W04 Transistors and Applications
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This week’s reference: http://www.electronics-tutorials.ws/transistor/tran_1.html
Diodes are made up from two pieces of semiconductor material, either silicon or germanium to form a simple PN-junction. If we join together two individual signal diodes back-to-back, this will give us two PN-junctions connected together in series that share a common P or N terminal. The fusion of these two diodes produces a three layer, two junction, three terminal device forming the basis of a Bipolar Junction Transistor, or BJT for short.
Transistors...

Transistors are three terminal active devices made from different semiconductor materials that can act as either an insulator or a conductor by the application of a small signal voltage. The transistor's ability to change between these two states enables it to have two basic functions: "switching" (digital electronics) or "amplification" (analogue electronics). Then bipolar transistors have the ability to operate within three different regions:

1. **Active Region** - the transistor operates as an amplifier and $I_c = \beta I_b$

2. **Saturation** - the transistor is "fully-ON" operating as a switch and $I_c = I_{\text{saturation}}$

3. **Cut-off** - the transistor is "fully-OFF" operating as a switch and $I_c = 0$
There are two basic types of bipolar transistor construction, PNP and NPN, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

The **Bipolar Transistor** basic construction consists of two PN-junctions producing three connecting terminals with each terminal being given a name to identify it from the other two. These three terminals are known and labelled as the Emitter (E), the Base (B) and the Collector (C) respectively.
Bipolar Transistor

The construction and circuit symbols for both the PNP and NPN bipolar transistor are given above with the arrow in the circuit symbol always showing the direction of "conventional current flow" between the base terminal and its emitter terminal. The direction of the arrow always points from the positive P-type region to the negative N-type region for both transistor types, exactly the same as for the standard diode symbol.
Bipolar Transistor

Bipolar Transistor Configurations
As the Bipolar Transistor is a three terminal device, there are basically three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output. Each method of connection responding differently to its input signal within a circuit as the static characteristics of the transistor vary with each circuit arrangement.

1. Common Base Configuration  -  has Voltage Gain but no Current Gain.
2. Common Emitter Configuration  -  has both Current and Voltage Gain.
3. Common Collector Configuration  -  has Current Gain but no Voltage Gain.
The Common Base Transistor Circuit

In the **Common Base** or grounded base configuration, the BASE connection is common to both the input signal AND the output signal with the input signal being applied between the base and the emitter terminals. The corresponding output signal is taken from between the base and the collector terminals as shown with the base terminal grounded or connected to a fixed reference voltage point.

The input current flowing into the emitter is quite large as its the sum of both the base current and collector current respectively therefore, the collector current output is less than the emitter current input resulting in a current gain for this type of circuit of "1" (unity) or less, in other words the common base configuration "attenuates" the input signal.
The Common Base Transistor Circuit

This type of amplifier configuration is a non-inverting voltage amplifier circuit, in that the signal voltages Vin and Vout are in-phase. This type of transistor arrangement is not very common due to its unusually high voltage gain characteristics. Its output characteristics represent that of a forward biased diode while the input characteristics represent that of an illuminated photo-diode. Also this type of bipolar transistor configuration has a high ratio of output to input resistance or more importantly "load" resistance (RL) to "input" resistance (Rin) giving it a value of "Resistance Gain". Then the voltage gain (Av) for a common base configuration is therefore given as:

\[
A_v = \frac{V_{out}}{V_{in}} = \frac{I_C \times R_L}{I_E \times R_{IN}}
\]

Where: \( I_C / I_E \) is the current gain, alpha (\( \alpha \)) and RL/Rin is the resistance gain. The common base circuit is generally only used in single stage amplifier circuits such as microphone pre-amplifier or radio frequency (Rf) amplifiers due to its very good high frequency response.
The Common Emitter (CE) Configuration

