INTERNATIONAL
TECHNOLOGY ROADMAP
FOR
SEMICONDUCTORS

2007 EDITION

ENVIRONMENT, SAFETY, AND HEALTH

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SCOPE

INTRODUCTION

The semiconductor industry views responsible action 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. The four basic ESH strategies embodied in the roadmap are to:

1. Understand (characterize) processes and materials during the development phase
2. Use materials that are less hazardous or whose byproducts are less hazardous
3. Design products and systems (equipment and facilities) that consume less raw material and resources
4. Make the factory safe for employees

This approach is based on the belief that good business stewardship includes an active awareness and commitment to responsible ESH practices. Addressing these areas aggressively has resulted in the industry being an ESH as well as a technology leader.

EXPECTATIONS

For both engineers and research scientists, this roadmap identifies ESH R&D challenges that arise as new wafer processing and assembly technologies are designed and created. ESH technology requirements are listed in Tables ESH1–6. Potential technology and management solutions to meet these challenges are proposed in Figures ESH1–3.

Integrating ESH 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 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. The integration of global ESH initiatives has made the ESH objectives of this roadmap truly international.

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 for nanomaterial assessment methodologies. Secondly, they are the one place where anticipated regulatory and legislative limitations can be incorporated into future technology planning. Thirdly, they form 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.

The ESH Difficult Challenges are encompassed in the following high level categories: Chemicals and Materials Management; Process and Equipment Management; Facilities Technology Requirements; and Sustainability and Product Stewardship. These categories are used to organize the technology thrust requirements.

Chemicals and Materials Management focuses on chemical and materials selection and provides guidance to academic and industry researchers and process and equipment designers on identifying and addressing the environment, safety, and health characteristics of potential new process chemicals and materials. This approach is essential to the selection of preferred chemicals and materials to minimize ESH impact. Determining the physical/chemical, environmental, and toxicological properties of chemicals and materials as well as any reaction by-products is essential to protecting human health and the environment as well as minimizing business impacts after processes are developed and introduced into high volume manufacturing. *Refer to the chemical screening tool(Chemical Restrictions Table) online.*

Process and Equipment Management focuses on tool and process design and emphasizes the need for developing processes and equipment that meet technology demands while reducing impact on human health, safety, and the environment. Equipment design must minimize the potential for chemical exposures, the need for personal protective equipment (PPE), and ergonomic issues. Another important goal is resource conservation (water, energy, and chemicals) through process optimization and implementation of cost-effective use reduction solutions. Replacing hazardous chemicals with more benign materials, managing process emissions and by-products, and reducing consumables are also important considerations in the design and operation of tools. Design for ease of maintenance and equipment end-of-life is an additional challenge.

Facilities Technology Requirements focuses on fab support systems and stresses the need for environmentally friendly design and operation of factories and support systems. Resource conservation (water, energy, and chemicals) through more efficient cleanroom design, air management, heat removal, and demand-based generation of utilities is required. Another consideration is designing factories for end-of-life re-use, especially as factory sizes and building costs increase.

Sustainability and Product Stewardship are becoming important business considerations. To address these challenges in a cost-effective and timely way, sustainability metrics are required. In addition, Design for Environment, Safety, and Health (DFESH) must become an integral part of the facility, equipment, and product design as well as management's decision-making. Environmentally friendly end-of-life disposal and/or reclaim of facilities, manufacturing equipment, and industry products are globally in demand.

Table ESH1a ESH Difficult Challenges—Near-term

Difficult Challenges ≥ 22 nm	*Summary of Issues*
Chemicals and materials management	*Chemical Assessment*
	Evaluation and refinement of quality, rapid assessment methodologies to ensure that new materials such as nanomaterials can be utilized in manufacturing, while protecting human health, safety, and the environment without delaying process implementation Regional differences in regulations for chemicals; given regional movement for R&D, pre-manufacturing, and full commercialization Trend towards lowering exposure limits and more monitoring
	Chemical Data Availability
	Inability to forecast/anticipate future restrictions or bans on materials, especially nanomaterials 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
	Chemical Exposure Management
	Lack of information on how the chemicals and materials are used and what process by-products are formed Method to obtain information on how the chemicals and materials are used and what process by-products are formed
Process and equipment management	*Process Chemical Optimization*
	Need to develop equipment and 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
	Environment Management
	Capability for component isolation in waste streams Need to understand ESH characteristics of process emissions and by-products to identify the appropriate mitigation Need to develop effective management systems to address issues related to hazardous and non-hazardous residues from the manufacturing processes
	Global Warming Emissions Reduction
	Need to reduce emissions from processes using high GWP chemicals
	Water and Energy Conservation
	Need for innovative energy- and water-efficient processes and equipment
	Consumables Optimization
	Need for more efficient utilization of chemicals and materials, and increased reuse and recycling
	Byproducts Management
	Development of improved metrology for byproduct speciation.
	Chemical Exposure Management
	Need to design-out potential for chemical exposures and the necessity for personal protective equipment (PPE)
	Design for Maintenance
	Need to design equipment so that commonly serviced components and consumable items are easily and safely accessed Need to design equipment so that maintenance and service may be safely performed by a single person Need to minimize health and safety risks during maintenance activities.
	Equipment End-of-Life
	Need to develop effective management systems to address issues related to re-use and disposal of equipment
Facilities technology requirements	*Conservation*
	Need to reduce use of energy, water and other utilities Need for more efficient thermal management of cleanrooms and facilities systems
	Global Warming Emissions Reduction
	Need to design energy efficient manufacturing facilities Need to reduce total CO_2 equivalent emissions
Sustainability and product stewardship	*Sustainability Metrics*
	Need to identify the elements for defining and measuring the sustainability of a technology generation
	Design for ESH
	Need to make ESH a design parameter at the design stage of new equipment, processes and products
	End-of-Life Disposal/Reclaim
	Need to design facilities, equipment and products to facilitate re-use/disposal at end of life

Table ESH1b ESH Difficult Challenges—Long-term

Difficult Challenges < 22 nm	*Summary of Issues*
Chemicals and materials management	*Chemical Assessment*
	Evaluation and refinement of quality, rapid assessment methodologies to ensure that new materials such as nanomaterials can be utilized in manufacturing, while protecting human health, safety, and the environment without delaying process implementation
	Chemical Data Availability
	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
	Chemical Exposure Management
	Lack of information on how the chemicals and materials are used and what process by-products are formed
Process and equipment management	*Chemical Reduction*
	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 Need to reduce emissions from processes using high GWP chemicals
	Environment Management
	Need to understand ESH characteristics of process emissions and by-products to identify the appropriate mitigation Need to develop effective management systems to address issues related to hazardous and non-hazardous residues from the manufacturing processes
	Water and Energy Conservation
	Need to reduce water and energy consumption Need for innovative energy and water-efficient processes and equipment
	Consumables Optimization
	Need for more efficient utilization of chemicals and materials, and increased reuse and recycling
	Chemical Exposure Management
	Need to design-out potential for chemical exposures and need for personal protective equipment (PPE)
	Design for Maintenance
	Need to design equipment so that maintenance and service may be safely performed by a single person Need to design equipment so that commonly serviced components and consumable items are easily accessed Need to minimize health and safety risks during maintenance activities
	Equipment End-of-Life
	Need to develop effective management systems to address issues related to re-use and disposal of equipment
Facilities technology requirements	*Conservation*
	Need to reduce use of energy, water and other utilities Need for more efficient thermal management of cleanrooms and facilities systems
	Global Warming Emissions Reduction
	Need to design energy efficient facilities support equipment and manufacturing facilities. Need to reduce emissions from processes using high GWP chemicals
Sustainability and product stewardship	*Sustainability Metric*
	Need to identify the elements for defining and measuring the sustainability of a technology generation Need to identify the elements for defining and measuring sustainability at a factory infrastructure level
	Design for ESH
	Need method to holistically evaluate and quantify the ESH impacts of processes, chemicals, and process equipment for the total manufacturing process Need to make ESH a design parameter in development of new equipment, processes and products
	End-of-Life Disposal/Reclaim
	Need to design facilities, equipment, and products to facilitate re-use/disposal at end of life

ESH INTRINSIC REQUIREMENTS

For making ESH-related technology decisions, the scientists and engineers responsible for new technology development require an explicit set of targets that represent the intrinsic ESH requirements. The intent is to meet these requirements in parallel with the mainstream technology objectives. Many new materials are being evaluated and their usage will increase with the adoption of new technologies to satisfy IC performance requirements. Whereas in the past the same materials would easily support four to five technology generations, today nearly each technology generation requires the introduction of one or more new materials. ESH assessment is a critical element in the introduction of these new materials. The elementary chemical reactions in each process must be understood so that processes with the lowest ESH impact can be developed. Therefore, process analysis must include the characterization of emissions and by-products that may raise significant health and environmental issues that must be addressed. 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. The ESH impact assessment should include a material balance and should identify the paths by which the chemical or material enters the environment.

Table ESH2 outlines these overarching ESH goals under the four ESH Difficult Challenges headings. It sets goals for chemical risk assessment, energy and water consumption for tools and equipment as well as facility systems, chemical consumption, and waste and perfluorocompound (PFC) emission reduction. In addition, the table touches on product stewardship and sustainability requirements.

Potential ESH solutions include the development of key environmental performance indicators (KEPIs), the development and implementation of nano- and biological material risk assessment methodologies, and the development of biochips for rapid toxicity testing.

