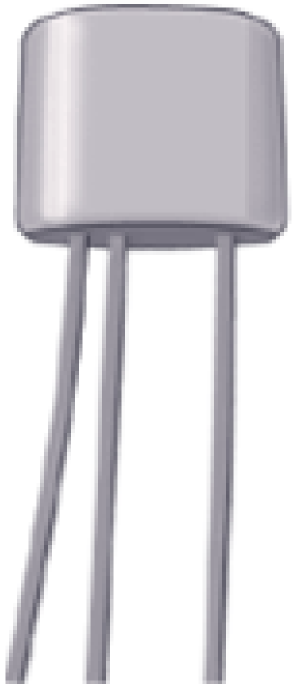
Transistors

- What is a Transistor?
- History
- Types
- Characteristics
- Applications

What is a Transistor?

- Semiconductors: ability to change from conductor to insulator
- Can either allow current or prohibit current to flow
- Useful as a switch, but also as an amplifier
- Essential part of many technological advances

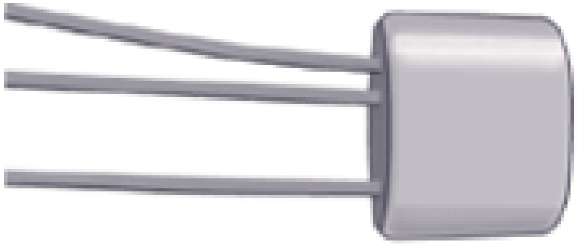


A Brief History

- Guglielmo Marconi invents radio in 1895
- Problem: For long distance travel, signal must be amplified
- Lee De Forest improves on Fleming’s original vacuum tube to amplify signals
- Made use of third electrode
- Too bulky for most applications

The Transistor is Born

- Bell Labs (1947): Bardeen, Brattain, and Shockley
- Originally made of germanium
- Current transistors made of doped silicon

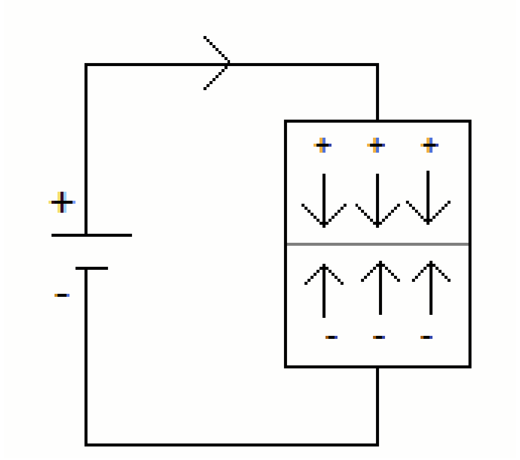


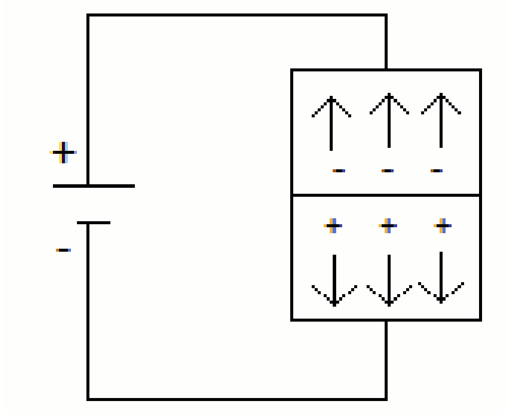
How Transistors Work

- Doping: adding small amounts of other elements to create additional protons or electrons
- P-Type: dopants lack a fourth valence electron (Boron, Aluminum)
- N-Type: dopants have an additional (5^{th}) valence electron (Phosphorus, Arsenic)
- Importance: Current only flows from P to N

Diodes and Bias

- Diode: simple P-N junction.
- Forward Bias: allows current to flow from P to N.
- Reverse Bias: no current allowed to flow from N to P.
- Breakdown Voltage: sufficient N to P voltage of a Zener Diode will allow for current to flow in this direction.

