This article appeared in:
Silicon Futures
December 2001, pp. 30-33
www.siliconfutures.eu.com

Emerging Trends in Fab Automation

As the manufacture of microelectronics devices becomes more complex and higher in volume, manufacturers look for ways to improve processes. Dr. Martin Aalund and Dr. Karl Mathia o PRI Automation, Inc. look at the historical growth of Automation in the fab and the increasing need for automation in new technologies.

Semiconductor factory automation, while limited for 150mm wafers, is increasingly important for 200mm wafer fabs, and will be crucial for 300mm wafer factories, or 'fabs.' The level of fab automation will increase greatly as 300mm technology and bridge technology for both 200mm and 300mm wafers is adopted by fabs. This is reflected by the cost of automation for new fabs: total automation for 300mm fabs is estimated to be $85 million, up from about $25 million for a 200mm fab. Fab automation will be utilized at all levels of wafer processing and metrology, from tool automation and intrabay to the most complex interbay material handling.

HISTORICAL PERSPECTIVE

In the early days of semiconductor manufacturing, factories were extensions of research laboratories. Process equipment was somewhat unreliable, and frequent process and equipment failures required a high level of human labor and assistance. Therefore the human operator was vital and provided the intelligent 'process control' needed for this manufacturing environment. This limited the benefits of factory automation at the time, since automatic control works best for consistent processes with sufficiently accurate process models. With new, improved equipment the semiconductor process has become dependable, and the value of automation was more and more utilised to improve process yields and tool efficiency. Automation has enabled wafer sizes to increase from below 100mm to 150mm, 200mm, and eventually 300mm, with decreasing manufacturing costs despite exponentially growing circuit complexity. The trend towards fab automation continued until today and will see unprecedented growth during the transition to 300mm.

For various reasons these changes in process control and fab automation took not just years, but decades to materialise. First, the semiconductor industry experienced several upturns and downturns since the early 1970s, which repeatedly delayed investments in new technologies. Second, the technological challenge for equipment manufacturers was underestimated, and roadmaps for the transition from 200mm to 300mm are several years behind the initial schedules. See, for example, the SIA National Technology Roadmap for Semiconductors. Although the transition began in the early 1980s, 150mm was not surpassed until the late 1980s, and the peak of the 200mm technology did not occur until 1997. These lengthy transitions also require equipment manufactures to support multiple product generations simultaneously, and it may be several years before a new fab turns a profit.

Robotics

Early robotics first replaced technicians that were handling wafers with tweezers and vacuum wands, and next automated vacuum cluster tools. The motivation was and still is to increase wafer throughput, safety, and cleanliness. Since the 1970s robots automated numerous processes and metrology applications, although the requirement for tool automation and robotics also increased dramatically with every wafer generation, as Moore's la

This article appeared in:
Silicon Futures
December 2001, pp. 30-33
www.siliconfutures.eu.com

drove the number of transistors per cm^2 to 10 million, clock rates beyond 1 GHz, and line widths below 0.1 microns. Today the automation industry offers a variety of robots for atmospheric and vacuum applications in all semiconductor manufacturing processes. Several criteria impact the selection of robotics for a given application, including wafer throughput, reliability, positional repeatability, cleanliness, and controller features such as user-friendly software.

The initial lack of industry standards for mechanical and software interfaces, as well as safety concerns were obstacles for original equipment manufacturers (OEMs) and end-users. The resulting difficulties of integrating products from various suppliers spurred the creation of standards such as the SEMI S and E series. The advent of standards accelerated the acceptance of automation, allowing OEMs to focus on their core technologies and processes and to outsource automation. OEMs now can provide automation solutions with reduced risk and development costs. This trend in fab automation is still gaining momentum.

TRANSITION FROM 200MM TO 300MM

The transition to larger wafer sizes is driven by cost per die. The current transition from 200mm to 300mm, which will more than double the number of dies per wafer, is expected to result in a 30% cost reduction. Automation contributed to this accomplishment by maximising equipment utilization and fab capacity, allowing manufactures to develop fewer fabs and still to meet increasing demand. Automation for the first time is a crucial factor in the semiconductor business equation.

The risks of transitioning from 200mm to 300mm are the enormous investments required, and the uncertain schedule. In order to mitigate these so-called ‘bridge tools’ that can process either 200mm and 300mm wafers are a common solution. These tools have several advantages:

- the useful life is maximised by a utilisation for 200mm and a subsequent 300mm application;
- they offer a possible retreat from 300mm back to 200mm;
- state-of-the-art automation helps to improve productivity of existing 200mm fabs;
- existing 200mm fabs can be used as pilot lines for 300mm technology (wafer cost: 200mm ~ \$150, 300mm ~ \$1000).

