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integrated circuit

Dictionary: in·te·grat·ed circuit

(ĭn'tĭ-grā'tĭd)

n.

A complex set of electronic components and their interconnections that are etched or imprinted onto a tiny slice of semiconducting material.

integrated circuitry **integrated circuitry** *n.*

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integrated circuit

Assembly of microscopic electronic components (transistors, diodes, capacitors, and resistors) and their interconnections fabricated as a single unit on a wafer of semiconducting material, especially silicon. Early ICs of the late 1950s consisted of about 10 components on a chip 0.12 in. (3 mm) square. Very large-scale integration (VLSI) vastly increased circuit density, giving rise to the microprocessor. The first commercially successful IC chip (Intel, 1974) had 4,800 transistors; Intel's Pentium (1993) had 3.2 million, and more than a billion are now achievable.

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How Products are Made:

How is an integrated circuit made?

Background

An integrated circuit, commonly referred to as an IC, is a microscopic array of electronic circuits and components that has been diffused or implanted onto the surface of a single crystal, or chip, of semiconducting material such as silicon. It is called an integrated circuit because the components, circuits, and base material are all made together, or integrated, out of a single piece of silicon, as opposed to a discrete circuit in which the components are made separately from different materials and assembled later. ICs range in complexity from simple logic modules and amplifiers to complete microcomputers containing millions of elements.

The impact of integrated circuits on our lives has been enormous. ICs have become the principal components of almost all electronic devices. These miniature circuits have demonstrated low cost, high reliability, low power requirements, and high processing speeds compared to the vacuum tubes and transistors which preceded them. Integrated circuit microcomputers are now used as controllers in equipment such as machine tools, vehicle operating systems, and other applications where hydraulic, pneumatic, or mechanical controls were previously used. Because IC microcomputers are smaller and more versatile than previous control mechanisms, they allow the equipment to respond to a wider range of input and produce a wider range of output. They can also be reprogrammed without having to redesign the control circuitry. Integrated circuit microcomputers are so inexpensive they are even found in children's electronic toys.

The first integrated circuits were created in the late 1950s in response to a demand from the military for miniaturized electronics to be used in missile control systems. At the time, transistors and printed circuit boards were the state-of-the-art electronic technology. Although transistors made many new electronic applications possible, engineers were still unable to make a small enough package for the large number of components and circuits required in complex devices like sophisticated control systems and handheld programmable calculators. Several companies were in competition to produce a breakthrough in miniaturized electronics, and their development efforts were so close that there is some question as to which company actually produced the first IC. In fact, when the integrated circuit was finally patented in 1959, the patent was awarded jointly to two individuals working separately at two different companies.

After the invention of the IC in 1959, the number of components and circuits that could be incorporated into a single chip doubled every year for several years. The first integrated circuits contained only up to a dozen components. The process that produced these early ICs was known as small scale integration, or SSI. By the mid-1960s, medium scale integration, MSI, produced ICs with hundreds of components. This was followed by large scale integration techniques, or LSI, which produced ICs with thousands of components and made the first microcomputers possible.

The first microcomputer chip, often called a microprocessor, was developed by Intel Corporation in 1969. It went into commercial production in 1971 as the Intel 4004. Intel introduced their 8088 chip in 1979, followed by the Intel 80286, 80386, and 80486. In the late 1980s and early 1990s, the designations 286, 386, and 486 were well known to computer users as reflecting increasing levels of computing power and speed. Intel's Pentium chip is the latest in this series and reflects an even higher level.

How Integrated Circuit Components Are Formed

In an integrated circuit, electronic components such as resistors, capacitors, diodes, and transistors are formed directly onto the surface of a silicon crystal. The process of manufacturing an integrated circuit will make more sense if one first understands some of the basics of how these components are formed.

Even before the first IC was developed, it was known that common electronic components could be made from silicon. The question was how to make them, and the connecting circuits, from the same piece of silicon? The solution was to alter, or dope, the chemical composition of tiny areas on the silicon crystal surface by adding other chemicals, called dopants. Some dopants bond with the silicon to produce regions where the dopant atoms have one electron they can give up. These are called N regions. Other dopants bond with the silicon to produce regions where the dopant atoms have room to take one electron. These are called P regions. When a P region touches an N region, the boundary between them is referred to as a PN junction. This boundary is only 0.000004 inches (0.0001 cm) wide, but is crucial to the operation of integrated circuit components.

Within a PN junction, the atoms of the two regions bond in such a manner as to create a third region, called a depletion region, in which the P dopant atoms capture all the N dopant extra electrons, thus depleting them. One of the phenomena that results is that a positive voltage applied to the P region can cause an electrical current to flow through the junction into the N region, but a similar positive voltage applied to the N region will result in little or no current flowing through the junction back into the P region. This ability of a PN junction to either conduct or insulate depending on which side the voltage is applied can be used to form integrated circuit components that direct and control current flows in the same manner as diodes and transistors. A diode, for example, is simply a single PN junction. By altering the amount and types of dopants and changing the shapes and relative placements of P and N regions, integrated circuit components that emulate the functions of resistors and capacitors can be also be formed.

Design

Some integrated circuits can be considered standard, off-the-shelf items. Once designed, there is no further design work required. Examples of standard ICs would include voltage regulators, amplifiers, analog switches, and analog-to-digital or digital-to-analog converters. These ICs are usually sold to other companies who incorporate them into printed circuit boards for various electronic products.

Other integrated circuits are unique and require extensive design work. An example would be a new microprocessor for computers. This design work may require research and development of new materials and new manufacturing techniques to achieve the final design.

Raw Materials

Pure silicon is the basis for most integrated circuits. It provides the base, or substrate for the entire chip and is chemically doped to provide the N and P regions that make up the integrated circuit components. The silicon must be so pure that only one out of every ten billion atoms can be an impurity. This would be the equivalent of one grain of sugar in ten buckets of sand. Silicon dioxide is used as an insulator and as a dielectric material in IC capacitors.

Typical N-type dopants include phosphorus and arsenic. Boron and gallium are typical P-type dopants. Aluminum is commonly used as a connector between the various IC components. The thin wire leads from the integrated circuit chip to its mounting package may be aluminum or gold. The mounting package itself may be made from ceramic or plastic materials.

