Lesson: Integrated Circuits

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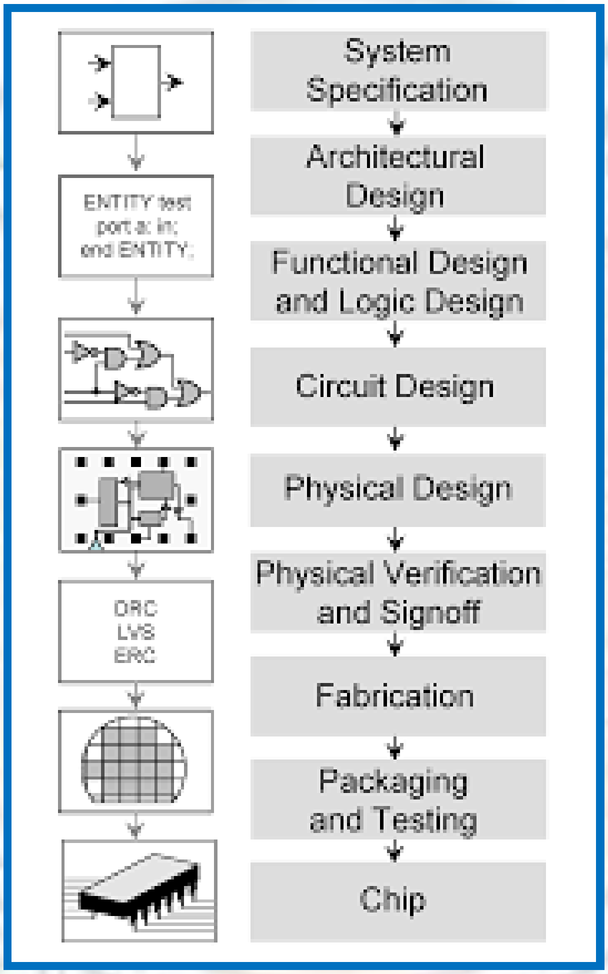
Integrated Circuits

The life story of a chip



Introduction

The discovery of bipolar junction based transistor (BJT) in 1947 by William B. Shockley and his team at the American Telephone and Telegraph Company’s (AT & Ts) Bell Laboratories in USA, led to a paradigm shift in the electronics industry and gave birth to a new field of science aptly called solid state electronics. BJTs replaced the difficult to operate, power hungry, costly and bulky ‘Vacuum Tubes’ and the electronics industry could for once envisage addressing the needs of billions of people around the world in years to come. W. B. Shockley along with John Bardeen and Walter H. Brattain exhibited that under some specific conditions certain crystals possessing semiconducting property could have electrons forming a barrier at the surface and that one could control the flow of electricity through the crystal by manipulating this barrier. A precise control on the electron flow enabled the trio to create a device that could perform rudimentary electrical operation of signal amplification that was hitherto the sole preserve of vacuum tubes.

For their effort the trio was awarded Nobel Prize in Physics in the year 1956 and the citation of the Nobel Foundation reads as - The Nobel Prize in Physics 1956 was awarded jointly to William Bradford Shockley, John Bardeen and Walter Houser Brattain "for their researches on semiconductors and their discovery of the transistor effect".

Figures 2 show the trio who designed and invented the first transistor.

Figure 2: a) Walter Houser Brattain b) Willaim Bradford Shockley c) John Bardeen

Figure 3 shows the first and transistor configuration

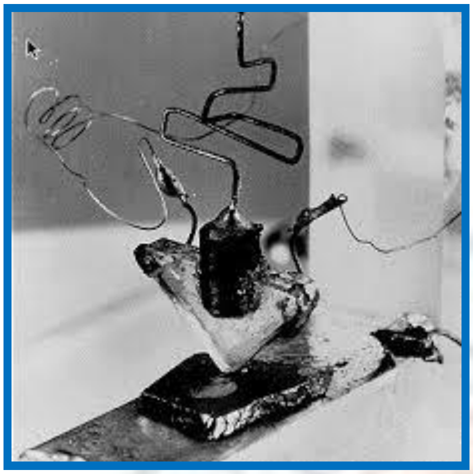


Figure 3: a) World's first transistor (BJT)

The trio named their new amplifier device component 'Transistor' by combining the words 'Transfer' and 'Resistor' since BJTs actually work as amplifiers by transferring low resistance at the input to a high resistance at the output while keeping current constant.

