Semiconductors

W. Bolton, "Mechatronics --- Electronic control systems in mechanical and electrical engineering," 5th edition, Pearson Education Limited 2012

J. Edward Carryer, R. Matthew Ohline, Thomas W. Kenny, "Introduction to Mechatronic Design," Prentice Hall 2011, Chap 10

線上學習網站：https://www.electronics-tutorials.ws

PowerPoint 中部分圖片擷取和修改自教科書和網路圖片

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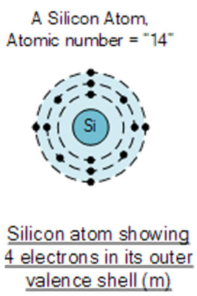
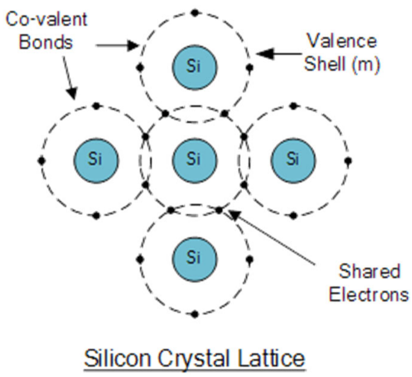
Semiconductor Basics -1

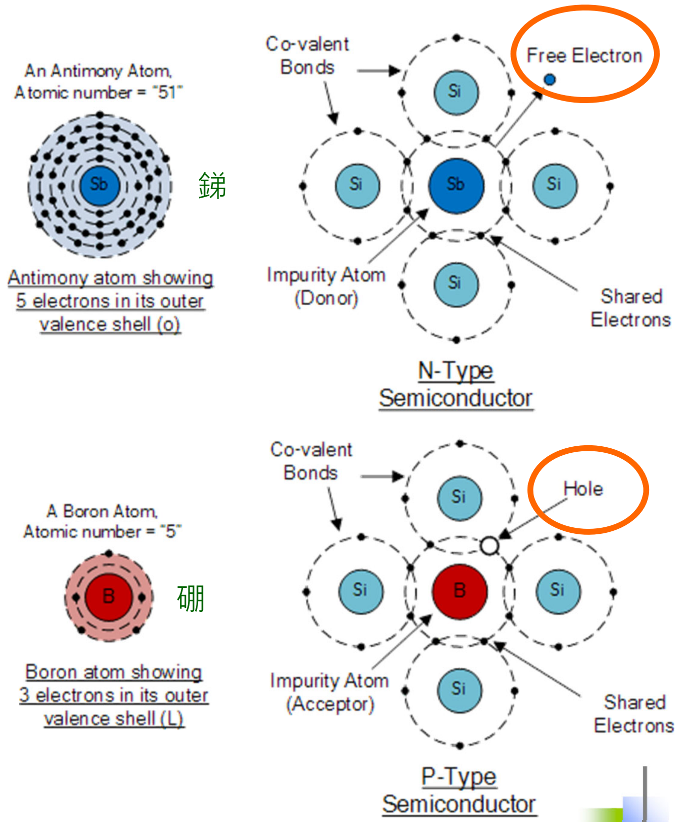
- Semiconductor
  - Materials such as silicon (Si) 矽, germanium (Ge) 鍺 and gallium arsenide (GaAs) 砷化鎵, have electrical properties somewhere in the middle, between those of a "conductor" and an "insulator"





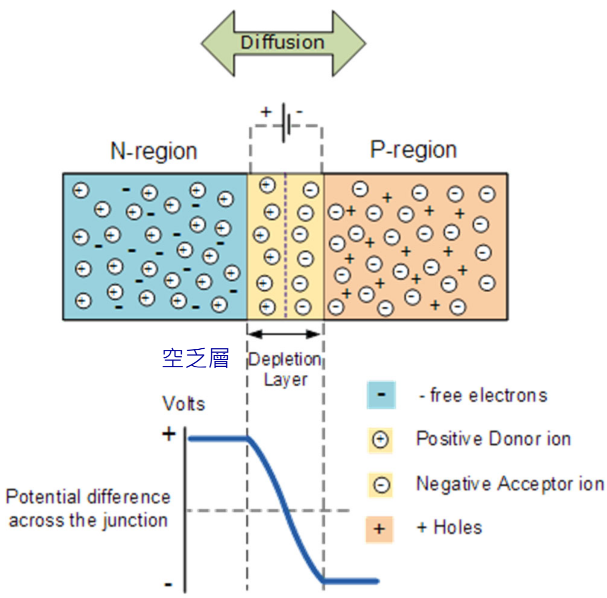
Semiconductor Basics -2

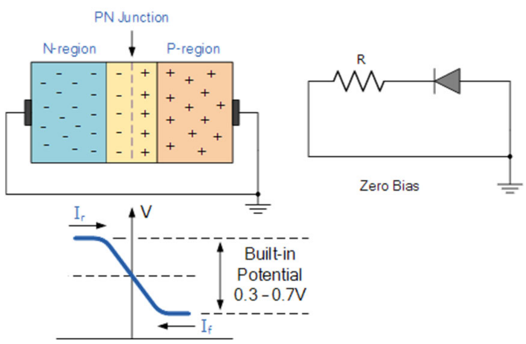
- Doping
  - The process of adding donor or acceptor atoms to semiconductor atoms (the order of 1 impurity atom per 10 million (or more) atoms of the semiconductor)



Semiconductor Basics -3

- The PN junction
  - Diffusion: The charge transfer of electrons and holes across the PN junction

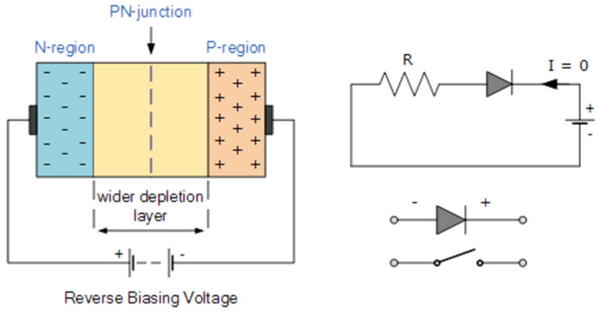




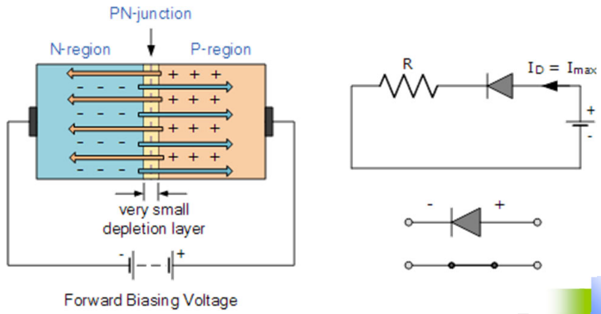
"Dynamic equilibrium"

Diode -1

- When an external voltage is applied
  - Zero bias: Maintaining a natural potential barrier (Si 0.5-0.7V, Ge 0.3V)
  - Reverse bias: Increasing thickness of the depletion region, like an “open circuit”
  - Forward bias: Reducing thickness of the depletion region, like a “short circuit”

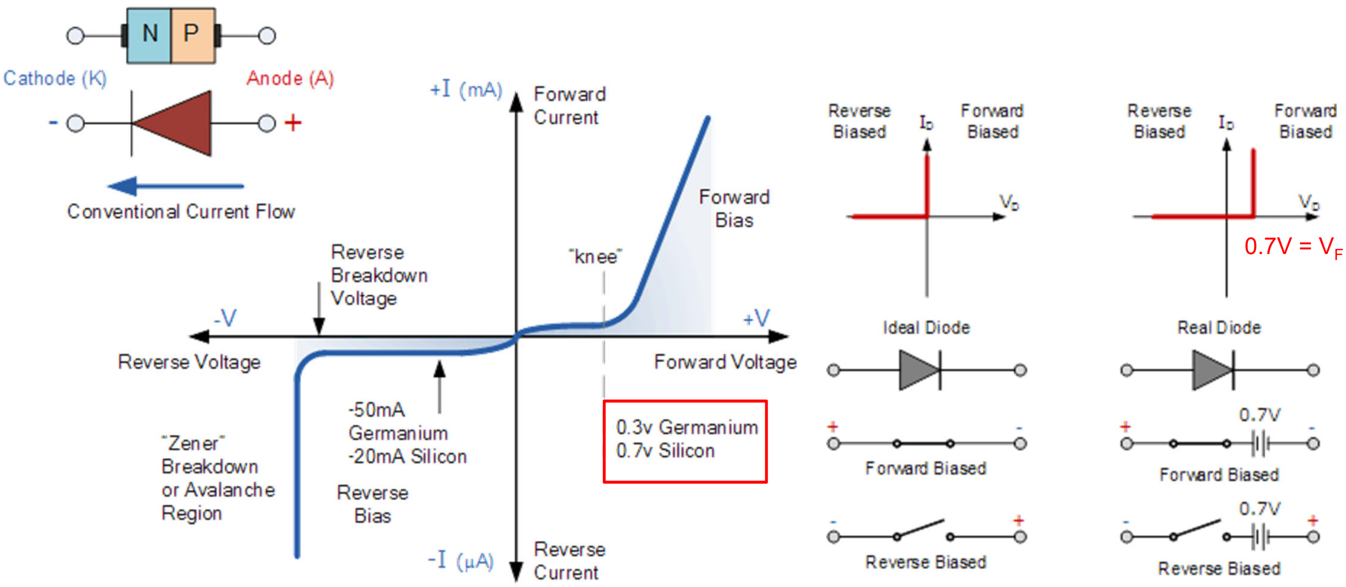


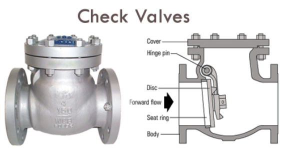
The positive voltage attracts electrons towards the positive electrode and away from the junction



