Transistor Characteristics

Introduction

Transistors are the most recent additions to a family of electronic current flow control devices. They differ from diodes in that the level of current that can flow through them is controlled by a control input (which unfortunately has different names in different devices) and in this sense they act like the control valves one might find in an hydraulic or pneumatic system. Indeed, the very first active devices consisted of systems of electrodes in an evacuated glass envelope and these were given the name "valves".

The detailed operation of these devices is not of interest in this module. Unlike water or gas which are fluids made of charge-neutral molecules, the moving particles (called electrons) that constitute an electric current carry an electric charge. In transistors and valves, control of flow is achieved by manipulating the electric field environment through which the electrons must travel in order to make it easier or harder for flow to occur. The devices are generally three terminal devices with one terminal common to the current flow path and the control input.

From an application point of view, transistors (and valves) are described by performance characteristics and there are two of these that are important in understanding device operation: The ***transconductance characteristic*** (the relationship between input control voltage and output (controlled) current) and the ***output characteristic*** (the relationship between output (controlled) current and the voltage across the current flow path terminals). After looking at transconductance and output characteristics in general terms, each of the three main transistor families will be introduced.

Transconductance characteristics

The transconductance characteristic of a transistor (or vacuum tube) is the relationship between the input (control) voltage to and the output (controlled) current through the device. It is a measure of the effectiveness of the control mechanisms within the device; a high value of transconductance means that small changes in the input (control) variable give rise to large changes in the output (controlled) variable.

Typical transconductance characteristics of a "bipolar junction transistor" (BJT), a "junction field effect transistor" (JFET) and an "enhancement mode MOSFET" are shown in figure 1a and relate to the circuits of figure 1b in which both the circuit symbol of each device and the variables used in figure 1a are given. I_C (I_D) is the controlled current and V_{BE} (V_{GS}) is the control voltage for the BJT (FET of either type). There are a few points to notice about the curves of figure 1a and the symbols of figure 1b.

(i) The transconductance curves are all basically the same shape - ie they all have some threshold after which the controlled current increases with increasing control voltage.

(ii) The BJT has a much steeper slope than the FETs - ie the control process is most effective with a BJT and least effective with a JFET.

(iii) The emitter (source) is the BJT (FET) terminal that is common to controlled current and control voltage.

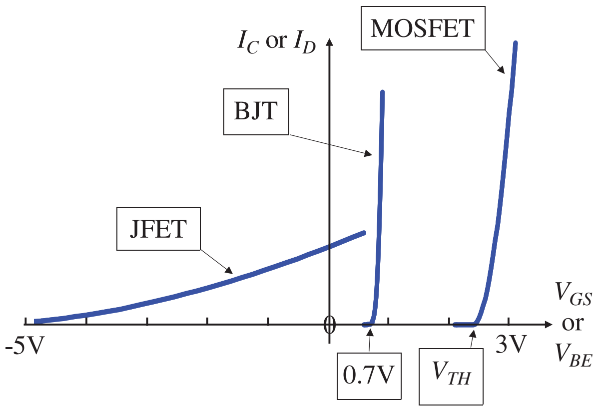

Figure 1a

Transconductance curves for a JFET, a BJT and a MOSFET.

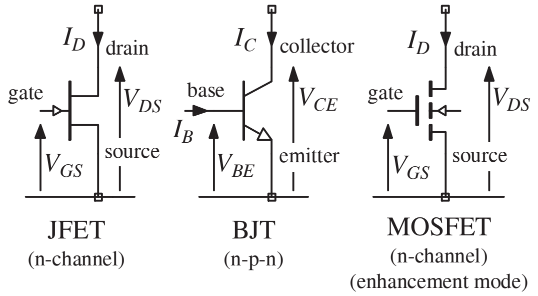

Figure 1b

The circuit symbols, terminal names and variable definitions for a JFET, a BJT and a MOSFET

(iv) The MOSFET has an extra terminal called the "substrate". In the majority of cases this is connected either to the source or to the most negative part of the circuit (ie the negative side of the power supply. Some MOSFETS, particularly power MOSFETS have source and substrate connected internally by the manufacturing process.

The slope of the transconductance characteristic is called the "transconductance" or "mutual conductance" of the device. It is given the symbol g_m and plays an important role in signal amplification.

Output Characteristics

The output characteristics are important because they indicate the degree of independence between output (controlled) current and the voltage difference imposed by the external circuit on the output terminals of the device. Transistors are often used as amplifiers or switches and in both applications a small input voltage change gives rise to a large change in voltage across the output terminals. Ideally the output (controlled) current will be determined entirely by the (control) input voltage.

