INTERNATIONAL
TECHNOLOGY ROADMAP
FOR
SEMICONDUCTORS

2011 EDITION

ENVIRONMENT, SAFETY, AND HEALTH

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ENVIRONMENT, SAFETY, AND HEALTH

1. SCOPE

The 2011 ESH section of the overall Roadmap continues to reflect the fact that the principles of successful ESH program execution remain largely independent of the specific technology thrust advances to which they are applied. Thus, many ESH Roadmap elements, such as the Difficult Challenges and the Technology Requirements, bear strong similarities to those in the 2009 Roadmap. As a result, the four basic ESH Roadmap strategies continue as in the 2009 Roadmap, namely:

- To understand (characterize) processes and materials during the development phase
- To use materials that are less hazardous or whose byproducts are less hazardous
- To design products and systems (equipment and facilities) that consume less raw material and resources
- To make the factory safe for employees

By applying these strategies as essential elements to success, the industry continues to be an ESH as well as a technology leader. Semiconductor manufacturers have adopted a business approach to ESH which uses principles that are integrated with manufacturing technologies, products, and services.

A unique consideration in the ESH section of the Roadmap results from the fact that while the Roadmap is by intent and execution a technology-focused document, the ESH section must necessarily comprehend and address various policy and regulatory issues. Any failure to do so could jeopardize the implementation of successfully developed technologies. Such issues for ESH were explicitly recognized for the first time in the 2009 Roadmap by the introduction of ESH Categories and Domains, as will be reviewed shortly. The 2011 ESH Roadmap extends this concept by the introduction of two new Subcategories to reflect the availability of Roadmap quality goals and metrics to address the ESH goals presented.

The ESH roadmap identifies challenges when new wafer processing and assembly technologies move through research and development phases, and towards manufacturing insertion. Following the presentation of ESH Domains & Categories (including the new Subcategories) in Table ESH2, ESH technology requirements are listed in Tables ESH3–7. Potential technology and management solutions to meet these challenges are proposed in Figures ESH1–3. Successful resolution of these challenges will best be realized when ESH concerns are integral in the thinking and actions of process, equipment, and facilities engineers; as well as those of chemical/material and tool suppliers; and finally those of academic and consortia researchers. ESH improvements must also contribute to (or at minimum, not conflict with) enhanced cost, technical performance, and product timing. They must inherently minimize risk, public and employee health & safety effects, and environmental impact. Successful global ESH initiatives must be timely, yet far reaching, to ensure long-term success over the Roadmap's life.

2. DIFFICULT CHALLENGES

The ESH Difficult Challenges (Table ESH1) serve three important purposes. First, there is a new overall challenge which is a consequence of the addition of Subcategories to the previous Categories designation, as will be explained in more detail in section 3.1. Second, the Difficult Challenges reflect inherent ESH science issues within the scope of evolving semiconductor technology (e.g., the need for nanomaterial assessment methodologies). Third, the Difficult Challenges are the starting point for evaluating each technology thrust with significant ESH concerns. This starting point for cross-thrust analysis provides information on needs to be incorporated into the ESH Technology Requirement tables.

The ESH Difficult Challenges are organized into four high level segments: Chemicals and Materials Management, Process and Equipment Management, Facilities Technology Requirements, and Sustainability and Product Stewardship. These segments also serve as the organizing scheme for the Technology Requirements tables.

Chemicals and Materials Management provides guidance on identifying and addressing potential new process chemicals' and materials' ESH characteristics. This guidance is key in selecting preferred chemicals and materials with minimal ESH impact. To protect human health and the environment (as well as to minimize business impacts after processes are developed and introduced into high volume manufacturing), it is essential to determine the physical/chemical, environmental, and toxicological properties of chemicals and materials (as well as any process by-products).

Process and Equipment Management focuses on process and tool design, emphasizing the need for processes and equipment development that meet technology demands, while also reducing impacts on human health, safety, and the environment. Equipment design should 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/materials) through process optimization and implementing cost-effective use reduction solutions (e.g., reduced utility consumption during tool idle periods). Goals should also be applied to process equipment and support equipment such as pumps, chillers and point of use abatement. Replacing hazardous chemicals/materials with more benign ones, managing process emissions and by-products, and reducing consumables are also important considerations in tool design and operation. Design for ease of maintenance and equipment end-of-life are additional challenges.

Facilities Technology Requirements focuses on fab support systems, emphasizing the need for ESH-friendly design and operation of factories and support systems. Resource conservation (water, energy, chemicals/materials, and consumables) is supported by more efficient cleanroom design, air management, heat removal, and demand-based utility consumption. Facility design must be flexible while maintaining efficiency through real-time systems control. Designing factories for end-of-life re-use, especially as factory sizes and building costs increase, is another important consideration.