Using BJTs and semiconducting materials for other electronic components a new branch of electronics called solid-state electronics came into being. Compared to vacuum tubes the solid-state devices could be seen to be much less power hungry, sturdier, reliable, easier to work with, smaller, and cheaper. Besides the aforementioned solid-state devices could be batch produced. Gradually with the passage of time fabrication technology of BJTs matured and faster components could be realized. Also, with the advent of technology besides amplifier components, the same BJTs could be configured to function as resistors, capacitors, diodes, switches, and oscillator components. Post development of the BJT, another aspect of electronic device development that occurred simultaneously was the constant reduction in size of device components that resulted in massive cost reduction in terms of the power consumption for the electronics industry.

Typical size of discrete components and surface mount device (SMD) components are compared in Figure 4.

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Figure 4: Comparison of discrete and SMD component sizes

With SMD electronic components in use the size has become so small that the largest part of any circuit is the inelegant and unmanageable size of the wiring connecting the various components.

During the time when Nobel Prize for development of transistor was being awarded, Jack Kilby of Texas Instruments Inc. US, and Robert Noyce of Fairchild Semiconductor Corporation, US independently thought of reducing circuit size further by laying very thin metallic aluminium (Al) or copper (Cu) inter-connects directly on the same piece of solid-state material of their devices. This device design gave birth to the concept of integrated devices (ICs) as we know them today.

All modern and fast electronics especially, those related to information and technology world work just because of existence of ICs e.g. computers, mobile/satellite phones, timers, counters, phablets, microwave ovens, cars, satellites, aeroplanes, missiles, radar, amusement park rides etc.

What are Integrated Circuits (ICs)?

An integrated circuit (IC) is also sometimes referred to as microelectronic circuit or more popularly as a chip. IC is what one gets when discrete electronic components are reduced in size by many orders of magnitude and ‘integrated’ on the same base with Cu or Al interconnects while being enclosed in some form of boxed structure made of resin/polymer with pins for inputs and outputs. The resulting circuit is a small monolithic “chip,” varying in size ranging from a few square centimetres or to a few square millimeters wherein microscopic individual circuit components are affixed.

ICs usually consist of a semiconducting base material (predominantly silicon) called the wafer onto which miniature electronic device components including resistors, capacitors, transistors, switches etc. numbering between hundreds to millions are fabricated with metal interconnections. While some ICs work in the analog mode as amplifiers, oscillators, timers, counters etc. some function in the digital realm as switches, gates, computer memory, microprocessors, microcontrollers etc. All ICs are categorized as either linear (analog) or digital, depending on their intended applications. Figures 5 show various types of integrated circuits.