Bridge tools, while enabling smoother transitions, also pose challenges. For example, it is difficult if not impossible to design and optimise a tool for two wafer sizes simultaneously. Such a compromise could result in higher cost for 200mm applications, and sub-optimal performance for 300mm applications. This is one lesson learned from the 150mm to 200mm transition, where bridge tools rarely offered an economical advantage over 150mm tools.

Standards

Historically most standards have been defined *post facto* based on the successful implementation of a technology. The huge cost and complexity of the 200-300mm transition in turn forced the industry to establish standards at the outset and to ensure its acceptance in the marketplace. This objective was supported by the US legislature in 1980, who allowed organizations such as SEMATECH to perform pre-competitive work. In 1995 the International 300mm Initiative (I300I) was established within SEMATECH. The goal was to jointly develop and accelerate the development of 300mm pilot lines.

Prior to 1997 membership growth of the I300I was slow. In fact, SELETE was founded in Japan, an organization similar but not related to SEMATECH. SELETE relied on J300 to set standards for Japan and possibly the Pacific Rim. The confusion resulting among equipment suppliers delayed progress on the 300m front. Finally, at SEMICON West 1997 the two standards bodies I300I and J300 published a unified set of standards. This initiated the final push to move forward on 300mm automation. I300I concluded its mission as of June 30^{th} 2001.

The driving force towards 300mm technology is reduced cost through improved equipment utilisation. Automatic Material Handling Systems (AMHS) and wafer handling equipment will

This article appeared in:
Silicon Futures
December 2001, pp. 30-33
www.siliconfutures.eu.com

enable the required wafer transport, handling, safety, and reliability, thus moving one step closer towards the future 24x7 'lights out' fab.

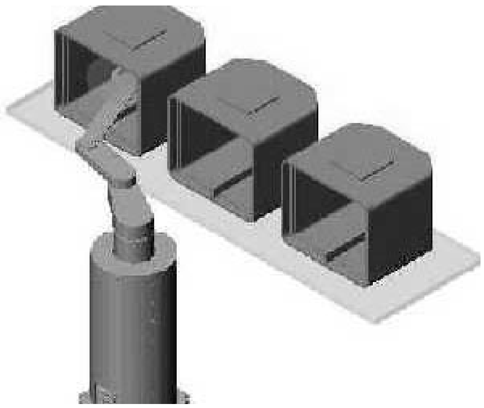

Figure 1. Concept of a 4-axes wafer handling robot.

Robotics

In the past wafer handling robotics in semiconductor manufacturing used a subset of features already available for industrial robots. Typical tool geometries and handling requirements resulted in moderate kinematic models and controller software features. This is changing with the development of wafer handling systems for 300mm tools: technology is being transferred from other industries, providing state-of-the-art hardware and software for advanced wafer transport and handling. Robots are no longer limited to simple three degree of freedom SCARA arms that operate in cylindrical coordinate systems. For example, Figure 1 shows the concept of a 4-axes wafer handling robot, which can serve three lined up wafer cassettes.

Wafer throughput is often defined as the number of wafers processed per hour, and depends on both wafer transport time and process time. Wafer swap time is usually defined as the time needed to replace a processed wafer with a new, unprocessed wafer. Advanced four-axes dual arm robots have been developed to optimise swap time (Figure 2). These robot models put the new wafer on the process chuck before turning and placing the processed wafer in a cassette or FOUP. This can save crucial seconds.

Figure 2. Dual-Arm Robot for wafer handling.

Cleanliness

Larger semiconductor wafer formats and smaller critical dimensions have forced both an understanding and elimination of contamination sources and process faults which impact product yield. It has been estimated that up to 80% of the yield loss in the production of high-volume, very-large-scale integrated (VLSI) circuits can be attributed to random visual pattern defects. Particles that were acceptable at 1.0 micron can now be categorised as "killer defects" as critical dimensions shrink below 0.25 micron towards 0.13 micron. Cleanliness requirements impact wafer handling in two aspects, airborne molecular contamination and wafer backside contamination.

- *Airborne molecular contamination*. – Wafer handling robots are often installed in Class 1 and Class 2 clean mini-environments and must generate minimal airborne particles. This can be accomplished, for example, by reducing the number of moving parts within the robot drive train (and generally above the wafer), and by controlling the pressure gradient between robot and environment. Direct drives are thus desirable.
- *Backside contamination.* – Contact between wafer and robot end-effector leaves particles on the wafer surface. Although only the backside is used for handling, backside particles can fall onto wafers below or migrate onto tool chucking surfaces, thus impacting yield. A widly accepted solution is edge-gripping.

