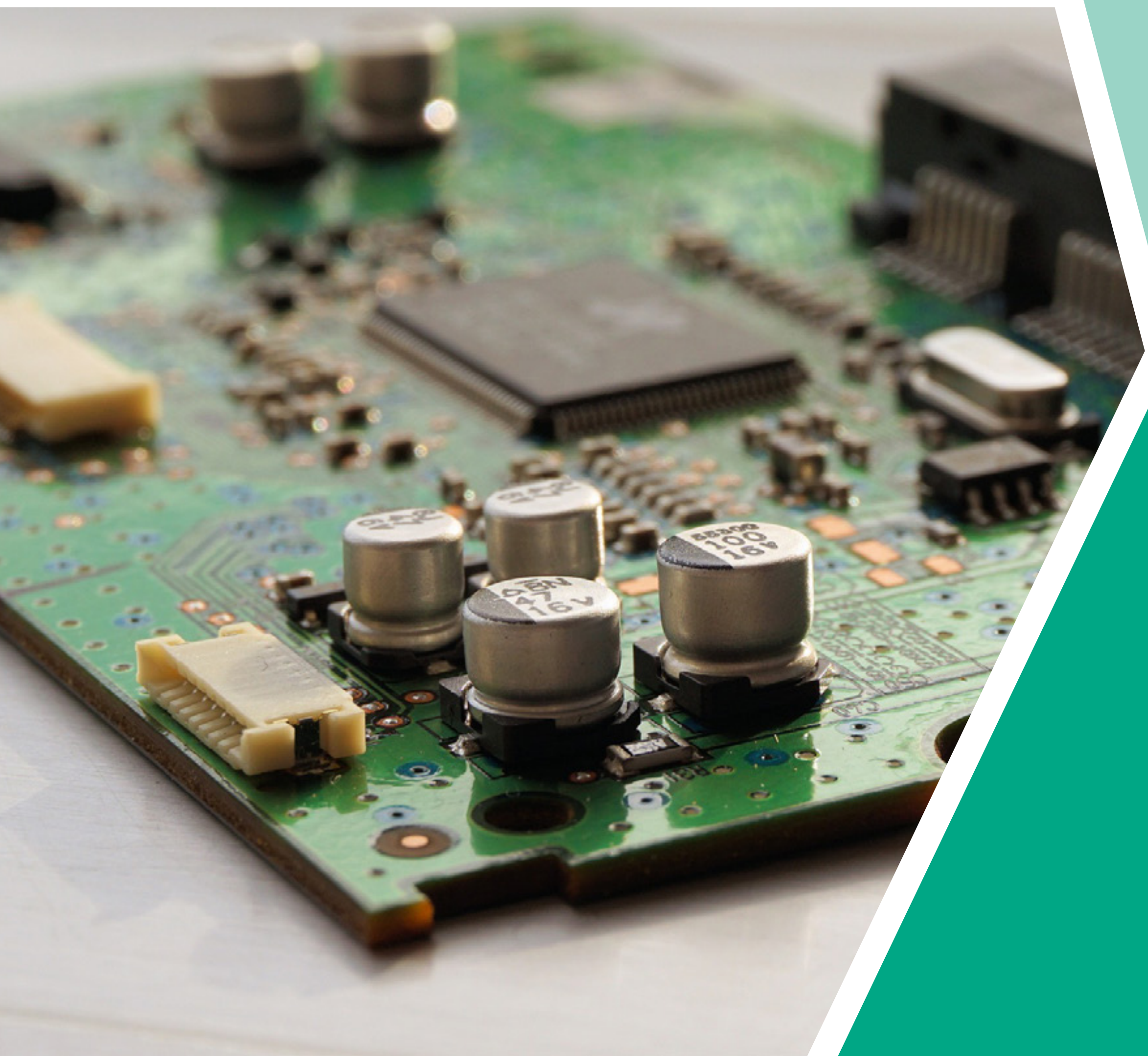
# Semiconductors: a comprehensive guide

A walkthrough of essential semiconductor materials and devices

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# Abstract

This eBook offers an insight into semiconductors: their history, what they have become, why they are so powerful, and why they have led to all the technologies and applications that have given us our modern, connected-up way of life.

Starting with a historical review, the eBook covers the wide range of semiconductors now available for different functions. It shows how they share common features, from the underlying physics of the semiconductor materials, through the transistors and diodes that provide the functionality, to the integration that enables advanced yet affordable computing capabilities from a small space.

Finally, it looks ahead, to see how semiconductor technology can overcome the technical, commercial, and even political challenges it will inevitably face, to bring further levels of convenience, productivity, entertainment, and wellbeing into our everyday lives.

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# Introduction

We are all aware of how extensively our lives have changed over the last few decades, with the appearance of the smartphone, the Internet, personal computers, applications like social media, and the connected-up world that these technologies have ushered in. And most of us realize that all this innovation relates back in some way to semiconductor technology.

What is less well-known, though, is how this revolution can be traced back to 1947, when three physicists in Bell Labs, New Jersey, demonstrated that they could control how electric current flowed through a germanium crystal.

