Robotics for Electronics Manufacturing

Principles and Applications in Cleanroom Automation

KARL MATHIA

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In my 16 years of serving the robotics industry, I have never come across a single book that explains the history, design, and use of cleanroom robotics for electronics manufacturing so thoroughly. The book provides an excellent description of the environment and challenges of this industry and gives valuable insight for designing robots and equipment to meet these challenges. This is a must read for anyone designing cleanroom equipment for electronics manufacturing!

Jeff Baird, Director of Engineering, Adept Technology, Inc.

A must read for anyone working on semiconductor or flat panel robotics. This book captures theory, applications and best practices. Chapters 2, 3, 4 and 7 are a concise reference for designing, specifying and implementing robots. Chapters 5 and 6 provide the technical background to both develop and control robotic systems.

Dr. Martin P. Aalund, Director NPI Engineering, KLA-Tencor Corp.

Karl has created the definitive reference for cleanroom robotics, as well as a practical guide for anyone who wishes to go beyond theory to the economic justifications and real world commercial requirements to deploy robot technology.

Dr. Rich Mahoney, Director of Robotics, Engineering & Systems Division, SRI International

This volume provides a comprehensive view of robot use as part of electronics manufacturing. The book gives a good overview of the different aspects to be considered in the design and deployment of robots for this sector. The text covers a sector overview, in-depth material for different applications areas and discusses also testing and deployment. It is a valuable reference both to engineers and technical managers in the field.

Dr. Henrik I. Christensen, KUKA Chair of Robotics, College of Computing, Georgia Institute of Technology

Robotics for Electronics Manufacturing is an important new reference work for anyone involved with manufacturing robots. The book provides design guidelines for robots in both air and vacuum environments, as well as a thorough overview of robot kinematics and dynamics. The chapter on testing and measuring robot performance is especially valuable as an accessible explanation of the many ISO, ANSI and RIA standards.

Dr. Trevor Blackwell, CEO and Founder, Anybots, Inc.

Robotics for Electronics Manufacturing is a fundamental and thorough reference for engineers practicing, or preparing to practice, automation design for the semiconductor and electronics equipment manufacturing industry. No other reference covers the disparate requirements and best practices for both atmospheric and vacuum robot design, as well as including test and characterization methods which are the key to the successful manufacturing of such products.

Dr. Jeffrey C. Hudgens, Director of Robotics, Applied Materials Inc.

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Robotics for Electronics Manufacturing

Understand the design, testing, and application of cleanroom robotics and automation with this practical guide. From the history and evolution of cleanroom robots to the latest applications and industry standards, this book provides the only complete overview of the topic available. Robotics for automating the most demanding cleanroom manufacturing process, the making of semiconductor devices, is used as an example throughout the book. The principles and applications also apply to related industries, including the flat panel display, solar panels, hard disk, nanotechnology, MEMS, and pharmaceutical industries.

With over 20 years of experience in robotics and cleanroom manufacturing, Dr. Karl Mathia covers the relevant subjects for the design and testing of clean robots that operate in both atmospheric and vacuum environments. He provides numerous real-world examples so the reader can learn from professional experience, maximize the design quality, and avoid expensive design pitfalls. The book also provides guidelines and hands-on tips for reducing development time and product cost. Compliance with industry standards for the design, assembly, and handling of cleanroom robots is stressed throughout, and detailed discussions of recommended materials for atmospheric and vacuum robots are included to help shorten product development cycles and avoid expensive material testing.

This book is the perfect practical reference for engineers working with robotics for electronics manufacturing in a range of industries that rely on cleanroom manufacturing.

DR. KARL MATHIA studied in Germany and the United States and holds advanced degrees in Electrical and Computer Engineering. He has over 20 years of experience in research and development, product development engineering, and also held management positions at leading robotic firms, including Brooks Automation and Newport Corporation. Dr. Mathia has published numerous articles in the area of automation, controls, and intelligent systems, and taught short courses in industry. He currently works as Chief Engineer at Zitech Engineering, LLC.

Preface

This book is about the design and application of industrial cleanroom robots in electronics manufacturing. It is intended as a hands-on technical reference for engineers and factory managers involved in manufacturing electronic devices in cleanroom environments. The book provides insight into the principles and applications of industrial cleanroom robotics, in particular in semiconductor manufacturing, the most demanding process in terms of cleanliness requirements. Other examples are the hard disk, flat panel display, and solar industries, which also use high levels of cleanroom automation and robotics. In contrast to the complex manufacturing process, the typical robotic designs often utilize relatively simple robot kinematics in the highly structured environments of process and metrology tools. Some industries, for example the semiconductor front-end industry, are governed by technical standards and guidelines, which are generally helpful during the design process of robotic systems. On the other hand, robotic engineers in electronics manufacturing face challenges that are unknown in other markets, most importantly the cleanliness required in certain factories. Strict cleanliness requirements have resulted in two categories of cleanroom robots: ‘atmospheric robots’ for high-quality cleanliness at ambient atmospheric pressure, and ‘vacuum robots’ for extreme cleanliness in enclosures under various vacuum pressures. These two categories are the focus of this book.

The book is organized into seven chapters. Chapters 1 and 2 provide an overview of industrial robotics and industrial cleanroom robotics and are not prerequisites for the technical Chapters 3 to 7:

Chapter 1 provides an overview of the history and different types of industrial robots, and their socioeconomic impact.
Chapter 2 provides an overview of electronics manufacturing in cleanroom environments, cleanliness standards, and the emergence of cleanroom robots in semiconductor manufacturing.
Chapter 3 presents guidelines and best practices for the design of atmospheric robots, including the design example of a wafer-handling robot.
Chapter 4 presents guidelines and best practices for the design of vacuum robots, including the design example of a wafer-handling vacuum robot for automating a six-sided cluster tool.
Chapter 5 reviews common kinematic structures before discussing the kinematics of SCARA-type robots that are commonly used in electronics manufacturing. The forward kinematics model of a three-link robot arm is derived.

Chapter 6 discusses a general dynamic model for robot manipulators and derives the specific model for a three-link robot arm. A decentralized joint control strategy suitable for networked robot control is established.

Chapter 7 introduces several test and characterization methods and their underlying theory. Suitable test fixture designs are described.

A total of 29 examples throughout the book illustrate applications of the presented theory and concepts. All numerical examples were programmed in Matlab®. The International System of Units (SI units) is used whenever possible. For convenience some obsolete units that are still in use are also provided. SI base units, derived SI units, and unit conversion tables for non-SI units are listed in Appendix A. Applicable industry standards are listed at the end of each chapter. Contact information for the relevant publishing standards organizations are listed in Appendix B. Standard sets of conditions for temperature and pressure (STP) are listed in Appendix C. These are used to allow comparisons between different sets of experimental data and are relevant for applications in controlled vacuum and atmospheric environments.

