CHAPTER 2
LOGIC DEVICES

As an aviation electronics technician (AT) in the U.S. Navy today, you have to understand solid-state devices if you are to become proficient in the use, maintenance, and repair of electronic equipment. Both analog and digital circuits are used in this chapter. First, semiconductor theory is covered to give you an overview of their operation and application. Then, transistor fabrication and integrated circuits (ICs) are discussed to give you an insight into the manufacturing methods. The functions of some ICs are discussed in detail to give you a working knowledge of their uses.

LEARNING OBJECTIVES

When you have completed this chapter, you will be able to do the following:

1. Describe the basic operation of a semiconductor diode.
2. Identify the different types of transistor configurations.
3. Recall the basic concepts of transistor theory and the operation of transistors.
4. Describe the purpose and use of thyristors.
5. Describe the purpose, fabrication, and operation of ICs.
6. Describe the purpose and use of transistor-transistor logic (TTL).

SEMICONDUCTORS

Semiconductors have electrical properties somewhere between those of insulators and conductors. The use of semiconductor materials in electronic components is not new. Some devices are as old as the electron tube. Two of the most widely known semiconductors in use today are the junction diode and transistor. These semiconductors fall under a more general heading called solid-state devices. A solid-state device is nothing more than an electronic device that operates by virtue of the movement of electrons within a solid piece of semiconductor material.

Since the invention of the transistor, solid-state devices have been developed and improved at an extremely high rate. Great strides have been made in the manufacturing techniques, and there is no foreseeable limit to the future of these devices. Solid-state devices made from semiconductor materials offer compactness, efficiency, ruggedness, and versatility. Consequently, these devices have permeated virtually every field of science and industry. In addition to the junction diode and transistor, a whole new family of related devices has been developed, including thyristors and field-effect transistors. One development that has dominated solid-state technology, and probably has had a greater impact on the electronics industry than either the electron tube or transistor, is the IC. The IC is a minute piece of semiconductor material that can produce complete electronic circuit functions.

Semiconductor devices are all around us. They can be found in just about every commercial product you touch, from the family car to the smart phone. Semiconductor devices are contained in television sets, portable radios, stereo equipment, and much more. Science and industry also rely heavily on semiconductor devices. Research laboratories use these devices in all sorts of electronic instruments to perform tests, measurements, and numerous other experimental tasks. Industrial control systems (such as those used to manufacture automobiles) and automatic telephone exchanges also use semiconductors. Even today, heavy-duty versions of the solid-state rectifier diode are being used to convert large amounts of power for electric railroads. Of the many different applications for solid-state
devices, space systems, computers, and data processing equipment are some of the largest consumers.

Various types of modern military equipment are literally loaded with semiconductor devices. Radar, communication, and navigation systems all contain solid-state equipment. Data display systems, data processing units, computers, and aircraft guidance-control assemblies are also good examples of electronic equipment that use semiconductor devices. All of the specific applications of semiconductor devices make a long, impressive list.

**Junction Diode**

If you join a section of positive (P)-type (positively charged, holes) semiconductor material with a similar section of negative (N)-type (negatively charged, electrons) semiconductor material, you obtain a device known as a positive/negative (PN) junction. The junction diode, referred to as a diode, is nothing more than a two-element semiconductor device that makes use of the rectifying properties of a PN junction to convert alternating current (ac) into direct current (dc) by permitting current flow in only one direction. In addition, they have special properties that make them particularly useful for bias and voltage stabilization. A diode is normally identified as a crystal rectifier (CR) on schematic drawings. If only one diode is on the drawing, it is labeled CR1. The symbol of a diode is shown in Figure 2-1. The heavy, dark line shows electron flow. Notice it is against the arrow. For further clarification, a pictorial diagram of a PN junction and an actual semiconductor (one of many types) is also illustrated.

Because diodes can be made of the same material as the transistor and have the same temperature coefficient and resistance, they will efficiently operate over the same temperature range, providing nearly ideal thermal compensation. Likewise, application of the avalanche breakdown phenomena provides a special voltage-stabilizing (zener) diode.

The junction diode has four important ratings that must be taken into consideration when used in a power supply. They are the maximum:

- Average forward current
- Repetitive reverse voltage
- Surge current
- Repetitive forward current

These ratings are important to you, as a technician, when it becomes necessary to troubleshoot a power supply or select junction diodes for replacement if the desired one is not readily available.

The maximum average forward current is the maximum amount of average current that can be permitted to flow in the forward direction. This rating is usually given for a specified ambient temperature and should not be exceeded for any length of time because damage to the diode will occur.

![Figure 2-1 — The PN junction diode.](image-url)
The maximum repetitive reverse voltage is that value of reverse bias voltage that can be applied to
the diode without causing it to break down.

The maximum surge current is that amount of current allowed to flow in the forward direction in
nonrepetitive pulses.

The repetitive forward current is that value of forward bias voltage that can be applied to the diode
without causing it to break down.

All of the ratings mentioned above are subject to change with temperature variations. If the
temperature increases beyond normal operating parameters, the ratings given on the specification
sheet may not be accurate.

Transistors

Semiconductor devices that have three or more
elements are called transistors. The term
“transistor” was derived from the words transfer
and resistor. A transistor is an active component
of an electronic circuit that may be used as an
amplifier, detector, or switch. There are many
different types of transistors (Figure 2-2), but their
basic theory of operation is all the same. The
operation of a transistor is similar to the operation
of a diode except that now two such PN junctions
are required to form the three elements of a
transistor. The two-junction transistor has three
elements: the emitter, which gives off, or emits,
current carriers (electrons or holes); the base,
which controls the flow of current carriers; and the
collector, which collects the current carriers.

This term was adopted because it best describes
the operation of the transistor—the transfer of an
input signal current from a low-resistance circuit to
a high-resistance circuit. Basically, the transistor is a solid-state device that amplifies by controlling
the flow of current carriers through its semiconductor materials. Transistors are of two general types;
bipolar and field-effect. The bipolar type involves excess minority current carrier injection. The field-
effect type involves only majority current carriers. Historically, the bipolar type was developed before
the field-effect type; both are widely used today. An unmodified transistor usually refers to the bipolar
type.

Bipolar Transistor

In a bipolar transistor, at least one contact is ohmic (nonrectifying), and at least one contact is
rectifying. Usually, there are two closely spaced rectifying contacts and one ohmic contact.

The operation of a simple transistor consists of the control of the current flowing in the high-resistance
direction through one rectifying contact (called the collector) by the current flowing in the low-
resistance direction in the other rectifying contact (called the emitter). The third contact, which is
ohmic, is called the base contact.

These contacts usually consist of two or more regions. The regions in which the actual rectification
processes take place are called the emitter barrier and collector barrier. The region between these
two barriers is called the base region, or simply the base. The regions outside these barriers are called the emitter and collector regions.

**Classification of Transistors**

Transistors are classified chiefly by four criteria: (1) the type and number of structural regions of the semiconductor crystal; (2) the technology used in fabrication; (3) the semiconductor material used; and (4) the intended use of the device. A typical designation following this scheme would be negative/positive/negative (NPN) double-diffused silicon switching transistor. It is not necessary to include all of the above criteria in a single designation or to rigidly follow this order.

A common transistor type is the NPN double-diffused silicon planar passivated transistor (Figure 2-3). The term “double-diffused” refers to the fabrication technique in which the base region is formed by diffusion through a mask into the body of the silicon wafer, which forms the collector region. In turn, the emitter region is formed by diffusion through a second mask into the previously formed base region. The term “planar” refers to the fact that all three electrical connections are found on a single surface of the device. The term “passivated” means that the surface to which all junctions return is protected by a layer of naturally grown silicon oxide, which, together with an overcoating of glass or other inert material, passivates the surface, electrically minimizing leakage currents. The double-diffusion process allows very close control of narrow base widths. The base diffusion provides a resistivity gradient in the base region, which has an associated electric field. In this field, charge transport is by drift. Such transistors have been called drift transistors to distinguish them from most other transistors in which the charge transport is by a diffusion process. Silicon planar transistors have power ratings in the 100 milliwart (mW) to 50 watt (W) range with characteristic frequencies between 50 and 2,000 megahertz (MHz), usually of the NPN type. The designation NPN stands for the conductivity type of the emitter, base, and collector regions, respectively. The n stands for negative because the charge on an electron is negative, and electrons carry most of the current in a region of N-type conductivity. In a region of P-type conductivity, most of the current is carried by electron vacancies called holes, which behave as if they were positively charged.

A historically important type was the NPN alloy-junction germanium transistor. This type was widely used in the first decade of the solid-state electronics era. The term “alloy-junction” in this transistor designation refers to the fabrication method. The emitter and collector regions were produced by recrystallization from an alloy of some suitable metal infused with a P-type impurity to increase current flow efficiency. The process of adding these impurities to crystals is referred to as “doping.” When the alloy that had previously been infused made contact with the opposite surfaces of the original N-type semiconductor body, it dissolved some of the semiconductor material and its junction was fused. Fused-junction is equivalent terminology. A wide variety of transistors are made depending on the desired application, function, and power requirements.

**Transistor Action**

To explain transistor action in more detail, some of the basic properties of a semiconductor material are presented first. As previously discussed, an N-type semiconductor contains electrons, and a P-type semiconductor contains holes. These electrons and holes are called the majority carriers of the two types. Actually, a small number of holes are always present in N-type semiconductors, and a small number of electrons are always present in P-type semiconductors. These electrons and holes are called the minority carriers of the two types. At a given temperature with a given material, the product of the densities of the majority and minority carriers is a constant. This means that if there is a high density of majority carriers (low-resistivity material) present, there will be a correspondingly low density of minority carriers.
The emitter current controls the collector current in a simple NPN transistor. To understand this concept, first consider the magnitude of the collector current in the absence of emitter current. In normal operation, the collector barrier is biased in the high-resistance (reverse) direction. Under this condition of bias, the majority carriers are stopped by the barrier, and only the minority carriers are free to flow. If the collector barrier is a silicon PN junction, the minority-carrier diffusion current is negligible, and the reverse-bias leakage current will consist of thermally generated carriers and be in the nanoampere range. If emitter current is present, the portion consisting of carriers entering the base will continue across the collector barrier, and thus control the collector current.

**Injection**

The emitter controls the density of minority carriers by injecting extra minority carriers into the base region when the emitter is biased in the low-resistance (forward) direction. This is the fundamental process of simple transistor action. Whenever a rectifying barrier is forward-biased, extra minority carriers are added to the semiconductor near the barrier. Because the source of these minority carriers is the majority-carrier density on the other side of the barrier, it is clear that the largest part of the forward current will be carried by those carriers that come from the largest majority density. A PN junction will have a high injection efficiency for electrons if the n region has a much larger density of carriers (lower resistivity) than the p region. Therefore, in the NPN transistor, the emitter n region should have a low resistivity compared to the P-type base region. Also, the phenomenon of minority-carrier injection is observed in rectifying metal semiconductor contacts, and such contacts may be used as emitters as well as PN junctions.
Current Gain

The current gain of a simple transistor may be expressed as the product of three factors: (1) the fraction \( \gamma \) (gamma) of the emitter current earned by the injected carriers, (2) fraction \( \beta \) (beta) of the injected carriers that arrive at the collector barrier, and (3) the current multiplication factor \( \alpha^* \) (alpha) of the collector. For a double-diffused transistor, typical values of these factors are \( \gamma = 0.985 \), \( \beta = 0.999 \), and \( \alpha^* = 1.000 \), giving \( \alpha = 0.984 \). From these values you can see that most of the current that flows into the emitter flows right on through the base region and out the collector, while only a small fraction (here 0.016) flows out the base connection.

For a fixed value of emitter current \( I_e \) there is a fixed value of collector current \( (\alpha I_e) \) added to the collector-barrier leakage current \( I_{co} \), giving a total collector current, \( I_c = I_{co} + \alpha I_e \). This means that the slope of the dc characteristics should be the same as the slope of the collector-barrier leakage current curve for \( I_e = 0 \). The typical characteristics shown in Figure 2-4, views A and B, illustrate collector and emitter leakage current, respectively. The slope of the collector leakage curve is very low because the collector voltage does not influence the relatively fixed number of minority carriers carrying the current.

