FET, BJT, OpAmp Guide

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1 FETs

1.1 What is a Field Effect Transistor?

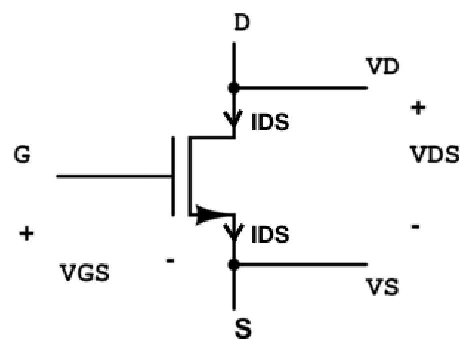

Figure 1: FET with all relevant values labelled.

FET stands for Field Effect Transistor, it is an active electronic device (meaning it needs to be powered) that uses an electric field to regulate the conductivity of its terminals. Specifically the conductivity between the drain and source terminals is controlled by the electric field generated by the voltage difference between the body and the gate of the device. The inner workings of the device are interesting but will not be fully explored here, we are most interested in the constitutive equations of the device and how it is used experimentally. N-channel FETs will be the primary focus.

An FET is a voltage controlled current source. The voltages V_{GS} and V_{DS} determine the output current I_{DS} as shown below. FETs are characterized by having an extremely high input impedance at the Gate terminal, so we can assume $I_G = 0$. The drain and source terminal currents are equal, the current that flows into the Drain flows out of the Source and can be referred to as I_{DS}. Additionally there are two important constants that are inherent to the FET itself, these constants are I_{DSS} and $V_{GS}(off)$. I_{DSS} is known as the saturation drain-source current, it is the maximum current that this device can output when being used as a current source. $V_{GS}(off)$ determines when the device enters its active region (the active region is when the FET is being used as a current source).

So what is the Active region exactly and what other regions are there? The Active region, also known as the Saturation region, is when the device is acting as an optimal current source. The Active region is entered when $V_{DS} > V_{GS} - V_{GS}(off)$, this is illustrated by the graph below. When this condition is not met (V_{DS} not high enough) then the FET is in its Ohmic, or Linear, region. In the linear region the FET becomes a variable resistor. There are additional breakdown regions which will occur if V_{DS} is very low or very high that are not shown.

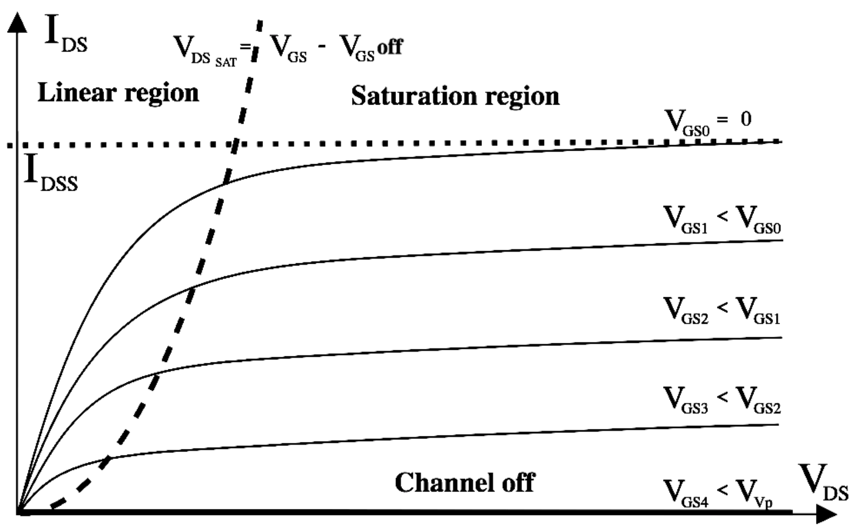

Figure 2: Five plots of I_{DS} vs V_{DS} for five different values of V_{GS}.

Since these devices are meant to be used as current sources it is useful to look at just the active regions behavior. In this active region a single current will be outputted that will not change even if V_{DS} has a slight change. When it is being used as a current source we can refer to the current I_{DS} as the Quiescent Current, or I_{DSQ}. Figure **??** shows the relationship between this Quiescent Current (labeled without the 'Q') and V_{GS}, their relationship is governed by the equation $I_{DS} = I_{DSS}(1 - \frac{V_{GS}}{V_{GS}(off)})^2$.

