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Introduction

Within the last five decades we have witnessed a gradual evolution in the field of electronics which has provided a new technology—a technology whose impact on the industry, presently is greater and more spread than that of any development or invention since the turn of the century—a technology known as integrated circuits (ICs).

Integrated circuits are meeting the needs of present electronic world which may be characterized by increased densities of men and machines, transportation speed, telecommunication volume and information processing volume. This revolutionary change in the art of electronic design, brought about by the development of integrated circuits, is the result of the invention of the transistor (in 1948) by Bardeen, Brattain and Schockley who were awarded Nobel Prize in Physics for their such invention. Just as the transistor revolutionized electronics by offering more flexibility, convenience and reliability than the vacuum tube, the integrated circuit enables new applications for electronics which were not possible with discrete devices. An *integrated circuit* is a collection of discrete elements (diodes, resistors, capacitors and transistors) created by means of a single construction process in which all elements are formed.

The first integrated circuit was developed in 1958 by J.S. Kilby at Texas Instruments. The real keys to IC manufacturers were the planar transistor and batch processing. The planar process used transistors in which the base and emitter regions were diffused into the collector. Batch processing permitted many IC *chips*, as ICs were colloquially known, to be made from a single silicon wafer. By 1961, both Fairchild and Texas Instruments were producing ICs commercially, followed soon afterwards by other companies. The term "integrated" is used because the components and wiring are all an integrated part of the chip and cannot be separated from each other.

Today, in addition to individual circuits, sub-systems and even entire systems containing thousands of components can be fabricated on a single silicon chip. The term "Microelectronics" refers to the design and fabrication of these high-component-density ICs. The number of components per chip has shown an exponential growth since 1960.

1.1. MINIATURIZATION

At present we find three major IC groups : MOSFET, bipolar transistor, and IC made from III-V compound semiconductors. At the beginning of IC development, the bipolar transistor technology was dominant. However, because of the advantages in device miniaturization, low power consumption, and high yield, the production volume of MOS technology based IC has increased steadily. Therefore, it is appropriate to emphasize the trend in the MOS device miniaturization. Fig. 1.1 shows the rapid growth in the number of components per MOS Dynamic Random Access Memory (DRAM) IC chip. As seen, the MOS IC complexity has advanced from small-scale integration (SSI), to medium-scale integration (MSI), to large-scale integration (LSI), to very large scale integration (VLSI), and finally to ultralarge-scale integration (ULSI). The scale of integration may be quantified as below :

SSI : less than 30 devices per chip
MSI : 30 to 10^3 devices per chip
LSI : 10^3 to 10^5 devices per chip
VLSI : 10^5 to 10^7 devices per chip
ULSI : 10^7 to 10^9 devices per chip.

It can be seen that since 1975 the growth has been maintained at a rate of about 40% annually, *i.e.*, the number of components has doubled every two years. At this rate, the components per chip has crossed 100 millions. In the early 21st century, we will move into the gigabit range, with IC chips having more than one billion components.

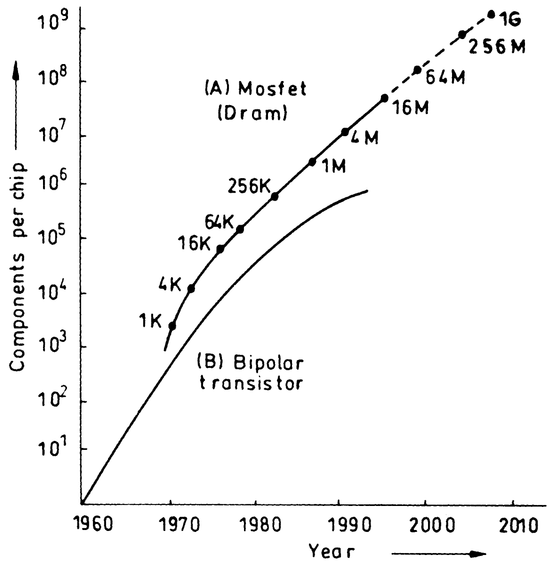

Fig. 1.1. Rapid growth of the number of components per (*a*) MOS IC chip (*b*) Bipolar IC chip.

