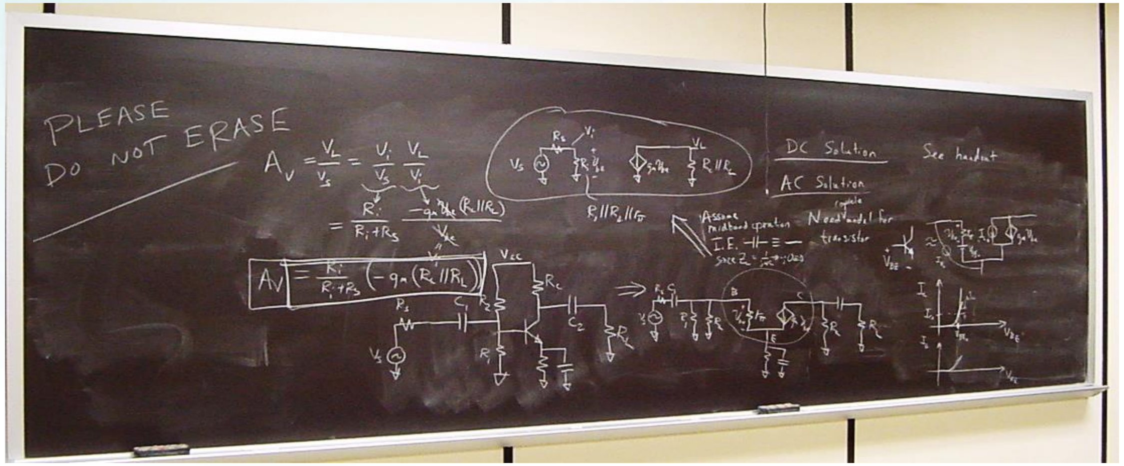
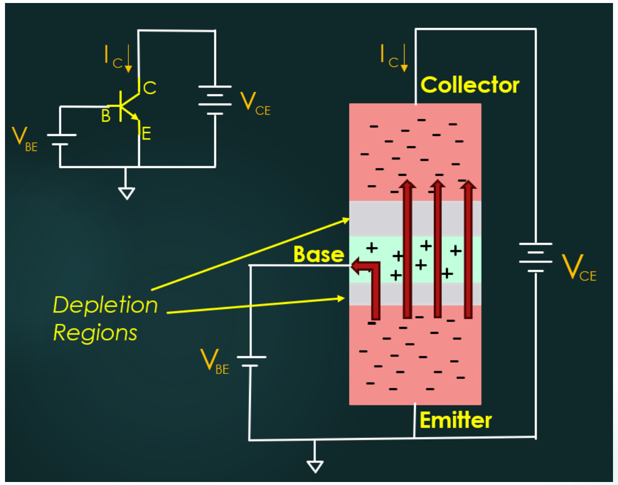
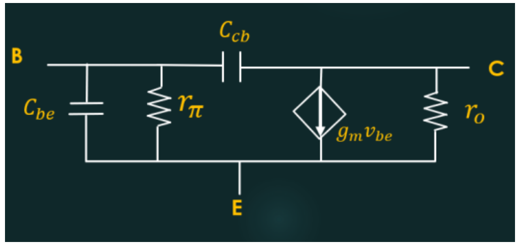
Radio Design 101
Appendix A (Episode 3 Part2) – Transistors and Amplifiers at RF

Slides downloaded from: https://ecefiles.org/rf-design/
Companion video at: https://youtu.be/m9X0mfg_8lQ

This is Episode 3, Part 2, but is optional, so it is placed in the Radio Design 101 video series as Appendix A. The material here is not essential for design and construction of our FM radio receiver. Rather, it is provided for those who want more background in the analysis of small signal RF amplifiers, and the operation of transistors used in their design. We review Episode 3 (Part 1), and then show how BJT transistors are created and how they are modeled. The goal is to provide a broader foundation for those interested in different amplifier types (such as common-emitter and cascode), and in the underlying mathematics from which gains, input and output impedances, and operating frequency limitations can be understood.



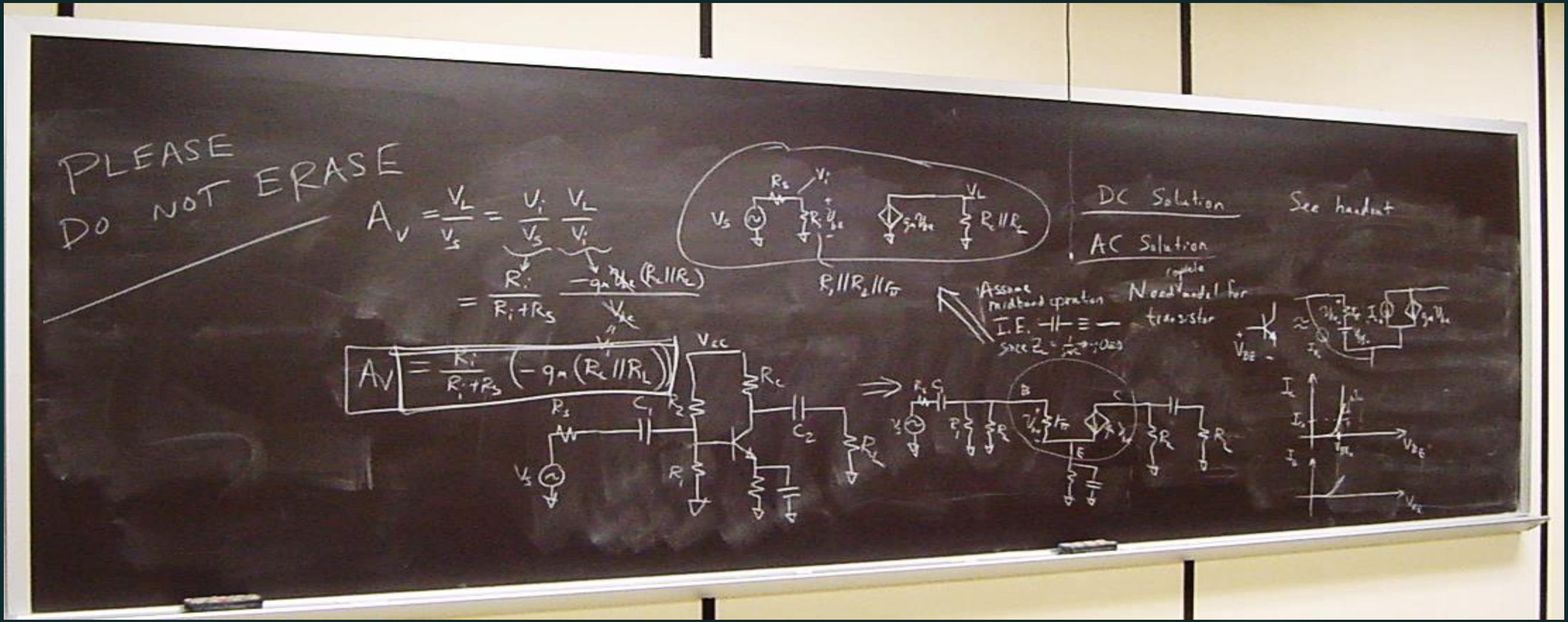




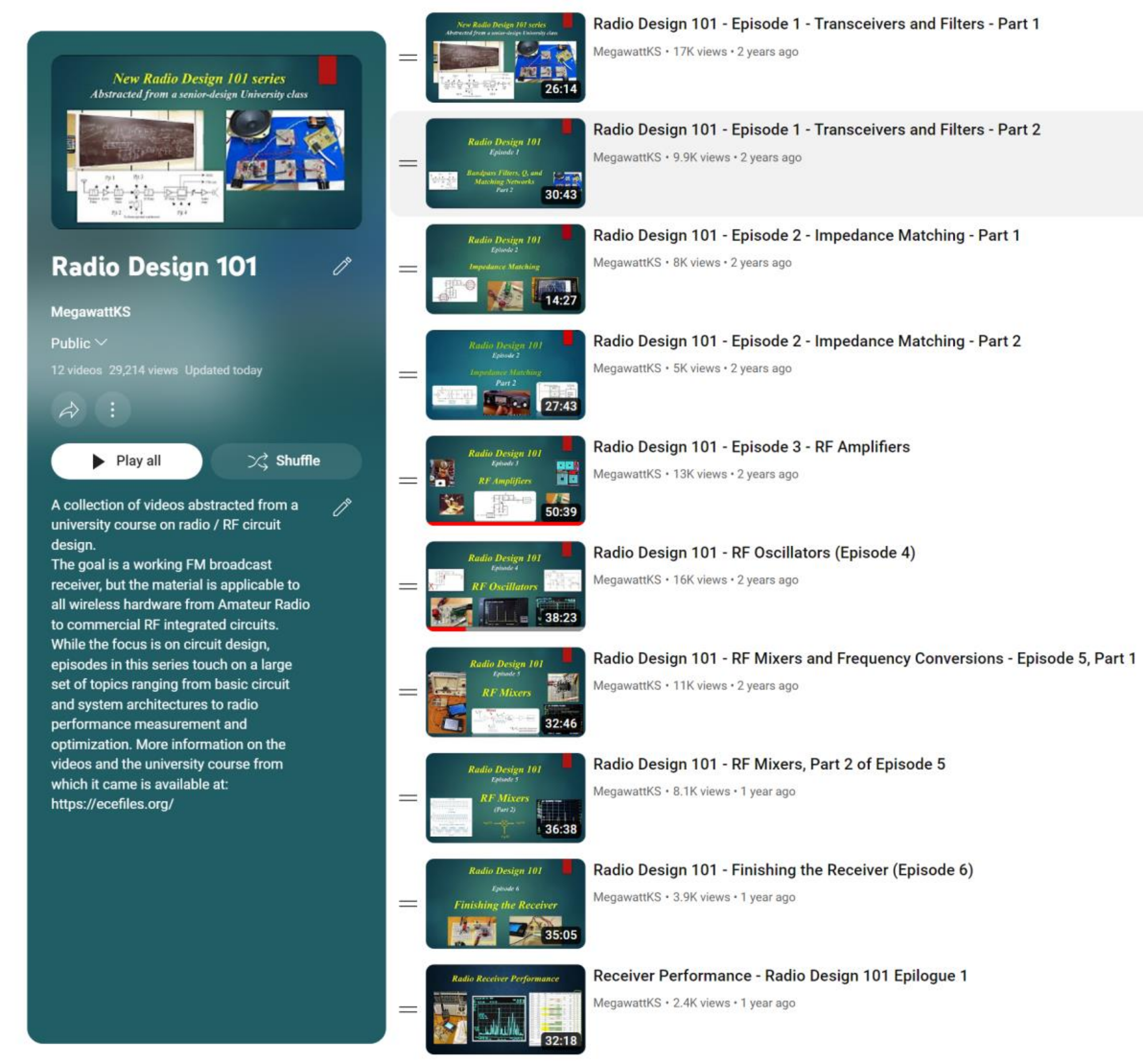
Radio Design 101

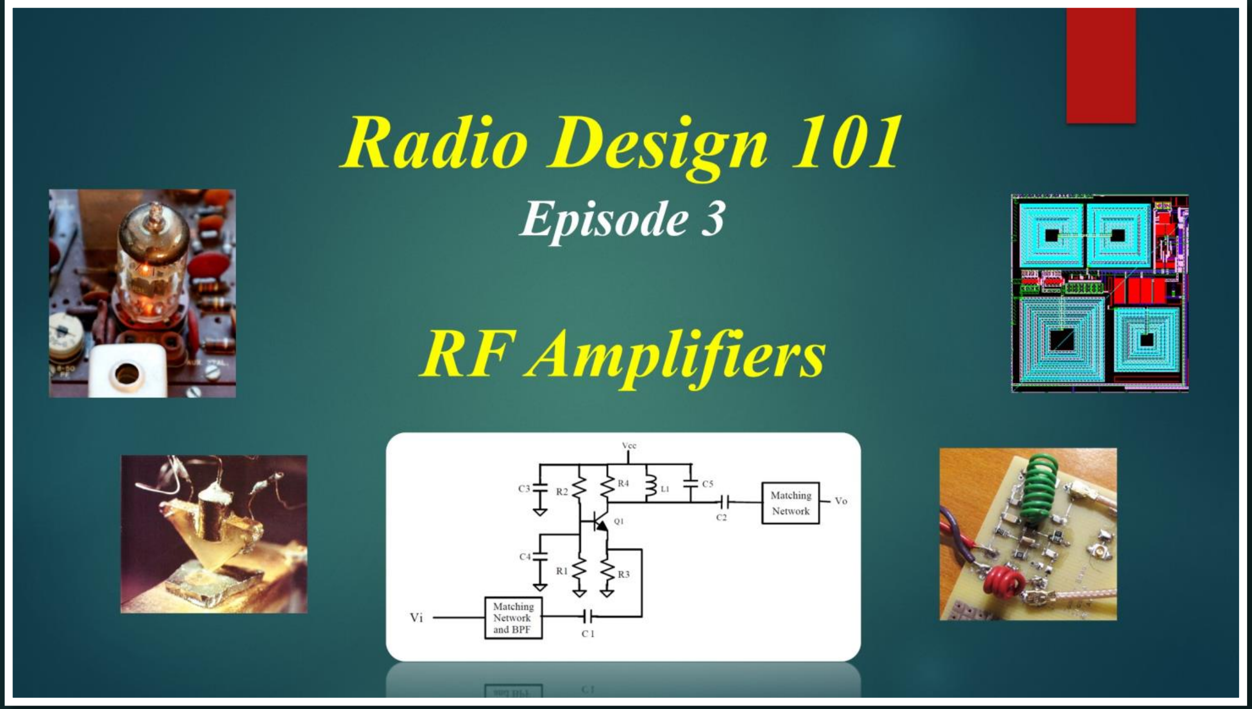
Episode 3 – Part 2 (Optional ☺)