In the **Common Emitter** or grounded emitter configuration, the input signal is applied between the base, while the output is taken from between the collector and the emitter as shown. This type of configuration is the most commonly used circuit for transistor based amplifiers and which represents the "normal" method of bipolar transistor connection. The common emitter amplifier configuration produces the highest current and power gain of all the three bipolar transistor configurations. This is mainly because the input impedance is LOW as it is connected to a forward-biased PN-junction, while the output impedance is HIGH as it is taken from a reverse-biased PN-junction.
The Common Emitter (CE) Configuration

In this type of configuration, the current flowing out of the transistor must be equal to the currents flowing into the transistor as the emitter current is given as $I_e = I_c + I_b$. Also, as the load resistance (RL) is connected in series with the collector, the current gain of the common emitter transistor configuration is quite large as it is the ratio of $I_c/I_b$ and is given the Greek symbol of Beta, ($\beta$). As the emitter current for a common emitter configuration is defined as $I_e = I_c + I_b$, the ratio of $I_c/I_e$ is called Alpha, given the Greek symbol of $\alpha$. Note: that the value of Alpha will always be less than unity. Since the electrical relationship between these three currents, $I_b$, $I_c$ and $I_e$ is determined by the physical construction of the transistor itself, any small change in the base current ($I_b$), will result in a much larger change in the collector current ($I_c$). Then, small changes in current flowing in the base will thus control the current in the emitter-collector circuit. Typically, Beta has a value between 20 and 200 for most general purpose transistors.
The Common Emitter (CE) Configuration

By combining the expressions for both Alpha, $\alpha$ and Beta, $\beta$ the mathematical relationship between these parameters and therefore the current gain of the transistor can be given as:

$$\text{Alpha}, (\alpha) = \frac{I_C}{I_E} \quad \text{and} \quad \text{Beta}, (\beta) = \frac{I_C}{I_B}$$

Where: "$I_c$" is the current flowing into the collector terminal, "$I_b$" is the current flowing into the base terminal and "$I_e$" is the current flowing out of the emitter terminal.

\[\begin{align*}
\therefore I_C &= \alpha I_E = \beta I_B \\
\text{as: } \alpha &= \frac{\beta}{\beta + 1} \quad \beta = \frac{\alpha}{1 - \alpha} \\
I_E &= I_C + I_B
\end{align*}\]
The Common Collector (CC) Configuration

In the **Common Collector** or grounded collector configuration, the collector is now common through the supply. The input signal is connected directly to the base, while the output is taken from the emitter load as shown. This type of configuration is commonly known as a **Voltage Follower** or **Emitter Follower** circuit. The emitter follower configuration is very useful for impedance matching applications because of the very high input impedance, in the region of hundreds of thousands of Ohms while having a relatively low output impedance.
The Common Collector (CC) Configuration

The common emitter configuration has a current gain approximately equal to the β value of the transistor itself. In the common collector configuration the load resistance is situated in series with the emitter so its current is equal to that of the emitter current. As the emitter current is the combination of the collector AND the base current combined, the load resistance in this type of transistor configuration also has both the collector current and the input current of the base flowing through it. Then the current gain of the circuit is given as:

\[ I_E = I_C + I_B \]

\[ A_i = \frac{I_E}{I_B} = \frac{I_C + I_B}{I_B} \]

\[ A_i = \frac{I_C}{I_B} + 1 \]

\[ A_i = \beta + 1 \]
# Bipolar Transistor Characteristics

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<td>Power Gain</td>
<td>Low</td>
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<td>Medium</td>
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The NPN Transistor

The standard **Bipolar Transistor** or BJT, comes in two basic forms. An NPN (Negative-Positive-Negative) type and a PNP (Positive-Negative-Positive) type, with the most commonly used transistor type being the **NPN Transistor**. An NPN transistor along with the transistors current flow characteristics is given below.
The NPN Transistor

The voltage between the Base and Emitter ($V_{BE}$), is positive at the Base and negative at the Emitter because for an NPN transistor, the Base terminal is always positive with respect to the Emitter. Also the Collector supply voltage is positive with respect to the Emitter ($V_{CE}$). So for an NPN transistor to conduct the Collector is always more positive with respect to both the Base and the Emitter.