In 1950s germanium was a popular semiconductor material to manufacture solid-state devices. However, germanium proved unsuitable due to its high leakage current resulting from its relatively narrow energy band gap of 0.785 eV (0 K). For this reason silicon having band gap of 1.21 eV (0 K) became a practical substitute and has almost fully supplanted germanium as a material for solid-state device fabrication. Silicon also has the following advantages :

(*i*) Silicon devices can operate up to 150°C versus 100°C for germanium.

(*ii*) Silicon grows a stable oxide (SiO_2), which is one of the very important process steps in the fabrication of ICs. In fact, planar processing technology derives its success from the properties of thermally grown SiO_2. Germanium oxide is unsuited for device applications.

(*iii*) The intrinsic, *i.e.*, undoped resistivity of germanium is about 47 Ω-cm, which precludes the fabrication of rectifying devices with high breakdown voltages. In contrast, the intrinsic resistivity of silicon is about 23×10^4 Ω-cm. Thus, high-voltage rectifying devices are practical with silicon.

(*iv*) Over the years silicon technology is very highly developed. Electronic grade germanium is more costly than silicon.

The silicon element will remain dominant semiconductor for many years to come. Nevertheless, another material, gallium arsenide (GaAs), has become popular for very high speed device fabrication. The major advantage that GaAs offers over silicon is that electrons travel much faster in *n*-type GaAs than in silicon. The major limitation of GaAs is that its technology is not as developed as that of silicon. GaAs technology suffers from yield and reliability problems and generally limited to low levels of integration.

Discrete vs. Integrated Circuits. When components are put into separate containers, or one component per container, they are called *discrete components*, or discrete devices. For instance, a single transistor or a diode is put into a container. A discrete component is also a single resistor (made of carbon compound or metal glaze) or a single capacitor (made of wax paper sheets sandwiched between aluminium foils, mica sheets sandwiched between aluminium foils, or others). To make circuit using these components the user mounts these discrete components on a printed circuit (*pc*) *board* which is a thin insulator sheet on which flat metal conductors are placed, as if being printed.

In the case of an *integrated circuit*, all components are placed on a single small thin semiconductor sheet measuring a few to a few hundred square mils, that is called a *chip*. A chip is sometimes also called a *die* (plural : dice). This is called "integrated" because the components and wiring are all an "integrated" part of the chip and cannot be separated from each other.

Main IC Components. The main components used to manufacture ICs are diode, transistor, resistor and capacitor. Transistors are either bipolar or unipolar type. Bipolar transistors are of two types : *npn* and *pnp*. Unipolar transistors are mainly metal-oxide-semiconductor field-effect transistors abbreviated as MOSFETs. There are two types of MOSFETs : *n*-channel MOSFET and *p*-channel MOSFET. Further, the MOSFET is either enhancement mode or depletion mode type. The gate of MOSFET is made of metal or silicon. Accordingly we have metal-gate MOSFET and silicon gate MOSFET. Obviously, the gate associated with MOSFET is different than a logic gate used in digital circuits. A logic gate which consists of MOSFETs is called *MOS cell* so that it is differentiated from MOS gate (*i.e.* gate electrode).

The components mentioned above are fabricated by employing silicon technology. GaAs technology is used to Fabricate metal semiconductor FET or MESFET.

1.2. GENERAL CLASSIFICATION OF INTEGRATED CIRCUITS

There are several ways of categorizing ICs as their use and method of fabrication. The most common categories based on fabrication are (*i*) Monolithic (*ii*) Hybrid ICs. The categories of ICs based on application are (*i*) Analog ICs and (*ii*) Digital ICs.