Transistors & Amplifiers @ RF



Radio Design 101 Series





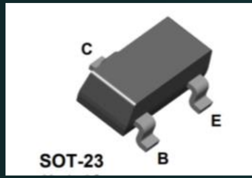
Outline of this Episode

Part 1

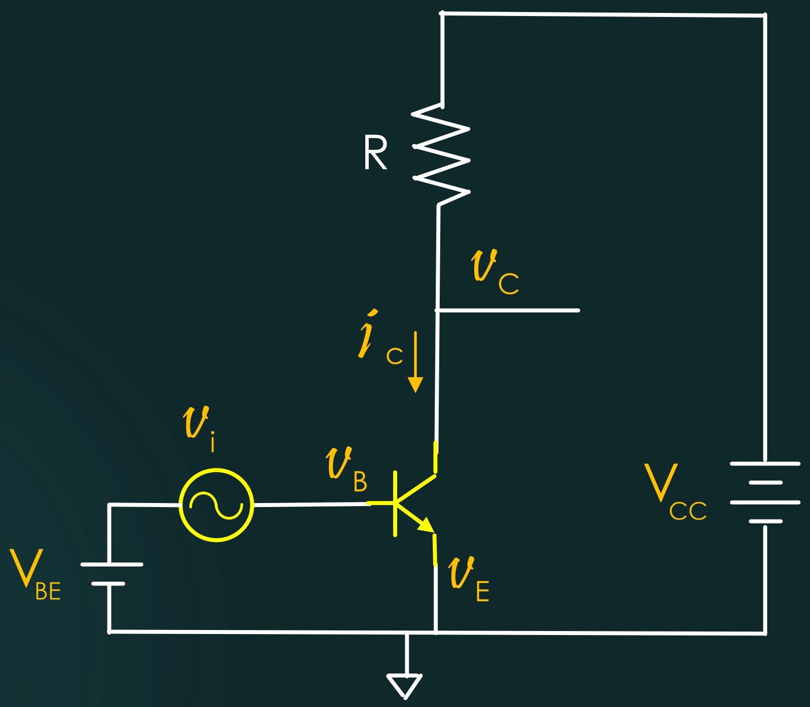
- *Triode Devices*
- *DC Biasing*
- *AC Gain and I/O Impedances*
- *Small Signal Amplifier Configurations*

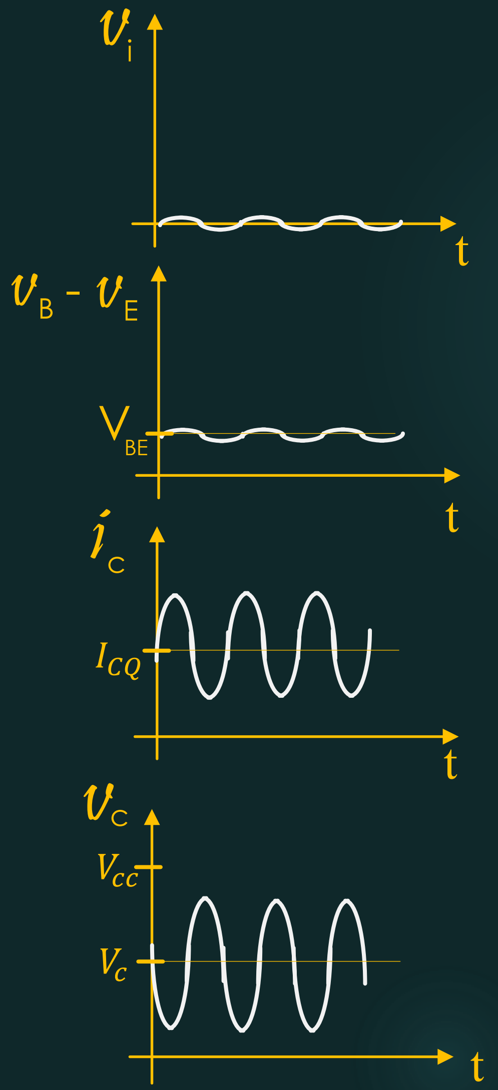
Part 2

- ***Transistors, Data Sheets and Models***
- ***High Frequency Model and Limitations***



Recall Basic Amplifier Concept

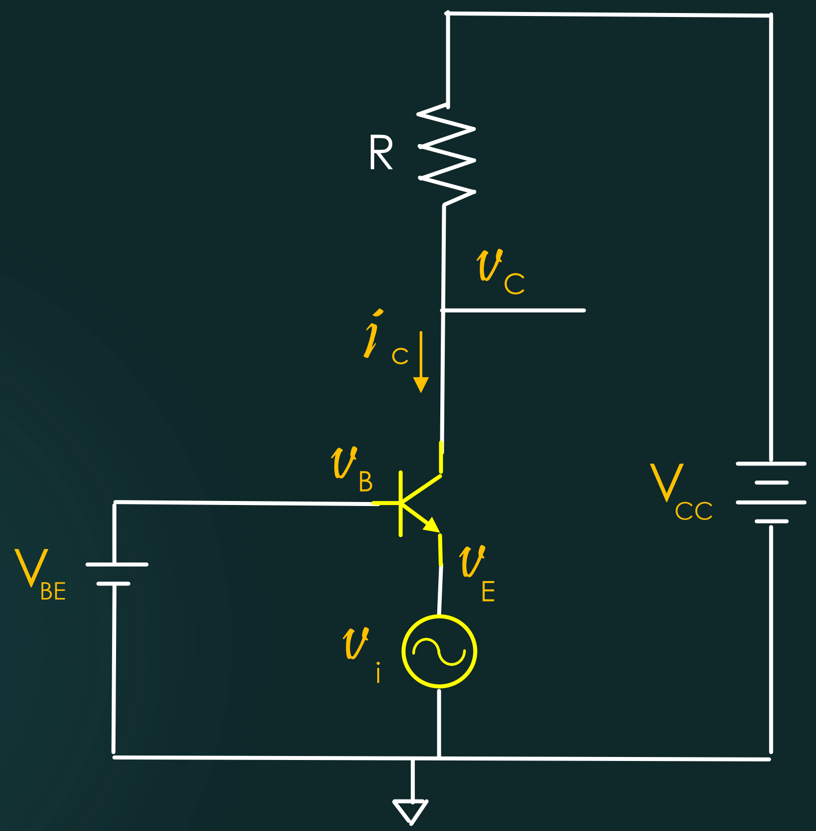




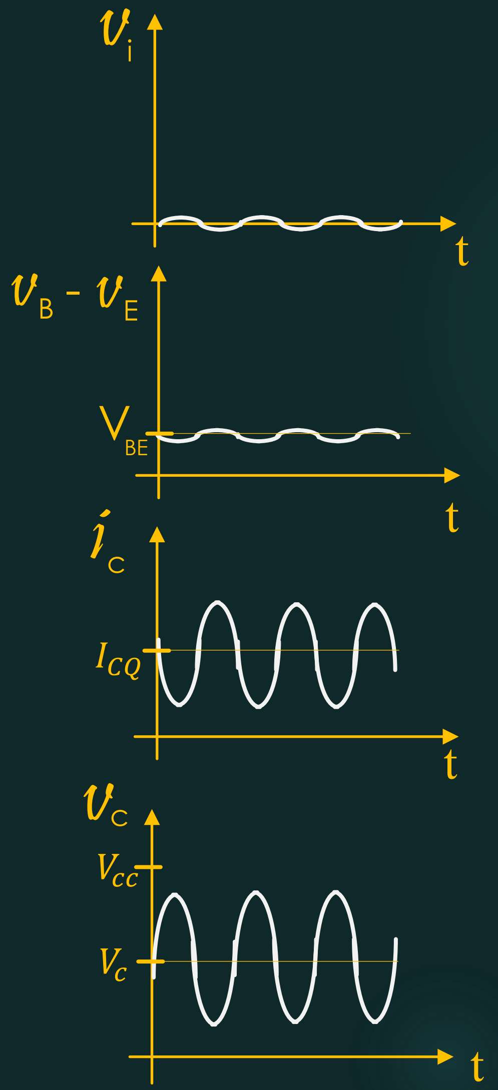
"*Transconductance*" $g_m \triangleq \frac{\Delta I_c}{\Delta V_{BE}}$

