FUNDAMENTALS OF SEMICONDUCTOR MANUFACTURING AND PROCESS CONTROL

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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*.

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1

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

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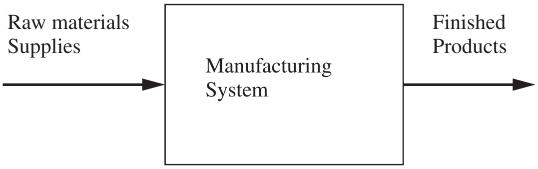

Figure 1.1. Block diagram representation of a manufacturing system.

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

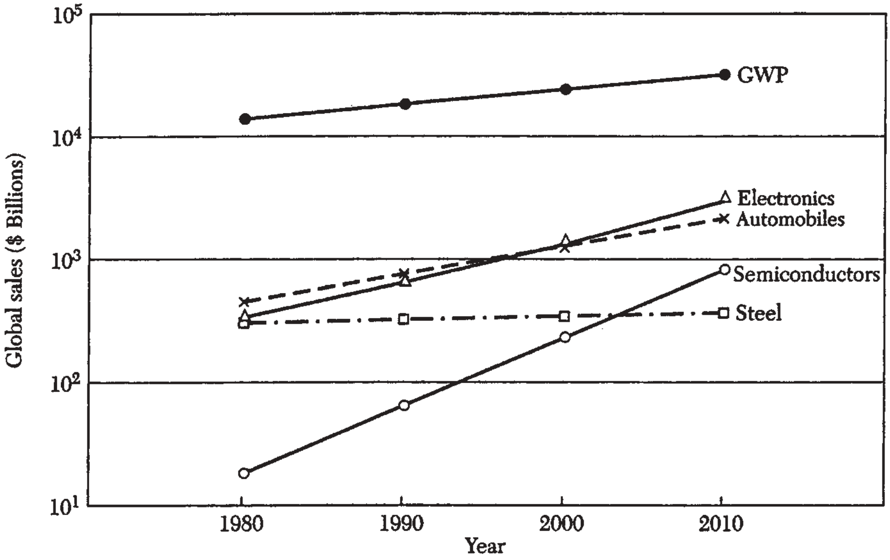

Figure 1.2. Gross world product (GWP) and sales volumes of various industries from 1980 to 2000 and projected to 2010 [1].

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 Paraszczak 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

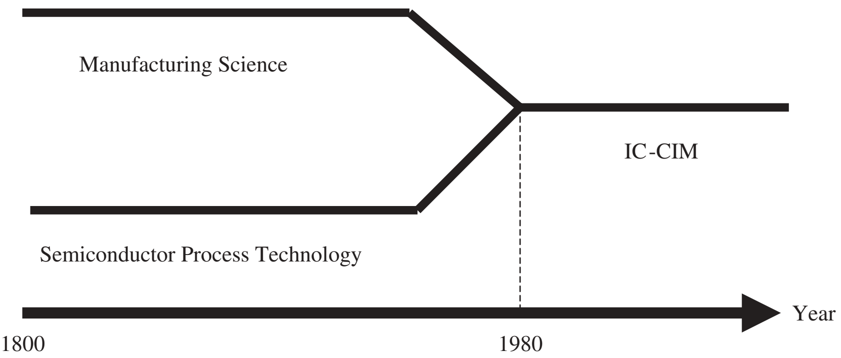

Figure 1.3. Timeline indicating convergence of manufacturing science and semiconductor processing into IC-CIM.

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.