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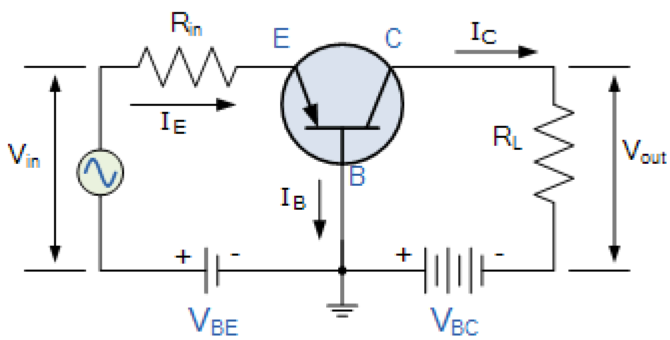
Nandikotkur Road, Venkayapalli, Kurnool – 518452

Department of Electronics and Communication Engineering

Bridge Course
On
VLSI Design

Bipolar Transistor

If we now join together two individual signal diodes back-to-back, this will give us two PN-junctions connected together in series that share a common P or N terminal. The fusion of these two diodes produces a three layer, two junctions, three terminal device forming the basis of a **Bipolar Junction Transistor,** or **BJT** for short.



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

- Active Region – the transistor operates as an amplifier and Ic = β.Ib
- Saturation – the transistor is "Fully-ON" operating as a switch and Ic = I(saturation)
- Cut-off – the transistor is "Fully-OFF" operating as a switch and Ic = 0

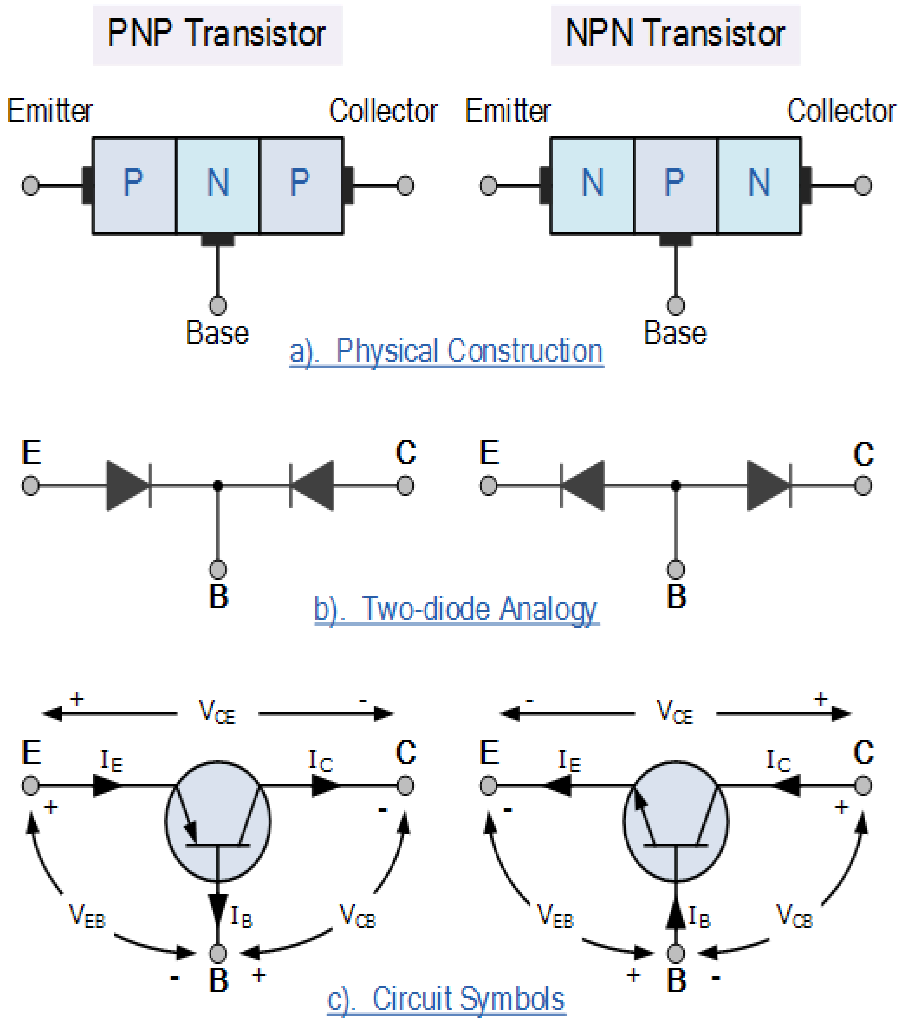
A Typical Bipolar Transistor

The word Transistor is an acronym, and is a combination of the words Transfer Varistor used to describe their mode of operation way back in their early days of development. There are two basic types of bipolar transistor construction, PNP and NPN, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

