# INTERNATIONAL
# TECHNOLOGY ROADMAP
# FOR
# SEMICONDUCTORS

## 2005 EDITION

## ENVIRONMENT, SAFETY, AND HEALTH

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# ENVIRONMENT, SAFETY, AND HEALTH

## SCOPE

### BACKGROUND

The semiconductor industry views responsible performance in environment, safety, and health (ESH) as critical to success. Continued ESH improvement is a major consideration for semiconductor manufacturers, whose business approach to ESH employs strategies that are integrated with manufacturing technologies, products, and services. This approach is structured around the belief that good business stewardship includes an active awareness and commitment to responsible environmental, safety, and health practices. Addressing these areas aggressively has resulted in the industry being an ESH leader as well as a technology leader.

### EXPECTATIONS

For both engineers and research scientists, this roadmap identifies ESH R&D challenges that occur as new wafer processing and assembly technologies are designed and created. Technology requirements are listed in Tables 103–107. It also proposes possible technology and management solutions to meet the challenges, as illustrated in Figures 98–100.

By giving direction to research centers, suppliers, and semiconductor manufacturers, this roadmap focuses the search for solutions. ESH integration into manufacturing and business practices is clearly a priority. A high expectation of success and improvement requires that ESH is integral to the thoughts and actions of process, equipment and facilities engineers, and to university and consortia researchers. Improvements must meet local, national, and international needs, with positive impact on cost, technical performance, and product timing. They must also minimize risk, public and employee health effects, and environmental impact. Solutions must be timely, yet far reaching, to assure long-term success. Integration of international initiatives and other notable ESH-focused entities sponsored by the semiconductor industry, universities, consortia, and government have made the ESH objectives of this roadmap truly international.

### *ENVIRONMENTAL HEALTH AND SAFETY IN NANO ELECTRONICS*

As materials used in semiconductor manufacturing enter the nano-sized realm, a renewed focus on the environmental, safety, and health implications of these materials is warranted. It is well documented that nano-sized materials often have unique and diverse properties from their bulk form. These differences must be understood from an ESH perspective and may present unique challenges. In addition, the small size of the new materials may make traditional ESH controls (such as emission control equipment) less than optimal. As a result, the following ESH considerations should be taken into account for future technology development:

- Development of effective monitoring tools to detect the presence of nanomaterials in the workplace, the waste streams, and the environment
- Evaluation and development of appropriate protocols to ensure worker health and safety
- Evaluation and development of pollution control equipment to ensure effective treatment of waste streams containing nanomaterials
- Understanding of the toxicity of new nanomaterials which may differ from their bulk form

## DIFFICULT CHALLENGES

The ESH Difficult Challenges serve three important functions with respect to the ITRS. Firstly, they capture the inherent considerations of ESH science within the scope of evolving semiconductor technology, such as the need of metrology tools for nano materials. Secondly, they are the one place where external public policy, regulation, and legislative limitations can be incorporated into future technology planning. Thirdly, the inherent and external ESH considerations, structured as the ESH Difficult Challenges, are the framework for evaluating each technology thrust. The resultant “cross-thrust filtering” provides information on needs that are incorporated into the ESH Technology Requirement Tables.

Following are four global ESH challenges essential to a synergistic ESH strategy that must be integrated into the technical thrust areas: Chemicals and Materials Management; Process and Equipment Management; Facilities Energy and Water Optimization, and Sustainability and Product Stewardship.

*Chemicals and Materials Management* must provide timely ESH information to equipment design engineers and equipment users regarding the environmental, safety, and health characteristics of potential new process chemicals and materials. This information is essential to the selection of the preferred chemicals and materials with respect to performance and minimal ESH impact. Accurate information on the physical/chemical, environmental, and toxic properties of chemicals and materials as well as any reaction by-products is essential for minimizing business impacts after processes are developed and introduced into high volume manufacturing. *Refer to the link to the chemical screening tool (Chemical Restrictions Table)*.

*Process and Equipment Management* includes a continuing need for water, energy, and chemical conservation through process optimization, implementation of cost-effective use reduction solutions, and replacement of hazardous chemicals with more benign materials. Management of by-products, chemical exposure, ergonomics, and the consumption of consumables are important considerations in the design and operation of tools. Design for ease of maintenance of the tools is another challenge vital to the safe operation of any manufacturing facility.

*Facilities Energy and Water Optimization* focuses on the need for resource conservation of the factory's support systems. The reduction of global warming emissions from both the generation of electricity and the use of etch and chamber clean process chemicals is a major consideration, because it could limit the use of energy and chemicals essential to the manufacturing process. More efficient design of clean rooms and facility systems for heat removal is another challenge.

*Sustainability and Product Stewardship* are becoming important considerations driven by public opinion and the customers of the industry's products. To address these challenges in a cost-effective and timely way, *Design for Environment, Safety, and Health (DFESH)* must become an integral part of the design process and management's decision-making. Environmentally friendly end-of-life disposal and/or reclaim of manufacturing equipment and industry products are demanded globally.

*Table 103a ESH Difficult Challenges—Near-term*

| *Difficult Challenges ≥ 32 nm* | *Summary of Issues* |
|---|---|
| Chemicals and materials management | *Chemical Assessment*<br>Lack of quality rapid assessment methodologies to ensure that chemicals can be utilized in manufacturing, while protecting human health, safety, and the environment without delaying process implementation<br>*Chemical Data Availability*<br>Lack of comprehensive ESH data for new, proprietary chemicals and materials to respond to the increasing external and regional requirements on the use of chemicals<br>*Chemical Exposure Management*<br>Lack of information on how the chemicals and materials are used and what process by-products are formed |
| Process and equipment management | *Chemical Reduction*<br>Need to develop processes that meet technology demands while reducing impact on human health, safety and the environment, both through the use of more benign materials, and by reducing chemical quantity requirements through more efficient and cost-effective process management<br>*Environment Management*<br>Need to develop effective management systems to address issues related to re-use and disposal of equipment, and hazardous and non-hazardous residues from the manufacturing processes<br>*Water and Energy Conservation*<br>Need to reduce water and energy consumption<br>Need for innovative energy and water-efficient processes and equipment<br>*Consumables Optimization*<br>Need for more efficient utilization of chemicals and materials, and increased reuse and recycling<br>*Byproducts Management*<br>Need to understand ESH characteristics of process by-products to identify the appropriate mitigation<br>*Chemical Exposure Management*<br>Need to design-out potential for chemical exposures and need for personal protective equipment (PPE)<br>*Equipment Ergonomics*<br>Need to design ergonomically correct and safe equipment<br>*Design for Maintenance*<br>Need to design equipment so that maintenance and service may be safely performed by a single person<br>Need to design equipment so that commonly serviced components and consumable items are easily accessed<br>Need to minimize health and safety risks during maintenance activities. |
| Facilities energy and water optimization | *Conservation*<br>Need to reduce energy and water use<br>*Tool Heat Removal*<br>Need for more efficient thermal management of cleanrooms and facilities systems<br>*Global Warming Emissions Reduction*<br>Need to design energy efficient processing equipment and manufacturing facilities<br>Need to reduce emissions from processes using GWP chemicals |
| Sustainability and product stewardship | *End-of-Life Disposal/Reclaim*<br>Need to design tools, equipment and products to facilitate disposal at end of life<br>*Design for ESH*<br>Need method to holisticly evaluate and quantify the ESH impacts of processes, chemicals, and process equipment for the total manufacturing process<br>Need to make ESH a design parameter in development of new equipment, processes and products<br>*Sustainability Metric*<br>Need to identify the elements for defining and measuring the sustainability of a technology generation |

*Table 103b ESH Difficult Challenges—Long-term*

| *Difficult Challenges < 32 nm* | *Summary of Issues* |
|---|---|
| Chemicals and materials management | *Chemical Assessment*<br>Lack of quality rapid assessment methodologies to ensure that chemicals can be utilized in manufacturing, while protecting human health, safety, and the environment without delaying process implementation<br>*Chemical Data Availability*<br>Lack of comprehensive ESH data for new, proprietary chemicals and materials to respond to the increasing external and regional requirements on the use of chemicals<br>*Chemical Exposure Management*<br>Lack of information on how the chemicals and materials are used and what process by-products are formed |
| Process and equipment management | *Chemical Reduction*<br>Need to develop processes that meet technology demands while reducing impact on human health, safety, and the environment, both through the use of more benign materials, and by reducing chemical quantity requirements through more efficient and cost-effective process management<br>*Environment Management*<br>Need to develop effective management systems to address issues related to re-use and disposal of equipment, and hazardous and non-hazardous residues from the manufacturing processes<br>*Water and Energy Conservation*<br>Need to reduce water and energy consumption<br>Need for innovative energy and water-efficient processes and equipment<br>*Consumables Optimization*<br>Need for more efficient utilization of chemicals and materials, and increased reuse and recycling<br>*Byproducts Management*<br>Need to understand ESH characteristics of process by-products to identify the appropriate mitigation<br>*Chemical Exposure Management*<br>Need to design-out potential for chemical exposures and need for personal protective equipment (PPE)<br>*Equipment Ergonomics*<br>Need to design ergonomically correct and safe equipment<br>*Design for Maintenance*<br>Need to design equipment so that maintenance and service may be safely performed by a single person<br>Need to design equipment so that commonly serviced components and consumable items are easily accessed<br>Need to minimize health and safety risks during maintenance activities |
| Facilities energy and water optimization | *Conservation*<br>Need to reduce energy and water use<br>*Tool Heat Removal*<br>Need for more efficient thermal management of cleanrooms and facilities systems<br>*Global Warming Emissions Reduction*<br>Need to design energy efficient processing equipment and manufacturing facilities.<br>Need to reduce emissions from processes using GWP chemicals |
| Sustainability and product stewardship | *End-of-Life Disposal/Reclaim*<br>Need to design tools, equipment, and products to facilitate disposal at end of life<br>*Design for ESH*<br>Need method to holisticly evaluate and quantify the ESH impacts of processes, chemicals, and process equipment for the total manufacturing process<br>Need to make ESH a design parameter in development of new equipment, processes and products<br>*Sustainability Metric*<br>Need to identify the elements for defining and measuring the sustainability of a technology generation |

# ESH TECHNOLOGY REQUIREMENTS AND POTENTIAL SOLUTIONS

## ESH INTRINSIC REQUIREMENTS

For making ESH-related technology decisions, the scientists and engineers responsible for new technology development require an explicit set of guidelines and targets that represent the intrinsic ESH requirements. The intent is to meet the ESH intrinsic requirements in parallel to the mainstream technology objectives.

