

FUNDAMENTALS OF SEMICONDUCTOR MANUFACTURING AND PROCESS CONTROL

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 **WILEY-INTERSCIENCE**

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada.

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Library of Congress Cataloging-in-Publication Data:

May, Gary S.

Fundamentals of semiconductor manufacturing and process control / Gary S.

May, Costas J. Spanos.

p. cm.

"Wiley-Interscience."

Includes bibliographical references and index.

ISBN-13: 978-0-471-78406-7 (cloth : alk. paper)

ISBN-10: 0-471-78406-0 (cloth : alk. paper)

1. Semiconductors—Design and construction. 2. Integrated circuits—Design and construction. 3. Process control—Statistical methods. I. Spanos, Costas J. II. Title.

TK7871.85.M379 2006

621.3815'2—dc22

2005028448

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

To my children,
Simone and Jordan,
who inspire me.

—Gary S. May

To my family,
for their love and understanding.

—Costas J. Spanos

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PREFACE

In simple terms, manufacturing can be defined as the process by which raw materials are converted into finished products. The purpose of this book is to examine in detail the methodology by which electronic materials and supplies are converted into finished integrated circuits and electronic products in a high-volume manufacturing environment. This subject of this book will be issues relevant to the industrial-level manufacture of microelectronic device and circuits, including (but not limited to) fabrication sequences, process control, experimental design, process modeling, yield modeling, and CIM/CAM systems. The book will include theoretical and practical descriptions of basic manufacturing concepts, as well as some case studies, sample problems, and suggested exercises.

The book is intended for graduate students and can be used conveniently in a semester-length course on semiconductor manufacturing. Such a course may or may not be accompanied by a corequisite laboratory. The text can also serve as a reference for practicing engineers and scientists in the semiconductor industry.

Chapter 1 of the book places the manufacture of integrated circuits into its historical context, as well as provides an overview of modern semiconductor manufacturing. In the Chapter 2, we provide a broad overview of the manufacturing technology and processes flows used to produce a variety of semiconductor products. Various process monitoring methods, including those that focus on product wafers and those that focus on the equipment used to produce those wafers, are discussed in Chapter 3. As a backdrop for subsequent discussion of statistical process control (SPC), Chapter 4 provides a review of statistical fundamentals. Ultimately, the key metric to be used to evaluate any manufacturing process is cost, and cost is directly impacted by yield. Yield modeling is therefore presented in Chapter 5. Chapter 6 then focuses on the use of SPC to analyze quality issues and improve yield. Statistical experimental design, which is presented in Chapter 7, is a powerful approach for systematically varying controllable process conditions and determining their impact on output parameters which measure quality. Data derived from statistical experiments can then be used to construct process models that enable the analysis and prediction of manufacturing process behavior. Process modeling concepts are introduced in Chapter 8. Finally, several advanced process control topics, including run-by-run, supervisory control, and process and equipment diagnosis, are the subject of Chapters 9 and 10.

Each chapter begins with an introduction and a list of learning goals, and each concludes with a summary of important concepts. Solved examples are provided throughout, and suggested homework problems appear at the end of the chapter. A complete set of detailed solutions to all end-of-chapter problems has been prepared. This *Instructor's Manual* is available to all adopting faculty. The figures in the text are also available, in electronic format, from the publisher at the web site: <http://www.wiley.com/college/mayspanos>.

ACKNOWLEDGMENTS

G. S. May would like to acknowledge the support of the Steve W. Chaddick School Chair in Electrical and Computer Engineering at the Georgia Institute of Technology, which provided the environment that enabled the completion of this book. C. J. Spanos would like to acknowledge the contributions of the Berkeley students who, over the years, helped shape the material presented in this book.

INTRODUCTION TO SEMICONDUCTOR MANUFACTURING

OBJECTIVES

- Place the manufacturing of integrated circuits in a historical context.
- Provide an overview of modern semiconductor manufacturing.
- Discuss manufacturing goals and objectives.
- Describe manufacturing systems at a high level as a prelude to the remainder of the text.

INTRODUCTION

This book is concerned with the manufacturing of devices, circuits, and electronic products based on semiconductors. In simple terms, *manufacturing* can be defined as the process by which raw materials are converted into finished products. As illustrated in Figure 1.1, a manufacturing operation can be viewed graphically as a system with raw materials and supplies serving as its inputs and finished commercial products serving as outputs. In semiconductor manufacturing, input materials include semiconductor materials, dopants, metals, and insulators. The corresponding outputs include integrated circuits (ICs), IC packages, printed circuit boards, and ultimately, various commercial electronic systems and products (such as computers, cellular phones, and digital cameras). The types of processes that arise in semiconductor manufacturing include crystal

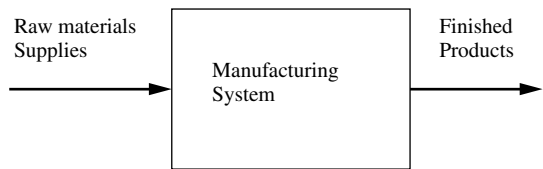


Figure 1.1. Block diagram representation of a manufacturing system.

growth, oxidation, photolithography, etching, diffusion, ion implantation, planarization, and deposition processes.

Viewed from a systems-level perspective, semiconductor manufacturing intersects with nearly all other IC process technologies, including design, fabrication, integration, assembly, and reliability. The end result is an electronic system that meets all specified performance, quality, cost, reliability, and environmental requirements. In this chapter, we provide an overview of semiconductor manufacturing, which touches on each of these intersections.

1.1. HISTORICAL EVOLUTION

Semiconductor devices constitute the foundation of the electronics industry, which is currently (as of 2005) the largest industry in the world, with global sales over one trillion dollars since 1998. Figure 1.2 shows the sales volume of the semiconductor device-based electronics industry since 1980 and projects sales to the year 2010. Also shown are the gross world product (GWP) and the sales volumes

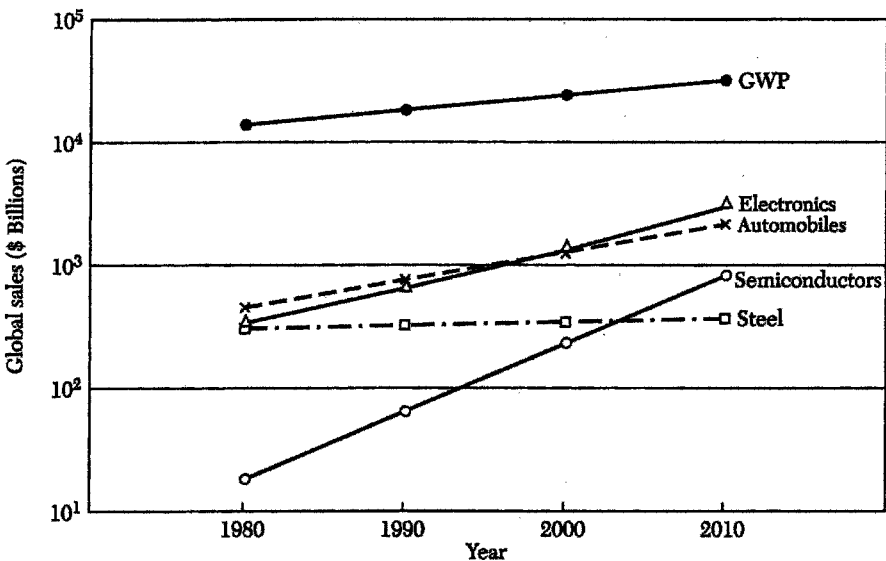


Figure 1.2. Gross world product (GWP) and sales volumes of various industries from 1980 to 2000 and projected to 2010 [1].

of the automobile, steel, and semiconductor industries [1]. If current trends continue, the sales volume of the electronic industry will reach three trillion dollars and will constitute about 10% of GWP by 2010. The semiconductor industry, a subset of the electronics industry, will grow at an even higher rate to surpass the steel industry in the early twenty-first century and to constitute 25% of the electronic industry in 2010.