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

Bipolar Transistors are current regulating devices that control the amount of current flowing through them in proportion to the amount of biasing voltage applied to their base terminal acting like a current-controlled switch. The principle of operation of the two transistor types PNP and NPN, is exactly the same the only difference being in their biasing and the polarity of the power supply for each type.

Bipolar Transistor Construction



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

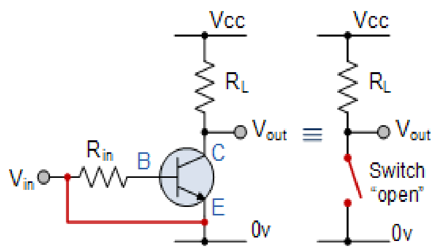
Bipolar Transistor Configurations

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

- Common Base Configuration – has Voltage Gain but no Current Gain.
- Common Emitter Configuration – has both Current and Voltage Gain.
- Common Collector Configuration – has Current Gain but no Voltage Gain.

Transistor as a Switch

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



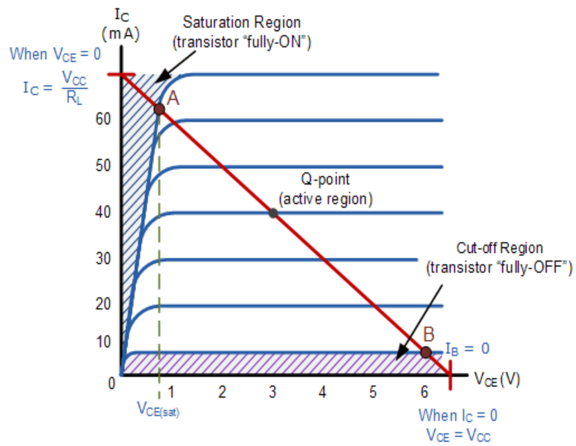
However, both the NPN & PNP type bipolar transistors can be made to operate as "ON/OFF" type solid state switch by biasing the transistors Base terminal differently to that for a signal amplifier.

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

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

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

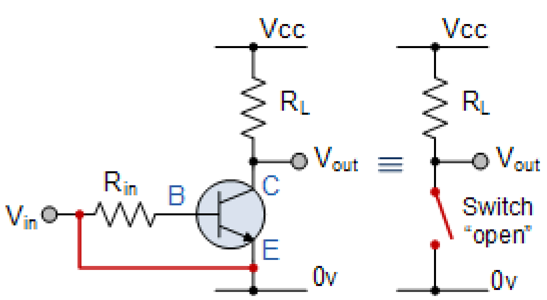
Operating Regions



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

1. Cut-off Region

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



- The input and Base are grounded (0v)
- Base-Emitter voltage $V_{BE} < 0.7$v
- Base-Emitter junction is reverse biased
- Base-Collector junction is reverse biased
- Transistor is "fully-OFF" (Cut-off region)
- No Collector current flows ($I_C = 0$)
- $V_{OUT} = V_{CE} = V_{CC}$ = "1"
- Transistor operates as an "open switch"

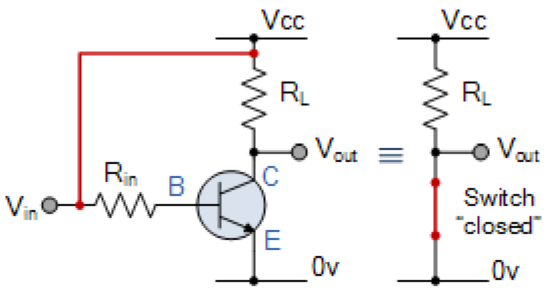
Then we can define the "cut-off region" or "OFF mode" when using a bipolar transistor as a switch as being, both junctions reverse biased, $V_B < 0.7$v and $I_C = 0$. For a PNP transistor, the Emitter potential must be negative with respect to the Base.