![Figure 2-4 — Transistor dc characteristics.](image)

High-Frequency Effects

High-frequency effects originate in three distinct properties of transistors: the transit time of injected carriers across the base region, the charging time of the collector- or emitter-barrier capacitance through the base region and collector-region resistance in series, and the time required to build up the proper density of injected carriers in the base region (called storage-capacity effect). In alloy-junction transistors with a base region of uniform resistivity, the transport of injected carriers across the base is usually the limiting factor. Base transit time alone (Figure 2-5, view A) introduces only a phase shift between the emitter and collector signals (Figure 2-5, view B), but this time also gives a chance for injected carriers, bunched by the emitter signal, to diffuse apart, and therefore degrade the signal.

In double-diffused (drift) transistors, the base transit time is usually negligible compared to the charging time of the collector or emitter capacitance. In some units, the storage capacity (often called diffusion capacity) seems to be an appreciable limitation.

Storage capacity also shows up in another way in transistors used as switches. Here it introduces a time delay in both turning on and turning off the transistor. The turn-off delay is usually longer than
the turn-on delay because the density of injected carriers in the base region has had time to build up
to large values during the time the transistor was on, and therefore takes a long time to subside to the
level where the transistor can turn off. These delays are only slightly related to the actual time of rise
or fall of the collector level, which is determined primarily by the collector-capacitance base-
resistance time constant.

To minimize the storage capacity effects in high-speed transistors, a fabrication technique called
epitaxial growth is used. In this process, a transistor structure is formed entirely in a thin skin of good
semiconductor material grown upon the surface of a wafer of heavily doped material. The heavily
doped material has low lifetime for excess carriers and, therefore, a low storage effect, as well as a
low series resistance. The collector junction of such a transistor is close to this low-lifetime material
but is formed in the high-quality, epitaxially grown skin so that its properties are not degraded by the
heavily doped material. Such transistors are called epitaxial transistors.

Close control of the injection ratio $\gamma$, is afforded by the fabrication technique of ion implantation. In this
technique, a beam of ions composed of the desired dopant material is accelerated to a specific kinetic
energy and caused to strike the surface of the region to be doped. The ions penetrate the surface and
remain embedded in the semiconductor material. By controlling the ion-beam current and the time of
bombardment, a very accurate control of the total number of dopant ions in the region is achieved.
After heating the semiconductor to diffusion temperature, the ions move on into the material, creating
the emitter and base regions of the double-diffused structure. These regions now have precisely
controlled doping, and hence, show a $\gamma$-factor within $\pm1$ percent of the design value.

Transistor Noise

Noise is quite low if low source impedance is used. With source impedances of about 1,000 ohms, a
good junction transistor will have a noise factor of about 4 decibels (dB). The noise factor is
independent of the connection but rises with source impedances above 10,000 ohms and with
frequencies below 1,000 Hz.
Temperature Effects

Temperature effects are most often marked in connection with the collector-barrier leakage current with no emitter current flowing $I_{co}$. This current increases exponentially with temperature and leads to a phenomenon called “thermal runaway.” If a transistor is operated at a given ambient temperature and a given initial power dissipation, this power will soon raise the temperature of the collector barrier, which then draws more current, and, in turn, increases the dissipation. The process is cumulative, and precautions must be taken to stabilize against it. Current gain increases slightly with increased temperature in most NPN transistors, but this gain is a small effect unless the current gain is unusually close to unity.

Power Switching

Several transistor structures are that are used for power switching also make use of current gains greater than unity. This type of device, is commonly called the thyristor, is discussed later in this chapter. These devices are often called “four-layer” devices because they usually contain four regions of alternating N- and P-type semiconductor material. Connections are made to the end regions and to one of the interior regions. The end regions are oppositely biased so that the center junction is reverse-biased. The connection to the interior region is then the control and is usually called the “gate.” When the gate is biased to cause injection of excess carriers across the junction between it and the nearest end connection, the device is triggered on, and a saturation current is drawn between the two end connections, normally called anode and cathode. Such devices are normally classified as rectifiers, but, in reality, they are a form of transistor.

Field-Effect Transistor

In contrast to the bipolar transistor, which uses bias current between base and emitter to control conductivity, the field-effect transistor (FET) uses voltage to control an electrostatic field within the transistor. There are two major types of field-effect transistors—the junction-gate FET (JFET) and the insulated-gate FET (IGFET). The IGFET is more commonly known as a metal-oxide-semiconductor (MOS) FET, MOSFET, or MOS transistor, which describes, in order, the structure of the device from the gate toward the channel. The JFET, developed first because it involved no technology beyond that of the planar bipolar silicon transistor, functions similar to a voltage-controlled vacuum tube. The MOSFET is used in applications that require high input impedance combined with high current gain, such as amplifiers, mixers, and test equipment.

Junction Field-Effect Transistor

A cross-section of a JFET is shown in Figure 2-6, view A. The channel consists of relatively low-conductivity semiconductor material sandwiched between two regions of high-conductivity material of opposite type. When these junctions are reverse-biased, the junction depletion regions encroach upon the channel, and finally, at a high reverse bias, pinch it off entirely. The thickness of the channel, and hence its conductivity, is controlled by the voltage on the two gates. Therefore, this device is normally on and may be switched off. It is called a “depletion-mode” FET. In practice, this FET has an input impedance several orders of magnitude greater than that of a silicon bipolar transistor. JFETs are made in both N- and P-channel types. They are used in amplifiers, oscillators, mixers, and switches. The general performance limits are about 500 MHz, 1 W, 100 volts (V), and 100 milliamps (mA) (saturation drain current). They also find application in ICs employing bipolar transistors because their technology is compatible.
A cross-section of a MOSFET is shown in Figure 2-6, view B. Here the source and drain regions consist of n diffusion in a P-type substrate. The gate is a metal film evaporated on a thin silicon dioxide (SiO₂) insulator spanning the separation between the source and drain. With no voltage on the gate, the source and drain are insulated from each other by their surrounding junctions. When a positive voltage is applied to the gate, electrons are induced to move to the surface of the P-type substrate immediately beneath the gate, producing a thin surface of induced N-type material, which now forms a channel connecting the source and drain. Such a surface layer is called an inversion layer because it is of opposite conductivity type to the substrate. The number of induced electrons is directly proportional to the gate voltage, so that the conductivity of the channel increases with gate voltage. This device is called an N-channel enhancement-mode MOSFET. It is normally off at zero gate voltage.

Because of the quality of the SiO₂ gate insulator, the input impedance of a MOSFET is several orders of magnitude greater than that of a JFET. Typical MOSFET dc characteristics are shown in Figure 2-7. The low-drain voltage channel resistance is inversely proportional to \((V_{gs} - V_{th})\), where \(V_{gs}\) is the gate source voltage and \(V_{th}\) is the threshold voltage, and the saturation drain current is proportional to \((V_{gs} - V_{th})^2\).

MOSFET devices are fabricated in both P- and N-channel types, as well as for both depletion (normally on) and enhancement (normally off) modes of operation. In a MOSFET, the mode of operation is determined by a threshold voltage of the gate at which the device changes from off to on, or vice versa. In modern technology, this threshold voltage can be set for a wide range of values by the use of ion implantation through the gate oxide.

MOSFET discrete devices are used for ultrahigh-input impedance amplifiers, such as electrometers where the input leakage current is less than \(10^{-14}\) amps (A). Dual-gate depletion types can be used as mixers up to 1,000 MHz, and power-switching types are good to 25 W, 2 A, or 100 V. Most integrated circuits using MOSFETs are called complementary metal-oxide-
semiconductor (CMOS) integrated circuits. These circuits use N- and P-channel types together to achieve digital logic. Typical propagation delay time through small-scale integrated (SSI) building-block circuits is about 20 nanoseconds (ns) for a 20-picofarad load. At a 100 MHZ clock rate, the power dissipation for such a gate is about 10 mW. For large-scale integration, typical 16-kilobit random-access memory has an access time as low as 20 ns, an active power of 500 mW, and a standby power of 20 mW. Technological advances have dramatically decreased access times and power consumption even beyond these parameters.

There are a number of variations of the MOS technology. Two of particular interest are the VMOS (V for vertical) and silicon on sapphire (SOS). The VMOS device is fabricated by etching a notch down through a planar double-diffused structure similar to that of an NPN bipolar transistor. The surface of the notch is first oxidized and then covered with the gate metallization. The source contact bridges the n+-p junction near the surface, and the drain connection corresponds to the collector contact of the bipolar structure. The channel length is now determined by the thickness of the p region allowing short channels and gives both high-current and high-voltage capability.

The SOS device is fabricated in a very small silicon body grown epitaxially on a sapphire substrate. MOS/SOS 64,000-bit memory has shown a standby power of only 1 microwatt.

Transistor Manufacture

The manufacture of transistors has required a whole new field of exacting technology. Good semiconductor material requires the maintenance of chemical purities far beyond the spectroscopic range. A few years ago a purity of 1 part in $10^6$ was not unusual. Today, raw materials slated for use in the semiconductor manufacturing process start at a purity level greater than 99.9999 percent. Electronic-grade silicon (EGS) or semiconductor-grade silicon (SGS) contains individual impurity levels in the parts per billion (ppb) range, with gold being near the smallest at less than 0.00001 ppb. Most devices must be made from oriented single crystals of semiconductor material and are highly susceptible to the effects of structural defects caused by impurities during the growth process.

Physical tolerances of the high-frequency transistor structures are microscopic; the separation of emitter and collector junctions must be of the order of a few nanometers in these units. In fact, it is possible for more than 30 million transistors to fit on a pin head in some microcomputer applications.

To solve these problems new techniques have appeared. Purity is achieved by melting a small zone of a bar, or ingot, and gradually passing this molten zone from one end of the bar to the other. Impurities in the material remain in the liquid phase and are earned along with the molten zone, leaving high-purity material behind.

Tolerances are achieved by a collection of new techniques, such as epitaxial growth, solid-state diffusion, ion implantation, and the photolithographic delineation of diffusion masks.

Transistor Configurations

It is important for you to understand the method of connecting a transistor into a circuit. Bipolar transistor connections and FET connections are discussed in the following text.

Bipolar Transistor Connections

A transistor may be connected in any one of three basic configurations (Figure 2-8): (1) common emitter, (2) common base, and (3) common collector. The term “common” is used to denote the element that is common to both input and output circuits. Because the common element is often grounded, these configurations may be referred to as grounded emitter, grounded base, and grounded collector.
Each configuration has particular characteristics that make it suitable for specific applications. An easy way to identify a specific transistor configuration is to follow two simple steps: (1) Identify the element (emitter, base, or collector) to which the input signal is applied, (2) Identify the element (emitter, base, or collector) from which the output signal is taken. The remaining element is the common element and gives the configuration its name.

**Common-Emitter Configuration**

The common-emitter configuration shown in Figure 2-8, view A is the arrangement most frequently used in practical amplifier circuits because it provides good voltage, current, and power gain. The common emitter also has a somewhat low input resistance (500 to 1,500 ohms) because the input is applied to the forward-biased junction and has a moderately high output resistance (30 to 50 kilohms or more), and because the output is taken off the reverse-biased junction. Because the input signal is...
applied to the base-emitter circuit and the output is taken from the collector-emitter circuit, the emitter is the element common to both input and output.

When a transistor is connected in a common-emitter configuration, the input signal is injected between the base and emitter, which is a low-resistance, low-current circuit. As the input signal swings positive, it also causes the base to swing positive with respect to the emitter. This action decreases forward bias, which reduces collector current \( I_c \) and increases collector voltage \( V_c \) making \( V_c \) more negative. During the negative alternation of the input signal, the base is driven more negative with respect to the emitter increasing forward bias and allowing more current carriers to be released from the emitter. The result is an increase in collector current and a decrease in collector voltage (making \( V_c \) less negative or swing in a positive direction). The collector current that flows through the high-resistance, reverse-biased junction also flows through a high resistance load, resulting in a high level of amplification.

Because the input signal to the common emitter goes positive when the output goes negative, the two signals (input and output) are 180 degrees out of phase. The common-emitter circuit is the only configuration that provides a phase reversal.

The common emitter is the most popular of the three transistor configurations because it has the best combination of current and voltage gain. The term “gain” is used to describe the amplification capabilities of the amplifier. It is basically a ratio of output versus input. Each transistor configuration gives a different value of gain, even though the same transistor is used. The transistor configuration used is a matter of design consideration. However, as a technician, you will become interested in this output-versus-input ratio (gain) to determine whether or not the transistor is working properly in the circuit.