Table 104 outlines these overarching ESH goals under the four *ESH Difficult Challenges* headings. It spells out targets for energy and water consumption for tools and equipment as well as facility systems. It provides guidance on the reduction for chemical consumption as well as waste generation. In case of the later, it addresses both hazardous liquid and solid waste generation as well as perfluorocompound (PFC) emissions. In addition, it spells out basic requirements for worker and workplace protection, and points out the need for environmental load/impact assessment for all new materials.

## CHEMICALS AND MATERIALS MANAGEMENT

*Chemical risk assessment*—Prior to employing a new chemical or material, it is necessary to accurately and quickly evaluate the safety, health danger, and environmental load/impact. A decision is then made whether to employ the chemical, based on the quantity to be used, the way it is used, and the risk assessment. Operator and maintenance worker exposure to the chemical or material must be reduced for safety and health reasons, and emissions must be controlled to minimize environmental load/impact. It is important to link the consideration of exposure to the material hazard in the risk assessment process.

Process analysis is an important element of the environmental impact assessment process. Process by-products, for example from plasma processes, may raise significant health and environmental issues that cannot be ignored. The elementary chemical reactions in each process must be understood for developing processes that have the lowest ESH impact.

In addition, the risk assessment should include a check of the chemical against the *Chemical Restrictions Table*, to ensure that the chemical is not banned or under some regulatory watch.

### *CHEMICAL DATA AVAILABILITY*

A database should be established to store the chemical data required for accurately conducting risk assessment on the materials and chemicals used in the semiconductor industry. The database should contain information such as safety data, environmental load/impact data, process data, emission distribution factor (dispersion model) and emission treatment methods to use the material in compliance with existing and anticipated laws and regulations. At present, the general database for chemicals and materials is generated by the chemical/material industry, but in many cases the data are not sufficient, especially with regards to long-term environmental and chronic toxicity effects. However, there should probably be a consideration of risk when determining chemical data requirements for materials.

### *CHEMICAL EXPOSURE MANAGEMENT*

It is necessary to control the chemicals and materials in each plant to reduce the quantity used and their emissions. Therefore, the ESH impact assessment should include a material balance and an identification of the path by which the chemical or material enters the environment. Efforts have been made to find alternative materials, especially for greenhouse gases and ozone-depleting substances. Alternative materials for bromine and antimony used as fire resistant materials in plastic packages and lead used for soldering and tinning, continue being developed.

An industry need exists for safe, cost-effective materials of construction. Fire-resistant, process-compatible materials that meet the needs of manufacturing and the expectations of insurers are necessary for both tools and wafer carriers.

Electromagnetic waves exhibit various wavelength-dependent characteristics. When the wavelength used for pattern exposure is shortened to the X-ray region, the health effects must be evaluated

## PROCESS AND EQUIPMENT MANAGEMENT

### *CHEMICAL REDUCTION*

New chemicals and materials will be used and their usage will be rapidly increased with introductions and development of new technologies to satisfy technology requirements. Whereas in the past the same materials would easily support four to five technology generations, today nearly each technology generation requires introduction of one or more new materials. Though total quantity of chemicals and materials usage in semiconductor industry is quite small compared to other industries, resource efficient processing and production equipment are needed.

### *WATER AND ENERGY CONSERVATION*

Water and energy consumption have increased due to the more complex semiconductors and larger diameter wafers. Changes in areas such as cleanroom design, equipment design, and wafer transfer/storage methods are needed. The greatest need is efficiency improvement in vacuum pumps, POU chillers and heaters, uninterrupted power systems, and power transforming devices (for example, RF generators and transformers). In addition to the need for more energy efficient tools, it is necessary to reduce the heat load/impact of the tools on the cleanroom and to develop the capability to put the tools into “idle-mode” when they are not processing wafers.

### *CONSUMABLES OPTIMIZATION*

Consumables such as the slurry in CMP and the brushes used in post-CMP cleaning can have a major impact on the cost of operation of a tool as well as on the amount of waste generated by the manufacturing facility. Therefore, optimization of the process to minimize the consumption of consumables becomes very important.

### *BYPRODUCTS MANAGEMENT*

The identification of process by-products in the exhaust or drain leaving tools is very important for the safety of the tool operators and maintenance technicians as well as for preventing undesirable emissions to the environment.

### *ENVIRONMENT MANAGEMENT*

The semiconductor manufacturers should aim at realizing a “zero waste” plant like other industries. To achieve that objective the waste recycle rate must be improved and cooperation with the recycling industry and governments will be necessary.

### *CHEMICAL EXPOSURE MANAGEMENT*

For equipment, processes, maintenance, factory design, and factory integration, the industry must accept and fully employ a standard protocol for hazard control utilizing the following ranking for solutions: 1) hazard elimination, 2) engineering controls, 3) administrative controls, and 4) personal protective equipment (PPE).

### *EQUIPMENT ERGONOMICS*

Increases in wafer size and throughput will require wafer-handling systems that may increase worker risk during operation and maintenance. The movement of automated wafer transport systems and their interface with manufacturing equipment are potentially dangerous to nearby workers. Design controls and procedures comprehending ergonomics and robotics to improve equipment operability and prevent incorrect operation need to be established.

### *DESIGN FOR MAINTENANCE*

As the size and complexity of the tools increases due to the advanced technologies, the design of the tools for safe and ergonomically friendly maintenance becomes more difficult and challenging. However, in keeping with the industry’s reputation for safe factories and a low incidence of work related injuries, attention must be paid to this challenge during the design of the tools.

## FACILITIES ENERGY AND WATER OPTIMIZATION

### *CONSERVATION*

*Energy*—The increase in wafer size and the number of process steps as well as the need for higher purity water and chemicals indicates a potential trend for greater resource (water, energy, and chemicals) usage per wafer. This trend can be reversed by development of higher efficiency processes and tools and by a combination of strategies including recycling of spent chemicals, water, and waste for process applications and reuse for non-process applications. Resource utilization efficiency in semiconductor tools can be greatly improved. For example, in the photolithography process a significant amount of the photoresist applied to the wafer is slung off during the spin-on process step and becomes waste. (However, significant progress has already been made in the reduction of resist waste.) Also, optimization of tool exhaust requirements and cleanroom HEPA velocities are required to reduce overall fab energy consumption.

Limits on sources of energy could potentially limit industry's ability to expand existing factories or build new ones. While the semiconductor manufacturers have demonstrated improved energy efficiencies over the past decade, potential resource limitations require the industry to continue the trend.

*Water*—Water used in semiconductor manufacturing is mostly ultrapure water (UPW). Since the production of UPW requires large quantities of chemicals, an increase in UPW consumption and quality results in greater chemical consumption (and ultrapure water production cost). A decrease in UPW consumption will reduce environmental effects caused by the chemicals as well as reduce manufacturing costs. Recycling of higher quality water for process applications and reuse of lower quality water for non-process applications is important. In areas where water is plentiful, wastewater recycling will depend on local water reuse options and associated recycling costs.

Changes in areas such as cleanroom design and wafer transfer/storage methods are needed. In addition to the need for more energy efficient tools, it is necessary to reduce the heat load/impact of the tools on the cleanroom.

### *GLOBAL WARMING EMISSIONS REDUCTION*

Global climate change concerns are driving international efforts to not only reduce emissions of greenhouse gases, such as PFCs used in semiconductor manufacturing, but also emissions of carbon dioxide resulting from the generation of the electricity used in semiconductor manufacturing.

## SUSTAINABILITY AND PRODUCT STEWARDSHIP

Design for Environment, Health and Safety (DFESH) is the term applied to the integration and proliferation of ESH improvements into the technology design. It allows for the early evaluation of ESH issues related to critical technology developments and ensures that there are no ESH-related "showstoppers." It requires a comprehensive understanding of tools and materials development, facility design, waste and resource management and the way they affect ESH results. DFESH allows us to build ESH improvements into the way products are manufactured, while maintaining desirable product price/performance and quality characteristics.