The Manufacturing Process

Hundreds of integrated circuits are made at the same time on a single, thin slice of silicon and are then cut apart into individual IC chips. The manufacturing process takes place in a tightly controlled environment known as a clean room where the air is filtered to remove foreign particles. The few equipment operators in the room wear lint-free garments, gloves, and coverings for their heads and feet. Since some IC components are sensitive to certain frequencies of light, even the light sources are filtered. Although manufacturing processes may vary depending on the integrated circuit being made, the following process is typical.

Preparing the silicon wafer

- A cylindrical ingot of silicon about 1.5 to 4.0 inches (3.8 to 10.2 cm) in diameter is held vertically inside a vacuum chamber with a high-temperature heating coil encircling it. Starting at the top of the cylinder, the silicon is heated to its melting point of about 2550°F (1400°C). To avoid contamination, the heated region is contained only by the surface tension of the molten silicon. As the region melts, any impurities in the silicon become mobile. The heating coil is slowly moved down the length of the cylinder, and the impurities are carried along with the melted region. When the heating coil reaches the bottom, almost all of the impurities have been swept along and are concentrated there. The bottom is then sliced off, leaving a cylindrical ingot of purified silicon.
- A thin, round wafer of silicon is cut off the ingot using a precise cutting machine called a wafer slicer. Each slice is about 0.01 to 0.025 inches (0.004 to 0.01 cm) thick. The surface on which the integrated circuits are to be formed is polished.
- The surfaces of the wafer are coated with a layer of silicon dioxide to form an insulating base and to prevent any oxidation of the silicon which would cause impurities. The silicon dioxide is formed by subjecting the wafer to superheated steam at about 1830°F (1000°C) under several atmospheres of pressure to allow the oxygen in the water vapor to react with the silicon. Controlling the temperature and length of exposure controls the thickness of the silicon dioxide layer.

Masking

- The complex and interconnected design of the circuits and components is prepared in a process similar to that used to make printed circuit boards. For ICs, however, the dimensions are much smaller and there are many layers superimposed on top of each other. The design of each layer is prepared on a computer-aided drafting machine, and the image is made into a mask which will be optically reduced and transferred to the surface of the wafer. The mask is opaque in certain areas and clear in others. It has the images for all of the several hundred integrated circuits to be formed on the wafer.
- A drop of photoresist material is placed in the center of the silicon wafer, and the wafer is spun rapidly to distribute the photoresist over the entire surface. The photoresist is then baked to remove the solvent.
- The coated wafer is then placed under the first layer mask and irradiated with light. Because the spaces between circuits and components are so small, ultraviolet light

with a very short wavelength is used to squeeze through the tiny clear areas on the mask. Beams of electrons or x-rays are also sometimes used to irradiate the photoresist.
- The mask is removed and portions of the photoresist are dissolved. If a positive photoresist was used, then the areas that were irradiated will be dissolved. If a negative photoresist was used, then the areas that were irradiated will remain. The uncovered areas are then either chemically etched to open up a layer or are subjected to chemical doping to create a layer of P or N regions.

Doping—Atomic diffusion

- One method of adding dopants to create a layer of P or N regions is atomic diffusion. In this method a batch of wafers is placed in an oven made of a quartz tube surrounded by a heating element. The wafers are heated to an operating temperature of about 1500-2200°F (816-1205°C), and the dopant chemical is carried in on an inert gas. As the dopant and gas pass over the wafers, the dopant is deposited on the hot surfaces left exposed by the masking process. This method is good for doping relatively large areas, but is not accurate for smaller areas. There are also some problems with the repeated use of high temperatures as successive layers are added.

Doping—Ion implantation

- The second method to add dopants is ion implantation. In this method a dopant gas, like phosphine or boron trichloride, is ionized to provide a beam of high-energy dopant ions which are fired at specific regions of the wafer. The ions penetrate the wafer and remain implanted. The depth of penetration can be controlled by altering the beam energy, and the amount of dopant can be controlled by altering the beam current and time of exposure. Schematically, the whole process resembles firing a beam in a bent cathode-ray tube. This method is so precise, it does not require masking—it just points and shoots the dopant where it is needed. However it is much slower than the atomic diffusion process.

Making successive layers

- The process of masking and etching or doping is repeated for each successive layer depending on the doping process used until all of the integrated circuit chips are complete. Sometimes a layer of silicon dioxide is laid down to provide an insulator between layers or components. This is done through a process known as chemical vapor deposition, in which the wafer's surface is heated to about 752°F (400°C), and a reaction between the gases silane and oxygen deposits a layer of silicon dioxide. A final silicon dioxide layer seals the surface, a final etching opens up contact points, and a layer of aluminum is deposited to make the contact pads. At this point, the individual ICs are tested for electrical function.

Making individual ICs

- The thin wafer is like a piece of glass. The hundreds of individual chips are separated by scoring a crosshatch of lines with a fine diamond cutter and then putting the wafer under stress to cause each chip to separate. Those ICs that failed the electrical test are discarded. Inspection under a microscope reveals other ICs that were damaged by the separation process, and these are also discarded.
- The good ICs are individually bonded into their mounting package and the thin wire leads are connected by either ultrasonic bonding or thermocompression. The mounting package is marked with identifying part numbers and other information.
- The completed integrated circuits are sealed in anti-static plastic bags to be stored or shipped to the end user.

Quality Control

Despite the controlled environment and use of precision tools, a high number of integrated circuit chips are rejected. Although the percentage of reject chips has steadily dropped over the years, the task of making an interwoven lattice of microscopic circuits and components is still difficult, and a certain amount of rejects are inevitable.

Hazardous Materials and Recycling

The dopants gallium and arsenic, among others, are toxic substances and their storage, use, and disposal must be tightly controlled.

Because integrated circuit chips are so versatile, a significant recycling industry has sprung up. Many ICs and other electronic components are removed from otherwise obsolete equipment, tested, and resold for use in other devices.