Then the voltage sources are connected to an NPN transistor as shown. The Collector is connected to the supply voltage $V_{CC}$ via the load resistor, $R_L$ which also acts to limit the maximum current flowing through the device. The Base supply voltage $V_B$ is connected to the Base resistor $R_B$, which again is used to limit the maximum Base current.
The NPN Transistor

The transistor is a "current" operated device (Beta model) and that a large current (I_c) flows freely through the device between the collector and the emitter terminals when the transistor is switched "fully-ON". However, this only happens when a small biasing current (I_b) is flowing into the base terminal of the transistor at the same time thus allowing the Base to act as a sort of current control input.

The transistor current in an NPN transistor is the ratio of these two currents (I_c/I_b), called the DC Current Gain of the device and is given the symbol of hfe or nowadays Beta, (β). The value of β can be large up to 200 for standard transistors, and it is this large ratio between I_c and I_b that makes the NPN transistor a useful amplifying device when used in its active region as I_b provides the input and I_c provides the output. Note that Beta has no units as it is a ratio.
The NPN Transistor

Also, the current gain of the transistor from the Collector terminal to the Emitter terminal, \( I_{c}/I_{e} \), is called Alpha, \( (\alpha) \), and is a function of the transistor itself (electrons diffusing across the junction). As the emitter current \( I_{e} \) is the product of a very small base current plus a very large collector current, the value of alpha \( \alpha \), is very close to unity, and for a typical low-power signal transistor this value ranges from about 0.950 to 0.999

DC Current Gain = \frac{\text{Output Current}}{\text{Input Current}} = \frac{I_{c}}{I_{B}}

\[ I_{E} = I_{B} + I_{C} \quad \text{(KCL)} \quad \text{and} \quad \frac{I_{C}}{I_{E}} = \alpha \]

Thus: \[ I_{E} = I_{B} + \frac{I_{C}}{\alpha} \]

and \[ I_{B} = I_{C} \left(1 - \frac{1}{\alpha}\right)\]

\[ \therefore \beta = \frac{I_{C}}{I_{B}} = \frac{1}{\left(1 - \frac{1}{\alpha}\right)} = \frac{\alpha}{1 - \alpha} \]

\[ \beta = \frac{\alpha}{1 - \alpha} \quad \text{and} \quad \alpha = \frac{\beta}{\beta + 1} \]

If \( \alpha = 0.99 \) \[ \beta = \frac{0.99}{0.01} = 99 \]
The NPN Transistor - Example

An NPN Transistor has a DC current gain, $(\beta)$ value of 200. Calculate the base current $I_b$ required to switch a resistive load of 4mA.

$$I_B = \frac{I_C}{\beta} = \frac{4 \times 10^{-3}}{200} = 20\mu A$$

Therefore, $\beta = 200$, $I_c = 4mA$ and $I_b = 20\mu A$.

The collector voltage, $(V_c)$ must be greater and positive with respect to the emitter voltage, $(V_e)$ to allow current to flow through the transistor between the collector-emitter junctions. Also, there is a voltage drop between the Base and the Emitter terminal of about 0.7v (one diode volt drop) for silicon devices as the input characteristics of an NPN Transistor are of a forward biased diode. Then the base voltage, $(V_{be})$ of a NPN transistor must be greater than this 0.7V otherwise the transistor will not conduct with the base current given as.

$$I_B = \frac{V_B - V_{BE}}{R_B}$$

$I_b$ is the base current, $V_b$ is the base bias voltage, $V_{be}$ is the base-emitter volt drop (0.7 [V]) and $R_b$ is the base input resistor. Increasing $I_b$, $V_{be}$ slowly increases to 0.7V but $I_c$ rises exponentially.
The Common Emitter Configuration.