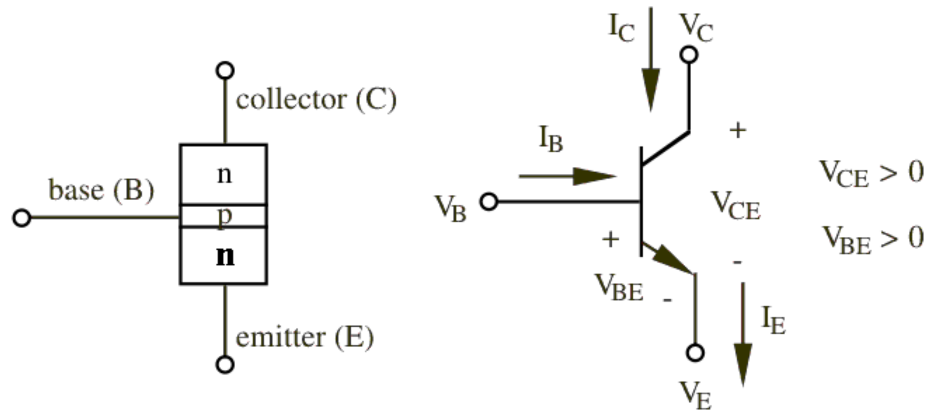




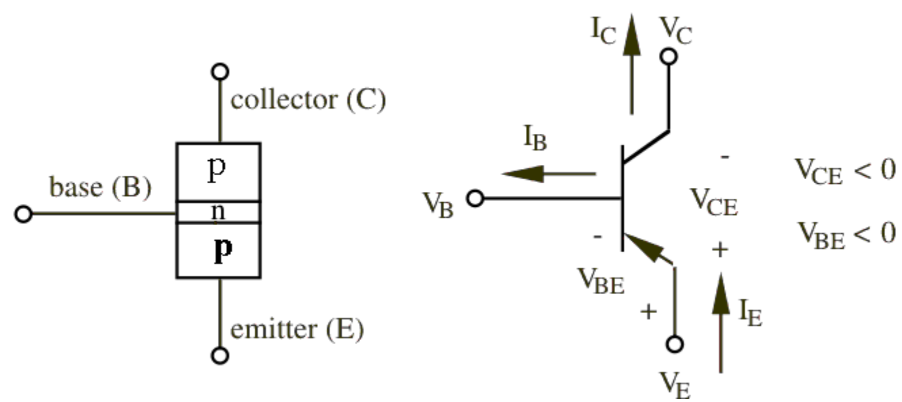
Bipolar Junction Transistor (BJT)

- 3 adjacent regions of doped Si (each connected to a lead):
  - Base. (thin layer,less doped).
  - Collector.
  - Emitter.
- 2 types of BJT:
  - npn.
  - pnp.
- Most common: npn (focus on it).

Developed by Shockley (1949)



npn bipolar junction transistor



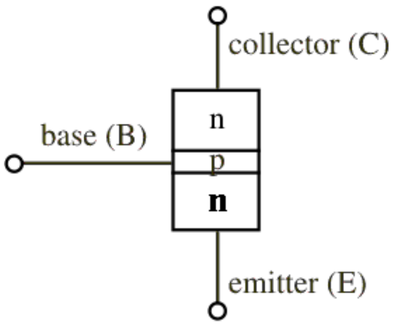
pnp bipolar junction transistor

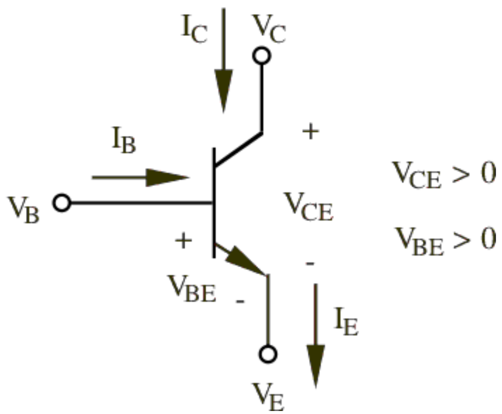
BJT npn Transistor

- 1 thin layer of p-type, sandwiched between 2 layers of n-type.
- N-type of emitter: more heavily doped than collector.
- With $V_C > V_B > V_E$:
  - Base-Emitter junction forward biased, Base-Collector reverse biased.
  - Electrons diffuse from Emitter to Base (from n to p).
  - There's a depletion layer on the Base-Collector junction → no flow of e^- allowed.
  - **BUT** the Base is thin and Emitter region is n^+ (heavily doped) → electrons have enough momentum to cross the Base into the Collector.
  - The small base current I_B controls a large current I_C

$$V_C > V_B > V_E$$

$$I_E = I_C + I_B$$
$$V_{BE} = V_B - V_E$$
$$V_{CE} = V_C - V_E$$
$$I_C = \beta I_B$$





BJT characteristics

- Current Gain:
  - α is the fraction of electrons that diffuse across the narrow Base region
  - 1- α is the fraction of electrons that recombine with holes in the Base region to create base current
- The current Gain is expressed in terms of the **β** (beta) of the transistor (often called h_{fe} by manufacturers).
- β (beta) is Temperature and Voltage dependent.
- It can vary a lot among transistors (common values for signal BJT: 20 - 200).

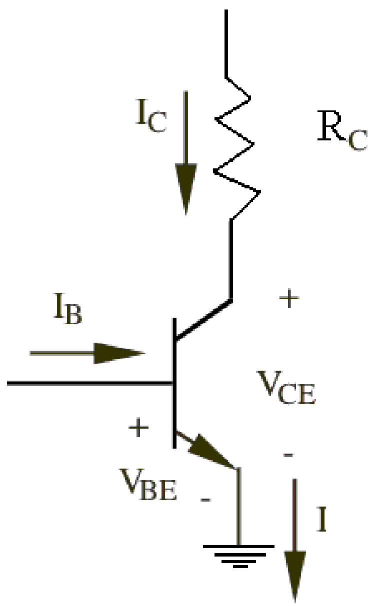
$$I_C = \alpha I_E$$

$$I_B = (1-\alpha) I_E$$

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

npn Common Emitter circuit

- Emitter is grounded.
- Base-Emitter starts to conduct with V_{BE}=0.6V,I_C flows and it's $I_C=\beta * I_B$.
- Increasing I_B, V_{BE} slowly increases to 0.7V but I_C rises exponentially.
- As I_C rises ,voltage drop across R_C increases and V_{CE} drops toward ground. (transistor in saturation, no more linear relation between I_C and I_B)