The Future

It is difficult to tell with any certainty what the future holds for the integrated circuit. Changes in technology since the device's invention have been rapid, but evolutionary. Many changes have been made in the architecture, or circuit layout, on a chip, but the integrated circuit still remains a silicon-based design.

The next major leap in the advancement of electronic devices, if such a leap is to come, may involve an entirely new circuit technology. Better devices than the very best microprocessor have always been known to be possible. The human brain, for example, processes information much more efficiently than any computer, and some futurists have speculated that the next generation of processor circuits will be biological, rather than mineral. At this point, such matters are the stuff of fiction. There are no immediate signs that the integrated circuit is in any danger of extinction.

Where To Learn More

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[Article by: Joel Simon/; *Chris Cavette]*

Sci-Tech Encyclopedia:

Integrated circuits

Miniature electronic circuits produced within and upon a single semiconductor crystal, usually silicon. Integrated circuits range in complexity from simple logic circuits and amplifiers, about $^{1}/_{20}$ in. (1.3 mm) square, to large-scale integrated circuits up to about ½ in. (12 mm) square. They can contain millions of transistors and other components that provide computer memory circuits and complex logic subsystems such as microcomputer central processor units. *See also* Semiconductor; Silicon.

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-state diffusion, ion implantation, vacuum deposition, and sputtering.

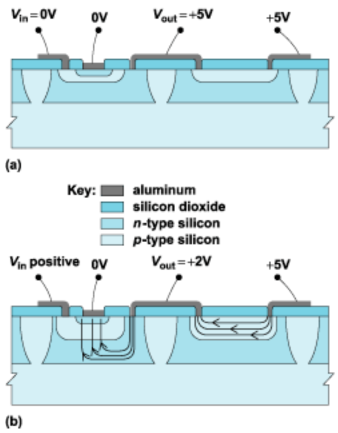
Generally, integrated circuits are not straightforward replacements of electronic circuits assembled from discrete components. They represent an extension of the technology by which silicon planar transistors are made. Because of this, transistors or modifications of transistor structures are the primary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

Integrated circuits can be classified into two groups on the basis of the type of transistors which they employ: bipolar integrated circuits, in which the principal element is the bipolar junction transistor; and metal oxide semiconductor (MOS) integrated circuits, in which the principal element is the 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. High-performance bipolar transistors and complementary MOS (CMOS) transistors have been combined on the same chip (BiCMOS) to obtain circuits combining high speed and high density.

Bipolar integrated circuits

A simple bipolar inverter circuit using a diffused resistor and an *npn* transistor is shown in Fig. 1. The input voltage $V_{\mathbf{in}}$ is applied to the base of the transistor. When $V_{\mathbf{in}}$ 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 $V_{\mathbf{out}}$ will be the same as the externally applied biasing voltage, +5 V in this example. 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.



Operation of bipolar inverter circuit (cross-sectional view). (a) Input voltage $V_{\mathbf{in}}$ is zero. (b) Positive input voltage applied; arrows indicate direction of current flow.

The 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, in order to keep costs down, to crowd more circuitry onto a given chip rather than to increase the number of chips on a wafer.

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 modems (data communications modulator-demodulator units). *See also* Analog-to-digital converter; Data communications.

In the continuing effort to increase the complexity and speed of digital circuits, and the performance characteristics and versatility of linear circuits, a significant role has been played by the discovery and development of new types of active and passive semiconductor devices which are suitable for use in integrated circuits. Among these devices is the *pnp* transistor which, when used in conjunction with the standard *npn* transistors described above, lends added flexibility to the design of integrated circuits.

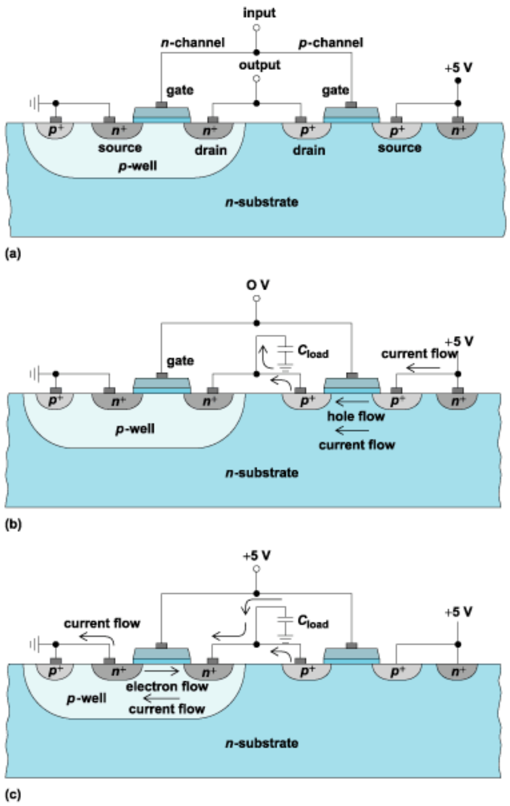
MOS integrated circuits

The other major class of integrated circuits is called MOS because its principal device is a metal oxide semiconductor field-effect transistor (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 10^{-7} in.$^{-2}$ (10^{-5} mm^{2}). This has made it practical to use millions of 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. *See also* Computer storage technology; Microprocessor; Semiconductor memories.

Several major types of MOS device fabrication technologies have been developed since the mid-1960s. They 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) *n*-channel MOS (NMOS), which is usually silicon gate; and (4) complementary MOS (CMOS), which employs both *p*-channel and *n*-channel devices.

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. What kept this simple device from commercial utilization until 1964 is the fact that 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 very great degree.

A simple CMOS inverter circuit is shown in Fig. 2. The gates of the *n*-channel 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.



Simple CMOS inverter circuit. (a) Schematic cross section. (b) Current flow when input is "low" at 0 V. (c) Current flow when input is "high" at 5 V.

When the input node is in the "low state," at 0 V, 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-V gate-to-source potential is clearly less 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, just the opposite occurs. The *n*-channel transistor will be turned on while the *p*-channel will be off. This will allow the load capacitor to discharge through the *n*-channel transistor resulting in the output voltage dropping 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.