The current gain in the common-emitter circuit is called “beta” (\( \beta \)). Beta is the relationship of collector current (output current) to base current (input current). To calculate beta, use the following formula:

\[
\beta = \frac{\Delta I_c}{\Delta I_b} \quad (\Delta \text{ is the Greek letter delta; it is used to indicate a small change})
\]

For example, if the input base current \( I_b \) in a common emitter changes from 75 to 100 microamps (\( \mu A \)) and the output current \( I_c \) changes from 1.5 to 2.6 mA, the current gain (\( \beta \)) will be 44:

\[
\beta = \frac{\Delta I_c}{\Delta I_b} = \frac{11 \times 10^{-3}}{25 \times 10^{-6}} = 44
\]

This simply means that a change in base current produces a change in collector current that is 44 times as large.

The resistance gain of the common emitter can be found in a method similar to the one used for finding beta:

\[
R = \frac{R_{out}}{R_{in}}
\]

Once the resistance gain is known, the voltage gain is easy to calculate because it is equal to the current gain \( \beta \) multiplied by the resistance gain \( (E = \beta R) \). Also, the power gain is equal to the voltage gain multiplied by the current gain \( \beta \) \( (P = \beta E) \).

**Common-Base Configuration**

The common-base configuration shown in Figure 2-8, view B is mainly used for impedance matching because it has a low input resistance (30 to 160 ohms) and a high output resistance (250 k to 550 kilohms). However, two factors limit its usefulness in some circuit applications: (1) its low input resistance and (2) its current gain of less than 1. Because the common-base configuration will give
voltage amplification, there are some additional applications, which require both a low input resistance and voltage amplification, that could use a circuit configuration of this type, for example, some microphone amplifiers.

In the common-base configuration, the input signal is applied to the emitter-base, the output is taken from the collector-base, and the base is the element common to both input and output. Because the input is applied to the emitter, it causes the emitter-base junction to react in the same manner as it did in the common-emitter circuit. For example, an input that aids the bias will increase transistor current, and one that opposes the bias will decrease transistor current.

Unlike the common-emitter circuit, the input and output signals in the common-base circuit are in phase. To illustrate this point, assume the input to the NPN version of the common-base circuit in Figure 2-8, view B is positive. The signal adds to the forward bias because it is applied to the emitter, causing the collector current to increase. This increase in $I_c$ results in a greater voltage drop across the load resistor $R_L$, thus lowering the collector voltage $V_c$. The collector voltage, in becoming less negative, is swinging in a positive direction and is therefore in phase with the incoming positive signal.

The current gain in the common-base circuit is calculated in a method similar to that of the common emitter except that the input current is $I_E$, not $I_B$, and the term “alpha” ($\alpha$) is used in place of beta for gain. Alpha is the relationship of collector current (output current) to emitter current (input current). Alpha is calculated using the formula:

$$\alpha = \frac{\Delta I_c}{\Delta I_e}$$

For example, if the input current ($I_e$) in a common base changes from 1 to 3 mA and the output current ($I_c$) changes from 1 to 2.8 mA, the current gain ($\alpha$) will be 0.90, or:

$$\alpha = \frac{\Delta I_c}{\Delta I_e} = \frac{18 \times 10^{-3}}{2 \times 10^{-3}} = 0.90$$

This is a current gain of less than 1.

Because part of the emitter current flows into the base and does not appear as collector current, collector current will always be less than the emitter current that causes it. (Remember that $I_e = I_B + I_c$.) Therefore, alpha is always less than 1 for a common-base configuration.

Many transistor manuals and data sheets only list transistor current gain characteristics in terms of beta. To find alpha when given beta, use the following formula to convert beta to alpha for use with the common-base configuration:

$$\alpha = \frac{\beta}{\beta + 1}$$

To calculate the other gains (voltage and power) in the common-base configuration when the current gain alpha is known, follow the procedures described earlier under the common-emitter section.

**Common-Collector Configuration**

The common-collector configuration shown in Figure 2-8, view C is used mostly for impedance matching. It is also used as a current driver because of its substantial current gain. It is particularly useful in switching circuitry because it has the ability to pass signals in either direction (bilateral operation).

In the common-collector circuit, the input signal is applied to the base-collector, the output is taken from the emitter-collector, and the collector is the element common to both input and output. The common collector has a high input and low output resistance. The input resistance for the common collector ranges from 2 to 500 kilohms, and the output resistance varies from 50 to 1,500 ohms. The current gain is higher than that in the common emitter, but it has a lower power gain than either the...
common base or common emitter. Similar to the common base, the output signal from the common collector is in phase with the input signal. The common collector is also referred to as an emitter-follower because the output developed on the emitter follows the input signal applied to the base.

Transistor action in the common collector is similar to the operation explained for the common base, except that the current gain is not based on the emitter-to-collector current ratio, alpha. Instead, it is based on the emitter-to-base current ratio called “gamma” (\( \gamma \)) because the output is taken off the emitter. Because a small change in base current controls a large change in emitter current, it is still possible to obtain high current gain in the common collector. However, because the emitter current gain is offset by the low output resistance, the voltage gain is always less than 1 (unity), exactly as in the electron-tube cathode follower. The common-collector current gain, gamma, is defined as

\[ \gamma = \frac{\Delta I_e}{\Delta I_b} \]

and is related to collector-to-base current gain, beta, of the common-emitter circuit by the formula:

\[ \gamma = \beta + 1 \]

Because a given transistor may be connected in any of three basic configurations, there is a definite relationship, as pointed out earlier, between alpha, beta, and gamma. These relationships are listed again for your convenience:

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

Take, for example, a transistor that is listed on a manufacturer’s data sheet as having an alpha of 0.90. We wish to use it in a common-emitter configuration. This means we must find beta. The calculations are:

\[ \beta = \frac{\alpha}{1 - \alpha} = \frac{0.90}{1 - 0.90} = \frac{0.90}{0.10} = 9 \]

A change in base current in this transistor will thus produce a change in collector current that will be 9 times as large. If you wish to use this same transistor in a common collector, you can find gamma by:

\[ \gamma = \beta + 1 = 9 + 1 = 10 \]

To summarize the properties of the three transistor configurations, a comparison chart is provided in Table 2-1 for your convenience.

<table>
<thead>
<tr>
<th>Amplifier Type</th>
<th>Common Base</th>
<th>Common Emitter</th>
<th>Common Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input/Output Phase Relationship</td>
<td>0°</td>
<td>180°</td>
<td>0°</td>
</tr>
<tr>
<td>Voltage Gain</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Current Gain</td>
<td>Low (( \alpha ))</td>
<td>Medium (( \beta ))</td>
<td>High (( \gamma ))</td>
</tr>
<tr>
<td>Power Gain</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>
Field Effect Transistor Configuration

The largest use of FETs today is in the large-scale integration of computer memory and logic circuits. Inverter circuits most commonly use N-channel MOSFET technology (NMOS), shown in Figure 2-9, view A. In this circuit, a depletion-mode MOSFET is used to load an enhancement-mode MOSFET switching device. The switching device is designated Q and is shown at the bottom of Figure 2-9, view A. The load device is designated L and is shown at the top of Figure 2-9, view A. The grounded arrows indicate that the substrates of both devices are grounded. The two states of the inverter are given in Figure 2-9, view B and are shown in the loaded drain characteristic diagram shown in Figure 2-9, view C.

![Figure 2-9 — Typical N-channel MOSFET inverter.](image)

The nature of an inverter circuit is that if the input voltage goes up, the output voltage goes down, and vice versa (Figure 2-9, view B). Considering the circuit of the inverter (Figure 2-9, view B), it can be seen that Q and L are in series between the supply voltage $V_{DD}$ and ground. The load device is always conducting because it is a depletion-mode device and its gate is permanently connected to its source. The switching device may be either conducting or nonconducting, depending on the input signal $V_i$ on its gate terminal. When $V_i$ is positive, electrons are collected in the channel of Q, and it is conducting. When conducting, the channel resistance of Q is much lower than that of L and the output voltage $V_O$ is held just above ground. When $V_i$ is nearly zero, the switching device is not conducting and the conducting channel of L holds $V_O$ just below the positive supply voltage $V_{DD}$. The circuit thus fulfills the criterion for inverter action. This behavior is illustrated in Figure 2-9, view C. Here, the drain characteristic of the load device is drawn as a nonlinear load line on the drain characteristic curves of the switching device. This load line is marked L. The intersection of the load line with the operating characteristic of the Q device determines the quiescent point of the circuit. For a switching inverter, there are two quiescent points. One, where the Q device is not conducting, is designated A in Figure 2-9, view C, and is called the off-state. The second, where the Q device is conducting, is designated B in Figure 2-9, view C, and is called the on-state. There is a single load line, while there are several curves in the family of the switching characteristics. The reason for this is that the gate of the load device is connected to its source and cannot change its voltage relative to
the source, whereas the gate of the switching device can take on any value of input (gate-source) voltage. In the circuit shown, however, the Q device gate voltage moves between the limits of zero and +V_{DD}. Some intermediate gate voltage curves are shown as a reminder that there are a multiplicity of states of the inverter between the off-state and the on-state, and that considerable power may be dissipated during the switching process. The off-state (A) has negligible standby power drain. The on-state (B) dissipates typically about 0.1 mW. The switching time ratio (pull-up time to pull-down time) is about 4 to 1, and the total switching delay time of a pair of inverters is approximately 20 nanoseconds.

In small-scale integrated circuit chip components, it is customary to use complementary MOSFET devices (CMOS). In such circuits, both N- and P-channel devices are used together, one as the load of the other. The use of complementary devices this way greatly reduces standby power to about 10 nanowatts.

**Thyristors**

A semiconductor thyristor is a three-terminal semiconductor switching device with separate input (control) and output (load) circuits. Relatively low control current causes the output section of the thyristor to be turned on, allowing high current to flow in the load. Once the device is turned on, the input section no longer has control of the device. Turn-off is controlled only by the output circuit supply voltage. The two major components in the thyristor family are the silicon-controlled rectifier and the bidirectional triode ac switch. Thyristors are generally called ac switches and are used in a variety of power applications. Whereas diodes use two alternate layers of PN-type semiconductor material and transistors use three such layers, thyristor devices use four layers, forming three or more junctions within a slice of silicon semiconductor material. Thyristor devices exhibit regenerative, or latching-type, switching action in one or two quadrants of their volt-ampere characteristic. They can be switched into the on state (conducting condition) but must usually be restored to their off state (voltage-blocking condition) by circuit action.

**Silicon-Controlled Rectifier**

The silicon-controlled rectifier (SCR), is one of the family of semiconductors that includes transistors and diodes. A drawing of an SCR and its schematic representation is shown in Figure 2-10, views A and B. Not all SCRs use the casing shown, but this example is typical of most of the high-power units.

Although it is not the same as either a diode or a transistor, the SCR combines features of both. Circuits using transistors or rectifier diodes may be greatly improved in some instances through the use of SCRs.
The basic purpose of the SCR is to function as a switch that can turn on or off small or large amounts of power. It performs this function with no moving parts that wear out and no points that require replacing. There can be a tremendous power gain in the SCR. In some units, a very small triggering current is able to switch several hundred amperes without exceeding its rated abilities. The SCR can often replace much slower and larger mechanical switches. It even has many advantages over its more complex and larger electron-tube equivalent, the thyratron.

The SCR is an extremely fast switch. It is difficult to cycle a mechanical switch several hundred times a minute, yet some SCRs can be switched 25,000 times a second. It takes just microseconds (millionths of a second) to turn on or off these units. Varying the time that a switch is on as compared to the time that it is off regulates the amount of power flowing through the switch. Because most devices can operate on pulses of power (alternating current is a special form of alternating positive and negative pulse), the SCR can be used readily in control applications. Motor-speed controllers, inverters, remote switching units, controlled rectifiers, circuit overload protectors, latching relays, and computer logic circuits all use the SCR. The SCR is made up of four layers of semiconductor material, arranged PNPN. The construction is represented in Figure 2-11, although the regions are not drawn to scale. In function, the SCR has much in common with a diode, but the theory of operation of the SCR is best explained in terms of transistors.

Consider the SCR as a transistor pair, one PNP and the other NPN, connected as shown in Figure 2-12. The anode (A) is attached to the upper p-layer; the cathode (C) is part of the lower n-layer; and the gate terminal (G) goes to the p-layer of the NPN triode.