This article appeared in:
Silicon Futures
December 2001, pp. 30-33
www.siliconfutures.eu.com

SEMI has proposed a non-critical edge-exclusion zone of 3mm for 300mm wafers (expected to shrink to 1mm), so the wafer can be safely gripped at the edge exclusion zone. This will solve many of the problems associated with backside handling.

Figure 3 shows one of many concept of a 300mm edge gripper, including the wafer position in a FOUP. It also illustrates an additional feature of edge gripping, that is, wafer centering. Note that most edge grippers will slide the wafer on the FOUP rails or gripper pads, potentially generating particles.

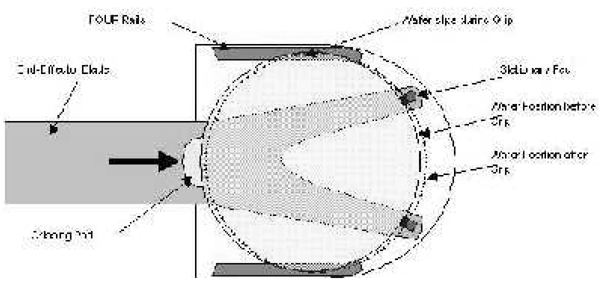

Figure 3. Concept of a 300mm Edge Gripper.

Controller Technology

Software features are becoming more important to users. Significant advances in controller software have been made throughout the semiconductor industry in recent years. For example, advanced software for trajectory generation, teaching, graphical simulation and other value-added tasks are becoming common. Complex trajectories have allowed motions to be optimised and provided greater flexibility in tool layout. New features include auto-teaching of robot positions, networking capability, graphical user interfaces (GUIs), and real-time simulation.

- *Auto-Teaching*. – The goal is to automatically 'teach' the robot the fixed positions within the tool. Common procedures still include human operators for this, sometimes time-consuming, task. Sensory inputs from tool positions provide that data needed for robot self-calibration, that is, identifying the environment, to learn its location relative to tool stations. The benefits over manual teaching are reduced tool downtimes, and consistent robot performance.
- *Trajectory planning.* – After station teaching the optimized paths (trajectories) between these reference points can be automatically generated, also resulting in reduced downtimes and increased throughput.
- *Networking capabilit* . – The popular internet protocol TCP-IP and high-speed Ethernet protocols are common features to provide networking capabilities to robotics equipment. The motives for this feature include remote performance monitoring and remote upgrades of system parameters and software.
- *Real-time simulation.* – The advantages of both off-line and in real-time graphical simulations are obvious. First, the complete wafer handling application can be tested off-line before risking wafer and equipment damage. Also, wafer throughput can be simulated and optimized off-line, thus tool efficiency is determined without any downtime. Also, the operator is always informed about the handling process, even if a handling system cannot be accessed or is not visible (see Figure 4).

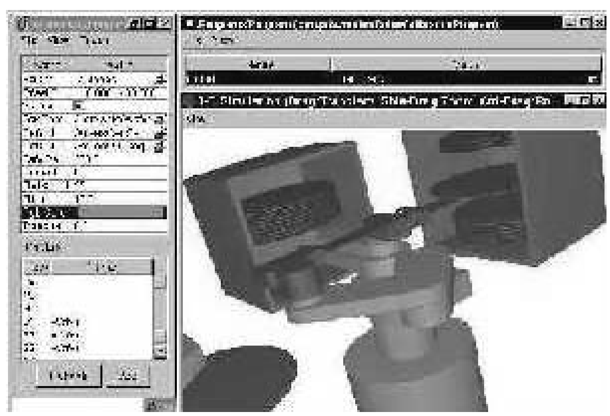

Figure 4. Graphical User Interface.

System Solutions

While wafer handling components as robots, aligners and PDOs become standardised commodities, the trend toward total solutions in the semiconductor industry is gaining momentum. Equipment manufacturers desire to focus on their core competency, which is the process, and not the integration of automation and wafer handling systems. Thus OEMs increasingly outsource automation solutions, for example Integrated Front-End Systems (IFEs).

Figure 5. Integrated Front-End System.

IFEs are clean mini-environments and serve typically as interfaces between the human operator and the process or, for example, between the inside and outside of a manufacturing 'bay' in wafer fabs. Most IFEs comprise one, two, or four PDOs, a wafer handling system, and a wafer pre-aligner. Figure 5 shows an IFE with four Pod Door Openers (PDOs) and FOUPs.