Sustainability and Product Stewardship have become increasingly important business considerations. To address these challenges in a cost-effective and timely way, robust sustainability metrics are required. In addition, Design for Environment, Safety, and Health (DFESH) should become an integral part of the facility, equipment, and product design as well as management's decision-making. Environmentally friendly end-of-life reuse/recycle/reclaim of facilities, manufacturing equipment, and industry products are increasingly important to serve both business and ESH needs.

Table ESH1 ESH Difficult Challenges

Difficult Challenges ≥ 16 nm	*Summary of Issues*
Overall challenge	There is a need for Roadmap quality goals and metrics need to be defined for a substantial number of ESH technology requirements
Chemicals and materials management	• *Chemical Assessment*: There is a need for robust and rapid assessment methodologies to ensure that new chemicals/materials achieve timely insertion in manufacturing, while protecting human health, safety, and the environment. Given the global options for R&D, pre-manufacturing, and full commercialization, these methodologies must recognize regional regulatory/policy differences, and the overall trends towards lower exposure limits and increased monitoring. • *Chemical Data Availability*: Comprehensive ESH data for many new, proprietary chemicals/materials is incomplete, hampering industry response to the increasing regulatory/policy requirements on their use. In addition, methods for anticipating and forecasting such future regulatory requirements are not well developed.. • *Chemical Exposure Management*: There is incomplete information on how chemicals/materials are used and how process by-products are formed. Also, while methods used to obtain such information are becoming more standardized, their availability varies depending on the specific issue being addressed.
Process and equipment management	• *Process Chemical Optimization* There is a need to develop processes and equipment meeting technology requirements, while at the same time reducing their impact on human health, safety and the environment (e.g., using more benign materials, reducing chemical quantity requirements by more efficient and cost-effective process management). • *Environment Management:* There is a need to understand ESH characteristics, and to develop effective management systems, for process emissions and by-products. In this way, the appropriate mitigations (including the capability for component isolation in waste streams) for such hazardous and non-hazardous emissions and by-products can be properly addressed. Global Warming Emissions Reduction: There is a need to limit emissions of high GWP chemicals from processes which use them, and/or produce them as by-products. • *Water and Energy Conservation:* There is a need for innovative energy- and water-efficient processes and equipment. • *Consumables Optimization:* There is a need for more efficient chemical/material utilization, with improved reuse/recycling/reclaiming of them and their process emissions and by-products. • *Byproducts Management*: There is a need for improved metrology for by-product speciation. • *Chemical Exposure Management:* There is a need to design-out chemical exposure potentials and the requirements for personal protective equipment (PPE) • *Design for Maintenance:* There is a need to design equipment so that commonly serviced components and consumable items are easily and safely accessed, with such maintenance and servicing safely performed by a single person with minimal health and safety risks. • *Equipment End-of-Life:* There is a need to develop effective management systems to address issues related to equipment end-of-life reuse/recycle/reclaim.
Facilities technology requirements	• *Conservation*: There is a need to reduce energy, water and other utilities consumption and for more efficient thermal management of cleanrooms and facilities systems. • *Global Warming Emissions Reduction*: There is a need to design energy efficient manufacturing facilities, to reduce total CO_2 equivalent emissions.
Sustainability and product stewardship	• *Sustainability Metrics:* There is a need for methodologies to define and measure a technology generation's sustainability. • *Design for ESH:* There is a need to make ESH a design-stage parameter for new facilities, equipment, processes and products.

	• *End-of-Life Reuse/Recycle/Reclaim:* There is a need to design facilities, equipment and products to facilitate these end-of-life issues
Difficult Challenges < 16 nm	*Summary of Issues*
Chemicals and materials management	• *Chemical Assessment*: There is a need for robust and rapid assessment methodologies to ensure that new chemicals/materials achieve timely insertion in manufacturing, while protecting human health, safety, and the environment. • *Chemical Data Availability*: There is incomplete comprehensive ESH data for many new, proprietary chemicals/materials, to be able to respond to the increasing regulatory/policy requirements on their use
Process and equipment management	· *Chemical Reduction*: There is a need to develop processes and equipment meeting technology requirements, while also reducing their impact on human health, safety and the environment (e.g., using more benign materials, reducing chemical quantity requirements by more efficient and cost-effective process management). There is a need to limit emissions of high GWP chemicals from processes which use them, and/or produce them as by-products. • *Environment Management:* There is a need to understand ESH characteristics, and to develop effective management systems, for process emissions and by-products. In this way, the appropriate mitigations for such hazardous and non-hazardous emissions and by-products can be addressed. • *Water and Energy Conservation:* There is a need to reduce water and energy consumption, and for innovative energy- and water-efficient processes and equipment. • *Consumables Optimization:* There is a need for more efficient chemical/material utilization, including their increased reuse/recycle/reclaim (and of their process emissions and by-products). • *Chemical Exposure Management:* There is a need to design-out chemical exposure potentials and personal protective equipment (PPE) requirements. • *Design for Maintenance:* There is a need to design equipment so that commonly serviced components and consumable items are easily and safely accessed, with such maintenance and servicing safely performed by a single person with minimal health and safety risks. • *Equipment End-of-Life:* There is a need to develop effective management systems to address issues related to equipment reuse/recycle/reclaim.
Facilities technology requirements	• *Conservation*: There is a need to reduce energy, water and other utilities use, and for more efficient thermal management of cleanrooms and facilities systems. • *Global Warming Emissions Reduction*: There is a need to design energy efficient manufacturing facilities, to enable reducing total CO_2 equivalent emissions.
Sustainability and product stewardship	• *Sustainability Metrics:* There is a need for methodologies to define and measure sustainability by technology generation, as well as at the factory infrastructure level. • *Design for ESH:* There is a need to make ESH a design-stage parameter for new facilities, equipment, processes and products, with methodologies to holistically evaluate and quantify the ESH impacts of facilities operations, processes, chemicals/materials, consumables, and process equipment for the total manufacturing flow. • *End-of-Life Reuse/Recycle/Reclaim*: There is a need to design facilities, equipment and products to facilitate these end-of-life issues