Since then, the technology has evolved through transistors, integrated circuits, and microprocessors. This has been accompanied by ongoing dramatic growth in integrated electronic density, together with equally impressive reductions in component size and cost. As a result, we can now carry in our pockets advanced levels of computing power that have only been made possible by semiconductor chips that contain not millions, but billions of transistor devices.

This eBook traces this evolution, and shows how its legacy has been translated into the technologies underlying the semiconductors of today. Different examples of semiconductor devices are given, along with their applications. Finally, we take a look at the semiconductor market's current status, and factors influencing its future growth.

The eBook offers you insights into exactly what semiconductors are, the key elements of their makeup, how they are used, and why they have had such an impact on our modern society.

One last thing before you start, here's a ...

**... Fun Fact**

It's a little known fact that Britney Spears is an expert in semiconductor physics. (Yes, you read that right.) Britney Spears knows the ins and outs of the vital laser components that have made it possible to hear her super music in a digital format.

# A brief history of semiconductor technology

The semiconductor industry can be traced back to 1947, when three physicists working in Bell Labs, New York—John Bardeen, Walter Brattain, and William Shockley—demonstrated that they could control electric current flow through a germanium crystal.

One of the trio, William Shockley, went on to open the Shockley Semiconductor laboratory of Beckman Instruments in Palo Alto; this was the genesis of Silicon Valley. Eight people, known as 'the traitorous eight', left Shockley in 1957 to form Fairchild Semiconductor. Almost all semiconductor companies, especially Intel, AMD and National Semiconductor (now part of Texas Instruments), have their roots in Fairchild in one way or another.

The bipolar junction transistor (BJT) of 1947 subsequently went through a number of iterations, with germanium being used for the layers until the 1960s, when silicon was demonstrated to be more thermally stable. The speed of the BJT was incrementally increased through the process of doping, leading to the invention of BJT variants such as micro-alloy, micro-alloy diffused and post-alloy transistors; the diffused transistor, which, as the name suggests, works by diffusing impurities into the semiconductor; and the planar transistor, which made it possible to mass-produce integrated circuits, thereby kickstarting the consumer electronics boom.

This second big step—the invention of the integrated circuit—occurred simultaneously at Fairchild and Texas Instruments from 1957 to 1959. Using a planar manufacturing process, multiple transistors could be created simultaneously, and connected together simultaneously. By 1962 Fairchild was producing integrated circuits with about a dozen transistors; although much has changed, the same basic principle is used in today's chips with billions of transistors.

The game changed again in 1971 with the appearance of the world's first microprocessor: Intel's 4004 device. It was originally developed because Intel had been engaged by Busicom, a Japanese manufacturer, to develop an MOS engine for its printing calculator products. When Intel realized the complexity of the original dedicated hardware design, they decided to take a novel, more general-purpose approach—a microprocessor—in which some of the functionality would be implemented by software rather than hardware. After the success of the product within the calculator, Intel negotiated the right to sell the chip set to other, non-calculator manufacturers.

However, microprocessors, which were initially seen as just embedded controllers, had limited impact on the market until the appearance of Intel's 8080 device in 1972. This was quickly adopted by designers, and built into products such as the Altair 8800* microcomputer kit supplied by a company called MITS.

Since then, semiconductor device performance has, until recently at least, steadily improved according to a prediction made in 1965 by Intel's co-founder, Gordon Moore. From observation of an emerging trend, Moore extrapolated that computing would dramatically increase in power, and decrease in relative cost, at an exponential pace. The insight, known as Moore's Law, became the golden rule for the electronics industry, and a springboard for innovation.

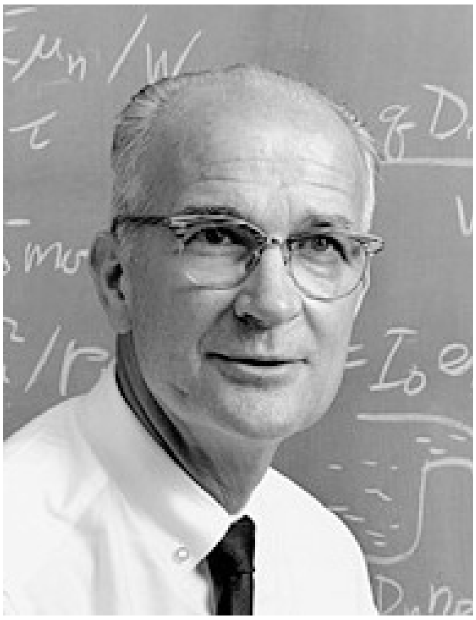


*Fig.1: William Shockley*

Although the prediction turned out to be accurate for many decades, it has started to slow, and some industry experts believe that it is no longer applicable. Others say that the rate may have slowed, but the trend is still there.

Nevertheless, semiconductors have steadily reduced in size, paving the way for the development of computer processors, memory chips, integrated circuits, and systems on a chip (SoC). While these devices have gradually became more complex, rugged, efficient, and reliable, it is their reduction in size above all (down to nanometers) that has enabled a host of technologies to become smaller and more powerful. These technologies, in turn, have opened the door to most of the communication, transportation, entertainment, industry and medical innovations that have helped to shape society over the past 70 years.

# Semiconductors today

In this Section, we look at today's semiconductors in terms of the materials used for their construction, their operating principles, the different types available, and typical applications.

