Lecture 21

Bipolar Junction Transistors (BJT): Part 5

Hand Example, SPICE Example, and Limits on output swing imposed by having to stay within Forward Active Mode

Reading:

Notes

An Example that puts it all together!

Consider an Integrated Circuit npn BJT with:
Emitter Doping, N_{DE}=7.5e18 cm^{-3}
Base Doping, N_{AB} =10e17 cm^{-3}
Collector Doping, N_{DC}=1.5e16cm^{-3}
Substrate doping N_{Sub}= 5e15 cm^{-3}
Minority Carrier Diffusion coefficient in the emitter, $D_{pE\text{-(holes)}}$ = 5 cm^2/s
Minority Carrier Diffusion coefficient in the base, $D_{nB\text{-(electrons)}}$ = 10 cm^2/s
Base Quasi-neutral width, W = 300 nm
Minority Carrier Diffusion length in the emitter, L_E = 250 nm
Minority Carrier Diffusion length in the base, L_B = 100 um
Areas:
$A_{emitter\text{-}base}$ = 25 um^2 , $A_{collector\text{-}Base}$ = 100 um^2 , $A_{substrate\text{-}Collector}$ = 500 um^2
Resistances and Early Voltage: r_b = 250 Ω , r_c = 200 Ω , r_{ex} = 5 Ω, V_A = 35 V

Find the complete small- signal model for:
I_C =100 mA, V_{CE} =2V, and V_{CS}=2V and V_{be}=0.5V_{bi} For the emitter-base

An Example that puts it all together!

First recognize that $W \ll L_B$ so we can use the simplest form of the transport parameters.

Next, recognize that our choice of generic labeling allows us to use the equations developed for the pnp transistor here even though you were given a npn transistor.

$$\beta_{DC} = \frac{1}{\dfrac{D_E W N_B}{D_B L_E N_E} + \dfrac{1}{2}\left(\dfrac{W}{L_B}\right)^2} \Rightarrow \frac{D_B L_E N_E}{D_E W N_B} = \frac{\alpha_{DC}}{1-\alpha_{DC}} = 125$$

$$\alpha_{DC} = \frac{1}{1+\dfrac{D_E W N_B}{D_B L_E N_E} + \dfrac{1}{2}\left(\dfrac{W}{L_B}\right)^2} \Rightarrow \frac{1}{1+\dfrac{D_E W N_B}{D_B L_E N_E}} = \frac{\beta_{DC}}{1+\beta_{DC}} = 0.992$$

Note: The formulas here were derived in the optional material but are not considered optional

An Example that puts it all together!

Transconductance:

$$g_m = y_{21} = \frac{I_C}{V_T} = 3.86\ mS$$

Input Resistance:

$$r_\pi = \frac{1}{y_{11}} = \frac{\beta_o V_T}{I_C} = \frac{\beta_o}{g_m} = 32.4\ k\Omega$$

Output Resistance:

$$r_o = \frac{1}{y_{22}} = \frac{V_A + V_{CE}}{I_C} = 370\ k\Omega$$

or using the approximate solution,

$$r_o = \frac{1}{y_{22}} \approx \frac{V_A}{I_C} = 350\ k\Omega, \quad (still\ a\ large\ value)$$

An Example that puts it all together!

Forward Base Transport Time:

$$\tau_F = \frac{W^2}{2D_B} = 45\ pS \longleftarrow$$

Watch the units!

Maximum base transport limited operational frequency ~ 3.5 GHz!

Base-Emitter Diffusion Capacitance:

$$C_B = g_m \tau_F = 173\ fF \qquad C_\pi = C_B + C_{jE}$$

An Example that puts it all together!