3. TECHNOLOGY REQUIREMENTS

3.1 ESH CATEGORIES AND SUBCATEGORIES

The 2009 ESH Roadmap departed from earlier versions which had presented the technology requirements as basically undifferentiated. Instead, the 2009 Roadmap recognized that given the limited resources available to address the total ESH requirements set, guidance should be provided to focus on areas of greatest added benefit, in addition to the ESH improvements gained. To accomplish this goal, all ESH requirements were placed in one of three Categories:

- Critical: Any requirement in this category is an essential item for technology success/implementation as well as ESH benefits. If not addressed, it could compromise the technology’s ability to insert into manufacturing, due to potential or existing policy/regulatory issues (whether internally or externally driven) in at least one of the ITRS member regions. These requirements have the highest priority for action.

- Important: Any requirement in this category is a key item for process success as well as ESH benefits. If not addressed, it could compromise the technology’s cost of ownership (CoO) in manufacturing, due to factors such as throughput, yield, and chemical/material and/or tool costs (including disposal/abatement). These requirements have the next highest priority for action.

- Useful: Any requirement in this category is a key item for ESH benefits (“best practices”), but without any clear additional factors which would place it in either of the above two categories. If not addressed, it could compromise the technology's ability to achieve the lowest ESH impact when inserted into manufacturing. These requirements have a lower priority for action.

As noted in the 2009 Roadmap, requirements in the Critical category are generally straightforward to define, based on an understanding of policy/regulatory actions underway or being contemplated. Some judgment was recognized as needed in distinguishing between Important and Useful; i.e., how large should a CoO benefit be to categorize an item as Important? Such decisions continue to be imprecise, but they provide an initial assessment for further consideration and updates in future Roadmaps.

The 2011 ESH Roadmap further refines the Category designation by the addition of two new Subcategories. These Subcategories were developed based on considering the specific needs defined in the Technology Requirements tables, versus the guiding principles of the overall Roadmap. The 2009 Roadmap Executive Summary states such principles as including "to present industry-wide consensus on the 'best current estimate' of the industry's research and development needs out to a 15-year horizon," and to "assess … the principal technology needs to guide the shared research, showing the 'targets' that need to be met."

Now, in a substantial number of cases, ESH Roadmap goals have historically been stated in incremental (that is, evolutionary) terms. These goals included improving process chemical utilizations and process emissions by defined percentages over certain periods, versus baselines either established or to be determined. While these do in fact represent important goals for improving the industry's ESH performance, goals framed in this way fall short of the Roadmap principles noted above.

That is, the ESH Roadmap should provide the basis for action for the full range of developers who support and enable the industry's technologies. Those actions will be most meaningful when goals can be set which challenge the developers beyond the incremental improvements which are already an integral part of the industry's continuous improvement focus. To this end, the ESH Roadmap now includes a new element in the ESH Categories scheme, namely, the addition of two Subcategories, as follows:

- D = Data available: there is a consensus definition, and there is adequate data available, to drive meaningful action under the ITRS.
- N = No data available: there is not a consensus definition, and/or there is inadequate data available, to drive meaningful action under the ITRS.

The Requirements tables will contain only the Critical and Important items, with each of those items also carrying the appropriate Subcategory designation. As will be seen, this results in what appears to be a major simplification of many of the Requirements tables. In fact, what has occurred is that much of the guidance to suppliers has shifted from the incremental – essentially place-holding – goals of earlier ESH Roadmaps to a clearer expression of the need to define Roadmap-quality goals, which have been clearly lacking in many instances. Such definition can be expected to be a significant focus for the ESH Roadmap in the coming years.