2. Saturation Region

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

GPCET

Pioneering Innovative Education



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

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

Then the transistor operates as a "single-pole single-throw" (SPST) solid state switch. With a zero signal applied to the Base of the transistor it turns "OFF" acting like an open switch and zero collector current flows. With a positive signal applied to the Base of the transistor it turns "ON" acting like a closed switch and maximum circuit current flows through the device.

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

Advantages of BJT

- High driving capability
- High frequency operation
- Digital logic family has an emitter coupled logic used in BJTs as a digital switch

Applications of BJT

Following are the two different types of applications in BJT they are

- Switching
- Amplification

Field Effect Transistor:

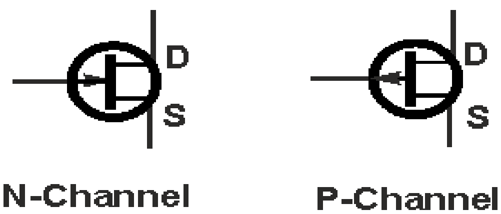
Field effect circuits are used in many different areas of electronics. FET circuits are able to provide characteristics that are not possible when using the more traditional bipolar transistors.

Accordingly FET circuit design techniques are often used in overall circuit design.

With the number of different types of FET, there are several differ types of FET circuit that can be used both as discrete circuits and within integrated circuits as well.

The FET has three electrodes:

- ***Source:*** The Source, S is the electrode on the FET through which the majority carriers enter the channel, i.e. at acts as the source of carriers for the device. Current entering the channel through the source is designated by IS
- ***Drain:*** The Drain, D is the FET electrode through which the majority carriers leave the channel, i.e. they are drained from the channel. Conventional current entering the channel at D is designated by the letters ID. Also Drain to Source voltage is often designated by the letters VDS
- ***Gate:*** The Gate G), is the terminal that controls the channel conductivity. By applying voltage to G, one can control ID



Circuit symbols for the basic JFET components

FET types for circuit design

As there are several different types of field effect transistor that can be used, it is necessary to define at least some of the FETs that can be used within the circuit design process.

The table below defines some of the different types and characteristics that can be encountered.

FETs for Use in Circuit Design

Characteristic	Details
J-FET	The J-FET or junction FET is a form of FET where the gate is formed by using a diode junction onto the channel. The isolation is maintained by ensuring that the diode junction remains reverse biased when operated within the circuit. IT is a key requirement of the FET circuit design to ensure the junction remains reverse biased for satisfactory operation.
MOSFET	This type of field effect transistor relies on a metal oxide later between the gate and channel. It offers a very high input resistance.
Dual-gate MOSFET	As the name implies, this form of MOSFET has two gates. In FET circuit design, this gives additional options.
Enhancement mode	Enhancement mode FETs are OFF at zero gate-source voltage. They are turned on by pulling the gate voltage in the direction of the

FETs for Use in Circuit Design

Characteristic	Details
	drain voltage, i.e. towards the supply rail, which is positive for N-channel devices and negative for P-channel devices. In other words by pulling the gate voltage towards the drain voltage, the number of carriers in the active layer of the channel is enhanced.
Depletion mode	In a depletion-mode MOSFET, the device is normally ON at zero gate-source voltage. Any gate voltage in the direction of the drain voltage will tend to deplete the active area of channel of carriers and reduce the current flowing.
N-channel	An N channel FET has a channel made from N-type semiconductor in which the majority carriers are electrons.
P-channel	An P channel FET has a channel made from P-type semiconductor in which the majority carriers are holes.

When designing an FET circuit, one of the first steps is to determine what type of FET will be suitable for the application required. Channel type, mode type and the basic type of FET will all need to be determined to enable the FET circuit design to proceed.

Advantages, disadvantages and application of FET over BJT

Advantages

1. FET gas high input impedance of several mega ohms.
2. The noise produced by a FET is less than that produced by a BJT.
3. FETs are less effect by radiation compared to BJT.
4. FET has no offset voltage at zero drain current and hence it forms an excellent signal chopper.
5. FETs are voltage controlled devices.
6. FETs have better thermal stability.
7. In the integrated circuit form FET is simpler to fabricate and it occupies less – space.

Disadvantages

FETs have a drawback of smaller gain bandwidth product compared to BJT.

Applications

The high input impedance and low output impedance and low noise level make FET for superior of the bipolar transistor. Some of the circuit applications of FET are

1. **As a buffer amplifier:** Because of high input impedance and low output impedance, a FET can act as an excellent buffer amplifier.
2. **Phase shift oscillators:** The high input impedance of FET is especially valuable in phase shift oscillator to minimize the loading effect.
3. **In Voltmeters:** The high input impedance of FET is useful in Voltmeters to act as an input stage.

