

Transistor as a Switch

When used as an AC signal amplifier, the transistors Base biasing voltage is applied in such a way that it always operates within its “active” region, that is the linear part of the output characteristics curves are used.

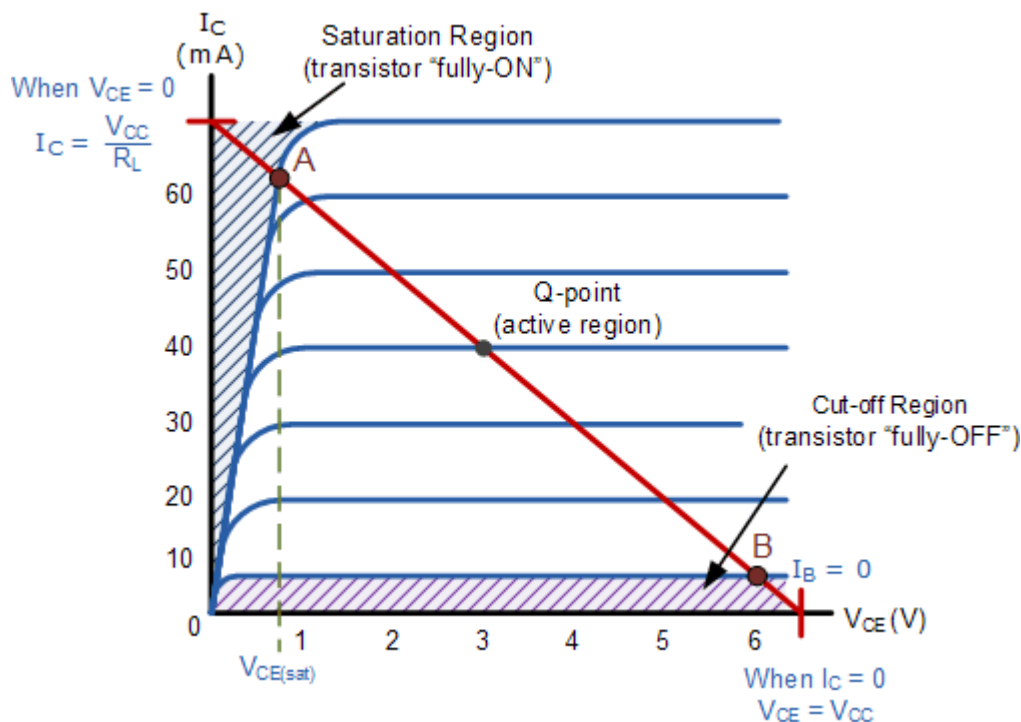
However, both the NPN & PNP type bipolar transistors can be made to operate as “ON/OFF” type solid state switch by biasing the transistors Base terminal differently to that for a signal amplifier.

Solid state switches are one of the main applications for the use of transistor to switch a DC output “ON” or “OFF”. Some output devices, such as LED’s only require a few milliamps at logic level DC voltages and can therefore be driven directly by the output of a logic gate. However, high power devices such as motors, solenoids or lamps, often require more power than that supplied by an ordinary logic gate so transistor switches are used.

If the circuit uses the Bipolar Transistor as a Switch, then the biasing of the transistor, either NPN or PNP is arranged to operate the transistor at both sides of the “ I-V ” characteristics curves we have seen previously.

The areas of operation for a transistor switch are known as the Saturation Region and the Cut-off Region. This means then that we can ignore the operating Q-point biasing and voltage divider circuitry required for amplification, and use the transistor as a switch by driving it back and forth between its “fully-OFF” (cut-off) and “fully-ON” (saturation) regions as shown below.

Operating Regions

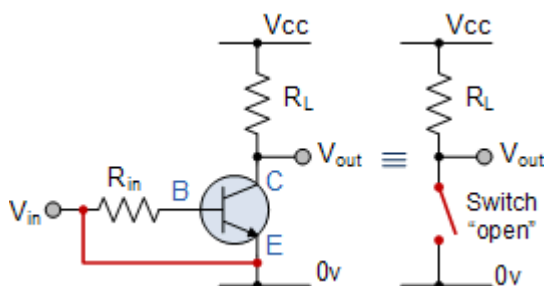


The pink shaded area at the bottom of the curves represents the “Cut-off” region while the blue area to the left represents the “Saturation” region of the transistor. Both these transistor regions are defined as:

1. Cut-off Region

Here the operating conditions of the transistor are zero input base current (I_B), zero output collector current (I_C) and maximum collector voltage (V_{CE}) which results in a large depletion layer and no current flowing through the device. Therefore the transistor is switched “Fully-OFF”.