$$A_v = -g_m \mathrm{R}$$

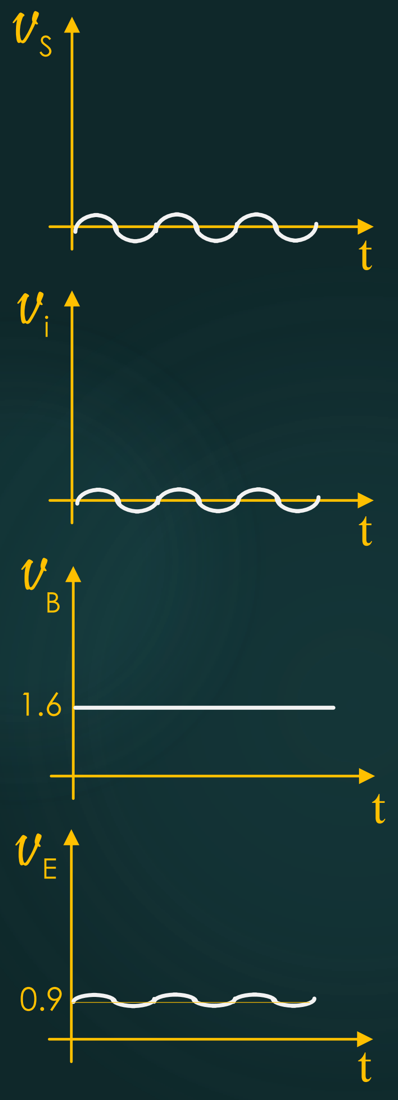
Alternative "Common-Base" Configuration

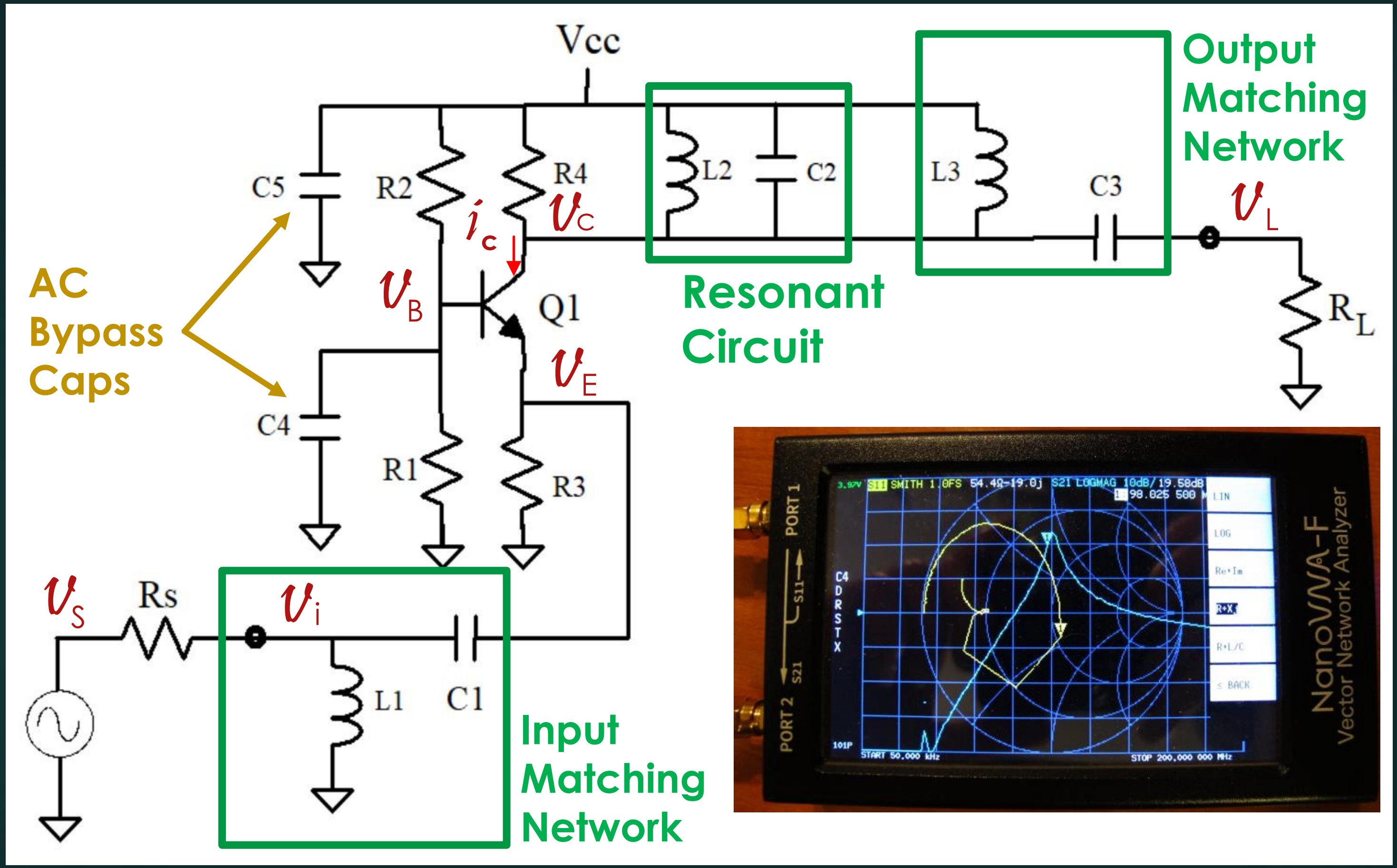


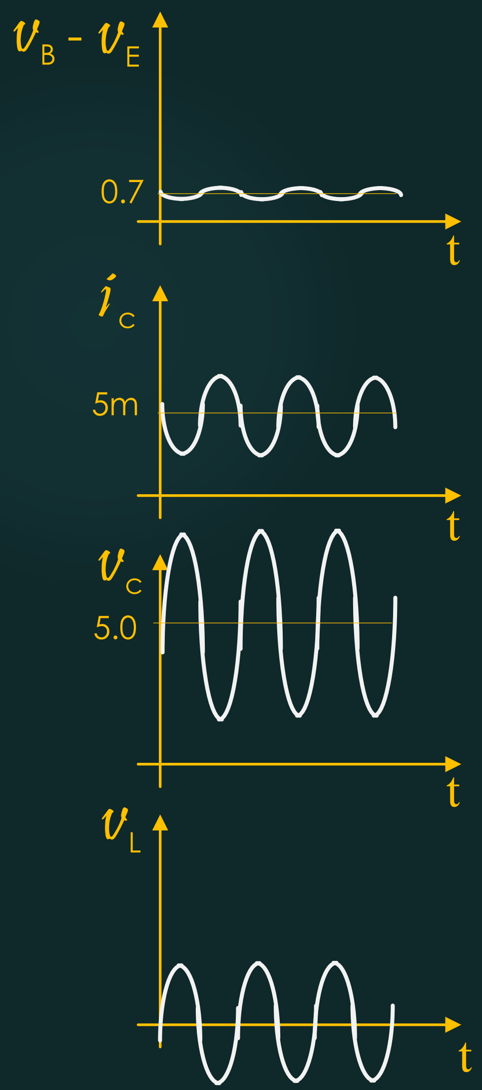
$$A_v = g_m R$$



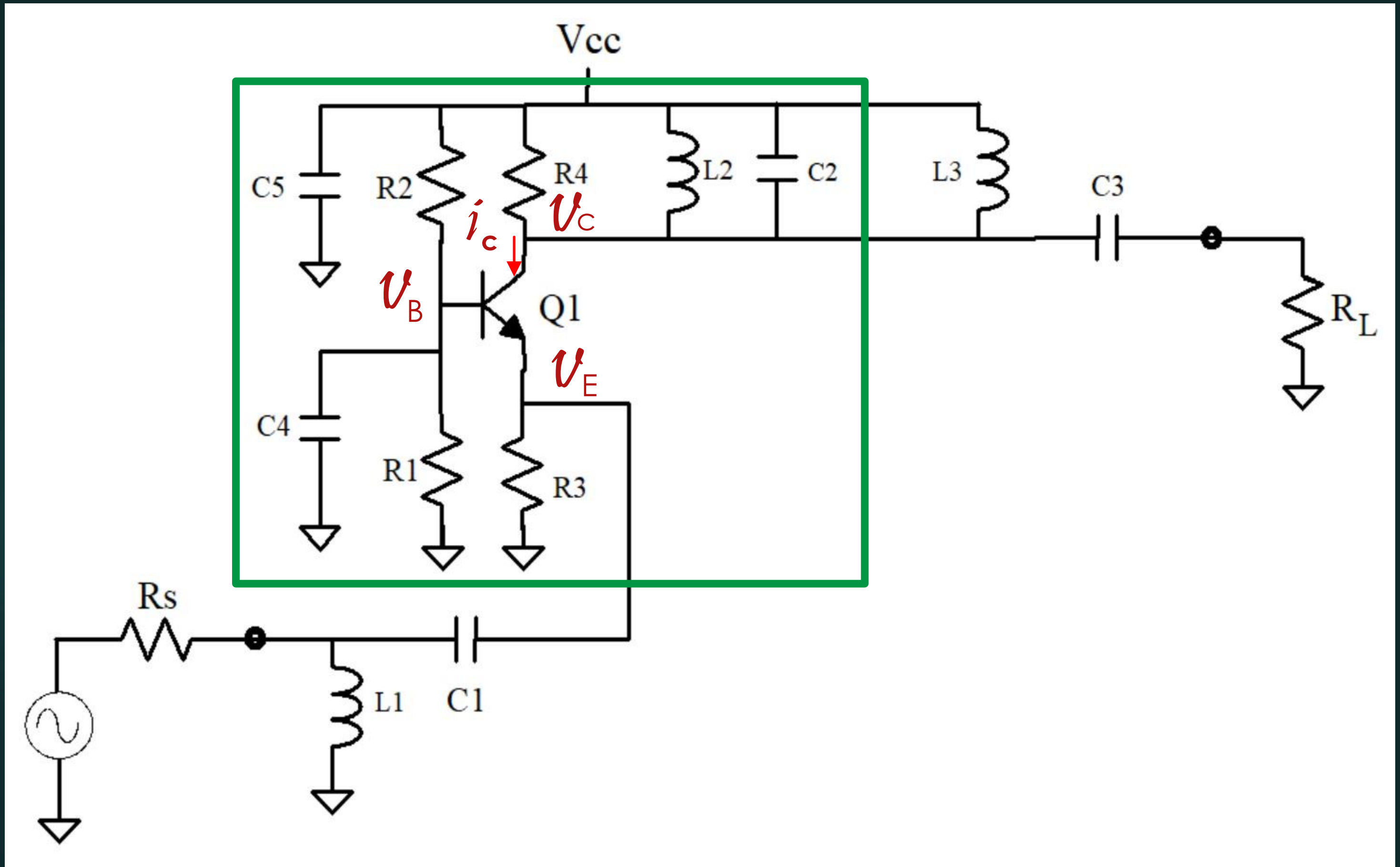
Practical Common-Base RF Amplifier
DC+AC Solution (From Part 1)







Core Amplifier Circuit Analysis



Analysis Method

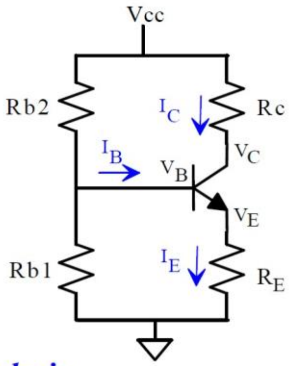
Based on superposition theory and linearized device models

- Solve DC bias to get I_c and g_m
- Solve AC small signal circuit to find gain (and R_i, R_o), and AC voltages, currents
- Add two solutions to get full waveforms, if designed

Practical BJT Biasing (From Part 1)

DC Biasing of Class A BJT Amplifiers

A traditional "4-resistor bias circuit" is shown below.



Bias circuit analysis

Assume the transistor is operating in the active region, and that Beta or h_{FE} is "large". Then, I_B will be approximately zero (relative to the current in R_{b1}, R_{b2}), and we can use the simple voltage divider formula at the base to get,

$$V_B \approx V_{cc} \frac{Rb1}{Rb1+Rb2}$$

If the transistor is in the active region, the BE junction is forward biased and $V_{BE_{on}} \approx 0.7V$. Hence,

$$V_E \approx V_B - 0.7$$

The emitter current is then,

$$I_E = \frac{V_E}{R_E}$$

and the collector current is,

$$I_C \approx I_E$$

Finally, the collector voltage can be found from the IR drop in Rc as,

$$V_C = V_{CC} - I_C R_C \; *$$

Note that these equations are reasonably independent of the transistor gain h_{FE} , provided the current through R_{b1} and R_{b2} is >> I_B. Hence, the bias voltages and currents should not change significantly with changes in h_{FE}

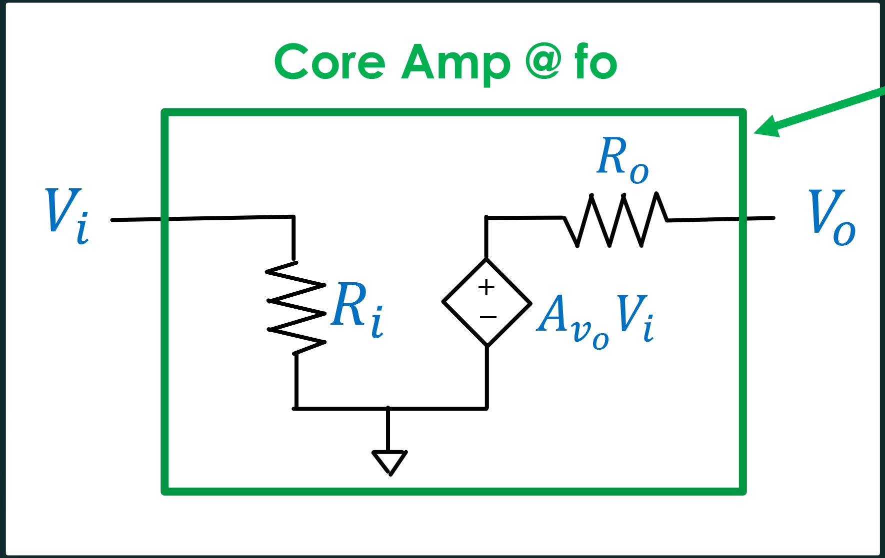
Note also that the bias current and DC voltages will be relatively insensitive to small variations in V_{BE} caused by temperature or manufacturing, provided that V_E is greater than about 0.5 to 1 volt.

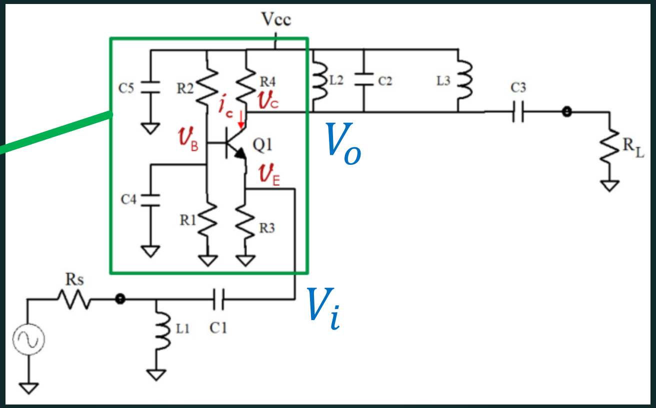
* For an RF amplifier with LC across Rc, Vc will be equal to Vcc

AC Small Signal Model
Of Voltage Amplifier Core

Simplified ***equivalent circuit (VCVS type)***

Based on Thevenin's theorem

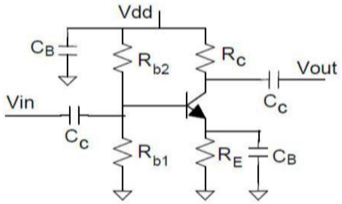
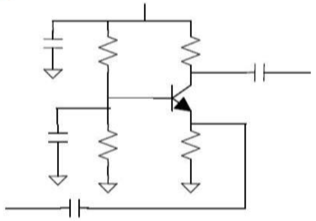
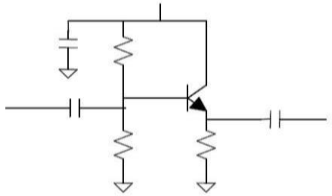




- R_i , R_o , and A_{vo} depend on amplifier device, circuit configuration, and biasing.
- In general, we should use Z_i, Z_o, and complex frequency-dependent gain …

SS Amplifier Configurations Review

(Low Frequency Formulas)

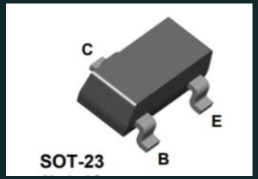
Configuration	Representative Circuit	Approx. Formulas	$A_{Vno\text{-}load}$	R_i	R_o
Common Emitter		$A_{Vno\text{-}load} = -\ g_m\ (R_c \vert\vert r_o)$ $R_i = r_\pi \vert\vert R_{b1} \vert\vert R_{b2}$ where $r_\pi = h_{fe}/g_m$ $R_0 = R_c \vert\vert r_o$	High	Med	Med
Common Base		$A_{Vno\text{-}load} = +g_m\ (R_c \vert\vert r_o)$ $R_i = 1/g_m \vert\vert R_E \vert\vert r_\pi$ $R_o = R_c \vert\vert r_o$	High	Low	Med
Common Collector (Emitter follower)		$A_{Vno\text{-}load} \approx 1$ $R_i = R_{b1} \vert\vert R_{b2} \vert\vert r_\pi(1+g_mR_E)$* $R_o = 1/g_m$**	Unity	High	Low

* Assumes unloaded output
** Assumes low source R

Where do these formulas come from ?

