm{NOM}}} - E_G(T)\right)/V_{\mathrm{TH}}} + \left(\frac{T}{T_{\mathrm{NOM}}}\right)^{X_{TI}/N_C} \tag{5}$$

$$I_{SS}(T) = I_{SS} e^{\left(E_g(T)\frac{T}{T_{\mathrm{NOM}}} - E_G(T)\right)/V_{\mathrm{TH}}} + \left(\frac{T}{T_{\mathrm{NOM}}}\right)^{X_{TI}/N_S} \tag{6}$$

$$V_{JE}(T) = V_{JE}(T_{\mathrm{NOM}})(T - T_{\mathrm{NOM}}) - 3V_{\mathrm{TH}}\ln\left(\frac{T}{T_{\mathrm{NOM}}}\right) E_G(T_{\mathrm{NOM}})\frac{T}{T_{\mathrm{NOM}}} - E_G(T) \tag{7}$$

$$V_{JC}(T) = V_{JC}(T_{\mathrm{NOM}})(T - T_{\mathrm{NOM}}) - 3V_{\mathrm{TH}}\ln\left(\frac{T}{T_{\mathrm{NOM}}}\right) E_G(T_{\mathrm{NOM}})\frac{T}{T_{\mathrm{NOM}}} - E_G(T) \tag{8}$$

$$V_{JS}(T) = V_{JS}(T_{\mathrm{NOM}})(T - T_{\mathrm{NOM}}) - 3V_{\mathrm{TH}}\ln\left(\frac{T}{T_{\mathrm{NOM}}}\right) E_G(T_{\mathrm{NOM}})\frac{T}{T_{\mathrm{NOM}}} - E_G(T) \tag{9}$$

Table 1: BJT model keywords. The model parameters that are scaled by the Area element parameter are designated in the Area column.

Name	Description	Units	Default	Area
AF	flicker noise exponent (A_F)	-	1	
BF	ideal maximum forward beta (β_F)	-	100	
BR	ideal maximum reverse beta (β_R)	-	1	
C2	alternative keyword for ISE PSpice only.			
C4	alternative keyword for ISC PSpice only.			
CCS	alternative keyword for CJS PSpice only.			
CJC	base-collector zero-bias depletion capacitance (C_{JC})	F	0	*
CJE	base-emitter zero-bias depletion capacitance (C_{JE})	F	0	*
CJS	zero-bias collector-substrate capacitance (C_{JS})	F	0	*
EG	energy gap voltage (barrier height) (E_G)	eV	1.11	
FC	coefficient for forward-bias depletion capacitance formula (F_C)	-	0.5	
IK	alternative keyword for IKF PSpice only.			
IKF	corner of forward beta high current roll-off (I_{KF})	A	∞	*
IKR	corner of reverse beta high current roll-off $(I_K F)$	A	∞	*
IRB	current where base resistance falls halfway to its minimum value (I_{RB})	-	∞	*
IS	transport saturation current (I_S)	A	1.0E-16	*
ISC	base-collector leakage saturation current (I_{SC}) If ISC is greater than 1 it is treated as a multiplier. In this case $I_{SC} = \mathtt{ISC}\, I_S$	A	0	*
ISE	base-emitter leakage saturation current (I_{SE}) If ISE is greater than 1 it is treated as a multiplier. In this case $I_{SE} = \mathtt{ISE}\, I_S$	A	0	*
ISS	substrate p-n junction saturation current (I_{SS}) PSpice only.	A	0	*
ITF	high-current parameter for effect on TF $(I_{\tau F})$	A	0	*
KF	flicker-noise coefficient (K_F)	-	0	