TECHNICAL THRUST ESH TECHNOLOGY REQUIREMENTS

The specific ESH technology requirements for each technical thrust (i.e., Interconnect, Front End Processes, Lithography, Assembly and Packaging, and Emerging Research Materials) can be found in Tables ESH3 and ESH4, which correspond to two of the four ESH Difficult Challenges headings, Chemicals Management and Equipment Management, respectively. Table ESH3 focuses on the selection and management of chemical and materials and Table ESH4 on process and equipment design. ESH requirements were established based on mapping the technical thrust needs against the ESH Difficult Challenges. In many cases, the goal is to establish a baseline for chemical utilization and emissions and, then, to increase chemical utilization, reduce emissions over time, and identify ESH-friendly alternative chemicals or processes. Worker protection measures should address chemical hazards as well as potential physical hazards (such as thermal, non-ionizing radiation, laser, and robotics hazards), especially during equipment maintenance.

As the size and complexity of the process equipment increase due to advanced technologies, the design of tools for safe and ergonomically friendly maintenance becomes more 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 tool design. 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 interfaces 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 must be updated to accommodate these changes.

The specific technical thrust technology requirements and potential solutions are discussed below.

INTERCONNECT

The Interconnect area poses several unique 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 dielectrics, low down-force planarization, surface cleaning, 3D interconnect and carbon nanotubes. The ESH impacts of these new materials, processes, and subsequent reaction by-products must be determined as early as possible, ideally at the university and early supplier research stages, to ensure that the ESH information is available to the material users. This determination will allow the optimal process materials to be selected based on both function and lowest ESH impact with respect to health and safety, process emissions and byproducts, materials compatibility with both equipment and with other chemicals, flammability, and reactivity. This approach will minimize undesirable business impacts after processes are developed and used in large-scale production.

This includes solvents and polymers for spin-on processes, CVD/ALD precursors, low-κ pore sealers, copper interconnect barrier and seed materials, planarization consumables (slurries, pads, and 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 copper plating bath life or recycling, and more efficient utilization of planarization slurries in the process or slurry recycling.

Greenhouse gas emissions are contributing to climate change. PFCs, a family of high global warming potential chemicals, are used extensively in interconnect dry etch and chamber cleaning applications. A potential new source of substantial PFC emissions is 3D interconnect where PFCs such as sulfur hexafluoride are being considered for through-silicon via etch. The semiconductor industry near-term goal is to reduce absolute PFC emissions 10% 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 by process optimization, alternative chemistries, recycle, and/or abatement. In recent years, chamber clean processes that do not emit high global warming potential by-products have been successfully developed. This concept should be carried over to etch. Fluorinated heat transfer fluids also have high global warming potential, and emissions of these materials must be minimized.

The increasing use of planarization has resulted in interconnect becoming a major user of both chemicals and water. Therefore, efforts must be made to develop planarization processes that will reduce overall water consumption. Water recycle and reclaim for planarization and post-planarization cleans is a potential solution for water use reduction.

With increased focus on energy conservation, the power requirements of plasma-enhanced CVD and etch as well as CMP equipment must be minimized. Plasma processes are both energy-intensive and inefficient in the way they use input chemistries (often achieving only 10–30% 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 to remove heat from equipment rather than dissipating heat into the cleanroom results in fab energy savings.

Potential solutions for interconnect include additive processing, low ESH impact CMP processes (e.g., slurry recycle or slurry-less CMP), non-PFC emitting through-silicon via etch, POU chamber clean gas recycling, low cost/high efficiency plasma etch emissions abatement, low temperature wafer cleaning, and reduced volume process chambers for CVD and ALD.

FRONT END PROCESSING

Front end processing has several unique ESH challenges centered on new materials for gate dielectrics, electrodes, non-silicon active substrates, and memory; natural resource use (especially water); management of potential physical and chemical hazards to ensure worker protection; and optimization of processes to reduce chemical use and generation of wastes. New materials for 65 nm technology generations and beyond will require a thorough ESH review.

The primary chemical management strategy should be to select chemistries with the lowest ESH impact. ESH risk assessment tools should be used to evaluate all new materials and processes during the early stages of research and development.

ESH concerns for surface preparation focus on new clean techniques, chemical usage, and consumption of water and energy. Surface preparation methods continue to evolve to accommodate new materials. Understanding of surface and interface science must be improved to reduce chemical and water usage.

Chemical use optimization should be applied to conventional and alternative cleaning processes. Alternative clean processes (e.g., dilute chemistries, sonic solvent cleans, simplified process flows, DI/ozone cleans) should be pursued to reduce ESH hazards and chemical consumption. Fluid flow optimization and sensor-based process control should be evaluated. Potential increased use of anhydrous gases (HF/HCl and alternatives) should be reviewed through process hazards analysis.

The impact of alternative cleaning methods (such as cryogenic wafer and parts cleaning, and hot-UPW wafer cleaning) on energy consumption needs to be considered. Sustainable, optimized water use strategies such as more efficient UPW production, reduced water consumption, and efficient rinsing are being developed. Alternative solvent-based cleans need development. The optimization of test wafer usage can reduce chemical, water, and energy consumption. Wet-tool designs should continue to incorporate enclosed processes as well as ergonomic and robotics safety principles.

Current materials are primarily Czochralski (CZ)-polished silicon wafers with an epitaxial (Epi) silicon layer. Silicon-on-insulator (SOI) materials may offer ESH advantages in that they require fewer process steps, resulting in less chemical and energy usage. Due to their increased size, 450mm wafers will require more chemicals, energy, and water per wafer but efforts should be made to significantly reduce usage on a normalized (per cm^2) basis.

The evaluation of alternative high-κ and electrode materials must include a thorough assessment of potential hazards associated with both the materials and their associated deposition and etch processes. Alternative silicides (i.e., Co, Ni, others) pose 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 and single-wafer tools). Energy use by diffusion and implant tools and associated facility systems (exhaust) should be evaluated and optimized.

A wide variety of organic ligands are proposed as high-κ and gate electrode precursors. These materials as well as their reaction by-products may pose potential toxicity or flammability hazards; thus, it is important to characterize process emissions and byproducts.

The potential physical and chemical hazards of alternative doping technologies 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), and metal alkyls. Sub-atmospheric delivery systems should be developed for a wider variety of dopant materials. Alternative annealing technologies may use high power laser sources or intense electrical discharges.

Continued use of PFCs in front end plasma etch as well as chamber cleans 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 the review of potential ESH impacts.

Potential solutions for FEP include alternative surface preparation methods with dilute chemistries and increased chemical utilization, additive processing, non-PFC emitting etch processes, low temperature wafer cleaning, high efficiency rinses, and new energy efficient thermal processes.

LITHOGRAPHY

From the perspective of ESH, lithography is represented by three topical areas: 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 (193i, EUV, imprint, 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. Electromagnetic waves exhibit various wavelength-dependent characteristics. When the wavelength used for pattern exposure is shortened to the X-ray region, special attention must be paid to potential health effects.

Photolithography and mask manufacturing chemicals require ESH assessment of the chemicals used and emissions generated. Among the information required are chemical toxicity; health risk assessment data; and the presence of hazardous air pollutants (HAPs), volatile organic compounds (VOCs), and persistent, bioaccumulative, toxic (PBT) compounds. Process emissions from spin-on and bake processes as well as the subsequent etch and strip processes must be characterized. Another critical need is the identification of alternatives to the PFOS contained in developers, etchants, anti-reflective coatings (ARCs), and photoacid generators (PAGs) in chemically amplified resists.

The development of immersion technology must be closely monitored for any potential ESH impacts. Immersion lithography will initially use water as the working fluid. Second generation systems may use organic fluids and, therefore, require ESH assessments as well as means for efficient fluid reuse and/or disposal. Third generation fluids may again be water based with the addition of high refractive index nano-materials and other inorganic materials, all requiring ESH assessment.

Lithography processing equipment technology requirements include ergonomic equipment design, understanding and minimizing potential worker exposure to toxic materials; controlling emissions of HAPs, VOCs, and PBTs; minimizing hazardous waste generation; and reducing resource consumption and cost of ownership. Additional needs are characterizing and controlling plasma etch and ashing emissions and by-products.

Exposure equipment technology requirements include understanding the toxicity of any new chemicals (e.g., immersion fluids), minimizing potential exposure to radiation and/or hazardous energies, and minimizing total energy usage and cost-of-ownership.

Among the potential solutions for lithography are rapid ESH assessment of new lithography materials, use of sustainable chemistries, development of chemistries that do not contain PFAS or PFOA, improved chemical utilization, and application of pollution prevention and DFESH principles when designing new equipment and processes. Currently, EUV sources are energy inefficient. If not addressed, EUV steppers will become one of the major energy consumers in HVM fabs (≥25% of total fab energy use). Energy efficient sources must be designed. The design of equipment should also include effective radiation shielding, minimized ergonomic stressors, and adherence to SEMI S2, S8, and S23 guidelines.[1] Long-term potential solutions include additive processing and the design of novel patterning equipment for efficient materials use.

ASSEMBLY AND PACKAGING

The drive towards chip-scale and flip-chip packaging may improve the ESH performance of assembly and packaging, as these technologies eliminate the application of leadframes and conventional molding. While potentially reducing total the ESH impact, 3D packaging introduces new chemistries and processes (e.g., wafer thinning, bonding and through-silicon vias) with associated ESH concerns. The use of environmentally hazardous assembly and packaging materials, such as lead, hexavalent chromium, beryllium, antimony, and brominated flame retardants is under increasing international regulatory pressure and restrictions. Reducing energy consumption is important from a global warming as well as resource conservation point of view.

Potential solutions for assembly and packaging include the development of key environmental performance indicators; elimination of potentially restricted chemicals; and adoption of no/low-curing plastics, fine feature laser drilling for 3D interconnects, and recyclable packaging materials.