The multi-trillion-dollar electronics industry is fundamentally dependent on the manufacture of semiconductor integrated circuits (ICs). The solid-state computing, telecommunications, aerospace, automotive, and consumer electronics industries all rely heavily on these devices. A brief historical review of manufacturing and quality control, semiconductor processing, and their convergence in IC manufacturing, is therefore warranted.

1.1.1. Manufacturing and Quality Control

The historical evolution of manufacturing, summarized in Table 1.1, closely parallels the industrialization of Western society, beginning in the nineteenth century. It could be argued that the key early development in manufacturing was the concept of *interchangeable parts*. Eli Whitney is credited with pioneering this concept, which he used for mass assembly of the cotton gin in the early 1800s [2]. In the late 1830s, a Connecticut manufacturer began producing cheap windup clocks by stamping out many of the parts out of sheets of brass. Similarly, in the early 1850s, American rifle manufacturers thoroughly impressed a British delegation by a display in which 10 muskets made in 10 different preceding years were disassembled, had their parts mixed up in a box, and subsequently reassembled quickly and easily. In England at that time, it would have taken a skilled craftsman the better part of a day to assemble a single unit.

The use of interchangeable parts eliminated the labor involved in matching individual parts in the assembly process, resulting in a tremendous time savings and increase in productivity. The adoption of this method required new forms of technology capable of much finer tolerances in production and measurement methods than those required by hand labor. Examples included the

Table 1.1. Major milestones in manufacturing history.

Year(s)	Event
1800–1850	Concept of interchangeable parts introduced
1850–1860	Advances in measurement and machining operations
1875	Taylor introduces scientific management principles
1900–1930	Assembly line techniques actualized by Ford
1924	Control chart introduced by Shewhart
Late 1920s	Dodge and Romig develop acceptance sampling
1950s	Computer numeric control and designed experiments introduced
1970s	Growth in the adoption of statistical experimental design
1980	Pervasive use of statistical methods in many industries

vernier caliper, which allowed workers to measure machine tolerances on small scales, and wire gauges, which were necessary in the production of clock springs. One basic machine operation perfected around this time was mechanical drilling using devices such as the turret lathe, which became available after 1850. Such devices allowed a number of tedious operations (hand finishing of metal, grinding, polishing, stamping, etc.) to be performed by a single piece of equipment using a bank of tool attachments. By 1860, a good number of the basic steps involved in shaping materials into finished products had been adapted to machine functions.

Frederick Taylor added rigor to the manufacturing research and practice by introducing the principles of *scientific management* into mass production industries around 1875 [3]. Taylor suggested dividing work into tasks so that products could be manufactured and assembled more readily, leading to substantial productivity improvements. He also developed the concept of standardized production and assembly methods, which resulted in improved quality of manufactured goods. Along with the standardization of methods came similar standardization in work operations, such as standard times to accomplish certain tasks, or a specified number of units that must be produced in a given work period.

Interchangeable parts also paved the way for the next major contribution to manufacturing: the *assembly line*. Industrial engineers had long noted how much labor is spent in transferring materials between various production steps, compared with the time spent in actually performing the steps. Henry Ford is credited for devising the assembly line in his quest to optimize the means for producing automobiles in the early twentieth century. However, the concept of the assembly line had actually been devised at least a century earlier in the flour mill industry by Oliver Evans in 1784 [2]. Nevertheless, it was not until the concept of interchangeable parts was combined with technology innovations in machining and measurement that assembly line methods were truly actualized in their ultimate form. After Ford, the assembly line gradually replaced more labor-intensive forms of production, such as custom projects or batch processing.

No matter what industry, no one working in manufacturing today can overemphasize the influence of the computer, which catalyzed the next major paradigm shift manufacturing technology. The use of the computer was the impetus for the concept of *computer numeric control* (CNC), introduced in the 1950s [4]. Numeric control was actually developed much earlier. The player piano is a good example of this technique. This instrument utilizes a roll of paper with holes punched in it to determine whether a particular note is played. The numeric control concept was enhanced considerably by the invention of the computer in 1943. The first CNC device was a spindle milling machine developed by John Parsons of MIT in 1952. CNC was further enhanced by the use of microprocessors for control operations, beginning around 1976. This made CNC devices sufficiently versatile that an existing tooling could be quickly reconfigured for different processes. This idea moved into semiconductor manufacturing more than a decade later when the machine communication standards made it possible to have factorywide production control.

The inherent accuracy and repeatability engendered by the use of the computer eventually enabled the concept of *statistical process control* to gain a foothold in manufacturing. However, the application of statistical methods actually had a long prior history. In 1924, Walter Shewhart of Bell Laboratories introduced the control chart. This is considered by many as the formal beginning of statistical quality control. In the late 1920s, Harold Dodge and Harry Romig, both also of Bell Labs, developed statistically based acceptance sampling as an alternative to 100% inspection. By the 1950s, rudimentary computers were available, and *designed experiments* for product and process improvement were first introduced in the United States. The initial applications for these techniques were in the chemical industry. The spread of these methods to other industries was relatively slow until the late 1970s, when their further adoption was spurred by economic competition between Western companies and the Japanese, who had been systematically applying designed experiments since the 1960s. Since 1980, there has been profound and widespread growth in the use of statistical methods worldwide, and particularly in the United States.

1.1.2. Semiconductor Processes

Many important semiconductor technologies were derived from processes invented centuries ago. Some of the key technologies are listed in Table 1.2 in chronological order. For the most part, these techniques were developed independently from the evolution of manufacturing science and technology. For example, the growth of metallic crystals in a furnace was pioneered by Africans living on the

Table 1.2. Major milestones in semiconductor processing history.

Year	Event
1798	Lithography process invented
1855	Fick proposes basic diffusion theory
1918	Czochralski crystal growth technique invented
1925	Bridgman crystal growth technique invented
1952	Diffusion used by Pfann to alter conductivity of silicon
1957	Photoresist introduced by Andrus; oxide masking developed by Frosch and Derrick; epitaxial growth developed by Sheftal et al.
1958	Ion implantation proposed by Shockley
1959	Kilby and Noyce invent the IC
1963	CMOS concept proposed by Wanlass and Sah
1967	DRAM invented by Dennard
1969	Self-aligned polysilicon gate process proposed by Kerwin et al.; MOCVD developed by Manasevit and Simpson
1971	Dry etching developed by Irving et al.; MBE developed by Cho; first microprocessor fabricated by Intel
1982	Trench isolation technology introduced by Rung et al.
1989	CMP developed by Davari et al.
1993	Copper interconnect introduced to replace aluminum by Paraszcak et al.

western shores of Lake Victoria more than 2000 years ago [5]. This process was used to produce carbon steel in preheated forced-draft furnaces. Another example is the lithography process, which was invented in 1798. In this first process, the pattern, or image, was transferred from a stone plate (*lithos*) [6]. The diffusion of impurity atoms in semiconductors is also important for device processing. Basic diffusion theory was described by Fick in 1855 [7].