Let's find out …

Outline



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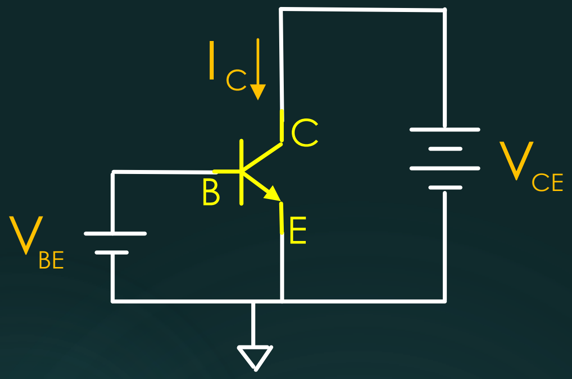
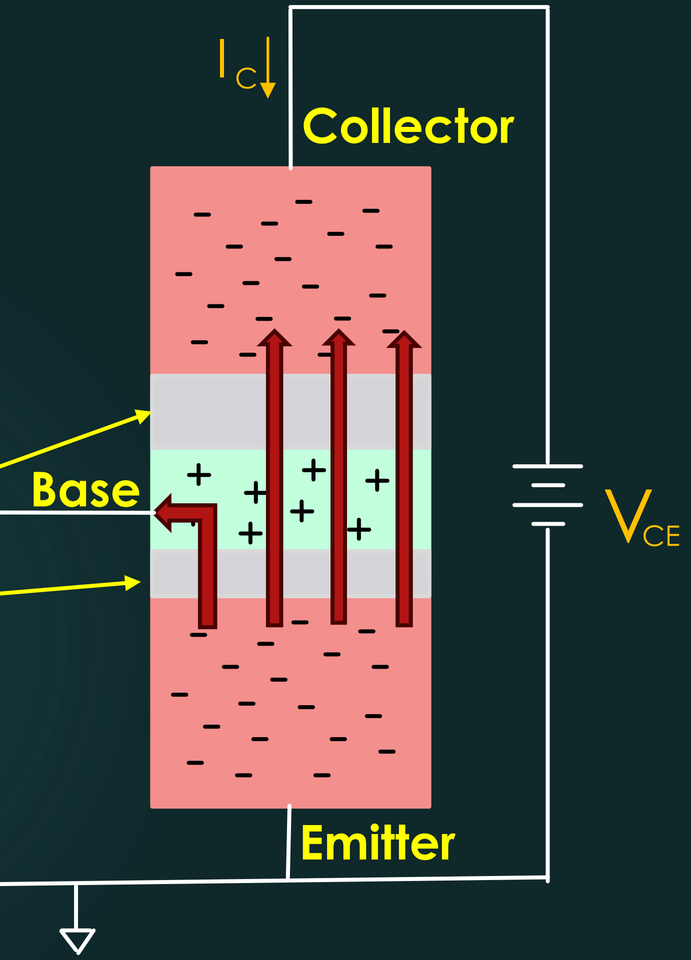
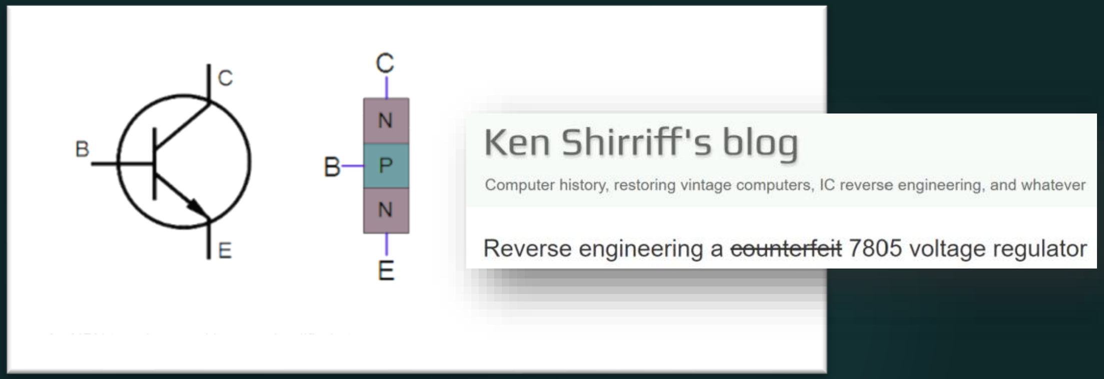
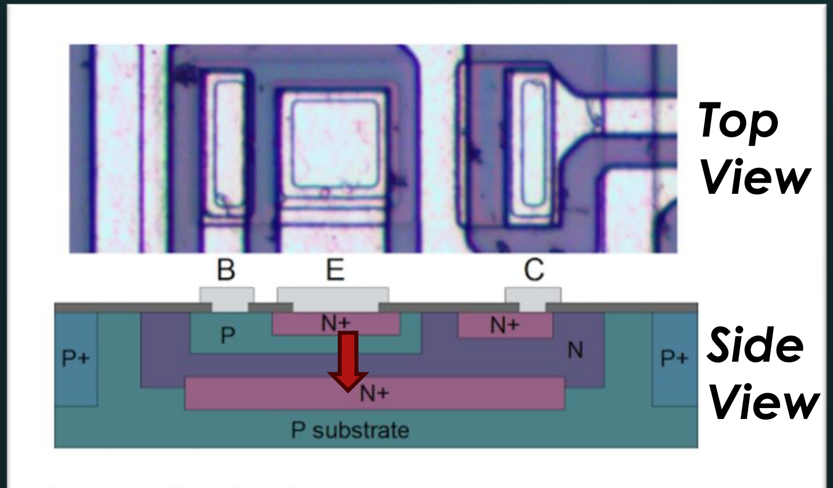
BJT Transistor Structure and Physics







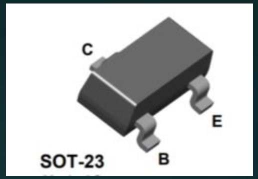


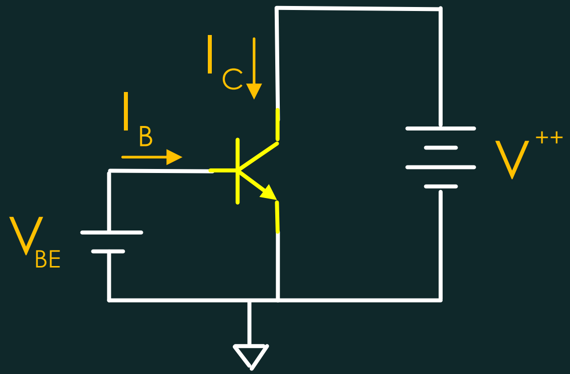
Structure of a NPN transistor inside the 7805 voltage regulator.

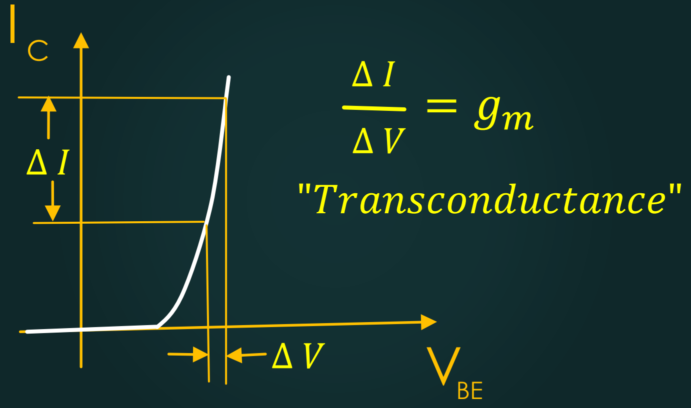
https://www.righto.com/2014/09/reverse-engineering-counterfeit-7805.html

BJTs vs MOSFETs
Similarities and Differences

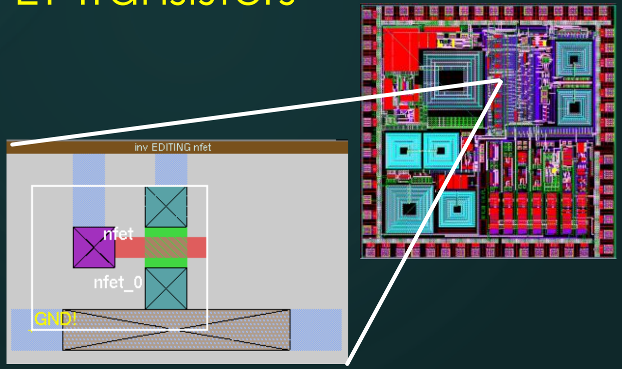
Bipolar Junction Transistor

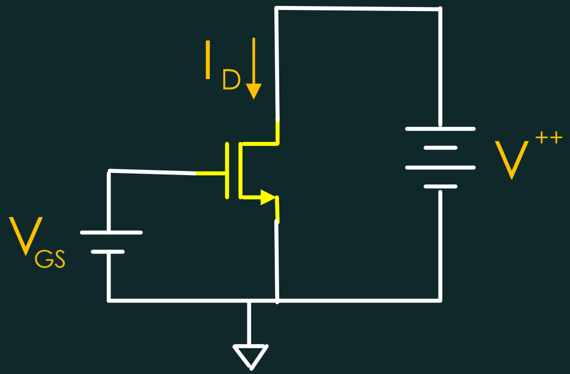


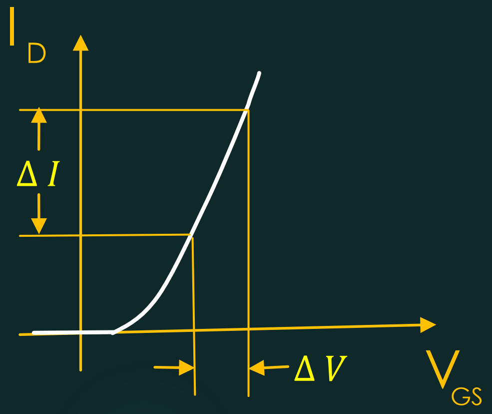




MOSFET Transistors





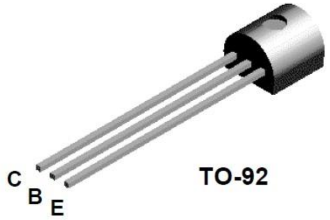


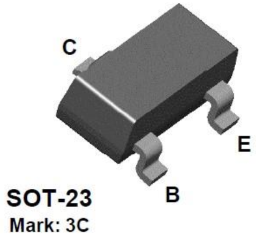
Example BJT Datasheet

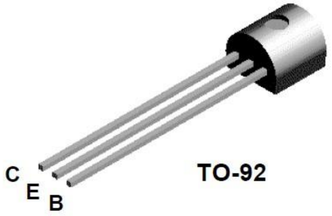
FAIRCHILD
SEMICONDUCTOR ™

MPS5179 / MMBT5179 / PN5179

MPS5179	MMBT5179	PN5179







NPN RF Transistor

This device is designed for use in low noise UHF/VHF amplifiers with collector currents in the 100 µA to 30 mA range in common emitter or common base mode of operation, and in low frequency drift, high ouput UHF oscillators. Sourced from Process 40.