Cut-off Characteristics



- 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

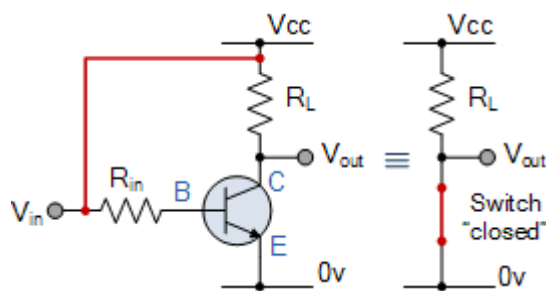
- Transistor is “fully-OFF” (Cut-off region)
- No Collector current flows ($I_C = 0$)
- $V_{OUT} = V_{CE} = V_{CC} = "1"$
- Transistor operates as an “open switch”

Then we can define the “cut-off region” or “OFF mode” when using a bipolar transistor as a switch as being, both junctions reverse biased, $V_B < 0.7\text{v}$ and $I_C = 0$. For a PNP transistor, the Emitter potential must be negative with respect to the Base.

2. Saturation Region

Here the transistor will be biased so that the maximum amount of base current is applied, resulting in maximum collector current resulting in the minimum collector emitter voltage drop which results in the depletion layer being as small as possible and maximum current flowing through the transistor. Therefore the transistor is switched “Fully-ON”.

Saturation Characteristics



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

Then we can define the “saturation region” or “ON mode” when using a bipolar transistor as a switch as being, both junctions forward biased, $V_B > 0.7\text{v}$ and $I_C = \text{Maximum}$. For a PNP transistor, the Emitter potential must be positive with respect to the Base.

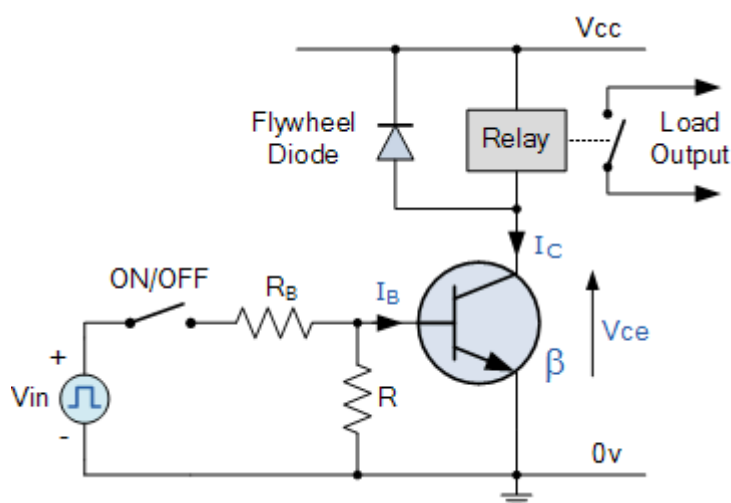
Then the transistor operates as a “single-pole single-throw” (SPST) solid state switch. With a zero signal applied to the Base of the transistor it turns “OFF” acting like an open switch and

zero collector current flows. With a positive signal applied to the Base of the transistor it turns “ON” acting like a closed switch and maximum circuit current flows through the device.

The simplest way to switch moderate to high amounts of power is to use the transistor with an open-collector output and the transistors Emitter terminal connected directly to ground. When used in this way, the transistors open collector output can thus “sink” an externally supplied voltage to ground thereby controlling any connected load.

An example of an NPN Transistor as a switch being used to operate a relay is given below. With inductive loads such as relays or solenoids a flywheel diode is placed across the load to dissipate the back EMF generated by the inductive load when the transistor switches “OFF” and so protect the transistor from damage. If the load is of a very high current or voltage nature, such as motors, heaters etc, then the load current can be controlled via a suitable relay as shown.