In operation, the collector of Q2 drives the base of Q1, while the collector of Q1 feeds back to the base of Q2. Beta 1 (β1) is the current gain of Q1, and beta 2 (β2) is the current gain of Q2. The gain of this positive feedback loop is their product, β1 times β2. When the product is less than 1, the circuit is stable; if the product is greater than unity, the circuit is regenerative. A small negative current applied to terminal G will bias the NPN transistor into cutoff, and the loop gain is less than unity. Under these conditions, the only current that can exist between output terminals A and C is very high.
When a positive current is applied to terminal G, transistor Q2 is biased into conduction, causing its collector current to rise. Because the current gain of Q2 increases with increased collector current, a point (called the breakover point) is reached where the loop gain equals unity and the circuit becomes regenerative. At this point, collector current of the two transistors rapidly increases to a value limited only by the external circuit. Both transistors are driven into saturation, and the impedance between A and C is very low. The positive current applied to terminal G, which served to trigger the self-regenerative action, is no longer required because the collector of PNP transistor Q1 now supplies more than enough current to drive Q2. The circuit will remain on until it is turned off by a reduction in the collector current to a value below that necessary to maintain conduction.

The characteristic curve for the SCR is shown in Figure 2-13. With no gate current, the leakage current remains very small as the forward voltage from cathode to anode is increased until the breakdown point is reached. Here the center junction breaks down, the SCR begins to conduct heavily, and the drop across the SCR becomes very low.

![Figure 2-13 — Characteristic curve for an SCR.](image)

The effect of a gate signal on the firing of an SCR is shown in Figure 2-14. Breakdown of the center junction can be achieved at speeds approaching a microsecond by applying an appropriate signal to the gate lead while holding the anode voltage constant. After breakdown, the voltage across the device is so low that the current through it from cathode to anode is essentially determined by the load it is feeding.

The important thing to remember is that a small current from gate to cathode can fire or trigger the SCR, changing it from practically an open circuit to a short circuit. The only way to change it back again (to commutate it) is to reduce the load current to a value less than the minimum forward-bias current. Gate current is required only until the anode current has completely built up to a point sufficient to sustain conduction (about 5 microseconds in resistive-load circuits). After conduction from cathode to anode begins, removing the gate current has no effect.

The applications of the SCR as a rectifier are many. The multiple applications as a rectifier give the SCR its name. When alternating current is applied to a rectifier, only the positive or negative halves of the sine wave flow through. All of each positive or negative half cycle appears in the output. When an SCR is used, however, the controlled rectifier may be turned on at any time during the half cycle, thus controlling the amount of dc power available from zero to maximum, as shown in Figure 2-15. Because the output is actually dc pulses, suitable filtering can be added if continuous direct current is
needed. Thus, any dc-operated device can have controlled amounts of power applied to it. Notice that the SCR must be turned on at the desired time for each cycle.

When an ac power source is used, the SCR is turned off automatically because current and voltage drop to zero every half cycle. By using one SCR on positive alternations and one on negative, full-wave rectification can be accomplished, and control is obtained over the entire sine wave. The SCR serves in this application just as its name implies—as a controlled rectifier of ac voltage.

Anode voltage applied to the SCR significantly in excess of the voltage rating of the SCR can trigger the device into conduction, even in the absence of a gate signal. Excess reverse voltage, however, can permanently damage the SCR, such as in the case of the silicon junction diode. SCRs, similar to the junction diode and all power semiconductors, have a failure mechanism called “thermal fatigue.” Thermal fatigue failure is due to the thermal stresses induced during repetitive temperature changes occurring in the normal operation of the device. These stresses are inherent in all devices undergoing substantial temperature changes.

**Figure 2-14** — SCR characteristic curve with various gate signals.

**Figure 2-15** — SCR gate control signals.
changes that contain dissimilar metals. When power semiconductors, such as rectifier diodes and SCRs, are properly applied to take into account their thermal fatigue limitations, they can be expected to perform their function faultlessly for the life of the equipment in which they are used.

Current ratings of SCRs range from under 1 to 5,000 amperes. Blocking voltage capability of commercially available devices typically extends to 4,400 V for the higher power types, with voltages up to 6 kilovolts (kV) having been achieved.

Like most semiconductor devices, SCRs are dependent on temperature in some of their characteristics. Usual operating junction temperatures are 125 degrees Celsius (°C) (257 degrees Fahrenheit [°F]), and some devices are available up to 150 °C (302 °F).

The mounting considerations for SCRs are similar to those for diodes. Small devices handling between 2-4 amps are lead-mounted to radiating fins or some type of heat sink for adequate cooling of the semiconductor junction.

Manufacturing techniques used in SCRs are similar to those of silicon diodes. In addition to alloy and diffusion processing technology, epitaxial processing is sometimes used. In small devices, a planar structure, such as that developed for signal transistors and monolithic integrated circuits, is used. Higher power SCR structures are of a mesa type of construction, with the edges of the pellet often shaped in a manner to reduce the surface field across the blocking junction for higher voltage-blocking capability.

**Triode for Alternating Current**

For specialized ac-switching power control, such as in lamp dimmers and heating controls, the bidirectional triode thyristor, popularly called the triode-alternating current (TRIAC), is in widespread use.

The TRIAC is a three-terminal device similar in construction and operation to the SCR. The TRIAC controls and conducts current flow during both alternations of an ac cycle instead of only one. The schematic symbols for the SCR and the TRIAC are compared in Figure 2-16. Both the SCR and the TRIAC have a gate lead. However, in the TRIAC, the lead on the same side as the gate is main terminal 1, and the lead opposite the gate is main terminal 2. This method of lead labeling is necessary because the TRIAC is essentially two SCRs back to back, with a common gate and common terminals.

Each terminal is, in effect, the anode of one SCR and the cathode of another, and either terminal can receive an input. In fact, the functions of a TRIAC can be duplicated by connecting two actual SCRs, as shown in Figure 2-17. The result is a three-terminal device identical to the TRIAC. The common anode-cathode connections form main terminals 1 and 2, and the common gate forms terminal 3.
The difference in current control between the SCR and the TRIAC can be seen by comparing their operation in the basic circuit, shown in Figure 2-18. In the circuit shown in Figure 2-18, view A, the SCR is connected in the familiar halfwave arrangement. Current will flow through the load resistor (RL) for one alternation of each input cycle. Diode CR1 is necessary to ensure a positive trigger voltage.

In the circuit shown in Figure 2-18, view B with the TRIAC inserted in the place of the SCR, current flows through the load resistor during both alternations of the input cycle. Because either alternation will trigger the gate of the TRIAC, CR1 is not required in the circuit. Current flowing through the load will reverse direction for half of each input cycle. To clarify this difference, a comparison of the waveforms seen at the input, gate, and output points of the two devices is shown in Figure 2-19.

**Thyristor Variants**

Thyristors come in a variety of specialized applications. Among them are the asymmetrical silicon-controlled rectifier (ASCR), reverse-conducting thyristor (RCT), and gate turn-off (GTO) devices shown in Figure 2-20.

These devices are all in the thyristor family and are mainly used in place of SCRs in power circuits requiring operation from a dc source. The ASCR (Figure 2-20, view A) and RCT (Figure 2-20, view B) have the advantage of faster turn-off time than the SCR and thus require a less costly auxiliary circuit to effectively turn-off. The RCT has an added circuit advantage because it has a built-in reverse rectifier diode in parallel with the device. (The RCT is the integrated equivalent of a discrete ASCR in
parallel with a discrete rectifier diode.) Along with faster turn-off times, the ASCR and RCT devices have lower forward-voltage drops for comparable forward-blocking voltage ratings and silicon area, thus increasing the device's efficiency.

The GTO (Figure 2-20, view C), is also a thyristor. Like the SCR, it is a symmetrical reverse-blocking triode thyristor (unlike the ASCR and RCT, which cannot block reverse voltages), but it has the added advantage of being able to turn off current when a negative signal is applied to the gate. Thus, the GTO does not require an auxiliary circuit to communicate it off as do the SCR, ASCR, and RCT devices.

It is necessary to operate thyristors from a dc supply in order to achieve power conversion from the dc (battery or rectified ac line) supply to a load requiring an alternating supply (dc to ac inversion) or to a load requiring a variable-voltage dc supply (dc to dc conversion). Because the rate of switching the thyristors in dc circuits can be varied by the control circuit, a thyristor inverter circuit can supply ac load with a variable frequency. An important application of this mode of operation is for adjustable speed operation of ac synchronous and induction motors.
A battery source can be converted to a variable-voltage dc source for a dc motor by “chopping” the dc source voltage either at a variable rate at constant pulse width (frequency power modulation) or by operating the chopper circuit at a constant frequency and varying the pulse width (pulse-width power modulation).

INTEGRATED CIRCUITS

Miniature electronic circuits are produced within and upon a single semiconductor crystal, usually silicon. Integrated circuits range in complexity, from simple logic circuits and amplifiers to large-scale applications containing millions of transistors and other components that provide computer memory circuits and complex logic subsystems, such as microcomputer central processor units.

Integrated circuits are the primary components of most electronic systems. Their low cost, high reliability, and speed have been essential in advancing and miniaturizing the use of digital computers. Microcomputers have spread the use of computer technology to instruments, personal electronic devices, automobiles, and other equipment. For analog signal processing, integrated subsystems such as frequency modulated stereo demodulators and switched-capacitor filters have been developed to bridge the digital divide.

Integrated circuits consist of the combination of active electronic devices, such as transistors and diodes, with passive components, such as resistors and capacitors, within and upon a single semiconductor crystal. The construction of these elements within the semiconductor is achieved through the introduction of electrically active impurities into well-defined regions of the semiconductor. The fabrication of integrated circuits thus involves such processes as vapor-phase deposition of semiconductors and insulators, oxidation, solid-stage diffusion, ion implantation, and vacuum deposition.

Generally, integrated circuits are not straight-forward replacements of electronic circuits assembled from discrete components. They represent an extension of the technology by which silicon planar transistors are made. For this reason, transistors or modifications of transistor structures are the primary devices of integrated circuits. Methods of fabricating good-quality resistors and capacitors have been devised. However, the third major type of passive component, inductors, must be simulated with complex circuitry or added to the integrated circuit as discrete components.

Simple logic circuits were the easiest to adapt to these design changes. The first of these circuits, such as inverters and gates, were produced in the early 1960s primarily for miniaturization of missile guidance computers and other aerospace systems. Analog circuits, called linear integrated circuits, did not become commercially practical until several years later because of their heavy dependence on passive components, such as resistors and capacitors. Today, integrated circuits are everywhere, including in the Common Access Card you may be using to access this course.

Types of Integrated Silicon Circuits

Basically, there are two general classifications of integrated circuits: monolithic and hybrid. In the monolithic integrated circuit, all elements (resistors, transistors, and so forth) associated with the circuit are fabricated inseparably within a continuous piece of material (called the substrate), usually silicon. The monolithic integrated circuit is made very much like a single transistor. While one part of the crystal is being doped to form a transistor, other parts of the crystal are being acted upon to form the associated resistors and capacitors. Thus, all the elements of the complete circuit are created in the crystal by the same processes and in the same time required to make a single transistor. This process results in a considerable cost savings over the same circuit made with discrete components by lowering assembly costs. A typical packaging sequence is shown in Figure 2-21.
Hybrid integrated circuits are constructed somewhat differently from the monolithic devices. The passive components (resistors and capacitors) are deposited onto a substrate (foundation) made of glass, ceramic, or other insulating material. Then the active components (diodes and transistors) are attached to the substrate and connected to the passive circuit components on the substrate using very fine (.001 inch) wire. The term “hybrid” refers to the fact that different processes are used to form the passive and active components of the device. Hybrid circuits are of two general types: (1) thin film and, (2) thick film. Thin and thick film refers to the relative thickness of the deposited material used to form the resistors and other passive components. Thick film devices are capable of dissipating more power, but are somewhat more bulky. Integrated circuits are being used in an ever-increasing variety of applications. Small size and weight and high reliability make them ideally suited for use in airborne equipment, missile systems, computers, spacecraft, and portable equipment. They are often easily recognized because of the unusual packages that contain the integrated circuit.

These tiny packages protect and help dissipate heat generated in the device. One of these packages may contain one or several stages, often having several thousand components. Some of the most common package styles are shown in Figure 2-22.