Absolute Maximum Ratings*

TA = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	12	V
V_{CBO}	Collector-Base Voltage	20	V
V_{EBO}	Emitter-Base Voltage	2.5	V
I_C	Collector Current - Continuous	50	mA

Tabular Data

NPN RF Transistor
(continued)

MPS5179 / MMBT5179 / PN5179

Electrical Characteristics
TA = 25°C unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{CEO(sus)}$	Collector-Emitter Sustaining Voltage*	I_C = 3.0 mA, I_B = 0	12		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 1.0 µA, I_E = 0	20		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10 µA, I_C = 0	2.5		V
I_{CBO}	Collector Cutoff Current	V_{CB} = 15 V, I_E = 0 V_{CB} = 15 V, T_A = 150°C		0.02 1.0	µA µA
ON CHARACTERISTICS					
h_{FE}	DC Current Gain	I_C = 3.0 mA, V_{CE} = 1.0 V	25	250	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA		0.4	V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA		1.0	V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	I_C = 5.0 mA, V_{CE} = 6.0 V, f = 100 MHz	900	2000	MHz
C_{cb}	Collector-Base Capacitance	V_{CB} = 10 V, I_E = 0, f = 0.1 to 1.0 MHz		1.0	pF
h_{fe}	Small-Signal Current Gain	I_C = 2.0 mA, V_{CE} = 6.0 V, f = 1.0 kHz	25	300	
$r_b'C_c$	Collector Base Time Constant	I_C = 2.0 mA, V_{CB} = 6.0 V, f = 31.9 MHz	3.0	14	ps
NF	Noise Figure	I_C = 1.5 mA, V_{CE} = 6.0 V, R_S = 50Ω, f = 200 MHz		5.0	dB
FUNCTIONAL TEST					
G_{pe}	Amplifier Power Gain	V_{CE} = 6.0 V, I_C = 5.0 mA, f = 200 MHz	15		dB
P_O	Power Output	V_{CB} = 10 V, I_E = 12 mA, f ≥ 500 MHz	20		mW

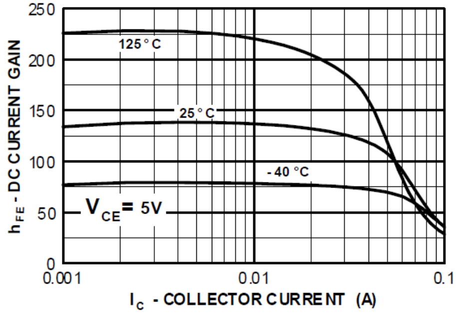
NOTE:
Current gain
$\beta \equiv h_{FE}$

Graphs

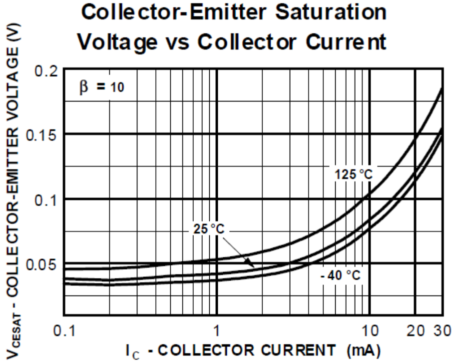
NPN RF Transistor
(continued)

Typical Characteristics

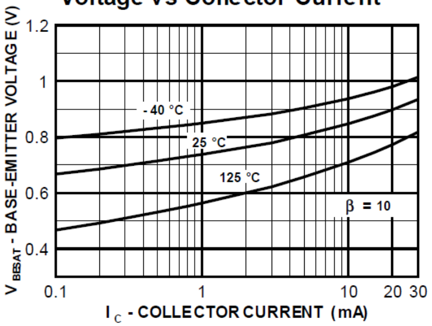
DC Current Gain vs Collector Current



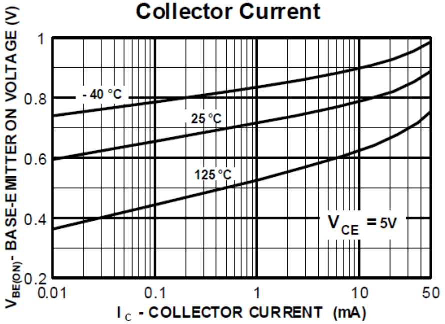
Collector-Emitter Saturation Voltage vs Collector Current



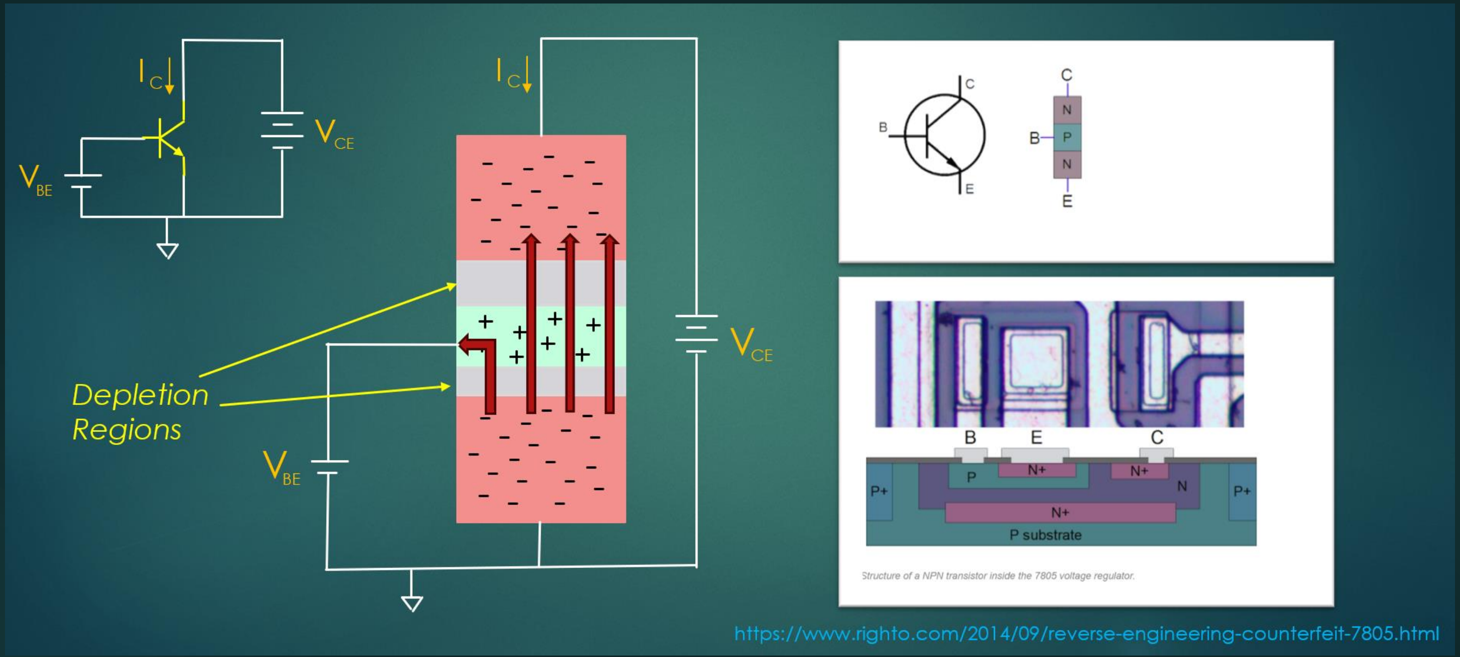
Base-Emitter Saturation Voltage vs Collector Current

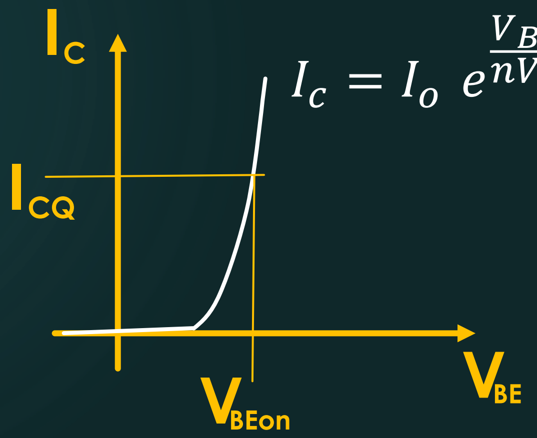


Base-Emitter ON Voltage vs Collector Current

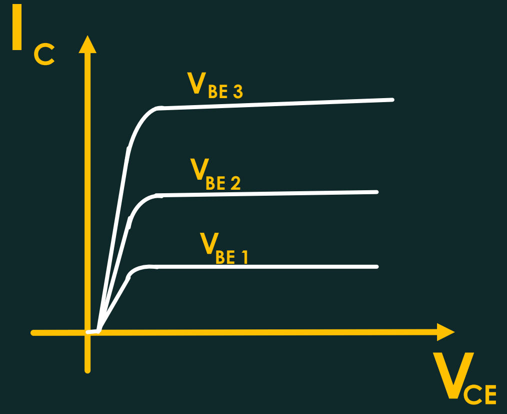


IV Curves





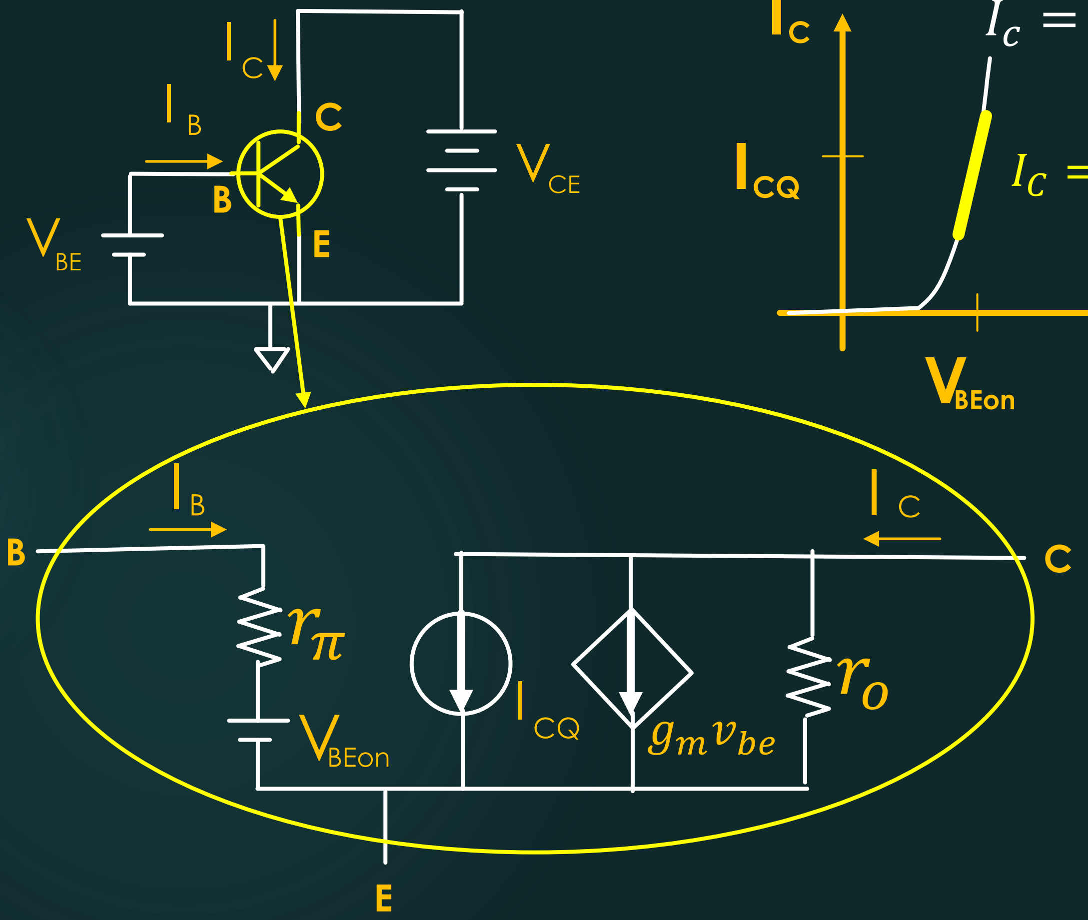
$$I_c = I_o\ e^{\frac{V_{BE}}{nV_T}}$$

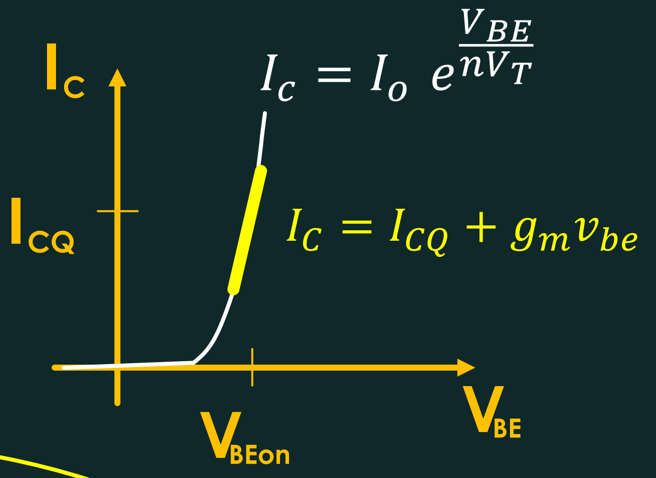


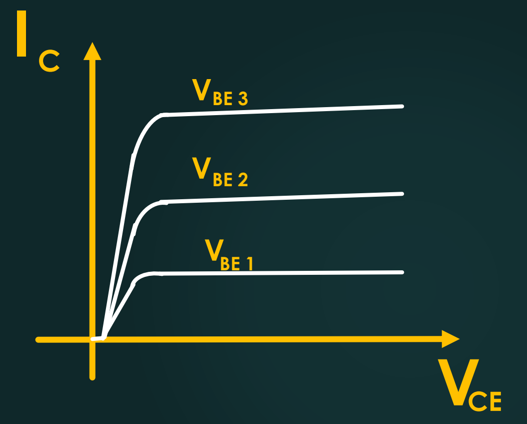
$$I_B = \frac{I_C}{\beta}$$

BJT Linearized Circuit Model

(at DC, low, and mid frequencies)







$$I_B = \frac{I_C}{\beta}$$

$$Transconductance:\quad g_m \triangleq \frac{\Delta I_c}{\Delta V_{BE}} = \frac{i_c}{v_{be}}$$

$$Small - signal\ input:\quad v_{be} \triangleq \left(v_{BE} - V_{BE_{on}}\right)$$