## *Table 104a ESH Intrinsic Requirements—Near-term Years*

| *Year of Production* | *2005* | *2006* | *2007* | *2008* | *2009* | *2010* | *2011* | *2012* | *2013* | *Driver* |
|---|---|---|---|---|---|---|---|---|---|---|
| *DRAM ½ Pitch (nm) (contacted)* | *80* | *70* | *65* | *57* | *50* | *45* | *40* | *36* | *32* | |
| *MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)* | *90* | *78* | *68* | *59* | *52* | *45* | *40* | *36* | *32* | |
| *Chemicals and Materials Management Technology Requirements* | | | | | | | | | | |
| CPIFs* completed for percent of new chemical candidates | **100%** | | | | | | | | | |
| Percent of chemical risk assessments (health and safety) completed | **100%** | | | | | **100%** | | | | |
| *Process and Equipment Technology Requirements* | | | | | | | | | | |
| *Energy Consumption* | | | | | | | | | | |
| Total fab tools (kWh/cm$^2$) [3] | **0.3–0.4** | | | | | | **0.25–0.3** | | | |
| Tool energy usage per wafer pass (300 mm versus 200 mm); baseline 1999 | **1** | **0.8** | | **0.6** | | | **Functional Area Goals TBD** | | | |
| *Water Consumption* | | | | | | | | | | *Sustainable growth and cost* |
| Wet bench UPW use (liters/300 mm wafer pass) | **42** | | | | | **TBD** | | | | |
| *Chemical Consumption and Waste Reduction* | | | | | | | | | | *Environmental stewardship and cost* |
| Improvement in process chemical utilization (liters [liquid] or grams [gas]/cm$^2$/mask layer) | **3% per year** | | | | | **3% per year** | | | | |
| *Worker and Workplace Protection* | | | | | | | | | | |
| Conformance of new tools to latest International ESH standards and guidelines such as SEMI S2 [1] and European CE mark requirements [2] | **100%** | | | | | **100%** | | | | |
| Conformance of AMHS/tool interface to latest SEMI S2 Guideline and CE mark directive. | **100%** | | | | | **100%** | | | | |
| *Facilities Energy and Water Optimization Technology Requirements* | | | | | | | | | | |
| *Energy Consumption* | | | | | | | | | | |
| Total fab support systems (kWh/cm$^2$) [3] | **0.5–0.6** | | | | | **0.35–0.5** | | | | |
| *Water Consumption* | | | | | | | | | | |
| Net feed water use (liters/cm$^2$) [3] | **8–10** | | | | | **3–5** | | | | |
| Fab UPW use (liters/cm$^2$) [3] | **4–6** | | | | | **4–6** | | | | |
| *Chemical Consumption and Waste Reduction* | | | | | | | | | | |
| Hazardous liquid waste recycle/reuse | **80%** | | | | | **80%** | | | | |
| Solid waste recycle/reuse | **85%** | | | | | **90%** | | | | |
| Reduce PFC emission | **10% absolute reduction from 1995 baseline by 2010 as agreed to by the World Semiconductor Council (WSC)** | | | | | | **Maintain 10% absolute reduction from 1995 baseline** | | | |
| *Sustainability and Product Stewardship Requirements* | | | | | | | | | | |
| Process environmental load/impact assessments for (%) of new materials | **75%** | | | **100%** | | | | | | |

*The status of some of the entries for 2005 is shown as "YELLOW", because the ESH TWG felt that there was still some work to be done. However, since the status was closer to the "WHITE" than the "RED", the TWG elected not to use the "INTERIM SOLUTIONS" color code for these line items.*

*Notes for Table 104a:*

*[1] SEMI. S2-93A—Safety Guidelines for Semiconductor Manufacturing Equipment*

*[2] European CE Mark Safety Requirements*

*[3] cm$^2$ per wafer out.*

***Net feed water use—Source water consumed in support of the operation of the wafer fabrication facility, including sanitary, irrigation, and facilities infrastructure. Net feed water may be obtained from a city supply, surface or ground water body.***

*UPW use—Water used in wafer contact processes, including water recovered from any source.*

** CPIF = Chemical Properties Information Form*

## *Table 104b ESH Intrinsic Requirements—Long-term Years*

| *Year of Production* | *2014* | *2015* | *2016* | *2017* | *2018* | *2019* | *2020* | *Driver* |
|---|---|---|---|---|---|---|---|---|
| *DRAM ½ Pitch (nm) (contacted)* | *28* | *25* | *22* | *20* | *18* | *16* | *14* | |
| *MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)* | *28* | *25* | *22* | *20* | *18* | *16* | *14* | |
| *Chemicals and Materials Management Technology Requirements* | | | | | | | | |
| *CPIFs* completed for percent of new chemical candidates* | 🟨 **100%** | | | | | | | |
| Percent of chemical risk assessments (health and safety) completed | 🟥 **100%** | | | | | | | |
| *Process and Equipment Technology Requirements* | | | | | | | | |
| *Energy Consumption* | | | | | | | | |
| Total fab tools (kWh/cm$^2$) [3] | 🟥 **0.25–0.3** | | | | | | | |
| Tool energy usage per wafer pass (300 mm versus 200 mm); baseline 1999 | 🟥 **Functional Area Goals TBD** | | | | | | | |
| *Water Consumption* | | | | | | | | *Sustainable growth and cost* |
| Wet bench UPW use (liters/300 mm-wafer pass) | 🟥 **TBD** | | | | | | | |
| *Chemical Consumption and Waste Reduction* | | | | | | | | *Environmental stewardship and cost* |
| Improvement in process chemical utilization (liters [liquid] or grams [gas]/cm$^2$/mask layer) | 🟥 **3% per year** | | | | | | | |
| *Worker and Workplace Protection* | | | | | | | | |
| Conformance of new tools to latest International ESH standards and guidelines such as SEMI S2 [1] and European CE mark requirements [2] | 🟥 **100%** | | | | | | | |
| Conformance of AMHS/tool interface to latest SEMI S2 Guideline and CE mark directive. | 🟥 **100%** | | | | | | | |
| *Facilities Energy and Water Optimization Technology Requirements* | | | | | | | | |
| *Energy Consumption* | | | | | | | | |
| Total fab support systems (kWh/cm$^2$) [3] | 🟥 **0.35–0.5** | | | | | | | |
| *Water Consumption* | | | | | | | | |
| Net feed water use (liters/cm$^2$) [3] | 🟥 **3–5** | | | | | | | |
| Fab UPW use (liters/cm$^2$) [3] | 🟥 **4–6** | | | | | | | |
| *Chemical Consumption and Waste Reduction* | | | | | | | | |
| Hazardous liquid waste recycle/reuse | 🟥 **80%** | | 🟥 **90%** | | | | | |
| Solid waste recycle/reuse | 🟥 **90%** | | | | | | | |
| Reduce PFC emission | 🟨 **Maintain 10% absolute reduction from 1995 baseline** | | | | | | | |
| *Sustainability and Product Stewardship Requirements* | | | | | | | | |
| Process environmental load/impact assessments for (%) of new materials | 🟨 **100%** | | | | | | | |

*The status of some of the entries for 2005 is shown as "YELLOW", because the ESH TWG felt that there was still some work to be done. However, since the status was closer to the "WHITE" than the "RED", the TWG elected not to use the "INTERIM SOLUTIONS" color code for these line items.*

*Notes for Table 104b:*

*[1] SEMI. S2-93A—Safety Guidelines for Semiconductor Manufacturing Equipment.*

*[2] European CE Mark Safety Requirements.*

*[3] cm$^2$ per wafer out.*

** CPIF = Chemical Properties Information Form*

| | |
|---|---|
| *Manufacturable solutions exist, and are being optimized* | ⬜ |
| *Manufacturable solutions are known* | 🟨 |
| *Interim solutions are known* | ◆ |
| *Manufacturable solutions are NOT known* | 🟥 |

## *Table 105a Chemicals and Materials Management Technology Requirements—Near-term Years**

** The Environment, Safety, and Health new chemical screening tool (Chemical Restrictions Table) is linked online*

| *Year of Production* | *2005* | *2006* | *2007* | *2008* | *2009* | *2010* | *2011* | *2012* | *2013* | *Driver* |
|---|---|---|---|---|---|---|---|---|---|---|
| *DRAM ½ Pitch (nm) (contacted)* | *80* | *70* | *65* | *57* | *50* | *45* | *40* | *36* | *32* | |
| *MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)* | *90* | *78* | *68* | *59* | *52* | *45* | *40* | *36* | *32* | |
| *Interconnect* | | | | | | | | | | |
| *Low-κ materials—spin-on and CVD* | **Minimum emission/waste processes** | | | **75% raw material (chemical) utilization** | | | **90% raw material (chemicals) utilization** | | | |
| *Copper processes (ECD)* | **75% copper reclaimed/recycled** | | | **85% copper reclaimed/recycled** | | | **100% copper reclaimed/recycled** | | | |
| Advanced metallization including Cu barrier and seed (PVD and ALD) | **Minimum emission/waste processes** | | | | | **Minimum emission/waste processes** | | | | |
| Planarization (metal CMP) | **15% reduction in consumables from baseline** | | | **> 15% Reduction in consumables from baseline** | | | **5% reduction in consumables per year** | | | |
| Plasma etch processes | **Alternative etch chemistries** | | | | | **Lowest ESH impact etch chemistries** | | | | |
| CVD chamber clean (plasma) | **Low ESH impact CVD chamber clean chemistries** | | | | | **Low ESH impact CVD chamber clean chemistries** | | | | |
| *Front end Processes* | | | | | | | | | | |
| High-κ materials | **Lowest ESH impact high-κ materials** | | | **ESH benign processes** | | | | | | *Transistor performance and device development* |
| High-κ materials | **Low-hazard deposition, etch, and cleans processes** | | | **ESH benign processes** | | | | | | |
| High-κ materials | **High-κ materials without potentially toxic/ bioaccumulative metals** | | | **Lowest hazard compounds and processes** | | | | | | |
| Doping (implantation and diffusion) | **Lowest hazard dopant materials and processes** | | | | | | | | | |
| Surface preparation (stripping, cleaning, rinsing) | **ESH-friendly wafer clean and rinse processes and tools evaluated** | | | | | **ESH-friendly wafer clean and rinse processes and tools incorporated into manufacturing** | | | | |
| Novel wafer cleaning (supercritical $CO_2$, etc) | **Novel wafer cleaning technologies evaluated** | | | | | **Novel wafer cleaning technologies implemented** | | | | |
| Front-end etch | **ESH-friendly etch processes evaluated** | | | | | **ESH-friendly etch processes implemented** | | | | |
| *Lithography* | | | | | | | | | | |
| *New Equipment* | | | | | | | | | | |
| Optical | **Charac-tization of ESH impacts** | **Minimal ESH impact from radiation, ergonomics, chemical consumption, and disposal** | | | | **Minimal ESH impact for ionizing radiation, ergonomics, chemical consumption, and disposal** | | | | *Next generation lithography* |
| 193 nm immersion lithography | **Low ESH impact resists** | | | **Low ESH impact immersion fluid additives, fluids and resists** | | | | | | |
| EUV | **Characterization of ESH impacts** | | | **Minimal ESH impact from ionizing radiation, ergonomics, energy consumption and source gas** | | | | | | |
| PFOS/PFAS** | **Non-critical uses eliminated** | | **Non-PFOS/PFAS alternatives researched** | | | | | | **Non-PFAS materials developed for critical uses in photo-lithography** | |
| Mask cleaning | **Cost-effective, ESH friendly technology (e.g., supercritical $CO_2$)** | | | | | | | | | |