Acknowledgments

This book would not have been possible without the advice and support of several engineers and scientists passionate about robotics. Special thanks go to Dr. Martin Aalund, Izya Kremerman, Ken Park, Jeff Thompson, and Enoch Wall. I also thank Andrew Ayre, Robert Bergner, Alan Campbell, Phil Danielson, Walter Henry, William Holtkamp, Dr. Jeff Hudgens, Peter Lundquist, Venu Menon, Frank Pavlik, Dr. John Tenney, and Dalton Victor. NxRev, Inc. kindly provided the Pro/ENGINEER software for creating robot drawings. The advice, guidance, and support from the editorial staff at Cambridge University Press is much appreciated. I am especially grateful to my wife Maria and our children Francisca and Dustin. Without their continuous encouragement and patience this book would have not been possible.

2 Cleanroom robotics

2.1 Manufacturing in cleanroom environments

Clean environments are required for manufacturing modern electronics devices, in particular semiconductor devices, but also hard disks, flat panel displays (FPDs), and solar panels. Wafer processing in the semiconductor industry includes some of the most demanding processes in terms of complexity and cleanliness, due to the submicron dimensions of modern semiconductor devices. This book focuses on industrial cleanroom robotics in semiconductor and FPD manufacturing. Both industries experienced phenomenal technical advancement and growth in the 1980s and 1990s and have established manufacturing facilities in several geographic regions: North America, Europe, and Asia/Pacific Rim. India may emerge as another manufacturing region. The market for semiconductor manufacturing equipment was valued at approximately US$45.5 billion in 2007. The market for FPD manufacturing equipment surpassed the US$1 billion mark in 1997 for the first time. In 2008 it was estimated at US$10 billion.

2.1.1 Cleanroom requirements

Cleanrooms are isolated environments in which humidity, temperature, and particulate contamination are monitored and controlled within specified parameters (SEMI standard E70). Particulates are fine particles, solid or liquid, that are suspended in a gas. Particulate sizes range from less than 10 nm to more than 100 μm. Particulates of less than 100 nm are called ultra-fine particles. Here the term ‘particle’ is used throughout, representing particles of all applicable sizes, either suspended in a gas or attached to a surface. Cleanroom environments are required if particle contamination is a concern, as is the case, for example, in semiconductor manufacturing. In 1997 the smallest connections in semiconductor devices measured 250 nm. In 2008 that critical dimension was 45 nm, as projected by the International Technology Roadmap for Semiconductors (ITRS). The critical particle size that poses a risk to a device is roughly half of that dimension. It is challenging and expensive to establish and maintain the most stringent levels of cleanroom conditions, especially when human operators, materials, and equipment are constant contamination sources. In fact, one motivation for highly automated fabrication facilities (‘fabs’) is the removal of humans from the clean manufacturing area. Suitable factory designs and strict protocols are required to maintain cleanroom integrity and minimize the risk of product damage and reduced yields. Typical cleanrooms provide

Table 2.1. Air cleanliness class limits per ISO 14 644–1 and Federal Standard 209E.

ISO 14 644–1 Class	Federal Standard 209E	Contamination limits (particles·m^{-3}) by particle size (µm)					
		≥ 0.1 µm	≥ 0.2 µm	≥ 0.3 µm	≥ 0.5 µm	≥ 1.0 µm	≥ 5.0 µm
1	-	10	2	1	-	-	-
2	-	100	24	10	4	-	-
3	1	1 000	237	102	35	8	-
4	10	10 000	2 370	1 020	352	83	-
5	100	100 000	23 700	10 200	3 520	832	29
6	1 000	1 000 000	237 000	102 000	35 200	8 320	293
7	10 000	-	-	-	352 000	83 200	2 930
8	100 000	-	-	-	3 520 000	832 000	29 300

laminar, vertical flow of filtered air in order to move particles to exit vents at the floor level. Protocols define procedures for operators on how to handle materials, including cleanroom attire and cleanroom-compatible materials for use within a factory (SEMI standards E70 and S20). A high degree of automation and automated materials handling minimizes the involvement of human operators in the manufacturing process. Industrial cleanroom robots became a critical component with the introduction of 200 mm wafers in 1995 and 300 mm wafers in 1998. In fact, robotics is emerging as a production-line integrator for flexible manufacturing strategies, with more than one robot collaborating within a work cell (Defosse, 2004; Kahaner, 1991; Thornton, 2002).

Cleanliness is measured by counting airborne particles under different operating conditions. The International Organization for Standardization (ISO) defines cleanliness classes that specify upper contamination limits per class. The ISO standard replaces the US Federal Standard (FED) 209E, which was officially withdrawn on November 29, 2001. The Japanese robotic industry uses the Japanese Industrial Standard JIS B9920. Table 2.1 lists air cleanliness classes per ISO standard 14 644–1 and the corresponding classes defined in FED 209E (Schicht, 2003). The ISO reference particle diameter of 0.1 µm offers a denomination scheme with simple, single-digit class numbers that correspond with FED 209E. For example, ISO Class 5 corresponds to class 100 in FED 209E.

The measurements performed for cleanroom certification track potential particle sources and their impact on a product. A good practice is first to measure the cleanliness of a cleanroom at the ‘as-built stage’ without humans and manufacturing equipment present. This step determines whether all filters are functioning to specification and whether there are any leaks. Second, a particle count is performed with the manufacturing equipment under operation. This step isolates the contamination originating from the equipment only. Third, a particle count is performed under normal manufacturing conditions with human operators present. This last step allows an estimate of the impact of humans, their attire, and any manufacturing procedures on the cleanroom environment.

2.1.2 History of cleanroom robotics

Robotics made inroads into cleanroom applications in the 1980s, motivated by increasingly demanding requirements for contamination control, product throughput, and

Table 2.2. Human contamination at different levels of motion.

Human motion	Heat emission (kW)	Moisture emission ($g \cdot h^{-1}$)	Particle emission* (particles$\cdot min^{-1}$)	Breathing requirements ($m^3 \cdot h^{-1}$)
At rest	0.12	90	100 000	0.50
Light work	0.18	180	1 000 000	1.00
4.8 $km \cdot h^{-1}$	0.3	320	5 000 000	2.15
6.4 $km \cdot h^{-1}$	0.4	430	10 000 000	2.55

* Measured particles were 0.3 μm and larger.

product safety. The semiconductor industry began to adapt robot technology from other industries, for example from electronics assembly and automotive manufacturing. The following definition is based on Definition 1.3.

Definition 2.1: Industrial cleanroom robotics refers to the study, design, and use of robot systems for manufacturing in industrial cleanroom environments.