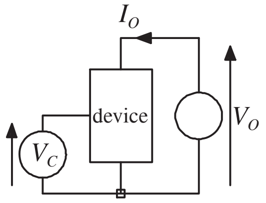

Figure 2a

definition of variables in the output characteristic of figure 2b.

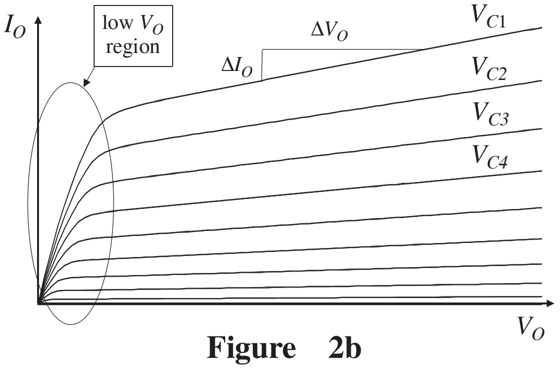

Figure 2b

A typical output characteristic. This one is for a JFET

Figure 2b shows an output characteristic typical of a transistor or vacuum tube labelled as "device" in figure 2a. The output characteristics usually take the form of a family of curves that show the V_O I_O relationship for a number of different control inputs, V_C. The slope of the output characteristic, $\Delta I_O/\Delta V_O$, is small and ideally zero; it depends mainly on device internal geometry. There is an obvious change in the behaviour at low values of V_O that arises because the insides of the device need a certain voltage across them before they start working as desired. The size of this low voltage region (which unfortunately has different names in different devices) is different for different device types and more detail is given in the discussion of each transistor type. There are a number of key points about output characteristics:

- **(i)** The output characteristic curves are all basically the same shape - they all have a low voltage region after which the controlled current is substantially independent of V_O.
- **(ii)** The BJT has a much smaller low voltage region than the FETs (a couple of hundred mV rather than a couple of V) and vacuum tubes.
- **(iii)** The slope of the output characterisic at high V_O increases with increasing I_O.

About the transistors

Three transistor types have been included in figure 1b. There are actually many more types of transistor in existence but most of these are variations designed for relatively specialised applications. The three already mentioned cover most application areas.

BJTs

BJTs are the oldest of the transistors. First demonstrated in 1949 it is now a very mature technology. Early devices were made of germanium and had maximum operating frequencies of about 10kHz. The frequency was limited by the technology, not the material. Silicon became the material of choice in the 1960s and by the end of that decade devices that would work up to 5GHz were becoming available. Bipolar transistors can now operate at frequencies in excess of 100GHz. Small signal transistors are designed to operate at currents of mA and a few 10s of volts whilst some power transistors can cope with 1000s A at around 1000V. Some transistors are made from materials other than silicon but most BJTs are made from silicon.

There are two main types of BJT structure; n-p-n and p-n-p, the names indicating the ordering of semiconductor material polarities (n-type or p-type) that make up the device. The BJT in figure 1b is an n-p-n structure in which a thin layer of p-type material (the base) is sandwiched between two layers of n-type material called the emitter and collector. (The p-n-p structure consists of a thin n-type base sandwiched between a p-type emitter and a p-type collector.) There is a p-n junction between base and collector and base and emitter. The base-collector junction is usually reverse biassed whilst the base-emitter junction is usually forward biassed. It is between the base and emitter that the control voltage is applied and this means that V_{BE} is always in the region of 0.7V.

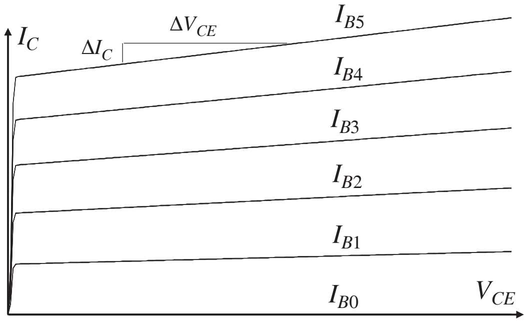

Figure 3

A BJT output characteristic.

The output characteristic of an n-p-n BJT is shown in figure 3. I_C is exponentially related to V_{BE} but is related to I_B by a constant, h_{FE}, called the "static current gain". Thus in output characteristic plots, base current (rather than base voltage) is increased in equal increments.

The thing to notice here is that the **collector current is mainly controlled by the base current (or base-emitter voltage)** although there is also a small dependence of I_C upon V_{CE}.

In other words as far as the circuit connected to the collector is concerned, the collector of the transistor looks like a Norton equivalent circuit with a current source (whose magnitude is controlled by I_B or V_{BE}) in parallel with a resistance $\Delta V_{CE}/\Delta I_C$.