Diode -2

- Junction diode ideal and real characteristics

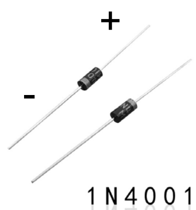




Mechanical analogue:
Check valve 止回閥
(Non-return valve)

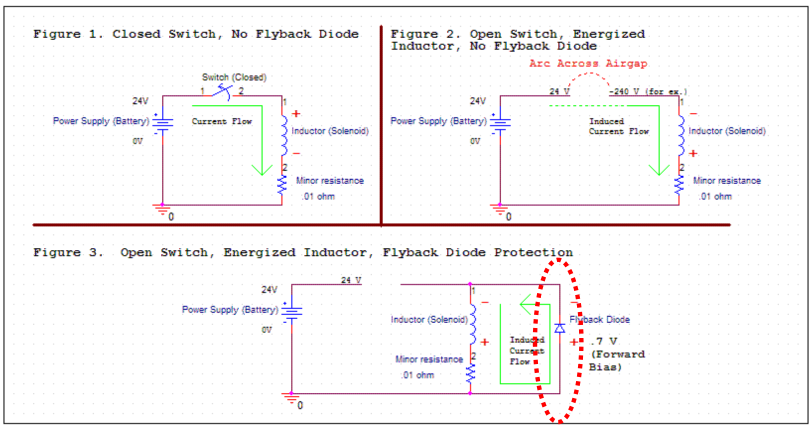
Diode -3

- Signal diode parameters
  - Forward voltage (V_F)
  - Maximum forward current (I_{Fmax})
    - The maximum forward current allowed to flow through the device
  - Peak inverse voltage (V_{Rmax})
    - The maximum allowable Reverse operating voltage that can be applied across the diode without reverse breakdown and damage occurring to the device
  - Total power dissipation (P_{Dmax})
  - Max operation temperature
- General purpose diode: IN400x



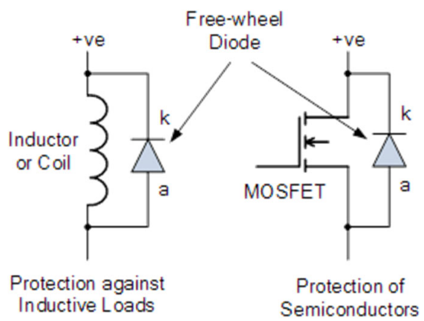
Diode -4

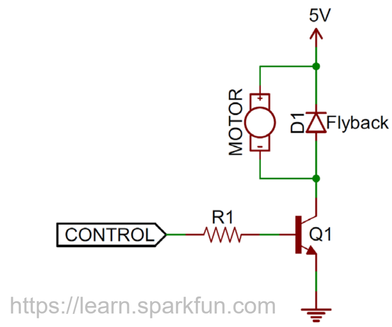
- Freewheel/flyback diode
  - Every time the switching device is turned “ON”, the diode changes from a conducting state to a blocking state (i.e. reversed biased)
  - When the device rapidly turns “OFF”, the collapse of the energy stored in the coil causes a current to flow through the freewheel diode (i.e. forward biased)



Diode -5

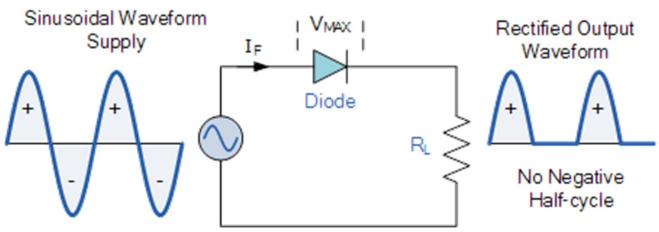
- Freewheel diode
  - For component protection





Diode -6

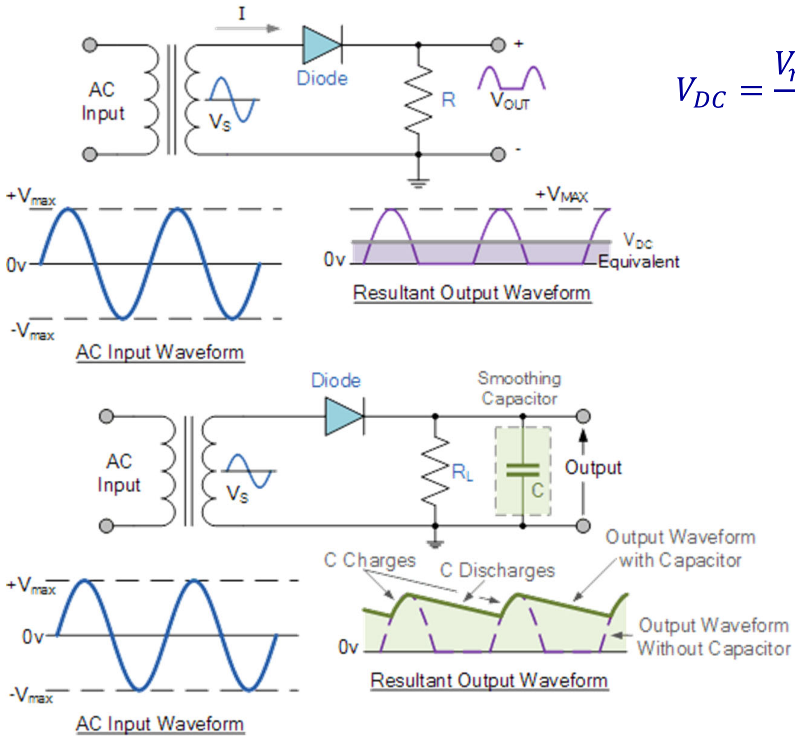
- Rectification
  - The conversion of an alternating voltage (AC) into a continuous voltage (DC)



  - Power diode
    - A high forward current capability of up to several hundred amps (KA) and a reverse blocking voltage of up to several thousand volts (KV)

Diode -7

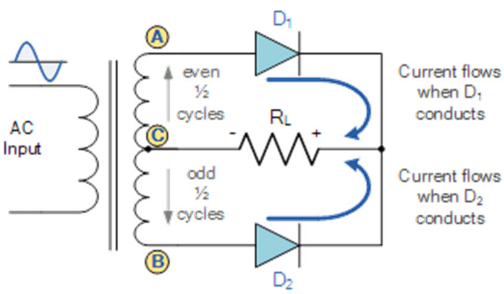
- Ex: A half-wave rectifier circuit



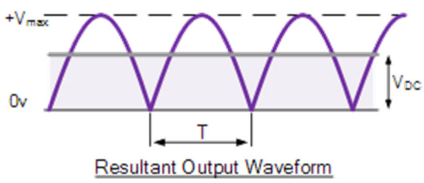
$$V_{DC} = \frac{V_{max}}{\pi} = 0.318V_{max}$$
$$= 0.45V_{rms}$$

Diode -8

- Ex: A full wave rectifier circuit
  - Requiring a center tapped transformer
    - Hard to manufacture
    - Using only one half of the transformer secondary voltage
    - Difficult to locate the center of the secondary for the tapping

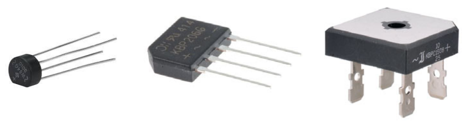


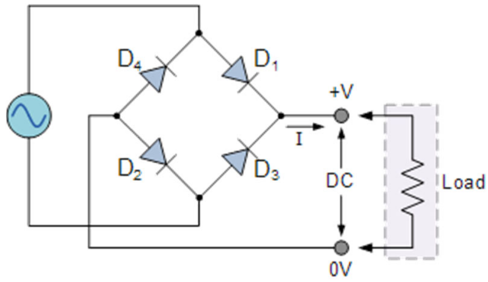
$$V_{DC} = \frac{2V_{max}}{\pi}$$

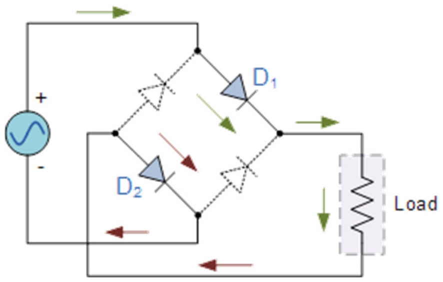


Diode -9

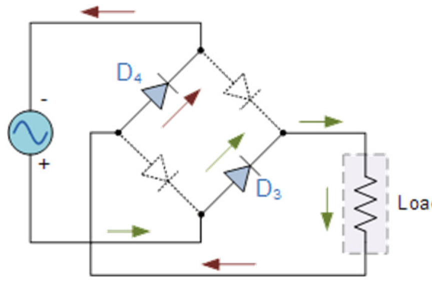
- A full bridge wave rectifier
  - Does not require a center tapped transformer
  - Two voltage drops: 2 x 0.7V = 1.4V
  - Off-the-shelf bridge rectifier