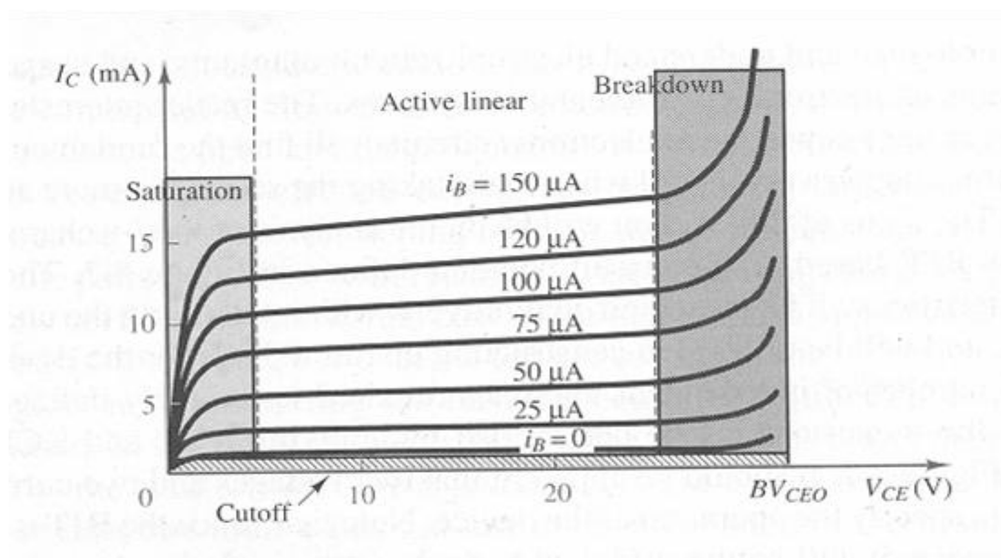


Figure 8.9(b) The collector-emitter output characteristics of a BJT

Common Emitter characteristics

Collector current controlled by the collector circuit. (Switch behavior)

In full saturation V_{CE}=0.2V.

Collector current proportional to Base current

The avalanche multiplication of current through collector junction occurs: to be avoided

No current flows

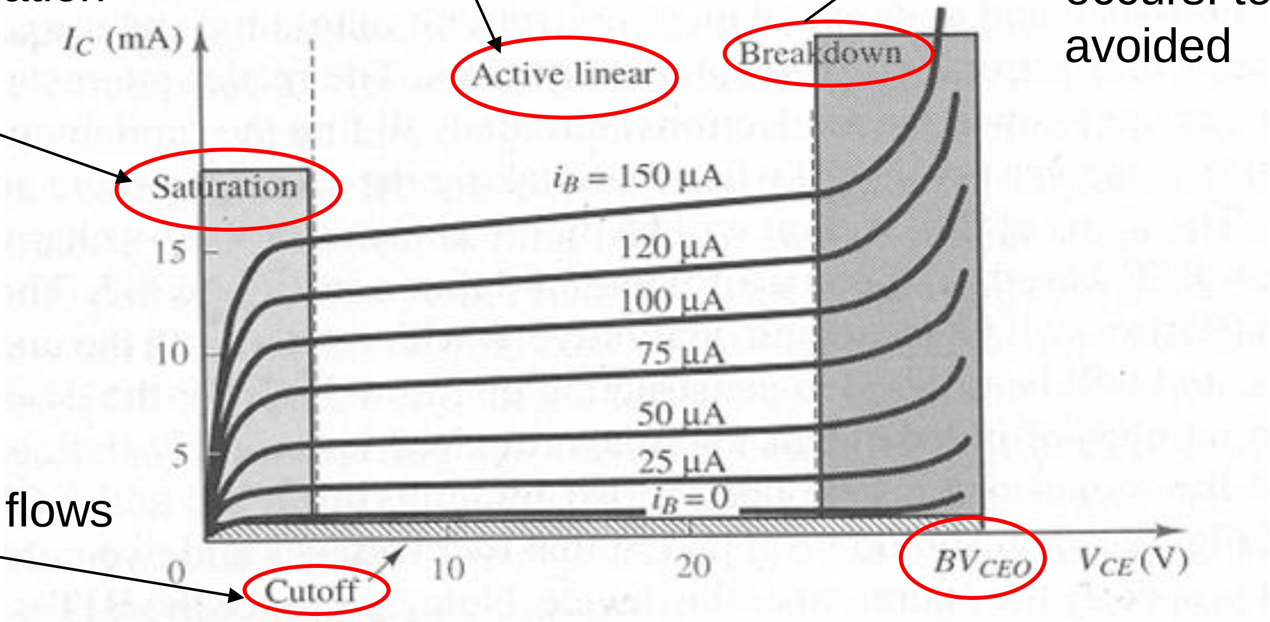
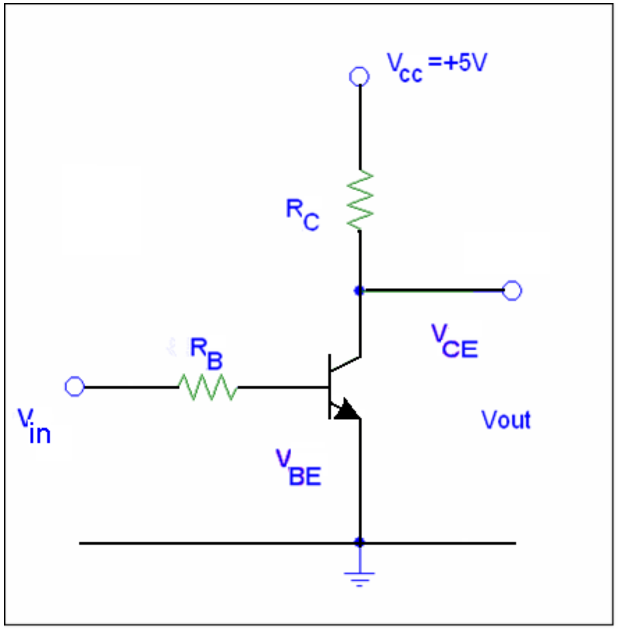