Basic NPN Transistor Switching Circuit



The circuit resembles that of the Common Emitter circuit we looked at in the previous tutorials. The difference this time is that to operate the transistor as a switch the transistor needs to be turned either fully “OFF” (cut-off) or fully “ON” (saturated). An ideal transistor switch would have infinite circuit resistance between the Collector and Emitter when turned “fully-OFF” resulting in zero current flowing through it and zero resistance between the Collector and Emitter when turned “fully-ON”, resulting in maximum current flow.

In practice when the transistor is turned “OFF”, small leakage currents flow through the transistor and when fully “ON” the device has a low resistance value causing a small saturation voltage (V_{CE}) across it. Even though the transistor is not a perfect switch, in

both the cut-off and saturation regions the power dissipated by the transistor is at its minimum.

In order for the Base current to flow, the Base input terminal must be made more positive than the Emitter by increasing it above the 0.7 volts needed for a silicon device. By varying this Base-Emitter voltage V_{BE} , the Base current is also altered and which in turn controls the amount of Collector current flowing through the transistor as previously discussed.

When maximum Collector current flows the transistor is said to be Saturated. The value of the Base resistor determines how much input voltage is required and corresponding Base current to switch the transistor fully "ON".

Transistor as a Switch Example No1

Using the transistor values from the previous tutorials of: $\beta = 200$, $I_c = 4\text{mA}$ and $I_b = 20\mu\text{A}$, find the value of the Base resistor (R_b) required to switch the load fully "ON" when the input terminal voltage exceeds 2.5v.

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{2.5\text{v} - 0.7\text{v}}{20 \times 10^{-6}} = 90\text{k}\Omega$$

The next lowest preferred value is: 82k Ω , this guarantees the transistor switch is always saturated.

Transistor as a Switch Example No2

Again using the same values, find the minimum Base current required to turn the transistor "fully-ON" (saturated) for a load that requires 200mA of current when the input voltage is increased to 5.0V. Also calculate the new value of R_b .

Transistor Base current:

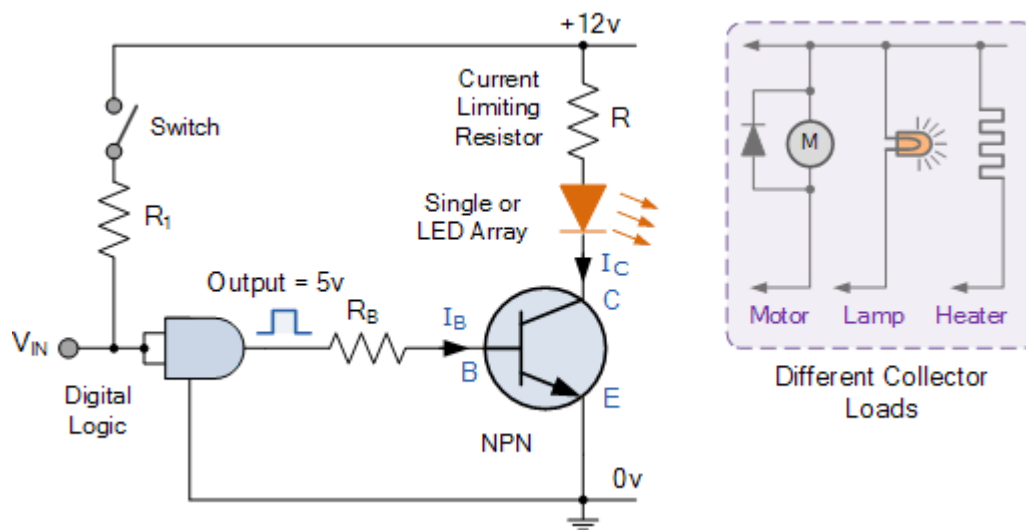
$$I_B = \frac{I_C}{\beta} = \frac{200\text{mA}}{200} = 1\text{mA}$$

Transistor Base resistance:

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{5.0\text{v} - 0.7\text{v}}{1 \times 10^{-3}} = 4.3\text{k}\Omega$$

Transistor switches are used for a wide variety of applications such as interfacing large current or high voltage devices like motors, relays or lamps to low voltage digital IC's or logic gates like AND gates or OR gates. Here, the output from a digital logic gate is only +5v but the device to be controlled may require a 12 or even 24 volts supply. Or the load such as a DC Motor may need to have its speed controlled using a series of pulses (Pulse Width Modulation). transistor switches will allow us to do this faster and more easily than with conventional mechanical switches.