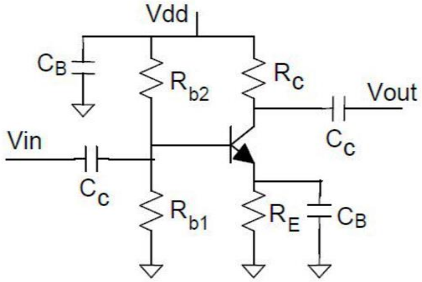
$$g_m = \frac{I_{CQ}}{nV_T} \approx \frac{I_{CQ}}{0.04}$$

$$r_\pi = \beta \frac{1}{g_m}$$

$$r_o \cong \infty$$

NOTE: Circuit model is a Taylor Series expansion of $I_c(V_{BE})$ around bias point $V_{BE_{on}}, I_{CQ}$

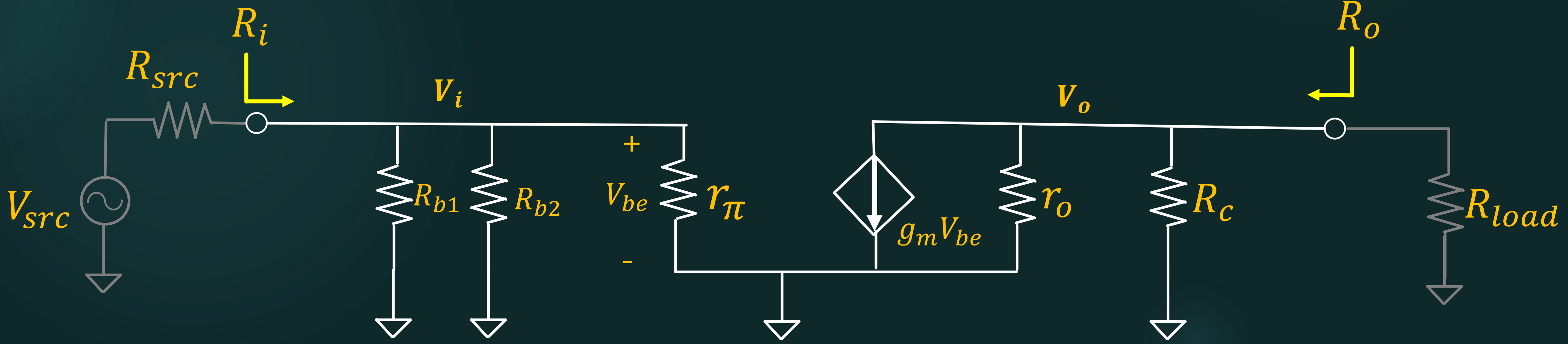
BJT Amp Small Signal AC Analysis At "Midband" Frequencies

Configuration	Representative Circuit	Approx. Formulas	$A_{Vno\text{-}load}$	R_i	R_o
Common Emitter		$A_{Vno\text{-}load} = -\, g_m (R_c \| r_o)$ $R_i = r_\pi \| R_{b1} \| R_{b2}$ where $r_\pi = h_{fe}/g_m$ $R_0 = R_c \| r_o$	High	Med	Med

$$V_o|_{R_{load}=\infty} = -\, g_m v_{be}(R_c \parallel r_o)$$

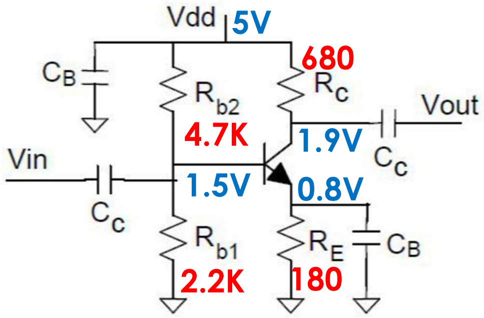
$$V_{be} \equiv V_i$$

$$\Rightarrow \left.\frac{V_o}{V_i}\right|_{R_{load}=\infty} = -\, g_m(R_c \parallel r_o)$$

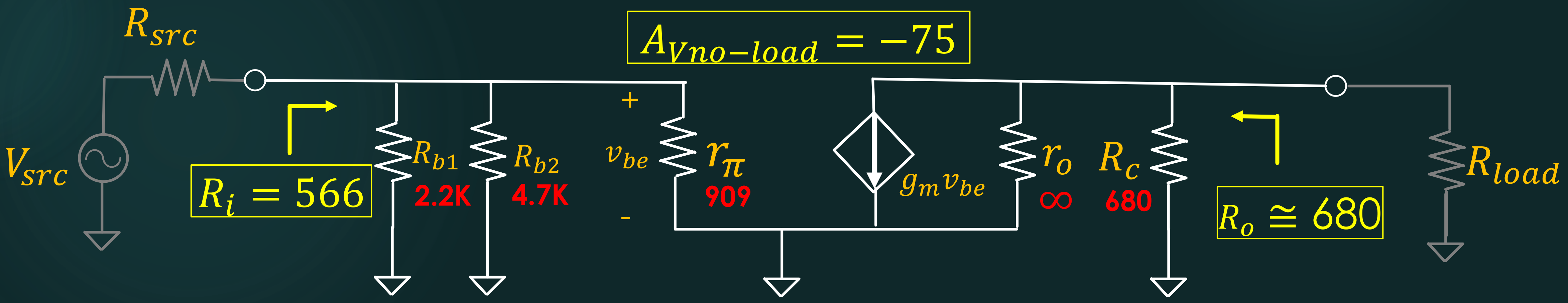


Example Values

Ic=4.5 mA => gm = 0.11A/V $r_\pi = \frac{100}{0.11} = 909$ $r_o \cong \infty$

Configuration	Representative Circuit	Approx. Formulas	$A_{Vno\text{-}load}$	R_i	R_o
Common Emitter		$A_{Vno\text{-}load} = -g_m(R_c \Vert r_o)$ $R_i = r_\pi \Vert R_{b1} \Vert R_{b2}$ where $r_\pi = h_{fe}/g_m$ $R_0 = R_c \Vert r_o$	"High" 75	Med 566	Med 680

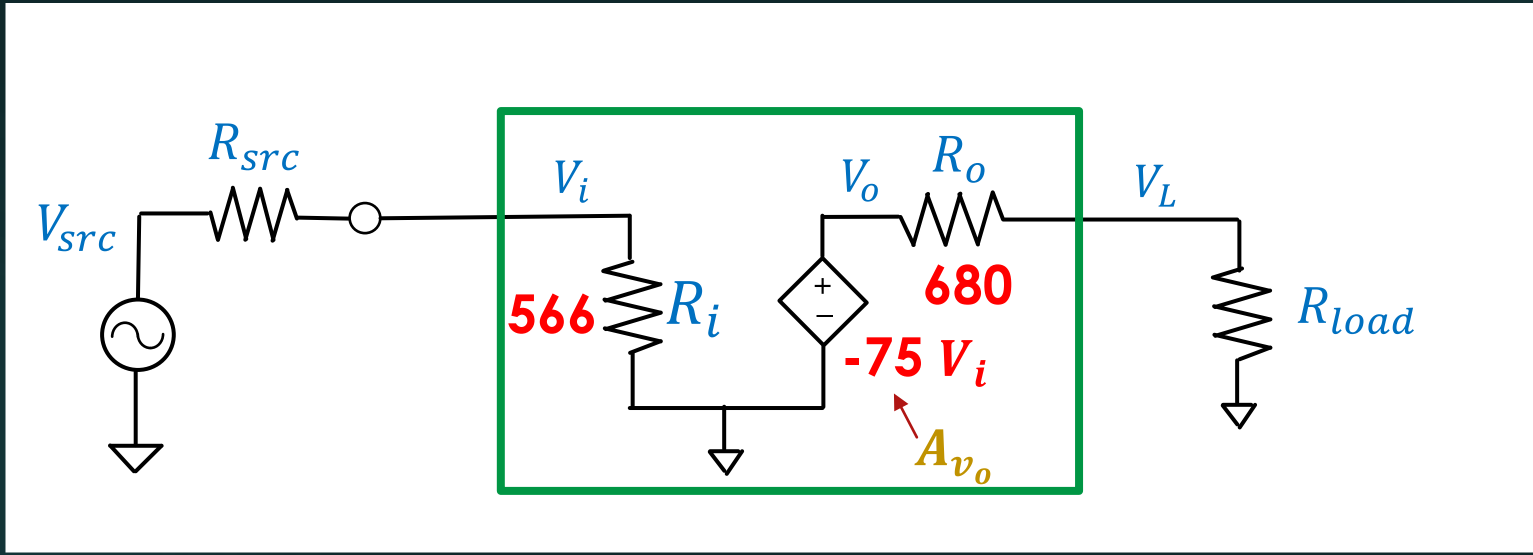
$h_{fe} \cong \beta = \frac{I_C}{I_B}$



$|A_{V\ loaded}| < 75$ *Why?*

$A_{V\ loaded}$

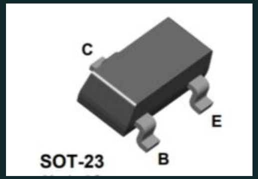
NOTE: Voltage amplifier model below can be derived from previous one using Thevenin's Theorem



Then:

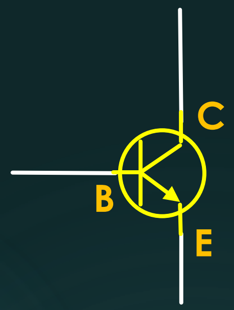
$$A_{V\ loaded} \triangleq \frac{V_L}{V_{src}} = \left(\frac{V_i}{V_{src}}\right)\left(\frac{V_o}{V_i}\right)\left(\frac{V_L}{V_o}\right) = \left(\frac{R_i}{R_i+R_{src}}\right)\left(A_{v_o}\right)\left(\frac{R_{load}}{R_{load}+R_o}\right)$$

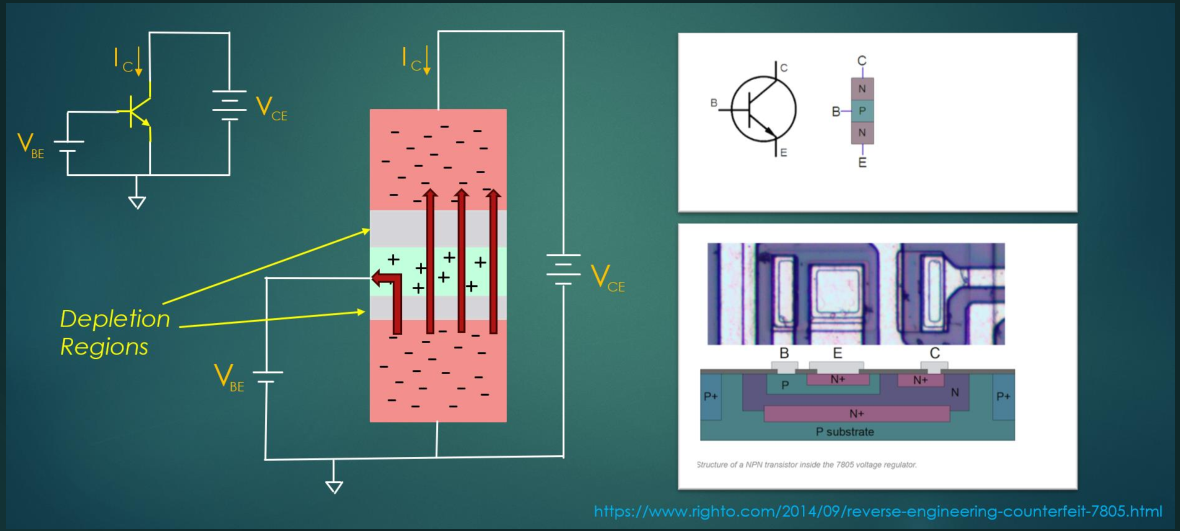
Outline



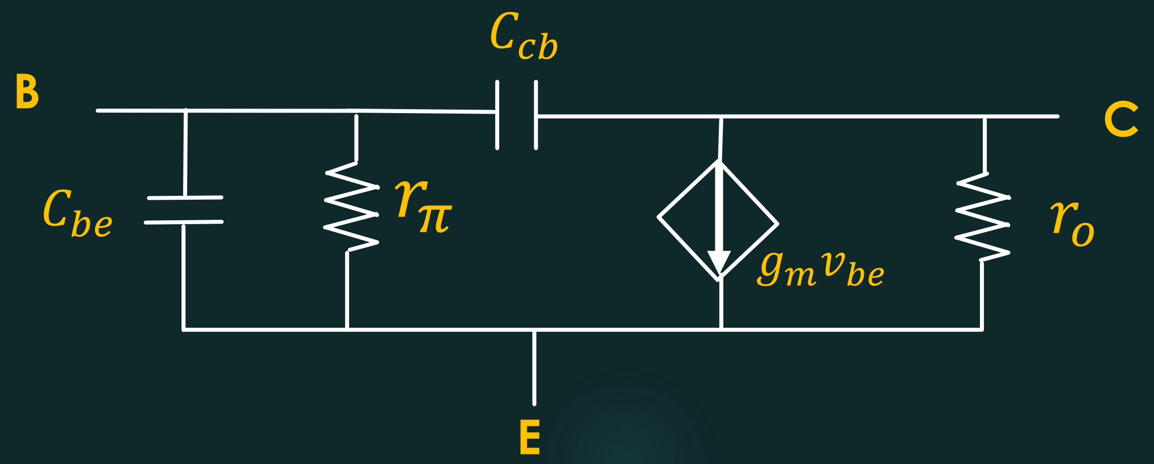
- *Triode Devices*
- *DC Biasing*
- *AC Gain and I/O Impedances*
- *Small Signal Amplifier Configurations*
- ***Transistors, Data Sheets and Models***
- ***High Frequency Model and Limitations***