BJTs and FETs are two different kinds of transistors and also known as active semiconductor devices. The acronym of the BJT is Bipolar Junction Transistor and FET stands for Field Effect Transistor. BJTS and FETS are available in a variety of packages based on the operating frequency, current, voltage and power ratings. These types of devices allow a greater degree of control over their working. BJTS and FETs can be used as switches and amplifiers in electrical and electronics circuits. The major difference between BJT and FET is that, in a field effect transistor only majority charge carries flows, whereas in BJT both majority and minority charge carriers flows.

BJT vs MOSFET

The transistors BJT and MOSFET are both useful for amplification and switching applications. Yet, they have significantly different characteristics.

BJT, as in Bipolar Junction Transistor, is a semiconductor device that replaced the vacuum tubes of the old days. The contraption is a current-controlled device where the collector or emitter output is a function of the current in the base. Basically, the mode of operation of a BJT transistor is driven by the current at the base. The three terminals of a BJT transistor are called the Emitter, Collector and Base.

A BJT is actually a piece of silicon with three regions. There are two junctions in them where each region is named differently -the P and N. There two type of BJTs, the NPN transistor and the PNP transistor. The types differ in their charge carriers, wherein, NPN has holes as its primary carrier, while PNP has electrons.

The operation principles of the two BJT transistors, PNP and NPN, are practically identical; the only difference is in biasing, and the polarity of the power supply for each type. Many prefer BJTs for low current applications, like for switching purposes for instance, simply because they're cheaper.

Metal Oxide Semiconductor Field-Effect Transistor, or simply MOSFET, and sometimes MOS transistor, is a voltage-controlled device. Unlike the BJT, there is no base current present. However, there's a field produced by a voltage on the gate. This allows a flow of current between the source and the drain. This current flow may be pinched-off, or opened, by the voltage on the gate.

In this transistor, a voltage on an oxide-insulated gate electrode can generate a channel for conduction between the other contacts - the source and drain. What's great about MOSFETs is that they handle power more efficiently. MOSFETs, nowadays, are the most common transistor used in digital and analog circuits, replacing the then very popular BJTs.

Summary:

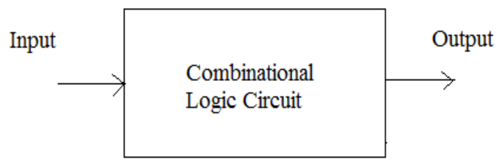
1. BJT is a Bipolar Junction Transistor, while MOSFET is a Metal Oxide Semiconductor Field-Effect Transistor.
2. A BJT has an emitter, collector and base, while a MOSFET has a gate, source and drain.
3. BJTs are preferred for low current applications, while MOSFETs are for high power functions.

4. In digital and analog circuits, MOSFETs are considered to be more commonly used than BJTs these days.
5. The operation of MOSFET depends on the voltage at the oxide-insulated gate electrode, while the operation of BJT is dependent on the current at the base.

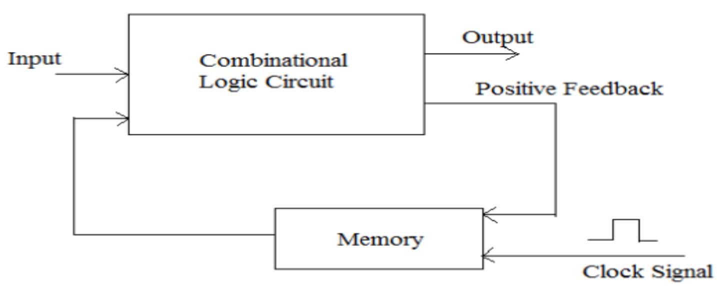
Difference between Combinational and Sequential logic circuits:

Combinational and Sequential circuits are the most essential concepts to be understood in digital electronics.

Combinational logic (sometimes also referred to as time-independent logic) is a type of digital logic which is implemented by Boolean circuits, where the output is a pure function of the present input only.



Sequential logic is a type of logic circuit whose output depends not only on the present value of its input signals but on the sequence of past inputs.