EMERGING RESEARCH MATERIALS

As materials used in semiconductor manufacturing enter the nano-sized realm, a renewed focus on the ESH implications of these materials is warranted. It is well documented that nano-sized materials often have unique and diverse properties compared to 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:

- Developing effective monitoring tools to detect the presence of nanomaterials in the workplace, the waste streams, and the environment.
- Evaluating and developing appropriate protocols to ensure worker health and safety.
- Evaluating and developing pollution control equipment to ensure effective treatment of waste streams containing nanomaterials.
- Understanding the toxicity of new nanomaterials that may differ from their bulk forms.

Potential solutions for emerging research materials include the development and implementation of ESH risk assessment methodologies for nano- and biological materials. Refer to the Emerging Research Materials chapter.

FACILITIES

Responsible ESH performance for the semiconductor industry begins with factory planning, design, and construction. Table ESH5 establishes goals for facilities design and operation. Factory design and the interfaces between factory, equipment, and workers strongly influence ESH performance for the industry. Standardization of safety and environmental systems, procedures, and methodologies, when applicable, will prove to be an efficient and cost-effective approach. Sharing these practices can reduce start-up schedules and will result in greater cooperation by equipment suppliers for interfacing their products into factories. 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. This is especially important as the industry transitions from 300 to 450 mm wafers, which require larger process equipment and potentially greater quantities of chemicals and resources.

Accepted protocols for risk management, in order of priority, are hazard elimination, engineering controls, administrative controls (procedural), and personal protective equipment.

One opportunity for greater standardization is with manufacturing and assembly/test equipment. Standardization in ESH aspects of equipment design, design verification, ESH qualification, and signoff will greatly improve ESH performance,

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[1] *SEMI. S2—**Environment, Health and** Safety Guidelines for Semiconductor Manufacturing Equipment*
SEMI S8—Safety Guidelines for Ergonomics Engineering of Semiconductor Equipment
SEMI S23 - Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment

start-up efficiency, and cost. Additionally, standardization of ESH practices in equipment maintenance, modification, 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 their interfaces with process equipment will improve safety and also increase efficiency of installations and reduce start-up time. 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.

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 during operation and maintenance.

The safety issues associated with factory support systems must also be aggressively improved in future factories. 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 the 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 process equipment with which they interface, and the interfaces themselves. Additionally, factory planning and layout should include ergonomic design criteria for wafer handling, especially for 450 mm wafers.

The industry faces increasing permit, code, and emissions limitations. Planning for future factories and for modifications to existing factories should involve cooperative efforts with code entities and government bodies to ensure that advancements in technology of equipment and factories are comprehended and used 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.

Factory design defines the systems that deliver process materials to process equipment, that manage by-products, and that control the workplace. 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.

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 developing higher efficiency processes and tools and by combining 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.

Most water used in semiconductor manufacturing is 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 UPW production cost). A decrease in UPW consumption will reduce both environmental effects caused by the chemicals and manufacturing costs. Recycling higher quality water for process applications and reusing lower quality water for non-process applications are important. Where water is plentiful, wastewater recycling will depend on local water reuse options and associated recycling costs.

Limitations on sources of energy could potentially limit the 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. 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.

While much of the responsibility for reducing the use of limited resources and minimizing waste rests with the equipment suppliers and process technologists, the 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 the 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.

Potential solutions for factory integration include developing and implementing semiconductor facility-specific LEED[2] practices; integrating idle mode capabilities into facilities systems; and developing real-time speciating, on-line sensors for UPW recycling.

SUSTAINABILITY AND PRODUCT STEWARDSHIP

Table ESH6 spans all areas of semiconductor product design and process development. It outlines criteria for sustainability and environmentally sound design of products, processes, equipment, and facilities.

Climate change is the greatest global environmental challenge of the 21st century, driving international efforts to reduce not only emissions of greenhouse gases, such as PFCs used in semiconductor manufacturing, but also emissions of carbon dioxide resulting from the generation of electricity. Carbon footprint, a means to track the impact of a product or process on global climate, is defined as the total amount of CO_2 and other greenhouse gases emitted over the full life cycle of a product. A reduced carbon footprint is vital to the industry's sustainability; therefore, carbon footprint metrics should be developed to track progress over time. Fortunately, semiconductor devices are essential to improving the carbon footprint of the products and systems in which they are used.

DFESH is the term applied to the integration and proliferation of ESH improvements into 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.

Finally, attention must be paid to the design of facilities, equipment, and products for ease of disassembly and re-use at end of life.

Potential solutions for sustainability and product stewardship include the development of KEPIs to measure improvements in environmental impact of products, materials, processes, and facilities over subsequent technology generations.

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[2] *LEED – Leadership in Energy and Environmental Efficient Design*

Table ESH2a ESH Intrinsic Requirements—Near-term Years

Year of Production	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
I. Chemicals and Materials Management Technology Requirements									
Chemical risk assessments (environmental, health and safety) defined and completed	**100%**		**100%**		**100%**				
ESH risk assessment techniques for nano-materials and nano-particles	**Develop assessment methodology.**		**Implement risk assessment methodology.**						
II. Process and Equipment Technology Requirements									
Energy Consumption									
Total fab tools (kWh/cm^2) [2]	**0.40–0.35**			**0.35-0.30**			**0.30-0.25**		
Tool energy usage (% of 2005 baseline)	**90**			**80**			**Functional Area Goals TBD**		
Tool total equivalent energy* (% of 2007 baseline)	**100**		**80**	**70**			**60**		
Water Consumption (driven by sustainable growth and cost)									
Surface preparation UPW use (% of 2005 baseline)	**90**			**80**			**75**		
Tool UPW usage (% of 2005 baseline)	**90**			**80**			**75**		
Chemical Consumption and Waste Reduction (driven by environmental stewardship and cost)									
Improvement in process chemical utilization (% of 2005 baseline)	**90**			**80**			**75**		
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**				
Liquid and solid waste reduction (% of 2007 baseline)	**100**		**90**	**80**			**75**		
Worker and Workplace Protection									
Safety screening methodologies for new technologies (e.g., 450mm, EUV lithography, ERM)	**Develop methodologies.**			**Implement methodologies.**					
III. Facilities Technology Requirements									
Energy Consumption									
Total fab energy usage (kWh/cm^2)	**1.5-1.3**			**1.3-1.1**			**1.1-1.0**		
Total fab support systems energy usage (kWh/cm^2) [2]	**0.8–0.6**			**0.6–0.5**			**0.5-0.4**		
Reduce total fab energy usage (% of 2007 baseline)	**100**		**90**	**80**			**70**		
Water Consumption									
Net feed water use (liters/cm^2) [2]	**15**	**15-12**		**12-10**			**10-8**		
Fab UPW use (liters/cm^2) [2]	**8**	**8-7**		**7-6**			**6-4**		
Chemical Consumption and Waste Reduction									
Reduce hazardous liquid waste by recycle/reuse** (% of 2007 baseline)	**100**		**90**	**80**			**75**		
Reduce solid waste by recycle/reuse** (% of 2007 baseline)	**100**		**90**	**80**			**75**		
IV. Sustainability and Product Stewardship Requirements									
Define environmental footprint metrics for process, equipment, facilities, and products; reduce from baseline year.	**Define metrics and baseline.**			**90% of baseline**			**80% of baseline**		
Integrate ESH priorities into the design process for new processes, equipment, facilities, and products.	**Define metrics and baseline.**								
Facilitate end-of-life disposal/reclaim	**Define metrics and baseline.**								

Table ESH2b ESH Intrinsic Requirements—Long-term Years

Year of Production	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
I. Chemicals and Materials Management Technology Requirements							
Chemical risk assessments (environmental, health and safety) defined and completed	**100%**						
II. Process and Equipment Technology Requirements							
Energy Consumption							
Total fab tools (kWh/cm^2) [2]	**0.25**						
Tool energy usage (kWh per wafer pass)	**Functional Area Goals TBD**						
Tool total equivalent energy* (% of baseline)	**50**						
Water Consumption (driven by sustainable growth and cost)							
Surface preparation UPW use (liters per wafer pass)	**50**						
Tool UPW usage (% of 2005 baseline)	**50**						
Chemical Consumption and Waste Reduction (driven by environ-mental stewardship and cost)							
Improvement in process chemical utilization (% of 2005 baseline)	**50**						
Reduce PFC emission	**Maintain 10% absolute reduction from 1995 baseline**						
Reduce liquid and solid waste (% of 2007 baseline)	**50**						
III.. Facilities Technology Requirements							
Energy Consumption							
Total fab energy usage (kWh/cm2)	**1.0-0.75**						
Total fab support systems energy usage (kWh/cm^2) [2]	**0.4-0.25**						
Reduce total fab energy usage (% of 2007 baseline)	**50**						
Water Consumption							
Net feed water use (liters/cm^2) [2]	**8-6**						
Fab UPW use (liters/cm^2) [2]	**4-3**						
Chemical Consumption and Waste Reduction							
Reduce hazardous liquid waste by recycle/reuse** (% of 2007 baseline)	**50**						
Reduce solid waste by recycle/reuse** (% of 2007 baseline)	**50**						
IV. Sustainability and Product Stewardship Requirements							
Define environmental footprint metrics for process, equipment, facilities, and products; reduce from baseline year.	**50% of baseline**						

Notes for Table ESH2a and b:
[1] CPIF = Chemical Properties Information Form
[2] cm^2 per wafer out
** as defined by SEMI guideline S23*
***Recycle = Re-use after treatment*
***Reuse = Use in secondary application (without treatment)*
***Reclaim = Extracting a useful component from waste*