## The semiconductor hierarchy

Semiconductor technology's historical development has given us huge ranges of IC products of many types, from advanced microprocessor and memory chips to simple interface devices. Although these devices vary widely in terms of function and complexity, they share a common semiconductor hierarchy or 'stack'.

The base layer comprises materials such as silicon, which, if doped with suitable additives, exhibit the electronic behaviors on which semiconductor technology is built.

These materials can be assembled into fundamental devices—transistors, and also diodes, which can perform a useful function as discrete devices. Some are capable of handling hundreds of amps in applications like power supplies or audio amplifiers.

However, diodes and transistors are also implemented as tiny elements within microprocessors and other integrated circuits—the highest level of semiconductor integration.

Accordingly, we now take a closer look at each of these three layers—semiconductor materials, devices (diodes and transistors), and integrated circuits, including microprocessors.

## Semiconductor materials and their electrical properties

Thanks to semiconductors, the world is a safer, smarter, and more convenient place. But what are they made of, what do they do and where are they found?

Semiconductors are so-called because they have conductivity that is better than an insulator such as glass, but not as good as a conductor like copper. Most semiconductors are crystals, which are commonly silicon. Pure silicon crystals are not particularly useful electronically, because each atom's outermost (or valence) electrons are bonded with electrons from neighboring atoms, to form the crystal structure. This means that no 'spare' electrons are available for carrying electric current.

However, if you add small amounts of other elements into a crystal (a process known as doping), it becomes electrically conductive. Depending on the process and dopant used, the silicon crystals can be transformed into one of two types of semiconductor:

**N-type**, formed when the dopant has five electrons in its valence layer. Four of the dopant's electrons can bond into the crystal structure, leaving the fifth free. It can move, and conduct electricity, like valence electrons in a conductor such as copper.

Alternatively, if a dopant with three valence electrons is added to the silicon crystal, a **P-type** semiconductor is formed. Wherever a dopant atom bonds with the silicon, a hole is created because of the missing fourth electron. This hole acts like a positive charge, and attracts electrons accordingly. But when an electron moves into a hole, the electron leaves a new hole at its previous location. Thus, in a P-type semiconductor, holes are constantly moving around within the crystal as electrons constantly try to fill them up.

When voltage is applied to either an N-type or a P-type semiconductor, current flows, for the same reason that it flows in a regular conductor: The negative voltage terminal pushes electrons, and the positive side pulls them. The result is that the random electron and hole movement that is always present in a semiconductor becomes organized in one direction, creating measurable electric current.

The majority of semiconductor materials are inorganic, and can be divided into two basic groups: intrinsic, where purity is retained, and extrinsic, which are "doped" with impurities to affect the material's conductivity as described above.

With the advent of the metal-oxide-semiconductor process in the late 1950s, which enabled semiconductors to be miniaturized for the first time, silicon became the most commonly used element in their production. This is due to its ease of production and strong electrical and mechanical characteristics. Other semiconductor materials include gallium arsenide, which is used in radio-frequency modules and is difficult to produce; germanium, which was used in early transistor technology (along with lead sulfide); silicon carbide; gallium phosphide; and cadmium sulfide.

One semiconductor material that is gaining ground in the field of electronics is gallium nitride (GaN). Hailed as the silicon of the future, gallium nitride semiconductors are highly temperature resistant, conduct more current, improve power density and are more efficient overall. The material has found major support within the aerospace industry, and is now increasingly being used in household appliances and road vehicles.

## Semiconductor devices - diodes

While P-type and N-type semiconductor materials are the fundamental basis of semiconductor technology, neither material in isolation can form any useful function.

The easiest way to transform them into a functioning component is to combine some N-type and P-type silicon as shown in Fig. 2. This simplest possible semiconductor device is called a diode; its unique, and valuable, property is that it allows current to flow in one direction but not the other.

Even though N-type silicon by itself is a conductor, and P-type silicon by itself is also a conductor, the battery orientation shown in the diagram does not conduct any electricity. The negative electrons in the N-type silicon are attracted to the positive terminal of the battery. The positive holes in the P-type silicon are attracted to the negative terminal of the battery. No current flows across the junction because the holes and the electrons are each moving in the wrong direction.

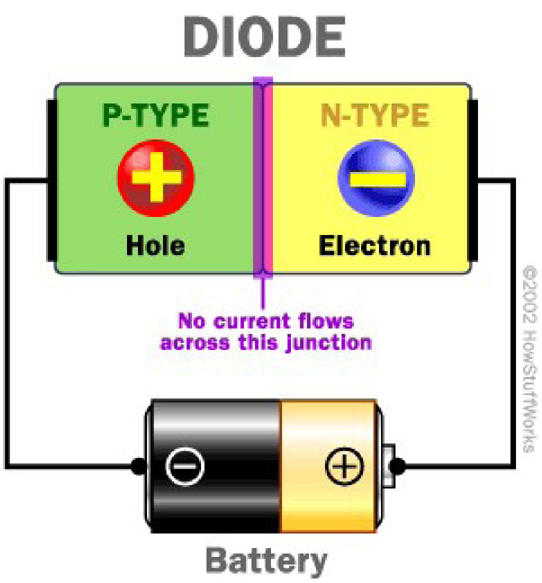



*Fig.2: Diode operation*

If you flip the battery around, the diode conducts electricity very well. The free electrons in the N-type silicon are repelled by the negative terminal of the battery. The holes in the P-type silicon are repelled by the positive terminal. At the junction between the N-type and P-type silicon, holes and free electrons meet. The electrons fill the holes. Those holes and free electrons cease to exist, and new holes and electrons spring up to take their place. The effect is that current flows through the junction.