Figure 8.9(b) The collector-emitter output characteristics of a BJT

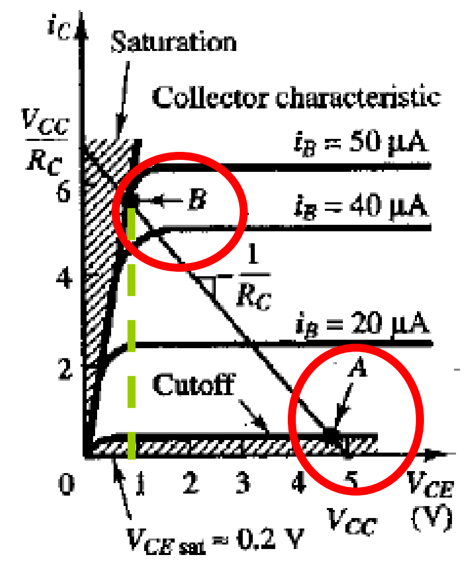
Operation region summary

Operation Region	***I_B or V_{CE} Char.***	***BC and BE Junctions***	***Mode***
Cutoff	I_B = Very small	Reverse & Reverse	Open Switch
Saturation	V_{CE} = Small	Forward & Forward	Closed Switch
Active Linear	V_{CE} = Moderate	Reverse & Forward	Linear Amplifier
Break-down	V_{CE} = Large	Beyond Limits	Overload

BJT as Switch



- V_{in}(Low) < 0.7 V
  - BE junction not forward biased
  - Cutoff region
  - No current flows
  - $V_{out} = V_{CE} = V_{cc}$
- V_{out} = High

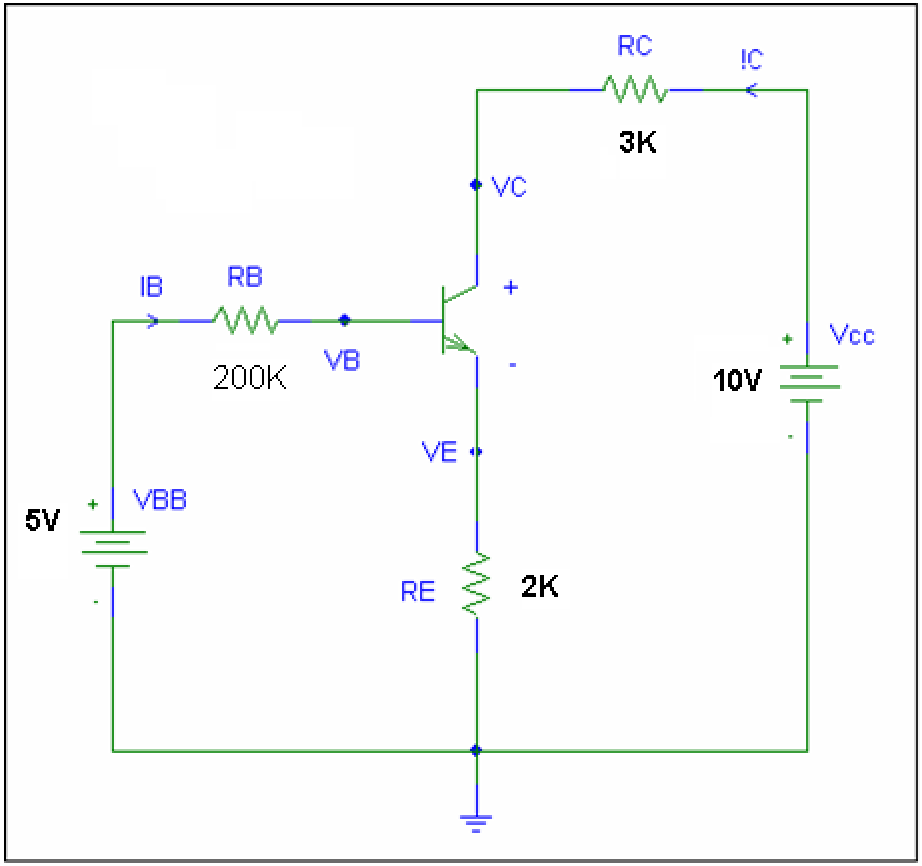


- V_{in}(High)
  - BE junction forward biased (V_{BE}=0.7V)
  - Saturation region
  - V_{CE} small (~0.2 V for saturated BJT)
  - V_{out} = small
  - $I_B = (V_{in}-V_B)/R_B$
- V_{out} = Low