Table 2: BJT model keywords continued

Name	Description	Units	Default	Area
MC	alternative keyword for MJC PSPICE only.			
ME	alternative keyword for MJE PSPICE only.			
MJC	base-collector junction exponential factor (M_{JC})	-	0.33	
MJE	base-emitter junction exponential factor (M_{JE})	-	0.33	
MJS	substrate junction exponential factor (M_{JS})	-	0	
MS	alternative keyword for MJS PSPICE only.			
NC	base-collector leakage emission coefficient (N_C)	-	2	
NE	base-emitter leakage emission coefficient (N_E)	-	1.5	
NF	forward current emission coefficient (N_F)	-	1.0	
NR	reverse current emission coefficient (N_R)	-	1	
NS	substrate p-n emission coefficient (N_S) PSPICE only.	-	1	*
PC	alternative keyword for VJC PSPICE only.			
PE	alternative keyword for VJE PSPICE only.			
PS	alternative keyword for VJS PSPICE only.			
PT	alternative keyword for XTI PSPICE only.			
PTF	excess phase at frequency=1.0/(TF 2π) Hz ($P_{\tau F}$)	degree	0	
RB	zero bias base resistance (R_B)	Ω	0	*
RBM	minimum base resistance at high currents (R_{BM})	Ω	RB	*
RC	collector resistance (R_C)	Ω	0	*
RE	emitter resistance (R_E)	Ω	0	*
TF	ideal forward transit time (τ_F)	s	0	
TR	ideal reverse transit time (τ_R)	s	0	
TRB1	RB linear temperature coefficient (T_{RB1}) PSPICE only.	$^\circ$C^{-1}	1	*

Table 3: BJT model keywords continued

Name	Description	Units	Default	Area
TRB2	RB quadratic temperature coefficient (T_{RB2}) PSpice only.	°C^{-2}	1	*
TRC1	RC linear temperature coefficient (T_{RC1}) PSpice only.	°C^{-1}	1	*
TRC2	RC quadratic temperature coefficient (T_{RC2}) PSpice only.	°C^{-2}	1	*
TRE1	RE linear temperature coefficient (T_{RE1}) PSpice only.	°C^{-1}	1	*
TRE2	RE quadratic temperature coefficient (T_{RE2}) PSpice only.	°C^{-2}	1	*
TRM1	RBM linear temperature coefficient (T_{RM1}) PSpice only.	°C^{-1}	1	*
TRM2	RBM quadratic temperature coefficient (T_{RM2}) PSpice only.	°C^{-2}	1	*
VA	alternative keyword for VAF PSpice only.			
VB	alternative keyword for VAR PSpice only.			
VAF	forward Early voltage (V_{AF})	V	∞	
VAR	reverse Early voltage (V_{AR})	V	∞	
VJC	base-collector built-in potential (V_{JC})	V	0.75	
VJE	base-emitter built-in potential (V_{JE})	V	0.75	
VJS	substrate junction built-in potential (V_{JS})	V		
VTF	voltage describing V_{BC} dependence of TF ($V_{\tau F}$)	V	∞	
XCJC	fraction of B-C depletion capacitance connected to internal base node (X_{CJC})	-	1	
XTB	forward and reverse beta temperature exponent (X_{TB})	-		
XTI	temperature exponent for effect on IS (X_{TI})	-	3	
XTF	coefficient for bias dependence of TF ($X_{\tau F}$)	-		

$$
\begin{aligned}
C_{JC}(T) &= C_{JC}\{1 + M_{JC}[0.0004(T - T_{\mathrm{NOM}}) + (1 - V_{JC}(T)/V_{JC}(T_{\mathrm{NOM}}))]\} && (10)\\
C_{JE}(T) &= C_{JE}\{1 + M_{JE}[0.0004(T - T_{\mathrm{NOM}}) + (1 - V_{JE}(T)/V_{JE}(T_{\mathrm{NOM}}))]\} && (11)\\
C_{JS}(T) &= C_{JS}\{1 + M_{JS}[0.0004(T - T_{\mathrm{NOM}}) + (1 - V_{JS}(T)/V_{JS}(T_{\mathrm{NOM}}))]\} && (12)\\
\beta_F(T) &= \beta_F(T_{\mathrm{NOM}})^{X_{TB}} && (13)\\
\beta_R(T) &= \beta_R(T_{\mathrm{NOM}})^{X_{TB}} && (14)\\
E_G(T) &= E_G(T_{\mathrm{NOM}}) - 0.000702\frac{T^2}{T + 1108} && (15)\\
R_B(T) &= R_B(T_{\mathrm{NOM}})\left[1 + T_{RB1}(T - T_{\mathrm{NOM}}) + T_{RB2}(T - T_{\mathrm{NOM}})^2\right] && (16)\\
R_{BM}(T) &= R_{BM}(T_{\mathrm{NOM}})\left[1 + T_{RM1}(T - T_{\mathrm{NOM}}) + T_{RM2}(T - T_{\mathrm{NOM}})^2\right] && (17)\\
R_C(T) &= R_C(T_{\mathrm{NOM}})\left[1 + T_{RC1}(T - T_{\mathrm{NOM}}) + T_{RC2}(T - T_{\mathrm{NOM}})^2\right] && (18)\\
R_E(T) &= R_E(T_{\mathrm{NOM}})\left[1 + T_{RE1}(T - T_{\mathrm{NOM}}) + T_{RE2}(T - T_{\mathrm{NOM}})^2\right] && (19)
\end{aligned}
$$