This simple circuit illustrates a very important feature of CMOS circuits. Once the loading capacitor has been either charged to 5 V or discharged back to 0 V, there is no current flow, and the standby power is very low. This 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 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 price for CMOS's lower power are the additional fabrication steps required (10–20% more) when compared to NMOS.

BiCMOS integrated circuits

There is a strong interest in combining high-performance bipolar transistors and high-density CMOS transistors on the same chip (BiCMOS). This concept originated with work on bipolar circuits when power limitations became important as more functionality (and thus more transistors) was added to the chip. It is possible to continue adding more circuits on a chip without increasing the power by combining the low-power CMOS circuits with the bipolar circuits. This is done with both memory circuits and logic circuits, resulting in speeds somewhere between those of typical CMOS and bipolar-only circuits, but with the functional density of CMOS. The disadvantage of BiCMOS is its additional cost over plain CMOS or bipolar circuits, because the number of processing steps increases 20–30%. However, this increased complexity is expected to be used when either the additional functionality over bipolar circuits or the increased speed over CMOS circuits justifies the cost.

Fabrication

Integrated-circuit fabrication begins with a thin, polished slice of high-purity, single-crystal semiconductor (usually silicon) and employs a combination of physical and chemical processes to create the integrated-circuit structures described above. Junctions are formed in the silicon slice by the processes of thermal diffusion or high-energy ion implantation. Electrical isolation between devices on the integrated circuit is achieved with insulating layers grown by thermal oxidation or deposited by chemical deposition. Conductor layers to provide the necessary electrical connections on the integrated circuit are obtained by a variety of deposition techniques. Precision lithographic processes are used throughout the fabrication sequence to define the geometric features required.

Design

VLSI chips containing 10^6 transistors and operating at tens of megahertz have been designed and fabricated and are commercially available. Projections indicate that silicon chips containing as many as 10^8 transistors may be feasible for digital applications and that perhaps even a 10^9 transistor chip is feasible for dynamic random access memories (DRAMs) before fundamental limits constrain the growth of complexity. (The limits beyond which the size of a transistor cannot be reduced are thought to depend on the degradation of its material properties when it is operated at high-field conditions and the general degradation of its performance and reliability.) Computer-aided engineering (CAE) systems provide the environment, specific computer tools, data management, and other services that are intended to support the design of these very complex, high-performance products. In many cases, the design of complex chips requires the cooperative endeavors of large design teams; thus the CAE system must also manage the design process to ensure that proper documentation has occurred, needed changes in the design database are made, and a chosen design methodology is enforced. The design process must be adapted to the very short design cycle times from product conception to production of a salable product that are characteristic of the semiconductor industry.

Gallium arsenide circuits

Integrated circuits based on gallium arsenide (GaAs) have come into increasing use since the late 1970s. The major advantage of these circuits is their fast switching speed.

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. Unlike the MOSFET, the gate of the GaAs FET is a Schottky barrier composed of metal and gallium arsenide. 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 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. 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 gallium arsenide) 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 cm/s or 3×10^5 ft/s for gallium arsenide). At that point the device is in the saturated region of operation; that is, the current is independent of the drain voltage.

Modern Science:

integrated circuit

integrated circuit

A miniaturized electrical circuit built on a microchip.

Business Dictionary:

Integrated Circuit

Electronic device consisting of many miniature transistors and other circuit elements on a single silicon chip. The number of components that can be placed on a single chip has been steadily rising. The ultimate integrated circuit is the Microprocessor, which is a single chip that contains the complete arithmetic and logic unit of a computer.

Columbia Encyclopedia:

integrated circuit

integrated circuit (IC), electronic circuit built on a semiconductor substrate, usually one of single-crystal silicon. The circuit, often called a chip, is packaged in a hermetically sealed case or a nonhermetic plastic capsule, with leads extending from it for input, output, and power-supply connections, and for other connections that may be necessary when the device is put to use. Integrated circuits can be classified into two groups based on the type of transistors they contain. Bipolar integrated circuits contain bipolar junction transistors as their principle elements. Metal-oxide-semiconductor (MOS) integrated contain MOS transistors as their principle elements. Some integrated circuits contain both types of transistors. Integrated circuits are also categorized according to the number of transistors or other active circuit devices they contain. An IC is said to use small-scale integration (SSI) if it contains fewer than 10 transistors. An IC that contains from 10 to 100 transistors is said to use medium-scale integration. A large-scale integration (LSI) IC contains from 100 to 1,000 transistors, and one that uses very-large-scale integration (VLSI) contains more than 1,000 transistors. All ICs now employ VLSI, and these distinctions are only of historical importance. Some integrated circuits are analog devices; an operational amplifier is an example. Other ICs, such as the microprocessors used in computers, are digital devices. Some hybrid integrated circuits contain both analog and digital circuitry; a bilateral switch, which switches analog signals by means of a digital control signal is an example of a hybrid IC. Integrated circuit functions are virtually limitless. Improvements in IC manufacturing have led to increasingly dense and capable integrated circuits. Some microprocessors, for example, contain more than one billion transistors on their chips. The smaller, denser chips can also provide speed benefits, because in high-speed devices, the length of time it takes a signal to travel a given distance can become a factor. The major fabricating steps for integrated circuits include film formation, impurity doping, photolithography, etching, and packaging. See microelectronics.

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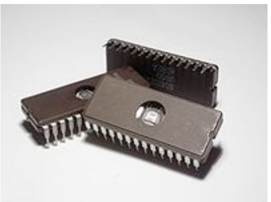
Wikipedia:

Integrated circuit

Integrated circuit of Atmel Diopsis 740 System on Chip showing memory blocks, logic and input/output pads around the periphery



Microchips (EPROM memory) with a transparent window, showing the integrated circuit inside. Note the fine silver-colored wires that connect the integrated circuit to the pins of the package. The window allows the memory contents of the chip to be erased, by exposure to strong ultraviolet light in an eraser device.