BJT as Switch 2

- Basis of digital logic circuits
- Input to transistor gate can be analog or digital
- Building blocks for TTL – Transistor Transistor Logic
- Guidelines for designing a transistor switch:
  - $V_C > V_B > V_E$
  - $V_{BE} = 0.7$ V
  - I_C independent from I_B (in saturation).
  - Min. I_B estimated from by ($I_{Bmin} \approx I_C/\beta$).
  - Input resistance → such that I_B > 5-10 times I_{Bmin} because β varies among components, with temperature and voltage and R_B may change when current flows.
  - Calculate the max I_C and I_B not to overcome device specifications.

BJT as Amplifier



- Common emitter mode
- Linear Active Region
- Significant current Gain

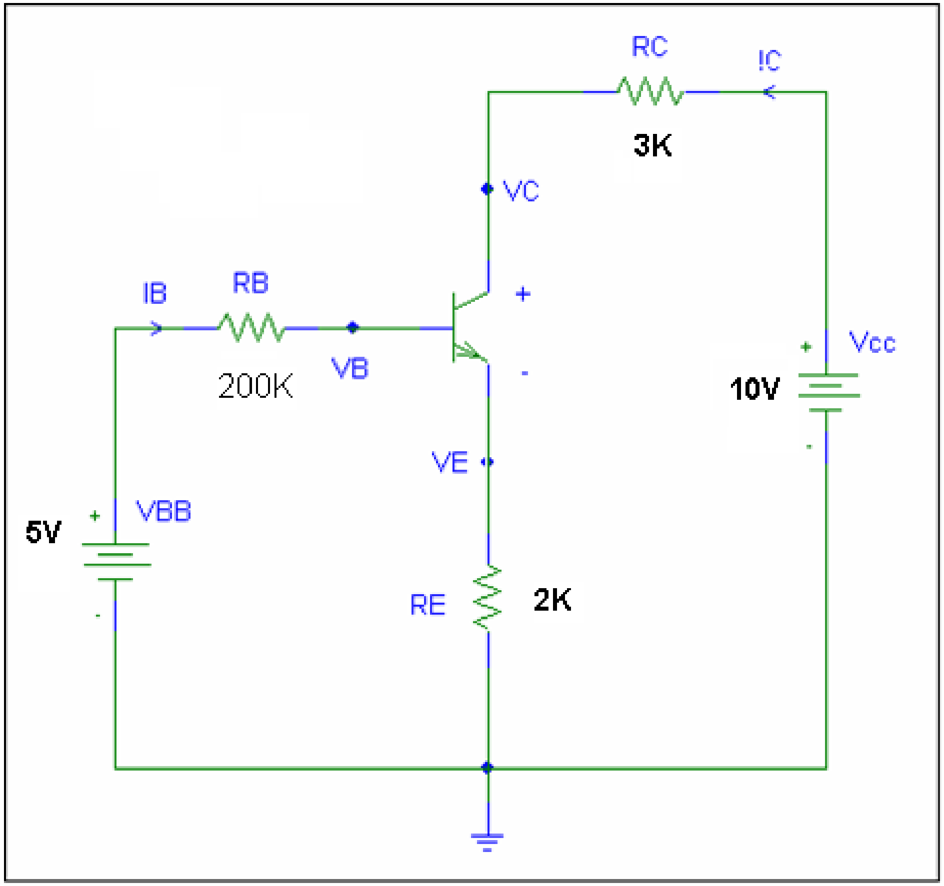
Example:

- Let Gain, $\beta = 100$

- Assume to be in active region -> $V_{BE}=0.7V$

- Find if it's in active region

BJT as Amplifier



$$\underline{V_{BE}} = 0.7V$$

$$\underline{I_E} = I_B + I_C = (\beta + 1) I_B$$

$$\underline{I_B} = \frac{V_{BB} - V_{BE}}{R_B + R_E * 101} = \frac{5 - 0.7}{402} = 0.0107 mA$$

$$\underline{I_C} = \beta * I_B = 100 * 0.0107 = 1.07 mA$$

$$\underline{V_{CB}} = V_{CC} - I_C * R_C - I_E * R_E - V_{BE} =$$

$$= 10 - (3)(1.07) - (2)(101 * 0.0107) - 0.7 =$$

$$= 3.93V$$

$V_{CB}>0$ so the BJT is in active region

Field Effect Transistors

- In 1925, the fundamental principle of FET transistors was establish by Lilienfield.
- 1955 : the first Field effect transistor works
- Increasingly important in mechatronics.
- Similar to the BJT:
  - Three terminals,
  - Control the output current