*The status of some of the entries for 2005 is shown as "YELLOW", because the ESH TWG felt that there was still some work to be done. However, since the status was closer to the "WHITE" than the "RED", the TWG elected not to use the "INTERIM SOLUTIONS" color code for these line items.*

| | |
|---|---|
| *Manufacturable solutions exist, and are being optimized* | ⬜ |
| *Manufacturable solutions are known* | 🟨 |
| *Interim solutions are known* | ◆ |
| *Manufacturable solutions are NOT known* | 🟥 |

*Notes for Table 105a:*

** Everything that is not identified as a critical use.*

*** Critical uses of PFOS includes use in a photo-microlithography process to produce semiconductors or similar components of electronic or other miniaturized devices as a:*

- *Component of a photoresist (including PAGs and surfactants)*
- *Component of an anti-reflective coating*

## *Table 105b Chemicals and Materials Management Technology Requirements—Long-term Years**

** The Environment, Safety, and Health new chemical screening tool (Chemical Restrictions Table) is linked online*

| *Year of Production* | *2014* | *2015* | *2016* | *2017* | *2018* | *2019* | *2020* | *Driver* |
|---|---|---|---|---|---|---|---|---|
| *DRAM ½ Pitch (nm) (contacted)* | *28* | *25* | *22* | *20* | *18* | *16* | *14* | |
| *MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)* | *28* | *25* | *22* | *20* | *18* | *16* | *14* | |
| *Interconnect* | | | | | | | | |
| *Low-κ materials—spin-on and CVD* | **90% raw material (chemicals) utilization** | | | | | | | |
| *Copper processes (ECD)* | **100% copper reclaimed/recycled** | | | | | | | |
| Advanced metallization including Cu barrier and seed (PVD and ALD) | **Minimum emission/waste processes** | | | | | | | |
| Planarization (metal CMP) | **5% reduction in consumables per year** | | | | | | | |
| Plasma etch processes | **Lowest ESH impact etch chemistries** | | | | | | | |
| CVD chamber clean (plasma) | **Low ESH impact CVD chamber clean chemistries** | | | | | | | |
| *Front end Processes* | | | | | | | | *Reduced feature size* |
| High-κ materials | **Lowest ESH impact metal compounds and processes** | | | | | | | *Transistor performance and device development* |
| High-κ materials | **ESH benign processes** | | | | | | | |
| High-κ materials | **Lowest hazard compounds and processes** | | | | | | | |
| Doping (implantation and diffusion) | **Lowest hazard dopant materials and processes** | | | | | | | |
| Surface preparation (stripping, cleaning, rinsing) | **ESH-friendly wafer clean and rinse processes and tools incorporated into manufacturing** | | | | | | | |
| Novel wafer cleaning (supercritical $CO_2$, etc) | **Novel wafer cleaning technologies implemented** | | | | | | | |
| Front-end etch | **ESH-friendly etch processes implemented** | | | | | | | |
| *Lithography* | | | | | | | | |
| *New Equipment* | | | | | | | | |
| Optical | **Minimal ESH impact for ionizing radiation, ergonomics, chemical consumption, and disposal** | | | | | | | *Next generation lithography* |
| 193 nm immersion lithography | | | | | | | | |
| EUV | **Energy-efficient EUV lithography and/or other low ESH impact innovative patterning technology** | | | | | | | |
| PFOS/PFAS** | **Non-PFAS materials developed for critical uses in photolithography** | | | | | | | |
| Mask cleaning | | | | | | | | |

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** The Environment, Safety, and Health new chemical screening tool (Chemical Restrictions Table) is linked online*

*Manufacturable solutions exist, and are being optimized* ⬜
*Manufacturable solutions are known* 🟨
*Interim solutions are known* ◆
*Manufacturable solutions are NOT known* 🟥

*Notes for Table 3b:*
*** Critical uses of PFOS includes use in a photo-microlithography process to produce semiconductors or similar components of electronic or other miniaturized devices as a:*
- *Component of a photoresist (including PAGs and surfactants)*
- *Component of an anti-reflective coating*

*Table 106a Resource Conservation Technology Requirements—Near-term Years*

| *Year of Production* | *2005* | *2006* | *2007* | *2008* | *2009* | *2010* | *2011* | *2012* | *2013* | *Driver* |
|---|---|---|---|---|---|---|---|---|---|---|
| *DRAM ½ Pitch (nm) (contacted)* | *80* | *70* | *65* | *57* | *50* | *45* | *40* | *36* | *32* | |
| *MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)* | *90* | *78* | *68* | *59* | *52* | *45* | *40* | *36* | *32* | |
| *Interconnect* | | | | | | | | | | *Increasing number of interlayers* |
| Copper processes (ECD) | **Copper processes optimized to minimize waste to water and land** | | | | | | | | | |
| Planarization | **Water recycle/reclaim** | | | | | | | | | |
| Plasma processing | **Reduced tool idle energy use** | | | | | | | | | |
| *Front End Processes* | | | | | | | | | | |
| High-κ | **Energy-efficient deposition processes** | | | | | **Energy efficient deposition processes** | | | | |
| Implantation | **Energy use and heat removal optimized** | | | | | **Minimum implanting energy for future technologies** | | | | |
| Surface preparation | **Energy efficient clean processes (reduced exhaust flow rates)** | | | | | **Energy efficient clean processes (optimized exhaust flow rates)** | | | | |
| | **Novel wafer cleans based on surface/interface science** | | | | | **Wafer cleans with more dilute chemistries and lower water consumption** | | | | |
| Front end etch | **Reduced tool idle energy** | | | | | | | | | |
| Starting materials | **Quantified energy/water reduction from SOI-based process flows** | | | | | | | | | |
| *Lithography* | | | | | | | | | | *Reduced feature size* |
| Equipment resource consumption: optical, e-beam, and EUV | **Optimized energy consumption, equipment related chemicals/ gases/materials, and water consumption** | | | | | | | | | |
| *Assembly and Packaging* | | | | | | | | | | |
| Eliminate waste from molding process | **Zero waste (after recycling) from molding technologies** | | | | | **Zero waste (after recycling) from molding technologies** | | | | |
| Reduce water use | **0.8X (X = 1999 baseline)** | | | | | **0.5X (X = 1999 baseline)** | | | | |
| Reduce chemical use and consumption | **0.8X (X = 1999 baseline)** | | | | | **0.5X (X = 1999 baseline)** | | | | |

*The status of some of the entries for 2005 is shown as "YELLOW", because the ESH TWG felt that there was still some work to be done. However, since the status was closer to the "WHITE" than the "RED", the TWG elected not to use the "INTERIM SOLUTIONS" color code for these line items.*

| | |
|---|---|
| *Manufacturable solutions exist, and are being optimized* | ☐ |
| *Manufacturable solutions are known* | 🟨 |
| *Interim solutions are known* | ◆ 🟨 |
| *Manufacturable solutions are NOT known* | 🟥 |

## *Table 106b Resource Conservation Technology Requirements—Long-term Years*

| *Year of Production* | *2014* | *2015* | *2016* | *2017* | *2018* | *2019* | *2020* | *Driver* |
|---|---|---|---|---|---|---|---|---|
| *DRAM ½ Pitch (nm) (contacted)* | *28* | *25* | *22* | *20* | *18* | *16* | *14* | |
| *MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)* | *28* | *25* | *22* | *20* | *18* | *16* | *14* | |
| ***Interconnect*** | | | | | | | | *Increasing number of interlayers* |
| Copper processes (ECD) | **Copper processes optimized to minimize waste to water and land** | | | | | | | |
| Planarization | **Water recycle/reclaim** | | | | | | | |
| Plasma processing | **Reduced tool idle energy use** | | | | | | | |
| *Front End Processes* | | | | | | | | |
| High-κ | **Energy efficient deposition processes** | | | | | | | |
| Implantation | **Minimum implanting energy for future technologies** | | | | | | | |
| Surface preparation | **Energy efficient clean processes (optimized exhaust flow rates)** | | | | | | | |
| | **Wafer cleans with more dilute chemistries and lower water consumption** | | | | | | | |
| Front End etch | **Reduced tool idle energy** | | | | | | | |
| Starting materials | **Quantified energy/water reduction from SOI-based process flows** | | | | | | | |
| *Lithography* | | | | | | | | *Reduced feature size* |
| Equipment resource consumption: optical, e-beam, and EUV | **Optimized energy consumption, equipment related chemicals/ gases/materials, and water consumption** | | | | | | | |
| *Assembly and Packaging* | | | | | | | | |
| Eliminate waste from molding process | **Zero waste (after recycling) from molding technologies** | | | | | | | |
| Reduce water use | **0.5X (X = 1999 baseline)** | | | | | | | |
| Reduce chemical use and consumption | **0.5X (X = 1999 baseline)** | | | | | | | |