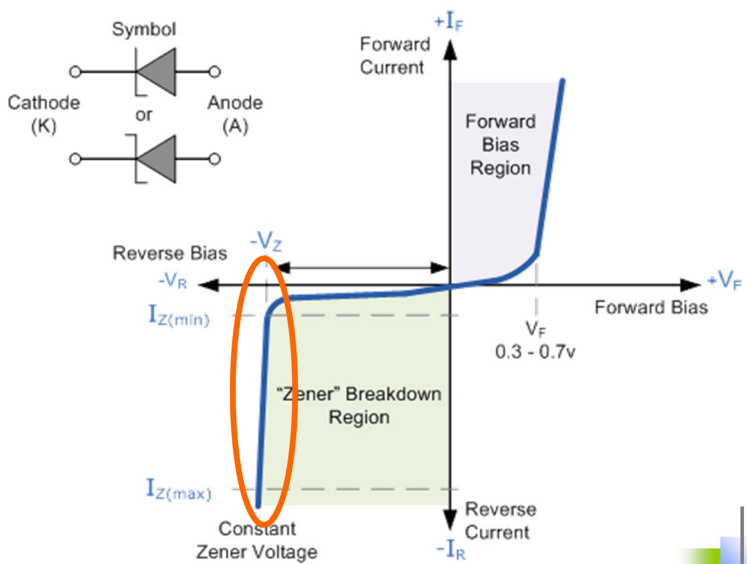
Positive half-cycle



Negative half-cycle

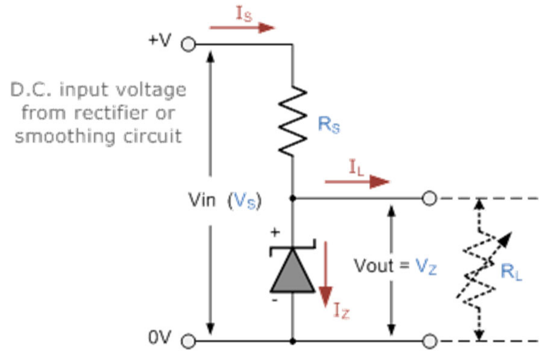
Diode -10

- Zener diode 稽納二極體
  - Operated in its reverse biased condition
  - The voltage across the diode in the breakdown region is almost constant, V_z
  - General purpose
    - BZX55 series, 500mW
    - BZX85 series, 1.3W



Diode -11

- Zener diode regulator
  - R_S: Connected in series with the diode to limit the current flow
  - V_{out}: Always the same as the zener voltage, V_z (note: $V_s > V_z$)



- Example

If no load $R_L = 0$

If $V_{in} > V_z$ $\quad V_{out} = V_z$ and $I_z = \frac{V_{in}-V_z}{R_s}$

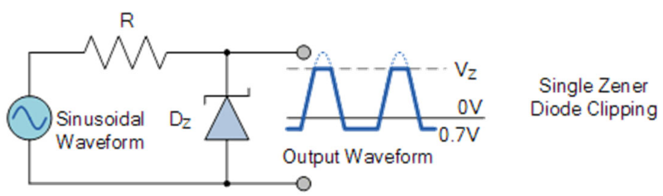
If with load $R_L \neq 0$, compute $V = \frac{R_L}{R_s+R_L}V_{in}$

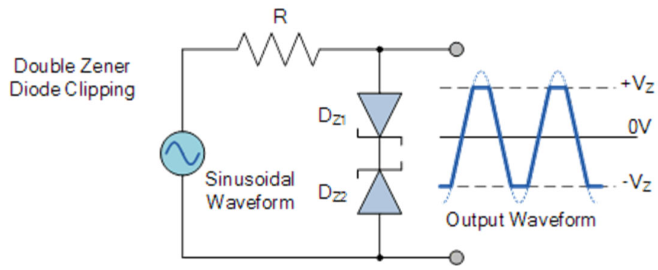
If $V < V_Z$ $\quad I_L = I_S = \frac{V_{in}}{R_S+R_L}$ and $V_{out} = I_L R_L$

If $V \geq V_Z$ $\quad V_{out} = V_Z,\ I_L = \frac{V_Z}{R_L},\ I_S = \frac{V_{in}-V_Z}{R_S},\ I_Z = I_S - I_L$

Diode -12

- Zener diode clipping circuits
  - Limit or cut-off part of the waveform across them; mainly used for circuit protection or in waveform shaping circuits

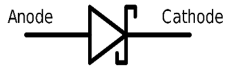


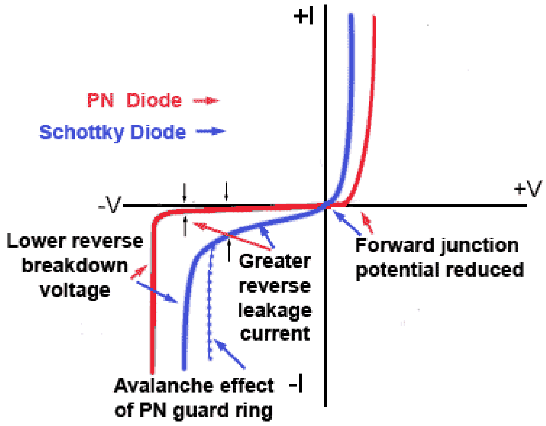


Ex: If $V_{z1} = V_{z2} = 7.5$, then $V_z = 7.5 + 0.7$

Diode -13

- Schottky diode 蕭特基二極體
  - Junction: metal and semiconductor
  - Low forward operation voltage: 0.15-0.45V
  - Faster switching between conducting and blocking
  - (Disadvantage) Low reverse breakdown voltage and high reverse leakage current (10 times)
  - Ex: 1N5817





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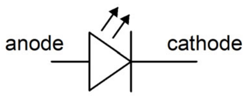
Diode -14

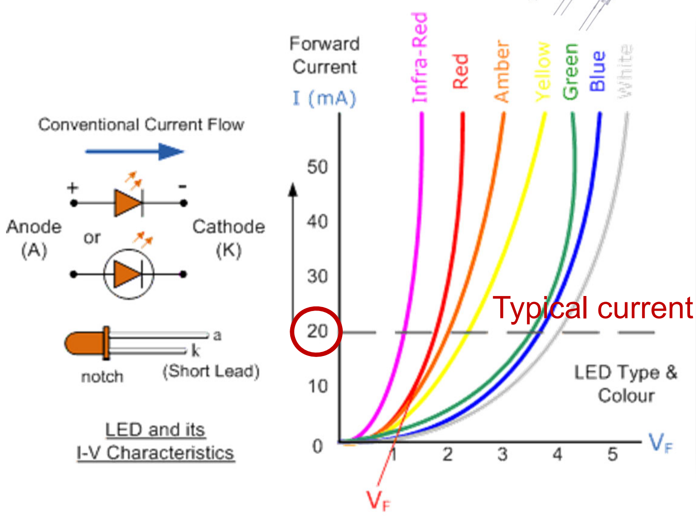
- Light emitting diode (LED)



  - Made from exotic semiconductor compounds such as GaAs, GaP, GaAsP, SiC, or GaInN at different ratios to produce a distinct wavelength of color

砷化鎵 砷化磷

Different color
Different V_F



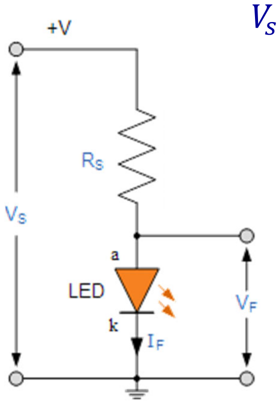
Typical LED Characteristics

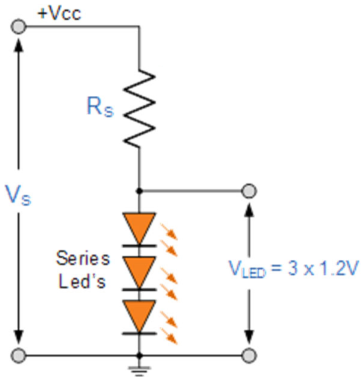
Semiconductor Material	Wavelength	Colour	V_F @ 20mA
GaAs	850-940nm	Infra-Red	1.2v
GaAsP	630-660nm	Red	1.8v
GaAsP	605-620nm	Amber	2.0v
GaAsP:N	585-595nm	Yellow	2.2v
AlGaP	550-570nm	Green	3.5v
SiC	430-505nm	Blue	3.6v
GaInN	450nm	White	4.0v

Diode -15

- Ex: LED examples

$V_s = 5V$





Amber LED $V_F = 2V,\ I_F = 10mA$

$R_S = \frac{V_S - V_F}{I_F} = \frac{5-2}{0.01} = 300\Omega$

$P_S = R_S {I_F}^2 = 300 \times 0.01^2 = 0.03W$

$P_F = 2 \times 0.01 = 0.02\text{W}$

Not efficient

IR LED

$R_S = \frac{V_S - 3V_F}{I_F} = \frac{5-3\times1.2}{0.01} = 140\Omega$

$P_S = R_S {I_F}^2 = 140 \times 0.01^2 = 0.014W$

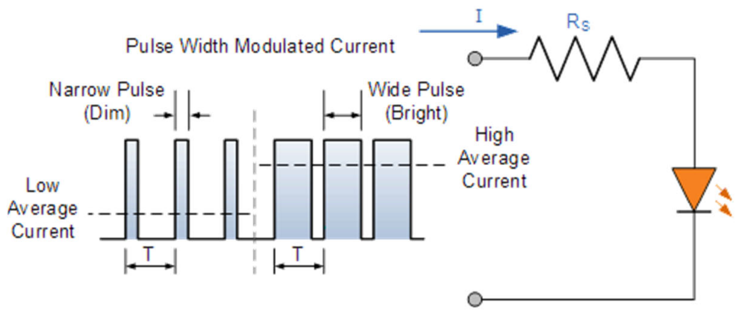
$P_F = 3 \times 1.2 \times 0.01 = 0.036\text{W}$