As well as being used as a semiconductor switch to turn load currents "ON" or "OFF" by controlling the Base signal to the transistor in either its saturation or cut-off regions, **NPN Transistors** can also be used in its active region to produce a circuit which will amplify any small AC signal applied to its Base terminal with the Emitter grounded. If a suitable DC "biasing" voltage is firstly applied to the transistors Base terminal thus allowing it to always operate within its linear active region, an inverting amplifier circuit called a single stage common emitter amplifier is produced.
The Common Emitter Configuration.

A "Class A Amplifier" operation is one where the transistors Base terminal is biased in such a way as to forward bias the Base-emitter junction. The result is that the transistor is always operating halfway between its cut-off and saturation regions, thereby allowing the transistor amplifier to accurately reproduce the positive and negative halves of any AC input signal superimposed upon this DC biasing voltage. Without this "Bias Voltage" only one half of the input waveform would be amplified. This common emitter amplifier configuration using an NPN transistor has many applications but is commonly used in audio circuits such as pre-amplifier and power amplifier stages.
The Common Emitter Configuration.

A DC "Load Line" can also be drawn onto the output characteristics curves to show all the possible operating points when different values of base current are applied. It is necessary to set the initial value of $V_{ce}$ correctly to allow the output voltage to vary both up and down when amplifying AC input signals and this is called setting the operating point or Quiescent Point, **Q-point** for short.
The Common Emitter Configuration.

The most important factor to notice is the effect of $V_{ce}$ upon the collector current $I_c$ when $V_{ce}$ is greater than about 1.0 volts. We can see that $I_c$ is largely unaffected by changes in $V_{ce}$ above this value and instead it is almost entirely controlled by the base current, $I_b$. When this happens we can say then that the output circuit represents that of a "Constant Current Source". It can also be seen from the common emitter circuit that the emitter current $I_e$ is the sum of the collector current, $I_c$ and the base current, $I_b$, added together so we can also say that $I_e = I_c + I_b$ for the common emitter (CE) configuration.
The Common Emitter Configuration.

By using the output characteristics curves in our example above and also Ohm’s Law, the current flowing through the load resistor, (RL), is equal to the collector current, Ic entering the transistor which in turn corresponds to the supply voltage, (Vcc) minus the voltage drop between the collector and the emitter terminals, (Vce) and is given as:

\[
\text{Collector Current, } I_C = \frac{V_{CC} - V_{CE}}{R_L}
\]

Also, a straight line representing the **Dynamic Load Line** of the transistor can be drawn directly onto the graph of curves above from the point of "Saturation" (A) when \(V_{ce} = 0\) to the point of "Cut-off" (B) when \(I_c = 0\) thus giving us the "Operating" or **Q-point** of the transistor. These two points are joined together by a straight line and any position along this straight line represents the "Active Region" of the transistor.
The Common Emitter Configuration.

The actual position of the load line on the characteristics curves can be calculated as follows:

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

Then, the collector or output characteristics curves for Common Emitter NPN Transistors can be used to predict the Collector current, \( I_C \), when given \( V_{CE} \) and the Base current, \( I_B \). A Load Line can also be constructed onto the curves to determine a suitable Operating or Q-point which can be set by adjustment of the base current. The slope of this load line is equal to the reciprocal of the load resistance which is given as: \(-1/R_L\)

Then we can define a NPN Transistor as being normally "OFF" but a small input current and a small positive voltage at its Base (B) relative to its Emitter (E) will turn it "ON" allowing a much large Collector-Emitter current to flow. NPN transistors conduct when \( V_C \) is much greater than \( V_E \).
The PNP Transistor

The **PNP Transistor** is the exact opposite to the **NPN Transistor**. Basically, in this type of transistor construction the two diodes are reversed with respect to the NPN type giving a Positive-Negative-Positive configuration, with the arrow which also defines the Emitter terminal this time pointing inwards in the transistor symbol.