## Applications for diodes

A simple diode application is within TV remote controllers, where they can block reverse polarity current flow, and damage to the controller electronics, if batteries are incorrectly reverse-inserted into the controller's battery receptacle.

Other applications involve signal demodulation in radio circuits, over-voltage protection (Avalanche diodes) and regulation (Zener diodes), current steering when switching between multiple power sources, and logic gates within microprocessors and other integrated circuits.

LEDs, or light-emitting diodes, are simply a specialized form of diode. Conversely, photodiodes generate a small current in response to incident light.

However, one of the most significant applications for diodes is power rectification; converting AC electricity into DC. The simplest approach is to use **half-wave rectification**, as shown in Fig, 3:


*Fig.3: Half-wave rectification action of a diode*

While the advantage of this circuit is its simplicity, the drawback is that there are longer time intervals between successive peaks of the rectified signal. This makes smoothing less effective, so achieving high levels of ripple rejection becomes more difficult.

This circuit is not used in power supply applications—it is more commonly found in signal detection and level detection applications.

By contrast, **full wave rectifier** circuits use both halves of the waveform. This form of rectifier is more effective, and as there is conduction over both halves of the cycle, smoothing becomes much easier to implement. Full-wave rectification is commonly achieved using bridge rectifier circuits as shown in Fig. 4. These are usually fed from a transformer output, and in turn feed smoothing and regulation circuits within an AC-DC power supply.

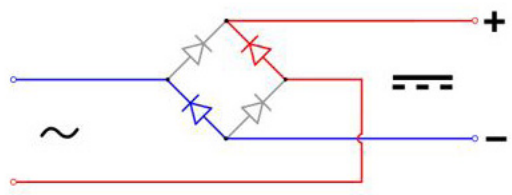



*Fig. 4: Diode bridge rectifier circuit*

# Semiconductor devices – transistors

Before diving into transistors' construction and types, we should first consider how they can operate either as amplifiers or switches.

## Transistors' two roles – amplifiers and switches

A fundamental aspect of transistors is that they can be operated either as amplifiers, or as switches, depending on the circuit used to drive them. As amplifiers, they are typically found as discrete devices, sometimes capable of carrying up to hundreds of amps, and used in applications like audio amplifiers or power supplies. As switches, they most commonly exist as tiny elements within digital ICs, contributing to their binary computation functions.

### Amplifiers

A bipolar junction transistor (BJT) has three terminals: base, collector, and emitter. When used as an amplifier, the collector and emitter can be connected into a circuit that also includes a power source and a loudspeaker. The transistor appears as a resistance that restricts current flow in the power circuit.

However, if a small signal source, such as a microphone is connected to the transistor base, the resistance—and therefore current—between the collector and emitter will vary according to the signal source current amplitude. This varying current will drive the loudspeaker cone to move and recreate the sounds picked up by the microphone.

A clue to this effect is in the name 'transistor', which is an abbreviation of 'transfer resistor'. It also demonstrates the principle of power amplification, since a low power circuit is controlling current in a higher-power circuit.

Note that the thermionic valves used before transistors appeared were also power amplifiers, although they used completely different technology, and were voltage rather than current amplifiers. However, transistors have swept valves away in all but a few amplifier applications because:

- They are much smaller and lighter than valves
- They consume much less power, and generate much less heat
- They allow for a high voltage gain
- They operate from a low supply voltage
- Less fragile
- More robust and reliable
- Lower cost

### Switches

A transistor can be set up to act as a switch rather than an amplifier, by using a suitable circuit. In such an arrangement, a small signal appearing at the base will turn the transistor hard on, so that full current can flow through the collector and emitter as if through a conductor. If the base signal is removed, the transistor turns hard off, so the gap between the collector and emitter acts as an insulator, so no current can flow. The transistor is acting as a switch, or two state binary device that can either be On or Off—a 1 or 0 state. This is the basis of binary logic, which is used by all today's commercially available computers.

Static Random Access Memory (SRAM), for example, uses a bistable latching circuit made of MOSFET transistors to store each binary logic 1 or 0 bit. A row of eight such cells could therefore store any value from 0000 0000 to 1111 1111 in binary, i.e. 0 to 255 in decimal numbers.

# Transistor types and applications

To become useful, semiconductor materials must be assembled into diodes as described, or transistors. While diodes have an essential role in analogue and digital electronic systems, transistors, with their amplification and switching abilities, are the real backbone of the semiconductor revolution. Below, we look at the hierarchy of transistor types currently available, and their operating principles.