General Zero-Bias Depletion Capacitance:

$$C_{j?} = \frac{C_{j?o}}{\sqrt{1+\frac{V_{??}}{V_{bi\ for\ that\ junction}}}} \quad where, \begin{cases} C_{j?o} \equiv zero\ bias\ depletion\ capaci\tan ce \\ V_{bi\ for\ that\ junction} \equiv built\ in\ voltage\ for\ the\ E-B\ junction \end{cases}$$

$$C_{J?o} = C_{junction}\Big|_{V_A=0} = A\sqrt{\frac{qK_S\varepsilon_o}{2}\frac{N_AN_D}{(N_A+N_D)}\frac{1}{(V_{bi})}} \qquad V_{bi} = \frac{kT}{q}\ln\left[\frac{N_AN_D}{n_i^2}\right]$$

Junction	V_{BI}	Area (cm^2)	$C_{j?o}$ fF	Applied Voltage	$C_{j?}$ fF
E-B	0.947	2.50E-07	23.335	-0.473	33.000
B-C	0.786	1.00E-06	37.248	2.000	19.782
C-Substrate	0.768	5.00E-06	177.201	2.000	93.332

Thus,

$$C_\pi = C_B + C_{jE} = 206\ fF$$

$$C_\mu = 19.8\ fF$$

$$C_{CS} = 93.3\ fF$$

SPICE BJT Modeling

SPICE models capacitors slightly different than we have discussed.

Consider for example the Base-Collector capacitance:

$$C_{\mu} = \frac{CJC}{\left(1 - \frac{VBC}{VJC}\right)^{MJC}} \quad where, \begin{cases} CJC \equiv zero\ bias\ depletion\ capacitance \\ VJC \equiv built\ in\ voltage\ for\ the\ B-C\ junction \\ MJC \equiv B-C\ exponential\ factor\ related\ to\ the\ doping\ profile \end{cases}$$

Note the negative sign here

SPICE BJT Modeling

Most Common Model Parameters	PSPICE Name	Units
*Transport saturation current (I_S)	IS	A
Ideal maximum forward bias beta (β_F)	BF	-
Forward Early voltage (V_A)	VAF	V
Ideal maximum reverse bias beta (β_R)	BR	-
Base resistance (r_b)	RB	Ω
Emitter resistance (r_{ex})	RE	Ω
Collector resistance (r_c)	RC	Ω
B- E zero- bias depletion capacitance (C_{jE0})	CJE	F
B- E built- in potential (V_{bi} or ϕ_{BE})	VJE	V
B- E junction exponential factor	MJE	-
B- C zero- bias depletion capacitance ($C_{j\mu 0}$)	CJC	F
B- C built- in potential (V_{bi} or ϕ_{BC})	VJC	V
B- C junction exponential factor	MJC	-
Substrate zero- bias depletion capacitance (C_{CS0})	CJS	F
Substrate built- in potential (V_{bi} or ϕ_{BS})	VJS	V
Substrate junction exponential factor	MJS	-
Ideal forward transit time (τ_F)	TF	seconds

*The Transport saturation current (I_S) results from the simplified model which assumes forward active operation.
This can optionally be replaced with the Ebers-Moll parameters:

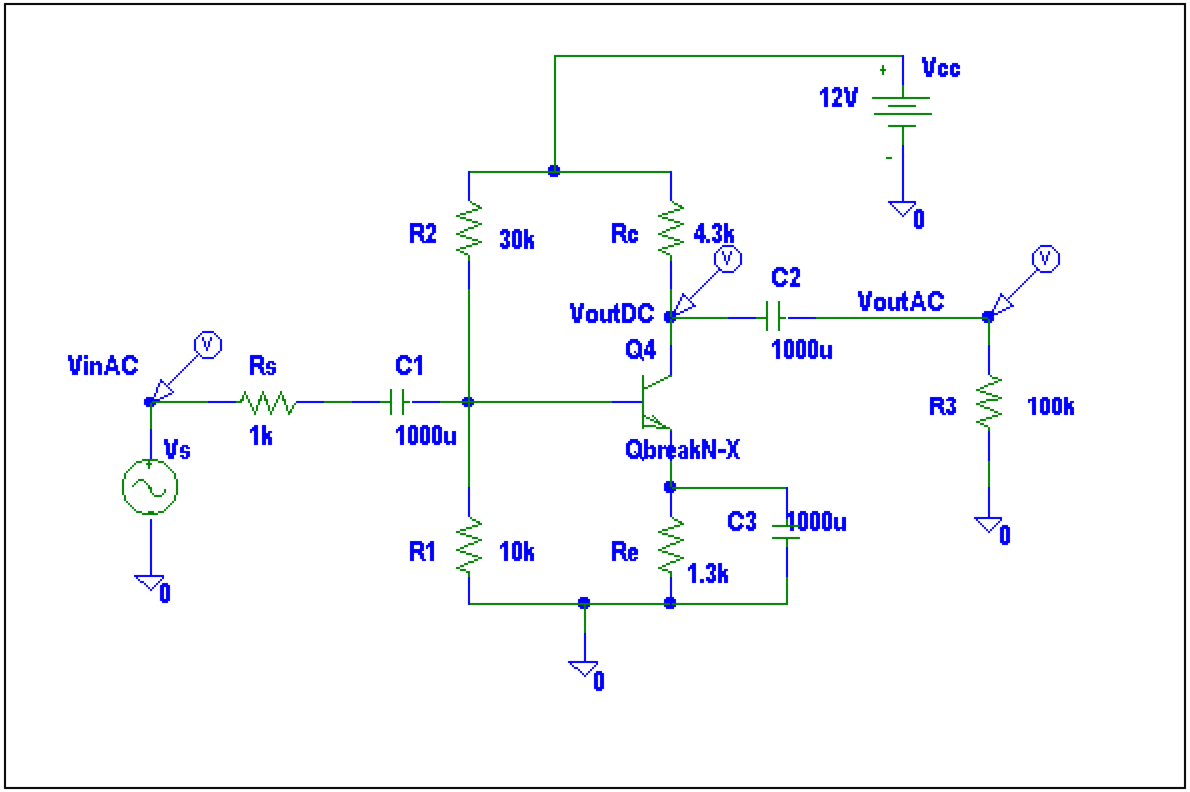
Base-collector leakage saturation current ($I_{R0}\alpha_R$)	ISC	A
Base-emitter leakage saturation current ($I_{F0}\alpha_F$)	ISE	A
Substrate-collector leakage saturation current	ISS	A

SPICE BJT Modeling

In class example: Simulate this circuit using Vs=1 mV and determine the voltage gain via a transient analysis, and an AC analysis.

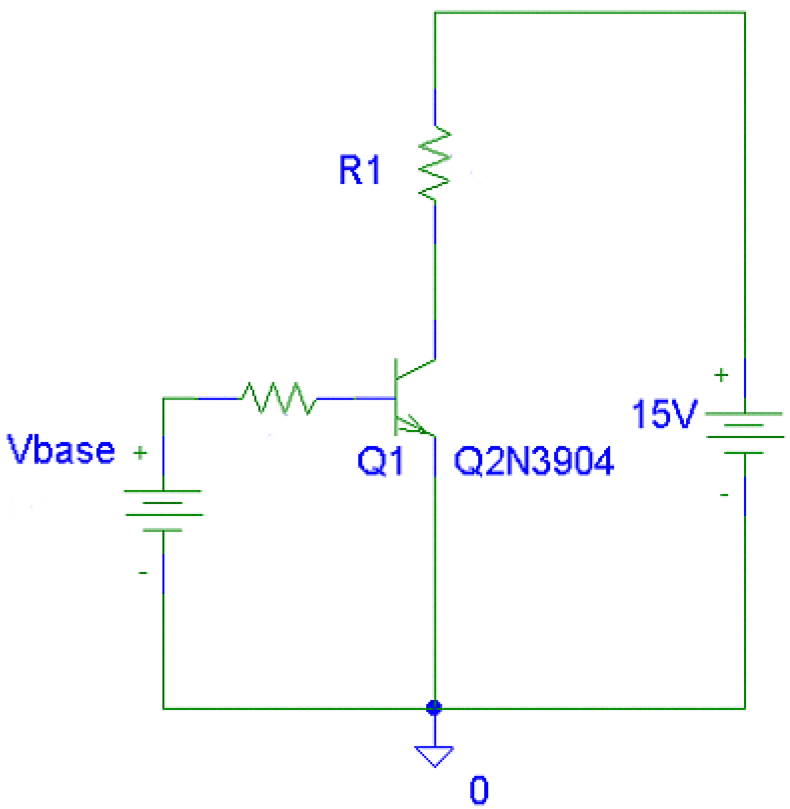
What happens to the gain when C3 is removed? Why?