Industrial cleanroom robotics serves three main purposes: (1) reducing costs, (2) improving workplace safety, and (3) improving product yield through cleanliness. Of course, cost reduction and workplace safety are common objectives of automated manufacturing. However, improved product yield through cleanliness is a specific objective in electronics manufacturing. The requirement for extreme cleanliness separates semiconductor manufacturing from other industries. This requires isolating the product from human operators, whose presence makes it difficult to maintain an ultra-clean environment. Table 2.2 lists the measured contamination (particles, moisture, heat) generated by a human at different levels of activity (Egan, 2000). The table emphasizes why contamination from humans is a serious concern: particle emission at rest, even when counting only particles 0.3 μm or larger, exceeds by far the applicable ISO limits in Table 2.1.

2.2 Semiconductor manufacturing

This section reviews the basics of automation in semiconductor manufacturing.

2.2.1 Automation levels and history

Automation in modern semiconductor factories is implemented at three levels:

- Tool automation
- Intrabay automation
- Interbay automation.

Robotics is utilized for material handling at every step within a process or metrology tool, and for material handling between tools. The handling of individual substrates within tools is called tool automation. The transport of substrate carriers between the tools in a process bay (a large cleanroom) is provided by an automated material handling system (AMHS) and is called intrabay automation. The transport of substrate carriers by an AMHS between process bays is called interbay automation.

The first semiconductor factories were extensions of research laboratories, where human operators were vital for process control, substrate handling, and assisting with the frequent equipment failures. Cleanroom robotics was not a pressing issue for several reasons. First, cleanliness was not as critical as in modern factories: device line widths were at 10 μm in the early 1970s and 2 μm in the early 1980s. Second, ergonomics was not an issue: the weight of 50 mm and 100 mm wafer cassettes was suitable for repetitive handling by human operators. Third, cost was less pressing than it is in mature high-technology industries. Fourth, system incompatibilities due to the lack of standards limited the use of robots. Fifth, unreliable semiconductor process tools caused frequent downtimes and therefore limited the benefits of robotics. Finally, suitable robotics technology was not readily available for substrate handling.

Automation and robotics became a priority with the industry transition from 150 mm to 200 mm wafers, and became critical for 300 mm wafer handling in the late 1990s:

- Cleanliness became critical for device line widths below 100 nm.
- Ergonomic concerns prevented humans from repetitively handling fully loaded 300 mm wafer cassettes, a load of about 8 kg.
- Manufacturing costs in the maturing semiconductor industry became a critical economic factor.

Several factors now enable a high degree of automation:

- Industry standards allow the integration of robotic systems with other automation systems and subsystems.
- Modern semiconductor process tools are more reliable, and with longer uptimes automation does improve tool efficiency.
- Suitable cleanroom robotic systems are commercially available.

Figure 2.1 shows the industry transitions from smaller to larger wafer sizes over time. The usual substrates are ‘wafers.’ Data are shown only for those years in which the number of processed wafers exceeded one million. Transitions occurred roughly every five years. The increase in available wafer area emphasizes the improved economy of scale despite exponentially growing circuit complexity (Grecu and Kücher, 2000). For example, the transition from 200 mm to 300 mm more than doubled the number of dies per wafer, offering a potential 30% cost reduction per die. In fact, if the reduced die size is factored in, the number of devices per wafer increased ten-fold for many logic devices from 1998 to 2008 (Ken Park, personal communication, 2008). The proposed transition to 450 mm wafers in 2012 is also shown. For memory chips the number of bits per wafer increased by a factor of about 1 000 in the same time frame. Automation contributed to this leap in performance. Cleanroom automation and robotics became a crucial factor in the semiconductor business equation during the transition to 300 mm wafers (Aalund and Mathia, 2001; Mathia and Aalund, 2002).

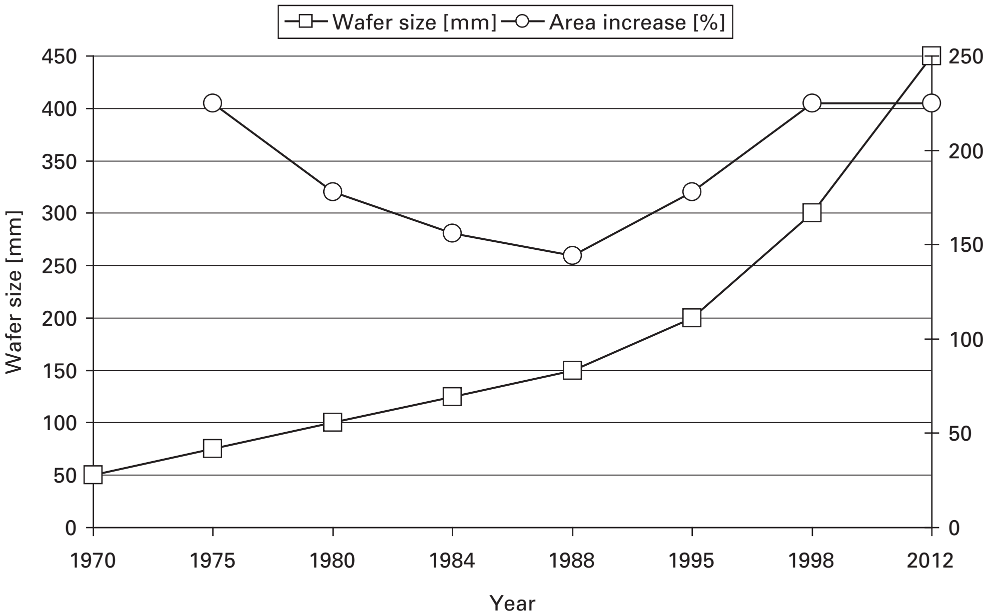

Figure 2.1 Wafer size transition history 1970 to 2012.

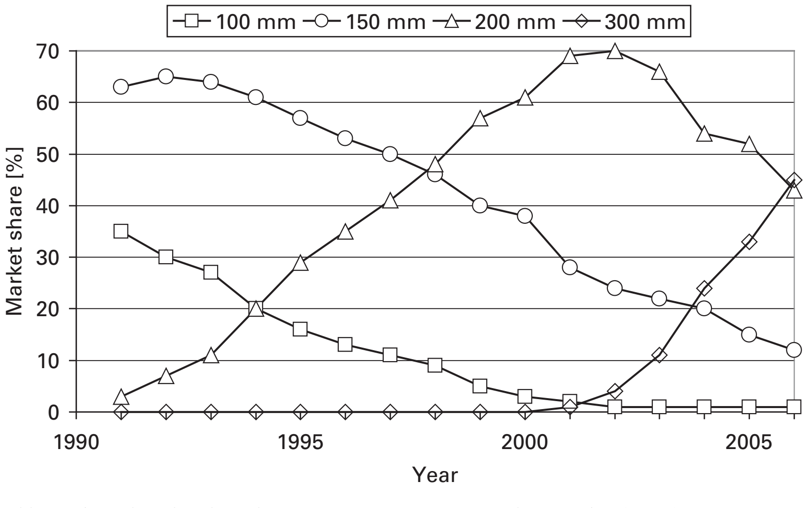

Figure 2.2 Life cycles of wafer sizes from 100 mm to 300 mm, after Vogler (2002).