Also, all the polarities for a *PNP transistor* are reversed which means that it "sinks" current into its Base as opposed to the NPN transistor which "sources" current through its Base. The main difference between the two types of transistors is that holes are the more important carriers for PNP transistors, whereas electrons are the important carriers for NPN transistors. Then, PNP transistors use a small base current and a negative base voltage to control a much larger emitter-collector current. In other words for a PNP transistor, the Emitter is more positive with respect to the Base and also with respect to the Collector.
The PNP Transistor

The voltage between the Base and Emitter (\( V_{BE} \)), is now negative at the Base and positive at the Emitter because for a PNP transistor, the Base terminal is always biased negative with respect to the Emitter. Also the Emitter supply voltage is positive with respect to the Collector (\( V_{CE} \)). So for a PNP transistor to conduct the Emitter is always more positive with respect to both the Base and the Collector.
The PNP Transistor

This time the Emitter is connected to the supply voltage $V_{CC}$ with the load resistor, RL which limits the maximum current flowing through the device connected to the Collector terminal. The Base voltage $V_B$ which is biased negative with respect to the Emitter and is connected to the Base resistor $R_B$, which again is used to limit the maximum Base current.
The PNP Transistor

To cause the Base current to flow in a PNP transistor the Base needs to be more negative than the Emitter (current must leave the base) by approx 0.7 volts for a silicon device or 0.3 volts for a germanium device with the formulas used to calculate the Base resistor, Base current or Collector current are the same as those used for an equivalent NPN transistor and is given as.

\[ I_C = I_E - I_B \]

\[ I_C = \beta I_B \quad I_B = \frac{I_C}{\beta} \]

Generally, the PNP transistor can replace NPN transistors in most electronic circuits, the only difference is the polarities of the voltages, and the directions of the current flow.
The PNP Transistor

PNP transistors can also be used as switching devices and an example of a PNP transistor switch is shown below.

The **Output Characteristics Curves** for a PNP transistor look very similar to those for an equivalent NPN transistor except that they are rotated by 180° to take account of the reverse polarity voltages and currents, (the currents flowing out of the Base and Collector in a PNP transistor are negative). The same dynamic load line can be drawn onto the I-V curves to find the PNP transistors operating points.
Transistor Matching

A pair of corresponding NPN and PNP transistors with near identical characteristics to each other are called **Complementary Transistors** for example, a TIP3055 (NPN transistor) and the TIP2955 (PNP transistor) are good examples of complementary or matched pair silicon power transistors. They both have a DC current gain, Beta, \( \left( \frac{I_c}{I_b} \right) \) matched to within 10% and high Collector current of about 15A making them ideal for general motor control or robotic applications.

Class B amplifiers use complementary NPN and PNP in their power output stage design. The NPN transistor conducts for only the positive half of the signal while the PNP transistor conducts for negative half of the signal. This allows the amplifier to drive the required power through the load loudspeaker in both directions at the stated nominal impedance and power resulting in an output current which is likely to be in the order of several amps shared evenly between the two complementary transistors.
The 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 switches by biasing the transistors base differently to that of a signal amplifier. Solid state switches are one of the main applications for the use of transistors, and transistor switches can be used for controlling high power devices such as motors, solenoids or lamps, but they can also used in digital electronics and logic gate circuits.

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.
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.
The Transistor as a Switch

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".

- 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, \(I_B < 0.7V\) and \(I_C = 0\). For a PNP transistor, the Emitter potential must be negative with respect to the Base.
2. Saturation Region

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".

- 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 (\(I_C = V_{cc}/R_L\))
- \(V_{CE} = 0\) (ideal saturation)
- \(V_{OUT} = V_{CE} = "0"\)
- Transistor operates as a "closed switch"

We can define the "saturation region" or "ON mode" when using a bipolar transistor as a switch as being, both junctions forward biased, \(I_B > 0.7V\) and \(I_C = \text{Maximum}\). For a PNP transistor, the Emitter potential must be positive with respect to the Base.
The Transistor as a Switch
Basic NPN Transistor Switching Circuit

An example of an NPN Transistor as a switch being used to operate a relay. 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.
The Transistor as a Switch
Basic NPN Transistor Switching Circuit