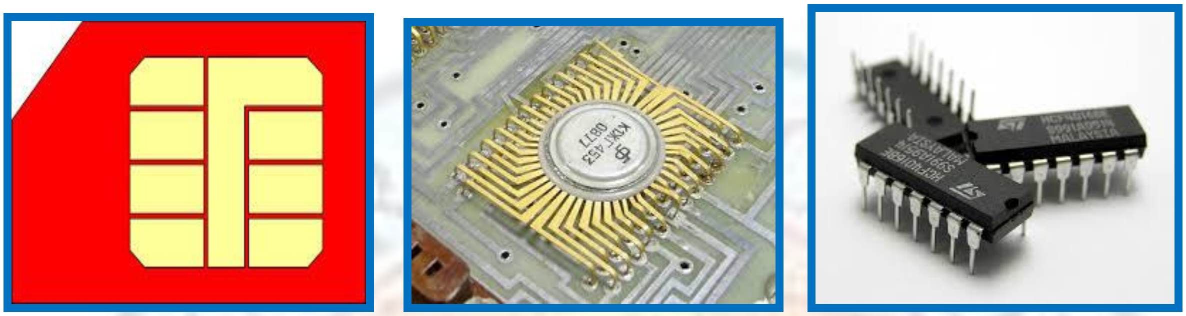


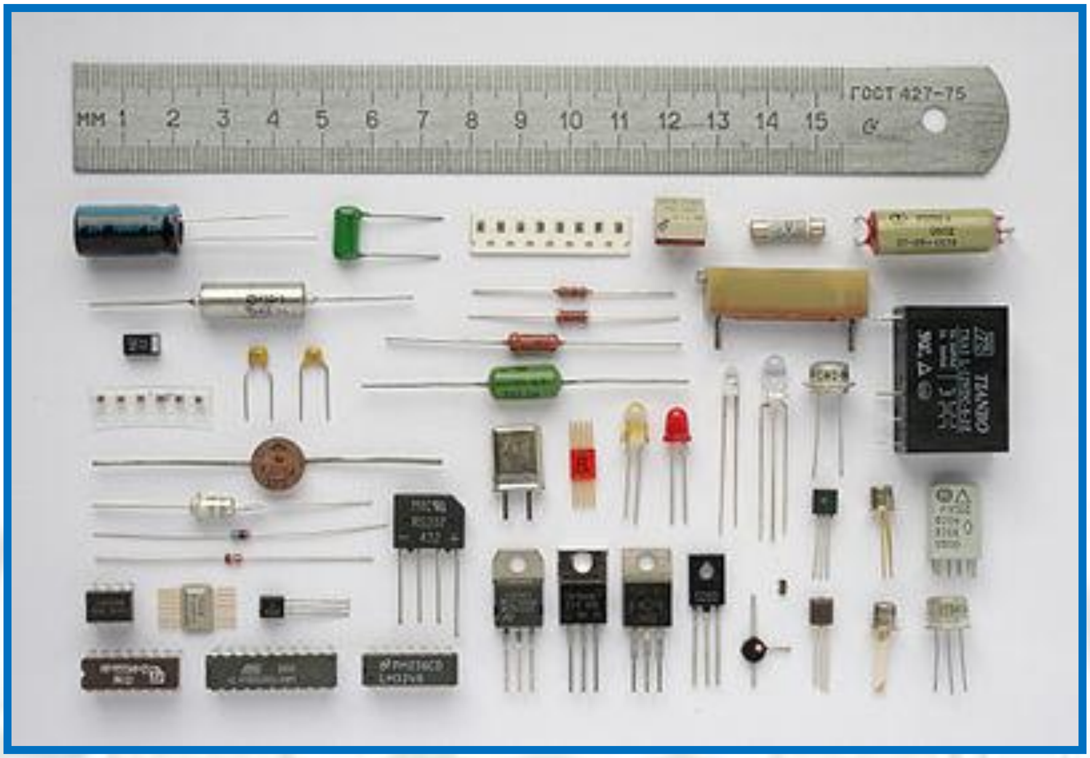
Figure 5 a) Mobile SIM chip b) Motherboard chip IC c) Analog (linear) IC

Monolithic ICs

The word monolithic is derived from a geological feature that implies a single massive stone or rock and in the same way a monolithic IC indicates an electronic circuit that is built on a single semiconductor base material or single chip.

What are discrete circuit components?

The usual electronic device components including resistors, capacitors, diodes, diacs, transistors, FETs, UJTs, current limiters, voltage regulators etc. that make up circuits like amplifier, oscillators, switches etc. are referred to as discrete components. Usually any two or three terminal electronic component (besides antennas which may be single terminal) can be considered as a discrete component as long as it is able to influence the flow of electrons in a circuit in a controllable manner. Mostly industrial in nature, some of the components are shown in Figure 6.



Figures 6: Discrete components that are used to make an electronic circuit

Discrete components are characterized by their ability to be integrated manually over Printed Circuit Boards (PCBs). Large component sizes and manual assembly allows one to easily trace faults and replace faulty components thus saving money. On the flipside discrete component assembly occupies a lot of space, consumes high power, offers large area for dust collection and is time-consuming during industrial manufacture when large quantities are involved.

What are active and passive components?

All electronic components can be classified as having active or passive nature. Electronic components that are able to induce some sort of gain (voltage/current) while influencing the flow of electrons are popularly referred to as active components e.g. BJTs, FETs etc. while those that do not, are named as passive components e.g. resistors, capacitors, inductors.

Some of the places describe components that require external power for their operation as active devices while those that do not require the same, as passive devices.

Diodes are sometimes classified as both passive (no gain in current/voltage) as well as active (Si diodes require 0.7 V for operation)

As a thumb rule, passive components can be identified as having only two terminals while active components generally have three or more terminals. Most of the passive components exhibit characteristics in the linear range while active components show electrical characteristics in the non-linear range.