Figure 2.2 illustrates the life cycles of various wafer sizes from 1991 to 2006 in terms of their market shares. The introduction of a new wafer size requires the industry to build new factories or to ‘retool’ existing factories. SEMI plans to introduce 450 mm wafers in 2012, although it will take several years to complete the transition, as illustrated in Figure 2.2 for previous transitions. For 300 mm technology a total life cycle of 25 to 30 years is expected.

2.2.2 Semiconductor manufacturing process

The manufacturing or fabrication process for semiconductor devices such as logic and memory includes three process phases: (1) wafer fabrication (producing raw, polished wafers), (2) wafer processing (the 'front-end' manufacturing process), and (3) final manufacturing (the 'back-end' manufacturing process). Figure 2.3 illustrates the front-end process, the most complex of the three process phases. The loops that indicate repetitive process cycles are needed to create several conductive circuitry layers on the device. Dedicated process and metrology tools perform each of the process steps. Inspection and metrology steps are not shown in the figure. The entire process takes several weeks to complete, while wafers travel several kilometers through a factory.

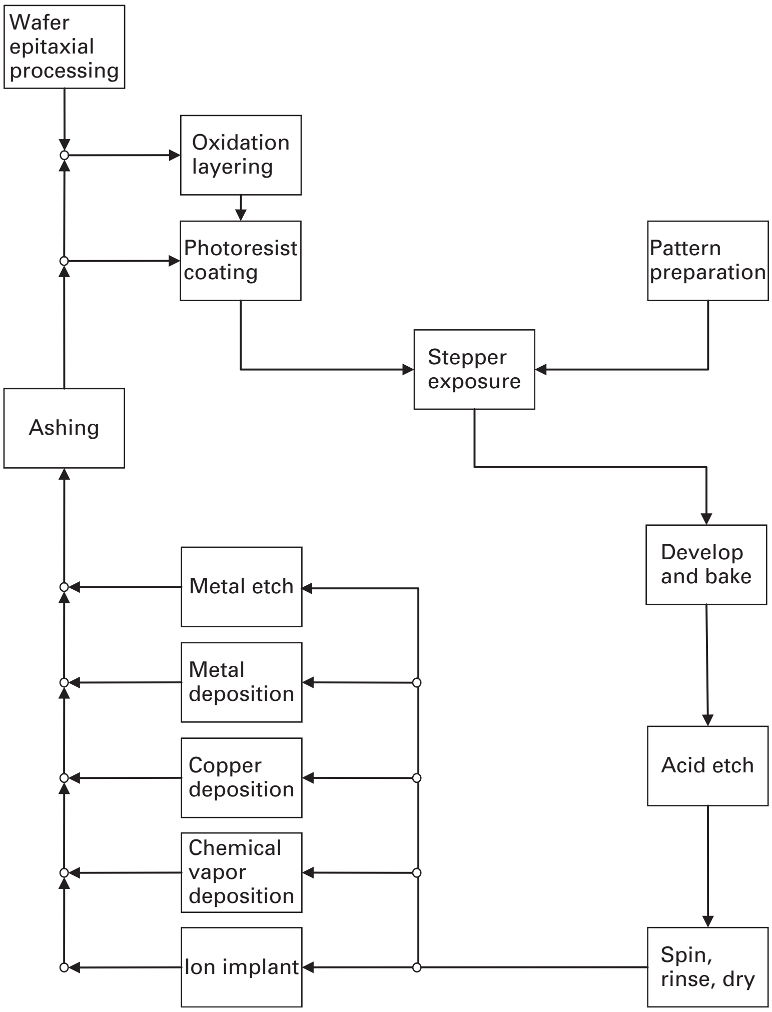

Figure 2.3 Flowchart of a typical front-end semiconductor manufacturing process. Repetitive 'loops' allow the manufacture of multiple circuitry layers.

Dozens or hundreds of process steps are needed, depending on the product. Between the process steps the substrate or wafer is handled by robots or other automation equipment.

The main process steps for the three semiconductor manufacturing phases are summarized below.

Wafer fabrication

- Polysilicon creation: raw polycrystalline silicon is created in a reaction furnace at temperatures exceeding 1000 °C.
- Crystal pulling: silicon crystal ingots are grown by transforming polycrystalline silicon into single crystals with uniformly oriented crystallites.
- Wafer slicing: each silicon crystal ingot is sliced into individual substrates (‘wafers’).
- Substrate lapping and polishing: the substrate surface is flattened using mechanical lapping and polished using chemical mechanical planarization (CMP).

Wafer processing (‘front-end’ processing)

- Wafer epitaxial (EPI) processing: a layer of single crystal silicon is grown from vapor onto a silicon substrate at high temperatures.
- Oxidation layering: a thin layer of silicon dioxide or oxide is produced on the substrate.
- Photoresist coating: a uniform layer of photoresist, between 2 and 200 µm thick, is applied to the substrate.
- Pattern preparation: the reticle, the mask with the circuitry pattern for one layer, is placed for the lithography exposure.
- Photolithography (stepper exposure): a device layer is created on the wafer by exposing the photoresist to UV light passing through the pattern mask (reticle).
- Develop and bake: the substrate is developed to remove the exposed photoresist areas. The remaining photoresist is hardened by ‘soft-baking.’
- Acid etch: selected areas of material are removed from the substrate using different types of acid, base, or caustic solutions.
- Spin, rinse, dry (SRD): the substrate is repeatedly cleaned to remove any contamination from its surface.
- Ion implant: the electrical characteristics of the substrate layer are changed by bombarding the surface with ions of a particular dopant.
- Chemical vapor deposition (CVD): controlled chemical reactions from various processes create desired device layers on the substrate surface.
- Metal deposition: a conductive layer is created using physical vapor deposition (for aluminum, gold, tungsten) or damascene patterning (for copper).
- Metal etch: conductive circuit paths are created by selectively removing portions of the metal layer. An alternative for many devices is chemical mechanical planarization (CMP).
- Photoresist develop and strip (ashing): the remaining photoresist is removed with an ashing process that uses high-temperature plasma.

Final manufacturing (‘back-end’ processing)

- Probe test and die cut: the operation of each device on a substrate is tested using automated methods.

- Wafer slicing: the substrate is sliced into individual ‘chips.’
- Wire bonding: copper, aluminum, or gold leads are attached to the individual dies via thermal compression or ultrasonic welding.
- Packaging: each device is sealed into a ceramic or plastic enclosure.