The characteristics of a p-n-p transistor are shown in figure 4. Notice that the shapes are the same as those for the n-p-n but the characteristics have been rotated by 180° about their origins. The characteristics of p-n-p devices are sometimes described as complementary to those of n-p-n devices and pairs of devices with matched characteristic shapes are sometimes called "complementary pairs".

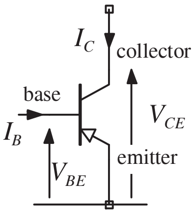

Figure 4a

The symbol for a p-n-p BJT. Note that the arrow on the emitter points towards the base.

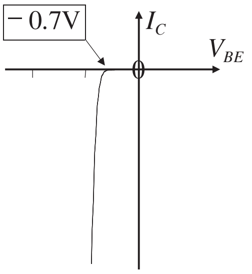

Figure 4b

The transconductance characteristic of a p-n-p BJT. Note that VBE is typically -0.7V

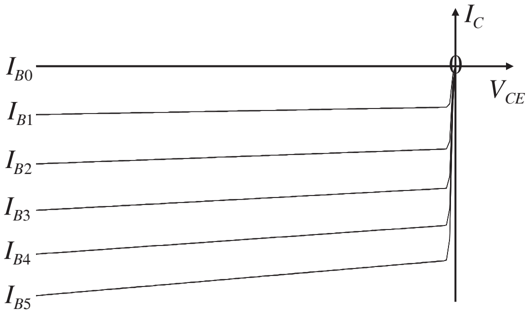

Figure 4c

The output characteristic of a p-n-p BJT. Note that I_{B1} to I_{B5} will be negative since I_B will be in a direction opposite to that shown in figure 4a.

The BJT differs from other transistors in that its transconductance characteristic is accurately defined by the behaviour of electrons in semiconductors and is relatively independent of device geometry. The relationship between I_C and V_{BE} is given by

$$I_C = I_{C0}\left(\exp\left(\frac{eV_{BE}}{kT}\right) - 1\right) \qquad \textbf{(1)}$$

For forward bias of the base emitter junction, the normal operating mode for amplifier applications, the exponential term is much larger than unity and equation **(1)** can be approximated by

$$I_C \approx I_{C0}\exp\left(\frac{eV_{BE}}{kT}\right). \qquad \textbf{(2)}$$

The dc or static current gain of the transistor is usually written symbolically as h_{FE} and is simply the ratio of collector to base current. h_{FE} is slightly dependent on I_C, being lower at the extremes of low and high I_C than it is for middle values of I_C. h_{FE} is very dependent on process variations and geometry (particularly the base layer thickness) and a range of 100 to 400 is not unusual in BJTs of the same nominal type designed for small signal amplifier applications. The relationship between I_C, I_B and h_{FE} is

$$h_{FE} = \frac{I_C}{I_B} \qquad \textbf{(3)}$$

Summing currents into the BJTs in both figures 1b and 4a leads to $I_B + I_C = I_E$ where I_E is the current flowing out of the emitter of the BJT. Since I_C is typically very much greater than I_B, this relationship can usually be approximated by $I_C \approx I_E$.

MOSFETS

MOSFETS (the name is an acronym made from Metal-Oxide-Semiconductor Field Effect Transistors) first appeared in the mid 1960s as small signal amplifiers and as small scale logic ICs but really took off at the end of the 1970s when the power MOSFET appeared. Power MOSFETS offered qualities that made them attractive alternatives to BJTs in many switching applications - especially in the 100s kHz range. Also in the late 1970s, MOSFETS entered the computer processor and memory arena in the form of large scale integrated circuits. They now dominate the computer arena.

The control electrode of a MOSFET is called the "gate", a metallised rectangle on the surface of the semiconductor that is insulated from it by a thin layer of insulator (usually silicon dioxide). This means that in principle no current is drawn through the control input and the device is a true field effect device. In practice there is always a tiny current, usually of the order of pA, flowing into the control input because no insulator is perfect. A conducting channel is induced on the surface of the semiconductor underneath the gate by applying a postive voltage to the gate with respect to the source, V_{GS}. One end of the gate overlaps the drain and the other overlaps the source and the channel, when formed, connects drain and source and forms the controlled current path. The channel begins to form at a particular V_{GS} known as the "threshold voltage" V_{TH}, and gets wider (more conductive) as V_{GS} increases above V_{TH}.

The output characteristics of MOSFETs are very similar in appearance to those of BJTs. They are usually plotted in the form of a family of curves of drain-source current, I_D, against drain-source voltage, V_{DS}, for a number of equal increments in the control input, V_{GS}, as shown in figure 5. The voltage increments have been added here to show the effect of threshold voltage - nothing happens in this particular MOSFET until V_{GS} gets somewhere between 2V and 2.5V. Other MOSFETS would have a different V_{TH} so activity would start at a different V_{GS}. The effect of V_{TH} can also be seen on the transconductance characteristic of figure 1a. The main difference between the characteristics of the BJT (figure 3) and the MOSFET (figure 5) is that in figure 5 the region at low V_{DS} where I_D is very dependent on V_{DS} extends over a couple of volts whereas in figure 3 this region extends typically over tens of mV to a couple of hundred mV.