BJT Terminal	FET Terminal
Base	Gate
Collector	Drain
Emitter	Source

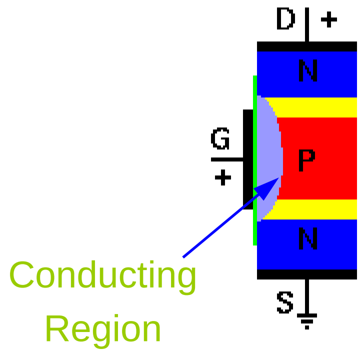
Field Effect Transistors

- Three Types of Field Effect Transistors
  - MOSFET (metal-oxide-semiconductor field-effect transistors)
  - JFET (Junction Field-effect transistors)
  - MESFET (metal-semiconductor field-effect transistors)
- Two Modes of FETs
  - Enhancement mode
  - Depletion mode

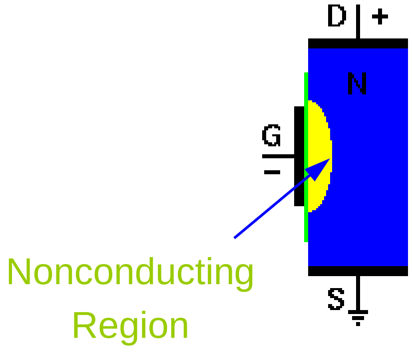
- The more used one is the n-channel enhancement mode MOSFET, also called NMOS

FET Architecture

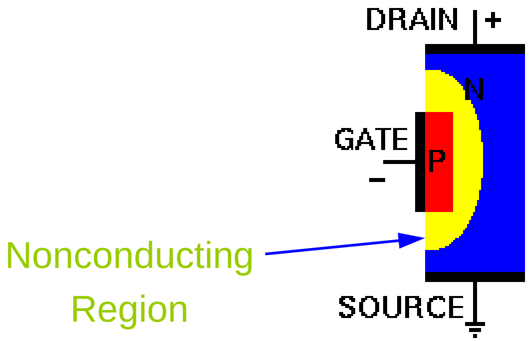
- Enhanced MOSFET



- Depleted MOSFET



- JFET



NMOS Voltage Characteristic

$V_{GS} < V_{th}$

$I_{DS}=0$

$V_{GS} > V_{th}$:

$0 < V_{DS} < V_{Pinch\ off}$

Active Region

I_{DS} controlled by V_{GS}

$V_{DS} > V_{Pinch\ off}$

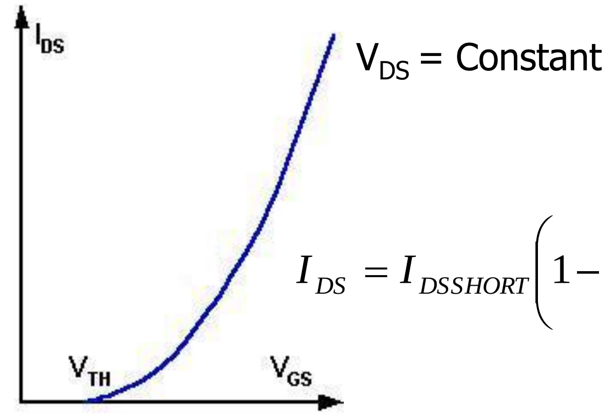
Saturation Region

I_{DS} constant

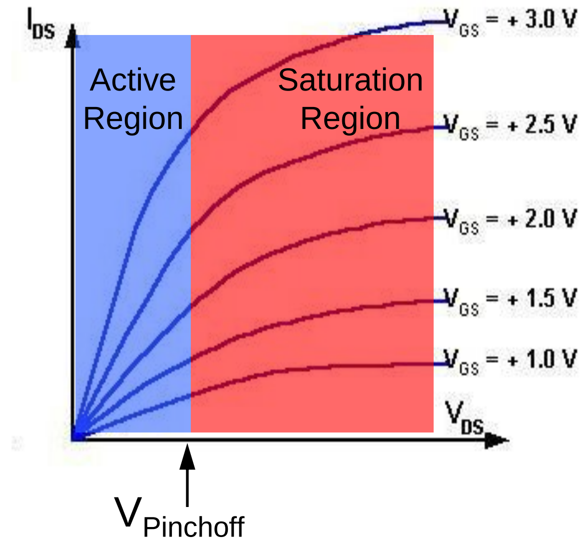
$V_{DS} > V_{Breakdown}$

I_{DS} approaches $I_{DSShort}$

Should be avoided



$$I_{DS} = I_{DSSHORT}\left(1-\frac{V_{GS}}{V_{TH}}\right)^2$$



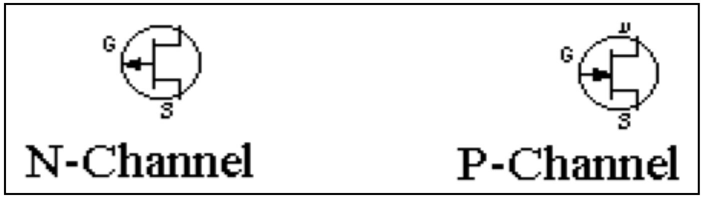
NMOS uses

- High-current voltage-controlled switches
- Analog switches
- Drive DC and stepper motor
- Current sources
- Chips and Microprocessors