2.2.3 Robot applications

Each of the semiconductor manufacturing processes in Figure 2.3 requires a process tool, often with distinctive process requirements that also influence the choice and specifications of the substrate-handling robot. For example, atmospheric and vacuum processes require atmospheric robots and vacuum robots, respectively. These two robot categories are discussed in Chapters 3 and 4.

Atmospheric robot applications

Tools that operate under atmospheric pressure utilize atmospheric robots for wafer handling. Examples are:

- Equipment front end module (EFEM): a standardized mini-environment at the interface between the factory’s automated material handling system and one or more process tools (SEMI standard E101-00-1104).
- Chemical mechanical planarization (CMP) tool: removes material from a substrate, creating a very flat surface. CMP allows for more accurate photolithography patterning and film layers with minimal height variations.
- Inspection and metrology tools: needed at various stages of the fabrication process, for example for the detection of contamination defects and for measuring the process quality.
- Rapid thermal processing (RTP) tool: subjects a substrate to rapid temperature bursts from 20 °C to over 1000 °C in less than 10 s. RTP modifies the properties of deposited films.

Vacuum robot applications

Tools that operate under vacuum pressure or in certain (aggressive) gas environments utilize vacuum robots. Examples are:

- Deposition tool: deposition is a fundamental step in semiconductor manufacturing. A layer of dielectric material (insulation) or electrically conductive metal is deposited on the substrate. The main processes are atomic layer deposition (ALD), chemical vapor deposition (CVD), physical vapor deposition (PVD), and epitaxial deposition.
- Etch tool: the substrate is first coated with photoresist, a light-sensitive film. Then a photolithography tool projects the circuit pattern onto the substrate. The etch process selectively removes material from the substrate surface where allowed by the photoresist pattern.
- Ion implementation tool: bombards the substrate with a beam of ions (dopants) that impregnate the film surface of a substrate to the specified depth.

Vacuum robots must withstand various vacuum pressures or (sometimes aggressive) gases or plasma.

2.3 Flat panel display manufacturing

Flat panel display (FPD) manufacturing includes semiconductor technologies and processes. The main differences from semiconductor manufacturing include the vastly larger substrate (panel) area, the relatively large line widths of the circuitry, and the small number of metal layers. FPDs for large television screens utilize liquid crystal technology (O'Halloran et al., 2002). Relevant technology, production steps, and process equipment for liquid crystal displays (LCDs) are outlined below.

2.3.1 FPD market

FPDs are used for computer monitors, televisions, and portable devices. Korea and Taiwan together manufacture about 90% of the world's FPD supply (2008 status). The production efficiency of FPD factories depends on several factors: the substrate size, substrate throughput, manufacturing yield, and product mix. Larger glass substrates ('sheets') offer economy-of-scale advantages by producing more displays from a single substrate. Sheets are categorized by the size of a particular generation. As a result of the lack of industry standards, different substrate sizes are in use. Even the size of a given generation is not always consistent. Typical sheet sizes for each generation are listed in Table 2.3.

Figure 2.4 illustrates the economy of scale of the exponentially increasing sheet area from Generation 1 to Generation 8. FPD factories and their equipment must be regularly upgraded for the next, larger FPD generation. Unfortunately, no standardization body coordinates and encourages technical advancements from generation to generation, as is done by SEMI for the semiconductor industry. A new generation is typically unspecified until some months before factories are planned and equipment is ordered. The robotics design challenges resulting from this fast sheet area increase include:

- The sheet size impacts the robot and end-effector size.
- The sheet weight impacts the robot stiffness and motor power.
- The short life cycle of FPD generations (typically two to three years) requires frequent new designs or design modifications.
- The lack of design standards creates uncertainty and requires accelerated engineering design projects.

Table 2.3. FPD sheet dimensions and area by generation.

Generation	Dimensions (m)	Area (m^2)
1	0.30 × 0.40	0.120
2	0.37 × 0.47	0.174
3	0.55 × 0.65	0.358
4	0.75 × 0.90	0.675
5	1.10 × 1.30	1.430
6	1.50 × 1.85	2.775
7	1.87 × 2.20	4.114
8	2.20 × 2.50	5.500

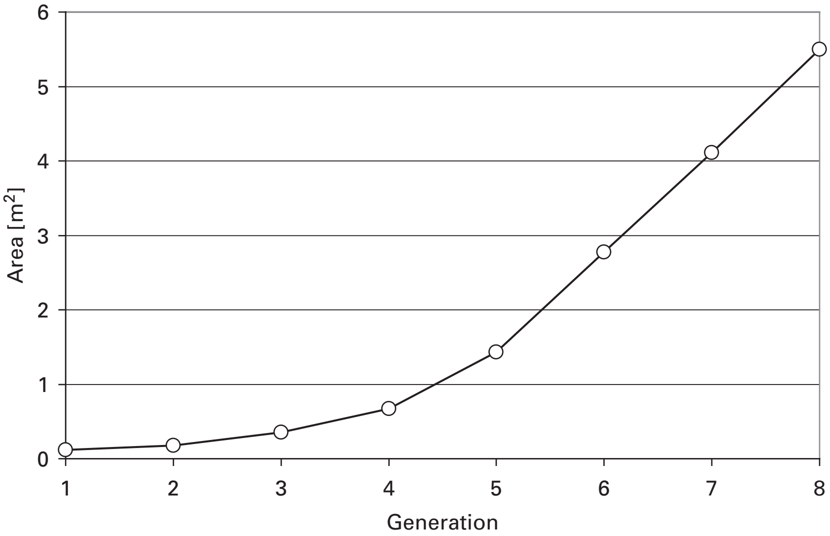

Figure 2.4 FPD sheet area for Generations 1 through 8.

2.3.2 Liquid crystal displays

Liquid crystal displays are made of liquid crystal (LC) compounds that flow like liquids but maintain a short-range crystalline order. The structure of an LC molecule is rod-like, and rotates the direction of polarized light based on its alignment. The molecular alignment, and thus the reflection of polarized light, is controllable by the application of an electric field. The weak intermolecular forces can be overcome, and the LC molecules can be oriented by weak electromagnetic fields. The LC layer in a display is contained between two glass panels. Its thickness is determined by spacers that fix the distance between the glass panels. Seals contain the fluid LC and protect the sensitive circuitry from contamination. Each glass panel has a polarizing layer on the outside. Light passing through one of the polarizers has its polarization rotated to the alignment direction of the liquid crystal. As the light reaches the second polarizer, it can be passed or blocked, depending on the extent of rotation. Transparent conductors on the inner surfaces of the glass plates are used to control the electric field on each cell, and thus the direction of the LC molecules. Depending on the orientation of the molecules, the panel is either transparent or dark. A LC cell acts as a ‘light switch.’ Light originating from a cold cathode fluorescent lamp or LED in the back of the display can be effectively modulated by using the appropriate conductors in the circuitry. There are passive, active, monochromatic, and color LCDs. In an active matrix display (AMLCD), polysilicon or amorphous thin film transistors (TFTs) are used to activate each pixel. In a passive display, this is accomplished by horizontal and vertical electrodes. There are at least 12 layers in a typical colored AMLCD panel: polarizer, front glass plate (substrate), transparent conductor, passivation layer (or hard coat), polyimide, liquid crystal, polyimide, passivation layer, circuitry, rear transparent conductor, polarizer, and rear glass plate.