Monolithic Circuits. Integrated circuits which are included entirely in a single chip of semi-conductor (usually Si) are called monolithic circuits. The word monolithic literally means "one stone" and implies that the entire circuit is contained in a single piece of semiconductor.

Hybrid Circuits. Hybrid circuit may contain one or more monolithic circuits or individual transistors bonded to an insulating substrate with resistors, capacitors or other circuit elements with appropriate inter-connections. When resistors and capacitors are made external to the monolithic silicon chip, basically two types of technology are used, these passive elements are fabricated and interconnected by *thick-film* or *thin- film* process. The dividing line between thick and thin films is not precise. In thick-film type hybrid circuits, the resistors and interconnection patterns are 'printed' on a ceramic substrate. Thin film interconnection patterns and resistors can be deposited by vacuum evaporation technique on a glass or glazed ceramic substrate.

Monolithic ICs offer the advantage that all components are contained in a single rigid structure which can be batch fabricated, *i.e.*, hundreds of identical circuits can be built simultaneously on a silicon wafer. On the other hand, hybrid circuits offer excellent isolation between components and allow the use of more precise resistors and capacitors. Further, hybrid circuits are often less expensive to build in small numbers.

Analog IC. An Analog IC is one which performs amplification or other essentially linear operations on signals. Hence it is also known as *linear IC.* An analog IC deals with *continuously* varying quantities such as temperature, pressure. Analog ICs include operational amplifiers, analog multipliers, analog-to-digital (A/D) and digital-to-analog (D/A) converters, Phase-locked loops, and a variety of other, more specialized ICs.

One of the most popular analog ICs is operational amplifier or op amp. The op amp is fabricated using bipolar, CMOS or BiCMOS technology. CMOS refers to complementary MOS. The CMOS op amps are designed to be used as a part of a VLSI circuit. The BiCMOS op amp combines bipolar and CMOS technology thus having advantages of both technologies. The GaAs technology makes possible the design of amplifiers having very wide bandwidths, in the hundreds of megahertz or even gigahertz range.

Digital IC. Digital IC performs the circuit function by dealing with *discrete* quantities, *i.e.*, integer or fractional number. In digital IC information is represented by binary digits, *bits.* A bit may assume either one of two values : 0 or 1. It is based on a number system that uses only two digits and is called a *binary system* as against decimal system with which we are familiar.

Digital ICs involve logic and memory, for applications in computers, calculators, microprocessors and the like. By far the greatest volume of ICs has been in the digital field, since large numbers of such circuits are required. Since digital circuits generally require only "on-off" operation of transistors, the design requirements for digital ICs are often less stringent than for analog circuits.

Initially the digital IC chip was containing one logic gate per chip. However, later, it became possible to fabricate several similar gates on a single chip at very little additional cost. The next step, therefore, was to obtain the lowest cost per gate by forming as many gates as possible on one chip. The increasing complexity, coupled with the variety of logic circuit types, generated the need for definition of complexity levels. The different levels of integration of MOS digital IC chips are defined as below :

SSI : 1 to 10 logic gates/chip
MSI : 10 to 100 logic gates/chip
LSI : 100 to 10000 logic gates/chip
VLSI : 10000 to one million logic gates/chip
ULSI : More than one million logic gates/chip

The above definitions are not unique. Note that above definitions are based on logic gates per chip as against components per chip as defined earlier for bipolar and MOS technologies separately. The choice of level of integration for any application is usually made by considering following major factors :

(*i*) Large production volume dictates LSI/VLSI chips suitable for use. However, flexibility in design becomes less as one goes for higher scale of integration. In other words, when new circuits are needed, any LSI prepared for previous design purpose must be abandoned. However if the previous circuit is assembled with SSI package, the new circuit can be assembled by replacing some of these packages.

(*ii*) The complexity of a required circuit may not need large integration.