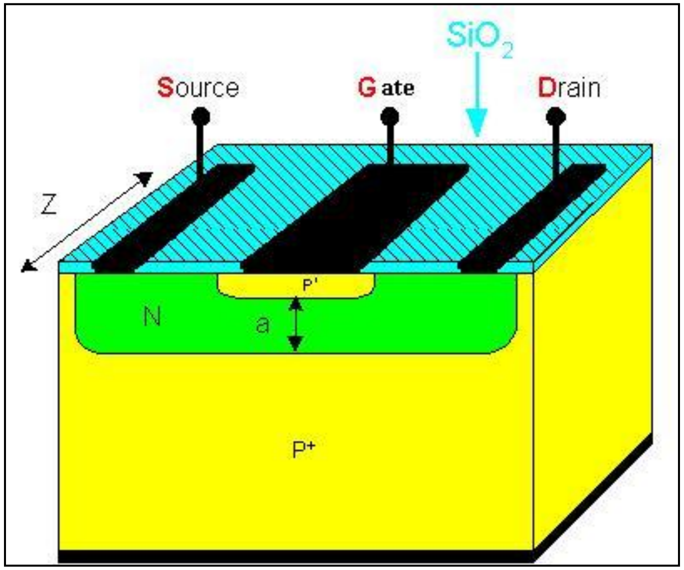
- CMOS: Complementary fabrication

JFET overview

The circuit symbols:



JFET design:



Junction Field Effect Transistor

$-V_{GS} > V_{th}$

Difference from NMOS

$I_{DS}=0$

$V_{GS} < -V_{th}$:

$0 < V_{DS} < V_{Pinch\ off}$

Active Region
I_{DS} controlled by V_{GS}

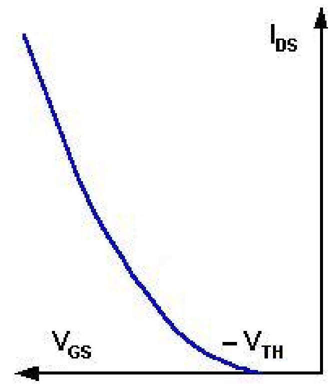
$V_{DS} > V_{Pinch\ off}$

Saturation Region
I_{DS} constant

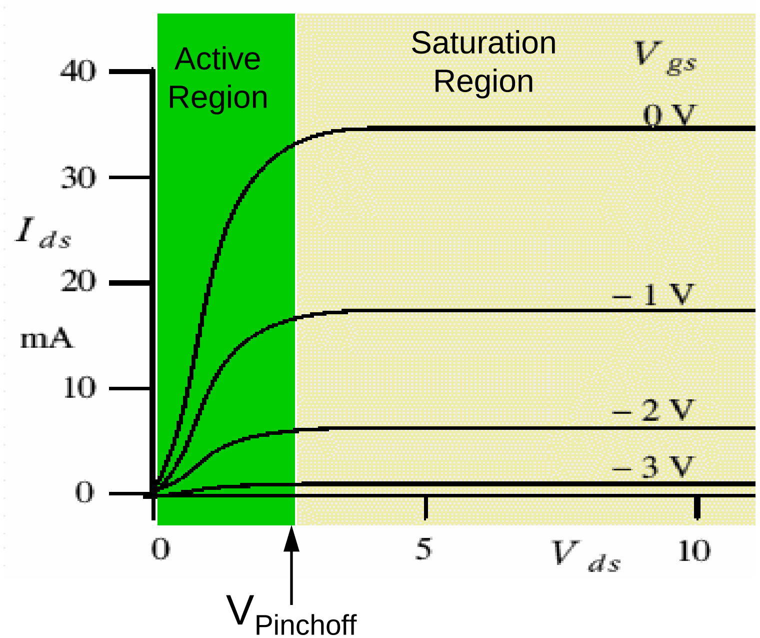
$V_{DS} > V_{Breakdown}$

I_{DS} approaches $I_{DSShort}$

Should be avoided



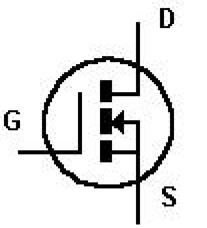
$$I_{DS} = I_{DSSHORT}\left(1-\frac{V_{GS}}{V_{TH}}\right)^2$$

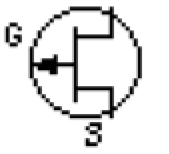


JFET uses

- Small Signal Amplifier
- Voltage Controlled Resistor
- Switch

FET Summary





- General:
  - Signal Amplifiers
  - Switches

JFET:

For Small signals

Low noise signals

Behind a high impedence system

Inside a good Op-Ampl.