Capacitances

The base-emitter capacitance, $C_{BE} = Area(C_{BE\tau} + C_{BEJ})$ (20)
where the base-emitter transit time or diffusion capacitance

$$C_{BE\tau} = \tau_{F,\mathrm{EFF}}\frac{\partial I_{BF}}{\partial V_{BE}} \tag{21}$$

the effective base transit time is empirically modified to account for base punchout, space-charge limited current flow, quasi-saturation and lateral spreading which tend to increase τ_F

$$\tau_{F,\mathrm{EFF}} = \tau_F\left[1 + X_{TF}(3x^2 - 2x^3)e^{(V_{BC}/(1.44V_{TF})}\right] \tag{22}$$

and $x = I_{BF}/(I_{BF} + AreaI_{TF})$. The base-emitter junction (depletion) capacitance

$$C_{BEJ} = \begin{cases} C_{JE}\left(1 - \frac{V_{BE}}{V_{JE}}\right)^{-M_{JE}} & V_{BE} \le F_C V_{JE} \\ C_{JE}\left(1 - F_C\right)^{-(1 + M_{JE})}\left(1 - F_C(1 + M_{JE}) + M_{JE}\frac{V_{BE}}{V_{JE}}\right) & V_{BE} > F_C V_{JE} \end{cases} \tag{23}$$

The base-collector capacitance, $C_{BC} = Area(C_{BC\tau} + X_{CJC}C_{BCJ})$ (24)
where the base-collector transit time or diffusion capacitance

$$C_{BC\tau} = \tau_R\frac{\partial I_{BR}}{\partial V_{BC}} \tag{25}$$

The base-collector junction (depletion) capacitance

$$C_{BCJ} = \begin{cases} C_{JC}\left(1 - \frac{V_{BC}}{V_{JC}}\right)^{-M_{JC}} & V_{BC} \le F_C V_{JC} \\ C_{JC}\left(1 - F_C\right)^{-(1 + M_{JC})}\left(1 - F_C(1 + M_{JC}) + M_{JC}\frac{V_{BC}}{V_{JC}}\right) & V_{BC} > F_C V_{JC} \end{cases} \tag{26}$$

The capacitance between the extrinsic base and the intrinsic collector

$$C_{BX} = \begin{cases} Area(1 - X_{CJC})C_{JC}\left(1 - \frac{V_{BX}}{V_{JC}}\right)^{-M_{JC}} & V_{BX} \leq F_C V_{JC} \\ \\ (1 - X_{CJC})C_{JC}\,(1 - F_C)^{-(1+M_{JC})} & V_{BX} > F_C V_{JC} \\ \quad \times \left(1 - F_C(1 + M_{JC}) + M_{JC}\frac{V_{BX}}{V_{JC}}\right) & \end{cases} \tag{27}$$

The substrate junction capacitance

$$C_{JS} = \begin{cases} AreaC_{JS}\left(1 - \frac{V_{CJS}}{V_{JS}}\right)^{-M_{JS}} & V_{CJS} \leq 0 \\ AreaC_{JS}\left(1 + M_{JS}\frac{V_{CJS}}{V_{JS}}\right) & V_{CJS} > 0 \end{cases} \tag{28}$$

I/V Characteristics

The base-emitter current, $I_{BE} = \frac{I_{BF}}{\beta_F} + I_{LE}$ (29)

the base-collector current, $I_{BC} = \frac{I_{BR}}{\beta_R} + I_{LC}$ (30)

and the collector-emitter current, $I_{CE} = \frac{I_{BF} - I_{BR}}{K_{QB}}$ (31)

where the forward diffusion current, $I_{BF} = I_S\left(e^{V_{BE}/(N_F V_{\mathrm{TH}})} - 1\right)$ (32)

the nonideal base-emitter current, $I_{LE} = I_{SE}\left(e^{V_{BE}/(N_E V_{\mathrm{TH}})} - 1\right)$ (33)

the reverse diffusion current, $I_{BR} = I_S\left(e^{V_{BC}/(N_R V_{\mathrm{TH}})} - 1\right)$ (34)

the nonideal base-collector current, $I_{LC} = I_{SC}\left(e^{V_{BC}/(N_C V_{\mathrm{TH}})} - 1\right)$ (35)

and the base charge factor, $K_{QB} = \frac{1}{2}\left[1 - \frac{V_{BC}}{V_{AF}} - \frac{V_{BE}}{V_{AB}}\right]^{-1}\left(1 + \sqrt{1 + 4\left(\frac{I_{BF}}{I_{KF}} + \frac{I_{BR}}{I_{KR}}\right)}\right)$ (36)