2.3.3 FPD manufacturing process

The LCD manufacturing process includes several semiconductor processes, including CVD, lithography, and etch. Fully integrated LCD manufacturing lines include over a dozen individual tools, including (in this order): loader, wet cleaner, polyimide coater, inspection, rubbing, cleaner, after-rubbing cleaner, spacer spray, spacer checker, dispenser, seal dispenser, pre-cure oven, assembly machine, hot press oven, alignment checker, and unloader (robot). Many tools are available as stand-alone machines or are integrated in production clusters. Automated substrate handling is essential. The front and rear glass sheets serve as substrates for several material layers: the front sheet holds the color filter, while the rear sheet is the substrate for the circuitry TFTs.

The front and rear glass sheets are manufactured in different production lines. The two lines merge at an assembly cell, where the glass sheets are combined and sealed. Each pair of glass sheets is large enough to produce several displays. This reduces production costs based on the economy-of-scale principle. Finished panels are cut to fit different products, much like fabrics. The optimal product mix per sheet is flexible and is determined in real time by software tools, depending on any detected defects.

The following summarizes the main steps of a color LCD manufacturing process for TFT technology. Metrology and cleaning steps are not listed.

Front glass manufacturing

- Polarizer is applied to the outside of the front glass sheet.
- Color filter is applied to the inside of the front glass sheet.
- Transparent conductor is deposited using sputtering or printing. A typical material is indium tin oxide (ITO), which serves as the electrode in LCDs.
- A passivation layer, or ‘hard coat,’ that insulates the ITO electrically is printed, then cured and annealed in a furnace.
- A polyimide (PI) layer is printed using a hot cure process with inert gas. PI rubbing aligns the LC with the polyimide surface parallel to the polarizer direction.
- Spacers, small glass or plastic balls, are sprayed using a dry, semi-dry, or wet process. They ensure a uniform distance between the sheets.
- A seal is deposited and pre-cured in a hot press oven.

Rear glass manufacturing

- Polarizer is applied to the inside (sometimes outside) of the rear glass sheet.
- Transparent conductor is deposited using sputtering or printing.
- Circuitry is created using a series of vacuum processes, including plasma-enhanced chemical vapor depostion (PECVD), sputter deposition, oxidation, lithography, passivation, and etching.
- A passivation layer (‘hard coat’) is deposited in a furnace.
- A polyimide (PI) layer is printed.

Assembly of the two glass sheets

- The front and rear glass sheets are assembled, including alignment and attachment using UV hardened polymer spots.
- The panel seal is attached using pressure and curing in a clean convection oven.
- The glass sheets are scribed and broken into various display panels.
- The individual displays are filled with liquid crystals using vacuum pressure, and then sealed.
- Polarizer is applied to the front side and the rear side of the LCD panel.
- External contacts are produced by printing with gold or silver paste on the substrate glass.
- The displays are packaged.

Key factors for good process yield are good surface cleanliness, low particle contamination of the manufacturing environment, good gap control, and layer thickness control. Cleanliness requirements are demanding, but not as challenging as in semiconductor manufacturing. For example, the critical particle size for high-resolution, low-power bistable displays is 1–3 µm. Particles exceeding that size can cause assembly defects and adversely impact yield. This refers to ISO Class 4 or 5 cleanliness, compared with the usual Class 1 requirements in 300 mm semiconductor fabs.

Organic LED (OLED) technology is becoming available in commercial products and is expected to eventually replace LCD and PDP technology. OLED displays are lighter and offer higher contrast because no backlighting is required.

2.4 Substrate-handling robots

The process flow of the front-end semiconductor manufacturing process in Figure 2.3 indicates that a high level of automation is needed, including substrate-handling robots, to transport and handle the substrates between the many process steps.

2.4.1 Cleanroom technology

Early cleanroom robots

Early cleanroom robots in semiconductor manufacturing replaced technicians who handled wafers with tweezers and vacuum wands. Starting in the 1970s robots were used in process and metrology tools. Fully automated substrate handling emerged in the early 1980s. Typical tool geometries and handling requirements resulted in relatively simple robot kinematics and controller features. However, the demand for tool automation increased with every new wafer size generation, as Moore's Law drove the number of transistors beyond 10 million per cm^2, clock rates beyond 1 GHz, and line widths below 0.1 µm. In particular the introduction of 300 mm wafers and Generation 5 FPDs required advanced automation and robotic systems. By the year 2000 a variety of atmospheric and vacuum cleanroom robots was available for electronics manufacturing in cleanroom environments.

Industry standards and performance specifications

The huge cost and complexity of new 300 mm factories forced the industry to establish standards at the outset to ensure their timely acceptance and implementation. The selection of a robotic system for a given semiconductor or FPD application is influenced by several technical criteria, including wafer throughput, reliability, positional and path repeatability, cleanliness, interoperability with the tool in question, and controller capabilities (Aalund and Mathia, 2001; Manji, 2000). Industry standards and guidelines are available for many criteria. General cleanliness and safety standards are provided by ISO standards (Section 2.1.1). SEMI established industry standards for 300 mm wafer processing, including standards for safety, communication protocols, electrical and mechanical interfaces, and control of the workplace environment in terms of cleanliness and electrostatic discharge (ESD). The throughput of a process or metrology tool is typically defined as the number of processed wafers per hour (wph), which also depends on the time needed for wafer handling and wafer processing. The ‘wafer swap time’ of a robot is an application-independent throughput metric. It refers to the time needed to replace a processed wafer at a fixed location with an unprocessed wafer, with an assumed zero process time. Selected standards that directly impact automation in the semiconductor front-end industry are listed in Section 3.8.

Robot cleanliness

Cleanliness is an overriding concern in electronics manufacturing, in particular in the semiconductor front-end industry. Cleanliness requires the elimination of contamination sources whenever possible. For example, up to 80% of the yield loss in the production of high-volume, very-large-scale integrated (VLSI) circuits can be attributed to random pattern defects, many caused by contaminating particles that were acceptable at critical dimensions of 1.0 μm, but below 0.25 μm are categorized as ‘killer defects’ (ICE, 1997). Consequently, ISO Class 1 cleanliness is often required for substrate-handling robots, depending on the application at hand.