(*iii*) The initial design and the manufacturing process of ICs are complicated, time consuming and costly. As the integration scale increases the yield in manufacturing decreases. The *yield* is defined as the ratio of the number of faultless products to the number of all products expressed in percentage. The decrease in yield, in turn increases the cost per gate.

Digital IC Technologies

Digital ICs employ following technologies : (*i*) CMOS, (*ii*) Bipolar, (*iii*) BiCMOS, (*iv*) MOS memory and (*v*) GaAs. *CMOS technology* is by a large margin the most dominant of all the IC technologies available for digital circuit design. During 1970s the fabrication of VLSI used *n*-type MOS or NMOS technology. However it has been replaced by CMOS technology. CMOS has also replaced bipolar as a technology of choice in digital system design and has made possible levels of integration or circuit packing densities and a range of applications that would never have been possible with bipolar technology. Furthermore, CMOS is continuously advancing, whereas bipolar digital technology advancement has very much retarded. Some of the reasons of CMOS popularity are :

— much less power consumption than bipolar circuits, thus allowing higher packing density.
— high input impedance of the MOS transistor. This allows the charge storage as a means for the temporary storage of information in both types of digital circuits, namely, logic and memory circuits. This technique cannot be employed using bipolar technology.
— the dramatic decrease in the *feature size* (the minimum channel length of MOSFET), which has reached to 0.15 μm. This permits very high packing density, thus leading to ultralarge integration.

Since 1960, the annual rate of reduction in the feature size has been 13%, which corresponds to a reduction by a factor of two every six years. At this rate the feature length has shrunk to 0.15 μm. The junction depth of the source and drain junctions and the gate oxide thickness are also being reduced at a similar rate.

CMOS circuits have various forms. The CMOS circuits based on inverter, called complementary CMOS, are the most widely used. They are available in all levels of integration. As stated above, CMOS in the complementary CMOS form are used not only in the deign of VLSI/ULSI logic circuits, but also in the design of memory circuit design. In addition to complementary CMOS form, the CMOS also has following form : Pseudo-NMOS, Pass Transistor Logic, (PTL) and Dynamic Logic.

The bipolar technology offers two logic circuit families : TTL and ECL. The transistor-transistor logic (TTL) is a viable digital-system design technology, especially for digital systems that are assembled from SSI and MSI packages. The emitter-coupled logic (ECL) is other bipolar logic circuit. This provides very high speed operation. Indeed, of all the commercially available logic circuit families, ECL is the fastest. ECL is also used in VLSI circuit design when very high operating speeds are required.

The *BiCMOS technology* combines the high operating speeds possible with bipolar transistor with the low power dissipation of CMOS. Like CMOS, *BiCMOS* allows for the implementation of both analog and digital circuits on the same chip. BiCMOS finds its special applications including memory chips.

The *GaAs technology* is an emerging technology having great potential. There are two GaAs devices : MESFET and SBD (Schottky barrier diode). GaAs devices have been used for some years in the design of discrete component amplifiers for microwave applications (in the GHz Frequency range). GaAs digital circuits have higher speed of operation than silicon devices and are available as SSI, MSI and LSI chips. However, they are costlier than silicon devices.

ICs are also classified into three types : standard parts, custom, and semicustom circuits. *Standard parts* are components used by many system manufacturers while *custom circuits* refer to components designed and manufactured for one customer. Custom circuits are used when suitable standard parts are not available, or to reduce cost by providing exactly the function needed for a specific application. *Semicustom circuits* have some standardized patterns or masking layers that are used in many different final ICs, and some patterns or layers that are designed to meet a particular user's requirements.

1.3. ADVANTAGES OF ICs OVER DISCRETE COMPONENTS

Size and Weight. IC technology offers reduction in size *i.e., miniaturization* and weight of the circuit. This is obvious because a circuit made of large number of discrete components (discrete component circuit) can be deposited on a chip which is housed in a package similar to that used for the encapsulation of discrete transistor. Thus, due so miniaturization many circuit functions can be packed into small space. This enables complex electronic equipments development. Such equipments can be suitably employed in many applications where weight and space are critical, such as aircraft or space vehicles and medical electronics.