In 1918, Czochralski developed a liquid–solid monocomponent growth technique used to grow most of the crystals from which silicon wafers are produced [8]. Another growth technique was developed by Bridgman in 1925 [9]. The Bridgman technique has been used extensively for the growth of gallium arsenide and related compound semiconductors. The idea of using diffusion techniques to alter the conductivity in silicon was disclosed in a patent by Pfann in 1952 [10]. In 1957, the ancient lithography process was applied to semiconductor device fabrication by Andrus [11], who first used photoresist for pattern transfer. Oxide masking of impurities was developed by Frosch and Derrick in 1957 [12]. In the same year, the epitaxial growth process based on chemical vapor deposition was developed by Sheftal et al. [13]. In 1958, Shockley proposed the method of using ion implantation to precisely control the doping of semiconductors [14].

In 1959, the first rudimentary integrated circuit was fabricated from germanium by Kilby [15]. Also in 1959, Noyce proposed the monolithic IC by fabricating all devices in a single semiconductor substrate and connecting the devices by aluminum metallization [16]. As the complexity of the IC increased, the semiconductor industry moved from NMOS (*n*-channel MOSFET) to CMOS (complementary MOSFET) technology, which uses both NMOS and PMOS (*p*-channel MOSFET) processes to form the circuit elements. The CMOS concept was proposed by Wanlass and Sah in 1963 [17]. In 1967, the dynamic random access memory (DRAM) was invented by Dennard [18].

To improve device reliability and reduce parasitic capacitance, the self-aligned polysilicon gate process was proposed by Kerwin et al. in 1969 [19]. Also in 1969, the metallorganic chemical vapor deposition (MOCVD) method, an important epitaxial growth technique for compound semiconductors, was developed by Manasevit and Simpson [20]. As device dimensions continued to shrink, dry etching was developed by Irving et al. in 1971 to replace wet chemical etching for high-fidelity pattern transfer [21]. Another important technique developed in the same year by Cho was molecular-beam epitaxy (MBE) [22]. MBE has the advantage of near-perfect vertical control of composition and doping down to atomic dimensions. Also in 1971, the first monolithic microprocessor was fabricated by Hoff et al. at Intel [23]. Currently, microprocessors constitute the largest segment of the industry.

Since 1980, many new technologies have been developed to meet the requirements of continuously shrinking minimum feature lengths. Trench technology was introduced by Rung et al. in 1982 to isolate CMOS devices [24]. In 1989, the chemical–mechanical polishing (CMP) method was developed by Davari et al. for global planarization of the interlayer dielectrics [25]. Although aluminum has been used since the early 1960s as the primary IC interconnect material, copper

interconnect was introduced in 1993 by Paraszczak et al. to replace aluminum for minimum feature lengths approaching 100 nm [26].

1.1.3. Integrated Circuit Manufacturing

By the beginning of the 1980s, there was deep and widening concern about the economic well-being of the United States. Oil embargoes during the previous decade had initiated two energy crises and caused rampant inflation. The U.S. electronics industry was no exception to the economic downturn, as Japanese companies such as Sony and Panasonic nearly cornered the consumer electronics market. The U.S. computer industry experienced similar difficulties, with Japanese semiconductor companies beginning to dominate the memory market and establish microprocessors as the next target.

Then, as now, the fabrication of ICs was extremely expensive. A typical state-of-the-art, high-volume manufacturing facility at that time cost over a million dollars (and now costs several billion dollars) [27]. Furthermore, unlike the manufacture of discrete parts such as appliances, where relatively little rework is required and a yield greater than 95% on salable product is often realized, the manufacture of integrated circuits faced unique obstacles. Semiconductor fabrication processes consisted of hundreds of sequential steps, with potential yield loss occurring at every step. Therefore, IC manufacturing processes could have yields as low as 20–80%.

Because of rising costs, the challenge before semiconductor manufacturers was to offset large capital investment with a greater amount of automation and technological innovation in the fabrication process. The objective was to use the latest developments in computer hardware and software technology to enhance manufacturing methods. In effect, this effort in *computer-integrated manufacturing of integrated circuits* (IC-CIM) was aimed at optimizing the cost-effectiveness of IC manufacturing as *computer-aided design* (CAD) had dramatically affected the economics of circuit design.

IC-CIM is designed to achieve several important objectives, including increasing chip fabrication yield, reducing product cycle time, maintaining consistent levels of product quality and performance, and improving the reliability of processing equipment. Table 1.3 summarizes the results of a 1986 study by Toshiba that analyzed the use of IC-CIM techniques in producing 256-kbyte DRAM memory circuits [28]. This study showed that CIM techniques improved the manufacturing process on each of the four productivity metrics investigated.

Table 1.3. Results of 1986 Toshiba study.

Productivity Metric	Without CIM	With CIM
Turnaround time	1.0	0.58
Integrated unit output	1.0	1.50
Average equipment uptime	1.0	1.32
Direct labor hours	1.0	0.75

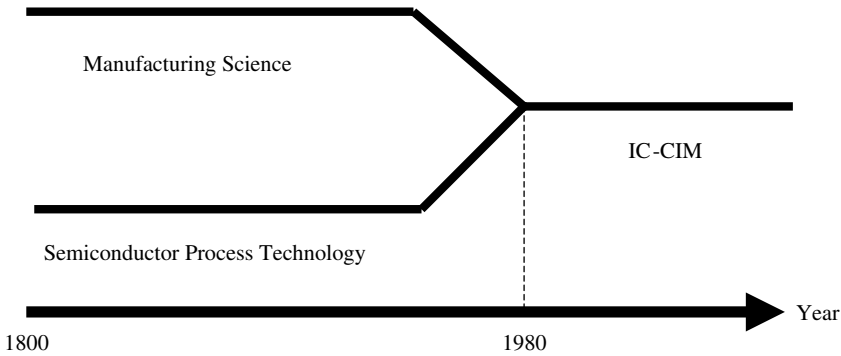


Figure 1.3. Timeline indicating convergence of manufacturing science and semiconductor processing into IC-CIM.

In addition to the demonstration of the effectiveness of IC-CIM techniques, economic concerns were so great in the early to mid-1980s that the Reagan Administration took the unprecedented step of partially funding a consortium of U.S. IC manufacturers—including IBM, Intel, Motorola, and Texas Instruments—to perform cooperative research and development on semiconductor manufacturing technologies. This consortium, SEMATECH, officially began operations in 1988 [29]. This sequence of events signaled the convergence of advances in manufacturing science and semiconductor process technology, and also heralded the origin of a more systematic and scientific approach to semiconductor manufacturing. This convergence is illustrated in Figure 1.3.