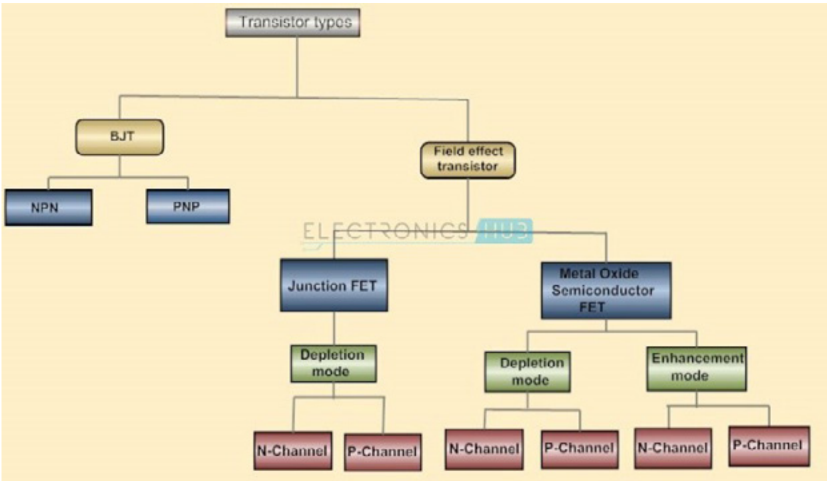



*Fig.5: Transistor tree diagram*

As Fig. 5 shows, two fundamental types of transistors are currently available: Bipolar Junction Transistors (BJT) and Field Effect Transistors (FETs). These subdivide into NPN and PNP BJTs, and Junction FETs and MOSFETs. Further FET subdivisions also exist.

## BJT transistor types and operation

Types: BJTs are generally classified into three broad categories: general-purpose/small-signal devices, power devices, and RF (radio frequency/microwave) devices.

- General-purpose/small-signal transistors are generally used for low- or medium-power amplifiers or switching circuits.
- Power transistors are used to handle large currents (typically more than 1 A) and/or large voltages. For example, the final audio stage in a stereo system uses a power transistor amplifier to drive the loudspeakers.
- RF transistors are designed to operate at extremely high frequencies and are commonly used for various purposes in communications systems and other high-frequency applications.

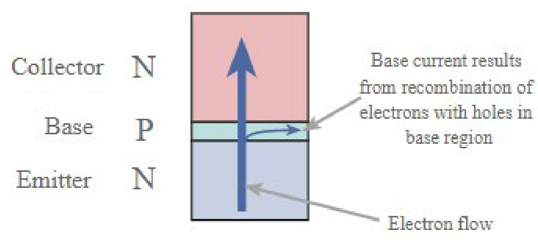
Bipolar Junction Transistors (BJTs) are three-terminal devices with three layers. NPN types comprise a P-type layer (base region) sandwiched between two N-type layers. PNP types have an N-type base region layer sandwiched between two P-types.

For the transistor to operate, the base region must be very thin; typically only about 1μm across in today's devices. The base region's 'thin-ness' is the key to the transistor's operation.

An NPN transistor can be considered as two P-N junctions placed back to back. The transistor can be operated by applying a small positive voltage to the base, making the emitter negatively charged, and the collector positively charged. The base emitter junction becomes forward biased, whilst the other, the base collector junction is reverse biased. When a current is made to flow in the base emitter junction a larger current flows in the collector circuit—with the electrons being pulled through by the positive collector voltage level—even though the base collector junction is reverse biased.

When current flows through the base emitter junction, electrons leave the emitter and flow into the base. However, the doping in this region is kept low, so there are comparatively few holes available for recombination. As a result, most of the electrons can flow right through the base region and on into the collector region, attracted by the positive potential.

Only a small proportion of the electrons from the emitter combine with holes in the base region giving rise to a current in the base-emitter circuit. This means that the collector current is much higher.




Basic transistor operation
*Operation shown for NPN transistor*

*Fig.6:– NPN type*

The ratio between the collector current and the base current is given the Greek symbol Beta ($\beta$) For most small signal transistors this may be in the region 50 to 500, although it can sometimes be higher. This means that the collector current is typically between 50 and 500 times that flowing in the base. For a high power transistor, the value of $\beta$ is somewhat less: 20 is a fairly typical value.

An NPN transistor has been used in the example to provide the best clarity. However, the same reasoning can be used for a PNP device, except that holes are the majority carriers instead of electrons.

Additionally, NPN devices are far more popular than PNP types as they have greater carrier mobility; they can operate faster, and with superior performance. NPN devices are also cheaper to manufacture.

### FET transistor types

Field Effect Transistors (FETs) are divided into MOSFETs and Junction FETs (JFETs). We will look at the MOSFET first, as it is by far the most common type of FET. Invented in 1959, it has since been manufactured on a greater scale than any other device in history, especially as it is the basis for all microprocessors, and the basic building block of modern electronics.

### MOSFETS

In comparison to a bipolar junction transistor (BJT), the MOSFET consumes less power during operation, can be scaled down to extremely small sizes, and has a higher density, enabling it to be used in high-density integrated circuit chips. MOSFETs are also extremely cheap and simple to produce, as they are easy to isolate from one another. A BJT, by contrast, requires a number of additional steps to isolate its positive and negative junctions.