Combinational Logic Circuits	Sequential Logic Circuits
Output is a function of the present inputs (Time Independent Logic).	Output is a function of clock, present inputs and the previous states of the system.
Do not have the ability to store data (state).	Have memory to store the present states that is sent as control input (enable) for the next operation.
It does not require any feedback. It simply outputs the input according to the logic designed.	It involves feedback from output to input that is stored in the memory for the next operation.

Used mainly for Arithmetic and Boolean operations.	Used for storing data (and hence used in RAM).
Logic gates are the elementary building blocks.	Flip flops (binary storage device) are the elementary building unit.
Independent of clock and hence does not require triggering to operate.	Clocked (Triggered for operation with electronic pulses).
Example: Adder [1+0=1; Dependency only on present inputs i.e., 1 and 0].	Example: Counter [Previous O/P +1=Current O/P; Dependency on present input as well as previous state].

Semiconductor memory

Semiconductor memory is an electronic data storage device, often used as computer memory, implemented on a semiconductor-based integrated circuit. There are many different types of implementations using various technologies.

Most types of semiconductor memory have the property of random access, which means that it takes the same amount of time to access any memory location, so data can be efficiently accessed in any random order. This contrasts with data storage media such as hard disks and CDs which read and write data consecutively and therefore the data can only be accessed in the same sequence it was written. Semiconductor memory also has much faster access times than other types of data storage; a byte of data can be written to or read from semiconductor memory within a few nanoseconds, while access time for rotating storage such as hard disks is in the range of milliseconds. For these reasons it is used for main computer memory (primary storage), to hold data the computer is currently working on, among other uses.

Shift registers, processor registers, data buffers and other small digital registers that have no memory address decoding mechanism are not considered as memory although they also store digital data.

Description

In a semiconductor memory chip, each bit of binary data is stored in a tiny circuit called a *memory cell* consisting of one to several transistors. The memory cells are laid out in rectangular arrays on the surface of the chip. The 1-bit memory cells are grouped in small units called *words* which are accessed together as a single memory address. Memory is manufactured in word length that is usually a power of two, typically N=1, 2, 4 or 8 bits.

Data is accessed by means of a binary number called a memory address applied to the chip's address pins, which specifies which word in the chip is to be accessed. If the memory address consists of M bits, the number of addresses on the chip is 2^M, each containing an N bit word. Consequently, the amount of data stored in each chip is $N2^M$ bits.[2] The memory storage capacity for M number of address lines is given by 2^M, which is usually in power of two: 2, 4, 8, 16, 32, 64, 128, 256 and 512 and measured in kibibits, mebibits, gibibits or tebibits, etc. Currently (2014) the largest semiconductor memory chips hold a few gibibits of data, but higher capacity memory is constantly being developed. By combining several integrated circuits, memory can be arranged into a larger word length and/or address space than what is offered by each chip, often but not necessarily a power of two.

The two basic operations performed by a memory chip are "*read*", in which the data contents of a memory word is read out (nondestructively), and "*write*" in which data is stored in a memory word, replacing any data that was previously stored there. To increase data rate, in some of the latest types of memory chips such as DDR SDRAM multiple words are accessed with each read or write operation.

In addition to standalone memory chips, blocks of semiconductor memory are integral parts of many computer and data processing integrated circuits. For example, the microprocessor chips that run computers contain cache memory to store instructions awaiting execution.

Types

RAM chips for computers usually come on removable memory modules like these. Additional memory can be added to the computer by plugging in additional modules.

RAM (*Random-access memory*) has become a generic term for any semiconductor memory that can be written to, as well as read from, in contrast to ROM *(below)*, which can only be read. All semiconductor memory, not just RAM, has the property of random access.

Volatile memory loses its stored data when the power to the memory chip is turned off. However it can be faster and less expensive than non-volatile memory. This type is used for the main memory in most computers, since data is stored on the hard disk while the computer is off. Major types are:

DRAM (*Dynamic random-access memory*) which uses memory cells consisting of one capacitor and one transistor to store each bit. This is the cheapest and highest in density, so it is used for the main memory in computers. However the electric charge that stores the data in the memory cells slowly leaks off, so the memory cells must be periodically refreshed (rewritten), requiring additional circuitry. The refresh process is automatic and transparent to the user.

FPM DRAM (*Fast page mode DRAM*) An older type of asynchronous DRAM that improved on previous types by allowing repeated accesses to a single "page" of memory to occur at a faster rate. Used in the mid-1990s.

EDO DRAM (*Extended data out DRAM*) An older type of asynchronous DRAM which had faster access time than earlier types by being able to initiate a new memory access while data from the previous access was still being transferred. Used in the later part of the 1990s.