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".
Using the transistor values 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 "ON" when the input terminal voltage exceeds 2.5 [V]

$$R_b = \frac{V_{\text{in}} - V_{\text{BE}}}{I_b} = \frac{2.5\text{V} - 0.7\text{V}}{20 \times 10^{-6}} = 90\text{k}\Omega$$

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

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 5.0 [V]. Also calculate the new value of $R_b$.

$$I_b = \frac{I_c}{\beta} = \frac{200\text{mA}}{200} = 1\text{mA} \quad R_b = \frac{V_{\text{in}} - V_{\text{BE}}}{I_b} = \frac{5.0\text{V} - 0.7\text{V}}{1 \times 10^{-3}} = 4.3\text{k}\Omega$$
The base resistor, $R_b$ is required to limit the output current from the logic gate.
PNP Transistor Switch

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

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 maximize the signal gain, the two transistors are connected in a "Complementary Gain Compounding Configuration" or what is more commonly called a "Darlington Configuration" were 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.
Darlington Transistor Switch

The overall current gain Beta ($\beta$) or $H_{fe}$ value of a Darlington device is the product of the two individual gains of the transistors.

So Darlington Transistors with very high $\beta$ 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 $100 \times 50 = 5000$. An example of the two basic types of Darlington transistor are given below.
Darlington Transistor Switch

The 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 of the second transistor therefore, the Emitter current of the first transistor becomes the Base current of the second transistor. The first or "input" transistor receives an input signal, amplifies it and uses it to drive the second or "output" transistors which amplifies it again resulting in a very high current gain.

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 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.
The Field Effect Transistor

For Bipolar Junction Transistor, the output Collector current of the transistor is proportional to input current flowing into the Base terminal of the device, thereby making the bipolar transistor a "CURRENT" operated device (Beta model). The Field Effect Transistor, or simply FET however, uses the voltage that is applied to their input terminal, called the Gate to control the current flowing through them resulting in the output current being proportional to the input voltage. As their operation relies on an electric field (hence the name field effect) generated by the input Gate voltage, this then makes the Field Effect Transistor a "VOLTAGE" operated device.

The Field Effect Transistor is a three terminal unipolar semiconductor device that has very similar characteristics to those of their Bipolar Transistor counterparts ie, high efficiency, instant operation, robust and cheap and can be used in most electronic circuit applications to replace their equivalent bipolar junction transistors (BJT) cousins.

<table>
<thead>
<tr>
<th>Bipolar Transistor</th>
<th>Field Effect Transistor</th>
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</thead>
<tbody>
<tr>
<td>Emitter - (E)</td>
<td>Source - (S)</td>
</tr>
<tr>
<td>Base - (B)</td>
<td>Gate - (G)</td>
</tr>
<tr>
<td>Collector - (C)</td>
<td>Drain - (D)</td>
</tr>
</tbody>
</table>
The Field Effect Transistor

The field effect transistor is a three terminal device that is constructed with no PN-junctions within the main current carrying path between the Drain and the Source terminals, which correspond in function to the Collector and the Emitter respectively of the bipolar transistor. The current path between these two terminals is called the "channel" which may be made of either a P-type or an N-type semiconductor material. The control of current flowing in this channel is achieved by varying the voltage applied to the Gate. As their name implies, Bipolar Transistors are "Bipolar" devices because they operate with both types of charge carriers, Holes and Electrons. The Field Effect Transistor on the other hand is a "Unipolar" device that depends only on the conduction of electrons (N-channel) or holes (P-channel).