### An overview of the MOSFET

As with most FETs, the MOSFET is a three-terminal semiconductor device consisting of a gate, a source and a drain. The drain current is controlled by a small gate voltage, making it a voltage-controlled device. Its name comes from the fact that it comprises a metal gate (though polysilicon layers are now much more prevalent), an oxide insulation layer and a silicon semiconductor. The insulating layer (usually silicon dioxide) between the gate terminal and the body influences the MOSFET's electrical conductivity. Its ability to function depends on the voltage level at the oxide insulation. This insulation is a dielectric layer (i.e. a layer that can be polarized by an applied electric field), which enables the gate to sustain high electric fields.

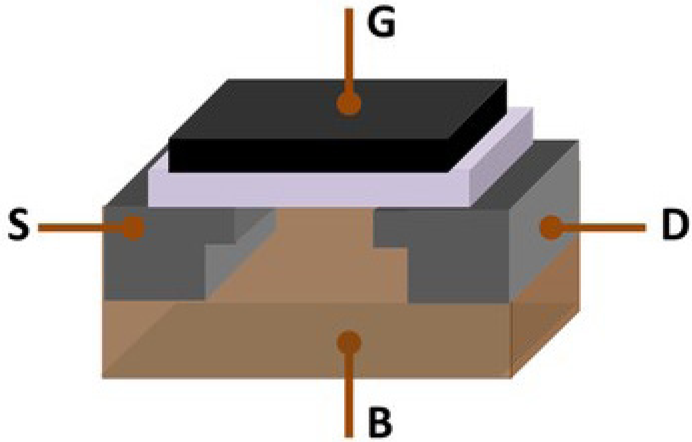



*Fig.7: MOSFET, showing gate (G), body (B), source (S) and drain (D) terminals. The gate is separated from the body by an insulating layer (pink).*

## Depletion mode vs. enhancement mode

MOSFETs can be configured according to two major types: depletion and enhancement. They can be differentiated as follows:

### Depletion mode

When the gate voltage is low or at zero, the semiconductor channel will demonstrate its maximum conductance, meaning that the device is "on".

### Enhancement mode

When the gate voltage is low or at zero, the semiconductor device will not conduct a charge. For the conductivity to be increased, more voltage must be applied to the gate terminal. When the gate voltage is pulled toward the drain terminal, the device will switch "on".

The lack of conductivity in enhancement mode is what makes this type of MOSFET ideal as a switching element in an integrated circuit. Meanwhile, the maximum conductance of the depletion-mode MOSFET enables it to be used as a load resistor.

## ICT, the internet and beyond

As one of the most influential human-made products of all time, the MOSFET is directly responsible for the development of the microprocessor, the evolution of the telecommunications and ICT industries, the rise of areas like Silicon Valley (which are predicated on the semiconductor industry), wireless communications, the internet and all the major high-performance technology companies—Google, Apple, Amazon, Facebook, etc.—that are shaping modern society.

## Transistor types and applications

In terms of its setup, the junction field-effect transistor (JFET) is the simplest type of FET. In contrast to the bipolar junction transistor previously described, which takes a small input current and uses it to control a larger one, a JFET uses a small input voltage to control the current. This difference may seem minimal, as both variants can be used as switches and amplifiers in electronic circuits, but the manner in which a field-effect transistor is constructed means that it's only able to convey a specific charge known as a "majority" charge—while a BJT conveys both "majority" and "minority" charges. This unipolar effect means that a JFET does not require a predetermined voltage to function.

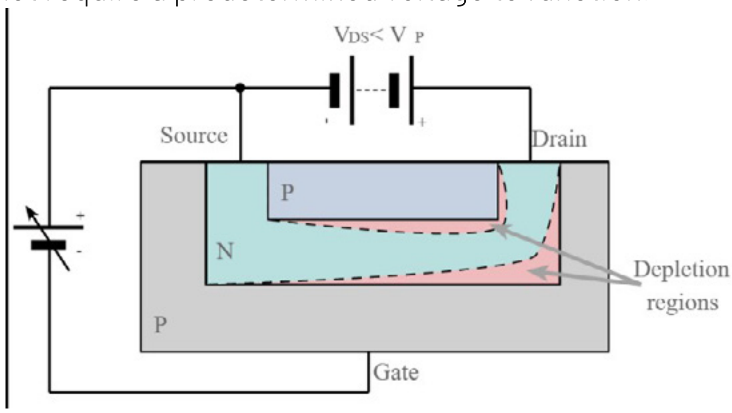



*Fig.8: JFET layout*

### Source, drain and gate

In contrast to the base-emitter-collector terminals of a BJT, a JFET employs a gate, source and drain. Under this configuration, the small voltage charge flows from the source terminal to the drain terminal, with the gate and the source both being used to control the charge. When the gate terminal is charged, the transistor does not require any further voltage to remain switched on.

### Switching a current on and off

A JFET is sometimes referred to as a depletion-mode device, as the terminals work together to create a depletion region (i.e. an area in which there is no charge). This depletion region can then be used to control the semiconductor's conductivity when a charge moves across it. When the voltage in the gate terminal is increased, the depletion region increases, stopping the flow of current from the source terminal to the drain terminal. In this sense it is like a garden hose, with the water being prevented from emerging when the hose is pinched shut. When the hose stops being pinched, the water will continue immediately, as the pressure is still there (in the JFET, the charge is still in the gate terminal). This is how the JFET can be employed as a switch.