1.2. MODERN SEMICONDUCTOR MANUFACTURING

The modern semiconductor manufacturing process sequence is the most sophisticated and unforgiving volume production technology that has ever been practiced successfully. It consists of a complex series of hundreds of unit process steps that must be performed very nearly flawlessly.

This semiconductor manufacturing process can be defined at various levels of abstraction. For example, each process step has inputs, outputs, and specifications. Each step can also be modeled, either physically, empirically, or both. Much can be said about the technology of each step, and more depth in this area is provided in Chapter 2. At a higher level of abstraction, multiple process steps are linked together to form a process sequence. Between some of these links are inspection points, which merely produce information without changing the product. The flow and utilization of information occurs at another level of abstraction, which consists of various control loops. Finally, the organization of the process belongs to yet another level of abstraction, where the objective is to maximize the efficiency of product flow while reducing variability.

1.2.1. Unit Processes

It is difficult to discuss unit process steps outside the context of a process flow. Figures 1.4 and 1.5 show the major unit processes used in a simple process flow. These steps include oxidation, photolithography, etching, ion implantation, and metallization. We describe these steps briefly in this section via a simple sequence used to fabricate a p - n junction [1].

The development of a high-quality silicon dioxide (SiO_2) has helped to establish the dominance of silicon in the production of commercial ICs. Generally, SiO_2 functions as an insulator in a number of device structures or as a barrier to diffusion or implantation during device fabrication. In the fabrication of a p - n junction (Figure 1.4), the SiO_2 film is used to define the junction area. There are two SiO_2 growth methods, dry and wet oxidation, depending on whether

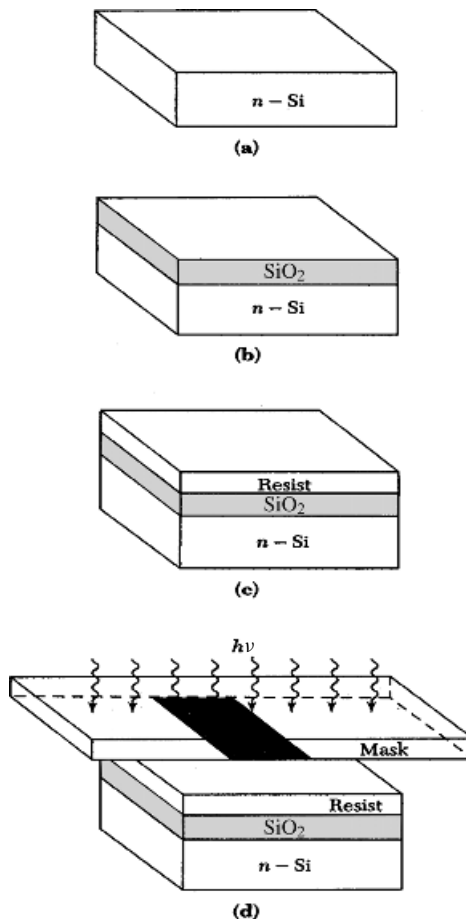


Figure 1.4. (a) A bare n -type silicon wafer; (b) an oxidized silicon wafer; (c) application of photoresist; (d) resist exposure through a mask [1].

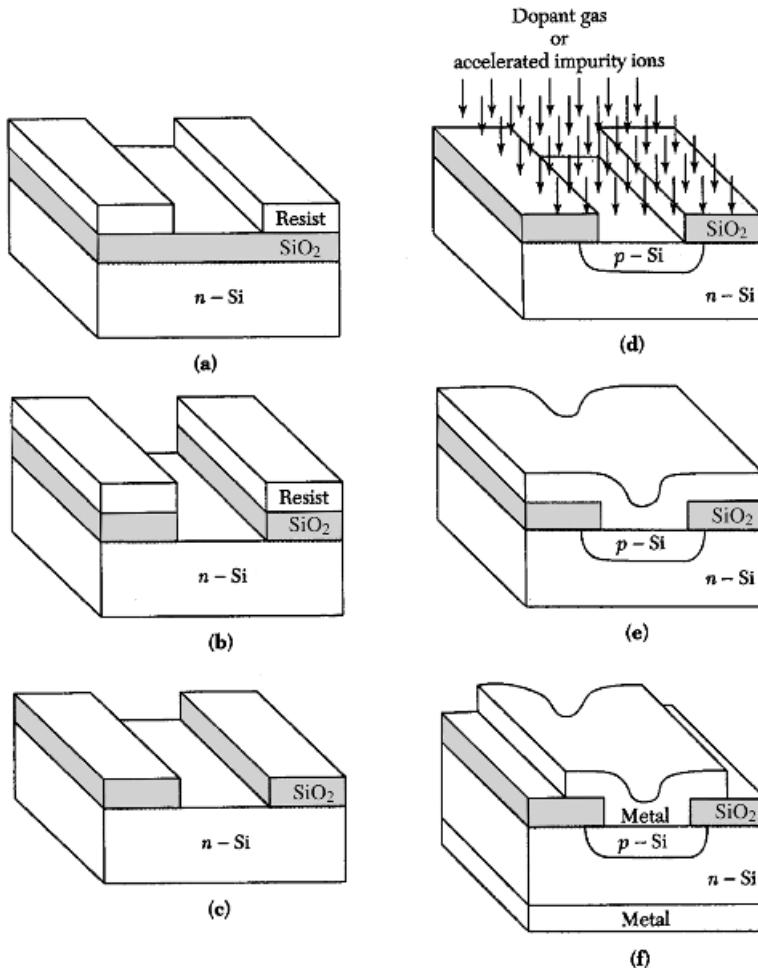


Figure 1.5. (a) Wafer after development; (b) wafer after SiO_2 removal; (c) result after photolithography; (d) formation of a p - n junction using diffusion or implantation; (e) wafer after metallization; (f) final product [1].

dry oxygen or water vapor is used. Dry oxidation is usually used to form thin oxides in a device structure because of its good Si-SiO_2 interface characteristics, whereas wet oxidation is used for thicker layers because of its higher growth rate. Figure 1.4a shows a section of a bare wafer ready for oxidation. After the oxidation process, a SiO_2 layer is formed all over the wafer surface. For simplicity, Figure 1.4b shows only the upper surface of an oxidized wafer.

Photolithography is used to define the geometry of the p - n junction. After the formation of SiO_2 , the wafer is coated with an ultraviolet (UV) light-sensitive material called *photoresist*, which is spun onto the wafer surface. Afterward (Figure 1.4c), the wafer is baked to drive the solvent out of the resist and to

harden the resist for improved adhesion. Figure 1.4d shows the next step, which is to expose the wafer through a patterned mask using an UV light source. The exposed region of the photoresist-coated wafer undergoes a chemical reaction. The exposed area becomes polymerized and difficult to remove in an etchant. The polymerized region remains when the wafer is placed in a developer, whereas the unexposed region dissolves away. Figure 1.5a shows the wafer after the development. The wafer is again baked to enhance the adhesion and improve the resistance to the subsequent etching process. Then, an etch using hydrofluoric acid (HF) removes the unprotected SiO_2 surface (Figure 1.5b). Last, the resist is stripped away by a chemical solution or an oxygen plasma. Figure 1.5c shows the final result of a region without oxide (a window) after the lithography process. The wafer is now ready for forming the p - n junction by a diffusion or ion implantation process.