The design of the circuits within these packages provides further classification into two sub-groups. Bipolar, when the principal element is the bipolar junction transistor, and linear when the principle element is the metal oxide semiconductor (MOS) transistor. Both depend upon the construction of a desired pattern of electrically active impurities within the semiconductor body, and upon the formation of an interconnection pattern of metal films on the surface of the semiconductor.
Bipolar circuits are generally used where highest logic speed is desired, and MOS for largest-scale integration or lowest power dissipation. Additionally, MOS ICs are simpler to fabricate and more cost effective. Linear circuits are mostly bipolar, but MOS devices are used extensively in switched-capacitor filters.

**Bipolar Circuits**

A simple bipolar inverter circuit using a diffused resistor and an NPN transistor is shown in Figure 2-23, view A. The input voltage $V_{in}$ is applied to the base of the transistor. When $V_{in}$ is zero or negative with respect to the emitter, no current flows. As a result, no voltage drop exists across the resistor, and the output voltage $V_{out}$ will be the same as the externally applied biasing voltage, +5 volts in this example shown in Figure 2-23, view B. When a positive input voltage is applied, the transistor becomes conducting. Current now flows through the transistor, hence through the resistor; as a result, the output voltage decreases. Thus, the change in input voltage appears inverted at the output. The change in the output voltage occurs slightly later than the change in the input voltage. This time difference, called propagation delay, is an important characteristic of all integrated circuits. Much effort has been spent on reducing it, and values less than one-billionth of a second have been achieved.

Most simple digital circuits can be fabricated, much as the inverter circuit described above. As an example, a photomicrograph of an early logic gate circuit is shown in Figure 2-24. This circuit is one of the earliest digital integrated circuits. For comparison, the field-programmable gate array shown in Figure 2-25 contains up to 1,124,022 gates, 51,000 slices, and 16 megabits of integrated block memory on a 5-layer 0.22 micrometer CMOS process, surface-mounted package.
This tendency toward increased complexity is dictated by the economics of integrated circuit manufacturing. Because of the nature of this manufacturing process, all circuits on a slice are fabricated together. Consequently, the more circuitry accommodated on a slice, the cheaper the circuitry becomes. Because testing and packaging costs depend on the number of chips, it is desirable, to keep costs down, to crowd more circuitry onto a given chip rather than to increase the number of chips on a wafer.

Linear Circuits

Integrated circuits based on amplifiers are called “linear” because amplifiers usually exhibit a linearly proportional response to input signal variations. However, the category includes memory sense amplifiers, combinations of analog and digital processing functions, and other circuits with nonlinear characteristics. Some digital and analog combinations include analog-to-digital converters, timing controls, and data communications modulator-demodulator units (modems).

A long-standing drawback in these circuits was the lack of inductors for tuning and filtering. That shortcoming was overcome by the use of resistor-capacitor networks and additional circuitry. For low-frequency circuits, the resistor in these networks is being replaced by the switched capacitor. At the higher frequencies, an oscillator-based circuit known as the phase-locked loop provides a general-purpose replacement for inductors in applications such as radio transmission demodulation.

At first, the development of linear circuits was slow because of the difficulty of integrating passive components, and also because of undesirable interactions between the semiconductor substrate and the operating components. Thus, much greater ingenuity was required to design and use the early linear circuits.

In addition, manufacturing economics favors digital circuits. A computer can be built by repetitious use of simple inverters and gates, while analog signal processing requires specialized linear circuits.
MOS Circuits

The other major class of integrated circuits is called MOS because its principal device is a MOSFET. It is more suitable for very large-scale integration (VLSI) than bipolar circuits because MOS transistors are self-isolating and can have an average size of less than a millionth of a square inch \((5 \times 10^{-5})\). This technological advance has made it practical to use over 1 million transistors per circuit. Because of this high-density capability, MOS transistors are used for high-density, random-access memories (RAMs), read-only memories (ROMs), and microprocessors. An example of radiation-hardened RAM is shown in Figure 2-26.

Several types of MOS device fabrication technologies have been developed. Among them are (1) metal-gate P-channel MOS (PMOS), which uses aluminum for electrodes and interconnections; (2) silicon-gate P-channel MOS, employing polycrystalline silicon for gate electrodes and the first interconnection layer; (3) NMOS, which is usually silicon gate; and (4) CMOS, which employs both P- and N-channel devices. NMOS and CMOS became the dominant technologies, with CMOS using silicon gates and becoming the most attractive for new designs. Both conceptually and structurally, the MOS transistor is a much simpler device than the bipolar transistor. In fact, its principle of operation has been known since the late 1930s, and the research effort that led to the discovery of the bipolar transistor was originally aimed at developing the MOS transistor. This simple device was kept from commercial use until 1964 because it depends on the properties of the semiconductor surface for its operation, while the bipolar transistor depends principally on the bulk properties of the semiconductor crystal. Hence, MOS transistors became practical only when understanding and control of the properties of the oxidized silicon surface had been perfected to a great degree. While the basic technical knowledge has been around for years, advances in manufacturing processes and materials have made MOS technology extraordinarily effective in the electronic world.

CMOS Circuits

A simple CMOS inverter is shown in Figure 2-27, view A, and a circuit schematic is shown in Figure 2-28, view A. The gates of the N- and P-channel transistors are connected together as are the drains. The common gate connection is the input node, while the common drain connection is the output node. A capacitor is added to the output node to model the loading expected from the subsequent stages on typical circuits.

When the input node is in the “low state,” at 0 V (Figure 2-27, view B), the N-channel gate-to-source voltage is 0 V, while the P-channel gate-to-source voltage is -5 V. The N-channel transistor requires a positive gate-to-source voltage, which is greater than the transistor threshold voltage (typically 0.5-1 V), before it will start conducting current between the drain and source. Thus, with a 0 V gate-to-source voltage, it will be off and no current will flow through the drain and source regions. The P-channel transistor, however, requires a negative voltage between the gate and source, which is less than its threshold voltage (typically -0.5 to -1.5 V). The -5 volt gate-to-source potential is clearly less

Figure 2-26 — RAM.
than the threshold voltage, and the P-channel will be turned on, conducting current from the source to the drain, and thereby charging up the loading capacitor. Once the capacitor is charged to the “high state” at 5 V, the transistor will no longer conduct because there will no longer be a potential difference between the source and drain regions.

When the input is now put to the high state at 5 V (Figure 2-27, view C), just the opposite occurs. The N-channel transistor will be turned on, while the P-channel will be off allowing the load capacitor to discharge through the N-channel transistor. The resulting in the output voltage drops from a high state at 5 V to a low state at 0 V. Again, once there is no potential difference between the drain and source (capacitor discharged to 0 V), the current flow will stop, and the circuit will be stable.

Figure 2-27 — CMOS inverter cross-section.
This simple circuit illustrates an important feature of CMOS circuits. Once the loading capacitor has been either charged to 5 V or discharged back to 0 V (Figure 2-28, view B), there is no current flow, and the standby power is very low. This simplicity is the reason for the high popularity of CMOS for battery-based systems. None of the other MOS technologies offers this feature without complex circuit techniques, and even then, they will typically not match the low standby power of CMOS. The bipolar circuits discussed above require even more power than these other MOS technologies. The additional fabrication steps required (10 to 20 percent more) are the price for CMOS’s lower power, compared to NMOS.

**Sampled-Data Device Circuits**

In addition to the digital logic applications discussed above with the simple CMOS inverter circuit, MOS devices also offer unique features for some analog circuit applications. These features include signal-processing applications that are based on sampled-data techniques. The charge-coupled device (CCD) is such an application.

In CCDs, the stored charge at the semiconductor surface can also be made to propagate along the surface via potential wells created by a series of these MOS structures. You may have noticed digital camera manufacturers advertise CCD pixel count as an indication of image quality.

Digital cameras incorporate an electronic component known as an image sensor. In most digital cameras, that sensor is a CCD that converts light into current. CCD sensors are made up of tiny components known as pixels. Each pixel is actually a photodiode that is sensitive to the intensity of the light that it comes in contact with and passes a corresponding amount of current to a processor that converts that signal into a digital image.

**Figure 2-28 — CMOS inverter circuit.**

**Transistor-Transistor Logic Devices**

Perhaps the best-known and most widely used implementation of logic switches is the bipolar TTL. Shown schematically in Figure 2-29, the basic TTL not AND (NAND) gate (turned on only if one input is low) is formed by a multi-emitter transistor, followed by an output transistor that acts as a pull-up/buffer. Thus, the first transistor performs an AND (turned on when all inputs are high) operation on the inputs, and the second transistor completes the NAND by performing an inversion.
TTL transistors are operated in the saturation mode; in other words, the transistors are driven hard to either the cutoff or the saturation limits. This overdriving introduces a time delay that does not exist if the transistors are operated in the non-saturated mode. Such non-saturating logic, while inherently faster, is more susceptible to noise because it is biased in the linear region.

The 7400 designation is a family of TTL devices that has a useful temperature range of 0 to 70 °C. Military-grade equipment required a greater range to handle the extreme temperature variations, and the 5400 series was developed that operated in the -55 to +125 °C range. Typical numbering systems for military- and commercial-grade TTL are shown in Table 2-2.

Several varieties of TTL have specific and special uses. Table 2-2 lists the military and commercial identifiers.

### Table 2-2 — Numbering System for TTL Types

<table>
<thead>
<tr>
<th>Types</th>
<th>-55° to +125°C</th>
<th>0° to +70°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>5400</td>
<td>7400</td>
</tr>
<tr>
<td>High-Power</td>
<td>54H00</td>
<td>74H00</td>
</tr>
<tr>
<td>Low-Power</td>
<td>54L00</td>
<td>74L00</td>
</tr>
<tr>
<td>Schottky</td>
<td>54S00</td>
<td>74S00</td>
</tr>
<tr>
<td>Low-Power</td>
<td>54LS00</td>
<td>74LS00</td>
</tr>
</tbody>
</table>

**Regular TTL**

Regular TTL is normally the widest available and the lowest priced type of TTL, and it has by far the greatest variety and second-sourcing. A typical gate-propagation time is 10 nanoseconds, the time it takes for a logic change at a gate input to appear as a logic change on the output. Typical TTL requires around 10 milliwatts per gate with counting flip-flops operating at speeds of 40 MHz and higher.
**Low-Power TTL**

Low-power TTL exchanges power consumption for speed and is identified by an “L” in the part number. For instance, a 74L00 is a low-power, commercial version of the 7400 regular TTL NAND gate. There is roughly a 10:1 tradeoff in the low-power version, one-tenth the speed to counters at one-tenth the power, although the simpler gates run one-fourth the speed on one-tenth the power. Flip-flops and counters have a maximum toggle frequency of 3 MHz or so. Within the low-power subfamily, the output-drive remains 10, but a low-power TTL gate can drive only one regular TTL gate. While the 54L00 and 74L00 series TTL do offer low-power consumption, their advantages are preempted by the CMOS logic families.

**High-Power TTL**

The high-power TTL devices are designated with an “H” in the part number; 74H00 is the equivalent of a 7400 gate, and so on. Typically, you get twice the speed for twice the power. Counters are good to 50 MHz. Within the high-power subfamily, the output-drive remains at 10, but the input is typically 1.3 times regular TTL loads. Thus, a regular TTL gate can drive at most only seven high-power TTL inputs. High-power TTL is normally handled by the Schottky TTL, which is faster and draws less supply power. Quite a few high-power devices remain available. One advantage they do have over the Schottky devices is that the outputs are “electrically quieter,” a handy feature in high-speed digital-to-analog converters.

**Schottky TTL**

Schottky TTL is an improved version of TTL that has a better speed/power tradeoff than the older types. To do this, Schottky diodes (a fast diode with a 0.3-volt forward drop) are placed across most of the transistors in the basic TTL gate. This arrangement prevents the transistors from saturating, and thus eliminates any storage-time delays inside the transistors. The part numbers have an “S” in them, as in 74S00. Propagation delays of 3 nanoseconds are combined with flip-flops that can run at 125 MHz.

Where high speed is essential, Schottky TTL is a logical choice. Its competitor is the emitter-coupled logic (ECL) families that in general are much faster, but considerably more difficult to use.

A high-speed, unsaturated logic family, such as Schottky TTL, presents serious restrictions in the type and quality of test equipment you must have to work with it intelligently. A 60 MHz triggered oscilloscope is essential, and a 120 MHz oscilloscope is preferable. As might be expected, Schottky devices are much more critical as to layouts and supply decoupling than ordinary TTL because of their higher speed. Nevertheless, where high speed is essential, they are often the simplest solution to system problems in the 30 to 120 MHz range.