VRAM (*Video random access memory*) An older type of dual-ported memory once used for the frame buffers of video adapters (video cards).

SDRAM (*Synchronous dynamic random-access memory*) This was a reorganization of the DRAM memory chip, which added a clock line to enable it to operate in synchronism with the computer's memory bus clock. The data on the chip is divided into *banks* so it can work on several memory accesses simultaneously, in separate banks. It became the dominant type of computer memory by about the year 2000.

DDR SDRAM (*Double data rate SDRAM*) This was an increased data rate modification, enabling the chip to transfer twice the memory data (two consecutive words) on each clock cycle by double pumping, transferring data on both the leading and trailing edges of the clock pulse. Extensions of this idea are the current (2012) technique being used to increase memory access rate and bandwidth. Since it is proving difficult to further increase the internal clock speed of memory chips, these chips increase data rate by transferring data in larger blocks:

- **DDR2 SDRAM** transfers 4 consecutive words per internal clock cycle
- **DDR3 SDRAM** transfers 8 consecutive words per internal clock cycle.
- **DDR4 SDRAM** transfers 16 consecutive words per internal clock cycle.

RDRAM (*Rambus DRAM*) an alternate double data rate memory standard that was used on some Intel systems but ultimately lost out to DDR SDRAM.

SGRAM (*Synchronous graphics RAM*) a specialized type of SDRAM made for graphics adaptors (video cards). It can perform graphics-related operations such as bit masking and block write, and can open two pages of memory at once.

PSRAM (*Pseudostatic RAM*) This is DRAM which has circuitry to perform memory refresh on the chip, so that it acts like SRAM, allowing the external memory controller to be shut down to save energy. It is used in a few portable game controllers such as the Wii.

- **SRAM** (*Static random-access memory*) which relies on several transistors forming a digital flip-flop to store each bit. This is less dense and more expensive per bit than DRAM, but faster and does not require memory refresh. It is used for smaller cache memories in computers.
- **Content-addressable memory** This is a specialized type in which, instead of accessing data using an address, a data word is applied and the memory returns the location if the word is stored in the memory. It is mostly incorporated in other chips such as microprocessors where it is used for cache memory.

Nonvolatile memory preserves the data stored in it during periods when the power to the chip is turned off. Therefore, it is used for the memory in portable devices, which don't have disks, and for removable memory cards among other uses. Major types are:

- **ROM** (*Read-only memory*) This is designed to hold permanent data, and in normal operation is only read from, not written to. Although many types can be written to, the writing process is slow and usually all the data in the chip must be rewritten at once. It is usually used to store system software which must be immediately accessible to the computer, such as the BIOS program which starts the computer, and the software (microcode) for portable devices and embedded computers such as microcontrollers.

- **Mask programmed ROM** In this type the data is programmed into the chip during manufacture, so it is only used for large production runs. It cannot be rewritten with new data.
- **PROM** (*Programmable read-only memory*) In this type the data is written into the chip before it is installed in the circuit, but it can only be written once. The data is written by plugging the chip into a device called a PROM programmer.
- **EPROM** (*Erasable programmable read-only memory*) In this type the data in it can be rewritten by removing the chip from the circuit board, exposing it to an ultraviolet light to erase the existing data, and plugging it into a PROM programmer. The IC package has a small transparent "window" in the top to admit the UV light. It is often used for prototypes and small production run devices, where the program in it may have to be changed at the factory.

- **EEPROM** (*Electrically erasable programmable read-only memory*) In this type the data can be rewritten electrically, while the chip is on the circuit board, but the writing process is slow. This type is used to hold firmware, the low level microcode which runs hardware devices, such as the BIOS program in most computers, so that it can be updated.
- **NVRAM** ***(Flash memory)*** In this type the writing process is intermediate in speed between EEPROMS and RAM memory; it can be written to, but not fast enough to serve as main memory. It is often used as a semiconductor version of a hard disk, to store files. It is used in portable devices such as PDAs, USB flash drives, and removable memory cards used in digital cameras and cell phones.

Logic Families

Logic Families indicate the type of logic circuit used in the IC. The main types of logic families are:

- TTL(Transistor Transistor Logic)
- CMOS (Complementary MOS)
- ECL (Emitter Coupled Logic)

Characteristics of Logic Families

The main characteristics of Logic families include:

- Speed
- Fan-in
- Fan-out
- Noise Immunity
- Power Dissipation

Speed: Speed of a logic circuit is determined by the time between the application of input and change in the output of the circuit.