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

Table ESH3a 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	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Interconnect									
Low-κ materials—spin-on and CVD	Establish chemical utilization* and process byproducts baseline	Maintain or improve chemical utilization* by 10%		Maintain or improve chemical utilization* by 10%			Maintain or improve chemicals utilization* by 10%		
Copper deposition processes (conventional and alternative)	75% copper reclaimed/recycled	85% copper reclaimed/recycled			99% copper reclaimed/recycled				
Advanced metallization including barrier and nucleation deposition	Establish chemical utilization* and process byproducts baseline	Maintain or improve chemical utilization* by 10%; minimize process byproducts		Maintain or improve chemical utilization* by 10%; minimize process byproducts			Maintain or improve chemicals utilization* by 10%; minimize process byproducts		
Planarization methods	Characterize emissions and consumables; establish baseline.	> 15% Reduction in consumables from baseline					2% reduction in consumables per year		
Plasma etch	Alternatives with improved ESH impacts. Maintain or improve chemical utilization*; characterize process byproducts.	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		Alternatives with improved ESH impacts. Low ESH impact chemistries. Maintain or improve chemical utilization* by 10%; minimize process byproducts.			Alternatives with improved ESH impacts. Low ESH impact chemistries. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		
CVD chamber clean (plasma)	Alternatives with improved ESH impacts (e.g. lower GWP, improve utilization); characterize process byproducts.	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		Alternatives with improved ESH impacts. Low ESH impact chemistries. Maintain or improve chemical utilization* by 10%; minimize process byproducts.			Alternatives with improved ESH impacts. Low ESH impact chemistries. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		
	Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk		
Surface preparation	Alternatives with improved ESH impacts. Maintain or improve chemical utilization*; characterize emissions.	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%.		Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%.			Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%.		
Through-silicon via etch using PFCs (e.g., 3D)	Characterize emissions; establish baseline.	Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization* by 10%.		Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization* by 10%.			Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization* by 10%.		
Front End Processes									
High-κ and metal gate materials	Conduct ESH risk assessment of materials. Maintain or improve chemical utilization*; minimize process byproducts			Maintain or improve chemical utilization* by 10% and minimize process byproducts			Maintain or improve chemical utilization* by 10% and minimize process byproducts		
Doping (implantation and diffusion)	Low hazard dopant materials			Low hazard dopant materials					
Conventional surface preparation (stripping, cleaning, rinsing, drying)	Characterize emissions; establish baseline.	Maintain or improve chemical usage by 10%.		Maintain or improve chemical usage by 10%.			Maintain or improve chemical usage by 10%.		

Table ESH3a 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	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Alternative surface preparation methods	Identify novel wafer cleaning materials. Conduct ESH risk assessment of materials			Maintain or improve chemical usage by 10% and minimize process byproducts			Maintain or improve chemical usage by 10% and minimize process byproducts		
Plasma etch	Alternatives with improved ESH impacts; minimize process byproducts.	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		Alternatives with improved ESH impacts. Low ESH impact chemicals Maintain or improve chemical utilization* by 10%; minimize process byproducts.			Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		
Non-silicon, active substrates (channel)	Conduct ESH risk assessment of materials. Maintain or improve chemical utilization*; minimize process byproducts.						Maintain or improve chemical utilization* by 10% and minimize process byproducts		
Novel memory materials	Conduct ESH risk assessment of materials. Maintain or improve chemical utilization*; minimize process byproducts.			Maintain or improve chemical utilization* by 10% and minimize process byproducts			Maintain or improve chemical utilization* by 10% and minimize process byproducts		
Lithography									
193 nm immersion resists	Conduct ESH risk assessment of materials.			Maintain or improve chemical utilization* by 10%.			Maintain or improve chemical utilization* by 10%.		
193 nm immersion fluids	Conduct ESH risk assessment of materials.	Maintain or improve chemical utilization by 10%.		Maintain or improve chemical utilization* by 10%.			Maintain or improve chemical utilization* by 10%.		
EUV resists	Conduct ESH risk assessment of materials.			Maintain or improve chemical utilization* by 10%.			Maintain or improve chemical utilization* by 10%.		
Imprint	Conduct ESH risk assessment of materials.			Conduct ESH risk assessment of materials.			Maintain or improve chemical utilization* by 10%.		
PFOS/PFAS** chemicals	PFOS/PFAS alternatives researched / implemented						Non-PFAS materials developed for critical uses in lithography		
Mask making and cleaning	Characterize emissions; establish baseline.	Alternatives with improved ESH impacts. Maintain or improve chemical utilization by 10%; minimize process byproducts.		Alternatives with improved ESH impacts. Low ESH impact chemistries Maintain or improve chemical utilization* by 10%; minimize process byproducts.			Alternatives with improved ESH impacts (PFOS-free). Maintain or improve chemical utilization* by 10%; minimize process byproducts.		
Assembly & Packaging									
Die thinning	Characterize emissions; establish baseline.	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		Alternatives with improved ESH impacts. Low ESH impact chemistries Maintain or improve chemical utilization* by 10%; minimize process byproducts.			Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		
Assembly and packaging wastes	Characterize emissions; establish baseline.	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		Alternatives with improved ESH impacts. Low ESH impact chemistries Maintain or improve chemical utilization* by 10%; minimize process byproducts.			Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.		

Table ESH3a 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	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Through-silicon via etch using PFCs (e.g., 3D)	Characterize emissions; establish baseline.	Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization* by 10%.		Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization* by 10%.			Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization* by 10%.		
Emerging Research Materials									
Nanomaterials	Conduct ESH risk assessment of materials.			Conduct ESH risk assessment of materials.					
Biological materials and their waste	Conduct ESH risk assessment of materials.			Conduct ESH risk assessment of materials.					
Materials for novel logic and memory	Conduct ESH risk assessment of materials.			Conduct ESH risk assessment of materials.					

* *Utilization = [(Feed - Output)/Feed] × 100%*

** *PFOS = perfluorooctane sulfonate; PFAS = perfluoroalkyl sulfonate*

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

Table ESH3b 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	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
Interconnect							
Low-κ materials—spin-on and CVD	Maintain or improve chemicals utilization* by 10% and minimize process byproducts						
Copper deposition processes (conventional and alternative)	100% copper reclaimed/recycled						
Advanced metallization including barrier and nucleation deposition	Maintain or improve chemicals utilization* by 10% and minimize process emissions and byproducts						
Planarization methods	2% reduction in consumables per year						
Plasma etch	Alternatives with improved ESH impacts. Low ESH impact chemistries. Maintain or improve chemical utilization* by 10%; minimize process byproducts.						
CVD chamber clean (plasma)	Alternatives with improved ESH impacts. Low ESH impact chemistries. Maintain or improve chemical utilization* by 10%; minimize process byproducts.						
	Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk						
Surface preparation	Alternatives with improved ESH impacts; 2% reduction in chemicals per year; recycle/reclaim						
Through-silicon via etch using PFCs (e.g., 3D)	Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization by 10%.						
Front end Processes							
High-κ and metal gate materials	Maintain or improve chemical utilization* by 10% and minimize process emissions and byproducts						
Doping (implantation and diffusion)	Low hazard materials						
Conventional surface preparation (stripping, cleaning, rinsing, drying)	Maintain or improve chemical usage by 10%						
Alternative surface preparation methods	Maintain or improve chemical usage by 10%.						
Plasma etch	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process emissions and byproducts						
Non-silicon, active substrates (channel)	Maintain or improve chemical utilization* by 10% and minimize process emissions and byproducts						
Novel memory materials	Maintain or improve chemical utilization* by 10% and minimize process emissions and byproducts						
Lithography							
193 nm immersion resists	Maintain or improve chemical utilization* by 10% and minimize process byproducts; low-hazard/non-hazardous solvents, PFAS-free resists.						
193 nm immersion fluids	Maintain or improve chemical utilization* by 10% and minimize process emissions and byproducts						
EUV resists	Maintain or improve chemical utilization* by 10% and minimize process byproducts; low-hazard/non-hazardous solvents, PFAS-free resists.						
Imprint	Maintain or improve chemical utilization* by 10% and minimize process emissions and byproducts						
PFOS/PFAS** chemicals	PFAS-free materials developed for critical uses in lithography						
Mask making and cleaning	Alternatives with improved ESH impacts (PFAS-free). Maintain or improve chemical utilization* by 10%; minimize process emissions and byproducts.						
Assembly & Packaging							
Die thinning	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.						
Assembly and packaging wastes	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; minimize process byproducts.						
Through-silicon via etch using PFCs (e.g., 3D)	Reduce Global Warming Impact (lower GWP emissions; alternative etchants, improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization by 10%.						
Emerging Research Materials							
Nanomaterials	Conduct ESH risk assessment of materials.						
Biological materials and their waste	Conduct ESH risk assessment of materials.						
Materials for novel logic and memory	Conduct ESH risk assessment of materials.						