Two types of contamination must be addressed during the design process of substrate-handling robots:

- Airborne molecular contamination (AMC) from particles and outgassing generated by the robot
- Contamination of the substrate surface from contact with the robot.

Best design practices, including the selection of suitable materials, minimize particle generation and mitigate the contamination risk. Recommended design guidelines are:

- Minimize the number of moving parts
- Place all moving parts below the substrate
- Enclose and seal the robot interior and evacuate generated particles
- Use internal robot cabling only
- Apply coating or treatment to external robot surfaces
- Use cleanroom approved lubricants
- Use stainless steel screws and washers

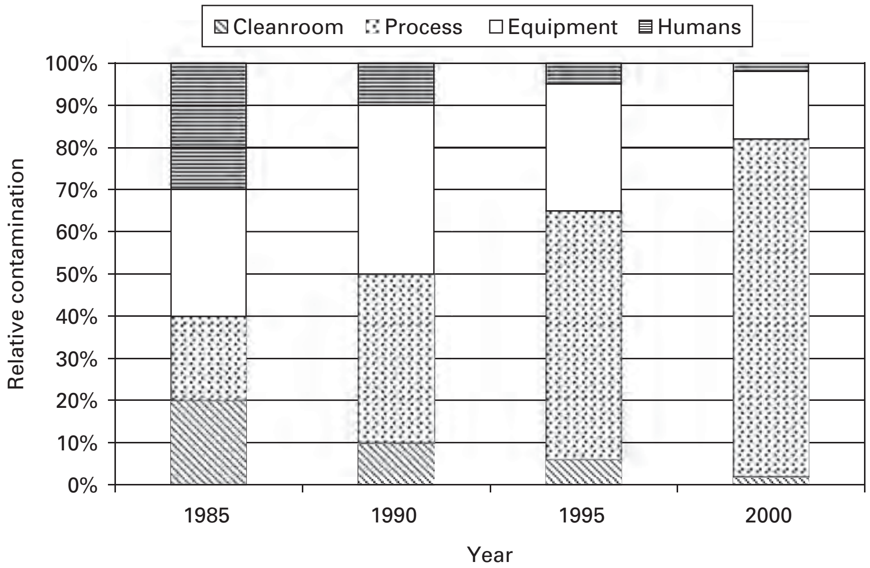

Figure 2.5 Sources of wafer-level contamination, after ICE (1997).

- Minimize the contact surface of end-effectors
- Consider brushless servo motors
- Consider direct-drive trains to eliminate belts and transmissions.

Detailed guidelines and best practices are presented in Chapters 3 and 4. Figure 2.5 demonstrates that the automation strategy of eliminating contamination sources is successful: from 1985 to 2000 the wafer-level contamination from humans and equipment was reduced to less than 3% and 15%, respectively. The 2000 values are estimates. The main contamination source is now the manufacturing process itself.

2.4.2 Economics

Figure 2.6 shows the estimated number of robot shipments to the semiconductor front-end industry (wafer processing). The estimate is based on the number of tool shipments and other secondary indicators (Ken Park, personal communication, 2008). The data shows the industry downturn from 2001 to 2003 and the subsequent recovery. The impact of the 2008–09 financial crisis is not included in the data. The figure also shows that the number of shipped atmospheric robots exceeds the number of shipped vacuum robots by a factor of about three. Possible reasons are:

- The number of shipped process and metrology tools that operate in atmosphere is larger than the number of vacuum tools.
- Many vacuum process tools employ both one vacuum robot (inside the vacuum cluster tool) and an atmospheric robot for tool loading and unloading.

Figure 2.6 also indicates that the average sales price for atmospheric robots continuously decreased from 2000 to 2007. This commoditization trend forced robot companies to

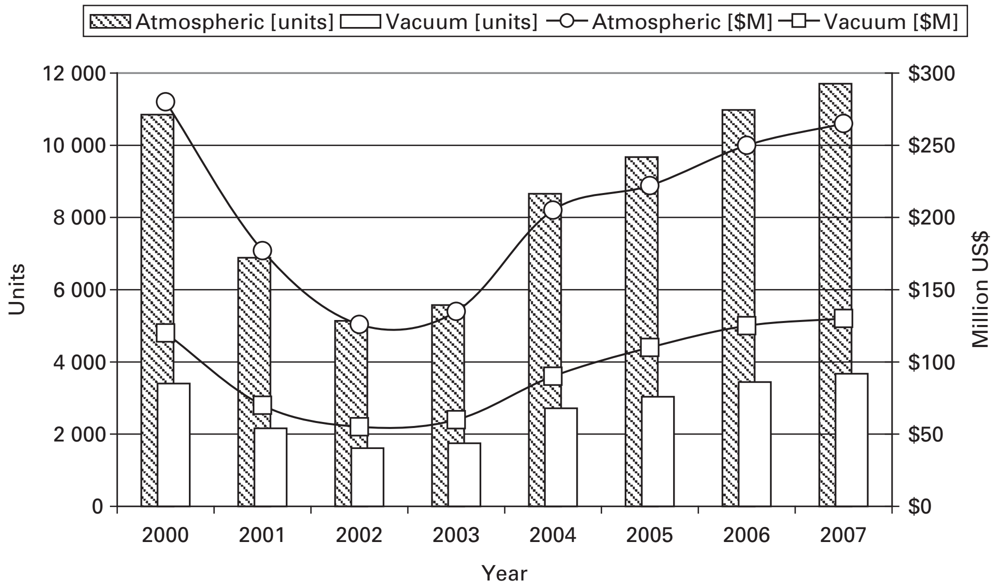

Figure 2.6 Shipment of wafer-handling robots (in units or in millions of US$).

reduce the design and manufacturing cost of atmospheric robots. However, the price of vacuum robots remained fairly constant. This may be due to the small number of suppliers that dominate that market, resulting in an only moderately competitive situation.

2.4.3 SCARA-type robots

Assembly robots

In the 1970s Professor Makino in Japan observed that 80% of assembly movements are vertically within the horizontal reach of a human arm. Motivated by this observation he invented the SCARA robot in 1979. SCARA stands for 'selective compliance arm for robot assembly' (ISO standard 8373:1994, No. 3.15.6); another interpretation is 'selective compliance articulated robot arm'. The term 'compliance' in robotics refers to the elasticity, the inverse of stiffness, of a manipulator, while 'selective compliance' refers to a robot manipulator geometry that provides motion with high rigidity in a selected plane. The kinematic structure of SCARA robots has four axes of motion and is sufficient to move and drop a work piece in any desired position within its workspace. SCARA robots utilize two or three parallel revolute joints to provide compliance in the horizontal plane against vertical loads. When the motors (not the encoders) for the horizontal axes of motion are powered off, the robot can vertically insert a part and compensate for small, horizontal displacements by horizontal sliding into the correct hole or opening.