*The status of some of the entries for 2005 is shown as "YELLOW", because the ESH TWG felt that there was still some work to be done. However, since the status was closer to the "WHITE" than the "RED", the TWG elected not to use the "INTERIM SOLUTIONS" color code for these line items.*

***Definitions:***
***Net feed water use—Source water consumed in support of the operation of the wafer fabrication facility, including sanitary, irrigation, and facilities infrastructure. Net feed water may be obtained from a city supply, surface or ground water body.***

| | |
|---|---|
| *Manufacturable solutions exist, and are being optimized* | ⬜ |
| *Manufacturable solutions are known* | 🟨 |
| *Interim solutions are known* | ◆ |
| *Manufacturable solutions are NOT known* | 🟥 |

*Table 107a Sustainability and Product Stewardship Technology Requirements—Near-term Years*

| *Year of Production* | *2005* | *2006* | *2007* | *2008* | *2009* | *2010* | *2011* | *2012* | *2013* |
|---|---|---|---|---|---|---|---|---|---|
| *DRAM ½ Pitch (nm) (contacted)* | *80* | *70* | *65* | *57* | *50* | *45* | *40* | *36* | *32* |
| *MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)* | *90* | *78* | *68* | *59* | *52* | *45* | *40* | *36* | *32* |
| *Factory Integration* | | | | | | | | | |
| Improved integration of ESH into factory and equipment design | **Incorporate ESH design guidelines, methodology, and criteria into tool and factory design** | | | | | | | | |

*Table 107b Sustainability and Product Stewardship Technology Requirements—Long-term Years*

| *Year of Production* | *2014* | *2015* | *2016* | *2017* | *2018* | *2019* | *2020* |
|---|---|---|---|---|---|---|---|
| *DRAM ½ Pitch (nm) (contacted)* | *28* | *25* | *22* | *20* | *18* | *16* | *14* |
| *MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)* | *28* | *25* | *22* | *20* | *18* | *16* | *14* |
| *Factory Integration* | | | | | | | |
| Improved integration of ESH into factory and equipment design | **Incorporate ESH design guidelines, methodology, and criteria into tool and factory design** | | | | | | |

*The status of some of the entries for 2005 is shown as "YELLOW", because the ESH TWG felt that there was still some work to be done. However, since the status was closer to the "WHITE" than the "RED", the TWG elected not to use the "INTERIM SOLUTIONS" color code for these line items.*

| | |
|---|---|
| *Manufacturable solutions exist, and are being optimized* | ⬜ |
| *Manufacturable solutions are known* | 🟨 |
| *Interim solutions are known* | ◆ |
| *Manufacturable solutions are NOT known* | 🟥 |

## ESH INTRINSIC REQUIREMENTS

ESH requirements were established based on mapping of the technical thrust needs against the ESH Difficult Challenges. The specific technical thrust influences are discussed below.

### INTERCONNECT

The interconnect area poses several unique environment, safety, and health (ESH) challenges. Because of the new processes being developed to meet the performance requirements of the advanced technology generations, the industry is evaluating many, new materials in the area of advanced metallization, low κ, chemical mechanical planarization, wafer cleaning, and copper/ porous low-κ integration. The ESH impacts of these new materials, processes, and subsequent reaction by-products must be determined as early as possible, ideally in the university and early supplier research stages, to ensure that the ESH information is available to the users. This determination will allow selection of optimal process materials based on both function and lowest ESH impact with respect to reaction product emissions, health and safety properties, materials compatibility with both equipment and other chemical components, flammability, and reactivity. This approach will minimize undesirable business impacts after processes are developed and used in large-scale production.

The technology requirements for Chemicals, and Materials Management (Table 105) include the development of the lowest impact materials and processes for all aspects of interconnect. This includes solvents and polymers for spin-on processes, CVD/ALD precursors, low-κ pore sealers, copper interconnect barrier and seed materials, CMP slurry chemistries, CMP pads, post-CMP brushes, and etch chemistries. It also calls for reduced chemical requirements and reduced waste in these areas, which may be achieved by increasing chemical utilization efficiency in CVD/ALD processes, extending bath life or recycling in copper plating, and decreasing CMP slurry requirements by more efficient utilization in the process or some form of recycling of the slurry. The use of supercritical fluids such as supercritical carbon dioxide for removing etch residues from low-κ materials, if it becomes a mainstream technology, will significantly reduce chemical and water waste. Since there are currently no suitable cleaning methods for low-κ dielectrics, supercritical fluid processes may become an enabling technology for via veil and post-etch low-κ cleans. This is a good example of how a more environmentally benign process can also have significant process advantages.

Global warming resulting from the emission of greenhouse gases has been identified as one of the possible causes of climate change. Perfluorocompounds (PFCs), a family of high global warming potential chemicals, are used almost exclusively in interconnect in dry etch and chamber cleaning applications. The semiconductor industry near-term goal is to achieve a 10% absolute reduction of PFC emissions from the 1995 baseline by 2010. To achieve this aggressive goal and to ensure that these chemicals remain available for industry use, the industry must strive to reduce emissions of PFCs compounds via process optimization, alternative chemistries, recycle, and/or abatement. The development of new materials results in the implementation of new etch chemistries; the lowest ESH impact etch processes should be developed that do not emit high global warming potential by-products. This concept also applies to CVD chamber cleaning.

The increasing use of CMP will result in interconnect becoming a major user by volume of both chemicals and water. Therefore, efforts must be made to develop the lowest ESH impact CMP and post-CMP clean chemistries while reducing overall water consumption. Rinse water minimization in copper electroplating and post-CMP cleaning is necessary. Water recycle and reclaim for CMP and post-CMP cleans is a potential solution for water use reduction.

With increased focus on energy conservation, the power requirements of plasma processing and CMP tools and related infrastructure must be minimized. RF generators are energy-intensive. Plasma processes are neither energy-efficient nor efficient in the way they utilize the input chemistries (often only 10–70% dissociation). Future generation tools will require R&D in low-energy consuming plasma systems. Etchers and CVD tools use point-of-use (POU) chillers and heat exchangers to maintain wafer and chamber temperatures in a vacuum. More efficient heating and cooling control systems could help decrease energy use. Greater use of cooling water for heat removal from tools versus heat dissipation to the clean room results in fab energy savings.

## FRONT END PROCESSING

Key ESH concerns for Front End Processes center on the new materials for gate dielectrics and electrodes; natural resources use (especially water); management of potential physical and chemical hazards to ensure worker protection; and optimization of processes to reduce chemical use and the generation of wastes that require abatement. New materials for 100 nm technologies and beyond (and corresponding precursors, clean techniques and etch gases) will require thorough ESH review.

The global ESH challenges affect all areas of Front End Processes. The primary chemical management strategy should be to optimize processes to maximize chemical and tool utilization while minimizing waste generation, especially hazardous materials. On-demand, *in situ* chemical generation can contribute to improved efficiency. Energy needs (tool and facility systems) must be evaluated for new technologies. Worker protection measures should address potential physical hazards (such as thermal, non-ionizing radiation, laser, and robotics hazards) as well as chemical hazards, especially during equipment maintenance. Factory planning and layout should include ergonomic design criteria for wafer handling, especially for 300 and 450 mm wafers. ESH cost-of-ownership (CoO) and risk assessment tools should be utilized to evaluate process improvements and identify potential risks of new materials.

In addition, key ESH issues apply to specific areas of Front End Processes:

*Surface preparation*—ESH concerns for surface preparation focus on new clean techniques, chemical use efficiency, and consumption of water and energy. Surface preparation methods will undergo fundamental changes to accommodate new materials after the 2005 timeframe for expected adoption of new gate dielectrics and electrodes. There is a need for improved understanding of surface and interface science with the potential for significant reductions in chemical or water use.

Chemical use optimization should be applied to conventional and alternative cleaning processes. Several alternative clean processes have potential for significant chemical use reduction (supercritical fluids, dilute chemistries, sonic solvent cleans, simplified process flows, DI/ozone cleans). Fluid flow optimization and sensor-based process control should be evaluated. The potential, increased use of anhydrous gases (HF/HCl and alternatives) should be reviewed through process hazards analysis.

Sustainable, optimized water use strategies such as more efficient UPW production, reduced water consumption, and efficient rinsing are being developed. However, the impact of alternative cleaning methods (such as cryogenic wafer and parts cleaning, and hot-UPW wafer cleaning) or UPW production methods (such as continuous electrolytic ion-exchange) on energy consumption needs to be considered. Alternative solvent-based cleans need development. Development of reliable, on-line, quick-response sensors to speciate low-level organics is needed to mitigate the process risk of UPW recycling. The optimization of test wafer usage can reduce chemical, water, and energy consumption. Wet-tool designs should continue to incorporate enclosed processes, ergonomic and robotics safety principles.

*Starting materials*—Current materials are primarily Czochralski (CZ) polished silicon wafers with an epitaxial (Epi) silicon layer. Silicon-on-insulator (SOI) materials may offer ESH advantages of fewer process steps, resulting in less chemicals and less energy usage. Larger wafers (300–450 mm) will require more chemicals, energy, and water per wafer, although industry initiatives have been advanced to hold usage the same.

*Thermal/thin films*—The evaluation of alternative higher-κ materials must include thorough assessment of potential process hazards associated with both the materials and associated deposition processes. Alternative silicides (such as Co, Ni, others) present potential hazards requiring mitigation through engineering controls and appropriate personal protective equipment. Chemical use efficiency can be optimized through improved delivery systems and tool designs (such as small batch furnaces, single-wafer tools). Energy use, for diffusion and implant tools and associated facility systems (exhaust) should be evaluated and optimized.