Thus the conductive current flowing into the base, $I_B = I_{BE} + I_{BC}$ (37)
the conductive current flowing into the collector, $I_C = I_{CE} - I_{BC}$ (38)
and the conductive current flowing into the emitter, $I_C = I_{BE} + I_{CE}$ (39)

Parasitic Resistances

The resistive parasitics R_B, R_E, are R_C are scaled by the area factor, $Area$, specified on the element line. This enables the model parameters `RB`, `RE` and `RC` to be absolute quantities if $Area$ is omitted as it defaults to 1, or as sheet resistivities.

$$\begin{aligned} R'_B &= R_B/Area \quad (40) \\ R'_C &= R_C/Area \quad (41) \\ R'_E &= R_E/Area \quad (42) \end{aligned}$$

$$R'_B = \begin{cases} R_{BM} + \dfrac{R_B - R_{BM}}{K_{QB}} & I_{RB} \text{ omitted} \\ R_{BM} + 3(R_B - R_{BM})\dfrac{\tan x - x}{x\tan^2(x)} & I_{RB} \text{ defined} \end{cases} \tag{43}$$

$$\text{where } x = \left(\sqrt{1 + \frac{144 I_B}{I_{RB}\pi^2}} - 1\right)\left(\frac{24}{\pi^2}\sqrt{\frac{I_B}{I_{RB}}}\right)^{-1} \tag{44}$$

AC Analysis

The AC analysis uses the model of figure ?? with the capacitor values evaluated at the `DC` operating point with

$$g_m = \frac{\partial I_{CE}}{\partial V_{BE}} \tag{45}$$

and

$$R_O = \frac{\partial I_{CE}}{\partial V_{CE}} \tag{46}$$

Noise Analysis

The BJT noise model accounts for thermal noise generated in the parasitic resistances and shot and flicker noise generated in the base-emitter and base-collector junction regions. The rms (root-mean-square) values of thermal noise current generators shunting the three parasitic resistance R_B, R_C, and R_E are

$$I_{n,B} = \sqrt{4kT/R_B}\ \mathrm{A}/\sqrt{\mathrm{Hz}} \tag{47}$$

$$I_{n,C} = \sqrt{4kT/R_C}\ \mathrm{A}/\sqrt{\mathrm{Hz}} \tag{48}$$

$$I_{n,E} = \sqrt{4kT/R_E}\ \mathrm{A}/\sqrt{\mathrm{Hz}} \tag{49}$$

The rms value of the base noise current generator is

$$I_{n,B} = \left(I^2_{\mathrm{SHOT},B} + I^2_{\mathrm{FLICKER},B}\right)^{1/2} \tag{50}$$

where

$$I_{\mathrm{SHOT},B} = \sqrt{2qI_B} \quad \mathrm{A}/\sqrt{\mathrm{Hz}} \tag{51}$$

$$I_{\mathrm{FLICKER},B} = \sqrt{K_F I_B^{A_F}/f} \quad \mathrm{A}/\sqrt{\mathrm{Hz}} \tag{52}$$

and f is frequency. The rms value of the collector noise current generator is

$$I_{n,C} = \left(I^2_{\mathrm{SHOT},C} + I^2_{\mathrm{FLICKER},C}\right)^{1/2} \tag{53}$$

where

$$I_{\mathrm{SHOT},C} = \sqrt{2qI_C} \quad \mathrm{A}/\sqrt{\mathrm{Hz}} \tag{54}$$

$$I_{\mathrm{FLICKER},C} = \sqrt{K_F I_C^{A_F}/f} \quad \mathrm{A}/\sqrt{\mathrm{Hz}}. \tag{55}$$

Notes:
The actual element in *f*REEDA™is the `Q` element. See `Q` for full documentation.

Credits:

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