In electronics, an **integrated circuit** (also known as **IC**, **microcircuit**, **microchip**, **silicon chip**, or **chip**) is a miniaturized electronic circuit (consisting mainly of semiconductor devices, as well as passive components) that has been manufactured in the surface of a thin substrate of semiconductor material. Integrated circuits are used in almost all electronic equipment in use today and have revolutionized the world of electronics. Computers, cellular phones, and other digital appliances are now inextricable parts of the structure of modern societies, made possible by the low cost of production of integrated circuits.

A hybrid integrated circuit is a miniaturized electronic circuit constructed of individual semiconductor devices, as well as passive components, bonded to a substrate or circuit board. A monolithic integrated circuit is made of devices manufactured by diffusion of trace elements into a single piece of semiconductor substrate, a chip.

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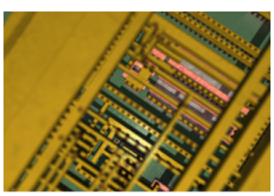
Introduction



Synthetic detail of an integrated circuit through four layers of planarized copper interconnect, down to the polysilicon (pink), wells (greyish), and substrate (green).

Integrated circuits were made possible by experimental discoveries which showed that semiconductor devices could perform the functions of vacuum tubes and by mid-20th-century technology advancements in semiconductor device fabrication. The integration of large numbers of tiny transistors into a small chip was an enormous improvement over the manual assembly of circuits using electronic components. The integrated circuit's mass production capability, reliability, and building-block approach to circuit design ensured the rapid adoption of standardized ICs in place of designs using discrete transistors.

There are two main advantages of ICs over discrete circuits: cost and performance. Cost is low because the chips, with all their components, are printed as a unit by photolithography and not constructed as one transistor at a time. Furthermore, much less material is used to construct a circuit as a packaged IC die than as a discrete circuit. Performance is high since the components switch quickly and consume little power (compared to their discrete counterparts) because the components are small and close together. As of 2006, chip areas range from a few square millimeters to around 350 mm^2, with up to 1 million transistors per mm^2.

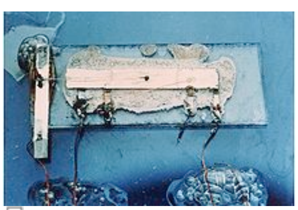
Invention

Early developments of the integrated circuit go back to 1949, when the German engineer Werner Jacobi (Siemens AG) filed a patent for an integrated-circuit-like semiconductor amplifying device [1] showing five transistors on a common substrate arranged in a 2-stage amplifier arrangement. Jacobi discloses small and cheap hearing aids as typical industrial applications of his patent. A commercial use of his patent has not been reported.

The idea of the integrated circuit was conceived by a radar scientist working for the Royal Radar Establishment of the British Ministry of Defence, Geoffrey W.A. Dummer (1909–2002), who published it at the Symposium on Progress in Quality Electronic Components in Washington, D.C. on May 7, 1952.[2] He gave many symposia publicly to propagate his ideas. Dummer unsuccessfully attempted to build such a circuit in 1956.

A precursor idea to the IC was to create small ceramic squares (wafers), each one containing a single miniaturized component. Components could then be integrated and wired into a bidimensional or tridimensional compact grid. This idea, which looked very promising in 1957, was proposed to the US Army by Jack Kilby, and led to the short-lived Micromodule Program (similar to 1951's Project Tinkertoy).[3] However, as the project was gaining momentum, Kilby came up with a new, revolutionary design: the IC.

Robert Noyce credited Kurt Lehovec of Sprague Electric for the *principle of p-n junction isolation* caused by the action of a biased p-n junction (the diode) as a key concept behind the IC.[4]



Jack Kilby's original integrated circuit

Jack Kilby recorded his initial ideas concerning the integrated circuit in July 1958 and successfully demonstrated the first working integrated circuit on September 12, 1958.[5] In his patent application of February 6, 1959, Kilby described his new device as "a body of semiconductor material ... wherein all the components of the electronic circuit are completely integrated." [6] Kilby won the 2000 Nobel Prize in Physics for his part of the invention of the integrated circuit.[7]

Robert Noyce also came up with his own idea of an integrated circuit half a year later than Kilby. Noyce's chip solved many practical problems that Kilby's had not. Noyce's chip, made at Fairchild Semiconductor, was made of silicon, whereas Kilby's chip was made of germanium.

Generations

SSI, MSI and LSI

The first integrated circuits contained only a few transistors. Called "**Small-Scale Integration**" (**SSI**), digital circuits containing transistors numbering in the tens provided a few logic gates for example, while early linear ICs such as the Plessey SL201 or the Philips TAA320 had as few as two transistors. The term Large Scale Integration was first used by IBM scientist Rolf Landauer when describing the theoretical concept, from there came the terms for SSI, MSI, VLSI, and ULSI.

SSI circuits were crucial to early aerospace projects, and vice-versa. Both the Minuteman missile and Apollo program needed lightweight digital computers for their inertial guidance systems; the Apollo guidance computer led and motivated the integrated-circuit technology[*citation needed*], while the Minuteman missile forced it into mass-production.

These programs purchased almost all of the available integrated circuits from 1960 through 1963, and almost alone provided the demand that funded the production improvements to reduce production costs from $1000/circuit (in 1960 dollars) to merely $25/circuit (in 1963 dollars).[*citation needed*] They began to appear in consumer products at the turn of the decade, a typical application being FM inter-carrier sound processing in television receivers.

The next step in the development of integrated circuits, taken in the late 1960s, introduced devices which contained hundreds of transistors on each chip, called "**Medium-Scale Integration**" (**MSI**).

They were attractive economically because while they cost little more to produce than SSI devices, they allowed more complex systems to be produced using smaller circuit boards, less assembly work (because of fewer separate components), and a number of other advantages.

Further development, driven by the same economic factors, led to "**Large-Scale Integration**" (**LSI**) in the mid 1970s, with tens of thousands of transistors per chip.

Integrated circuits such as 1K-bit RAMs, calculator chips, and the first microprocessors, that began to be manufactured in moderate quantities in the early 1970s, had under 4000 transistors. True LSI circuits, approaching 10000 transistors, began to be produced around 1974, for computer main memories and second-generation microprocessors.

VLSI

Main article: Very-large-scale integration

Upper interconnect layers on an Intel 80486DX2 microprocessor die.