The Field Effect Transistor has one major advantage over its standard bipolar transistor cousins, in that their input impedance, \( R_{\text{in}} \) is very high, (thousands of Ohms), while the BJT is comparatively low. This very high input impedance makes them very sensitive to input voltage signals, but the price of this high sensitivity also means that they can be easily damaged by static electricity. There are two main types of field effect transistor, the Junction Field Effect Transistor or JFET and the Insulated-gate Field Effect Transistor or IGFET), which is more commonly known as the standard Metal Oxide Semiconductor Field Effect Transistor or MOSFET for short.
The Junction Field Effect Transistor (JUGFET or JFET) has no PN-junctions but instead has a narrow piece of high-resistivity semiconductor material forming a "Channel" of either N-type or P-type silicon for the majority carriers to flow through with two ohmic electrical connections at either end commonly called the Drain and the Source respectively.
Bias arrangement for an N-channel JFET and corresponding circuit symbols.

The cross sectional diagram above shows an N-type semiconductor channel with a P-type region called the Gate diffused into the N-type channel forming a reverse biased PN-junction and it is this junction which forms the *depletion region* around the Gate area when no external voltages are applied.
The Field Effect Transistor

Output characteristic V-I curves of a typical junction FET.

The voltage $V_{GS}$ applied to the Gate controls the current flowing between the Drain and the Source terminals. $V_{GS}$ refers to the voltage applied between the Gate and the Source while $V_{DS}$ refers to the voltage applied between the Drain and the Source. Because a Junction Field Effect Transistor is a voltage controlled device, "NO current flows into the gate!" then the Source current ($I_S$) flowing out of the device equals the Drain current flowing into it and therefore ($I_D = I_S$).
The Field Effect Transistor

The four different regions of operation for a JFET and these are given as:

**Ohmic Region** - When \( V_{GS} = 0 \) the depletion layer of the channel is very small and the JFET acts like a voltage controlled resistor.

**Cut-off Region** - This is also known as the pinch-off region were the Gate voltage, \( V_{GS} \) is sufficient to cause the JFET to act as an open circuit as the channel resistance is at maximum.

**Saturation or Active Region** - The JFET becomes a good conductor and is controlled by the Gate-Source voltage, \( V_{GS} \) while the Drain-Source voltage, \( V_{DS} \) has little or no effect.

**Breakdown Region** - The voltage between the Drain and the Source, \( V_{DS} \) is high enough to causes the JFET's resistive channel to break down and pass uncontrolled maximum current.
The Field Effect Transistor

The characteristics curves for a P-channel junction field effect transistor are the same as those above, except that the Drain current $I_D$ decreases with an increasing positive Gate-Source voltage, $V_{GS}$. The Drain current is zero when $V_{GS} = V_P$. For normal operation, $V_{GS}$ is biased to be somewhere between $V_P$ and 0. Then we can calculate the Drain current, $I_D$ for any given bias point in the saturation or active region as follows:

Drain current in the active region.

\[ I_D = I_{DSS} \left( 1 - \frac{V_{GS}}{V_P} \right)^2 \]

Note that the value of the Drain current will be between zero (pinch-off) and $I_{DSS}$ (maximum current). By knowing the Drain current $I_D$ and the Drain-Source voltage $V_{DS}$ the resistance of the channel ($I_D$) is given as:

Drain-Source channel resistance.

\[ R_{DS} = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{1}{g_m} \]

Where: $g_m$ is the "transconductance gain" since the JFET is a voltage controlled device and which represents the rate of change of the Drain current with respect to the change in Gate-Source voltage.
The Field Effect Transistor

Biasing of JFET Amplifier

\[ V_S = I_D R_S = \frac{V_{DD}}{4} \]

\[ V_S = V_G - V_{GS} \]

\[ V_G = \left( \frac{R_2}{R_1 + R_2} \right) V_{DD} \]

\[ I_D = \frac{V_S}{R_S} = \frac{V_G - V_{GS}}{R_S} \]
The MOSFET

As well as the Junction Field Effect Transistor (JFET), there is another type of Field Effect Transistor available whose Gate input is electrically insulated from the main current carrying channel and is therefore called an **Insulated Gate Field Effect Transistor** or **IGFET**. The most common type of insulated gate FET which is used in many different types of electronic circuits is called the **Metal Oxide Semiconductor Field Effect Transistor** or **MOSFET** for short.