A wide variety of organic ligands (potentially including halogens) are proposed as high-κ precursors. The resulting metallorganic compounds may pose potential toxicity or flammability hazards. Anneals are probably necessary, utilizing $N_2$, $FNO_2$, $O_2$, $NH_3$, $H_2/N_2$ (forming gas).

Various metals and sources (gas phase, solution, and solid) are being considered for gate electrodes. Gate metals will range from doped-polysilicon to metals (Ta, Ti, Nb, Al, Mo, Zr, V, Co W, Ru, Rh, Ni, Re, Ir, Pt) and various silicides and nitrides. Most CVD precursors will be organometallics, but they may be dissolved in a matrix solution with stabilizers, and carrier liquid that will be injected as a liquid.

*Doping*—The potential physical and chemical hazards of alternative technologies (a variety of new techniques are being considered) need to be evaluated and mitigated. Process hazards analysis tools will assist in managing hydrides ($SiH_4$, $B_2H_6$, $PH_3$, $SbH_3$, $AsH_3$, possibly others), metal alkyls and laser sources. Sub-atmospheric delivery sytems should be developed for a wider variety of dopant materials.

*Front-end plasma etch*—Continued use of PFCs will necessitate near-term process optimization/increased gas utilization (conversion efficiency within the process). Over the longer term, alternative chemistries for PFCs that do not emit PFCs as by-products need to be developed. Changes in gate dielectric materials will drive corollary changes in etch chemistries, necessitating review of potential ESH impacts. High-κ materials will require an anisotropic selective etch over doped Si. The chemistry for these etches have not been determined but will most likely include Cl-based chemistries.

## LITHOGRAPHY

From the perspective of ESH, lithography is represented by three subject areas. These are 1) photolithography and mask manufacturing chemicals (photoresists, ARCs, adhesion promoters, edge bead removers, thinners, developers, rinses, and strippers), 2) processing equipment (spin coaters, vapor-phase deposition systems, and silylation ovens) and 3) exposure equipment (EUV, E-beam, X-ray, and ion beam). In particular, the ESH impact of the new process chemicals, compliance with environmental regulations, equipment safety, and worker protection must be considered before changes are made.

*Photolithography and mask manufacture chemicals*—The first critical need in this category is the need for information related to properties and availability of new chemicals used in photolithography and mask manufacture. Among the information required are chemical toxicity, health risk assessment data, status under TSCA, ability to monitor potential exposures, process emissions (HAPs and VOCs) from the spin-on and bake process as well as the subsequent etch and strip processes.. Another critical need is the identification of alternatives to the traces of PFOS contained in developers, surfactants, anti-reflective coatings (ARCs), photoacid generators (PAGs) and resists. Also the development of immersion technology must be closely monitored for any potential ESH impacts.

Immersion lithography will initially use water as the working fluid in a once-through mode, which will result in additional water waste. Second generation systems may use non-aqueous fluids and, therefore, require ESH assessments as well as means for efficient fluid reuse and/or disposal.

Potential solutions for these critical needs include preparation of a list of acceptable lithography chemicals based on evaluation of TSCA conformance, development of analytical protocols that enable monitoring of new chemicals, robust chemical selection criteria, risk assessment, and the use of pollution prevention principles. Additional potential solutions include alternative materials and chemistries, life cycle analysis of new materials and chemistries, use of additive technologies, and use of benign materials.

*Processing equipment*—Critical needs for processing equipment include understanding potential exposure to toxic materials, emission of HAPs and VOCs, hazardous waste disposal, cost of ownership, and energy consumption. Additional needs are ergonomic design of equipment, controlling emissions from PFC usage, and plasma byproducts.

Lastly, there is a need to minimize waste, for example, waste resulting from spin-on processes and assorted “wet” processes.

Among the potential solutions are effective point-of-use abatement, optimization of tool exhaust, use of pollution prevention and DFESH principles, and supplier use of S2 and S8 standards[1]. Further potential solutions include deployment of zero impact processes, elimination of the need for materials with significant global warming potentials, and utilization of DFESH tools in design of new tools.

*Exposure equipment*—Critical needs with respect to new exposure equipment include understanding of toxicity of any new chemicals, HAPs and VOC emissions, potential exposure to radiation and/or hazardous energies, total energy usage and cost-of-ownership. Potential solutions include performing risk assessments, analysis of cost-of-ownership and establishing radiation protection programs, if necessary.

## *FACTORY INTEGRATION*

Responsible safety, health, and environmental performance for the semiconductor industry begins with factory pre-design (training and planning), design and construction. Standardization of safety and environmental systems, apparatus, procedures, and methodologies, when applicable, will prove to be an efficient and cost effective approach. Sharing of these practices can reduce start-up schedules and will result in greater cooperation by equipment suppliers for interfacing their products into factories. Factory design, manufacturing equipment, the interface between these elements and their interaction with the people who work in this environment strongly influence ESH performance for the industry.

Early comprehension of safe and environmentally responsible design coupled with an understanding of code and regulatory requirements is essential for designers to develop factories that meet ESH expectations, reduce start-up schedules, and avoid costly retrofits and changes.

Accepted protocol and order of selection for risk management are hazard elimination, design controls (isolation or engineering design), administrative controls (procedural), and personal protective equipment.

One opportunity for greater standardization exists with manufacturing and assembly/test equipment. Standardization in ESH aspects of equipment design, design verification, ESH qualification, and signoff will greatly improve ESH performance, start-up efficiency, and cost. Additionally, standardization of ESH practices in equipment maintenance, modification, migration, decommissioning, and final disposition will also reap substantial performance improvements in ESH and cost over the life of equipment and factories.

Standardization of building safety systems and interface to tools will improve safety and also increase efficiency of installations and reduce start-up times. This standardization would include but is not limited to fire detection and suppression systems and their monitoring interface, gas detection systems, electrical and chemical isolation devices, emergency shut-off systems, and safety related alarms. These include building systems as well as those that are integral to manufacturing and assembly/test equipment.

Additionally, the careful selection of process and maintenance chemicals addressed in other sections of this roadmap should be complemented by designs that serve to isolate personnel from equipment and product during operation and maintenance of equipment and systems.

The safety issues associated with factory processing support systems must also be aggressively improved in future factories. As more is known about potential impacts of the work environment on the health and safety of workers, protection improvements must be incorporated into factory systems. Improved risk assessment methodologies and their consistent utilization during the design phase will enhance this effort.

A thorough understanding of the potential safety risks associated with automated equipment will drive development of standards that assure safe working conditions for both people and product. These standards and guidelines must be integrated into the automated systems, the tools with which they interface, and the interface between them.

The industry faces increasing permit, code, and emissions limitations. Planning for future factories and modifications to existing factories should involve cooperative efforts with code entities and government bodies to ensure that advancements in technology of tools and factories are comprehended and utilized in new regulations and amendments. These actions must be driven on a global level. The semiconductor industry should move to establish basic ESH specifications that apply to all equipment and factory practices that are recognized around the world.

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[1] *SEMI. S2-93A—Safety Guidelines for Semiconductor Manufacturing Equipment.*
*SEMI S8—Safety Guidelines for Ergonomics/Human Factors Engineering of Semiconductor Equipment.*

Factory design defines the systems that deliver process materials to tools, manage by-products, and control work place environments. Future factory design must balance resource conservation, reduction, and management. These conservation and reduction programs are driven by increasing competition for limited water and energy resources, pollution concerns, and industry consumption of these limited resources.

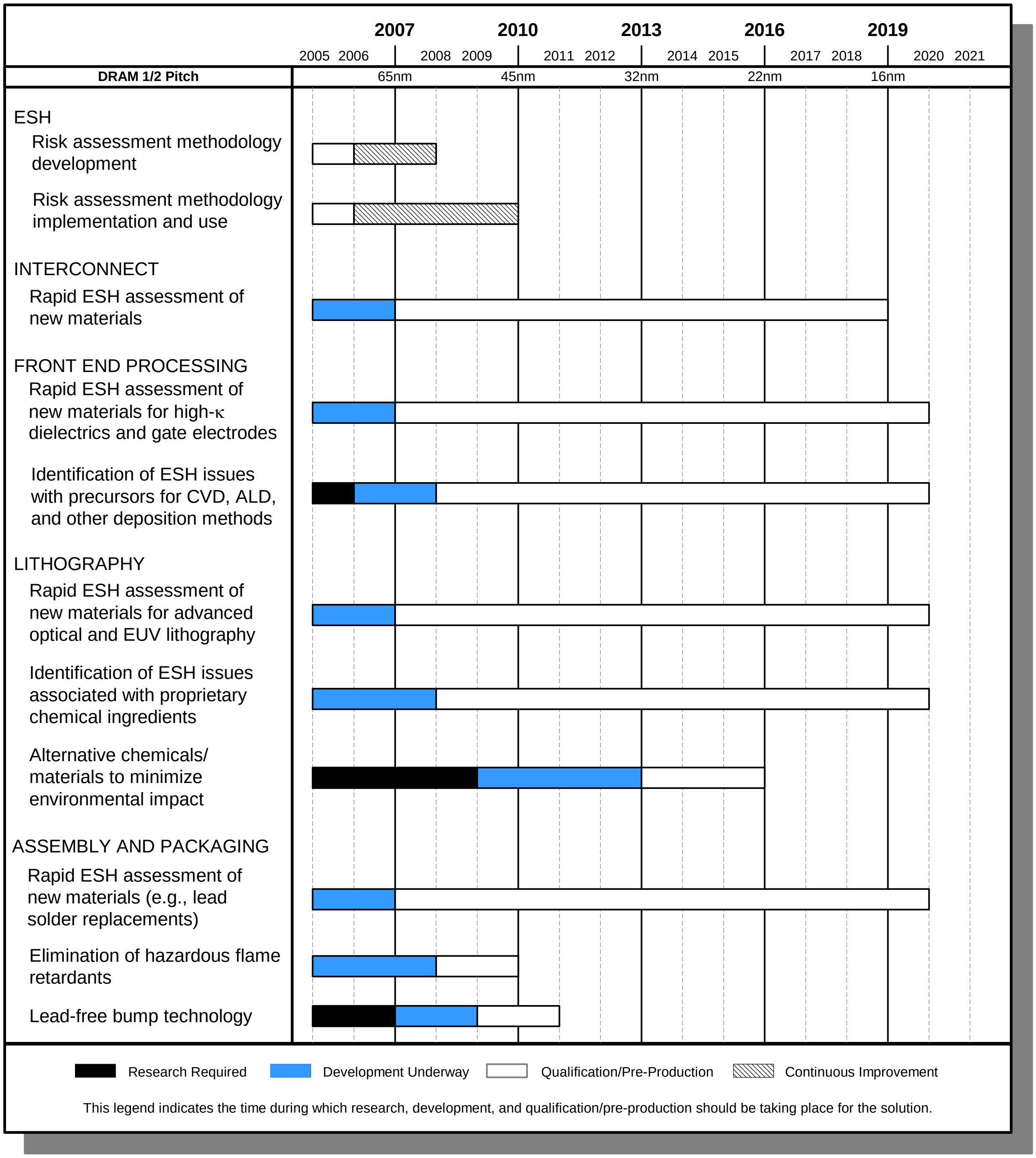
ESH standardization and design improvements for factories and equipment can be greatly enhanced through training programs established for and by the industry. Technology now allows for computer based training (CBT) programs to be developed to address all of the design and procedural challenges noted in this section.