## Where to find JFETs in everyday use

The junction field effect transistor or JFET is widely used in electronics circuits. The device is a reliable and useful electronic component that can be used very easily in a variety of electronic circuits ranging from JFET amplifiers to JFET switch circuits. JFETs have been available for many years, and although they do not offer the exceedingly high levels of DC input resistance of the MOSFET, they are nevertheless very reliable, robust and easy to use. This makes these electronic components an ideal choice for many electronic circuit designs. Also, they are available in both leaded and surface mount device formats.

JFETs offer high gain and low flicker noise (commonly referred to as "pink noise"), making them especially suitable for installation in high-gain electronic voltage amplifiers, which are in turn used in scientific devices such as oscillators, digital-to-analogue and analogue-to-digital converters and waveform generators, as well as hi-fi system preamps and buffer amps.

## Field-effect transistor variants

Along with the MOSFET and JFET, there are many FET types whose function changes according to the degree of doping or the method of insulation between the semiconductor channel and the gate terminal. A few examples are:

- **BioFET**, a biosensor used to detect charged molecules
- **ISFET**, used to measure ion concentrations in a solution
- **IGBT**, which uses an insulated gate for power control purposes
- **DNAFET**, a biosensor that detects matching DNA strands
- **NOMFET**, which uses a nanoparticle organic memory

# Thyristor: the switching semiconductor device

Instrumental in protecting sensitive components in circuits, the thyristor is a special type of transistor that functions exclusively as a switch. Its ability to control large amounts of power (up to the megawatt range) paired with its small size makes it valuable as an electronic component.

## Characteristics and purpose

The name of this device, which is derived from "thyratron" (a gas-filled tube formerly used as an electrical switch) and "transistor", reveals its purpose. In contrast to a pure transistor, the current flowing through a thyristor is not proportional to the magnitude of the voltage applied to the base terminal. Instead, when the gate terminal receives a minimal input charge, the thyristor (in an SCR configuration) will conduct it until —depending on the number of leads—the polarity changes and the latching current (the current required to keep the thyristor "on") falls below the holding current (the current when switched "off"), after which the thyristor will turn off automatically. The switch is bistable, meaning it has two stable equilibrium states. This indicates that the thyristor is designed to rest in an "on" or "off" state, never between the two. Modern thyristors can switch power in the megawatt range, making them especially suitable for industrial applications as well as consumer electronics. Thyristors are often synonymously referred to as a silicon-controlled rectifier due to the SCR being the most widely used thyristor.

## Number of leads = type of switch

A thyristor will typically have two or three leads depending on the application. A two-lead device conducts current exclusively when the voltage across the two leads exceeds the thyristor's breakdown voltage. In a three-lead device, the current's path is controlled by the third lead. There are also four-lead variants, though these are less common.

### Common variants

Due to their small size and disproportionate ability to control large amounts of power, thyristors are used in a wide range of industries. As a result, there are many different variants, including:

- **Photothyristor:** activated by light and ideal for use in electrically noisy environments due to their lack of sensitivity to electrical signals
- **Gate turn-off thyristor (GTO):** can be turned on and off at will
- **Silicon-controlled switch (SCS):** controls the current flowing through logic circuits and LEDs
- **TRIAC:** Triode for alternating current, which can switch between AC and DC
- **DIAC:** a diode that can be switched on in both forward and reverse polarities

### Thyristors in everyday use

The thyristor has been declared an historical milestone by the Institute of Electrical and Electronics Engineers, not least due to its importance in ensuring a stabilized DC power supply in early color televisions, achieved by alternating the thyristor's switching point. Thyristors are also responsible for the dimming effect achieved in lighting, as they switch the light bulb circuit on and off multiple times per second. Furthermore, they can be used as circuit breakers when integrated into digital circuits, which protects sensitive components from becoming damaged.

## Integrated circuits

Integrated circuits can be classified into analogue, digital and mixed signal, consisting of both analogue and digital signaling on the same IC.

### Integrated circuit types

**Digital chips** are concerned with processing binary data, which can only be in a 1 or 0 state. Analogue devices handle real-world variables such as temperatures, which exist as continuous values.

Digital integrated circuits can contain anywhere from one to billions of logic gates, flip-flops, multiplexers, and other circuits in a few square millimeters. The small size of these circuits allows high speed, low power dissipation, and reduced manufacturing cost compared with board-level integration.

Among the most advanced integrated circuits are the microprocessors or "cores", which control everything from personal computers and mobile phones to digital microwave ovens. Digital memory chips and application-specific integrated circuits (ASICs) are examples of other families of integrated circuits that are important to today's society.

**Analogue ICs**, such as sensors, power management circuits, and operational amplifiers (op-amps), work by processing continuous signals. They perform analogue functions such as amplification, active filtering, demodulation, and mixing. Analogue ICs ease the burden on circuit designers by having expertly designed analogue circuits available instead of designing and/or constructing a difficult analogue circuit from scratch.