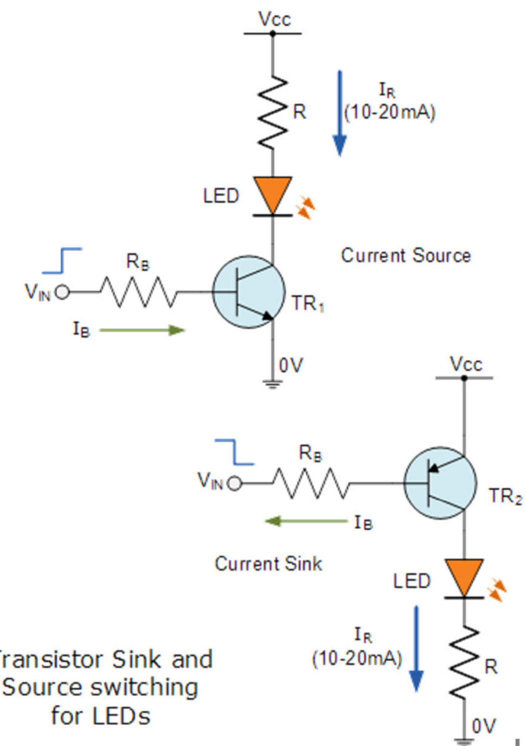
Better

Using 4 LEDs is even better

Diode -16

- LED light intensity using PWM
  - Change duty cycle
  - P.S. Change T?

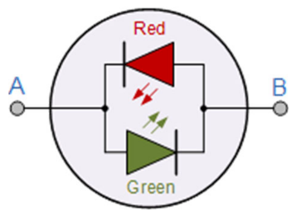




Transistor Sink and Source switching for LEDs

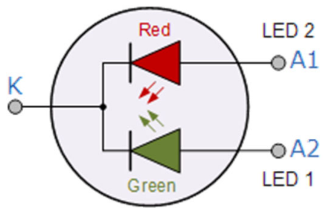
Diode -17

- Multi-colored LED
  - A bi-colored LED



LED Selected	Terminal A +	Terminal A -	AC
LED 1	ON	OFF	ON
LED 2	OFF	ON	ON
Colour	Green	Red	Yellow

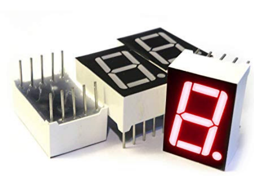
  - A tri-colored LED

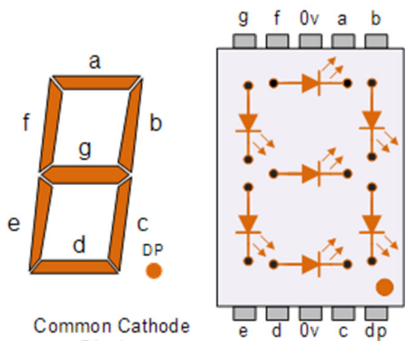


Output Colour	Red	Orange	Yellow	Green
LED 1 Current	0	5mA	9.5mA	15mA
LED 2 Current	10mA	6.5mA	3.5mA	0

Diode -18

- Seven segment LED displays
  - The Common Cathode Display (CCD): all the cathode connections of the LEDs are joined together and the individual segments are illuminated by application of a HIGH, logic “1” signal
  - The Common Anode Display (CAD): The individual segments are illuminated by connecting the terminals to a LOW, logic “0” signal.



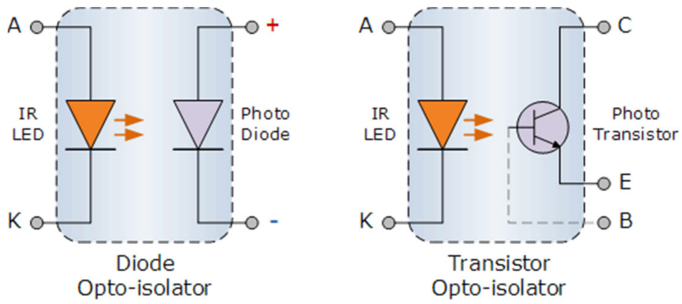


Common Cathode Display

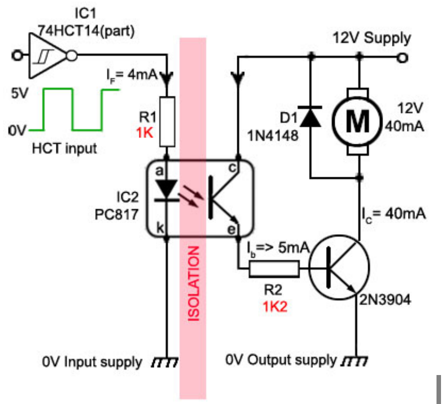
Diode -19

- Opto-coupler (opto-isolator) 

  - A single electronic device that consists of a light emitting diode combined with either a photo-diode or photo-transistor to provide an optical signal path between an input connection and an output connection while maintaining electrical isolation between two circuits
  - Ex: PC817 (Transistor)

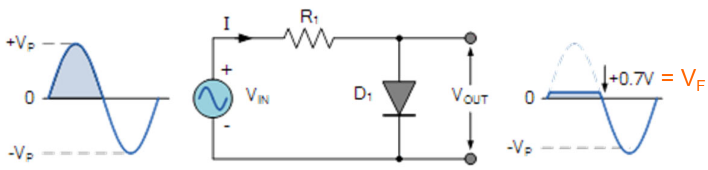


High-speed CMOS/TTL-input compatible (HCT)

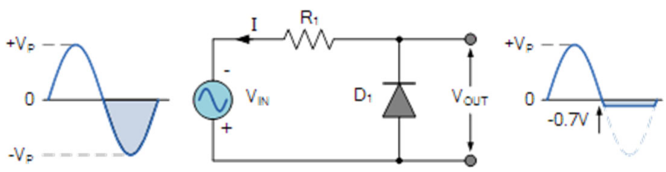


Diode -20

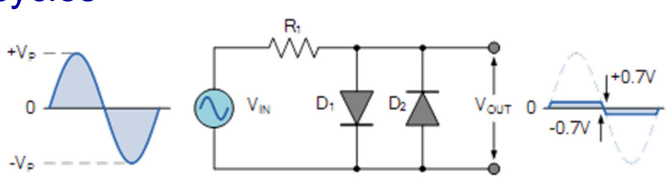
- Diode clipping circuits
  - Positive clipping



  - Negative clipping

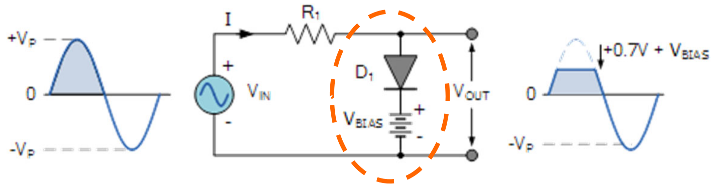


  - Clipping of both half-cycles

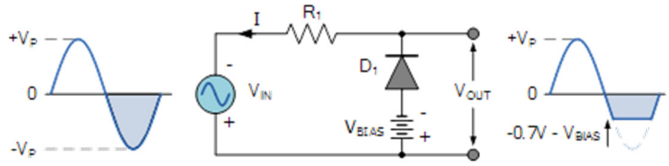


Diode -21

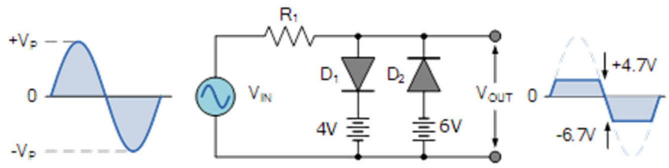
- Biased diode clipping circuits
  - Biased positive clipping



  - Biased negative clipping

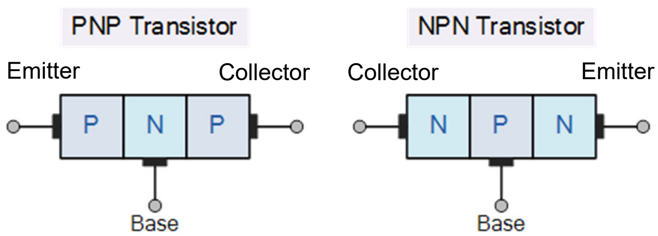


  - Biased clipping of different bias levels

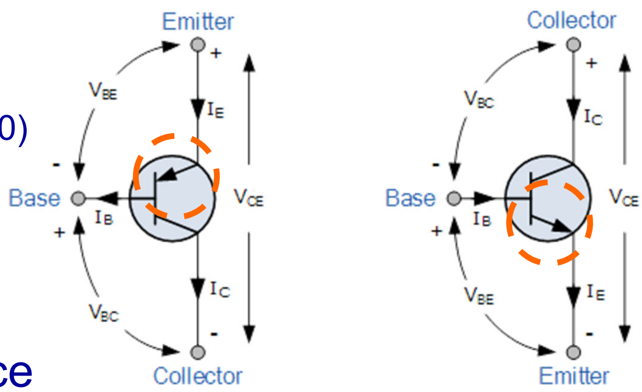


Bipolar Junction Transistor (BJT) -1

- Formation
  - Join two PN-junctions together in series that share a common P or N terminal