Like the previous JFET tutorial, MOSFETs are three terminal devices with a Gate, Drain and Source and both P-channel (PMOS) and N-channel (NMOS) MOSFETs are available. The main difference this time is that MOSFETs are available in two basic forms:

1. **Depletion Type** - the transistor requires the Gate-Source voltage, \( V_{GS} \) to switch the device "OFF". The depletion mode MOSFET is equivalent to a "Normally Closed" switch.

2. **Enhancement Type** - the transistor requires a Gate-Source voltage, \( V_{GS} \) to switch the device "ON". The enhancement mode MOSFET is equivalent to a "Normally Open" switch.
The MOSFET

MOSFET Channel Construction

N-channel MOSFET

P-channel MOSFET

Enhancement Type

Depletion Type
As the motor load is inductive, a simple flywheel diode is connected across the inductive load to dissipate any back emf generated by the motor when the MOSFET turns it "OFF". A clamping network formed by a zener diode in series with the diode can also be used to allow for faster switching and better control of the peak reverse voltage and drop-out time. An additional silicon or zener diode $D_1$ can also be placed across the channel of a MOSFET switch when using inductive loads, such as motors, solenoids, etc, for suppressing overvoltage switching transients and noise giving extra protection to the MOSFET switch if required. Resistor $R_2$ is used as a pull-down resistor to help pull the TTL output voltage down to 0V when the MOSFET is switched "OFF".
Complementary MOSFET Motor Driver

The two MOSFETs are configured to produce a bi-directional switch from a dual supply with the motor connected between the common drain connection and ground reference. When the input is LOW the P-channel MOSFET is switched-ON as its gate-source junction is negatively biased so the motor rotates in one direction. Only the positive $+V_{DD}$ supply rail is used to drive the motor.

When the input is HIGH, the P-channel device switches-OFF and the N-channel device switches-ON as its gate-source junction is positively biased. The motor now rotates in the opposite direction because the motors terminal voltage has been reversed as it is now supplied by the negative $-V_{DD}$ supply rail. Then the P-channel MOSFET is used to switch the positive supply to the motor for forward direction (high-side switching) while the N-channel MOSFET is used to switch the negative supply to the motor for reverse direction (low-side switching).
H Bridge Motor Controller

While controlling the speed of a DC motor with a single transistor has many advantages it also has one main disadvantage, the direction of rotation is always the same, its a "Uni-directional" circuit. In many applications we need to operate the motor in both directions forward and back. One very good way of achieving this is to connect the motor into a Transistor H-bridge circuit arrangement and this type of circuit will give us "Bi-directional" DC motor control as shown below.

![H-Bridge Motor Controller Diagram]

<table>
<thead>
<tr>
<th>TABLE 1: H-BRIDGE MODES OF OPERATION</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>Forward</td>
</tr>
<tr>
<td>Reverse</td>
</tr>
<tr>
<td>Coast</td>
</tr>
<tr>
<td>Brake</td>
</tr>
</tbody>
</table>
H Bridge Motor Controller

DPDT switch position determines direction of the motor.

A = Forward
B = Reverse

A pair of SPST switch positions determines direction of the motor.

A+D = Forward
B+C = Reverse
all OFF = Stopped
A+B = Stop + Brake
C+D = Stop + Brake
H Bridge Motor Controller
The Field Effect Transistor Family-tree

<table>
<thead>
<tr>
<th>Junction FET</th>
<th>Metal Oxide Semiconductor FET</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Depletion Mode</td>
</tr>
<tr>
<td><strong>Bias</strong></td>
<td>ON</td>
</tr>
<tr>
<td>N-channel</td>
<td>OFF</td>
</tr>
<tr>
<td>P-channel</td>
<td>-ve</td>
</tr>
<tr>
<td></td>
<td>0v</td>
</tr>
<tr>
<td></td>
<td>+ve</td>
</tr>
<tr>
<td></td>
<td>0v</td>
</tr>
</tbody>
</table>
Thank you,
Assist. Prof. Dr. Aytaç Gören.