Typical passive and active electronic components are shown in Figure 7

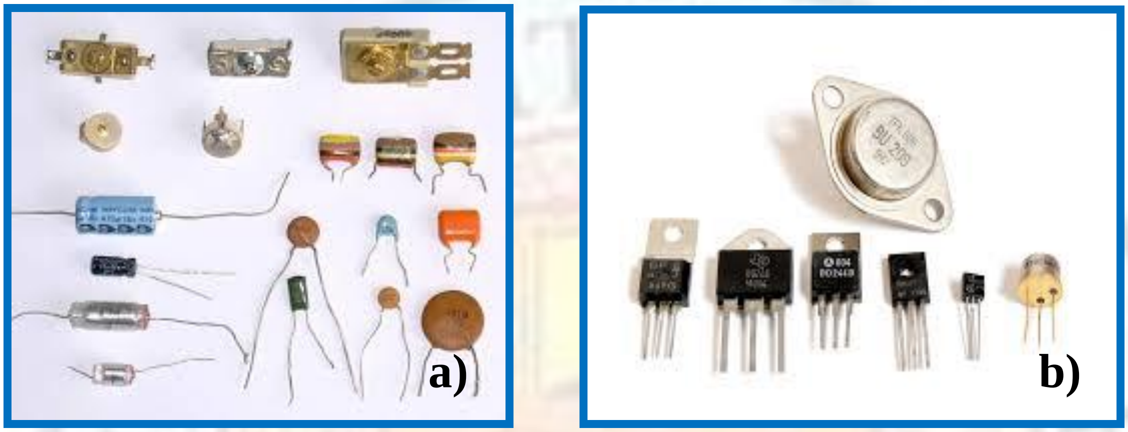


Figure 7: a) Passive electronic components b) a) Active electronic components

What is a wafer?

The base material onto which the entire IC is fabricated is popularly referred to as a wafer or a slice or a substrate. Wafer is a thin segment (usually round shaped) semiconducting material commonly made of crystalline silicon and is about a few mils thick (1 mil = 10^{-3} inches = 0.0254 mm). The wafer typically has a circular shape with a cut on one side indicating crystallographic orientation or indicating the origin of the processing side. The wafer or the substrate serves as the bedrock onto which the micro-miniaturized electronic devices are built into.

Typically a wafer is made to undergo a plethora of IC fabrication processes in a sequence of steps including implanting of ions or doping (n or p type), annealing, scrubbing, coating of materials to fabricate electronic components, patterning using photolithography, UV exposure, etching etc. Once the final micro-miniature integrated circuits are fabricated onto the wafer the individual microcircuits are diced into small pieces and packaged with input and output terminals.

Some of the standard wafer sizes that are in industrial production are enumerated as follows:
1-inch (25 mm diameter)
2-inch (51 mm diameter) with typical thickness around 275 µm.
3-inch (76 mm diameter) with typical thickness around 375 µm.
4-inch (100 mm diameter) with typical thickness around 525 µm.

5-inch (130 mm diameter) or 125 mm (4.9 inch diameter) with typical thickness around 625 µm.
150 mm (generally referred to as "6 inch" diameter) with typical thickness around 675 µm.
200 mm (generally referred to as "8 inch" diameter) with typical thickness around 725 µm.
300 mm (ganerally referred to as "12 inch" diameter) with typical thickness around 775 µm.

The IC industry ensures availability of Si wafers in standard sizes only wherein diameters are seen to range from 25.4 mm (1 inch) to about 300 mm (~ 12 inches). Based on the size of wafers that they typically process the standard IC fabrication laboratories are named as such e.g. 200 mm process line etc. Processing bigger diameter wafers allow the industries to obtain larger quantity of ICs in one go (high throughput) and thus reduce costs however this is possible with only fully automated plants. Further, industrial processing of large wafer sizes involves complex procedures that sometimes jacks-up the costs to such a high level that it becomes economically unviable to fabricate ICs e.g. 450 mm technology is still under development for the last few years. Another problem is the weight of the wafer with increase in its diameter. Industrial production has to ensure that the wafer does not crack under its own weight during handling and hence only ultra-pure materials have to be used for wafer fabrication that impart high mechanical strength.

Besides countries like USA and China most of the fabrication laboratories are located in the south-east asian countries including Singapore, Taiwan, Malaysia, Indonesia etc. and contribute to their economy in a massive way.

Figure 8 shows typical industrial wafer along with certain ICs diced out

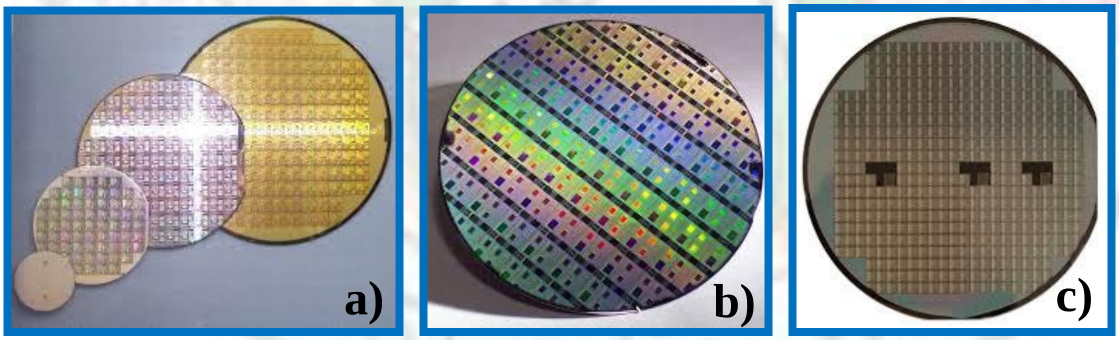


Figure 8: a) Various sizes of wafers b) Wafer with fabricated IC chips c) Wafer with IC chips diced out

What is a chip?