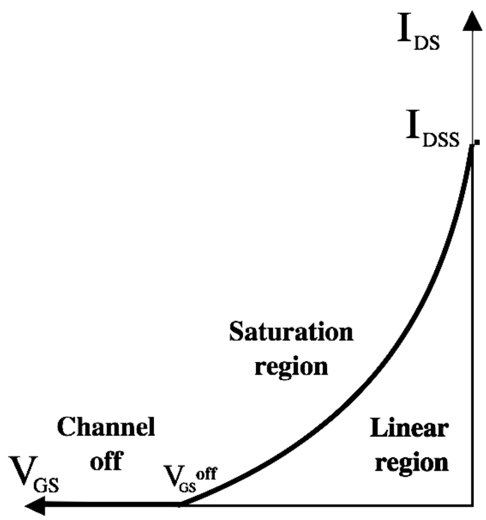

Figure 3: This plot only applies in the ACTIVE region. Plots of different I_{DS} currents one can make with different values of V_{GS} in the active region.

1.2 FET Constitutive Equations

$$I_G = 0 \tag{1}$$

$$I_D = I_S = I_{DS} \tag{2}$$

When in active region:

$$I_{DS} = I_{DSS}(1 - \frac{V_{GS}}{V_{GS}(off)})^2 \tag{3}$$

$$V_{DS} > V_{GS} - V_{GS}(off) \tag{4}$$

2 BJTs

2.1 What is a Bipolar Junction Transistor?

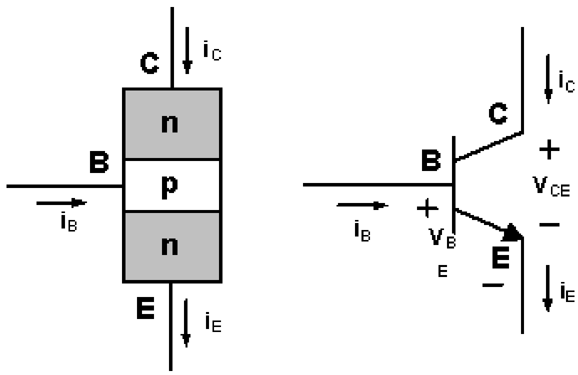

Figure 4: An npn BJT with relevant values labeled.

BJT stands for Bipolar Junction Transistor, this is another active electronic device similar to an FET. The three terminals of this device are the Base, Collector (collects electrons), and Emitter (emits electrons). "Bipolar" refers to the fact that there are two charge carriers being implemented, holes and electrons. The BJT is a Current controlled Current source. It can be used as a switch for digital logic (On/Off), or as a current amplifier that is amplified by a constant amount referred to as β (common Emitter current gain). NPN BJTs will be the primary focus.

The figure above show the base current, the collector current, and the emitter current flowing through the BJT. The first constitutive equation of this device is simple conservation of current, $I_E = I_B + I_C$. BJTs are characterized as current amplifiers, while in the active region the purpose is to have a small current flow into the Base terminal and amplify it in the Collector and Emitter terminals. The common Emitter current gain, written as β ($50 < \beta < 250$), amplifies the Collector current linearly with the Base current $I_C = \beta I_B$. If you were to plug this relationship into the current conservation equation you would also find that $I_C = \alpha I_E = \frac{\beta}{1+\beta} I_E$ where α is known as common Base current gain.

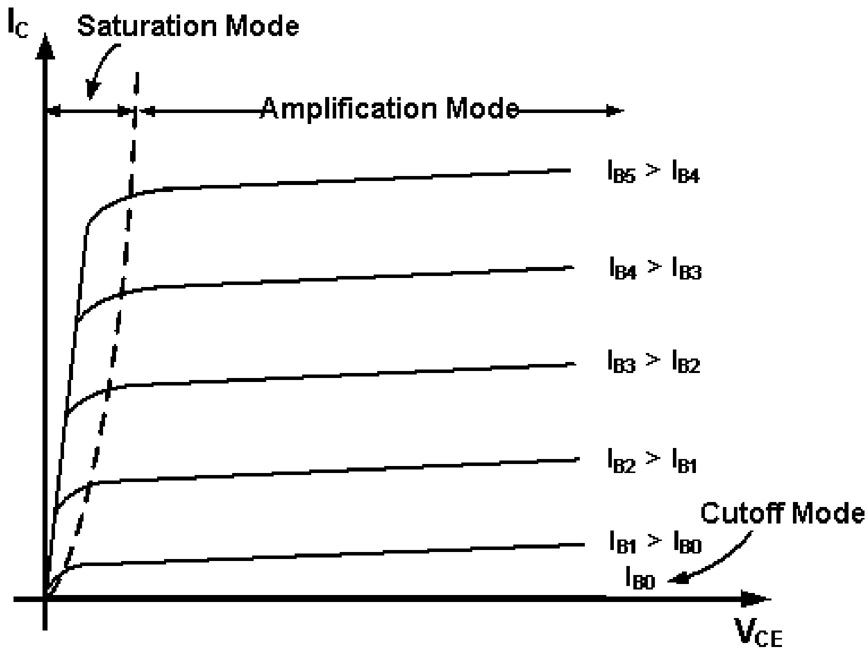

Figure 5: I_C as a function of V_{CE} for six different values of I_B with all three major regions labeled.