**Low-Power Schottky TTL**

Devices such as the 74LS00 are emerging as a more recent variation on TTL. The low-power Schottky TTL family is slightly faster than regular TTL but requires only one-fifth the power. It does this by using the Schottky diodes to eliminate storage-time effects, but then raises the circuit impedance levels to slow things down to normal and pick up power savings. For many applications, this capability represents a near-optimum combination of values.

**Emitter-Coupled Logic Devices**

The basic ECL gate, shown in Figure 2-30, is composed of current-steering transistors that perform an operation on the inputs. Typically, the gate output is amplified by an emitter-follower transistor, and both the true and complement signals can be made available with no added delays at the output. This circuit makes the switching of the transistors very fast by never allowing them to turn all the way on, a
condition known as saturation, resulting in propagation delays of less than 1 nanosecond. This configuration is not normally used in large, complex chips due to its characteristic of drawing large amounts of current, which produces large power dissipation.

**Types of Integrated Gallium Arsenide Circuits**

Integrated circuits based on gallium arsenide (GaAs) have been in use since the late 1970s. Gallium arsenide is a compound made up of the elements gallium and arsenic. While gallium is not generally considered toxic, arsenic, alone, is highly poisonous. GaAs has several advantages over silicon. It is relatively insensitive to heat, resistant to radiation, and versatile, with applications ranging from logic devices to solar panels.

The major advantage of these GaAs circuits is their fast switching speed.

**Gallium Arsenide FET**

The gallium arsenide field-effect transistor (GaAs FET) is a majority carrier device in which the cross-sectional area of the conducting path of the carriers is varied by the potential applied to the gate (Figure 2-31, view A). Unlike the MOSFET, the gate of the GaAs FET is a Schottky barrier composed of metal and GaAs. Because of the difference in work functions of the two materials, a junction is formed. The depletion region associated with the junction is a function of the difference in voltage of

![Figure 2-30 — ECL gate.](image)

![Figure 2-31 — Gallium arsenide FET.](image)
the gate and the conducting channel, and the doping density of the channel. By applying a negative voltage to the gate, the electrons under the gate in the channel are repelled, extending the depletion region across the conducting channel. The variation in the height of the conducting portion of the channel caused by the change in the extent of the depletion region alters the resistance between the drain and source. Thus, the negative voltage on the gate modulates the current flowing between the drain and the source (Figure 2-31, view B), as shown by the linear region of operation in Figure 2-31, view C. As the height of the conducting channel is decreased by the gate voltage or as the drain voltage is increased, the velocity of charge carriers (electrons for N-type GaAs) under the gate increases (similar to water in a hose when its path is constricted by passing through the nozzle). The velocity of the carriers continues to increase with increasing drain voltage, as does the current, until their saturated velocity is obtained (about \(10^7\) centimeter per second or \(3 \times 10^5\) feet per second for GaAs). At that point, the device is in the saturated region of operation; that is, the current is independent of the drain voltage.

The high-frequency operation of a device is limited by the transit time of the carriers under the gate. The time during which the velocity of electrons (output signal) is modulated by the voltage on the gate (input signal) must be short compared to any change of the input voltage. Because electrons in gallium arsenide have a high saturated velocity, GaAs FETs operate at very high frequencies. The high-frequency performance is also improved by decreasing the gate length (the length of the path of the electrons under the gate) by using special lithographic techniques to define the gate during processing. GaAs FETs with gate lengths as short as 0.1 micrometer (\(\mu\)m) (4 ×10^{-6} in) have been fabricated, resulting in a potential frequency of operation of approximately 100 gigahertz (GHz).

As noted above, the major advantage of gallium arsenide integrated circuits over silicon integrated circuits is the faster switching speed of the logic gate. The reason for the improvement of the switching speed of GaAs FETs with short gate lengths (less than 1 \(\mu\)m or \(4 \times 10^{-5}\) in) over silicon FETs of comparable size has been the subject of controversy. In essence, the speed or gain-bandwidth product of a FET is determined by the velocity with which the electrons pass under the gate. The saturated drift velocity of electrons in gallium arsenide is twice that of electrons in silicon; therefore, the switching speed of gallium arsenide might be expected to be only twice as fast.

However, this simplified model neglects several important aspects of the problem. One way to determine the switching speed of a logic circuit is to calculate the total capacitance that must be charged or discharged as the logic level is switched, and the current drive available. The larger the current drive and the smaller the capacitance, the faster the switching speed. Because gallium arsenide integrated circuits are fabricated on semi-insulating substrates, the parasitic capacitance to ground is much smaller than for silicon integrated circuits. The only comparable small-capacitance silicon technology is CMOS/SOS (silicon on sapphire). Also, because of the higher mobility, the transconductance of a GaAs FET is much higher than for a silicon FET, and the associated parasitic resistances are lower. Thus, there is more current change for a given amount of input voltage. Finally, the mobility of gallium arsenide is six to eight times that of silicon, and even though the saturated velocities of gallium arsenide and silicon are within a factor of 2, the electrical field necessary for the carriers to reach velocity saturation in gallium arsenide (about 4 kV/cm) is much less than in silicon (about 40 kV/cm). Therefore, when operating at the low voltages typical of GaAs FETs, similar gallium arsenide and silicon FETs have a speed ratio that is approximately proportional to their low-field mobilities. At higher voltages, the speed ratio decreases because the carrier velocity (current) continues to increase in silicon, whereas the carriers are saturated in gallium arsenide; however, this increase in speed is at the expense of increased power dissipation. This effect explains the experimental results plotted in Figure 2-32, where the power-delay products of silicon and gallium arsenide inverters with 1 \(\mu\)m gate length (4 × 10^{-6} in) FETs are plotted as functions of power dissipation. There are several device choices for high-speed gallium arsenide integrated circuits, each with certain advantages and disadvantages.
Depletion-Mode FET
Depletion-mode FET (DFET) is the most mature of the device technologies (Figure 2-33). The DFET has the largest current drive capacity per unit device width for all GaAs FET devices. This capacity contributes to its high speed and high power dissipation. The pinchoff voltage of the DFET is determined by the channel doping and thickness under the Schottky barrier gate. This voltage can be made quite large (about –2.5 V) in order to improve the noise immunity of logic gates in which they are used.

Enhancement-Mode FET (ENFET)
This low-current, low-power device is realized by increasing the pinchoff voltage to zero or above. The logic swing for the enhancement-mode FET (ENFET) is limited to the difference between the pinchoff voltage (approximately 0 V) and the forward turn-on voltage of the Schottky barrier gate (approximately +0.5 V), thus providing a significantly lower noise immunity for logic gates using ENFETs. The realization of medium-scale integration (MSI) and large-scale integration (LSI) chips in which the noise margins are small requires stringent process controls to fabricate devices across the wafer with small variations in pinchoff voltage.

Enhancement-Mode Junction FET (E-JFET)
In this device, the Schottky barrier of the ENFET is replaced with an implanted p region that forms a PN junction for the gate (Figure 2-34). The enhancement-mode junction FET (E-JFET) has all the advantages of the ENFET with respect to low power, plus the additional advantage of a slightly larger logic swing due to the larger turn-on voltage of the PN junction. The ultimate speed of the E-JFET will be less than an ENFET of similar dimensions because the added side wall gate capacitance of the PN-junction gate is a significant fraction of the total gate capacitance at sub-micrometer gate lengths.
LOGIC GATE CONFIGURATIONS

Three different logic gate configurations (Figure 2-35) are presently the most popular approaches to high-speed gallium arsenide logic circuits. The buffered-FET logic (BFL) gate (Figure 2-35, view A) is the fastest gate for reasonable fan-outs (the number of identical logic gates it must drive) but dissipates the most power (approximately 5 to 10 mW per gate). The Schottky diode FET logic (SDFL) gate (Figure 2-35, view B) dissipates about one-fifth the power of the BFL; however, it is slower by about a factor of 2. Finally, direct-coupled FET logic (DCFL) gates (Figure 2-35, view C) using ENFETs have the lowest power consumption (about 50 μW per gate) at gate delays two to four times those of BFL for complex logic circuits.

The BFL gate using DFETs requires level shifting to make the input and output logic levels compatible. This extra circuitry adds both delay to the switching time of the gate and extra power consumption; however, it provides buffering to the next stage, and therefore, has very good fan-out and on-off chip drive capabilities. Because of the high power dissipation and the huge device count per gate, BFL will not be suitable for circuits with the complexity of LSI (greater than 1,000 gates).
The SDFL gate incorporates very small Schottky barrier diodes to perform the input logical OR (high output if either input is high) function and to provide level shifting. The invert function is performed by the DFETs in the second stage. Because of the lower power dissipation and small diodes, packing densities of more than 1,000 gates/mm² (645,000 gates/in²) are achievable. Large fan-in (number of inputs a logic gate can handle) does not require any significant chip area because of the small diodes; however, SDFL gates are extremely fan-out sensitive, and for fan-outs (number of outputs a logic gate can feed) of greater than three, either buffers or much wider DFETs must be incorporated to maintain the speed. Because of the medium power dissipation and high packing density, SDFL is suitable for large-scale integration applications, but not for circuits with the complexity of very large-scale integration (VLSI) (more than 10,000 gates).

DCFL incorporating ENFETs is inherently much simpler than BFL or SDFL because there is no need for level shifting. The very low power consumption and circuit simplicity lead to high packing density (more than 5,000 gates/mm² or 3.2 × 10⁶ gates/in²) at only slightly slower speeds.

Table 2-3 lists the projected applications for each of the three logic gates, along with the competing silicon technology.

### Table 2-3 — Gallium Arsenide Logic Gate Applications and Issues

<table>
<thead>
<tr>
<th>Gallium Arsenide Technology</th>
<th>Applications</th>
<th>Feasibility Issues</th>
<th>Competing Silicon Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffered Field Effect Transistor logic (BFL)</td>
<td>Small-Scale Integration (SSI), Medium-Scale Integration (MSI), superfast logic-prescalers, multiplexers, demultiplexers, fast cache memory</td>
<td>Most producible, uses large logic swings with good noise margins; tolerant of FET threshold variations; least area efficient</td>
<td>Emitter-coupled logic (ECL) and submicrometer Metal Oxide Semiconductor (MOS)</td>
</tr>
<tr>
<td>Schottky diode FET logic (SSDFL)</td>
<td>High-speed large-scale integration (LSI), for example, 8 × 8 multiplexer; arithmetic-logic unit (ALU), gate arrays</td>
<td>Replaces FETs with diodes for logic function; usually smaller noise margin than BFL, but still fairly tolerant of threshold variations; circuit design complicated by fan-out sensitivity</td>
<td>Bipolar LSI; 1 μm MOS LSI</td>
</tr>
<tr>
<td>Direct-Coupled FET logic (DCFL)</td>
<td>Low power or very large scale integration (VLSI) applications, memory, gate arrays</td>
<td>Uses enhancement FETs; low noise margin; requires excellent threshold control</td>
<td>1 μm MOS VLSI</td>
</tr>
</tbody>
</table>

**Digital Counter**

A digital counter is an instrument that, in its simplest form, provides an output that corresponds to the number of pulses applied to its input.

Counters may be categorized into two types: the Moore machine or the Mealy machine. The simpler counter type, the Moore machine, has a single count input (also called the clock input or pulse input), while the Mealy machine has additional inputs that alter the count sequence. Digital counters take many forms, such as geared mechanisms (operating time counters and older odometers are
examples), relays (old telephone switching systems), and solid-state semiconductor circuits (most modern electronic counters). This section stresses solid-state electronic counters.

Most digital counters operate in the binary number system because binary is easily implemented with electronic circuitry. Binary allows any integer (whole number) to be represented as a series of binary digits, or bits, where each bit is either a 0 or 1 (off or on, low or high, and so forth).