** Utilization = [(Feed - Output)/Feed] × 100%*
*** PFOS = perfluorooctane sulfonate; PFAS = perfluoroalkyl sulfonate*

Table ESH4a Process and Equipment Management Technology Requirements—Near-term Years

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

Year of Production	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Interconnect									
Low-κ processing spin-on and CVD	Establish chemical utilization and process byproducts baseline	Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts					Maintain or improve chemicals utilization* by 10%; characterize process emissions and byproducts		
Copper deposition processes (conventional and alternative)	Baseline copper processes; optimize processes to minimize consumables and waste	Optimize copper processes to reduce consumables and waste by 25%							
Advanced metallization including barrier and nucleation deposition	Establish chemical utilization and process byproducts baseline	Maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts					Maintain or improve chemicals utilization* by 10% and characterize process emissions and byproducts		
Planarization methods	Establish baseline for consumables	>15% Reduction in consumables from baseline					Additional 2% reduction in consumables per year		
	Establish baseline for water usage	>15% Reduction in water usage from baseline					Additional 2% reduction in water usage for planarization (e.g., reduction, re-use, recycle)		
Plasma etch processes	Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk		
CVD chamber clean (plasma)	Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk			Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk		
Surface preparation	Establish baseline for chemical and water usage.; characterize emissions	> 15% Reduction in chemicals and water usage from baseline					Additional 2% reduction in chemicals and water usage per year; recycle/reclaim		
Through-silicon via etch using PFCs (e.g., 3D)	Characterize emissions; establish baseline	Reduce Global Warming impact (lower GWP emissions; improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization by 10%		Reduce Global Warming impact (lower GWP emissions; improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization by 10%			Reduce Global Warming impact (lower GWP emissions; improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization by 10%		
Front End Processes									
High-κ and metal gate processes	Characterize emissions; establish chemical utilization* and process emissions baseline			Low-ESH impact deposition, etch, and cleans processes					
	Establish energy usage baseline	Energy efficient deposition processes (process and ancillary equipment); reduce energy requirements by 15%							
Doping (implantation and diffusion)	Low hazard dopant materials and processes			Low hazard dopant materials and processes					
	Establish energy usage baseline	Energy efficient doping processes (process and ancillary equipment)							
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					
	Characterize emissions; establish water and chemical usage baselines.	Maintain or improve chemical and water utilization* by 10%		Maintain or improve chemical and water utilization* by 10%			Maintain or improve chemical and water utilization* by 10%		

Table ESH4a Process and Equipment Management Technology Requirements—Near-term Years

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

Year of Production	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
	Energy efficient clean processes (reduced exhaust flow rates, optimized heaters)			Energy efficient clean processes (optimized exhaust flow rates, optimized heaters)					
Alternative surface preparation methods	Identify novel wafer cleaning processes and equipment. Characterize emissions; establish water and chemical usage baselines. Conduct ESH risk assessment			Novel wafer cleaning technologies evaluated and optimized to minimize ESH impact			Novel wafer cleaning technologies implemented		
Plasma etch processing	Alternatives with improved ESH impacts; characterize process byproducts.	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process byproducts.		Alternatives with improved ESH impacts. Low ESH impact chemistries Maintain or improve chemical utilization* by 10%; characterize process byproducts.			Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process byproducts.		
Non-silicon, active substrates (channel)	Conduct ESH risk assessment of processes and equipment. Maintain or improve chemical utilization*; characterize process emissions and byproducts						Maintain or improve chemical utilization* by 10% and characterize emissions and process byproducts		
Novel memory materials	Conduct ESH risk assessment of processes and equipment. Maintain or improve chemical utilization*; characterize process emissions and byproducts			Maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts			Maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts		
Lithography									
193 nm immersion lithography	Conduct ESH risk assessment of processes and equipment			Minimal ESH impact from immersion fluids, processes, equipment and consumables			Minimal ESH impact from immersion fluids, processes, equipment and consumables		
EUV	Conduct ESH risk assessment of processes and equipment			Minimal ESH impact from ionizing radiation and ergonomics; high efficiency EUV source			Minimal ESH impact from ionizing radiation and ergonomics; high efficiency EUV source		
Imprint	Conduct ESH risk assessment of processes and equipment			Minimal ESH impact from processes, equipment and consumables			Minimal ESH impact from processes, equipment and consumables		
Mask cleaning	Characterize emissions; establish baseline	Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts		Identify minimal ESH impact cleaning technologies (e.g., supercritical CO2)			Novel mask cleaning technologies evaluated and optimized to minimize ESH impact		
Assembly and Packaging									
Molding process	Establish ESH impact baseline.	Minimize molding process waste		Reduce molding compound waste by 50%.			Zero waste (after recycling) from molding technologies		
Die thinning	Characterize emissions; establish baseline	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts		Alternatives with improved ESH impacts. Low ESH impact chemistries Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts			Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts		
Assembly and packaging wastes	Characterize emissions; establish baseline	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts		Alternatives with improved ESH impacts. Low ESH impact chemistries Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts			Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts		
Through-silicon via etch using PFCs (e.g., 3D)	Characterize emissions; establish baseline.	Optimize processes and equipment for improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts		Identify alternative processes and equipment with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts			Alternative processes and equipment with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts		
Emerging Research Materials									
Nanomaterials	Conduct ESH risk assessment of materials, processes and equipment			Conduct ESH risk assessment of materials, processes and equipment					

Table ESH4a Process and Equipment Management Technology Requirements—Near-term Years

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

Year of Production	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Biological materials and their waste	Conduct ESH risk assessment of materials, processes and equipment			🟨 Conduct ESH risk assessment of materials, processes and equipment					
Materials for novel logic and memory	Conduct ESH risk assessment of materials, processes and equipment			🟨 Conduct ESH risk assessment of materials, processes and equipment					
New Equipment Design									
Eco-design	Develop eco-design criteria, establishing metrics and targets for minimized environmental footprint and impact.			🟨 Design process and ancillary equipment to minimize environmental footprint, and safety and health impact					
Design for Maintenance	Develop safe maintenance criteria.			🟨 Design equipment so that commonly serviced components and consumable items are easily and safely accessed					
Energy Consumption (kWh per cm2) [1]	Characterize energy requirements for process and ancillary equipment.			🟨 Optimize energy consumption. Add idle capability to ancillary equipment (pumps, etc.); reduce energy requirements by 15% per technology node					
Water and other utilities (liters or m3 / cm2) [1]	Characterize water and utilities requirements for process. Optimize consumption. Determine feasibility for water recycle/reclaim; reduce water and utilities requirements 15% per technology node			🟨 Optimize consumption. Determine feasibility for water recycle/reclaim; reduce water and utilities requirements 15% per technology node					
Chemicals (gms/cm2) [1]	Conduct ESH risk assessment of processes and equipment.			🟨 Conduct ESH risk assessment of processes and equipment. Maintain or improve chemical utilization*; characterize process emissions and byproducts; reduce chemical consumption 15% per technology node					
Consumables**	Establish consumables baseline.			🟨 Optimize to minimize consumables and waste; reduce consumables and waste 15% per technology node					
Equipment thermal management	Establish baseline			🟨 Reduce heat rejection from process and ancillary equipment to cleanroom air by 15% from baseline			🟨 Reduce heat rejection from process and ancillary equipment to cleanroom air by additional 15%		
Design for End-of-Life	Design process and ancillary equipment for disassembly and re-use/reclaim								

** Utilization = [(Feed - Output)/Feed] x 100%*

*** Consumables = CMP pads, post-CMP brushes, filters, chamber liners, etc. (i.e., items that create solid waste)*

[1] cm^2 per wafer out

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

Table ESH4b Process and Equipment Management Technology Requirements—Long-term Years

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

Year of Production	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
Interconnect							
Low-κ processing spin-on and CVD	Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts			Maintain or improve chemicals utilization* by 5%; characterize process emissions and byproducts			
Copper deposition processes (conventional and alternative)	100% copper reclaimed/recycled; optimize copper processes to reduce consumables by additional 25%						
Advanced metallization including barrier and nucleation deposition	Maintain or improve chemicals utilization* by 10% and characterize process emissions and byproducts						
Planarization methods	Additional 2% reduction in consumables per year						
	Additional 2% reduction in water for planarization (e.g., reduction, re-use, recycle)						
Plasma etch processes	Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk						
CVD chamber clean (plasma)	Reduce Global Warming Impact (lower GWP emissions; improved utilization*) without increasing ESH risk						
Surface preparation	2% reduction in chemicals and water usage per year; recycle/reclaim						
3D (wafer thinning, drilling, bonding, metals)	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10% and characterize process emissions						
Through-silicon via etch using PFCs (e.g., 3D)	Reduce Global Warming impact (lower GWP emissions; improved utilization*) without increasing ESH risk. Maintain or improve chemical utilization by 10%						
Front End Processes							
High-κ and metal gate processes	Low-ESH impact deposition, etch, and cleans processes; maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts						
	Energy efficient deposition processes (process and ancillary equipment); reduce energy requirements by additional 25%						
Doping (implantation and diffusion)	Low hazard dopant materials and processes						
	Energy efficient deposition processes (process and ancillary equipment); reduce energy requirements by additional 25%						
Surface preparation (stripping, cleaning, rinsing)	ESH-friendly wafer clean and rinse processes and tools incorporated into manufacturing						
	Maintain or improve chemical and water usage by 10%						
	Energy efficient deposition processes (process and ancillary equipment); reduce energy requirements by additional 25%						
Alternative surface preparation methods	Novel wafer cleaning technologies implemented; maintain or improve chemical usage by 10%.						
Plasma etch processing	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts.						
Non-silicon, active substrates (channel)	Maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts						
Novel memory materials	Maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts						
Lithography							
193 nm immersion lithography	Minimal ESH impact from immersion fluids, processes, equipment and consumables; maintain or improve chemical utilization* by 10% and characterize process byproducts; low-hazard/non-hazardous solvents, PFAS-free resists.						
EUV	Minimal ESH impact from ionizing radiation, ergonomics, energy consumption and source gas; maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts						
Imprint	Minimal ESH impact from processes, equipment and consumables; maintain or improve chemical utilization* by 10% and characterize process emissions and byproducts						
Mask cleaning	Novel mask cleaning technologies evaluated and optimized to minimize ESH impact; alternatives with improved ESH impacts (PFAS-free). Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts						
Assembly and Packaging							
Die thinning	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts						
Assembly and packaging wastes	Alternatives with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts						
Through-silicon via etch using PFCs (e.g., 3D)	Alternative processes and equipment with improved ESH impacts. Maintain or improve chemical utilization* by 10%; characterize process emissions and byproducts						
Emerging Research Materials							
Nanomaterials	Conduct ESH risk assessment of materials, processes and equipment						
Biological materials and their waste	Conduct ESH risk assessment of materials, processes and equipment						
Materials for novel logic and memory	Conduct ESH risk assessment of materials, processes and equipment						