Many OEMs specify IFEs to be a black box with interfaces only at its inputs and outputs, and outsource these 'black boxes,' while IFE vendors are responsible for optimized cost, performance, and minimise footprint. Outsourcing is possible, as SEMI standards for the mechanical, electrical, and software interfaces of IFEs are in place, so that the integration effort can be moved up from the wafer handling component level to the systems level. Another advantage is that IFEs can be shipped directly to the fabs and integrated on site, rather than at the OEM facilities.

EMERGING TRENDS

New hardware and software technologies and being adopted and developed to completely automate 300mm wafer handling, and possibly 450mm wafer (and reticle) handling (Figure 6). In addition to robotics, integration of Intrabay and Interbay transport systems and wafer automation are being developed for future 'lights out' fabs. In the following a few examples of advanced automation devices are outlined.

End-Aligner

An end-aligner is an end-effector that aligns and centers a wafer during transport, thus eliminating traditional pre-aligners and enabling alignment and centering during robot motion. This will result in increased throughput and decreased manufacturing cost. There are still several technical challenges to be resolved, including possible wafer damage from rollers passing over wafer notch or surface, or cross-contamination between wafers. The next end-aligners generation will be capable of performing alignment and centering without sliding the wafer to meet future cleanliness requirements.

Contact-Free Wafer Handling

In an ideal world wafers are being handled without ever making contact to the end-effector. Several methods are being researched to levitate wafers, including air bearings, magnetic fields, ultrasonic and capacitive fields. One joint effort between PRI and the IWB in Munich has recently shown that near field ultrasonic levitation can be used to levitate the wafer without physical contact and without wafer sliding. In the future this technology could be utilised to develop wafer 'autobahns' that will allow for contact free transport within IFEs.

Advances in software will add intelligence to fab automation, with smart machines utilizing process data for additional productivity, functionality, safety, and control at all levels. At the highest, fab-wide level Manufacturing Execution Systems (MES) analyze data in for automated decision making and material scheduling, and optimise data flow and schedules for material flow, further improving equipment utilisation. Eventually schedules will be updated in real time for rescheduling hot lots within 10 minutes, or to predict scenarios one day ahead and possibly reschedule, for example based on required maintenance or mate-

This article appeared in:
Silicon Futures
December 2001, pp. 30-33
www.siliconfutures.eu.com

rial shortages. It is clear tat MES systems will model the complete work-in-progress (WIP) in a fab, and use predictive models to schedule operations and minimise cost. The days of full stockers and other bottlenecks are numbered.

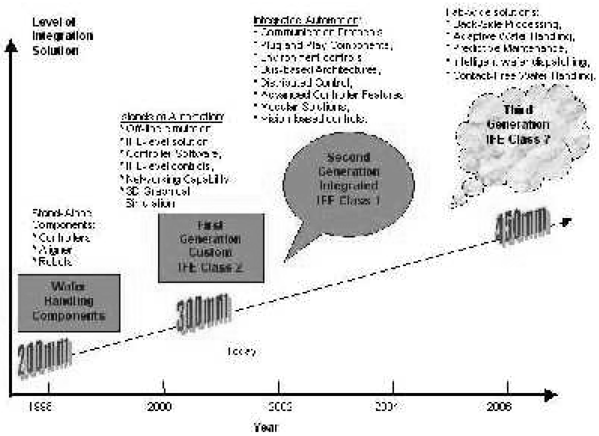

Figure 6. Roadmap of automation solutions.

This process already has begun for wafer automation, and will continue with reticles and other materials, although some unresolved challenges remain to be solved. It has been recognised that current MES systems cannot cost-effectively handle the advanced requirements of 300mm. In fact, 73% of new 300mm fabs have decided that they need next generation (not current) MES systems and fab-wide automation architectures. This need is being addressed by the SEMI International Standards organization (ISO). The user-level requirements for the capabilities needed to schedule and dispatch manufacturing activities within a semiconductor manufacturing plant are intended to form a basis for the development of standards within the SEMI ISO. Standards for the scheduler/dispatcher components of an MES will enable users and suppliers of compliant software products to more easily integrate solutions that meet the requirements defined here.

At a lower level of fab automation intelligent software will utilise vision systems to detect 'killer defects' as well as obstacles in the robot's path. Sensory data will allow for predictive maintenance and optimisation of controller algorithms, for example fault tolerant wafer handling. IFEs will require controllers that are adept at sensor fusion as well as motion and process control. This will require the automation of wafers, reticles, and data to be coordinated and correlated in real time. However the benefits will be substantial in both yield and throughput. Companies like PRI are applying proven automation concepts from other industries to provide tools, software and services to the semiconductor industry.