In diffusion, the wafer surface not protected by the oxide is exposed to a source with a high concentration of an opposite-type impurity. The impurity moves into the semiconductor crystal by solid-state diffusion. In ion implantation, the intended impurity is introduced into the wafer by accelerating the impurity ions to a high energy level and then implanting the ions in the semiconductor. The SiO_2 layer serves as barrier to impurity diffusion or ion implantation. After diffusion or implantation, the p - n junction is formed (Figure 1.5d).

After diffusion or ion implantation, a metallization process is used to form ohmic contacts and interconnections (Figure 1.5e). Metal films can be formed by physical vapor deposition or chemical vapor deposition. The photolithography process is again used to define the front contact, which is shown in Figure 1.5f. A similar metallization step is performed on the back contact without using a photolithography process.

1.2.2. Process Sequences

Semiconductor manufacturing consists of a series of sequential process steps like the one described in the previous section in which layers of materials are deposited on substrates, doped with impurities, and patterned using photolithography to produce ICs. Figure 1.6 illustrates the interrelationship between the major process steps used for IC fabrication. Polished wafers with a specific resistivity and orientation are used as the starting material. The film formation steps include thermally grown oxide films, as well as deposited polysilicon, dielectric, and metal films. Film formation is often followed by photolithography or impurity doping. Photolithography is generally followed by etching, which in turn is often followed by another impurity doping or film formation. The final IC is made by sequentially transferring the patterns from each mask, level by level, onto the surface of the semiconductor wafer.

After processing, each wafer contains hundreds of identical rectangular chips (or dies), typically between 1 and 20 mm on each side, as shown in Figure 1.7a. The chips are separated by sawing or laser cutting; Figure 1.7b shows a separated chip. Schematic top views of a single MOSFET and a single bipolar transistor

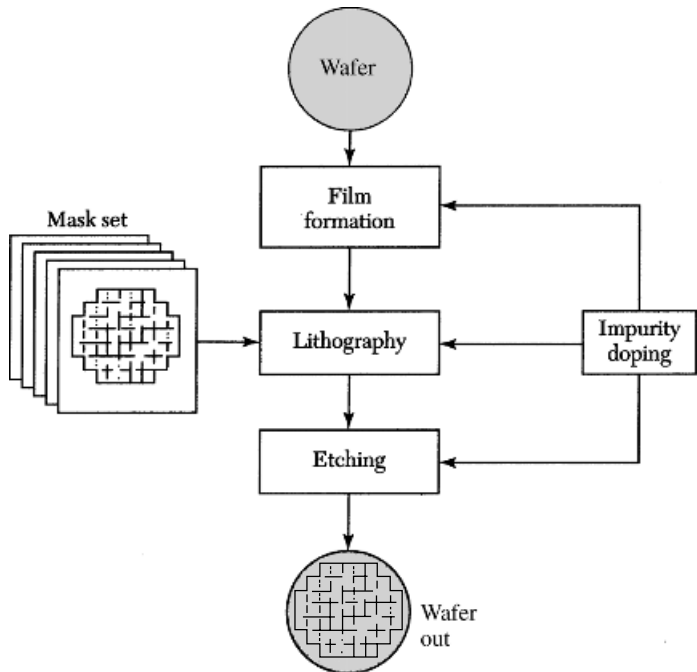


Figure 1.6. Flow diagram for generic IC process sequence [1].

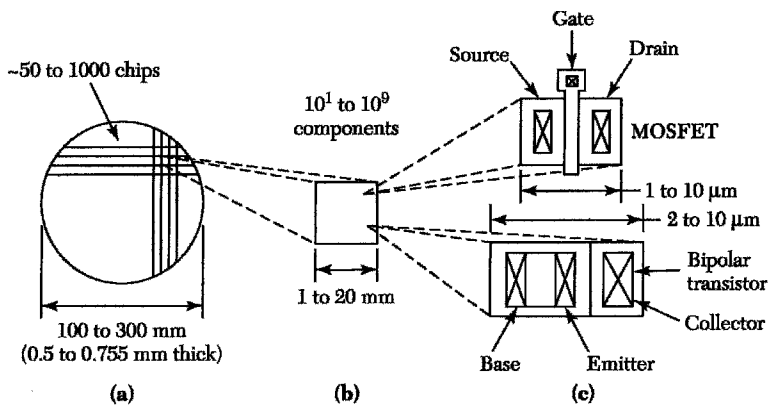


Figure 1.7. (a) Semiconductor wafer; (b) IC chip; (c) MOSFET and bipolar transistor [1].

are shown in Figure 1.7c. Inserted into this process sequence are various points at which key measurements are performed to ensure product quality.

1.2.3. Information Flow

The vast majority of quantitative evaluation of semiconductor manufacturing processes is accomplished via IC-CIM systems. The interdependent issues of

ensuring high yield, high quality, and low cycle time are addressed by several critical capabilities in a state-of-the-art IC-CIM system: work-in-process (WIP) monitoring, equipment communication, data acquisition and storage, process/equipment modeling, and process control, to name only a few. The emphasis of each of these activities is to increase throughput and prevent potential mis-processing, but each presents significant engineering challenges in their effective implementation and deployment.

A block diagram of a typical modern IC-CIM system is shown in Figure 1.8. This diagram outlines many of the key features required for efficient information flow in manufacturing operations [28]. The lower level of this two-level architecture includes embedded controllers that provide real-time control and analysis of fabrication equipment. These controllers consist of personal computers and the associated control software dedicated to each individual piece of equipment. The second level of this IC-CIM architecture consists of a distributed local-area network of computer workstations and file servers linked by a common distributed database.

Equipment communication with host computers is facilitated by an electronics manufacturing standard called the *generic equipment model* (GEM). The GEM standard is used in both semiconductor manufacturing and printed circuit board assembly. This standard is based on the *semiconductor equipment communications standard* (SECS) protocol. SECS is a standard for communication between intelligent equipment and a host. The SECS standard has two components that define the communications protocol (SECS-I) and the messages exchanged (SECS-II), respectively. SECS-I specifies point-to-point communications over a high-speed messaging service interface. GEM is a standard set of SECS capabilities that can be selected by users as needed to coordinate equipment control in an automated factory. The GEM standard defines semiconductor

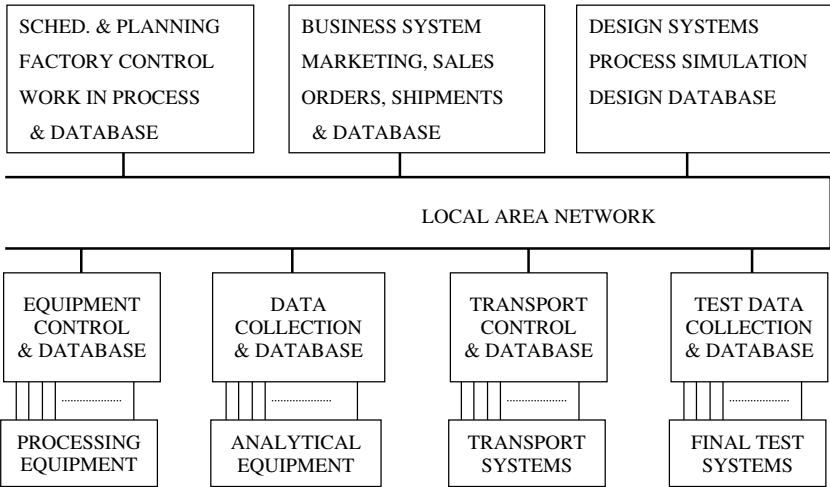


Figure 1.8. Two-level IC-CIM architecture [28].

equipment behavior as viewed through a communication link in terms of SECS-II messages communicated over that link. The GEM standard impacts equipment control and equipment–host communication and enables equipment to be integrated quickly and efficiently with a host computer [30].