Four-bit binary counters (Figure 2-36) count from 0 to 15; the 16th count input causes the counter to return to the 0 output state and generate a carry pulse. This action of the counter to return to the 0 state with a carry output on every 16th pulse makes the 4-bit binary counter a modulus 16 counter. The four binary-digit outputs $Q_D, Q_C, Q_B,$ and $Q_A$ are said to have an 8-4-2-1 “weighting” because, if $Q_D$ through $Q_A$ are all ones, then the binary counter output is $1111_2 = 1 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = 8 + 4 + 2 + 1 = 15_{10}$, where the subscripts indicate the base of the number system. In Figure 2-36, view A, the counter state-flow diagram is shown. Each possible state is represented by the numerical output of that state. Upon receiving a count pulse, the counter must change state by following an arrow from the present state to the next state. In Figure 2-36, view B, a table is given showing the counter output after a given number of input pulses, assuming that the counter always starts from the 0 state. The counter

<table>
<thead>
<tr>
<th>Number of Count Pulses</th>
<th>Binary Output</th>
<th>Octal (Base 0)</th>
<th>Decimal (Base 10)</th>
<th>Hexadecimal (Base 16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0001</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0010</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0011</td>
<td>3</td>
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<tr>
<td>4</td>
<td>0100</td>
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<td>15</td>
<td>13</td>
<td>D</td>
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<td>14</td>
<td>1110</td>
<td>16</td>
<td>14</td>
<td>E</td>
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<tr>
<td>15</td>
<td>1111</td>
<td>17</td>
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</tr>
<tr>
<td>16</td>
<td>0000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2-36 — Four-bit binary counter modified to be a decimal counter.
output is listed in binary, octal, decimal, and hexadecimal. Figure 2-36, view C, shows a block diagram of the counter built with T flip-flops, and Figure 2-36, view D, shows the counter waveforms through time, with a periodic count input. The T flip-flop is a device that has either a 0 or a 1 on its Q output at all times. When the count input T moves from the 1 state to the 0 state, the flip-flop output must change state, from a 0 to a 1 or a 1 to a 0. The carry output produces a 1-to-0 transition on every 16th count input, producing a divide-by-16 function.

The four bits of the counter of Figure 2-36 can be grouped together and used to represent a single hexadecimal digit; in Figure 2-36, view B, each counter output state represents one hexadecimal digit. A two-digit hexadecimal counter requires two sets of four-bit binary counters, the carry output from the first set of counters driving the count input of the second set of counters.

A decimal counter built from four binary counters is shown in Figure 2-37. Let four bits of data from the binary counter represent one decimal digit. The counter will work in the same way as the counter shown in Figure 2-36, except that all the flip-flops are reset to the 0 state when the counter moves from the 10012 = 9 state, instead of advancing to the 10102 = 10 state. Besides the AND gate that is now used to detect the 1001 state of the counter and enable the resets, the circuit block diagram shows a new type of flip-flop. The SR flip-flop acts like a T flip-flop with an additional input that forces the Q output to a 1 state when the S (set) input is high and the T input has had a 1-to-0 transition applied. An R (reset) input acts as the S input does, except that the Q output goes to 0. This example decimal counter has an 8-4-2-1 weighted output that is known as binary-coded decimal (BCD). A seven-segment display is easily interfaced to the binary-coded decimal counter using a widely available decoder/driver circuit that is binary coded decimal to seven segments.

Digital counters are found in much modern electronic equipment, especially equipment that is digitally controlled or has digital numeric displays. A frequency counter, as a test instrument or a channel frequency display on a radio tuner, consists simply of a string of decade counters that count the pulses of an input signal for a known period of time, and display that count on a seven-segment display. A digital voltmeter operates by using nearly the same idea, except that the counter counts a known frequency for a period of time proportional to the input voltage.
Digital computers may contain counters in the form of programmable interval timers that count an integral number of clock pulses of a known period, and then generate an output at the end of the count to signal that the time period has expired. Most of the counters in a microprocessor consist of arithmetic logic units (ALUs) that add one many-bit number to another, storing the results in a memory location. The program and data counters are examples of this kind of counter.

Counters have progressed from relays to light-wavelength-geometry, very large-scale ICs. There are several technologies for building individual digital counters. Single counters are available as integrated circuit chips in ECL, TTL, and CMOS. The three technologies are often used together in order to keep production costs down. In some applications, ECL or TTL is used towards the input end of a counter and CMOS towards the output where speed is critical, thus putting less expensive logic devices where the signal will never operate at a high-enough frequency to require an expensive CMOS circuit. Standard, high-volume production NMOS LIS can implement a one-bit binary counter in a $100 \times 100 \mu m^2$ ($39 \times 3.9 \text{ mil}^2$) area that will operate to 10 MHz. A gallium arsenide metal semiconductor field-effect transistor (MESFET) master-slave JK flip-flop has been reduced that operates at 610 MHz in a $390 \times 390 \mu m^2$ ($15 \times 15 \text{ mil}^2$) surface area while consuming the power of an NMOS.

**Comparator Circuit**

A comparator circuit is an electronic circuit that produces an output voltage or current whenever two input levels simultaneously satisfy predetermined amplitude requirements. A comparator circuit may be designed to respond to continuously varying (analog) or discrete (digital) signals. Its output may be in the form of signaling pulses that occur at the comparison point or in the form of discrete dc levels.

**Linear Comparator**

A linear comparator operates on continuous, or nondiscrete, waveforms. Most often one voltage, referred to as the reference voltage, is a variable dc or level-setting voltage, and the other is a time-varying waveform. One common application of the comparator is in a linear time-delay circuit. Inputs consist of a sawtooth waveform of linearly increasing magnitude (ramp function) and a variable dc reference voltage. The reference voltage can be calibrated in units of time, as measured from the beginning of the sawtooth.

A clipper and a coincidence amplifier, together with a resistance-capacitance (RC) differentiating circuit, can perform the function of comparator. In Figure 2-38, the series clipper, usually called a pick-off diode for this application, does not conduct until the input reaches level $V_R$. The diode input is a sawtooth as shown. Consequently, only the portion of the sawtooth above $V_R$ appears at the output of the clipper. This output is applied to the RC differentiating network, which passes only the initial part of the rise. This short pulse is then amplified to produce the resultant output waveform.

The particular amplifier illustrated is a two-transistor, high-gain amplifier with a relatively high input impedance and a low output impedance. A sharper pulse can be obtained if the amplifier is made regenerative. It may even take the form of a multivibrator or blocking oscillator to increase the gain at the point of coincidence.

**Regenerative Comparator**

Multivibrators can be used in several ways directly as comparators without need for the pick-off diodes; such comparators sense the required coincidence accurately and introduce little additional delay. A simple type is the direct-coupled bistable circuit, sometimes known as the Schmitt circuit, as shown in Figure 2-39. This example employs enhancement-mode P-channel field-effect transistors and can be made to function from either negative- or positive-going input waveforms. The example compares a negative-going input waveform with reference voltage $V_R$. 2-39
Under a variety of choices of supply voltage and resistances, the circuit will be bistable; that is, either of the two transistors can be conducting for a particular voltage at input gate G1. Until a predetermined value of reference voltage is reached, Q1 is nonconducting, and at time $T$, it switches from nonconducting to conducting, while Q2 simultaneously switches from conducting to nonconducting. With dc coupling, as shown in Figure 2-39, three outputs of differing dc levels and polarities are produced. If RC differentiating circuits are added as indicated, sharp pulses can then be obtained. When the input waveform ends, all points in the circuit return to their initial states.

Direct-coupled regenerative comparators, such as the Schmitt circuit, are usually bidirectional, responding to inputs approaching the reference level $V_R$ from either the positive or the negative side. If the input starts at a value lower than $V_R$, the output voltage $V_1$ will be at its high value until $V_R$ is
reached, and it then shifts to its low value. Polarities of the other output signals will be correspondingly reversed. Thus, at the voltage coincidence of \( V_i \) and \( V_R \), one of two possible output states, definable as logic level (1) or logic level (0) in digital terminology, will be generated. Because of design limitations in practical circuits, the input voltage at which the bistable circuit changes state is slightly less or greater than \( V_R \), depending upon whether the input signal is positive- or negative-going. This slight difference in level is referred to as the hysteresis of the circuit.

### Integrated Circuit Comparators

High-gain dc operational amplifiers operated in the nonfeedback mode are often used to perform the comparator function, and many such amplifiers are classified as comparators because they are specifically designed to meet the needs for accurate voltage comparison applications. Such “op-amps” have two inputs, the output being inverting with respect to one and noninverting with respect to the other, as shown in Figure 2-40. The voltage gain (amplification) of the amplifier is so high that its output will swing through its entire dynamic range, \( V_{\text{min}} \) to \( V_{\text{max}} \), for very small changes in input voltage. Thus, for \( V_{\text{im}} < V_R \), the amplifier will be cut off and the output voltage will be at \( V_{\text{max}} \), and for \( V_i > V_R \), the amplifier will saturate and the output will be at \( V_{\text{min}} \). For digital system applications, the output levels may be designed to coincide with logic level (0) and logic level (1) of the specific digital system, and thus be suitable for converting a specific level in a continuously varying signal to a specific logic number assigned to the level. Arrays of such comparators connected to a common input, each designed to respond at a distinct reference voltage and with the outputs connected to appropriate logic gates, may be used to convert a range of signal levels to a specific digital code, and as such form the basic building block of analog-to-digital converters.

![Figure 2-40 — Comparator circuit using integrated operational amplifier.](image)

The voltage gain, and hence the timing precision of the operational amplifier comparator, can be increased by converting it to a regenerative comparator, as shown in Figure 2-41.

### Digital Comparator

The term “digital comparator” has historically been used when the comparator circuit is specifically designed to respond to a combination of discrete level (digital) signals; for example, when one or more such input signals simultaneously reach the reference level that causes the change of state of the output. Among other applications, such comparators perform the function of the logic gate, such as the AND, OR (turned on when either input is high), and NAND functions. More often, however,
digital comparator is used to describe an array of logic gates designed specifically to determine whether one binary number is less than or greater than another binary number. Such digital comparators are sometimes called magnitude comparators or binary comparators.

Comparators may take many forms and can find many uses in addition to those that have been discussed. For example, the electronically regulated dc voltage supply uses a circuit that compares the dc output voltage with a fixed reference level. The resulting difference signal controls an amplifier, which, in turn, changes the output to the desired level. In a radio receiver, the automatic gain control circuit may be thought of broadly as a comparator; it measures the short-term average of the signal at the output of the detector, compares this output with a desired bias level on the radio-frequency amplifier stages, and changes that bias to maintain a constant average-level output from the detector.

**Analog-to-Digital Converter**

The analog-to-digital converter (sometimes called A-to-D converter) is a device for converting the information contained in the value or magnitude of some characteristics of an input signal, compared to a standard or reference. This input is compared to information in the form of discrete states of a signal, usually with numerical values assigned to the various combinations of discrete states of the signal.

A-to-D converters are used to transform analog information, such as audio signals or measurements of physical variables (for example, temperature, force, or shaft rotation) into a form suitable for digital handling, which might involve any of the following operations: (1) processing by a computer or by logic circuits, including arithmetical operations, comparison, sorting, ordering, and code conversion; (2) storage until ready for further handling; (3) display in numerical or graphical form; and (4) transmission.

If a wide-range analog signal can be converted, with adequate frequency, to an appropriate number of two-level digits, or bits, the digital representation of the signal can be transmitted through a noisy medium without relative degradation of the fine structure of the original signal.

Conversion involves quantizing and encoding. The term “quantizing” means partitioning the analog signal range into a number of discrete quanta and determining to which quantum the input signal belongs. The term “encoding” means assigning a unique digital code to each quantum and determining the code that corresponds to the input signal. The most common system is binary, in which there are $2^n$ quanta (where $n$ is some whole number), numbered consecutively; the code is a set of $n$ physical two-valued levels or bits (1 or 0) corresponding to the binary number associated with the signal quantum.

A typical three-bit binary representation of a range of input signals, partitioned into eight quanta, is shown in Figure 2-42. For example, a signal in the vicinity of $3/8$ full scale (between $5/16$ and $7/16$) will be coded 011 (binary 3).
Conceptually, the conversion can be made to take place in any kind of medium—electrical, mechanical, fluid, optical, and so on (for example, shaft-rotation to optical). By far the most commonly employed form of A-to-D converters comprises those devices that convert electrical voltages or currents to coded sets of binary electrical levels (for example, +5 V or 0 V) in simultaneous (parallel) or pulse-train (serial) form, as shown in Figure 2-43. The serial output is not always made available.