All requirements in all Categories are presented in an ESH Domains table (Table ESH2). The Domains chosen are not unique, but simply selected to provide a set of unifying ESH elements for a single representation of all requirements in all three Categories:

- Restricted Chemicals. By nature, this Domain highlights chemicals which fall into the Critical Category
- New Chemicals. There are a variety of emerging chemicals and materials, whose exact specifications and ESH properties are not always fully established when they enter into new process consideration.
- Nanotechnology. While formally only a subset of New Chemicals, nanometer-scale chemicals and materials can present unique ESH issues, which are highlighted by their separation into their own Domain.
- Utilization/Waste Reduction. The four basic ESH strategies defined in the Scope all have a prominent role in this Domain.
- Energy. Given the increasing attention to greenhouse gas control, carbon footprint, and similar energy-control metrics, this area stands out as one deserving attention at the Domain level.
- Green Fab. This is a broad – and at present not-well-defined or universally agreed-on – term meant to represent fab operations conducted with minimal ESH impact (and the process and economic benefits which may derive

from such practices). This Domain includes sustainability issues, as well as the full life-cycle considerations for chemicals/materials, tools and processes, the full fab infrastructure, and the products derived from them.

Note also that for all the succeeding Intrinsic and Technology Requirements tables, the Category designations are applied only to the *ESH#a* tables representing the near-term years, and not to the *ESH#b* tables representing the long-term years, for two reasons. First, the long-term value can likely be inferred from the near-term table entry. Second, although there is generally not a precise assessment of a Category in the long-term years, there is adequate opportunity to better define the designation in later Roadmap versions.

Table ESH2 ESH Requirements by Domain and Category

3.2 ESH INTRINSIC REQUIREMENTS

Scientists and engineers responsible for new technology development require an explicit target set for ESH-related technology decisions, to complement the mainstream technology objectives. Those ESH objectives for specific Roadmap technical thrusts are covered in Section 3.3. In addition, it is also important that such focused objectives lead to broader overall improvements in the consumption of energy, water, and chemicals, and in waste reduction, for the total fab tool set, and for fab facilities overall. Table ESH3 outlines these ESH goals for those items in the Critical and Important Categories (with the Useful items shown under the Intrinsic sub-headings in Table ESH2).

Tables ESH3A and B ESH Intrinsic Requirements

3.3 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 ESH4 and ESH5, which correspond to two of the four ESH Difficult Challenges themes (Chemicals and Materials Management, and Process and Equipment Management). ESH requirements were established based on mapping the technical thrust needs against the ESH Difficult Challenges. The most striking aspect of these tables versus those for the 2009 Roadmap is the absence, except in a few cases, of any specific ESH goals. Instead, the new goal in those cases is to “establish Roadmap quality goal and metrics.” This change results from the incorporation of Subcategories in the ESH Roadmap, as detailed in section 3.1. Thus, a principal near-term effort for the ESH Roadmap community will be to identify these goals and metrics, and to promulgate them to the ESH Roadmap’s audience in future Roadmap versions.

Specific thrust-based technology requirements and issues are discussed below.

Tables ESH4A and B Chemicals and Materials Management Technology Requirements

Tables ESH5A and B Process and Equipment Management Technology Requirements

3.3.1 INTERCONNECT

The only explicitly-defined ESH goal for Interconnect is on copper recycle/reclaim. Thus, the discussion here centers on those issues which need to be addressed in setting Roadmap quality goals and metrics for the interconnect technology requirements judged to be Critical and Important.

Through much of this decade, leading-edge interconnect technology is expected to generally follow that which has served the industry for the past ten years: copper-based metallization and low-k dielectrics, following damascene processing approaches. However, within that approach, there can be chemical/material changes, as well as process modifications, whose ESH implications must be considered. For metallization, these changes may include new formulations for copper ECD (including extending copper plating bath life or recycling), changes in barrier and nucleation films (especially if the dominant PVD processes move towards CVD/ALD processes), and the emergence of new capping layers and processes. For the dielectrics, increasingly porous films can involve new precursors and so new process emissions, all of which must be evaluated for ESH concerns. Such dielectrics can also require pore sealing agents. Finally, the supporting technologies of planarization and surface treatment will also evolve as any of the interconnect stack’s films change, and the same ESH considerations must apply there as well.

Planarization’s increasing use presents particular issues both in consumables (e.g., slurries, pads, and brushes), as well as major chemicals and water use. Therefore, efforts should be made to develop planarization processes that will reduce overall water consumption, including the possible implementation of water recycle/reclaim for planarization and post-planarization cleans.

High GWP (global warming potential) PFCs (perfluorocompounds) are used extensively in interconnect dry etch and chamber cleaning applications. For chamber cleaning, processes that do not use PFCs have been evaluated; note, however, that the residues of carbon-containing low-k films which are processed in such chambers can produce PFC emissions (e.g., CF_4) in any case. At present, dry etch processes for low-k dielectrics are all based on fluorocarbon compounds (whether or not they fall into the high GWP PFC family), and so PFC emissions (as either byproducts or unreacted starting compounds) must be managed. The semiconductor industry's present goal reduces absolute PFC emissions 10% from a 1995 baseline. To maintain this aggressive goal, and to ensure that these chemicals remain available for industry use, the industry must strive to reduce PFC emissions by process optimization, alternative chemistries, and/or abatement. Fluorinated heat transfer fluids also have high global warming potential, and these materials' emissions must be minimized. Another high GWP process chemical to be addressed is N_2O (used in oxynitride deposition processes).