Table ESH4b Process and Equipment Management Technology Requirements—Long-term Years

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

Year of Production	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
New Equipment Design							
Eco-design	Design process and ancillary equipment to minimize environmental footprint and safety and health impact						
Design for Maintenance	Design equipment so that commonly serviced components and consumable items are easily and safely accessed						
Energy Consumption [1]	Characterize energy requirements for process and ancillary equipment. Optimize energy consumption. Add idle capability to ancillary equipment (pumps, etc.); reduce energy requirements by 15% per technology node						
Water and other utilities [1]	Characterize water and utilities requirements for process. Optimize consumption. Determine feasibility for water recycle/reclaim; reduce water and utilities requirements 15% per technology node						
Chemicals [1]	Conduct ESH risk assessment of processes and equipment. Maintain or improve chemical utilization*; characterize process emissions and byproducts; reduce chemical consumption 15% per technology node						
Consumables**	Optimize processes to minimize consumables and waste; reduce consumables and waste 15% per technology node						
Equipment thermal management	Reduce heat rejection from process and ancillary equipment to cleanroom air by additional 15%			Reduce heat rejection from process and ancillary equipment to cleanroom air by additional 15%			
Design for End-of-Life	Design process and ancillary equipment for disassembly and re-use/reclaim						

** Utilization = [(Feed - Output)/Feed] x 100%*
*** Consumables = CMP pads, post-CMP brushes, filters, chamber liners, etc. (i.e., items that create solid waste)*
[1] cm^2 *per wafer out*

Table ESH5a Facilities Energy and Water Optimization Technology Requirements—Near-term Years

Year of Production	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Facilities Design									
Eco-friendly facility design	Design facilities to minimize environmental footprint and impact			Meet a recognized standard for designing and rating a reduced environmental impact facility; e.g., LEED, Green Globes, etc.					
Design for end-of-life re-use	Comprehend and implement potential re-use scenarios during facility design			Meet a recognized standard for reduced environmental impact through building re-use; e.g., LEED, etc.					
Water									
Total fab* water consumption (liters/cm^2) [1]	14			12.5			11		
Total site water consumption reduction	Establish baseline	Reduce total consumption 10% from baseline levels		Reduce total consumption additional 10%			Reduce total consumption additional 10%		
Total UPW consumption (liters/cm^2) [1]	8			7			6		
UPW recycled/reclaimed** (% of use)	70			75			80		
Energy (electricity, natural gas, etc.)									
Total fab* energy consumption (kWh per cm^2) [1]	1.9			1.6			1.35		
Total site energy consumption reduction	Establish baseline	Reduce total consumption 10% from baseline levels		Reduce total consumption additional 10%			Reduce total consumption additional 10%		
Cleanroom thermal management	Establish baseline			Reduce heat rejection from process and ancillary equipment to cleanroom air by 15% from baseline			Reduce heat rejection from process and ancillary equipment to cleanroom air by additional 15%		
Waste									
Non-hazardous solid waste (g per cm^2) [1]	50			45			40		
Hazardous waste (g per cm^2) [1]	6			5			4		
Air Emissions									
Exhaust and abatement optimization	Baseline DRE and utilities (exhaust, natural gas, etc.).			Maximize DRE while minimizing resource consumption by 10% from baseline.			Maximize DRE while minimizing resource consumption by additional 10% from baseline.		
Volatile Organic Compounds (VOCs) (g per cm^2) [1]	0.1			0.08			0.075		
Perfluorocompounds (PFCs)	10% absolute reduction from 1995 baseline by 2010 as agreed to by the World Semiconductor Council (WSC)				Maintain 10% absolute reduction from 1995 baseline				

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

Table ESH5b Facilities Energy and Water Optimization Technology Requirements—Long-term Years

Year of Production	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
Facilities Design							
Eco-friendly facility design	Meet a recognized standard for designing and rating a reduced environmental impact facility; e.g., LEED, Green Globes, etc.						
Design for end-of-life re-use	Meet a recognized standard for reduced environmental impact through building re-use; e.g., LEED, etc.						
Water							
Total fab* water consumption (liters/cm^2) [1]	10			9			
Total site water consumption reduction	Reduce total consumption by additional 10%			Reduce total consumption by additional 10%			
Total UPW consumption (liters/cm^2) [1]	5			5.5			
UPW recycled/reclaimed** (% of use)	85			90			
Energy (electricity, natural gas, etc.)							
Total fab* energy consumption (kWh per cm^2) [1]	1.2			1.1			
Total site energy consumption reduction	Reduce total consumption by additional 5%			Reduce total consumption by additional 5%			
Cleanroom thermal management	Reduce heat rejection from process and ancillary equipment to cleanroom air by additional 15%			Reduce heat rejection from process and ancillary equipment to cleanroom air by additional 15%			
Waste							
Non-hazardous solid waste (g per cm^2) [1]	30			25			
Hazardous waste (g per cm^2) [1]	3.5			3			
Air Emissions							
Exhaust and abatement optimization	Maximize DRE while minimizing resource consumption by additional 10% from baseline			Maximize DRE while minimizing resource consumption by additional 10% from baseline			
Volatile Organic Compounds (VOCs) (g per cm^2) [1]	0.07			0.065			
Perfluorocompounds (PFCs)	Maintain 10% absolute reduction from 1995 baseline						

Notes for Table ESH5a and b:
**Fab = manufacturing space + support systems*
***Recycle = Re-use after treatment*
***Reuse = Use in secondary application (without treatment)*
***Reclaim = Extracting a useful component from waste*
[1] cm2 per wafer out

Table ESH6 Sustainability and Product Stewardship Technology Requirements

Year of Production	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
Sustainability Metrics																
Facilities Eco-design	Develop eco-design criteria, establishing metrics and targets for minimized environmental footprint and impact			Design facilities, process and ancillary equipment to minimize environmental footprint, and safety and health impact												
Carbon footprint	Identify common metrics and establish baseline			Reduce carbon footprint.												
Product Eco-design	Develop key environmental performance indicators (KEPIs)* and establish baseline			Reduce KEPIs* 10% from baseline levels			Reduce KEPIs* additional 10%			Reduce KEPIs* additional 10%			Reduce KEPIs* additional 10%			
Design for ESH																
Materials	Develop key environmental performance indicators (KEPIs)* and establish baseline			Reduce KEPIs* 10% from baseline levels			Reduce KEPIs* additional 10%			Reduce KEPIs* additional 10%			Reduce KEPIs* additional 10%			
	Early assessment of ESH impacts during the very early stages of R&D (when materials are being compared and selected)															
Processes	Develop key environmental performance indicators (KEPIs)* and establish baseline			Reduce KEPIs* 10% from baseline levels			Reduce KEPIs* additional 10%			Reduce KEPIs* additional 10%			Reduce KEPIs* additional 10%			
				Alternative low-ESH impact processes for planarization and deposition						Paradigm shift to additive processing						
	Early assessment of ESH impacts during the very early stages of R&D (when processes are being compared and selected)															
Improved integration of ESH into factory and equipment design	Incorporate ESH design guidelines, methodology, and criteria into tool and factory design, e.g., LEED**															
End-of-Life																
Ease of decommissioning and decontamination for facility re-use/re-claim	Comprehend and implement potential re-use scenarios during facility design			Reduce environmental impact through building design for re-use						Reduce environmental impact through building design for re-use						
Ease of decommissioning and decontamination for equipment re-use/re-claim	Design process and ancillary equipment for disassembly and re-use/reclaim															

**KEPIs = Key Environmental Performance Indicators such as energy and water consumption, product content, human toxicity, ozone depletion, global warming potential, photochemical oxidation potential, resource depletion potential, etc.*
*** LEED = Leadership in Energy and Environmental Design (a U.S. "Green Building" rating system)*

POTENTIAL SOLUTIONS

Potential solutions are outlined in Figures ESH1, 2, and 3 referring to Chemicals and Materials, Process and Equipment, and Facilities, respectively. The tables present potential solutions for ESH, Interconnect, Front End Processes, Lithography, Assembly and Packaging, Emerging Research Materials, New Equipment, and Factory Integration; however, specific potential solutions for each area have been incorporated in the individual discussions above. Additive processing is a potential solution spanning all of the technical thrust areas, resulting in an ESH benefit through decreased chemical and resource consumption.