- Three modes
  - Active: $I_c = \beta I_B$
    - β: DC current gain (50~200)
  - Saturation: $I_c = I_{saturation}$
  - Cut-off: $I_c = 0$
- A "current" operated device

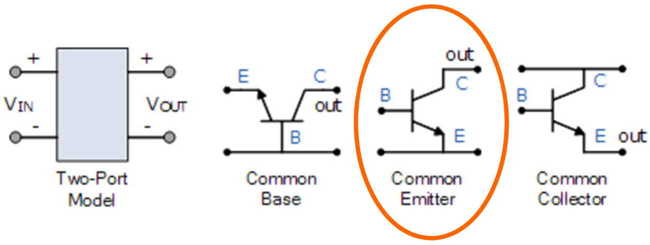


Current flow direction

FYI, a good video: https://www.youtube.com/watch?v=7ukDKVHnac4

Bipolar Junction Transistor (BJT) -2

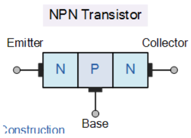
- Configurations (NPN as the example)



Most common connection

Characteristic	Common Base	Common Emitter	Common Collector
Input Impedance	Low	Medium	High
Output Impedance	Very High	High	Low
Phase Shift	0°	180°	0°
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

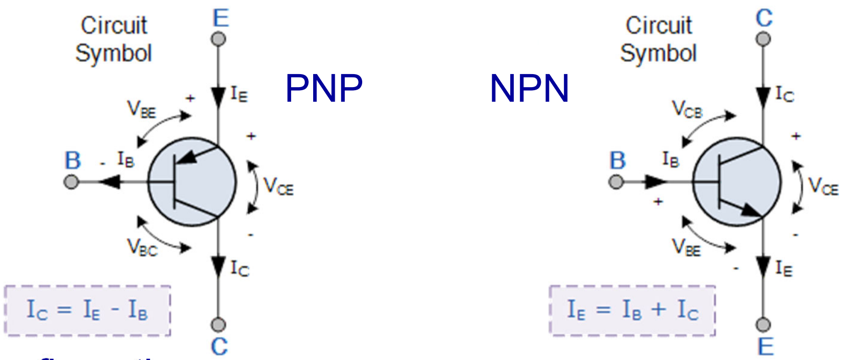
- V_{BE}: Forward biased
  - P -> N



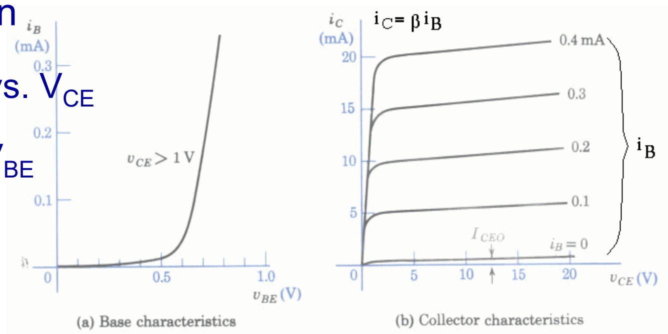
$V_B \uparrow$ $V_{CE}\downarrow$ $V_{out}\downarrow$

Bipolar Junction Transistor (BJT) -3

- PNP & NPN transistors
  - Ex: 2N4123, a general purpose transistor



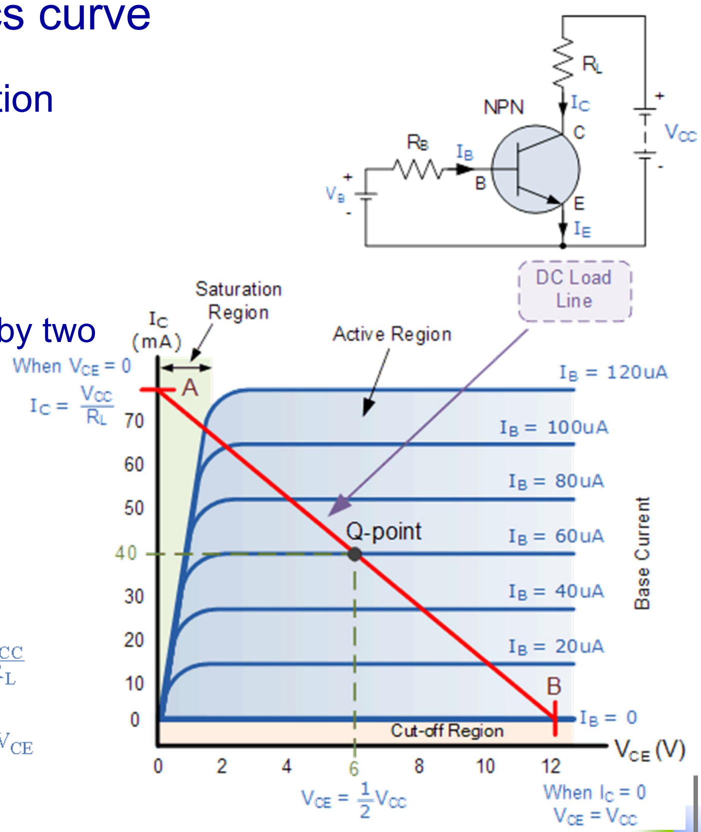
  - Common emitter configuration
    - Collector characteristics: I_C vs. V_{CE}
    - Base characteristics: I_B vs. V_{BE}



BE: Act just like a diode

Bipolar Junction Transistor (BJT) -4

- NPN output characteristics curve
  - Common emitter configuration
  - Use I_C vs. V_{CE} for analysis
  - (1) Active (linear) region
    - DC load line: Determined by two boundary conditions
    - Quiescent point (Q-point)



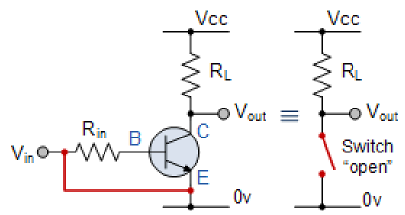
Collector Current, $I_C = \frac{V_{CC} - V_{CE}}{R_L}$

When: $(V_{CE} = 0)$ $I_C = \frac{V_{CC} - 0}{R_L}$, $I_C = \frac{V_{CC}}{R_L}$

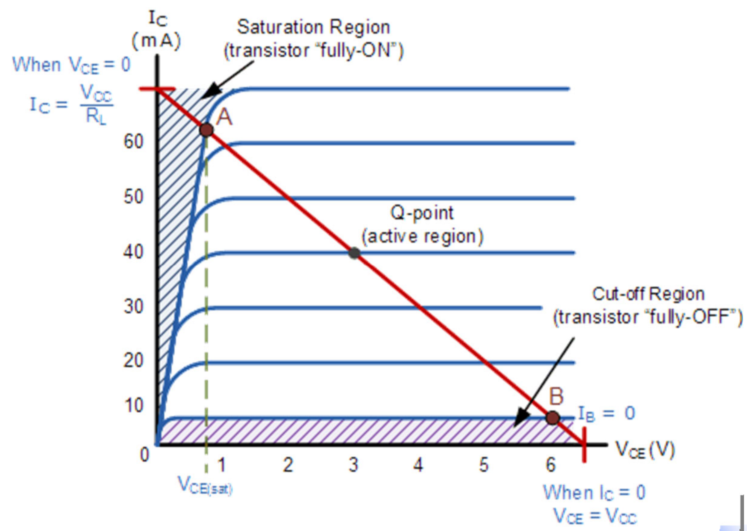
When: $(I_C = 0)$ $0 = \frac{V_{CC} - V_{CE}}{R_L}$, $V_{CC} = V_{CE}$

Bipolar Junction Transistor (BJT) -5

- NPN output characteristics curve
  - Common emitter configuration
  - Use I_C vs. V_{CE} for analysis
  - (2) Cut-off region

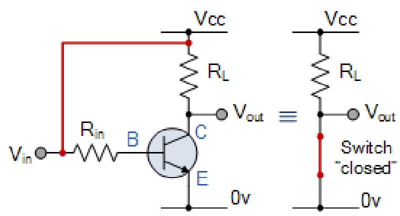


- The input and Base are grounded (0v)
- Base-Emitter voltage $V_{BE} < 0.7v$
- Base-Emitter junction is reverse biased
- Base-Collector junction is reverse biased
- Transistor is "fully-OFF" (Cut-off region)
- No Collector current flows ($I_C = 0$)
- $V_{OUT} = V_{CE} = V_{CC}$ = "1"
- Transistor operates as an "open switch"