The flow of information in this type of IC-CIM architecture enables equipment and process control at several levels. The highest level can be thought of as *supervisory control*, where the progression of a substrate is tracked from process to process. At this level, adjustments can be made to subsequent process steps to account for variation in previous procedures. The next lower level of control occurs on a *run-by-run* basis. For a single process, adjustments are made after each run to account for shifts and drifts that occur from wafer to wafer. Occasional shifts may occur when a new operator takes over or preventive maintenance is performed. A process may also experience drift due to equipment aging. *Real-time control* is at the lowest level of the hierarchy. In this case, adjustments are made to a process during a run to account for in situ disturbances. This hierarchy is diagramed in Figure 1.9.

1.2.4. Process Organization

As mentioned previously, the overall objective of process organization is to maximize the efficiency of product flow while minimizing variability and yield loss. Modern semiconductor factories [known as “fabs” (Fabrication Facilities)] are typically organized into *workcells*. In this approach, all the necessary equipment for completing a given process step is placed in the same room (see Figure 1.10). The workcell layout optimizes product flow, resulting in a minimal average distance traveled by semiconductor wafers as they migrate through the fabrication

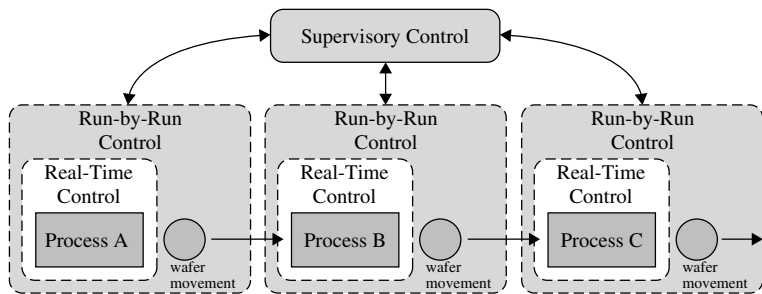


Figure 1.9. Process control hierarchy.

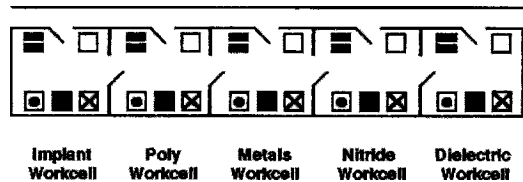


Figure 1.10. Workcell layout in a modern IC fabrication facility.

facility. This reduced distance translates into fewer chances for wafer mishandling and potential loss of product. Furthermore, the trend in equipment development since the mid-1990s has been toward single-wafer processing systems that enable enhanced reproducibility.

This modern IC factory also draws on powerful computing concepts, resulting in a highly flexible manufacturing system. In addition to the actual processing equipment, the factory consists of advanced in situ, postprocess, and end-of-the-line metrology and instrumentation necessary to quality control, equipment maintenance and diagnosis, rapid failure recovery, and inventory management. The physical factory is also augmented by simulation tools that allow various scenarios to be evaluated in a virtual manufacturing environment.

1.3. GOALS OF MANUFACTURING

From a systems-level perspective, semiconductor manufacturing intersects with design, fabrication, integration, assembly, and reliability. The fundamental goals of manufacturing are to tie all of these technologies together to achieve finished products with

- Low cost
- High quality
- High reliability

Cost is most directly impacted by yield and throughput. *Yield* is the proportion of products that meet the required performance specifications. Yield is inversely proportional to cost; that is, the higher the yield, the lower the cost. *Throughput* refers to the number of products processed per unit time. High throughput also leads to lower cost. The *quality* goal is virtually self-explanatory. It is obviously desirable to produce high-quality ICs that can be efficiently and repeatably mass-produced with a high degree of uniformity. Quality is derived from a stable and well-controlled manufacturing process. The *reliability* of electronic products is also impacted by the manufacturing process. High reliability results from the minimization of manufacturing faults. If each of the abovementioned goals is fulfilled, the end result is an IC that meets all specified performance, quality, cost, and reliability requirements.

1.3.1. Cost

Understanding the economics of IC manufacturing is important not only to the manufacturer but also to buyers and designers. A general rule of thumb is that IC fabrication, testing, and packaging each contribute about one-third of the total product cost. A variety of factors contribute to overall product costs, including the following [31]:

- Wafer processing cost

- Wafer processing yield
- Die size
- Wafer probe cost
- Probe yield
- Number of good dies
- Package cost
- Assembly yield
- Final test cost
- Final test yield

Wafer processing cost depends on wafer size, raw-wafer cost, direct labor cost, facility cost, and direct factory overhead (i.e., indirect labor costs, utilities, and maintenance). Direct costs (i.e., raw-wafer cost and direct labor) typically account for 10–15% of the wafer processing cost, with the remaining indirect costs accounted for by the equipment and facility depreciation, engineering support, facility operating costs, production control, and direct factory overhead. Increasingly, equipment costs contribute the lion's share, accounting for over 70% of the total indirect cost.

Currently, IC fabrication cost (excluding design costs) is about \$4/cm² at mature production levels [32]. The cost per IC to produce N chips (or equivalently, N circuit functions) is proportional to e^{kN} , where k is a constant proportional to the cost of assembly and testing [33]. The interplay between these factors and their impact on cost is illustrated in Figure 1.11. Cost per IC is minimized by maximizing both the number of chips per wafer and the proportion of good chips (also known as the *yield*).

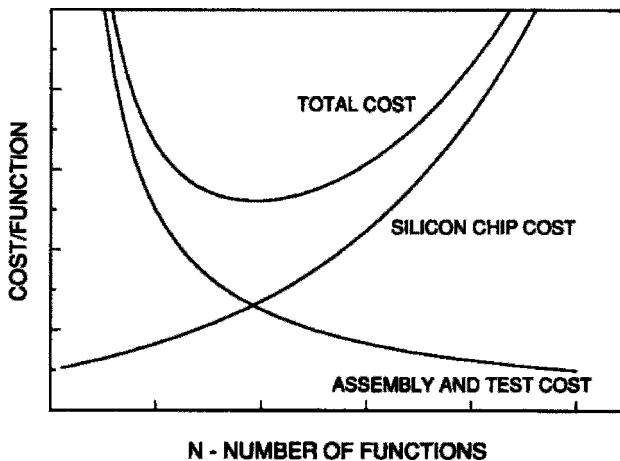


Figure 1.11. Cost per function versus number of functions [33].