When an entire IC is embedded on a small piece of wafer (usually silicon) then it is referred to as the chip. A typical chip is has a size of a less than 4 square inches and can contain millions of electronic components mainly transistors. There are many types of chips including those for Central Processing Units of the computer like microcontrollers and microprocessors and some like blank memory chips.

Chips come in a variety of packages wherein the three most common types are enumerated as follows:

1. Dual in-line packages (DIPs) – These constitute the bulk in the world with a traditional bug - like chip structure that have anywhere from 8 to 40 legs and which are evenly divided on both sides of the IC.

2. Single in-line packages (SIPs) – These are chips that have just one row of legs in a straight line like a comb.

3. Pin-grid arrays (PGAs) - These are square chips in which the pins are arranged in concentric squares on all the sides. These are mostly found as chipsets on mother boards of computers.

Figure 9 shows various forms of packaging of ICs

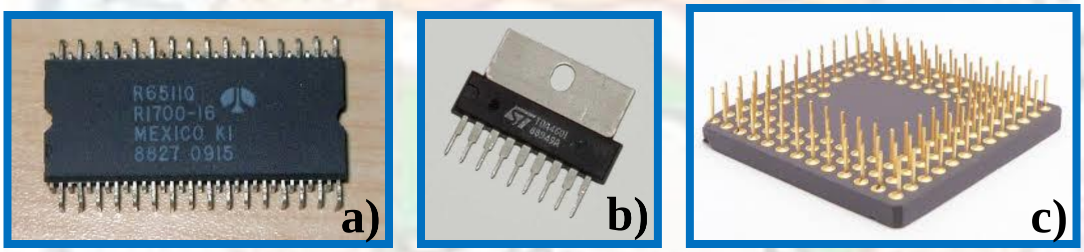


Figure 9: a) Dual inline packaging (DIP) b) Single inline packaging (SIP) and c) Pin Grid Arrays (PGAs)

What are advantages and disadvantages of ICs?

With discrete circuits having separate components interconnected using wires or plated conductors (PCBs and motherboards) there occurred two major problems - too many soldering joints causing unreliability and a very large footprint of the circuits due to hundreds of components being used. Advent of IC technology has made discrete component assembly technology obsolete mainly because it addressed the aforementioned problems besides offering low costs, faster processing circuits, ease of use, small form factor etc. which were some of the problems observed in discrete circuits.

Some of the advantages offered by IC based circuits are enumerated below:

1. Absence of soldering joints in ICs ensures reliable operation over long periods of time. There occurs no short-circuiting within the IC and no parasitic problems of dry soldering.

2. Since all components are fabricated onto the same substrate hence they can be micro-miniaturized thus making the IC lighter than discrete component based system while reducing its power consumption. The small form factor is advantageous because smaller circuits can be designed.

3. Compared to discrete component systems IC powered circuits can withstand higher extremes of temperature and environmental conditions. This is attributed to the ICs being encapsulated with a silicon oxide layer during manufacture.

4. IC based circuits are easier to design and offer ease of use facility as they are constrained to minimize the number of external connections right from manufacturing stage.

5. ICs consume very less power even during complex operations and this leads to lot of energy savings by the users as also cost cutting by the industry.

6. ICs have a very low cost of production since they are fabricated in bulk. Bulk production also ensures that number of bad ICs manufactured is very less and losses are cut to a minimum.

Integrated circuits have a flipside too and their limitations act as disadvantages

1. If there is a small failure even in one component of an IC then the whole IC has to be replaced. Replacement of an IC becomes a major issue especially if the circuit is old because then with constant hardware upgradations the old IC becomes incompatible. Sometimes even the pin-out of the IC or the socket where it needs to be fixed changes especially in the field of computers.

2. Even after years of technology advancement fabrication of transformers or any kind of inductors within the integrated circuits has not been possible. Hence requirement of the same, calls for joining of the IC with external discrete circuits which sometimes leads to awkward wiring and power supply issues.