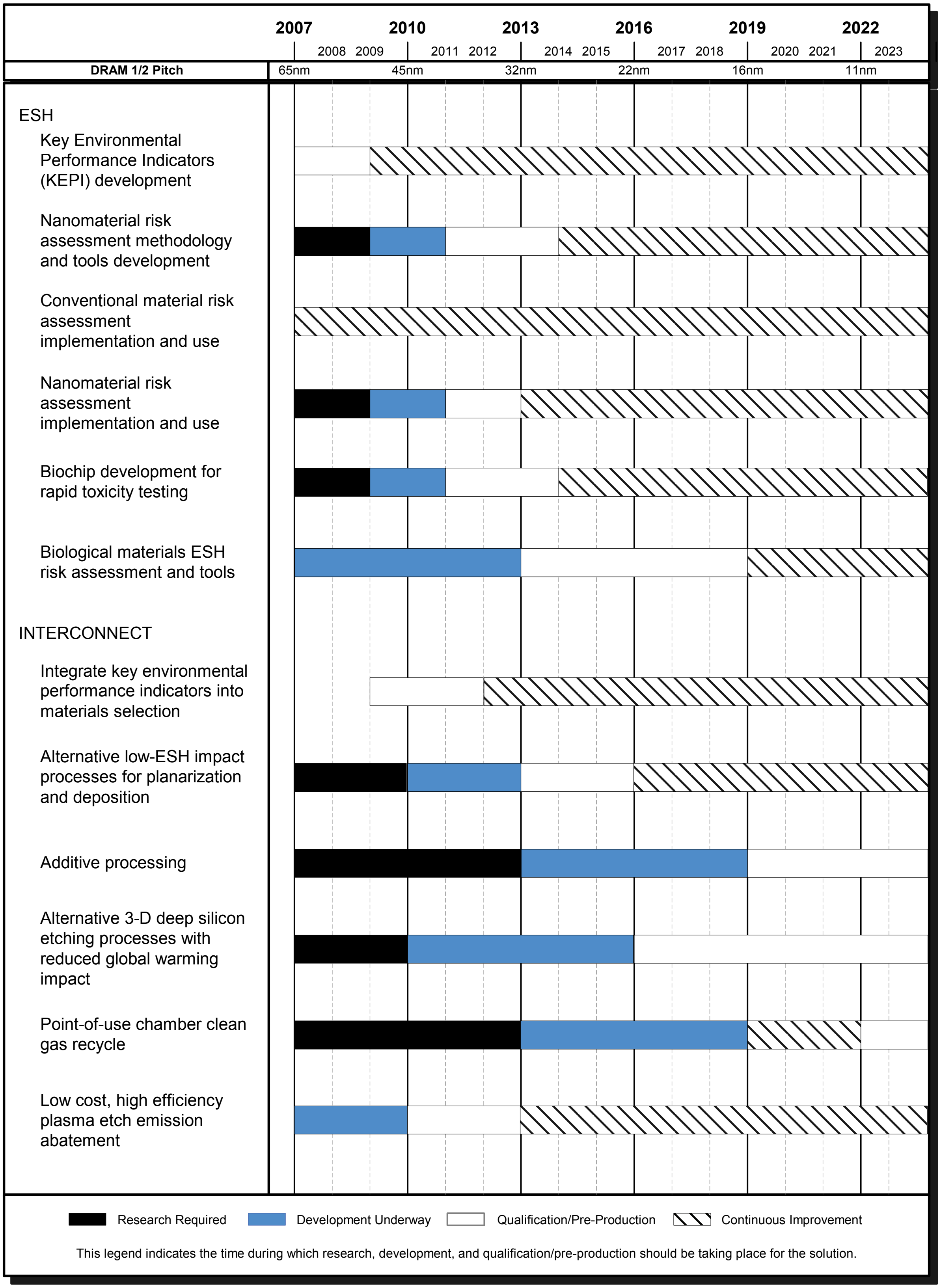


Figure ESH1 Potential Solutions for ESH: Chemicals and Materials Management

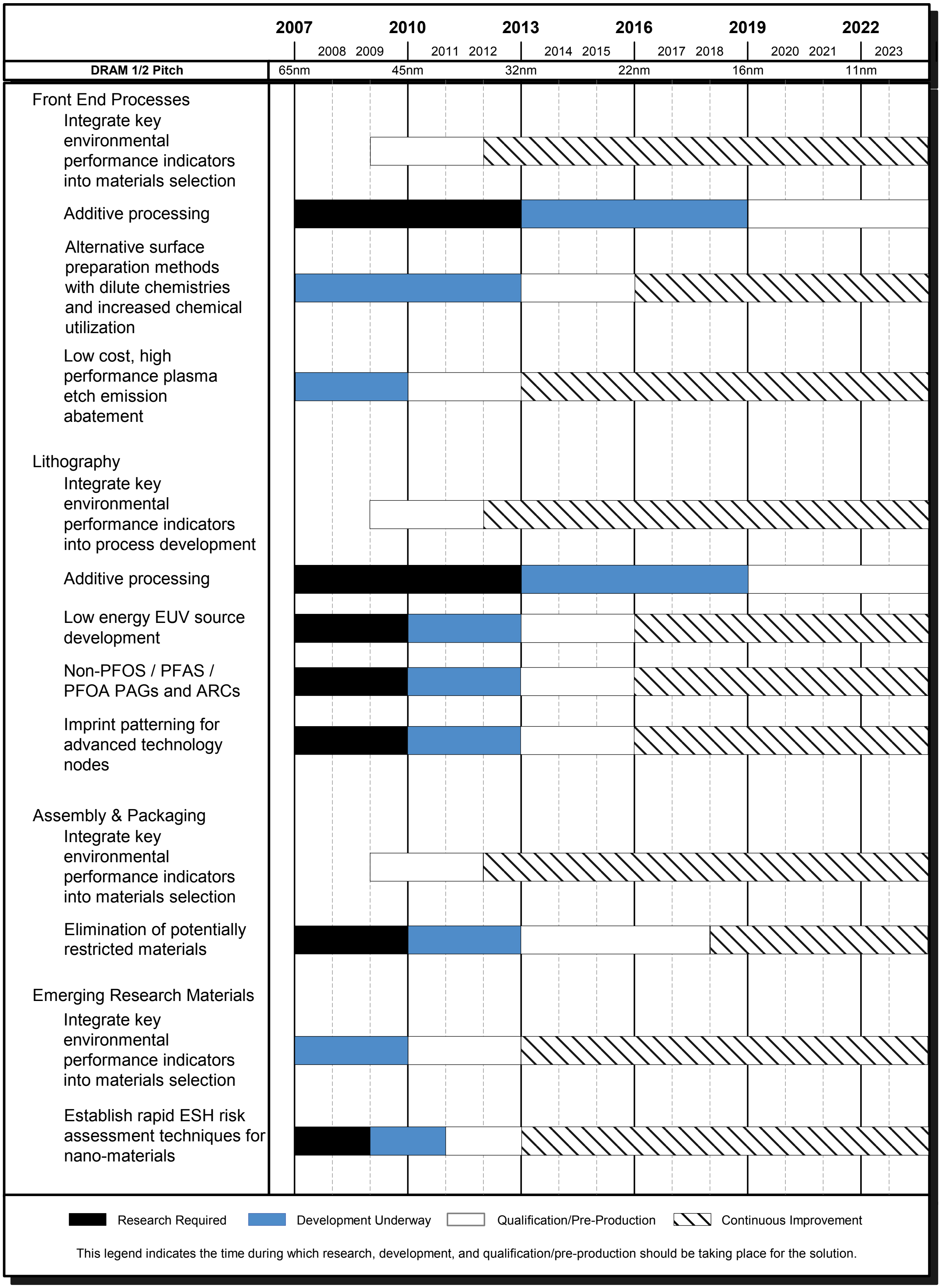


Figure ESH1 Potential Solutions for ESH: Chemicals and Materials Management (continued)