Small Signal AC Model at RF

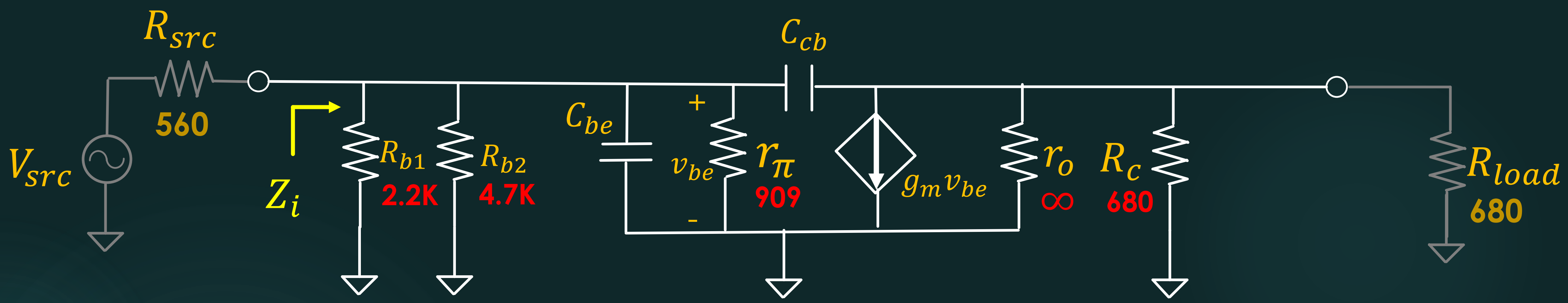




- Emitter, Base, and Collector are (semi) conducting regions
- They are separated by insulating “depletion” regions
- This is the basic structure of a capacitor !



Effects on Circuit Operation



- C_{be} and C_{cb} create lowpass filtering
- C_{cb} is magnified by "Miller Effect" ☹

$$\boldsymbol{C_{in} = C_{be} + (1 + |A_{Vloaded}|)C_{cb}}$$
$$\boldsymbol{\approx (13 + 37)pF \ @\ 4.5\ mA}$$

$$\Rightarrow Z_i \approx -j32\ \Omega\ @\ 100\ MHz\ !$$

- Solutions to this problem at RF include:
  - Use CB or Cascode configurations instead of typical CE amp
  - Use LC circuits for resonance and matching for good *power* gain
  - Incorporate parasitic C into matching network design

Finding C_{be} and C_{cb}

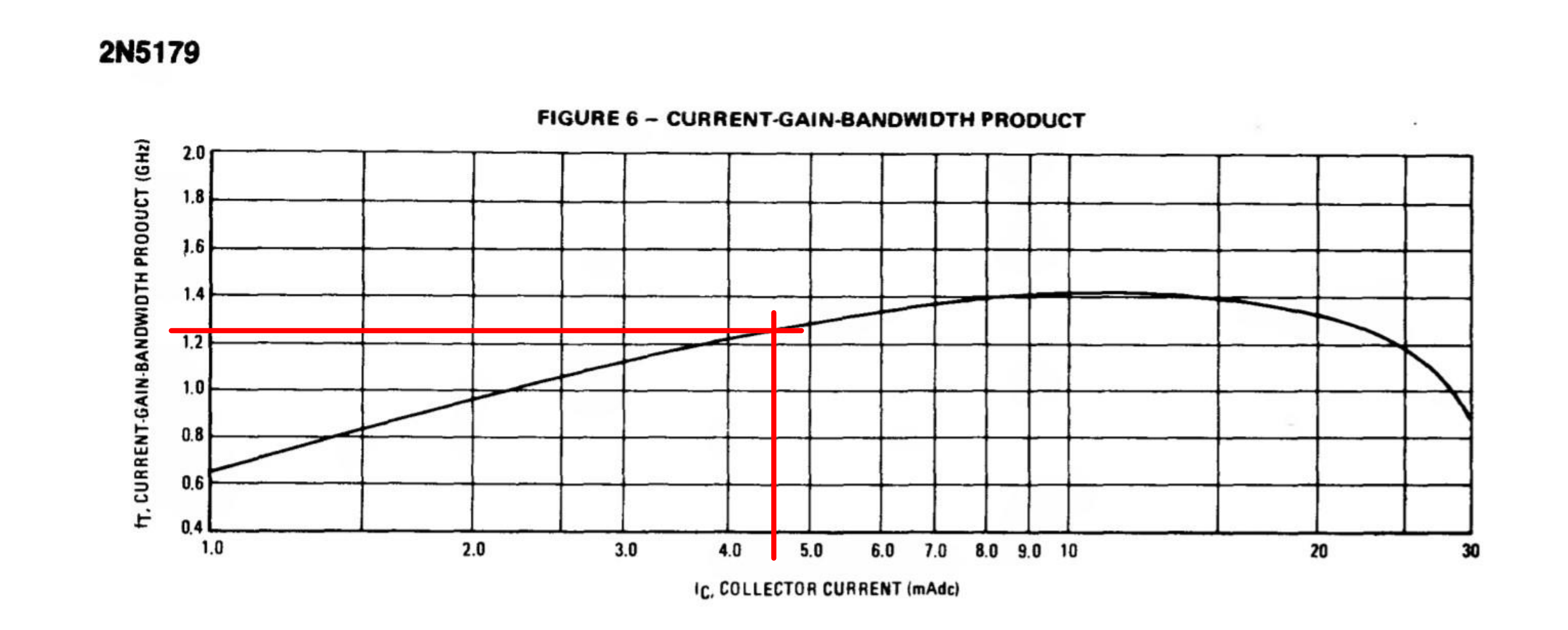
MPS5179 / MMBT5179 / PN5179

NPN RF Transistor
(continued)

Electrical Characteristics TA = 25°C unless otherwise noted

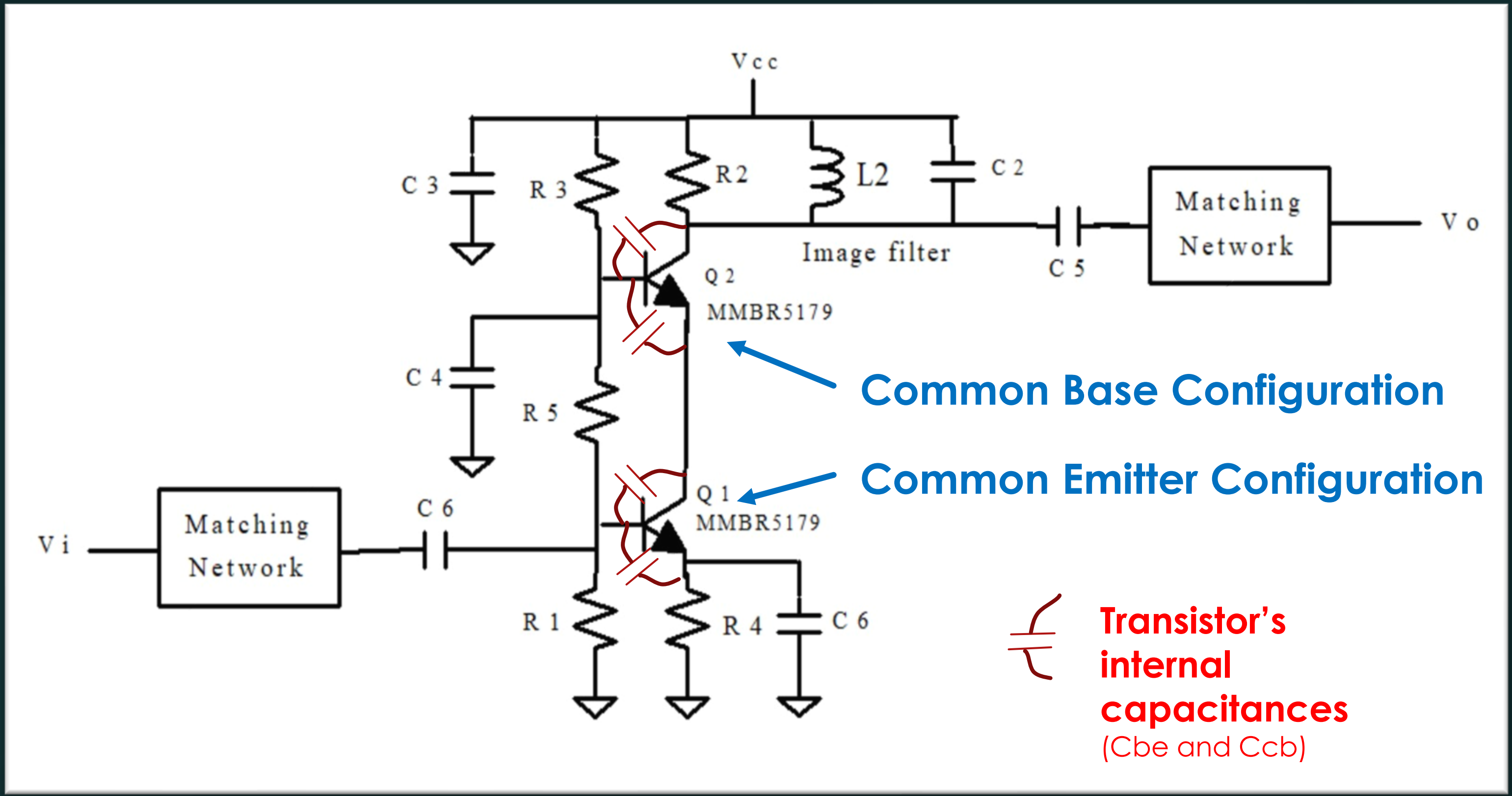
Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{CEO(sus)}$	Collector-Emitter Sustaining Voltage*	I_C = 3.0 mA, I_B = 0	12		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 1.0 μA, I_E = 0	20		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10 μA, I_C = 0	2.5		V
I_{CBO}	Collector Cutoff Current	V_{CB} = 15 V, I_E = 0 V_{CB} = 15 V, T_A = 150°C		0.02 1.0	μA μA
ON CHARACTERISTICS					
h_{FE}	DC Current Gain	I_C = 3.0 mA, V_{CE} = 1.0 V	25	250	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA		0.4	V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA		1.0	V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	I_C = 5.0 mA, V_{CE} = 6.0 V, f = 100 MHz	900	2000	MHz
C_{cb}	Collector-Base Capacitance	V_{CB} = 10 V, I_E = 0, f = 0.1 to 1.0 MHz		1.0	pF
h_{fe}	Small-Signal Current Gain	I_C = 2.0 mA, V_{CE} = 6.0 V, f = 1.0 kHz	25	300	
$rb'C_c$	Collector Base Time Constant	I_C = 2.0 mA, V_{CB} = 6.0 V, f = 31.9 MHz	3.0	14	ps
NF	Noise Figure	I_C = 1.5 mA, V_{CE} = 6.0 V, R_S = 50Ω, f = 200 MHz		5.0	dB
FUNCTIONAL TEST					
G_{pe}	Amplifier Power Gain	V_{CE} = 6.0 V, I_C = 5.0 mA, f = 200 MHz	15		dB
P_O	Power Output	V_{CB} = 10 V, I_E = 12 mA, f ≥ 500 MHz	20		mW