With the expected continuing growth of chip-to-chip interconnects (commonly referred to as 3D technology), etch processes based on PFCs such as sulfur hexafluoride are being increasingly used for through-silicon via etch. This growing application will place even greater demands on maintaining the PFC reduction goals versus the 1995 baseline.

To meet expected energy conservation goals, equipment (plasma-enhanced CVD, dry etch, and CMP) power requirements (including reducing support equipment energy consumption) must be minimized. Plasma processes are both energy-intensive and inefficient in using input chemistries (e.g., often achieving only 10–30% dissociation, by design, in etch processes). 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 (including eliminating simultaneous heating and cooling for temperature control devices) could help decrease energy use and improve control. Greater use of cooling water to remove heat from equipment, rather than dissipating heat into the cleanroom, results in fab energy savings.

Later in this decade, new interconnect materials sets may begin to emerge, including non-metallic conductors (likely based on carbon nanomaterials technology) and air-gap dielectrics (using fugitive materials). Thus, these new chemical/materials, and their process emissions, will need to be examined for ESH concerns – especially given the incomplete current definition of nanomaterials' ESH properties.

3.3.2 FRONT END PROCESSING

There are no explicitly-defined ESH goals for Front End Processing. Thus, the discussion here is entirely on those issues which need to be addressed in setting Roadmap quality goals and metrics for the front end technology requirements judged to be Critical and Important.

Front end chemicals/materials challenges include the thrust's evolving precursors and processes for substrates, dopants, gate stacks, conductors and insulators. The applications for contacts, memory structures, and supporting chemicals and processes should comprehend the ESH concerns of chemical/material selection for reduced ESH impact, and efficient use of natural resources (e.g., water and energy) in tools and processes. These principles should be applied throughout this thrust, as exemplified in the examples below.

ESH concerns for surface preparation focus on new clean techniques, chemical/material usage, and water and energy consumption. Chemical use optimization should be applied to both conventional and alternative cleaning processes. Fluid flow optimization and sensor-based process control can provide both ESH and process advantages.

Alternative clean processes (e.g., dilute chemistries, solvent-based, sonic energy enhancement, simplified process flows, DI/ozone, gas phase, cryogenic, hot-UPW) may reduce ESH hazards and chemical consumption. The impact of such alternative cleaning methods on energy consumption should be addressed. Sustainable, optimized water use strategies (e.g., more efficient UPW production, reduced water consumption, and efficient rinsing) all can contribute to enhanced ESH performance.

As wet tool designs enable such enhancements, attention should be paid to controlling process emissions, ergonomic and robotics safety principles, and ease and safety of equipment maintenance. The trend towards single-wafer cleaning needs to be managed for efficient use of chemicals and resources.

While CMP processes in the front end are generally fewer than for interconnects, they still apply in areas such as shallow trench isolation (STI), contact metallization, and gate stack processing. The ESH issues common to all CMP processes – chemicals, consumables, and water optimization (including recycle/reclaim in the last case) – are important here.

New gate stack materials (both high-κ and electrode) require assessing potential hazards associated with both the precursors, as well as their associated deposition and etch processes. Thus, precursor ESH properties, and of process byproducts, must be understood so that engineering controls and any needed personal protective equipment can be utilized. These processes should be optimized for maximum chemical utilization and efficient energy use.

As doping technologies evolve, there will be a continuing need to properly manage reactive hydrides (SiH_4, B_2H_6, PH_3, SbH_3, AsH_3, possibly others) and metal alkyls. Sub-atmospheric delivery systems have proved effective for their ESH benefits, and their use could expand in this area.

As for Interconnect, PFC use in front end plasma etch and chamber clean processes will be challenged by both general ESH considerations, as well as the industry's goal to maintain absolute PFC emissions at 10% from the 1995 baseline. Here again, the industry must strive to reduce PFC emissions by process optimization, alternative chemistries, and/or abatement. As another high GWP process chemical, N_2O's emissions from furnace nitride processes should be characterized and minimized.

Emerging technologies for new channel materials involve both heavy metals and arsenic, all of which are coming under increasing regulatory scrutiny, along with the overall ESH concerns for understanding and proper management of the precursors and processes. In addition, new channel materials may require new cleaning chemistries and processes whose ESH issues must be considered. Similarly, new memory technologies are proposing new heavy metals usage, and the same scrutiny must be applied here.

3.3.3 LITHOGRAPHY

The only explicitly-defined ESH goal for Lithography is on PFOS/PFAS/PFOA alternatives development. Thus, the discussion here centers on those issues which need to be addressed in setting Roadmap quality goals and metrics for the lithography technology requirements judged to be Critical and Important.