Fan-in: It determines the number of inputs the logic gate can handle.

Fan-out: Determines the number of circuits that a gate can drive.

Noise Immunity: Maximum noise that a circuit can withstand without affecting the output. Power: When a circuit switches from one state to the other, power dissipates.

Transistor–transistor logic (TTL)

Transistor–transistor logic (TTL) is a class of digital circuits built from bipolar junction transistors (BJTs) and resistors. It is called *transistor–transistor logic* because transistors perform both the logic function (e.g., AND) and the amplifying function (compare with resistor–transistor logic (RTL) and diode–transistor logic (DTL)).

TTL integrated circuits (ICs) were widely used in applications such as computers, industrial controls, test equipment and instrumentation, consumer electronics, and synthesizers. The designation *TTL* is sometimes used to mean TTL-compatible logic levels, even when not associated directly with TTL integrated circuits, for example as a label on the inputs and outputs of electronic instruments.

After their introduction in integrated circuit form in 1963 by Sylvania, TTL integrated circuits were manufactured by several semiconductor companies. The 7400 series (also called 74xx) by Texas Instruments became particularly popular. TTL manufacturers offered a wide range of logic gate, flip-flops, counters, and other circuits. Several variations of the original TTL circuit design were developed. The variations offered interchangeable functions that had higher speed or lower power dissipation to allow design optimization. TTL devices were originally made in ceramic and plastic dual-in-line (DIP) packages, and flat-pack form. TTL chips are now also made in surface-mount packages.

TTL became the foundation of computers and other digital electronics. Even after much larger scale integrated circuits made multiple-circuit-board processors obsolete, TTL devices still found extensive use as the glue logic interfacing more densely integrated components.

For logic gate built using TTL logic families, input are given to the emitters of the input transistor. In TTL logic family, analog value from 0 V to 0.8 V is logic 0 and 2 V to 5 V is logic 1. Advantages of the TTL logic families include high switching speed (125 MHz), less noise and more current (3 mA) driving capability.

Emitter-Coupled Logic (ECL)

In electronics, emitter-coupled logic (ECL) is a high-speed integrated circuit bipolar transistor logic family. ECL uses an overdriven BJT differential amplifier with single-ended input and limited emitter current to avoid the saturated (fully on) region of operation and its slow turn-off behavior. As the current is steered between two legs of an emitter-coupled pair, ECL is sometimes called *current-steering logic* (CSL), *current-mode logic* (CML) or *current-switch emitter-follower* (CSEF) logic.

In ECL, the transistors are never in saturation, the input/output voltages have a small swing (0.8 V), the input impedance is high and the output resistance is low; as a result, the transistors change states quickly, gate delays are low, and the fanout capability is high. In addition, the essentially-constant current draw of the differential amplifiers minimizes delays and glitches due to supply-line inductance and capacitance, and the complementary outputs decrease the propagation time of the whole circuit by reducing inverter count.

ECL's major disadvantage is that each gate continuously draws current, which means it requires (and dissipates) significantly more power than those of other logic families, especially when quiescent.

The equivalent of emitter-coupled logic made out of FETs is called source-coupled logic (SCFL).

A variation of ECL in which all signal paths and gate inputs are differential is known as differential current switch (DCS) logic.

Diode–transistor logic (DTL)

Diode–transistor logic (DTL) is a class of digital circuits that is the direct ancestor of transistor–transistor logic. It is called so because the logic gating function (e.g., AND) is performed by a diode network and the amplifying function is performed by a transistor (in contrast with RTL and TTL).

Resistor–transistor logic

Resistor–transistor logic (RTL) is a class of digital circuits built using resistors as the input network and bipolar junction transistors (BJTs) as switching devices. RTL is the earliest class of transistorized digital logic circuit used; other classes include diode–transistor logic (DTL) and transistor–transistor logic (TTL). RTL circuits were first constructed with discrete components, but in 1961 it became the first digital logic family to be produced as a monolithic integrated circuit. RTL integrated circuits were used in the Apollo Guidance Computer, whose design was begun in 1961 and which first flew in 1966.