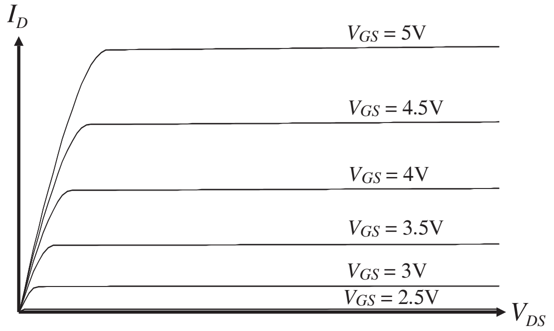

Figure 5

The output characteristics of a MOSFET

The slope of the characteristic at high V_{DS} is a function of the geometrical design of the MOSFET and a wide range of slopes can be observed from different devices. The Norton model of controlled current source in parallel with a large resistor that represents the behaviour of a BJT collector is also appropriate to model the behaviour of the drain of a MOSFET.

As for BJTs, there are two main types of MOSFET; n-channel and p-channel. The p-channel device is the complement of the n-channel device and the relationship between the characteristics of n-channel and p-channel MOSFETS is similar to that between n-p-n (shown in figures 1a and 3) and p-n-p (shown in figures 4b and 4c) BJTs. The symbol for a p-channel MOSFET is shown in figure 6 - note that the arrowhead on the substrate

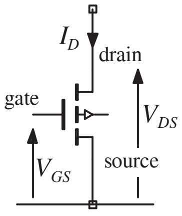

Figure 6

The symbol for a p-channel MOSFET .

connection points away from the p-channel.

The MOSFET is governed by a square law transconductance equation rather than the exponential law that governs a BJT. The drain current is given by

$$I_D = a(V_{GS} - V_{TH})^2 \tag{4}$$

"*a*" is a constant set mainly by device geometry. The square law relationship of equation **(4)** is much less steep than the exponential relationship for a BJT and this is why the MOSFET has a lower transconductance per unit device area than the BJT. The notion of current gain is meaningless in the context of a MOSFET because input current is ideally zero. When the MOSFET is fully conducting and the drain source voltage is close to zero, the device behaves like a resistance, $r_{DS\,ON}$, whose value (which is specified by manufacturers for devices designed for switching applications) depends upon device geometry.

JFETs

Although JFETs (the name comes from Junction Field Effect Transistor) were conceived before BJTs, technological difficulties delayed their realisation for a decade after the invention of the BJT. The terminal names are the same for the JFET as for the MOSFET (except that JFETs would not normally have a substrate connection). The JFET consists of a layer of semiconductor (the channel) with drain at one end and source at the other. If the channel is n-type, the gate is a p-type deposition on the channel surface, placed between source and drain, and thus the gate-channel combination forms a p-n junction. A V_{GS} of zero, gives maximum channel conductivity and reverse biassing the gate with respect to the source reduces the channel conductivity.

The reverse biassed gate-source junction control modality gives the JFET a high gate source resistance. The transconductance is low (see figure 1a) so getting high circuit gains is difficult. Parameter spread between devices of the same type is large and this makes circuit design a relatively difficult process. As discrete devices JFETs are now only used in specialised applications but they are often used as the input transistors in IC amplifiers where their high input impedance and relative (to a MOSFET) insensitivity to static electricity are attractive.

The JFET is governed by a square law transconductance relationship similar in nature to the MOSFET but with a different constant. Its output characteristics are qualitatively similar to the MOSFET and the BJT and the drain can be modelled using a Norton circuit. As for MOSFETS, both p-channel and n-channel devices exist, the characteristics of the two types having the same relative properties as those of the two BJT or MOSFET polarities. The symbol for a p-channel JFET is the same as the n-channel one except that the arrowhead direction is reversed. Occasionally a JFET symbol in which the arrowhead is on the source lead is used. In such cases, the arrowhead points away from the gate for the n-channel device and towards the gate for the p-channel device.

Vacuum tubes

Vacuum tubes are now used only in very specialised areas; guitar amplifiers, high end audio systems, high power (10kW to MW) continuous wave and pulsed radio frequency and microwave sources for communications and long range RADAR systems. From a characteristic point of view the signal amplifying types used in audio applications behave in a very similar way to JFETs except that whereas JFETs require a supply voltage of around 10V to 20V, tubes require a couple of hundred volts.