Digital Logic Transistor Switch

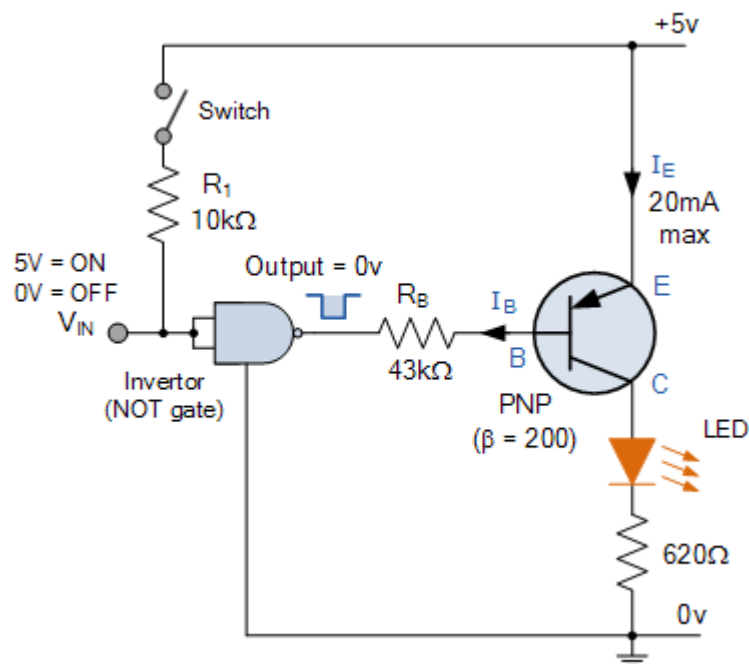


The base resistor, R_B is required to limit the output current from the logic gate.

PNP Transistor Switch

We can also use the PNP Transistors as a switch, the difference this time is that the load is connected to ground (0v) and the PNP transistor switches the power to it. To turn the PNP transistor operating as a switch "ON", the Base terminal is connected to ground or zero volts (LOW) as shown.

PNP Transistor Switching Circuit



The equations for calculating the Base resistance, Collector current and voltages are exactly the same as for the previous NPN transistor switch. The difference this time is that we are switching power with a PNP transistor (sourcing current) instead of switching ground with an NPN transistor (sinking current).

Darlington Transistor Switch

Sometimes the DC current gain of the bipolar transistor is too low to directly switch the load current or voltage, so multiple switching transistors are used. Here, one small input transistor is used to switch “ON” or “OFF” a much larger current handling output transistor. To maximise the signal gain, the two transistors are connected in a “Complementary Gain Compounding Configuration” or what is more commonly called a “Darlington Configuration” where the amplification factor is the product of the two individual transistors.