MOSFET:

Quick

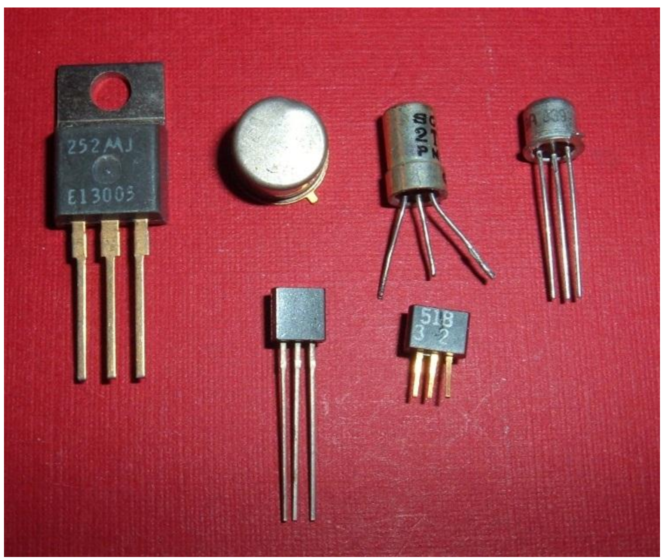
Voltage Controlled Resistors

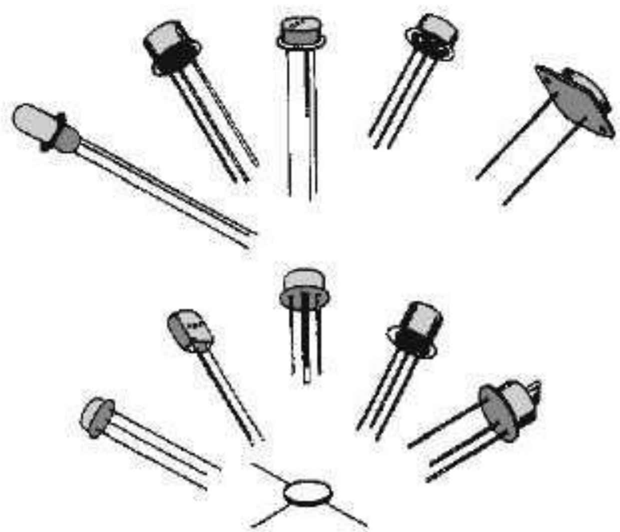
RDS can be really low : 10 mOhms

Power Transistors

- In General
  - Fabrication is different in order to:
    - Dissipate more heat
    - Avoid breakdown
  - So Lower gain than signal transistors
- BJT
  - essentially the same as a signal level BJT
  - Power BJT cannot be driven directly by HC11
- MOSFET
  - base (flyback) diode
  - Large current requirements

Other Types of Transistors





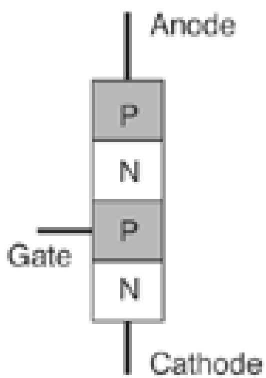
Typical transistor packages

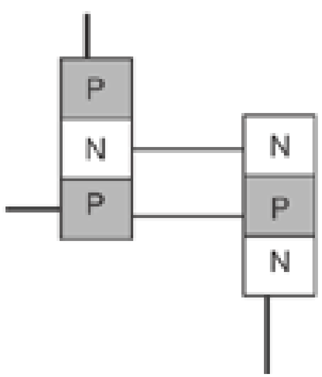
Various Types of Transistors

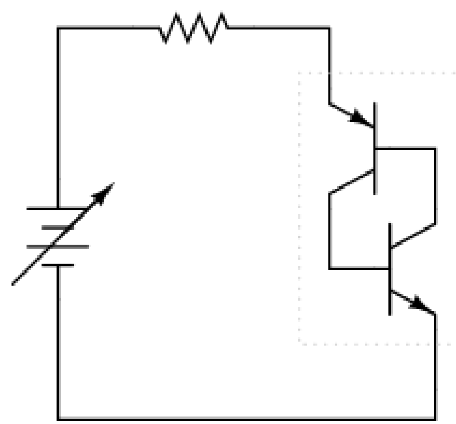
- TempFET – MOSFET's with temperature sensor
- High Electron Mobility Transistors (HEMTs) – allows high gain at very high frequencies
- Darlington – two transistors within the same device, gain is the product of the two inidvidual transistors

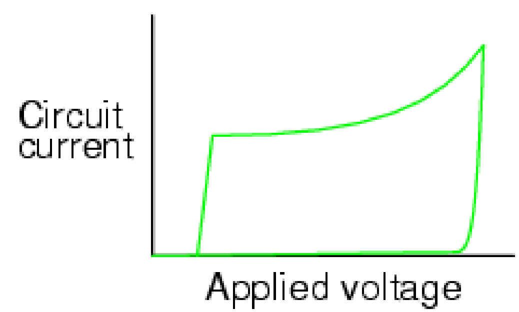
Shockley Diode/Thyristor

- Four-layer PNPN semiconductor devices
- Behaves as two transistors in series
- Once on, tends to stay on
- Once off, tends to stay off









TRIAC

- Triode alternating current switch
- Essentially a bidirectional thyristor
- Used in AC applications
- Con: Requires high current to turn on
- Example uses: Modern dimmer switch