Increase of Reliability. Unlike discrete component circuits where individual transistors and other components wired together or placed on a circuit board, IC allows many "extra" components to be included economically. This redundancy and "back up" circuitry can be included in the product, making it more reliable. Such extra addition of component does not raise greatly the cost of the product.

The reliability of ICs is superior to that of discrete circuits because when a large number of discrete components are assembled on a printed-card board, there is a chance of loose contacts or bed soldering wires, and this is often difficult to detect after assembly. But in the case of ICs, since the connections of IC are part of a package, there are few external connections to solder, and the reliability is high. Connections inside IC chips could be faulty, but the chance of encountering such faulty connections is much lower than for external faulty connections. It is observed that the failure rate of certain MSI chips with 70 to 100 gates each is only one seventh that of SSI chip.

Reduction in Circuit Cost. Since hundreds of identical circuits can be built simultaneously on a single silicon wafer (batch fabrication) the circuit cost is reduced. The total cost, *i.e.*, assembly plus component cost, decreases as the scale of integration increases. Although the processing steps for the wafer may be involved and expensive, the large number of resulting circuits makes the ultimate cost of each fairly low, Furthermore, the processing steps are essentially the same for a circuit containing 10000 transistors as for a simpler 100 transistor circuit. This means that the number of components in each circuit is relatively unimportant in terms of the ultimate cost of the system. In the past fifty years, prices have gone down by 100 million times, and the size has been reduced by a factor of one billion.

Reduction in Power Consumption. It is sometimes difficult to fully appreciate the revolutionary changes that were made possible through the development of ICs. For example, the largest early computers occupied a volume of hundreds of cubic meters and required many kilowatts of electrical power and a sizable air-conditioning plant to allow this amount of energy to be dissipated without raising the room temperature to undesirable values. The same type of computer is obtained today in a desk size or even smaller. However this drastic reduction in power consumption is not only due to IC technology but also due to on-off switching, *i.e.*, digital operation.

The reduced size of a digital system and also the realization of the majority of connections on chips results in a reduction of parasitic capacitance throughout the system, reducing the electric power to drive signals over parasitic capacitance. Logic gates inside chips have lower noise disturbances, allowing the use of lower signal voltage levels and consequently reducing power consumption. The reduction of power consumption results in the increase in integration size of each chip if the chip size is limited by high power consumption. Also since the power supply is expensive, the power consumption reduction reduces the system cost.

Improvement in Speed. The signal propagation time (propagation delay) is longer on connections made on printed circuit board than on connections inside the chip. Also, by making the physical size of the entire digital system small, the speed is improved. The propagation time of signal along a 30 cm wire is about 1 nanosec ; but parasitic capacitance on the printed circuit board further slows down the speed. As the switching speed of gates improves the propagation time along wires and also connections on the printed-circuit boards cannot be ignored. If the entire digital system is small, the length of the longest connections also becomes short ; and the parasitic capacitance is reduced. Consequently, the overall speed of the system improves.

It should be noted that device speed varies inversely with device feature length and power consumption varies approximately with the square of the feature length. Higher speeds lead to expanded IC functional throughput rates, so that future ICs can perform data processing, numerical computation, and signal conditioning at 100 and higher gigabit-per-second rates. Reduced power consumption results in lowering the energy required for each switching operation. Since 1960, the required energy, called the *power-delay product,* has decreased by six orders of magnitude.