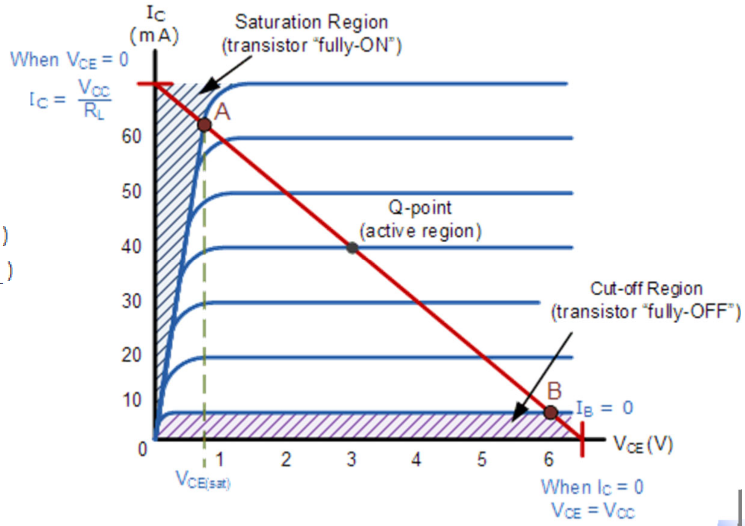


Bipolar Junction Transistor (BJT) -6

- NPN output characteristics curve
  - Common emitter configuration
  - Use I_C vs. V_{CE} for analysis
  - (3) Saturated region

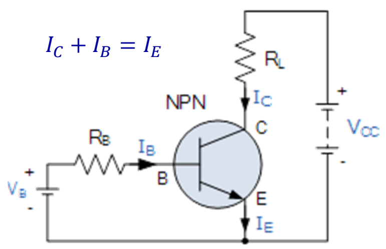


- The input and Base are connected to V_{CC}
- Base-Emitter voltage V_{BE} > 0.7v
- Base-Emitter junction is forward biased
- Base-Collector junction is forward biased
- Transistor is "fully-ON" (saturation region)
- Max Collector current flows ($I_C = Vcc/R_L$)
- V_{CE} = 0 (ideal saturation)
- $V_{OUT} = V_{CE}$ = "0"
- Transistor operates as a "closed switch"



Bipolar Junction Transistor (BJT) -7

- A NPN transistor example
  - Common emitter configuration



$V_B = 5V$ $\quad V_{CC} = 10V$

$R_B = 2.2k\Omega,$ $\quad R_L = 100\Omega$ (lamp)

$V_{BE} = 0.6V$ $\quad V_{CE} = 0.2V$

Linear or saturation?

Assume in saturation: $I_B = \frac{V_B - V_{BE}}{R_B} = \frac{5-0.6}{2200} = 2mA$

$I_C = \frac{V_{CC} - V_{CE}}{R_L} = \frac{10-0.2}{100} = 98mA$

$I_C : I_B = 98:2 = 49:1 \gg 10\sim20 \quad \rightarrow in\ saturation$

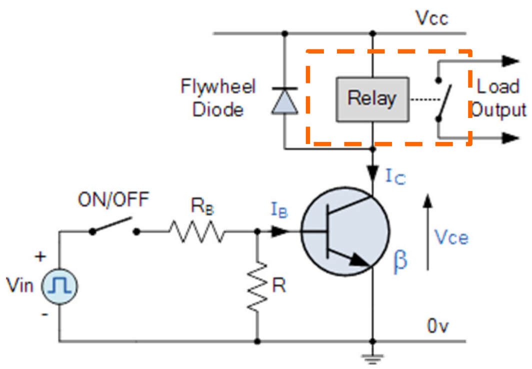
in linear region

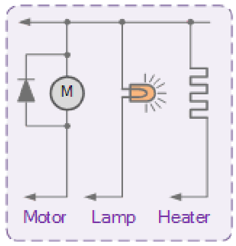
Want saturation? $R_B \downarrow \quad I_B \uparrow$

choose $R_B = 470\Omega \rightarrow I_B = 9.4mA \rightarrow I_C : I_B = 10.4:1$

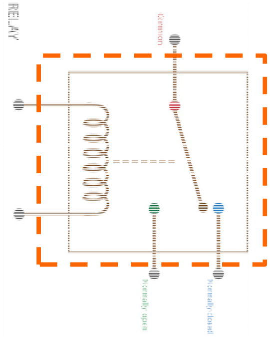
Bipolar Junction Transistor (BJT) -8

- A NPN transistor switching circuit





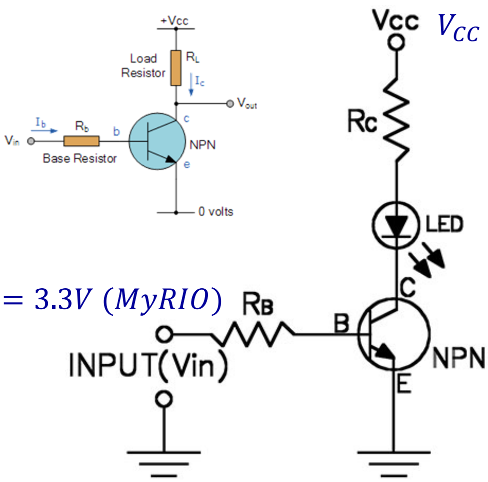
Different Collector Loads



- Relay: A electrically operated switch in which changing a current in one electric circuit switches a current on or off in another circuit
  - SPDT – Single pole, double throw（單軸雙切）

Bipolar Junction Transistor (BJT) -9

- A NPN transistor switching example



$V_{CC} = 5V$

$V_{in} = 3.3V\ (MyRIO)$

2N3904 Saturated

$I_B = 1.0mA$ $\quad I_C = 10mA$ $\quad V_{CE} = 0.2V$ $\quad V_{BE} = 0.7V$

$I_B = 5.0mA$ $\quad I_C = 50mA$ $\quad V_{CE} = 0.3V$ $\quad V_{BE} = 0.95V$

LN31GCPH Panasonic 5mm Green LED

$V_F = 2.0V$ $\quad I_F = 10mA$

$V_F = 2.2V$ $\quad I_F = 20mA$

Want $I_F = 10mA$

$$I_C = 10mA \quad \rightarrow I_B = 1mA \quad \rightarrow R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{3.3 - 0.7}{0.001} = 2.6k\Omega$$

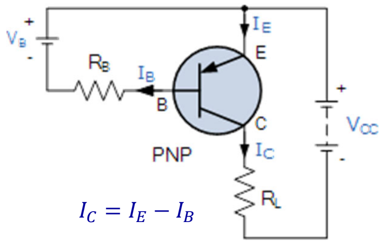
$$\rightarrow choose\ R_B = 2.7k\Omega \qquad E12, E24 \ldots..$$

$$R_C = \frac{V_{CC} - V_F - V_{CE}}{I_C} = \frac{5 - 2 - 0.2 - 0.2}{0.01} = 280\Omega$$

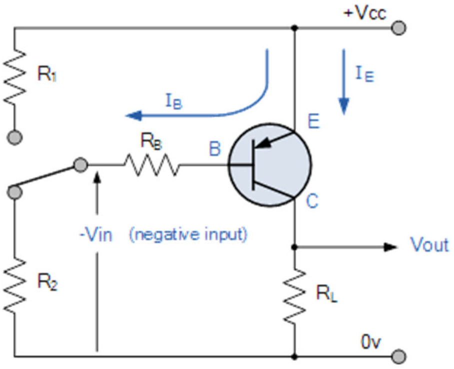
$$\rightarrow choose\ R_C = 270\Omega \qquad E12, E24 \ldots..$$

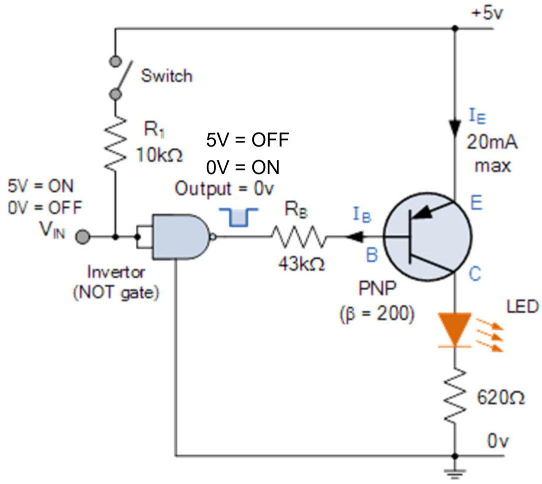
Bipolar Junction Transistor (BJT) -10

- PNP transistors



$I_C = I_E - I_B$

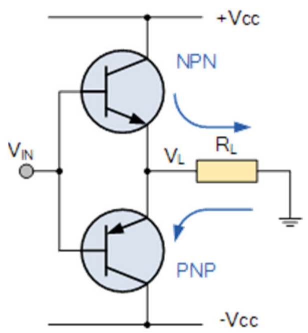




Using as a switching device

Bipolar Junction Transistor (BJT) -11

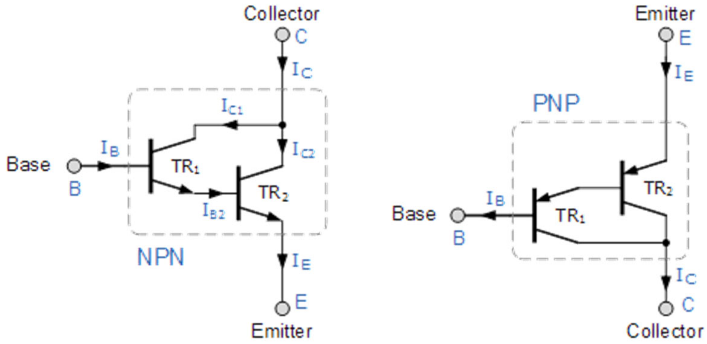
- Complementary transistors
  - Class B amplifier: using “Matched Pair” (PNP + NPN) transistors in its output stage where the flow of current can evenly through the load in both directions
  - EX: H-bridge motor control circuit