1.3.2. Quality

Quality is among the most important factors in any manufacturing process. Understanding and improving quality are key ingredients to business success, growth, and enhanced competitiveness. Significant return on investment may be realized from adequate attention to continuous quality improvement as an integral part of an overall business strategy.

The term “quality” may be defined in many ways. The traditional definition is based on the notion that products must meet the requirements of those who use them. Thus, in this text, we adopt the simple definition of “fitness for use.” This definition encompasses two general aspects: quality of design and quality of conformance. *Quality of design* is affected by choices in fabrication materials, component specifications, product size, and other features. *Quality of conformance* addresses how well a product conforms to the specifications required by the design. Quality of conformance is impacted by the manufacturing process, equipment performance, competence and training of the workforce, and the implementation of quality control procedures.

1.3.3. Variability

An alternative definition of quality of conformance is “the inverse of variability.” This definition implies that quality may be improved by reducing variation in the various figures of merit that define product performance. This reduced variability translates directly into lower manufacturing costs due to less misprocessing, rework, and waste. Thus, processes in which the degree of quality is repeatable with a high degree of uniformity are preferred.

Unfortunately, a certain amount of variability is inherent in every product. No two products are ever completely identical. For example, the dimensions of two thin metal films used for IC interconnect will vary according to the precise conditions and equipment used to deposit and pattern the films. Small variations might have negligible impact on the final product, but large variations can lead to final products that are unacceptable. *Quality improvement* is defined as the reduction of such variability in processes and products. Since variability is usually described in statistical terms, statistical methods are necessary for quality improvement efforts.

1.3.4. Yield

As previously mentioned, IC cost is minimized by maximizing both the number of chips produced (i.e., the throughput) and the proportion of functionally operational chips per wafer. The latter parameter is known as the *yield*. As a consequence of its direct impact on manufacturing cost, yield is perhaps the most important figure of merit in semiconductor manufacturing.

Yield improvement achieved over time is referred to as “yield learning.” Strategies for accelerated yield learning are critical for the economic viability of semiconductor manufacturing operations, as illustrated in Figure 1.12. Business goals

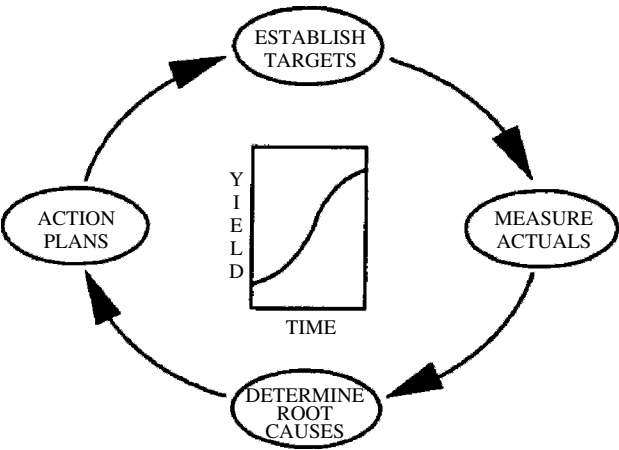


Figure 1.12. Yield learning cycle [33].

drive yield targets. The actual yield achieved is regularly monitored and tracked against those targets. The root causes of yield detractors are systematically identified and analyzed. Appropriate action plans to eliminate these causes are subsequently developed and implemented. Once target yields are achieved, they are modified (usually increased), and the learning cycle is repeated. It is of paramount importance to both reduce the duration of this cycle and optimize its efficiency.

1.3.5. Reliability

Another dimension of the quality of electronic products is their reliability. *Reliability* is a characteristic of a product that is associated with the probability that it will perform its intended function under specified conditions for a stated period of time. The enhancement of reliability is accomplished by failure-mode analysis, which is aimed at identifying the mechanisms for failure and translating this information into remedies that impact design and manufacturing processes. Reliability is usually quantified by statistical inference techniques applied to a suitable population of devices that have undergone extensive testing and failure-mode analysis. However, although the reliability of integrated circuits is often directly impacted by the manufacturing process, a detailed study of reliability and associated topics is beyond the scope of this text. Readers interested in a more thorough treatment are referred to Nash [34].

1.4. MANUFACTURING SYSTEMS

In general, manufacturing systems may be subdivided into two categories: (1) continuous-flow manufacturing and (2) discrete-parts manufacturing. *Continuous-flow* manufacturing involves chemical or physical processes that change the state of the part before the part is connected to other components to form a finished product. Most of the unit processes used in IC fabrication prior

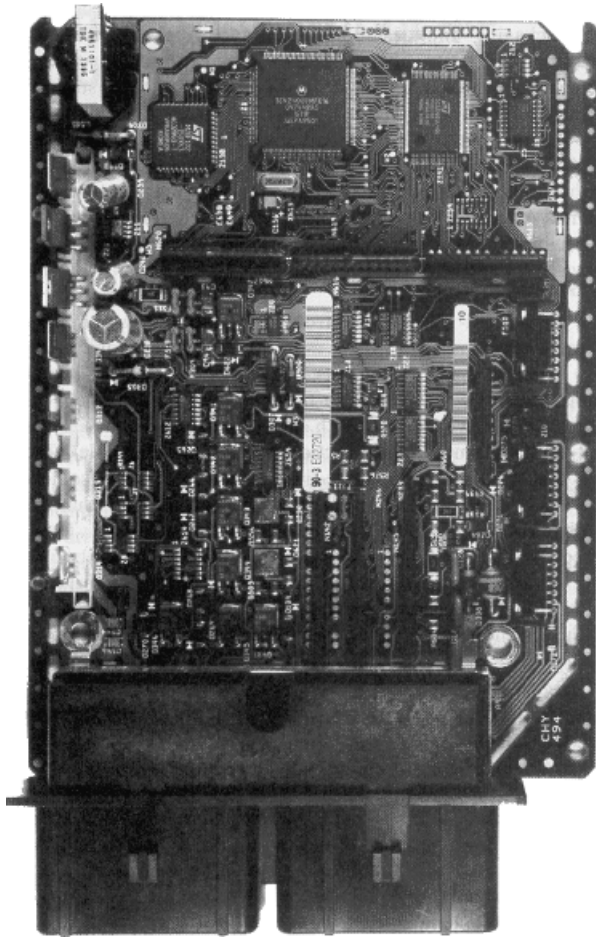


Figure 1.13. Printed circuit board for a single-board engine controller [35].

to wafer dicing and packaging are continuous flow manufacturing operations. *Discrete-parts manufacturing*, on the other hand, refers to the assembly of distinct pieces to yield a final product. In microelectronics manufacturing, an example of a product assembled using discrete parts manufacturing is a printed circuit board (PCB) populated by individual ICs (as shown in Figure 1.13).

1.4.1. Continuous Flow

Continuous-flow manufacturing refers to processing operations that do not involve assembly of discrete parts. For continuous-flow manufacturing operations, the process inputs (see Figure 1.1) are the semiconductor substrate and raw materials such as dopants, insulators, and metals. Continuous-flow processes consist of the steps such as those described in Section 1.2. These processes may be further subdivided into *batch* and *single-workpiece* (or *single-wafer*) operations.