LSI or VLSI/ULSI Packages Facilitate Quick Design. The design of digital systems can be done more quickly by assembling off-the-shelf LSI or VLSI/ULSI package than by the use of discrete components. When a manufacturer wants to sell a chip in high-volume production (say, on the order of millions), the chip with the smallest size is designed painstakingly, taking a long period of time. This is called the *full-custom design approach.* Thus, if we have to custom-design the VLSI/ULSI packages, the *design of IC is very time consuming. Assembly of digital systems using such IC packages is, however, quicker and cheaper.*

ICs Facilitates New Product Development. Since IC gates are so tiny, digital systems and computers are small and light. Because of this, very important features in many new products are being introduced as below :

— Electronic private branch exchanges, mobile phones.

— Personal computers (PCs), and intelligent terminals.

— Microcomputer based printers. In a typical printer 100 mechanical parts for control are reduced to about ten due to the use of LSI.

— Industrial robots and numerically controlled machines which improve productivity, reliability and design flexibility.

— ICs used in automobiles such as electronic fuel injection, anti-skid braking, seat-belt alarm, tire pressure sensor.

— LSI chip controlled sewing machine. The chip eliminates about three to four hundreds mechanical parts in a typical machine. It also provides number of stich patterns. It also optimizes stich width, length and density.

— Hi-fi and electronic musical instruments such as super-hi-fi by digital recording ; FM stereo-tuners, cordless infrared-transmitted head phones, and many electronic musical instruments with synthesized sounds available with LSI chips.

— Video games, electronic toys, automatic focussing cameras, electronic watches, and electronic locks.

— Medical electronics and health care products.

Because of the continuous introduction of products with new functions the marketing of products and the way of daily lives of the people are changing. *VLSI/ULSI is indeed causing significant technological and social changes and consequently is the basis of a second industrial revolution.* The first industrial revolution which was based upon the steam engine, enabled man to multiply his *physical capability* to do work. The second industrial revolution, which is based upon semiconductor electronics, is enabling man to multiply his *intellectual capability.* VLSI electronics, the most advanced state of semiconductor electronics, represents a remarkable application of scientific knowledge to the requirement of technology.

Prior to the invention of vacuum tube (in 1906) electro-mechanical design was more common. The development of the vacuum tube and the invention of transistors opened the field of electronic circuit design. The development of ICs led to a new generation of logic families. Since 1975, the beginning of VLSI, the frontier has moved to system organization of ICs and the associated software designs.

Earlier we used to find two types of work force in the world : Agricultural and industrial. Because of the development of the VLSI and ULSI, third type of work force has evolved. This can be referred as "information workers" ; they are involved in gathering, creating, processing, disseminating and using information. Advances in ULSI will have a profound effect on the world economy, because ULSI is the key technology for the Information Age.

1.4. ISSUES RELATED TO LEVELS OF INTEGRATION

As stated, the level of integration is directly related to the number of components placed on a single semiconductor chip. At one extreme, there is a discrete approach, *i.e.*, each component separately packaged. At the other extreme, there is VLSI approach providing highest possible level of integration. There is a whole range of levels between these limiting cases and the decision on choosing optimum level is complex economic one depending on such factors as projected market size and availability of ICs. In general, the more complex a system becomes, the more specialized it is and, therefore, the smaller is the number of applications. Thus, going for higher complexity means the fewer chips are likely to be sold. This implies, in turn, that such complex VLSI chips are not produced because they are not economic. The advent of the microprocessor was a specific attempt to overcome this problem. It combines a high degree of complexity with 'programmability' so that it may be used to perform a large number of different functions. Microprocessor has made it feasible for IC manufacturers to achieve high volume sales for very complex electronic systems, and made available to the system and circuit designers a powerful new tools at very low cost.

As stated earlier, the yield in manufacturing decreases as the level of integration increases. The greater the number of stages in the process the lower will be the yield, since each stage carries with it a finite probability that a malfunction will be induced in some of the circuits. If we suppose a fraction f still working after each stage in the process and it is same for each stage, the fraction working after N stages is

$$Y = f^N$$

Thus, for a given N, the overall yield Y increases as yield per stage, f, increases. However, if the number of process steps, N, is increased for a given f, then yield, Y, drops.