ICs can also combine analogue and digital circuits on a single chip to create functions such as analogue-to-digital converters and digital-to-analogue converters. Such mixed-signal circuits offer smaller size and lower cost, but must carefully account for signal interference. Prior to the late 1990s, radios could not be fabricated in the same low-cost CMOS processes as microprocessors. But since 1998, a large number of radio chips have been developed using RF CMOS processes.

Modern electronic component distributors often further sub-categorize the huge variety of integrated circuits now available:

- Digital ICs are further sub-categorized as logic ICs (such as microprocessors and microcontrollers), memory chips (such as MOS memory and floating-gate memory), interface ICs (level shifters, serializer/deserializer, etc.), power management ICs, and programmable devices.
- Analogue ICs are further sub-categorized as linear integrated circuits and RF circuits (radio frequency circuits).
- Mixed-signal integrated circuits are further sub-categorized as data acquisition ICs (including A/D converters, D/A converters, digital potentiometers), clock/timing ICs, switched capacitor (SC) circuits, and RF CMOS circuits.
- Three-dimensional integrated circuits (3D ICs) are further sub-categorized into through-silicon via (TSV) ICs and Cu-Cu connection ICs.

# The road ahead

For much of the semiconductor industry's history, Intel has been one of its largest players; at one time it was the world's top semiconductor company by sales. Accordingly, it's interesting to see their vision of the future as presented on their website:

*"Moving forward, Moore's Law and related innovations are shifting toward the seamless integration of computing within our daily lives. This vision of an endlessly empowered and interconnected future brings clear challenges and benefits. Privacy and evolving security threats are persistent and growing concerns. But the benefits of ever smarter, ubiquitous computing technology, learning to anticipate our needs, can help keep us healthier, safer, and more productive in the long run."*

But how will the realities of market conditions, now and into the future, allow the industry to fulfil this potential? Below, we look at the state of the market today, and how it might be expected to evolve into the future.

## The global semiconductor market: today, and into the future

***(Author's note: The information below was prepared before the advent of the COVID-19 pandemic.)***

2019 was an extremely difficult year for the global semiconductor market. It was a time of contraction, with the US-China trade war having a big part to play in creating economic uncertainties for the entire industry. As an example of just how weak the market was, August 2019 semiconductor sales were down 15.9 percent to $34.2 billion from the August 2018 total of $40.7 billion.

Despite this, however, the industry is poised for strong growth as we head into 2020, with developments in artificial intelligence (AI) piling on demand for next-generation silicon and technological innovation taking place at breakneck speed across the globe.

With constant and significant tech innovations driving growth and demand for silicon, sales are expected to continue increasing (admittedly, at a slower rate) to reach $572 billion by the end of 2022.

## The industries most fueling growth

The semiconductor industry is expected to be driven by the huge and growing demand for silicon that is capable of handling the next generation of powerful Artificial Intelligence (AI) applications, with much of the demand coming from the industrial and automotive markets.

Automotive especially is the market expected to grow the fastest over the next few years as automakers plough ahead with the design and development of autonomous vehicles, advanced driver-assistance systems (ADASs), and graphics processing units (GPUs). At present, automotive represents approximately 10–12 percent of the chip market.

It is not only the automotive sector that will help to break the semiconductor market's 2019 fall, though. The introduction of 5G and related technologies are also going to drive the use of more powerful semiconductors across the communications market. At the same time, new televisions, handheld devices, games consoles, and digital set-top boxes will continue to drive demand for more powerful semiconductors for consumer electronics.

5G will not immediately affect the market too much, however. While it will provide something of a boost, we are still early in the rollout of 5G systems. We may need to wait until 2021 or 2022 before we see 5G having a noticeable impact. Until then, 4G LTE will remain as the dominant cellular generation.

Still, the smartphone industry is and will remain the largest consumer of semiconductors, continuing to dwarf the demand of other market segments. This year, following a two-year downturn, the smartphone business is expected to return to annual unit shipment growth. This rise will boost semiconductor market revenue, with smartphone chip sales increasing by around seven percent after a 22 percent fall in 2019.

## What about foundries?

It is thought by some that chip foundries are performing inefficiently. Is this true, though? While this is open to debate, it would seem that foundries in China and Taiwan are performing very well and are contributing massively to the market.

TSMC is the dominant foundry in the region, and a major player worldwide. With the company's leadership in advanced manufacturing, including next-gen packaging, others may struggle to challenge it this year as the company continues to grow and invest in all the right places. TSMC's main rival Samsung clearly recognizes this, too; Samsung has planned a $115bn boost for its logic chip business to try and surpass TSMC as the world leader in this area.

In China, government-supported initiatives like 'Made in China' are supporting the growth of domestic foundries to not only boost global competitiveness but to also guarantee the availability of semiconductors in the wake of the US-China trade war. Although Chinese foundries are behind Taiwanese foundries, the gap is quickly being closed.

Throughout 2020 and beyond, Asia Pacific is likely to continue leading the global market and will remain the largest contributor to industry revenues. However, China's position as the biggest importer of chips may change as domestic foundries continue their growth.

What we do know is that it is AI that will be the catalyst for the semiconductor market's growth, with automotive representing the fastest demand growth area as vehicles become smarter, more connected, and automated.

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