Finding C_{be}

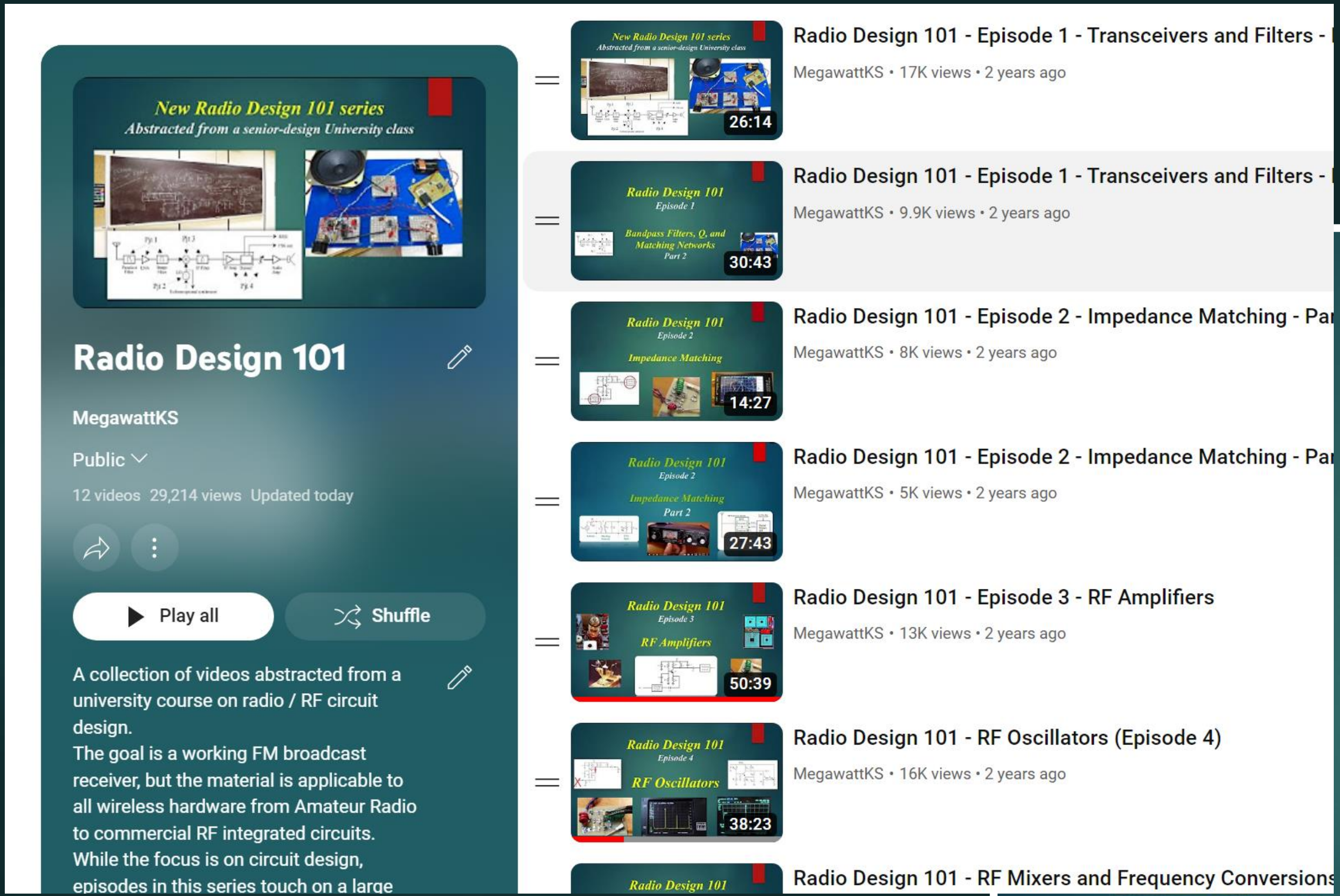


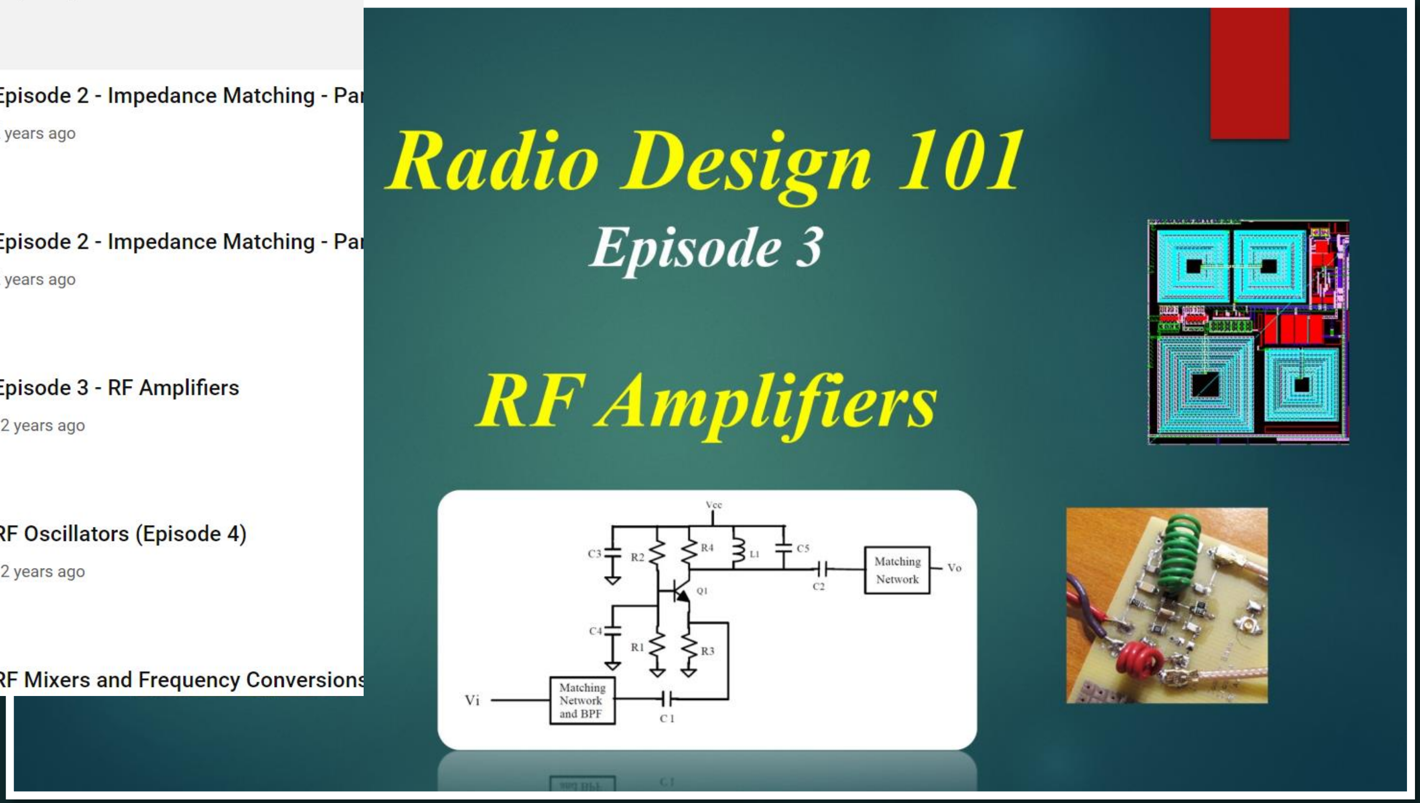
$$g_m = \frac{I_c}{nV_T} \qquad C_{be} \approx \frac{1}{2\pi \frac{1}{g_m} f_T} - C_{cb} \qquad r_\pi = \frac{1}{g_m} h_{fe}$$

Cascode Amplifier Solution
(Details coming in Part 3 ?)



For More Information

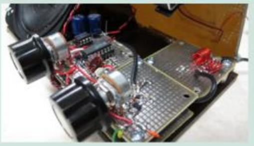


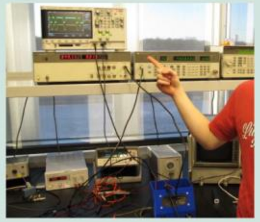


For More Information

https://ecefiles.org/rf-circuits-course-notes/

RF Circuits Course Notes





Designing and Building Transmitters and Receivers in a Single Semester

This page was created to document a senior design course taught by the author for 20 years at Kansas State University. It is related to the "Radio Design 101" series of videos on YouTube, but goes into more depth (at the expense of being less polished in presentation)

Lectures and Class Handouts

Each link below leads to lecture notes (hand written and a bit rough) plus course handouts (typed and much nicer) on the associated topic.

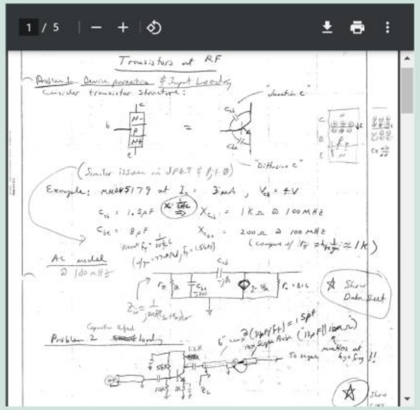
- Syllabus, Parts List, and Typical Assignments
- Prototyping Boards
  -
- Course Introduction
- Electronic Amplifier Design
- Transistors at RF
- Resonant Circuits
- Component Parasitics
- Impedance Matching and Power Gain
- Transmission Lines and Smith Charts
- Two Port Linear Circuit Modeling and S-Parameters
- RF Test Equipment
- Oscillators, Varactors, and VCOs plus Crystals and TCXOs
- Transmitters, Antennas, FCC Rules, and Midterm Exam

- Mixers and Frequency Downconversion
- Toroids, Transformers, and Cores
- Filters
- IF Amp, Demod, and Audio Amp
- Final Receiver Assembly

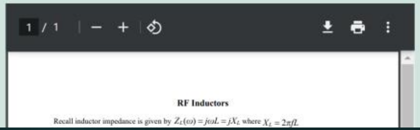
- Student Notes and Circuit/Measurement Pics

RF Circuits Course Section 3

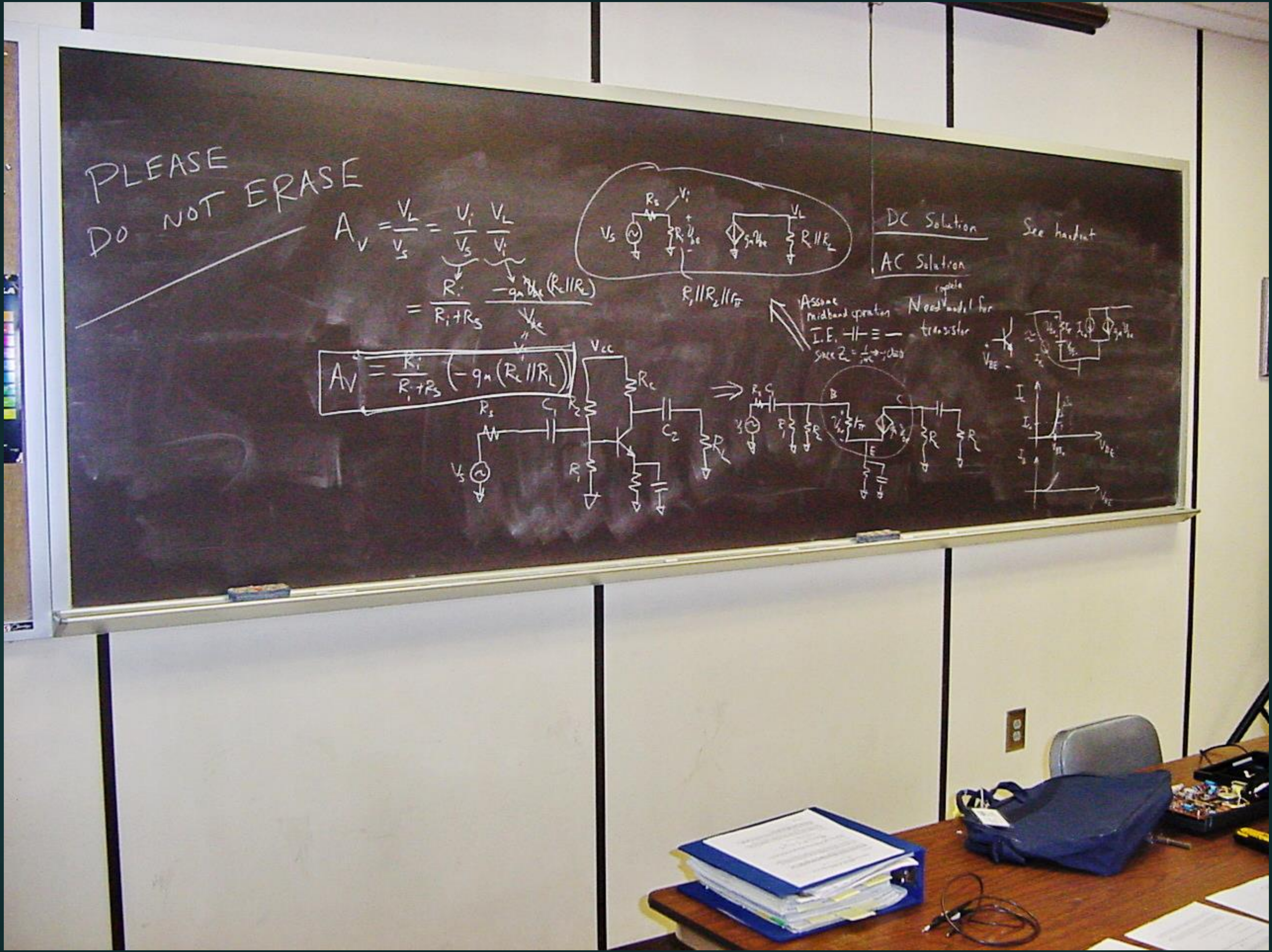
Transistors at RF



003_TransistorsAtRF-1 Download



Thanks For Watching !


PLEASE
DO NOT ERASE
DC Solution
See handout
AC Solution
Assume midband operation
transistor