The final step in the development process, starting in the 1980s and continuing through the present, was "very large-scale integration" (VLSI). The development started with hundreds of thousands of transistors in the early 1980s, and continues beyond several billion transistors as of 2009.

Mulitple developments were required to achieve this increased density. Manufacturers moved to smaller rules and cleaner fabs, so that they could make chips with more transistors and maintain adequate yield. The path of process improvements was summarized by the International Technology Roadmap for Semiconductors (ITRS). Design tools improved enough to make it practical to finish these designs in a reasonable time. The more energy efficient CMOS replaced NMOS and PMOS, avoiding a prohibitive increase in power consumption. Better texts such as the landmark textbook by Mead and Conway helped schools educate more designers, among other factors.

In 1986 the first one megabit RAM chips were introduced, which contained more than one million transistors. Microprocessor chips passed the million transistor mark in 1989 and the billion transistor mark in 2005[8]. The trend continues largely unabated, with chips introduced in 2007 containing tens of billions of memory transistors [9].

ULSI, WSI, SOC and 3D-IC

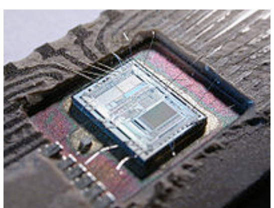
To reflect further growth of the complexity, the term *ULSI* that stands for "ultra-large-scale integration" was proposed for chips of complexity of more than 1 million transistors.

Wafer-scale integration (WSI) is a system of building very-large integrated circuits that uses an entire silicon wafer to produce a single "super-chip". Through a combination of large size and reduced packaging, WSI could lead to dramatically reduced costs for some systems, notably massively parallel supercomputers. The name is taken from the term Very-Large-Scale Integration, the current state of the art when WSI was being developed.

A system-on-a-chip (SoC or SOC) is an integrated circuit in which all the components needed for a computer or other system are included on a single chip. The design of such a device can be complex and costly, and building disparate components on a single piece of silicon may compromise the efficiency of some elements. However, these drawbacks are offset by lower manufacturing and assembly costs and by a greatly reduced power budget: because signals among the components are kept on-die, much less power is required (see Packaging).

A three-dimensional integrated circuit (3D-IC) has two or more layers of active electronic components that are integrated both vertically and horizontally into a single circuit. Communication between layers uses on-die signaling, so power consumption is much lower than in equivalent separate circuits. Judicious use of short vertical wires can substantially reduce overall wire length for faster operation.

Advances in integrated circuits



The die from an Intel 8742, an 8-bit microcontroller that includes a CPU running at 12 MHz, 128 bytes of RAM, 2048 bytes of EPROM, and I/O in the same chip.

Among the most advanced integrated circuits are the microprocessors or "**cores**", which control everything from computers to cellular phones to digital microwave ovens. Digital memory chips and ASICs are examples of other families of integrated circuits that are important to the modern information society. While the cost of designing and developing a complex integrated circuit is quite high, when spread across typically millions of production units the individual IC cost is minimized. The performance of ICs is high because the small size allows short traces which in turn allows low power logic (such as CMOS) to be used at fast switching speeds.

ICs have consistently migrated to smaller feature sizes over the years, allowing more circuitry to be packed on each chip. This increased capacity per unit area can be used to decrease cost and/or increase functionality—see Moore's law which, in its modern interpretation, states that the number of transistors in an integrated circuit doubles every two years. In general, as the feature size shrinks, almost everything improves—the cost per unit and the switching power consumption go down, and the speed goes up. However, ICs with nanometer-scale devices are not without their problems, principal among which is leakage current (see subthreshold leakage for a discussion of this), although these problems are not insurmountable and will likely be solved or at least ameliorated by the introduction of high-k dielectrics. Since these speed and power consumption gains are apparent to the end user, there is fierce competition among the manufacturers to use finer geometries. This process, and the expected progress over the next few years, is well described by the International Technology Roadmap for Semiconductors (ITRS).

Classification

A CMOS 4000 IC in a DIP

Integrated circuits can be classified into analog, digital and mixed signal (both analog and digital on the same chip).

Digital integrated circuits can contain anything from one to millions 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. These digital ICs, typically microprocessors, DSPs, and micro controllers work using binary mathematics to process "one" and "zero" signals.

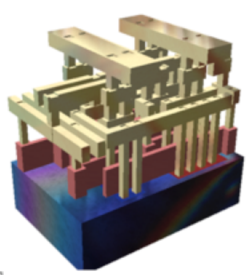
Analog ICs, such as sensors, power management circuits, and operational amplifiers, work by processing continuous signals. They perform functions like amplification, active filtering, demodulation, mixing, etc. Analog ICs ease the burden on circuit designers by having expertly designed analog circuits available instead of designing a difficult analog circuit from scratch.

ICs can also combine analog and digital circuits on a single chip to create functions such as A/D converters and D/A converters. Such circuits offer smaller size and lower cost, but must carefully account for signal interference.

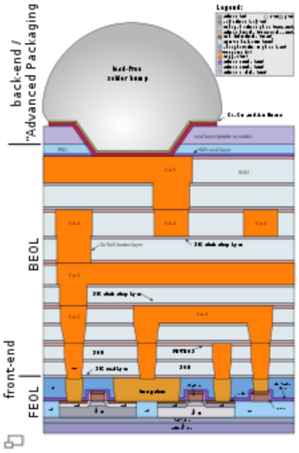
Manufacturing

Fabrication

Main article: Semiconductor fabrication



Rendering of a small standard cell with three metal layers (dielectric has been removed). The sand-colored structures are metal interconnect, with the vertical pillars being contacts, typically plugs of tungsten. The reddish structures are polysilicon gates, and the solid at the bottom is the crystalline silicon bulk.



Schematic structure of a CMOS chip, as built in the early 2000s. The graphic shows LDD-MISFET's on an SOI substrate with five metallization layers and solder bump for flip-chip bonding. It also shows the section for FEOL (front-end of line), BEOL (back-end of line) and first parts of back-end process.