3. Capacitances fabricated within the ICs have limited capacity and external components are required from time to time to augment the same (capacitance extension) thus reducing deficit. Involvement of external components again gives rise to power and wiring issues.

4. Power handling requirements of ICs leave a lot to be desired. ICs can only handle miniscule amounts of power and that is why wherever large amounts of power are required e.g. mobile phone antennas, RADARs etc. vacuum tubes are still in operation. This lack of power handling capacity is a serious drawback especially in military communication and detection hardware.

5. For a particular IC, parameters of its operation as well as number and types of components cannot be modified while in operation. For any required change a new IC has to be procured and sometimes design of efficient electronics suffers because of the lack of an IC with particular electronic parameters. Lack of flexibility in ICs is still a major issue.

The scale of integration over the last few decades

1. Small scale integration (**SSI**) – This type of integration allows for less than 100 components (typically about 10 gates).

2. Medium scale integration (**MSI**) - This type of integration allows less than 500 components, like having more than 10 but less than 100 gates.

3. Large scale integration (**LSI**) – Here number of components is between 500 and 300000 or the IC can have more than 100 gates.

4. Very large scale integration (**VLSI**) - This type of integration contains more than 300000 components per chip.

5. Ultra large scale integration (**ULSI**) - This type of integration allows more than 15,00,000 components per chip.

6. Wafer-scale integration (**WSI**) – In this case a silicon wafer in its entirety is made use of to produce a single "super-chip" and that finds use in parallel supercomputers.

7. A system-on-a-chip (**SoC** or **SOC**) – It is an IC in which a single chip encompasses all the components needed for a compute. The technology proffers lower manufacturing and assembly costs and by a greatly reduced power consumption.

8. A three-dimensional integrated circuit (**3D-IC**) – This technology includes integrating (both vertically and horizontally) two or more layers of active electronic components into a single circuit and is the latest technology that is available. It is the epitome of low power consumption since communication between layers uses on-die signaling.

IC fabrication process

1. Ingot Growth – IC production begins with the growth of an ingot also called the boule of Si semiconducting material that is almost perfectly crystalline in nature. Production of the ingot is achieved by suspending a small seed crystal of Si in molten material then slowly pulled like in Czochralski process or in technique of Bridgman–Stockbarger etc. Obtained ingots typically have sizes in the range of 1m length and about 75 - 300 mm in diameter. It is important to note that all dopants / additives are always added to the molten material before ingot growth.

2. Wafer Sawing – Si, Ge or GaAs ingots obtained from step #1 are sliced into thin wafers of 0.5 – 1 mm thickness using a diamond tipped saw. These wafer slices act as the base material (called substrate) for manufacturing of ICs. As-obtained wafers are cleaned using various chemical treatments and their surfaces are smoothened by polishing them using ultra-fine mechanical equipments sequentially.

3. Photolithography – An IC designer is a person who designs the internal circuitry of the IC including device layout, placement, interconnections and their design. The layout is transferred from the designer's board to the wafer surface using a process similar to old photographic development and which is technically known as photolithography. The somewhat delicate process involves use of micro-masks and costly mask aligners along with certain steps that are repeated a number of times.

4. Photolithography – Application of Photoresist – Fabrication of interconnects and devices on the wafer surface, requires its surface to be coated with a polymer called the photoresist of about ~1 μm thickness. High quality and uniform coating of the photoresist is paramount to successful fabrication of any IC since it acts as a medium wherein the required image of the IC's internal circuitry is transferred.

5. Photolithography - UV Exposure – Post-coating of the photoresist, it is exposed to ultraviolet (UV) radiation through a mask in a series of steps that includes low and high temperature baking in ovens. These processes generate the IC designer's pattern of the device placement and interconnections onto the wafer. The incident UV radiation interacts with the photoresist polymer and the ensuing chemical change facilitates transfer of information from the mask to the wafer surface. The change is seen to occur at only those places where the mask is transparent to UV radiation.

6. Photolithography – Development – Post-transfer of the IC designer device pattern onto the photoresist coated and UV treated Si wafer, it is developed using a specific solvent called a developer. Photoresist and their developers generally come together as pairs.

7. Photolithography – Final structure - The developer chemical is removed and depending on the type of photoresist used (Positive or Negative) developed photoresist is retained / not retained in the region of the mask used corresponding to its UV transparent part. IC components, interconnects etc. are then formed using this final structure in a series of steps.