NPN	PNP	V_{CE}	$I_{C(max)}$	P_d
BC547	BC557	45v	100mA	600mW
BC447	BC448	80v	300mA	625mW
2N3904	2N3906	40v	200mA	625mW
2N2222	2N2907	30v	800mA	800mW
BC140	BC160	40v	1.0A	800mW
TIP29	TIP30	100v	1.0A	3W
BD137	BD138	60v	1.5A	1.25W
TIP3055	TIP2955	60v	15A	90W

Bipolar Junction Transistor (BJT) -12

- Darlington transistor
  - V_{BE} = 2 x 0.6V = 1.2V
  - V_{CE} = 0.2V + 0.6V = 0.8V
  - Current gain 200~500



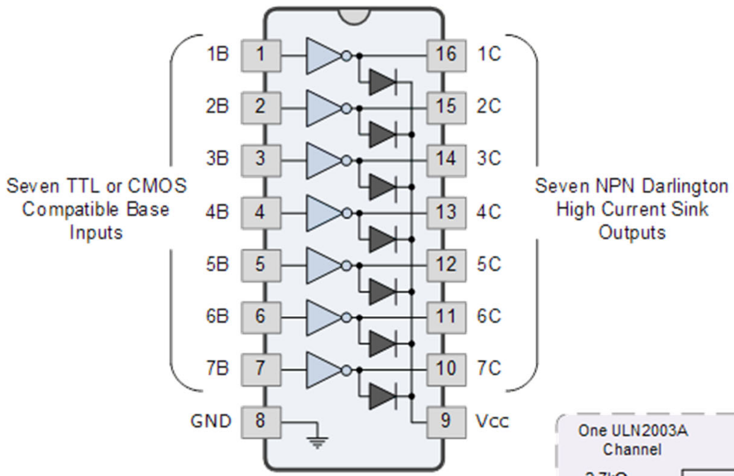
$$I_C = I_{C1} + I_{C2} = \beta_1 I_B + \beta_2 I_{B2} = \beta_1 I_B + \beta_2 \underline{I_{B2}} = \beta_1 I_B + \beta_2(\beta_1 + 1) I_B$$

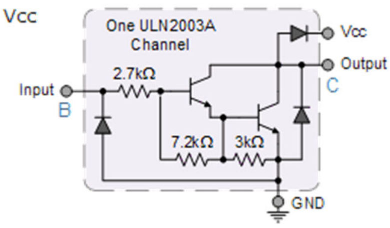
$$I_{B2} = I_{E1} = I_{C1} + I_B = \beta_1 I_B + I_B = (\beta_1 + 1) I_B$$

$$= (\beta_1 + \beta_2 + \beta_1\beta_2) I_B = \sim(\beta_1\beta_2) I_B$$

Bipolar Junction Transistor (BJT) -13

- Darlington transistor IC
  - Ex: ULN2003A (7 transistors)





Field Effect Transistor (FET) -1

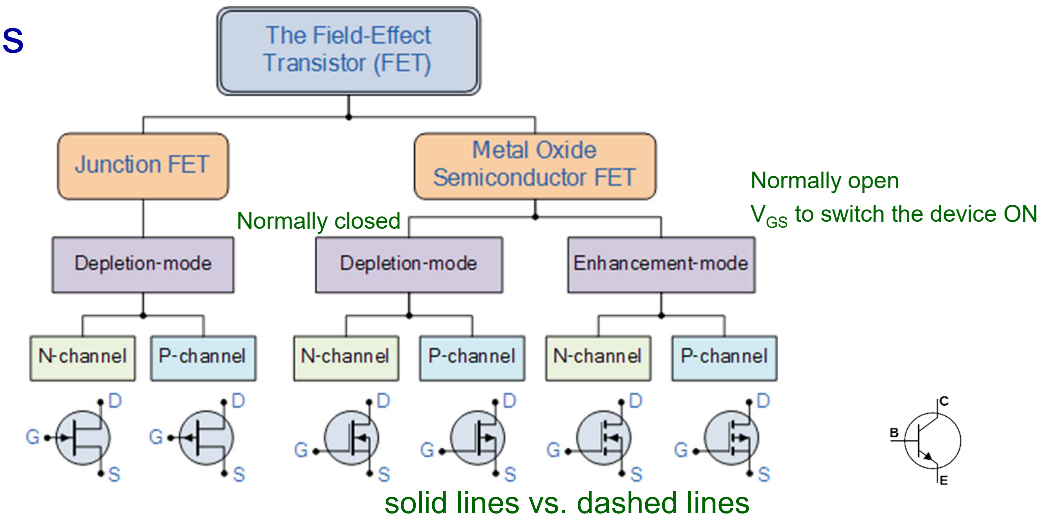
- A "voltage" operated device
- Three terminals

Bipolar Transistor (BJT)		Field Effect Transistor (FET)
Emitter – (E)	>>	Source – (S)
Base – (B)	>>	Gate – (G)
Collector – (C)	>>	Drain – (D)

- No PN-junctions within the main current carrying path (D-S, path is called the "channel")
- The control of current flowing in this channel is achieved by varying the voltage applied to the Gate
- "Unipolar" - the conduction of electrons (N-channel) or holes (P-channel)

Field Effect Transistor (FET) -2

- FET types



Type	Junction FET		Metal Oxide Semiconductor FET			
	Depletion Mode		Depletion Mode		Enhancement Mode	
Bias	ON	OFF	ON	OFF	ON	OFF
N-channel	0V	-ve	0V	-ve	+ve	0V
P-channel	0V	+ve	0V	+ve	-ve	0V

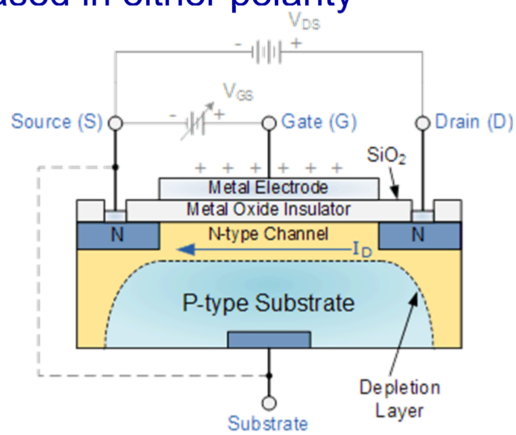
Field Effect Transistor (FET) -3

- BJT vs. FET

	Field Effect Transistor (FET)	Bipolar Junction Transistor (BJT)
1	Low voltage gain	High voltage gain
2	High current gain	Low current gain
3	Very high input impedance	Low input impedance
4	High output impedance	Low output impedance
5	Low noise generation	Medium noise generation
6	Fast switching time	Medium switching time
7	Easily damaged by static	Robust
8	Some require an input to turn it "OFF"	Requires zero input to turn it "OFF"
9	Voltage controlled device	Current controlled device
10	Exhibits the properties of a Resistor	
11	More expensive than bipolar	Cheap
12	Difficult to bias	Easy to bias

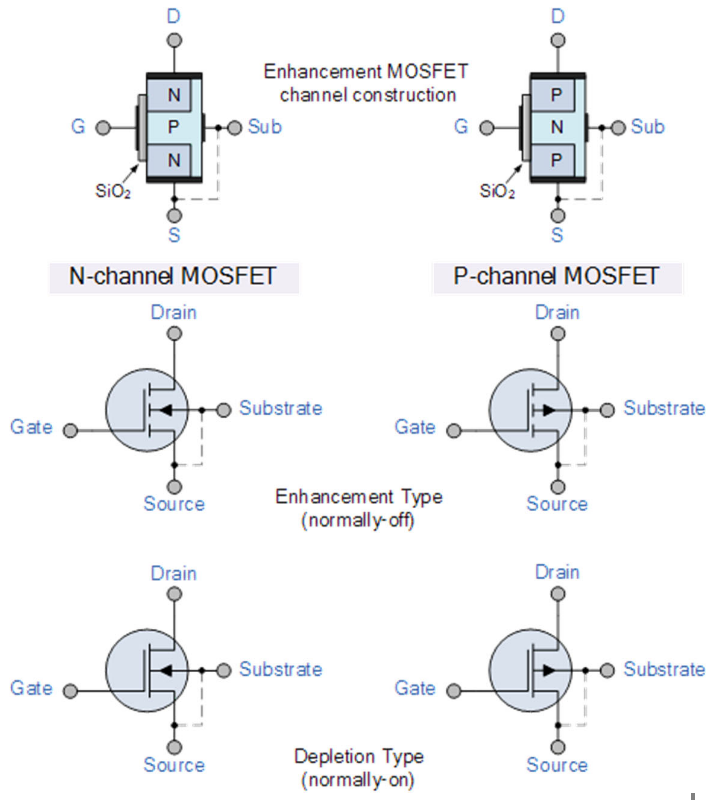
Field Effect Transistor (FET) -4

- MOSFET
  - Having a metal oxide gate electrode which is electrically insulated from the main semiconductor n-channel or p-channel by a very thin layer of insulating material (usually silicon dioxide) – high input resistance
  - Unlike JFET, the gate can be biased in either polarity