Handling robots

Substrates in electronics manufacturing are typically handled in horizontal planes at different vertical positions and within the reach of a human arm, often in a cylindrical coordinate frame. This resembles the kinematic structure of SCARA robots for assembly tasks and makes this robot type an obvious choice for substrate handling. There is one exception: the vertical axis of SCARA robots is located at the end of a two-link arm, which is not possible for substrate handling: silicon wafers and other flat substrates require a horizontal, thin end-effector that allows reaching into small openings. Consequently the vertical axis was relocated from the arm tip to the robot centre, creating a 'SCARA-type' robot that became the most common substrate-handling robot in semiconductor and FPD manufacturing. A second reason for moving the vertical axis is cleanliness: it avoids particle generation from moving parts in close proximity to the substrate.

Figure 2.7 shows an example of a SCARA-type robot. Such robots have three or four axes of motion: one for rotating the robot base clockwise and counterclockwise, one for vertical motion, and one for extending and retracting the two-link SCARA arm. The (optional) fourth axis allows horizontal orientation of the end-effector. The arm is attached to the robot base by a revolute joint, sometimes called the 'shoulder.'

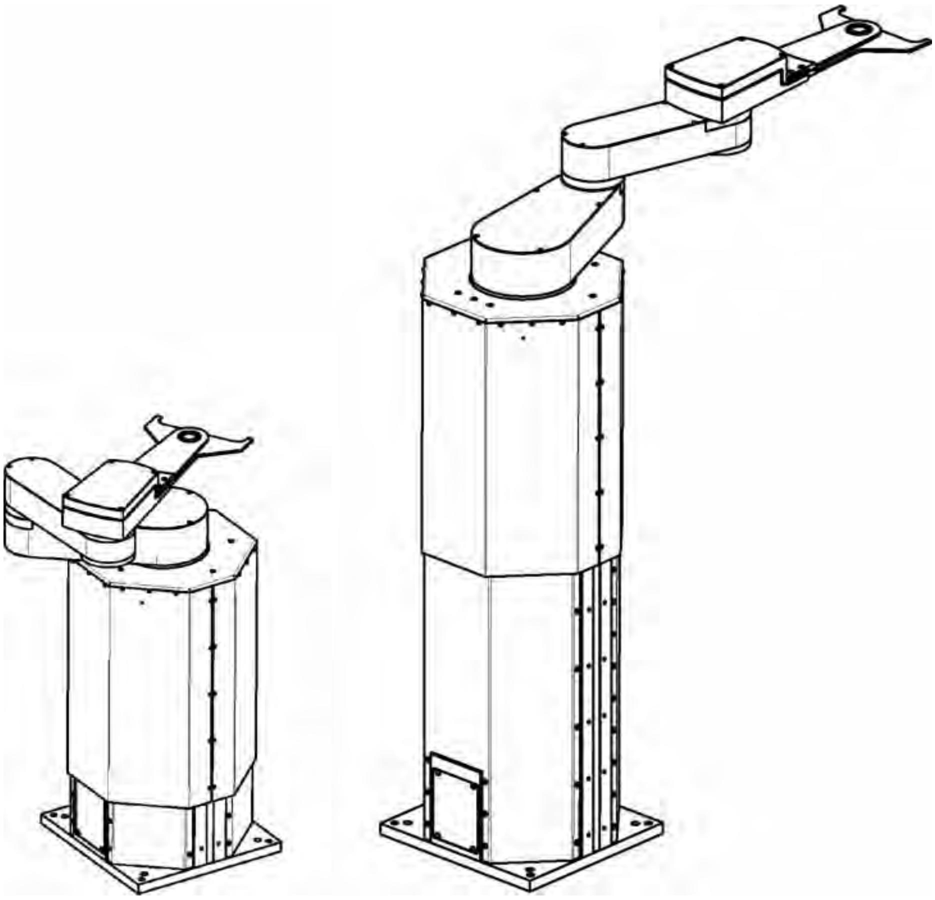

Figure 2.7 SCARA-type 300 mm wafer-handling robot with a fully retracted (left) and fully extended arm (right). Source: Cymechs Corp.

The second revolute joint is the ‘elbow,’ and the third is the ‘wrist.’ The vertical axis is usually implemented with a linear ball spline and driven by a ball screw. This SCARA-type kinematic structure has several advantages over more complex robot manipulators:

- Small foot print relative to the work envelope
- Good vertical arm stiffness
- Rugged against minor collisions
- Short pick-and-place time
- Good horizontal repeatability.

The robotic technology used in FPD manufacturing is similar to that in semiconductor manufacturing, although robots are scaled up in size for handling the large glass substrates. For example, the evolution from Generation 5 sheets (1100 mm by 1250 mm) to Generation 7 (1870 mm by 2200 mm) tripled the area and resulted in new requirements for the automation systems, including larger cleanroom robots with heights of up to 3 m. These robots handle FPD cassettes between tools as well as individual panels within a tool (Higuchi et al., 2003).

2.5 Applicable and related standards

Several industry standards and guidelines apply directly or indirectly to the robots discussed in this chapter. The following list provides a selection. ANSI standards are published by the American National Standards Institute (ANSI). ISO standards are published by the International Organization for Standardization (ISO). RIA standards are published by the Robotic Industries Association (RIA). SEMI standards are published by Semiconductor Equipment and Materials International (SEMI). Contact information for these organizations is listed in Appendix B.

ANSI/RIA R15.06:1999, Industrial Robots and Robot Systems – Safety Requirements.
ISO 14 644-1, Cleanrooms and associated controlled environments – Part 1: Classification of air cleanliness.
Sematech ITRS 2008, The International Technology Roadmap for Semiconductors.
SEMI E20-0697, Cluster Tool Module Interface: Electrical Power and Emergency Off Standard.
SEMI E22.1-1296, Cluster Tool Module Interface 300 mm: Transport module end-effector exclusion volume standard.
SEMI E23-1104, Specification for cassette transfer parallel I/O interface.
SEMI E32-0997, Material movement management.
SEMI E70-1103, Guide for Tool Accommodation Process.
SEMI E79-0304, Specification for definition and measurement equipment productivity.
SEMI E101-00-1104, Guide for EFEM functional structure.

SEMI F47-0706, Specification for Semiconductor Processing Equipment Voltage Sag Immunity.

SEMI E20-0697, Cluster Tool Module Interface: Electrical Power and Emergency Off Standard.

SEMI M1.15, Standard for 300 mm Polished Monocrystalline Silicon Wafers (Notched) specifies 300 mm silicon wafer attributes.

SEMI M1.9, Standard for 200 mm Polished Monocrystalline Silicon Wafers (Notched) specifies 200 mm silicon wafer attributes.

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