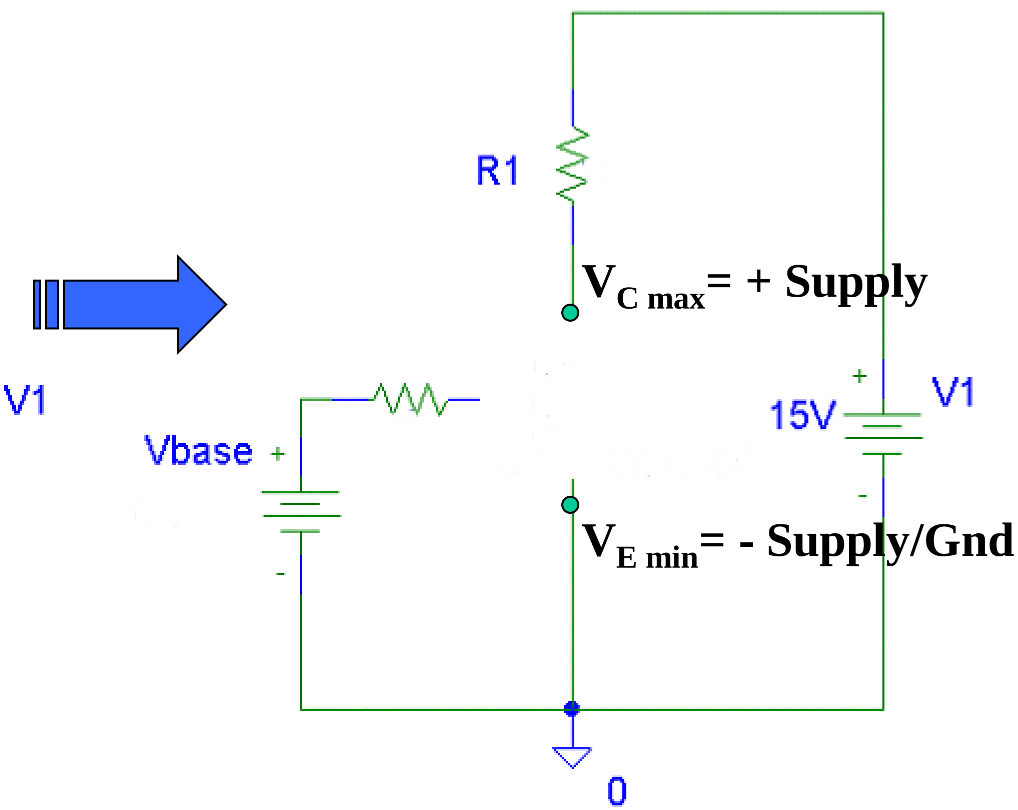
What happens when you do a transient analysis using VinAC=1 μV and when VinAc=1 V? Why is there a difference?



What sets the Maximum Limits of operation of the BJT Circuit?

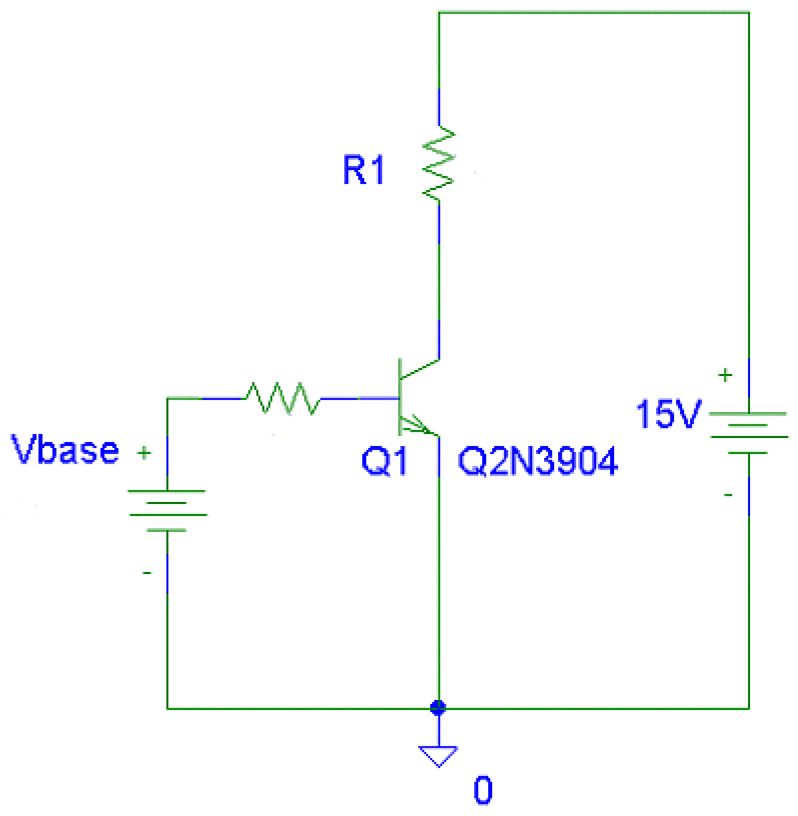
Forward active mode lies between saturation and cutoff. Thus, the maximum voltage extremes that one can operate an amplifier over can easily be found by examining the ***boundaries between forward active and cutoff*** and ….