While much of the responsibility for reduction in use of limited resources and waste minimization rests with the tool suppliers and process technologists, application of advanced resource management programs to factory systems will have a significant impact. The goal of these future programs is to build factories that minimize resource consumption and maximize reuse, recycle, or reclaim of by-products to produce near-zero discharge factories. Key factory-related ESH programs require water reuse in process and non-process applications, energy efficient facilities equipment, improved facilities system design, and new facilities operating strategies.

### *ASSEMBLY AND PACKAGING*

The drive towards flip-chip and chip-scale packaging will change the ESH needs for assembly and packaging eventually completely, as these technologies eliminate the application of leadframes, conventional molding, and substrates. However, the use of environmentally hazardous materials, such as lead, chromium, beryllium, antimony, and brominated flame retardants is under increasing international regulatory pressure. Restrictions on the use of these materials in the European market are expected soon. For example, the ban on the use of lead goes into effect on July 1, 2006. Lead (Pb) has special significance since alternative soldering processes will cause numerous problems in the electronics industry, where the current process is widely used and integrated in equipment assembly lines. Alternatives may cause a technology problem, as the soldering temperature has to be increased, leading to reduction of chip lifetime and quality. For power devices, an additional complication is the use of a lead-containing alloy to attach the chip to the leadframe.

The reduction of energy consumption is important from a global warming as well as resource conservation point of view. The needs for assembly and packaging are not tied to the generations of the wafer production, but to the requirements and technologies of our customers. However, to maintain the roadmap format, the same tables have been used.