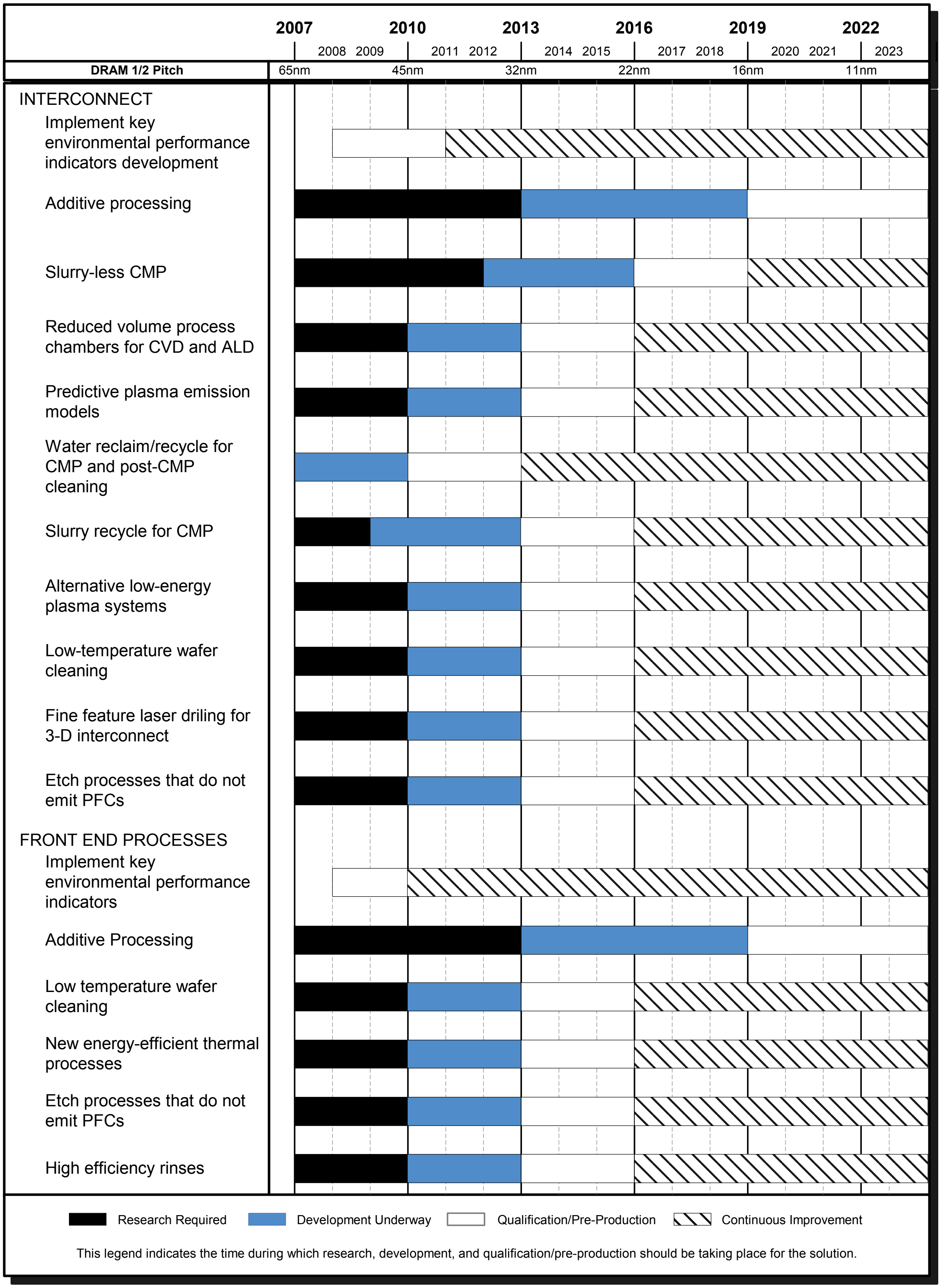


Figure ESH2 Potential Solutions for ESH: Processes and Equipment Management

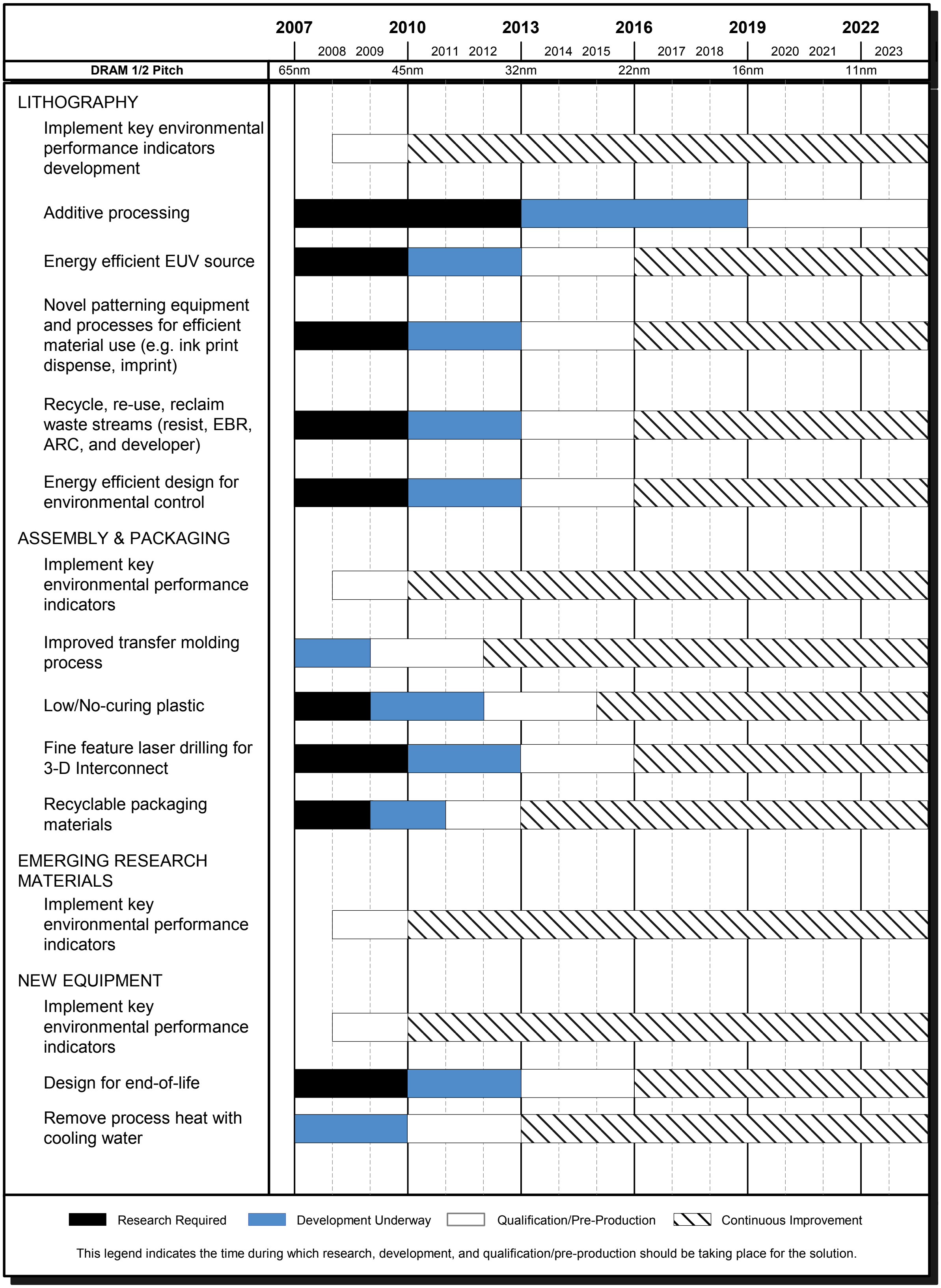
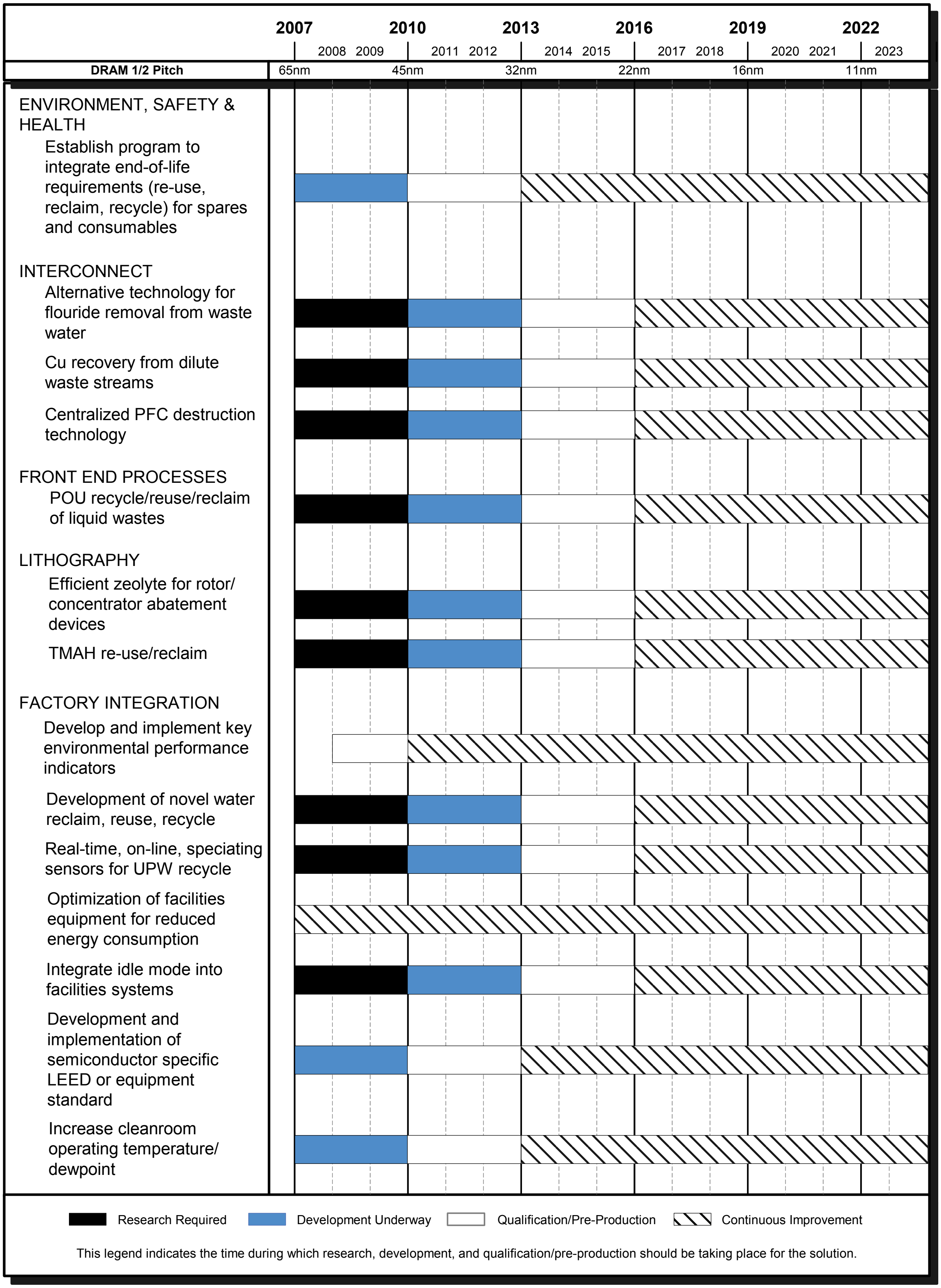


Figure ESH2 Potential Solutions for ESH: Processes and Equipment Management (continued)



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
DRAM 1/2 Pitch	65nm			45nm			32nm			22nm			16nm			11nm	
ENVIRONMENT, SAFETY & HEALTH																	
Establish program to integrate end-of-life requirements (re-use, reclaim, recycle) for spares and consumables	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
INTERCONNECT																	
Alternative technology for flouride removal from waste water	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨
Cu recovery from dilute waste streams	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨
Centralized PFC destruction technology	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨
FRONT END PROCESSES																	
POU recycle/reuse/reclaim of liquid wastes	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨
LITHOGRAPHY																	
Efficient zeolyte for rotor/ concentrator abatement devices	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨
TMAH re-use/reclaim	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨
FACTORY INTEGRATION																	
Develop and implement key environmental performance indicators		□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Development of novel water reclaim, reuse, recycle	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨
Real-time, on-line, speciating sensors for UPW recycle	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨
Optimization of facilities equipment for reduced energy consumption	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Integrate idle mode into facilities systems	■	■	■	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨
Development and implementation of semiconductor specific LEED or equipment standard	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Increase cleanroom operating temperature/ dewpoint	🟦	🟦	🟦	□	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

■ Research Required 🟦 Development Underway □ Qualification/Pre-Production ▨ Continuous Improvement

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

Figure ESH3 Potential Solutions for ESH: Facilities