The converter depicted in Figure 2-43 converts the analog input to a five-digit “word.” If the coding is binary, the first digit, the most significant bit (MSB), has a weight of 1/2 full scale, the second 1/4 full scale, and so on, down to the \( n \)th digit, the least-significant bit (LSB), which has a weight of \( 2^{-n} \) of full scale (1/32 in this example). Thus, for the output word shown, the analog input must be given approximately by the following equation:

\[
\frac{16}{32} + \frac{0}{32} + \frac{4}{32} + \frac{2}{32} + \frac{0}{32} + \frac{22}{32} = \frac{11}{16} \text{ FS (full scale)}
\]
The number of bits, \( n \), characterizes the resolution of a converter.

A commonly used configuration of connections to an A-to-D converter is shown in Figure 2-43. Note the analog signal and reference inputs, the parallel and serial digital outputs, and the leads from the power supply that provide the required energy for operation. Additionally, two control leads—a start-conversion input and a status-indicating output (busy) indicate when a conversion is in progress. The reference voltage or current is often developed within the converter.

Second in importance to the binary code and its many variations is the BCD, which is used rather widely, especially when the encoded material is to be displayed in numerical form. In BCD, each digit of a radix-10 number is represented by a four-digit binary subgroup. For example, the BCD code for 379 is 0011 0111 1001. The output of the A-to-D converter used in digital panel meters is usually BCD.

Many techniques are used for A-to-D conversion, ranging from simple voltage-level comparators to sophisticated closed-loop systems, depending on the input level, output format, control features, and the desired speed, resolution, and accuracy. The two most popular techniques are dual-slope conversion and successive-approximations conversion.

Dual-slope converters have high resolution and low noise sensitivity; they operate at relatively low speeds, usually a few conversions per second. They are primarily used for direct dc measurements requiring digital readout; the technique is the basis of the most widely used approach to the design of digital panel meters.

A simplified block diagram of a dual-slope converter is shown in Figure 2-44, view A. The input is integrated for a period of time determined by a clock-pulse generator and counter (Figure 2-44, view B). The final value of the signal integral becomes the initial condition for integration of the reference in the opposite sense, while the clock output is counted. When the net integral is zero, the count stops. Because the integral “up” of the input over a fixed time (\( N_0 \) counts) is equal to the integral “down” of the fixed reference, the ratio of the number of counts of the variable period to that of the fixed period is equal to the ratio of the average value of the signal to the reference. Successive-approximations

![Figure 2-44 — Example of dual-slope conversion block diagram and output.](image)
conversion is a high-speed technique used principally in data-acquisition and computer-interface systems. The simplified block diagram of a successive-approximations converter is illustrated in Figure 2-45, view A. In a manner analogous to the operation of an apothecary’s scale with a set of binary weights, the input is “weighed” against a set of successively smaller fractions of the reference, produced by a digital-to-analog (sometimes called a DAC) converter that reflects the number in the output register.

First, the MSB is tried (1/2 full scale). If the signal is less than the MSB, the MSB code is returned to zero; if the signal is equal to or greater than the MSB, the MSB code is latched in the output register (Figure 2-45, view B). The second bit is tried (1/4 full scale). If the signal is less than 1/4 or 3/4, depending on the previous choice, bit 2 is set to zero; if the signal is equal to or greater than 1/4 or 3/4; bit 2 is retained in the output register. The third bit is tried (1/8 full scale). If the signal is less than 1/8, 3/8, 5/8, or 7/8, depending on previous choices, bit 2 is set to zero; otherwise, it is accepted. The trial continues until the contribution of the LSB has been weighed and either accepted or rejected. The conversion is then complete. The digital code latched in the output register is the digital equivalent of the analog input signal.

The earliest A-to-D converters were large rack-panel chassis-type modules using vacuum tubes, requiring about 1.4 ft³ (1/25 m³) of space and many watts of power. Since then, they have become smaller in size and cost, evolving through circuit-board, encapsulated module, and hybrid construction, with improved speed and resolution. Single-chip A-to-D converters with the ability to interface with microprocessors are now available in small IC packages.

**Digital-to-Analog Converter**

A digital-to-analog converter (DAC) is a device for converting information in the form of combinations of discrete states or a signal, often representing binary number values, to information in the form of the value or magnitude of some characteristics of a signal, in relation to a standard or reference. Most often, it is a device that has electrical inputs representing a parallel binary number, and an output in the form of voltage or current.

The structure of a typical DAC is shown in Figure 2-46. The essential elements, found even in the simplest devices, are enclosed within the dashed rectangle. The digital inputs, labeled $u_i$, $i = 1, 2, ..., n$, are equal to 1 or 0. The output voltage $E_0$ is given by the following equation, where $V_{REF}$ is an analog reference voltage and $K$ is a constant.

$$E_0 = KV_{REF}(u_12^{-1} + u_22^{-2} + u_32^{-3} + \ldots + u_n2^n)$$
Thus, for a five-bit binary converter with latched input code 10110, the output is given by the following equation.

\[ E_0 = (\frac{16}{32} + \frac{0}{32} + \frac{4}{32} + \frac{2}{32} + \frac{0}{32}) KV_{REF} = \frac{11}{16} KV_{REF} \]

Bit 1 is the MSB, with a weight of 1/2; bit \( n \) is the LSB, with a weight of \( 2^{-n} \). The number of bits \( n \) characterizes the resolution.

DACs are used to present the result of digital computation, storage, or transmission, typically for graphical display or for the control of devices that operate with continuously varying quantities. DAC circuits are also used in the design of A-to-D converters that employ feedback techniques, such as successive-approximations and counter-comparator types. In such applications, the DAC may not necessarily appear as a separately identifiable entity.

The fundamental circuit of most DACs involves a voltage or current reference; a resistive "ladder network" that derives weighted currents or voltages, usually as discrete fractions of the reference; and a set of switches, operated by the digital input, that determines which currents or voltages will be summed to constitute the output.

An elementary three-bit DAC converter is shown in Figure 2-47. Binary-weighted currents developed in \( R_1, R_2, \) and \( R_3 \) by \( V_{REF} \) are switched either directly to ground or to the output summing bus (which is held at zero volts by the operational-amplifier circuit). The sum of the currents develops an output voltage of polarity opposite to that of the reference across the feedback resistor \( R_f \). The binary relationship between the input code and the output, both as a voltage and as a fraction of the reference, is shown in Table 2-4.

The output of the DAC converter is proportional to the product of the digital input value and the reference. In many applications, the reference is fixed, and the output bears a fixed proportion to the digital input. In other applications, the reference, as well as the digital input, can vary; a DAC converter that is used in these applications is thus called a multiplying DAC. It is principally used for...
impacting a digitally controlled scale factor, or gain, to an analog input signal applied at the reference terminal.

![Diagram of a digital-to-analog converter](image)

**Figure 2-47 — Elementary three-bit DAC.**

Except for the highest resolutions (beyond 16 bits), commercially available DACs are generally manufactured in the form of dual in-line-packaged (DIP or DIL package) ICs, using bipolar, MOS, and hybrid technologies. A single chip may include just the resistor network and switches, or it may also include a reference circuit, output amplifier, and one or more sets of registers (with control logic suitable for direct microprocessor interfacing).

<table>
<thead>
<tr>
<th>Digital Input Code</th>
<th>Analog Output</th>
<th>( \frac{E_0}{V_{REF}} )</th>
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<tr>
<td>( \mu_1 )</td>
<td>( \mu_2 )</td>
<td>( \mu_3 )</td>
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**Table 2-4 — Input and Output of Converter**
Review Questions

2-1. How many charged regions make up a basic PN junction diode?

A. Two  
B. Three  
C. Four  
D. Six

2-2. What junction diode rating indicates maximum average current that can be permitted to flow for any length of time before damage will occur?

A. Repetitive reverse voltage  
B. Average forward current  
C. Surge current  
D. Repetitive forward current

2-3. You are selecting a diode from the parts-expended bin for one that has failed due to high heat conditions. Which of the following ratings should you look for in your replacement diode?

A. Average forward current, surge current, peak current, and repetitive reverse voltage  
B. Surge current, repetitive forward current, average inductance, and repetitive reverse voltage  
C. Average reference voltage, surge current, repetitive forward current, and repetitive reverse voltage  
D. Average forward current, surge current, repetitive forward current, and repetitive reverse voltage

2-4. What functional property is most commonly associated with a junction diode?

A. Amplification  
B. Rectifying  
C. Passivation  
D. Diffusion

2-5. What term describes a transistor that has all three electrical connections found on a single surface?

A. Bipolar  
B. Planar  
C. Passivated  
D. Double-diffused
2-6. What term refers to the method in which a transistor’s active material is fabricated?

A. Bipolar  
B. Passivated  
C. Planar  
D. Double-diffused

2-7. Which of the following characteristic accounts for the time delay in turning off and on a transistor when it is used as a switch?

A. Phase shift  
B. Transit time  
C. Charging time  
D. Storage capacity

2-8. What term refers to the control connection of a four-layer power switching transistor?

A. Source  
B. Emitter  
C. Gate  
D. Base

2-9. What transistor normally operates conducting and must be cut off by a voltage on the gate?

A. Junction gate field-effect transistor  
B. Insulated-gate field-effect transistor  
C. Metal-oxide-semiconductor field-effect transistor  
D. Bipolar

2-10. Which of the following transistor configurations is most commonly used?

A. Common-collector  
B. Common-base  
C. Common-emitter  
D. Common-gate

2-11. What is the (a) input and (b) output of a common-emitter connected transistor?

A. (a) Base to collector (b) base to emitter  
B. (a) Base to emitter (b) collector to emitter  
C. (a) Emitter to base (b) collector to base  
D. (a) Base to collector (b) emitter to collector
2-12. Refer to the figure above. What happens to the output voltage \((V_o)\) of the inverter circuit shown if the input voltage \((V_i)\) goes to nearly 0 volts?

A. \(V_o\) increases to one-half the value of \(V_{DD}\).
B. \(V_o\) increases to a value almost equal to \(V_{DD}\).
C. \(V_o\) decreases to 0 volts.
D. \(V_o\) stays constant.

2-13. Thyristors are most commonly used in which of the following applications?

A. Mixer
B. Impedance matcher
C. Switch
D. Oscillator

2-14. Which of the following transistor devices is most commonly used for power controls?

A. Junction gate field-effect transistor
B. Metal-oxide-semiconductor field-effect transistor
C. Triode alternating-current
D. Silicon-controlled rectifier

2-15. What thyristor is a symmetrical reverse-blocking triode that is able to turn off current with a negative gate input signal?

A. Gate turn-off
B. Asymmetrical silicon-controlled rectifier
C. Resistive turn-off device
D. Silicon-controlled rectifier

2-16. What term describes the method of obtaining a variable-voltage direct current from a battery source?

A. Latch switching
B. Phase controlling
C. Voltage chopping
D. Reverse blocking
2-17. Which of the following discrete electronic components is the most difficult to fabricate as an integrated circuit?

A. Inductor  
B. Capacitor  
C. Resistor  
D. Transistor

Refer to the figure to the right in answering questions 2-18 and 2-19.

2-18. What is the (a) input node and (b) output node of the basic complementary metal-oxide-semiconductor (CMOS) invertor?

A. (a) Drain (b) gate  
B. (a) Gate (b) drain  
C. (a) Source (b) gate  
D. (a) Drain (b) source

2-19. With no input signal to the complementary metal-oxide-semiconductor (CMOS) invertor, what is the (a) state and (b) voltage of the loading capacitor?

A. (a) Discharged (b) 0 volts  
B. (a) Charged (b) 0 volts  
C. (a) Charged (b) 5 volts  
D. (a) Discharged (b) 5 volts

2-20. What is the designation for a military-grade Schottky transistor-transistor logic (TTL) device?

A. 5400  
B. 54S00  
C. 54L00  
D. 54H00

2-21. What is the major advantage of gallium arsenide integrated circuits over silicon integrated circuits?

A. Faster switching speed  
B. Lower power requirement  
C. Reduced output noise  
D. Higher audio fidelity
2-22. A particular logic gate can drive four following logic gates. What is the logic gate term that best describes this characteristic?

A. Flip-flop  
B. Fan-in  
C. Fan-out  
D. Reset-set

2-23. What number system is the simplest that can be directly implemented with electronic circuitry?

A. Binary  
B. Octal  
C. Decimal  
D. Hexadecimal

2-24. What circuit changes an audio signal to a numerical display?

A. Comparator  
B. Logic gate  
C. Digital to analog converter (DAC)  
D. Analog to digital converter (A-to-D)
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