For the lithography chemicals/materials and consumables, there are two principal issues. The first issue is the explicitly recognized need for alternatives to the PFOS contained in developers, etchants, anti-reflective coatings (ARCs), and photoacid generators (PAGs) in chemically amplified resists. Ultimately, compositions free of any PFOS/PFAS/PFOA species should be developed. The second issue on novel patterning chemicals/materials includes a number of areas, including 193nm immersion lithography, with new compositions such as water resistant photoresists and anti-reflective coatings. In addition, with the introduction of 193nm double processing schemes, new types of chemicals are appearing, such as those for "resist freeze" processes. Also, a wavelength shift from 193nm to EUV at 13.5nm will bring its own set of changes in photoresists and all the ancillary chemicals associated with them, and whose ESH impacts must be assessed and optimized. Finally, while the above discussion has focused on the 193nm and EUV exposure technologies, there are other patterning approaches under study, notably imprint, e-beam direct writing, and direct self-assembly (DSA). All the chemical/material concerns for current flood exposure technologies will apply in their own way to these areas as well.

In the process area, the concern is EUV technology, with energy consumption the major area to be addressed. The following brief analysis is only semi-quantitative, but serves to illustrate the nature of the concern. According to the Yield Enhancement thrust, a leading edge fab today consumes about 18 MW of power. According to the Lithography thrust, a single EUV exposure tool is expected to draw 0.5-2 MW. Thus, even for a fab containing only a few such tools, EUV process energy consumption becomes an important factor to be addressed in the industry's goals for energy metrics, carbon footprint, and greenhouse gas emissions.

3.3.4 ASSEMBLY AND PACKAGING

There are no explicitly-defined ESH goals for Assembly and Packaging. Thus, the discussion here is on the one issue which needs to be addressed in setting Roadmap quality goals and metrics for the assembly and packaging requirements judged to be Critical and Important.

A significant issue for 3D technology has already been noted for Interconnect, but it is one shared with Assembly & Packaging: silicon through-via etch processes based on PFCs such as sulfur hexafluoride will place even greater demands on reaching and holding the industry's PFC reduction goals.

3.3.5 EMERGING RESEARCH MATERIALS

There are no explicitly-defined ESH goals for Emerging Research Materials. Thus, the discussion here is entirely on those issues which need to be addressed in setting Roadmap quality goals and metrics for the emerging research materials requirements judged to be Critical and Important.

Some proposed new materials contain metals which are currently little-used in semiconductor manufacturing. Understanding their ESH properties, and the potential policy/regulatory restrictions on their use, will be critical to formulating plans for their further development and manufacturing applications.

Also, as nanometer-scale semiconductor manufacturing chemicals/materials come into wider use (beyond those currently found in, say, CMP slurry particles), there should be increased focus on these materials' ESH properties. It is well known that nano-sized materials can have unique and diverse properties compared to their macro/bulk (even at micron dimensions) forms. These differences must be understood for the unique ESH challenges they may present. In addition, the new materials' small size may make standard ESH controls (e.g., 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 nanomaterials' presence in the workplace, in waste streams, and in the environment.
- Evaluating and developing appropriate protocols to ensure worker health and safety.
- Evaluating and developing emission control equipment to ensure effective treatment of nanomaterial-containing waste streams.
- Understanding new nanomaterials' toxicity as it may differ from their bulk forms. This goal involves both developing rapid nanomaterials toxicity assessment methods, as well as nanomaterials toxicity models.

3.4 FACTORY INTEGRATION

Factory planning, design, and construction considerations are integral to the industry's responsible ESH performance. Table ESH6 establishes such goals for factory design and operation.

Tables ESH6A and B Facilities Technology Requirements

Factory design lacks explicitly-defined ESH goals. Thus, the discussion here centers on those issues which need to be addressed in setting Roadmap quality goals and metrics in this area. The interfaces between factory, equipment, and workers – which strongly influence the industry's ESH performance – will benefit from standardization of safety and environmental systems, procedures, and methodologies. Sharing these practices can reduce start-up schedules and will result in greater equipment supplier cooperation for interfacing their products into factories. Early incorporation 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 considers the transition from 300 to 450 mm wafers, which require larger process tools and potentially greater quantities of chemicals and resources.

Greater standardization in manufacturing and assembly/test equipment (equipment design, design verification, ESH qualification, and signoff) will improve ESH performance, start-up efficiency, and cost. Additionally, ESH practice standardization in equipment maintenance, modification, decommissioning, and final disposition will also result in substantial ESH performance and cost improvements over the life of equipment and factories.

Standardization of building safety systems, and their process equipment interfaces, will improve safety and also increase installation efficiency and reduce start-up time. This standardization would include, but is not limited to, fire detection and suppression systems (and their monitoring interfaces), 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 Roadmap sections should be complemented by designs that serve to isolate personnel from equipment during operation and maintenance.