The maximum complexity that the IC manufacturer can achieve with sufficient yields at a given moment of time also affects the choice of level of integration. At the lowest level of integration the minimum device size sets a limit on the component density. If the IC manufacturers attempt to make the component below the set limit, they will suffer a dramatic decrease in yield because the misalignment between successive layers (discussed in details in later chapter) exceeds what is necessary to produce a working circuit. At the highest level of integration there is maximum chip size above which the yield again decreases rapidly. The maximum chip size is limited by crystalline defects per unit volume. This aspect of IC manufacturing is discussed in chapter 4.

Thus, we conclude that there is a maximum achievable complexity in terms of the number of components per chip which can be increased by producing lower defect densities in the wafer and obtaining new processing equipments which permit a smaller minimum device size. However, such improvements only come slowly with time and at considerable expense. In later chapters, we shall discuss specific stages in the fabrication of ICs.

The reliability of ICs involves design, process, assembly, and test. From a customer's prospective, what is really required of the product is the continual functionality of the IC during the specified lifetime. Typically, manufacturers design an IC to last 10 years. Product reliability is ensured if each of the elements of the product is reliable for that length of time. There are three major elements of product reliability : design reliability, process reliability, and assembly reliability. If the reliability of each of these elements meets the required lifetime, then we can ensure the reliability of a product.

ULSI Related Issues

ULSI is the most advanced state of electronic technology. With ULSI technology, there is :

— decrease in the cost of electronic products
— increase in the system functionality and performance
— realisation of smart and brilliant electronic systems, and
— improvement of quality of life and global productivity.

However, to fabricate IC chips with ULSI complexity, we have to employ the most sophisticated process equipment, to follow the most precise process steps, and to adopt the most stringent clean room specifications. Some new topics, which have gained importance due to ULSI circuits, are covered in chapter 4. These topics are : cleanroom technology, wafer-cleaning technology, and rapid thermal process. In addition, many key processes, such as lithography, etching, metallization, are discussed in the light of ULSI requirements.

One major issue of ULSI is to increase the yield, *i.e.*, the number of working IC chips produced at the end of the process sequence. The yield can be increased by control of the wafer environment. The environmental factors include the control of temperature, relative humidity, electrostatic discharges, air borne particles, chemical contamination, electromagnetic fields, oxygen, and vibration. In practice, the control of the wafer environment is a crucial aspect of the wafer manufacturing process. It constitutes the basis for the design of the cleanroom systems and process utilities systems.

Another important aspect of increasing the yield is to reduce the defect density in the wafer. It is defined as the number of defects per cm^2 wafer that may occur during the processing due to all kinds of contamination. As feature size decreases and wafer size increases, purity requirements become more stringent. A low defect density demands a substantial improvement in the wafer environment.

The present state of the wafer cleaning technology still does not meet all the future requirements for more advanced ULSI devices. More in-depth understanding of the surface state physics and chemistry is required, not only to eliminate the surface contamination but also to provide the atomically flat surface.

Metallization is the process that connects individual devices of IC chip together by means of microscopic wires to form circuit. These wires are necessary for a circuit to function, but they introduce parasitic resistance and capacitance, which degrade the performance of devices. Often these wires carry currents in the mA range, resulting in very high current density (10^5 A/cm^2) that may break the submicron-size interconnects. Thus, as device scales down with ever-improved output, the loss within the metal interconnects dissipates a greater portion of the improved performance. So far, the scaling has progressed without a change in the 5-volt power supply system requirement. This has resulted in increased reliability risks because of various IC failure mechanisms. However, as system manufacturers change the power supply of 3.3 volt or even lower voltages, the reliability risks will be reduced. However, noise margins in digital circuits will be more difficult to maintain. Other reliability parameters, *e.g.*, latch-up, electrostatic discharge (ESD), and soft error, also require study during the early stage of technology development.