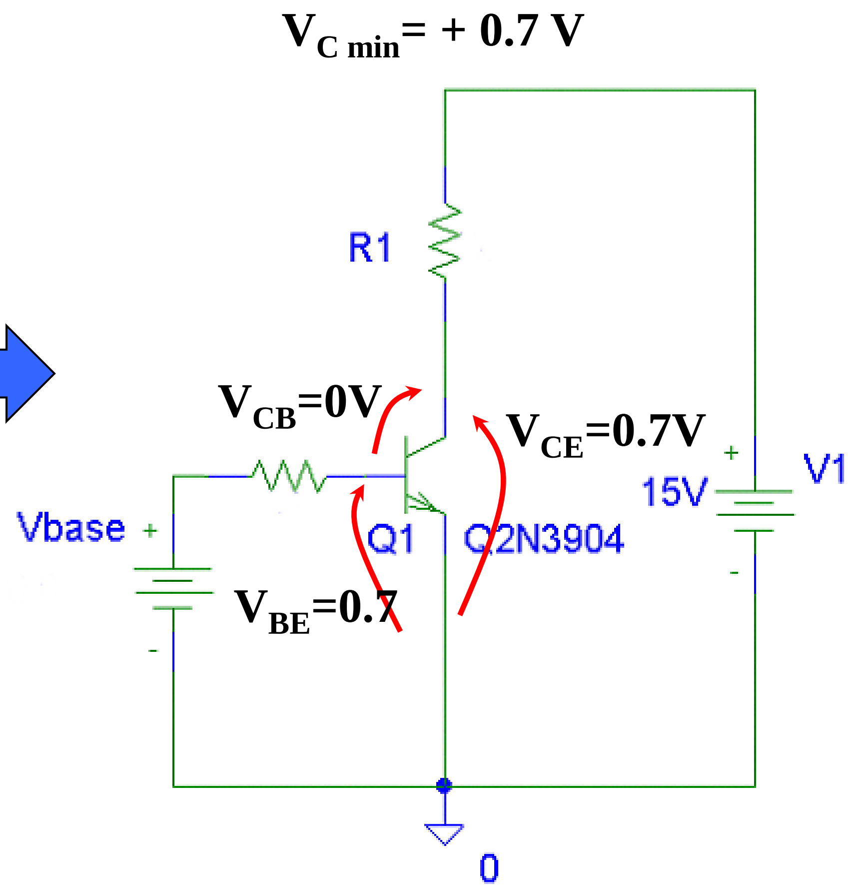




What sets the Maximum Limits of operation of the BJT Circuit?

… and the ***boundaries between forward active and saturation***





What sets the Maximum Limits of operation of the BJT Circuit?

Putting the two limits together…

Output signals that exceed the voltage range that would keep the transistor within it's Forward active mode will result in "clipping" of the signal leading to distortion. (Example: "Distortion found in loud Rock Music" - Heavy Metal)

The maximum voltage swing allowed without clipping depends on your choice of DC bias points.