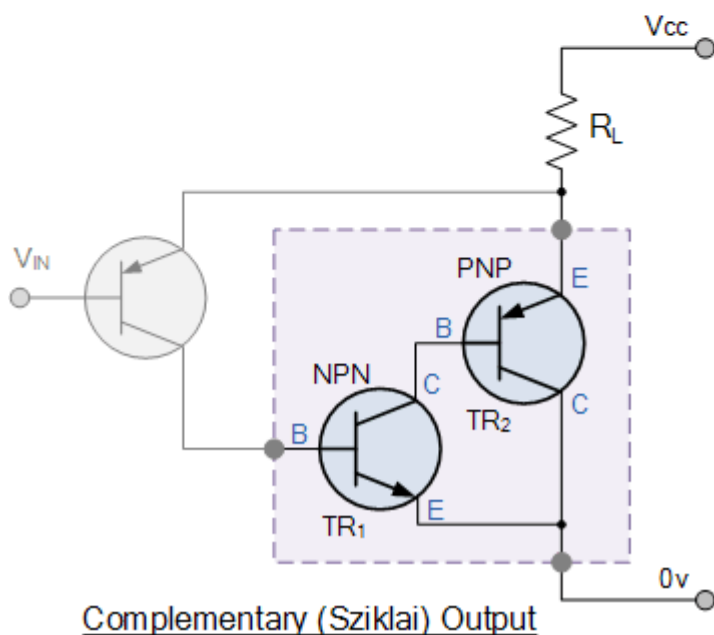
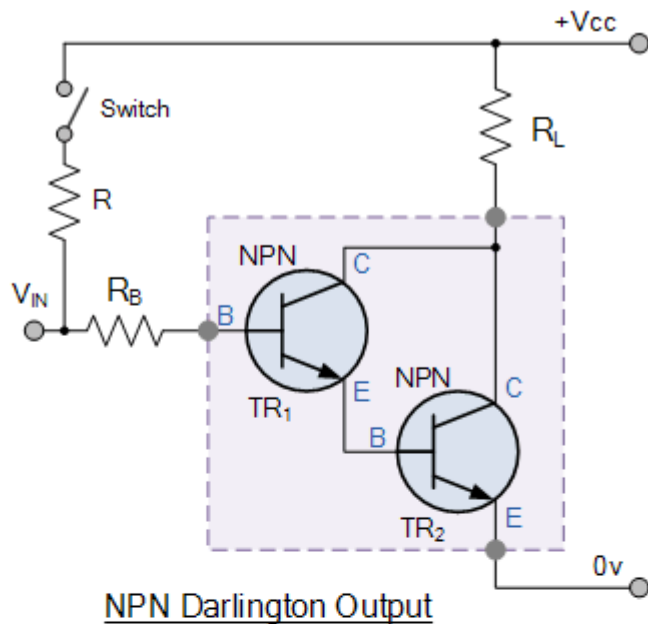
Darlington Transistors simply contain two individual bipolar NPN or PNP type transistors connected together so that the current gain of the first transistor is multiplied with that of the current gain of the second transistor to produce a device which acts like a single transistor with a very high current gain for a much smaller Base current. The overall current gain Beta (β) or hfe value of a Darlington device is the product of the two individual gains of the transistors and is given as:

$$\beta_{\text{TOTAL}} = \beta_1 \times \beta_2$$

So Darlington Transistors with very high β values and high Collector currents are possible compared to a single transistor switch. For example, if the first input transistor has a current gain of 100 and the second switching transistor has a current gain of 50 then the total current gain will be $100 \times 50 = 5000$. So for example, if our load current from above is 200mA, then the darlington base current is only $200\text{mA}/5000 = 40\mu\text{A}$. A huge reduction from the previous 1mA for a single transistor.

An example of the two basic types of Darlington transistor configurations are given below.

Darlington Transistor Configurations



The above NPN Darlington transistor switch configuration shows the Collectors of the two transistors connected together with the Emitter of the first transistor connected to the Base terminal of the second transistor therefore, the Emitter current of the first transistor becomes the Base current of the second transistor switching it "ON".

The first or "input" transistor receives the input signal to its Base. This transistor amplifies it in the usual way and uses it to drive the second larger "output" transistors. The second transistor amplifies the signal again resulting in a very high current gain. One of the main characteristics of Darlington Transistors is their high current gains compared to single bipolar transistors.

As well as its high increased current and voltage switching capabilities, another advantage of a "Darlington Transistor Switch" is in its high switching speeds making them ideal for use in inverter circuits, lighting circuits and DC motor or stepper motor control applications.

One difference to consider when using Darlington transistors over the conventional single bipolar types when using the transistor as a switch is that the Base-Emitter input voltage (V_{BE}) needs to be higher at approx 1.4v for silicon devices, due to the series connection of the two PN junctions.

Transistor as a Switch Summary

Then to summaries when using a Transistor as a Switch the following conditions apply:

1. Transistor switches can be used to switch and control lamps, relays or even motors.
2. When using the bipolar transistor as a switch they must be either “fully-OFF” or “fully-ON”.
3. Transistors that are fully “ON” are said to be in their Saturation region.
4. Transistors that are fully “OFF” are said to be in their Cut-off region.
5. When using the transistor as a switch, a small Base current controls a much larger Collector load current.
6. When using transistors to switch inductive loads such as relays and solenoids, a “Flywheel Diode” is used.
7. When large currents or voltages need to be controlled, Darlington Transistors can be used.