This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

*Figure 98 Potential Solutions for ESH: Chemicals and Materials Management*

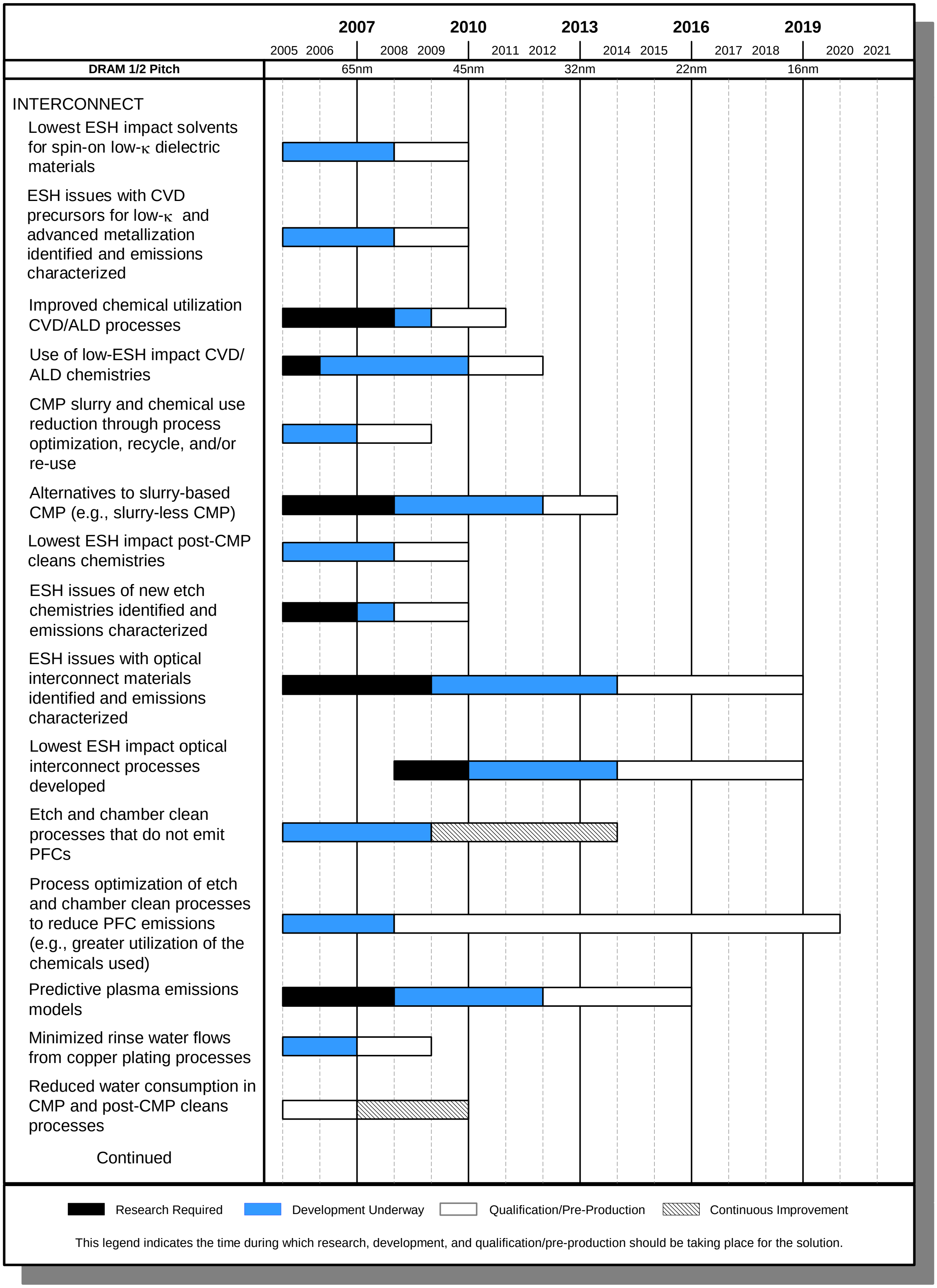


*Figure 99 Potential Solutions for ESH: Process and Equipment Management*

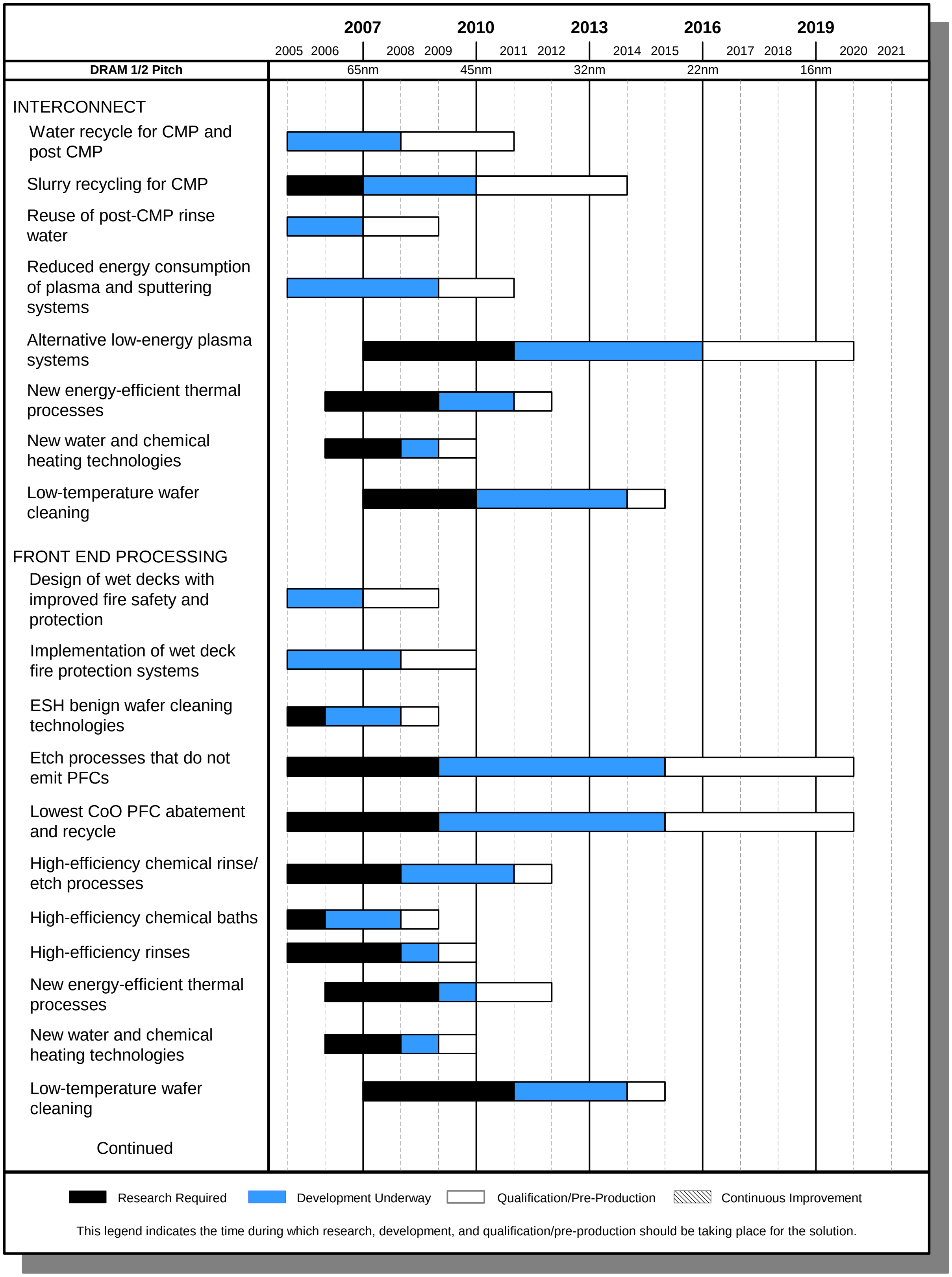
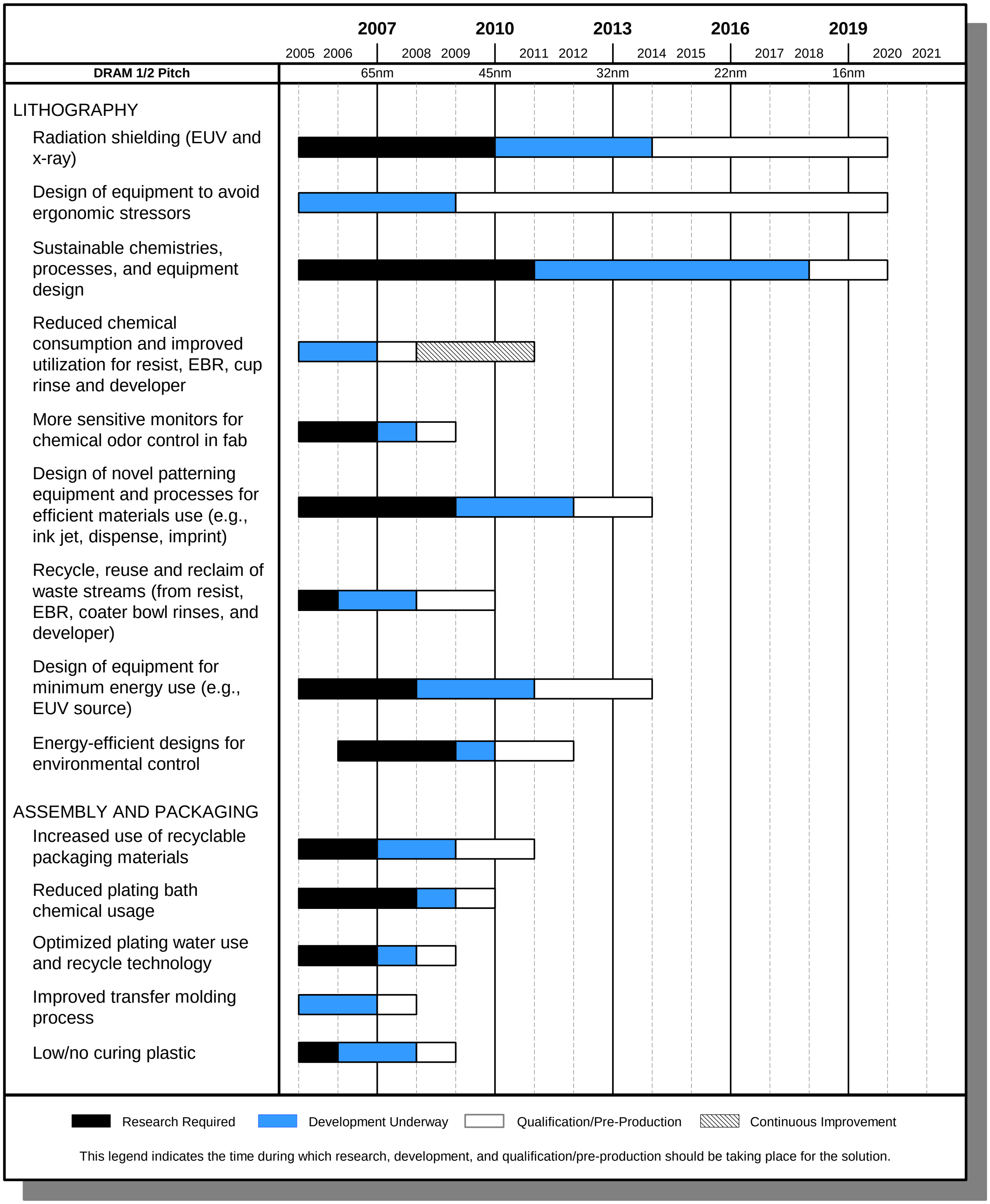


*Figure 99 Potential Solutions for ESH: Process and Equipment Management (continued)*



This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

*Figure 99 Potential Solutions for ESH: Process and Equipment Management (continued)*

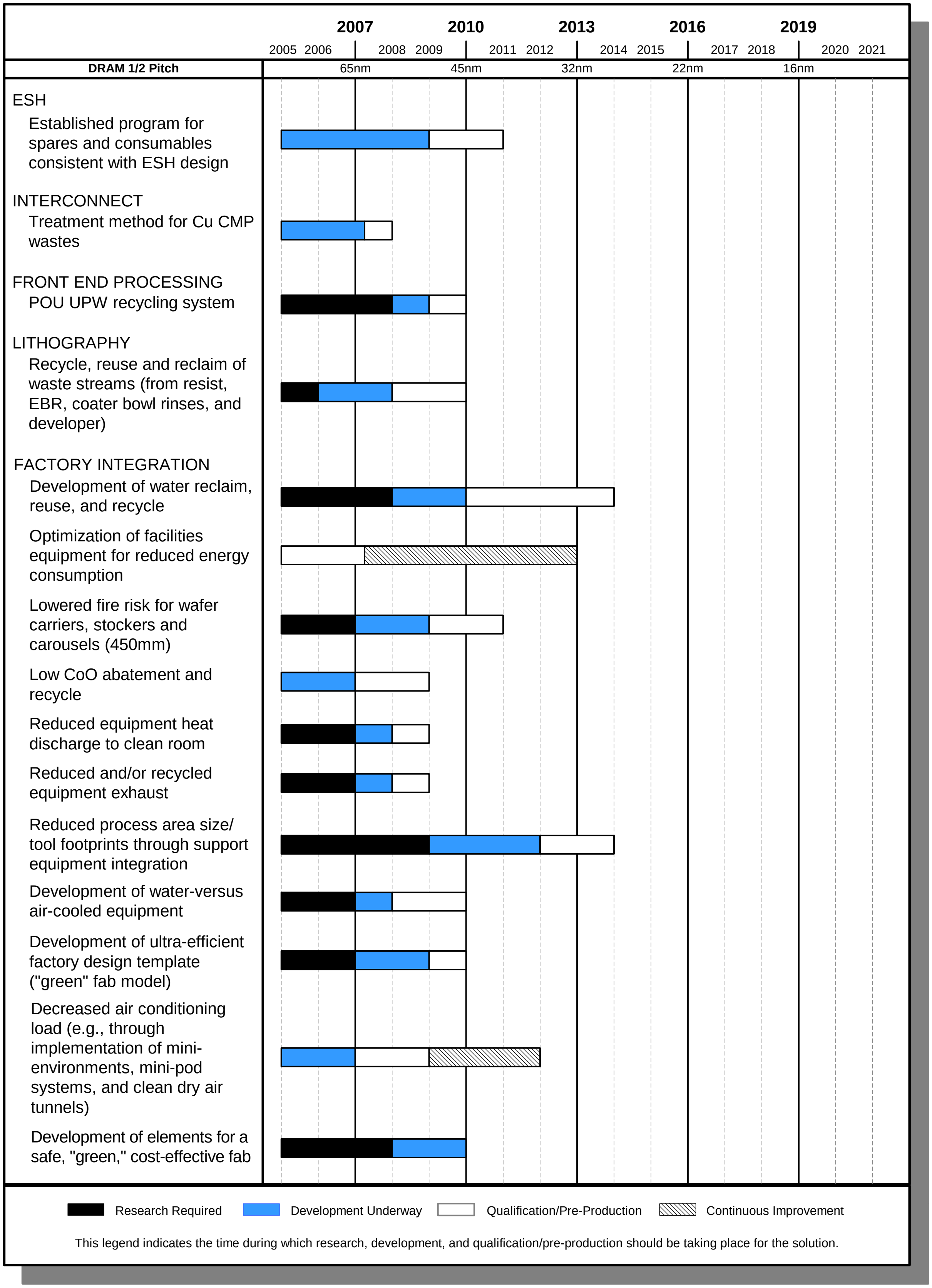


*Figure 100 Potential Solutions for ESH: Facilities Energy and Water Optimization*