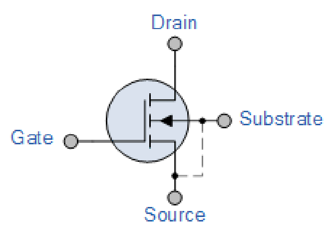
Field Effect Transistor (FET) -5

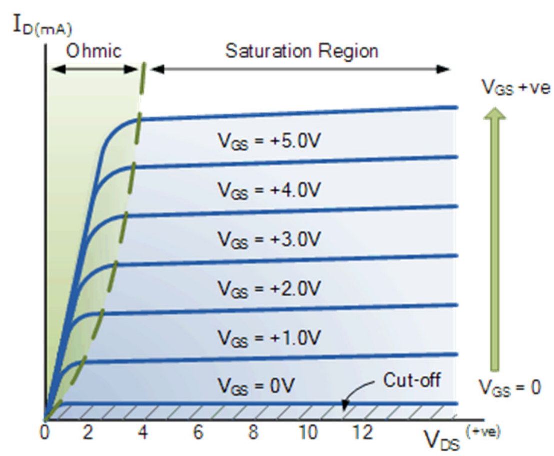
- MOSFET types
  - Enhancement type: "normally open," requiring V_{GS} to switch the device ON
  - Depletion type: "normally closed," requiring V_{GS} to switch the device OFF (less common)



Field Effect Transistor (FET) -6

- Enhanced-mode N-channel MOSFET

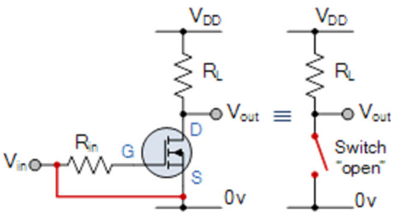




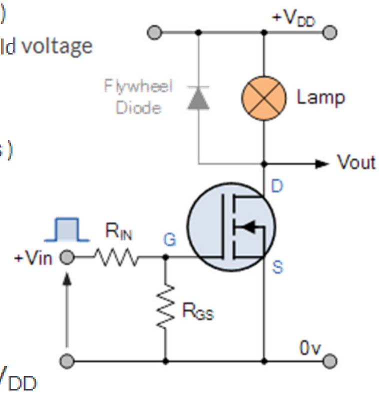
  - In linear region, the drain-source behaves like a small value resistor -> small voltage drop -> small power dissipation

Field Effect Transistor (FET) -7

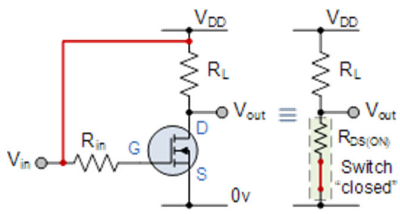
- Enhanced-mode N-channel MOSFET as a switch
  - Cut-off region



- The input and Gate are grounded (0V)
- Gate-source voltage less than threshold voltage $V_{GS} < V_{TH}$
- MOSFET is "OFF" (Cut-off region)
- No Drain current flows ($I_D = 0$ Amps)
- $V_{OUT} = V_{DS} = V_{DD} =$ "1"
- MOSFET operates as an "open switch"



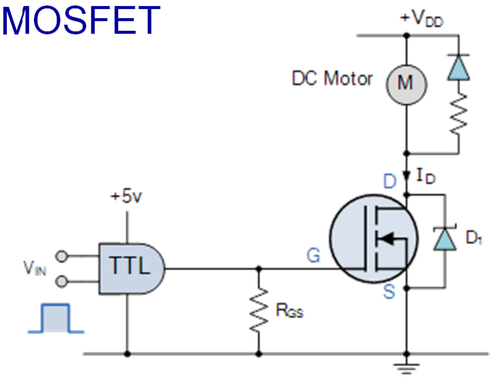
  - Saturation region



- The input and Gate are connected to V_{DD}
- Gate-source voltage is much greater than threshold voltage $V_{GS} > V_{TH}$
- MOSFET is "ON" (saturation region)
- Max Drain current flows ($I_D = V_{DD} / R_L$)
- $V_{DS} = 0V$ (ideal saturation)
- Min channel resistance $R_{DS(on)} < 0.1\Omega$
- $V_{OUT} = V_{DS} \cong 0.2V$ due to $R_{DS(on)}$
- MOSFET operates as a low resistance "closed switch"

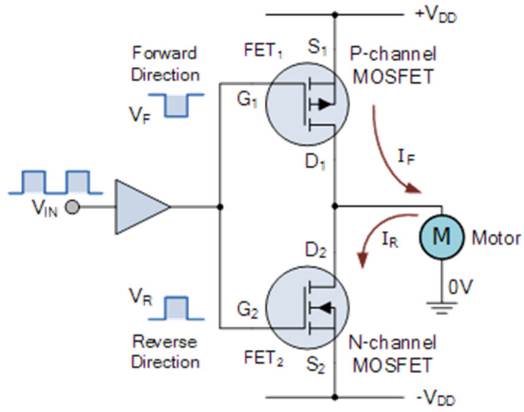
Field Effect Transistor (FET) -8

- Enhanced-mode N-channel power MOSFET for motor control
  - Clamping network: For faster switching and better control of the peak reverse voltage and drop-out time
  - D_1: For suppressing over voltage switching transients and noise giving extra protection to the MOSFET
  - R_{GS}: Pull-down resistor



Field Effect Transistor (FET) -9

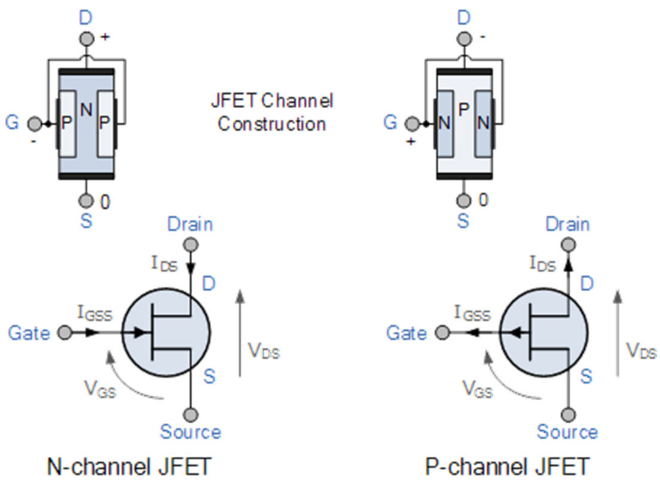
- Complementary MOSFET motor control

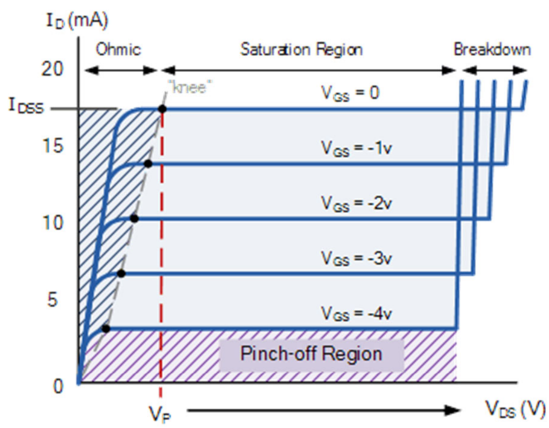


MOSFET 1	MOSFET 2	Motor Function
OFF	OFF	Motor Stopped (OFF)
ON	OFF	Motor Rotates Forward
OFF	ON	Motor Rotates Reverse
ON	ON	NOT ALLOWED

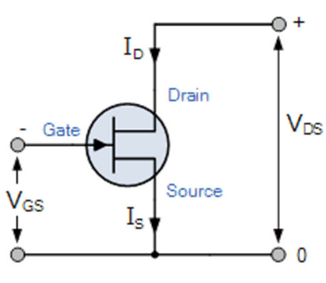
Field Effect Transistor (FET) -10

- JFET



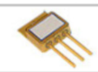


- Ex: 2N5457 – N-channel, TO-92



Transistor Packages

- Transistor outline (TO) packages

	TO-3 - Transistor Outline Package, Case Style 3
	TO-5 - Transistor Outline Package, Case Style 5
	TO-8 - Transistor Outline Package, Case Style 8
	TO-18 - Transistor Outline Package, Case Style 18
	TO-36 - Transistor Outline Package, Case Style 36
	TO-39 - Transistor Outline Package, Case Style 39
	TO-46 - Transistor Outline Package, Case Style 46
	TO-52 - Transistor Outline Package, Case Style 52
	TO-66 - Transistor Outline Package, Case Style 66
	TO-72 - Transistor Outline Package, Case Style 72
	TO-92 - Transistor Outline Package, Case Style 92
	TO-126 - Transistor Outline Package, Case Style 126
	TO-202 - Transistor Outline Package, Case Style 202
	TO-218 - Transistor Outline Package, Case Style 218
	TO-220 - Transistor Outline Package, Case Style 220
	TO-226 - Transistor Outline Package, Case Style 226
	TO-254 - Transistor Outline Package, Case Style 254
	TO-257 - Transistor Outline Package, Case Style 257
	TO-258 - Transistor Outline Package, Case Style 258
	TO-259 - Transistor Outline Package, Case Style 259
	TO-264 - Transistor Outline Package, Case Style 264
	TO-267 - Transistor Outline Package, Case Style 267

BJT vs. MOSFET

- BJT vs. MOSFET
  - BJT
    - When only small control voltage is available
    - Cheaper
  - MOSFET
    - When sufficient control voltage is available
    - When small voltage drop across the switching element is required (Ex: < 0.1V)
    - Simpler circuit
    - More efficient

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- Questions?