The safety issues associated with factory support systems should also be targeted for improvement. Improved risk assessment methodologies and their consistent utilization during the design phase will enhance this effort.

A thorough understanding of potential safety risks associated with automated equipment will drive the standards development needed to assure safe working conditions. 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. Future factory planning (and for existing factory modifications) should involve cooperative efforts (on a global level) with code and government bodies, to ensure that equipment and factory technology advances are comprehended and used in new and updated regulations. The semiconductor industry should move to establish basic ESH specifications that apply to all equipment and factory practices worldwide.

For the natural resource and chemical/material-based targets in Table ESH6, it is factory design that defines the systems to deliver process chemical/materials to process equipment, to manage by-products, and to control the workplace environment. Future factory design must balance the conservation, reduction, and management of resources and chemical/materials. 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.

Increases in wafer size and process steps, as well as the need for higher purity water and chemicals/materials, indicates a trend for greater resource (water, energy, and chemicals/materials) usage per wafer. This trend can be reversed by developing higher efficiency processes and tools, and by adopting strategies such as recycling of spent chemicals, water, and waste for process applications and reuse for non-process applications. Resource utilization efficiency in semiconductor tools can be improved.

Most water used in semiconductor manufacturing is ultrapure water (UPW). Since UPW production requires large chemical quantities, any increase in UPW consumption and quality results in greater chemical consumption (and UPW production cost). A UPW consumption decrease will reduce both chemicals' environmental effects, as well as manufacturing costs. Recycling higher quality water for process applications, and reusing lower quality water for non-process applications, are both important. Where water is plentiful, wastewater recycling will depend on local water reuse options and associated recycling costs.

Energy source limitations could potentially restrict the industry's ability to expand existing factories or build new ones. Continual evolution in processes, products and product volume requires design for flexibility and modulation without compromising energy efficiency. Semiconductor manufacturers have demonstrated improved energy efficiencies over the past decade; potential resource limitations require the industry to continue this trend. Significant efficiency improvement opportunities include vacuum pumps, POU chillers and heaters, uninterrupted power systems, and power transforming devices (for example, RF generators and transformers). Besides the need for more energy efficient tools (with the potential emergence of EUV lithographic tools being a particular concern), it is necessary to reduce tools' heat load/impact of the on the cleanroom, and to enhance idle mode tool capabilities.

While much of the responsibility for resource reduction and waste minimization rests with equipment suppliers and process technologists, applying advanced resource management programs to factory systems will have a significant impact as well. These future programs' goal is to build factories that minimize resource consumption and maximize the reuse, recycle, or reclaim of by-products, moving towards 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.

3.5 SUSTAINABILITY AND PRODUCT STEWARDSHIP

As indicated in Table ESH7, there are no explicitly-defined ESH goals for sustainability and product stewardship. Thus, the discussion here is on the issues which need to be addressed in setting Roadmap quality goals and metrics in the areas judged to be Critical and Important.