Similarly to an FET, a BJT has different properties depending on what region it is operating in. There are two major functions BJTs are used for that manifest in three major regions. Firstly, BJT can be used as a switch with an [ON] region and an [OFF] region. Secondly the BJT can be used as a Current controlled Current source in its Active region. The threshold from Saturation mode to Active mode can roughly be taken to be $V_{CE}(threshold) = 0.2V$. The characteristics of each region are outlined below.

1. Active Region: Acts as a current Amplifier, this is the most important region. $I_C = \beta I_B$ applies.
    - $I_B > 0$
    - $V_{CE} > 0.2V$

2. Saturation Region [ON]: Transistor is fully-on. Barrier potentials of the junctions cancel each other out causing a virtual short. $I_C = I_{Saturation}$
   - $I_B > 0$
   - $V_{CE} <= 0.2V$
3. Cut-Off Region [OFF]: Transistor is fully-off. Behaves like an open switch. $I_C = 0$
   - $I_B = 0$

2.2 BJT Constitutive Equations

$$I_E = I_B + I_C \tag{5}$$

$$V_{BE} \approx 0.7V \tag{6}$$

When in active region:

$$I_C = \beta I_B \tag{7}$$

$$I_C = \alpha I_E = \frac{\beta}{1+\beta} I_E \tag{8}$$

3 Op-Amps

3.1 What is an Operational Amplifier?

Operational Amplifiers are a widely used active electronic component that functions as a Differential Amplifier. Figure **??** has 5 labeled terminals, the $+V_S$ and $-V_S$ terminals are power sources for the OpAmp and are the upper and lower limits on V_{Out}, they are often omitted in circuit diagrams. V_+ and V_- are the input terminals which control V_{Out}. OpAmps function as voltage-controlled voltage sources, the Input Voltage is the difference in voltage of the input terminals: $(V^+ - V^-)$. The output voltage is also amplified from the input voltage, this is why it is considered a Differential Amplifier.

As a voltage controlled voltage source, the OpAmp needs characteristics of an ideal voltage reader and an ideal voltage source. Just like a Voltmeter, an OpAmp has extremely high input resistances on the + and - terminals. If it did not then it would draw current and alter the circuit it is reading voltage from! Similarly, the output impedance is extremely low so that the output

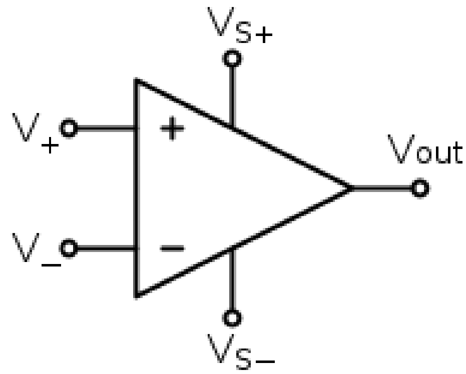

Figure 6: Operational Amplifier with labeled terminals.

current is determined by resistances after the output channel. Because of the high input impedance we assume they are infinite. For the real op amp the input currents are on the order of 10^{-7} amps, but in the ideal case we take $I_+ = I_- = 0$.

As previousy discussed, the input impedance across the input port is infinity, and the output impedance is zero. The output voltage is characterized by $V_{Out} = A(V_+ - V_-)$ where A is known as the open loop gain. In an ideal OpAmp $A \to \infty$, this also also implies that $V_+ \to V_-$. Both of these equations can be used in the case of an ideal OpAmp. For a real OpAmp, say model 741, A might be arround 300,000 with a maximum output current of $10mA$. It is straightforward to see that the power required for the input signals is orders of magnitude less than the power that can be controlled at the output. This is possible because the op amp is a powered circuit component, it requires a seperate set of inputs that supply power to the device.

3.2 Op-Amp Constitutive Equations

$$V_0 = A(V^+ - V^-)$$
$$I_+ = I_- = 0$$

$$A \to \infty$$
$$V_+ \to V_-$$