8. Etching – Dry and wet types – In order to remove excess material left over on the wafer during device fabrication the process of etching is initiated. Etching is of two types – dry and wet. A typical dry etching process is Reactive Ion Etching (RIE), wherein ions of a neutral material are intentionally and controllably accelerated towards the wafer surface causing ejection of all extraneous materials. In the case of wet etching, a chemical reaction is initiated to remove the extra material using a specific chemical called etchant. This etchant is also specific to material to be removed and also has to be compatible with the photoresist-developer combination.

9. Thermal Oxidation - Oxidation Furnace – In order to protect ICr components fabricated onto Si wafer a layer of SiO_2 is generally grown onto it. This is achieved by thermally oxidizing a few monolayers of the Si wafer to SiO_2 by subjecting the wafer to elevated temperatures of around 900 - 1200 °C in an environment of dry oxygen (O_2) or wet steam (H_2O). This is achieved using a special furnace called oxidation furnace and since Si is known to oxidize to SiO_2 quite readily hence Si is the preferred substrate material.

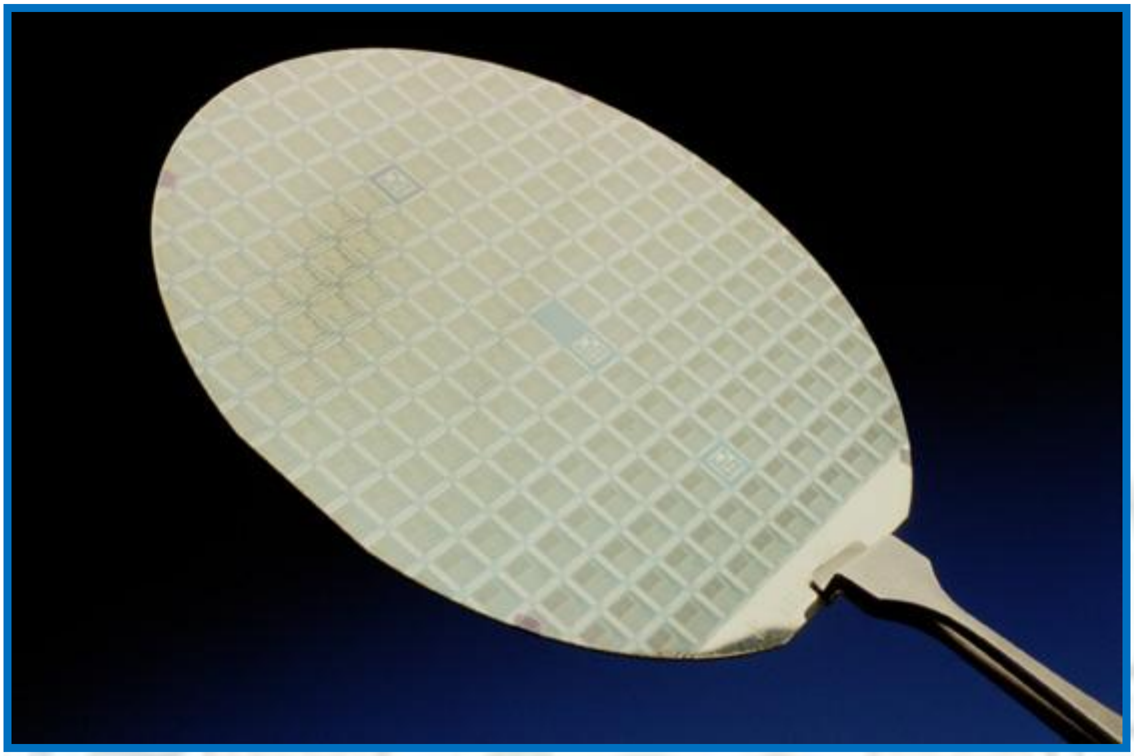
10. Dopant Diffusion – Acceptor or Donor impurities in the form of dopants are introduced into the substrate through the physical phenomena of diffusion wherein impurities (III / V types) are driven down a concentration gradient within the wafer. The substrate is heated in an ambient of dopant atoms, which causes them to diffuse into the Si substrate.

11. Ion Implantation – Another method to introduce impurities is ion implantation wherein swift heavy ions (dopant atoms) are accelerated by means of an accelerator and which embed into the substrate due to their kinetic energy. This technique is preferred since lateral diffusion is minimized unlike diffusion process.