The semiconductors of the periodic table of the chemical elements were identified as the most likely materials for a *solid state vacuum tube* by researchers like William Shockley at Bell Laboratories starting in the 1930s. Starting with copper oxide, proceeding to germanium, then silicon, the materials were systematically studied in the 1940s and 1950s. Today, silicon monocrystals are the main substrate used for *integrated circuits (ICs)* although some III-V compounds of the periodic table such as gallium arsenide are used for specialized applications like LEDs, lasers, solar cells and the highest-speed integrated circuits. It took decades to perfect methods of creating crystals without defects in the crystalline structure of the semiconducting material.

Semiconductor ICs are fabricated in a layer process which includes these key process steps:

- Imaging
- Deposition
- Etching

The main process steps are supplemented by doping and cleaning.

Mono-crystal silicon wafers (or for special applications, silicon on sapphire or gallium arsenide wafers) are used as the *substrate*. Photolithography is used to mark different areas of the substrate to be doped or to have polysilicon, insulators or metal (typically aluminium) tracks deposited on them.

- Integrated circuits are composed of many overlapping layers, each defined by photolithography, and normally shown in different colors. Some layers mark where various dopants are diffused into the substrate (called diffusion layers), some define where additional ions are implanted (implant layers), some define the conductors (polysilicon or metal layers), and some define the connections between the conducting layers (via or contact layers). All components are constructed from a specific combination of these layers.

- In a self-aligned CMOS process, a transistor is formed wherever the gate layer (polysilicon or metal) crosses a diffusion layer.

- Capacitive structures, in form very much like the parallel conducting plates of a traditional electrical capacitor, are formed according to the area of the "plates", with insulating material between the plates. Capacitors of a wide range of sizes are common on ICs.

- Meandering stripes of varying lengths are sometimes used to form on-chip resistors, though most logic circuits do not need any resistors. The ratio of the length of the resistive structure to its width, combined with its sheet resistivity, determines the resistance.

- More rarely, inductive structures can be built as tiny on-chip coils, or simulated by gyrators.

Since a CMOS device only draws current on the *transition* between logic states, CMOS devices consume much less current than bipolar devices.

A random access memory is the most regular type of integrated circuit; the highest density devices are thus memories; but even a microprocessor will have memory on the chip. (See the regular array structure at the bottom of the first image.) Although the structures are intricate – with widths which have been shrinking for decades – the layers remain much thinner than the device widths. The layers of material are fabricated much like a photographic process, although light waves in the visible spectrum cannot be used to "expose" a layer of material, as they would be too large for the features. Thus photons of higher frequencies (typically ultraviolet) are used to create the patterns for each layer. Because each feature is so small, electron microscopes are essential tools for a process engineer who might be debugging a fabrication process.

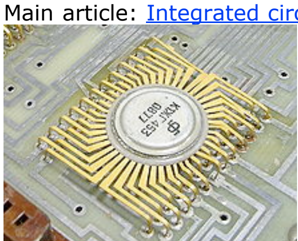
Each device is tested before packaging using automated test equipment (ATE), in a process known as wafer testing, or wafer probing. The wafer is then cut into rectangular blocks, each of which is called a *die*. Each good die (plural *dice*, *dies*, or *die*) is then connected into a package using aluminium (or gold) bond wires which are welded and/or Thermosonic Bonded to *pads*, usually found around the edge of the die. After packaging, the devices go through final testing on the same or similar ATE used during wafer probing. Test cost can account for over 25% of the cost of fabrication on lower cost products, but can be negligible on low yielding, larger, and/or higher cost devices.

As of 2005, a fabrication facility (commonly known as a *semiconductor lab*) costs over a billion US Dollars to construct[10], because much of the operation is automated. The most advanced processes employ the following techniques:

- The wafers are up to 300 mm in diameter (wider than a common dinner plate).
- Use of 65 nanometer or smaller chip manufacturing process. Intel, IBM, NEC, and AMD are using 45 nanometers for their CPU chips. IBM and AMD are in development of a 45 nm process using immersion lithography.
- Copper interconnects where copper wiring replaces aluminium for interconnects.
- Low-K dielectric insulators.
- Silicon on insulator (SOI)
- Strained silicon in a process used by IBM known as strained silicon directly on insulator (SSDOI)

Packaging

Main article: Integrated circuit packaging



Early USSR made integrated circuit

The earliest integrated circuits were packaged in ceramic flat packs, which continued to be used by the military for their reliability and small size for many years. Commercial circuit packaging quickly moved to the dual in-line package (DIP), first in ceramic and later in plastic. In the 1980s pin counts of VLSI circuits exceeded the practical limit for DIP packaging, leading to pin grid array (PGA) and leadless chip carrier (LCC) packages. Surface mount packaging appeared in the early 1980s and became popular in the late 1980s, using finer lead pitch with leads formed as either gull-wing or J-lead, as exemplified by small-outline integrated circuit -- a carrier which occupies an area about 30 – 50% less than an equivalent DIP, with a typical thickness that is 70% less. This package has "gull wing" leads protruding from the two long sides and a lead spacing of 0.050 inches.

In the late 1990s, PQFP and TSOP packages became the most common for high pin count devices, though PGA packages are still often used for high-end microprocessors. Intel and AMD are currently transitioning from PGA packages on high-end microprocessors to land grid array (LGA) packages.

Ball grid array (BGA) packages have existed since the 1970s. Flip-chip Ball Grid Array packages, which allow for much higher pin count than other package types, were developed in the 1990s. In an FCBGA package the die is mounted upside-down (flipped) and connects to the package balls via a package substrate that is similar to a printed-circuit board rather than by wires. FCBGA packages allow an array of input-output signals (called Area-I/O) to be distributed over the entire die rather than being confined to the die periphery.

Traces out of the die, through the package, and into the printed circuit board have very different electrical properties, compared to on-chip signals. They require special design techniques and need much more electric power than signals confined to the chip itself.

When multiple dies are put in one package, it is called SiP, for *System In Package*. When multiple dies are combined on a small substrate, often ceramic, it's called an MCM, or Multi-Chip Module. The boundary between a big MCM and a small printed circuit board is sometimes fuzzy.