Integrated injection logic

Integrated injection logic (IIL, I^2L, or I2L) is a class of digital circuits built with multiple collector bipolar junction transistors (BJT).[1] When introduced it had speed comparable to TTL yet was almost as low power as CMOS, making it ideal for use in VLSI (and larger) integrated circuits. Although the logic voltage levels are very close (High: 0.7V, Low: 0.2V), I2L has high noise immunity because it operates by current instead of voltage. It is sometimes also known as merged transistor logic.

Complementary metal–oxide–semiconductor(CMOS)

Complementary metal–oxide–semiconductor, abbreviated as CMOS, is a technology for constructing integrated circuits. CMOS technology is used in microprocessors, microcontrollers, static RAM, and other digital logic circuits. CMOS technology is also used for several analog circuits such as image sensors (CMOS sensor), data converters, and highly integrated transceivers for many types of communication. In 1963, while working for Fairchild Semiconductor, Frank Wanlass patented CMOS (US patent 3,356,858).

CMOS is also sometimes referred to as complementary-symmetry metal–oxide–semiconductor (or COS-MOS). The words "complementary-symmetry" refer to the fact that the typical design style with CMOS uses complementary and symmetrical pairs of p-type and n-type metal oxide semiconductor field effect transistors (MOSFETs) for logic functions.

Two important characteristics of CMOS devices are high noise immunity and low static power consumption. Since one transistor of the pair is always off, the series combination draws significant power only momentarily during switching between on and off states. Consequently, CMOS devices do not produce as much waste heat as other forms of logic, for example transistor–transistor logic (TTL) or NMOS logic, which normally have some standing current even when not changing state. CMOS also allows a high density of logic functions on a chip. It was primarily for this reason that CMOS became the most used technology to be implemented in VLSI chips.

The phrase "metal–oxide–semiconductor" is a reference to the physical structure of certain field-effect transistors, having a metal gate electrode placed on top of an oxide insulator, which in turn is on top of a semiconductor material. Aluminium was once used but now the material is polysilicon. Other metal gates have made a comeback with the advent of high-k dielectric materials in the CMOS process, as announced by IBM and Intel for the 45 nanometer node and beyond.

BiCMOS

BiCMOS is an evolved semiconductor technology that integrates two formerly separate semiconductor technologies, those of the bipolar junction transistor and the CMOS transistor, in a single integrated circuit device.

Bipolar junction transistors offer high speed, high gain, and low output resistance, which are excellent properties for high-frequency analog amplifiers, whereas CMOS technology offers high input resistance and is excellent for constructing simple, low-power logic gates. For as long as the two types of transistors have existed in production, designers of circuits utilizing discrete components have realized the advantages of integrating the two technologies; however, lacking implementation in integrated circuits, the application of this free-form design was restricted to fairly simple circuits. Discrete circuits of hundreds or thousands of transistors quickly expand to occupy hundreds or thousands of square centimeters of circuit board area, and for very high-speed circuits such as those used in modern digital computers, the distance between transistors (and the minimum capacitance of the connections between them) also makes the desired speeds grossly unattainable, so that if these designs cannot be built as integrated circuits, then they simply cannot be built.

In the 1990s,modern integrated circuit fabrication technologies began to make BiCMOS a reality. This technology rapidly found application in amplifiers and analog power management circuits, and has some advantages in digital logic. BiCMOS circuits use the characteristics of each type of transistor most appropriately. Generally this means that high current circuits use metal–oxide–semiconductor field-effect transistor (MOSFETs) for efficient control, and portions of specialized very high performance circuits use bipolar devices. Examples of this include radio frequency (RF) oscillators, bandgap-based references and low-noise circuits.

The Pentium, Pentium Pro, and SuperSPARC microprocessors also used BiCMOS.

Monolithic integrated circuit logic families compared

The following logic families would either have been used to build up systems from functional blocks such as flip-flops, counters, and gates, or else would be used as "glue" logic to interconnect very-large scale integration devices such as memory and processors. Not shown are some early obscure logic families from the early 1960s such as DCTL (direct-coupled transistor logic), which did not become widely available.

Propagation delay is the time taken for a two-input NAND gate to produce a result after a change of state at its inputs. *Toggle speed* represents the fastest speed at which a J-K flip flop could operate. *Power per gate* is for an individual 2-input NAND gate; usually there would be more than one gate per IC package. Values are very typical and would vary slightly depending on application conditions, manufacturer, temperature, and particular type of logic circuit. *Introduction year* is when at least some of the devices of the family were available in volume for civilian uses. Some military applications pre-dated civilian use.