1.4.1.1. Batch Processes

Batch processes are those that operate on multiple products simultaneously. In IC manufacturing, the items being processed are semiconductor wafers, and the batches are called “lots.” State-of-the-art semiconductor manufacturing factories employ a plethora of batch fabrication equipment, such as furnaces for high-volume wafer processing. This facilitates factory throughputs on the order of tens of thousands of wafers processed per month.

An example of a batch process in semiconductor manufacturing is chemical vapor deposition (CVD; see Chapter 2). Figure 1.14 shows a schematic of a typical CVD furnace. In this type of hot-wall, reduced-pressure reactor, the quartz furnace tube is heated in three individual zones, and reactive gas is introduced at one end and pumped out the opposite end. The wafers are placed vertically side-by-side in a container known as a “boat.” Gas reacting on the surface of the wafers causes the desired thin films to be deposited.

However, the high manufacturing throughput that is characteristic of batch processing is often achieved at the expense of uniformity and process control. In the case of CVD, for example, wafers farthest from the gas inlet may exhibit lower deposition rates as a result of the reduced availability of reactant gases, which are consumed by reactions closer to the inlet. This effect can be compensated for somewhat by increasing the deposition temperature in each subsequent reaction zone from the inlet.

1.4.1.2. Single Workpiece

Single-workpiece manufacturing operations involve individual items processed one at a time. In IC manufacturing, the workpiece is the semiconductor wafer. As wafer sizes have grown over the years, single-wafer processing approaches have proliferated. This has occurred for several reasons. First, scaling up batch tools and maintaining uniformity across the wafer surface becomes more difficult for wafers 200 mm in diameter and larger. At the same time, for submicrometer features, it is nearly impossible to maintain features size control across these large wafers. In addition, when only a single wafer is processed at a time, if any flaw in a process step is detected, it can be corrected before the next wafer is

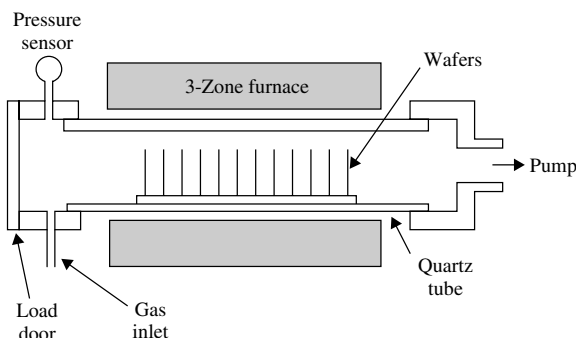


Figure 1.14. Example of a batch process: a CVD reactor [1].

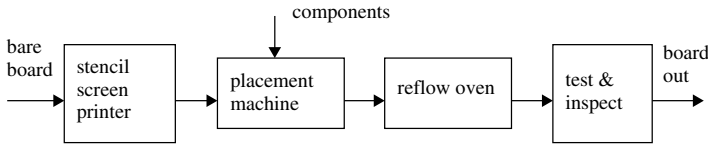


Figure 1.15. Surface mount printed circuit board assembly process.

processed. Finally, process development for large wafers has become increasingly expensive, and these costs are mitigated by the single wafer approach.

Therefore, semiconductor manufacturing has evolved from primarily a batch operation to an increasingly single-wafer operation. The advantages of single-wafer processing include (1) lower overall factory cost, (2) enhanced observability by in situ sensors for more robust process control, (3) rapid manufacturing cycle time, and (4) increased flexibility for manufacturing numerous products based on different technologies [36].

1.4.2. Discrete Parts

In discrete-parts microelectronics manufacturing, the inputs to the manufacturing system are the bare printed circuit board and the various circuit components. For example, in surface mount assembly, the manufacturing process consists of the following (Figure 1.15):

1. Screen-printing solder paste onto the bonding pads of the circuit board with a stencil printer
2. Placing the circuit components (ICs and passives) onto the pad locations using a placement machine
3. Melting the solder paste in a reflow oven to form the connection between components and the pads
4. Testing and inspecting the populated board for quality control

Following attachment of the ICs, the output of the process is the fully interconnected and populated circuit board.

The output of the process is a populated circuit board that is ready for integration into an electronic system.

1.5. OUTLINE FOR REMAINDER OF THE BOOK

In Chapter 2 we will provide a broad overview of the manufacturing technology and process flows used to produce a variety of semiconductor products. The individual unit processes used in fabricating ICs, as well as techniques for process integration and IC packaging, will be discussed. The unit processes include oxidation, photolithography, doping, etching, thin-film deposition, and planarization. The integrated process flows, which focus on silicon technology, include the complementary metal–oxide–semiconductor (CMOS), bipolar, and BiCMOS processes.

For all aspects of semiconductor manufacturing, testing and inspection are necessary to yield high-quality products. In Chapter 3, therefore, various process monitoring methods, including those that focus on product wafers and those that focus on the equipment used to produce those wafers, are discussed in detail. Maintaining quality involves the use of *statistical process control* (SPC). Since product variability is often described in statistical terms, statistical methods will necessarily play a central role in quality control and improvement efforts. Therefore, Chapter 4 will provide a review of statistical fundamentals.

Ultimately, the key metric to be used to evaluate any manufacturing process is cost, and cost is directly impacted by yield. *Yield* refers to the proportion of manufactured products that perform as required by a set of specifications. Yield is inversely proportional to the total manufacturing cost—the higher the yield, the lower the cost. *Yield modeling* is presented in Chapter 5. Chapter 6 will then focus on the use of SPC to analyze quality issues and improve yield.

A designed experiment is an extremely useful tool for discovering key variables that influence quality characteristics. *Statistical experimental design* is a powerful approach for systematically varying controllable process conditions and determining their impact on output parameters that measure quality. Data derived from such experiments can then be used to construct *process models* of various types that enable the analysis and prediction of manufacturing process behavior. Statistical experimental design is presented in Chapter 7, and process modeling concepts are introduced in Chapter 8.

Finally, several advanced process control topics are the subject of Chapters 9 and 10. These topics include run-by-run control of unit processes and supervisory control of process sequences, as well as the diagnosis of process and equipment malfunctions.

SUMMARY

In this chapter, we have provided background and motivation for the study of semiconductor manufacturing and process control. We have done so by surveying the history of integrated circuit processing, describing the attributes of manufacturing systems, and discussing the goals and objectives of modern electronics manufacturing operations. In so doing, this chapter has provided a foundation for the various issues relevant to semiconductor manufacturing that will be presented in the remainder of the book.

PROBLEMS

- 1.1. List the input and output parameters of a typical semiconductor manufacturing process.
- 1.2. What were the key milestones in the historical evolution of semiconductor manufacturing? How did the evolution of semiconductor process technology interact with and impact the development of manufacturing technology?

- 1.3. Describe the basic unit processes involved in IC fabrication and the sequences in which they are performed to yield products.
- 1.4. What is the significance of information flow within an IC factory?
- 1.5. Explain the differences between real-time, run-by-run, and supervisory control.
- 1.6. Why are IC factories organized into workcells?
- 1.7. List and prioritize the overall goals of IC manufacturing.
- 1.8. What is the difference between continuous-flow and discrete manufacturing processes? What role do each of these play in semiconductor manufacturing?
- 1.9. Why has semiconductor manufacturing evolved from batch operations toward single-wafer operations? What are the advantages and disadvantages of each approach?

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