Table ESH7 Sustainability and Product Stewardship Technology Requirements

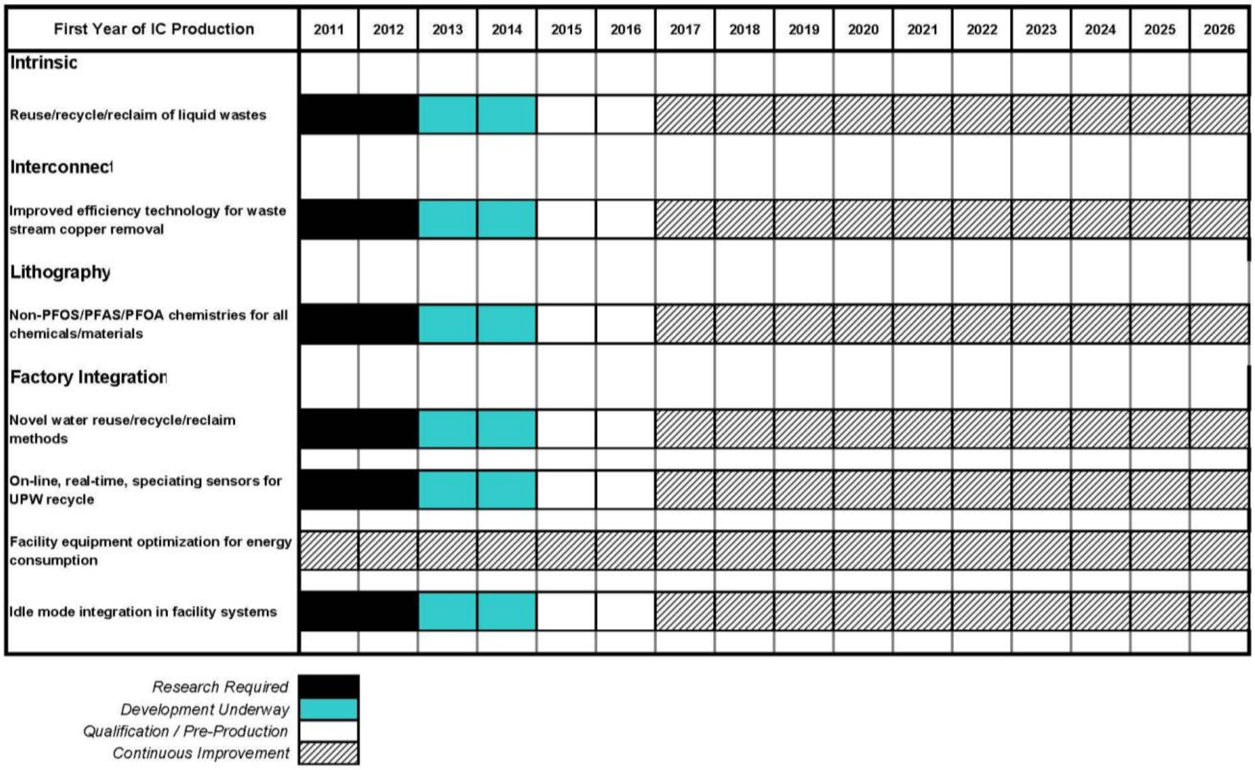
Climate change is a universally recognized 21st century global environmental challenge, driving international efforts to reduce not only emissions of semiconductor manufacturing greenhouse gases (e.g., PFCs, N_2O, fluorinated heat transfer fluids), but also carbon dioxide emissions. Carbon footprint (a means to track a product's or process' impact on global climate) is defined as the total greenhouse gas emissions over a product's full life cycle, including the CO_2 from electricity generation. A reduced carbon footprint is vital to the industry's sustainability; therefore, carbon footprint metrics should be developed to track progress.

Design for ESH (DFESH) is the term applied to ESH improvements' integration and proliferation into technology design. It allows for the early evaluation of ESH issues related to critical technology developments, and it ensures that there are no ESH-related "show stoppers." DFESH requires a comprehensive understanding of tools and materials development, facility design, waste and resource management, and their effects on ESH performance. DFESH incorporates ESH improvements into the way products are manufactured, while maintaining desirable product price/performance and quality characteristics.

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

4. POTENTIAL SOLUTIONS

Potential solutions are outlined in Figure ESH1. Note that this list is substantially shorter than in earlier Roadmap versions, since only those requirements having an explicit goal (that is, which fall in the D Subcategory as defined in section 3.1) are presented here. That is, until explicit ESH goals can be defined, efforts to suggest potential solutions will not be meaningful to the Roadmap's intended audience.



First Year of IC Production	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Intrinsic																
Reuse/recycle/reclaim of liquid wastes	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Interconnect																
Improved efficiency technology for waste stream copper removal	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Lithography																
Non-PFOS/PFAS/PFOA chemistries for all chemicals/materials	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Factory Integration																
Novel water reuse/recycle/reclaim methods	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
On-line, real-time, speciating sensors for UPW recycle	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Facility equipment optimization for energy consumption	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Idle mode integration in facility systems	■	■	🟦	🟦	□	□	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

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

Figure ESH1 ESH Potential Solutions

5. CROSS-CUT ISSUES

The cross-cut issues which have been long been central to the ESH Roadmap's development have been described in detail in Section 3. In addition, the 2011 Roadmap includes for the first time MEMS as a technical thrust. While the full details of ESH issues associated with that new thrust will be developed in the future, there is one area which is already clearly an ESH concern. MEMS structures often involve creating high aspect ratio (HAR) features by dry etching, in processes typically using PFCs such as SF_6 and c-C_4F_8. Given the WSC PFC emission reduction commitments, any expanded PFC use in MEMS application must be carefully considered against the established reduction goals.

6. OTHER CONSIDERATIONS

The 2009 Roadmap guidance indicates 450 mm wafer processing in pilot lines in 2012-2014, a possible production manufacturing ramp in 2014-2016. For chemicals/materials, the goal is to remain constant, and aim to reduce consumption, on a normalized (per cm^2) basis. There are currently goals being developed by industry groups to hold energy, water, and air emissions constant on an absolute (per wafer) basis. Such aggressive goals (given the more than doubling of the wafer surface area to be processed versus 300mm) will need to be reassessed in future Roadmap editions.

7. CONCLUSIONS

The 2011 ESH Roadmap differs significantly from its predecessors as a result of the full implementation of ESH Categories (first introduced in the 2009 Roadmap) and Subcategories (introduced here). That implementation has led to the exclusion of the (largely place-holding) incremental goals for many technology requirements, based on the absence of appropriate Roadmap-quality goals and metrics. As a result, a major focus for upcoming ESH Roadmap efforts will be to develop such goals and metrics in a way which is properly aligned with the principles and intent of the overall Roadmap.