Chip labeling and manufacture date

Most integrated circuits large enough to include identifying information include four common sections: the manufacturer's name or logo, the part number, a part production batch number and/or serial number, and a four-digit code that identifies when the chip was manufactured. Extremely small surface mount technology parts often bear only a number used in a manufacturer's lookup table to find the chip characteristics.

The manufacturing date is commonly represented as a two-digit year followed by a two-digit week code, such that a part bearing the code 8341 was manufactured in week 41 of 1983, or approximately in October 1983.

Legal protection of semiconductor chip layouts

Main article: Semiconductor Chip Protection Act of 1984

Prior to 1984, it was not necessarily illegal to produce a competing chip with an identical layout. As the legislative history for the Semiconductor Chip Protection Act of 1984, or SCPA, explained, patent and copyright protection for chip layouts, or topographies, were largely unavailable. This led to considerable complaint by U.S. chip manufacturers—notably, Intel, which took the lead in seeking legislation, along with the Semiconductor Industry Association (SIA)--against what they termed "chip piracy."

A 1984 addition to US law, the SCPA, made all so-called mask works (i.e., chip topographies) protectable if registered with the U.S. Copyright Office. Similar rules apply in most other countries that manufacture ICs. (This is a simplified explanation - see SCPA for legal details.)

Other developments

In the 1980s, programmable integrated circuits were developed. These devices contain circuits whose logical function and connectivity can be programmed by the user, rather than being fixed by the integrated circuit manufacturer. This allows a single chip to be programmed to implement different LSI-type functions such as logic gates, adders and registers. Current devices named FPGAs (Field Programmable Gate Arrays) can now implement tens of thousands of LSI circuits in parallel and operate up to 1.5 GHz (Achronix holding the speed record).

The techniques perfected by the integrated circuits industry over the last three decades have been used to create microscopic machines, known as MEMS. These devices are used in a variety of commercial and military applications. Example commercial applications include DLP projectors, inkjet printers, and accelerometers used to deploy automobile airbags.

In the past, radios could not be fabricated in the same low-cost processes as microprocessors. But since 1998, a large number of radio chips have been developed using CMOS processes. Examples include Intel's DECT cordless phone, or Atheros's 802.11 card.

Future developments seem to follow the multi-core multi-microprocessor paradigm, already used by the Intel and AMD dual-core processors. Intel recently unveiled a prototype, "not for commercial sale" chip that bears 80 microprocessors. Each core is capable of handling its own task independently of the others. This is in response to the heat-versus-speed limit that is about to be reached using existing transistor technology. This design provides a new challenge to chip programming. Parallel programming languages such as the open-source X10 programming language are designed to assist with this task.[11]

Silicon labelling and graffiti

To allow identification during production most silicon chips will have a serial number in one corner. It is also common to add the manufactuers logo. Ever since ICs were created, some chip designers have used the silicon surface area for surreptitious, non-functional images or words. These are sometimes referred to as Chip Art, *Silicon Art*, *Silicon Graffiti* or *Silicon Doodling*.

Notable ICs

- The 555 common multivibrator sub-circuit (common in electronic timing circuits)
- The 741 operational amplifier
- 7400 series TTL logic building blocks
- 4000 series, the CMOS counterpart to the 7400 series (see also: 74HC00 series)
- Intel 4004, the world's first microprocessor, which led to the famous 8080 CPU and then the IBM PC's 8088, 80286, 486 etc.
- The MOS Technology 6502 and Zilog Z80 microprocessors, used in many home computers of the early 1980s
- The Motorola 6800 series of computer-related chips, leading to the 68000 and 88000 series (used in some Apple computers).

See also

Electronics portal

General topics

- Computer engineering
- Electrical engineering

Related devices and terms

- Clean room
- Current mirror
- Hybrid integrated circuit
- Ion implantation
- MMIC
- Photonic integrated circuit
- Printed circuit board
- Silicon photonics
- Integrated circuit vacuum tube

IC device technologies

- BCDMOS
- BiCMOS
- Bipolar junction transistor
- CMOS
- GaAs
- Integrated injection logic
- Logic family
- Mixed-signal integrated circuit
- MOSFET
- NMOS
- RC delay
- SiGe

Other

- Automatic test pattern generation
- DatasheetArchive
- HDL,
- Memristor
- Microcontroller

- Moore's law
- Semiconductor manufacturing
- Simulation
- Sound chip
- SPICE
- Three-dimensional integrated circuit
- ZIF

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9. ^ Antone Gonsalves, EE Times, *Samsung begins production of 16-Gb flash*, 30 April 2007
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11. ^ Biever, C. "Chip revolution poses problems for programmers", New Scientist (Vol 193, Number 2594)

Further reading

- *Invention Of Integrated Circuits: Untold Important Facts*, 2009, Arjun N. Saxena, World Scientific Publishing, Singapore, ISBN 9789812814456 ISBN 9812814450

External links

Wikimedia Commons has media related to: ***Integrated circuit***

General

- Krazit, Tom "- AMD's new 65-nanometer chips sip energy but trail Intel," *C-net*, 2006-12-21. Retrieved on January 8, 2007
- a large chart listing ICs by generic number and A larger one listing by mfr. number, both including access to most of the datasheets for the parts.
- *Practical MMIC Design* published by Artech House ISBN 1-59693-036-5

Author S.P. Marsh

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- US3,138,743 – Miniaturized electronic circuit – J. S. Kilby
- US3,138,747 – Integrated semiconductor circuit device – R. F. Stewart
- US3,261,081 – Method of making miniaturized electronic circuits – J. S. Kilby
- US3,434,015 – Capacitor for miniaturized electronic circuits or the like – J. S. Kilby

Audio video

- A presentation of the chip manufacturing process, from Applied Materials

Silicon graffiti

- The Chipworks silicon art gallery

Integrated circuit die photographs

- IC Die Photography – A gallery of IC die photographs

v • d • e **Digital systems** [hide]

Components	Logic gate · Digital circuit · **Integrated circuit** (IC)
Theory	Boolean logic · Digital signal processing · Computer architecture
Applications	Digital audio · Digital photography · Digital video