12. Deposition – During IC fabrication SiO_2 or metallic layers (interconnects) need to be deposited onto substrate surface and this process is broadly referred to as deposition. Deposition is of two types – physical and chemical. In physical deposition technique (sputtering) the material to be deposited is made the target and Ar or other heavy ions bombarded it thereby ejecting atoms of material. The ejected atoms then adhere to the Si wafer substrate surface. In the case of chemical deposition coating of the desired material is precipitated onto the Si wafer by means of a chemical reaction. Epitaxy is another specialized form of deposition wherein a layer of crystalline semiconductor material is formed onto the surface of the substrate in the same orientation.

13. Patterning – Patterning technique involves a series of photoresist processes like deposition, exposure, development and etching to create regions of particular shapes.

14. Final Fabricated Wafer –



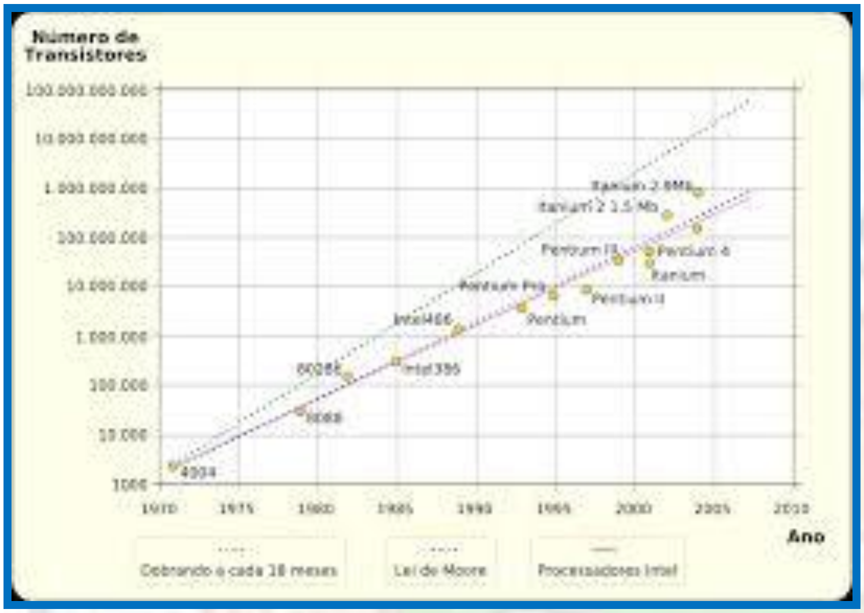
15. Scribing and Cleaving – Post processing of the wafer, they are separated into individual ICs by scribing and cleaving. Scribing involves creating a groove along scribe channels which are intentionally left between rows and columns of individual chips (during mask generation) whereas cleaving involves breaking the wafer apart into individual ICs (dice)

16. Packaging - IC packaging is the final stage of semiconductor device fabrication, in which the diced IC from the wafer gets encased or encapsulated in a supporting case that not only prevents physical damage and corrosion but also prevents short-circuiting with other components. The case, known as a "package", supports the electrical contacts through pins that jut out from the package and which connect the device to a circuit board or IC base.

Density of components in ICs

A very interesting observation popularly called "Moore's law" exists over the history of computing hardware and which is - that the number of transistors in a dense integrated circuit doubles approximately every two years. Gordon E. Moore, co-founder of the Intel Corporation famously described this trend in an article published in the year 1965. This observation has been so accurate that it is still used by the IC manufacturing industry to set targets for research and long-term planning. This goal has enabled IC industry to drastically reduce prices of digital electronics based devices including cameras, computers, memories, microcontrollers, televisions while increasing/improving their quality, enabling faster processing and enhancing storage. This has led to a sudden spurt in involvement of digital electronics in all realms of life and influencing nearly every section of the world’s economy.

The famous Moore’s Law is depicted as a graph below



Linear and Digital ICs

Depending on the input signal level linear or analog ICs theoretically can have a continuously variable output. In these ICs technically, the output signal varies as a linear function of the input signal level. Theoretically in an ideal environment the graph between the instantaneous output and the instantaneous input is supposed to be a straight line plot appears. Common examples of linear ICs include audio-frequency (AF), radio-frequency (RF) amplifiers and operational amplifiers. In the current course of study linear ICs that one would get to use are 741 op-amp and 555 timer.

Digital ICs are those that operate at only a few predefined levels or states, rather than over a continuous range of signal levels. These ICs are preferentially used in computers, flip-flops, digital communication devices, modems, shift registers and counters. Logic gates, which work with binary data act as the fundamental building blocks of digital ICs. In the current course of study some of the digital ICs that one would get introduced to are 74XX series of ICs including 7400, 7432, 7404, 7408, 7486 etc.