INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS 2.0

2015 EDITION

ENVIRONMENT, SAFETY, AND HEALTH

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ENVIRONMENT, SAFETY, AND HEALTH

1. SCOPE

The 2015 Environment, Safety, and Health (ESH) section of the overall ITRS 1.0 Roadmap continues the process of projecting the Environment, Safety, and Health (ESH) activities, strategies and vision for, Factory Integration, and the overall 2015 ITRS Roadmap. To this end, it continues the progressive work of the 2013 edition and 2014 updates with an aim of providing the principles of a successful, sustainable, long range, global, industry-wide ESH program. The Semiconductor Industry is a Global Leader in ESH and it is deemed essential that this primary position is maintained. Execution remains largely independent of the specific technology thrust advances to which the principles are applied. Thus, many ESH Roadmap elements, such as the Difficult Challenges and the Technology Requirements, feed directly into the Focus Group Roadmaps of ITRS 2.0, notably Factory Integration. Significant materials have been added to the Factory Integration section of this Roadmap in 2015. The six basic and overarching ESH Roadmap strategies have been well-communicated and are presented here:

- To fully 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 materials and resources;
- To make the factory, and fundamental industry supply chain safe for employees and the environment;
- To provide clear global ESH perspective in regards to new materials, sustainability and green chemistry;
- To provide proactive engagement with stakeholder partners and customers and reset strategic focus on the roadmap goals.

By applying these six core strategies as the essential elements to success, the Semiconductor Industry continues as an ESH leader as well as an overall technology leader. Semiconductor manufacturers have adopted a business approach to ESH which uses principles that are deeply integrated with factory manufacturing technologies, supply chain, products, and services. Product Lifecycle and Green Chemistry outlines are further added here for 2015.

Consistent with the principles and concepts of Green Chemistry, is the application of Alternative Assessment Methodology, enabling the selection of less ESH impactful materials, proactively. Such methods can be viewed as a practical implementation vehicle for Green Chemistry. Im the latter part of 2015, a project team completed work on a comprehensive evaluation of review of Alternative Assessment Evaluation Methods, based on key criteria, using several representative materials of process and product significance to the semiconductor and electronics industries. This effort was sponsored by The International Electronics Manufacturing Initiative (iNEMI), a not-for-profit, R&D consortium of ~100 leading electronics manufacturers, suppliers, associations, government agencies and universities. They develop roadmaps for the global electronics industry, describing future technology requirements, identifying and prioritizing technologies and infrastructure gaps, in a similar way to how the ITRS does this for the semiconductor industry. Given the increasing focus on product content regulations globally, INEMI was motivated to support this work, to promote processes and emphasize the value of tools which enable the selection of more benign materials. As part of this effort, the project team examined existing environmental/toxicology assessment tools, methods and frameworks which have been developed by various sources (industry, NGOs, academia and government agencies), with the goal of identifying their applicability to both current and future electronics manufacturing and products. Given that there is no universally applicable or accepted tool, this effort strove to conduct limited benchmark testing/evaluation of key alternative assessment tools, resulting in a gap analysis in matrix form, with pros/cons of each methodology. The completion of this first project phase, resulted in the development of an Alternative Assessment Framework, which was a stakeholder aligned methodology that represents a stakeholder aligned approach, forming the basis for a common industry approach to performing alternative assessments, and was based on the National Academies Report. Moreover, the 14 alternative assessment tools that were evaluated represented tools that have been shown to have future potential regulatory interest, and which can be used in the context of the aforementioned framework. These were also grouped into like categories, which can be useful to electronics manufacturers and upstream by the semiconductor industry. Utilization of these tools by semiconductor manufacturers and their suppliers upstream will provide greater insight and better decision making for materials design and selection. This proactive look ahead can be of significant value downstream, in terms of designing out product content issues. The second phase of this work is now being developed and should be finalized in early 2016.

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 global, local and industrial policy and regulatory issues. This is an increasingly large activity. Any failure to do so could jeopardize the implementation of successfully developed technologies. The ESH Roadmap improved for 2015 further extends this concept, and pays deeper attention to a wider range of global regulations covering materials and other ESH considerations. This is specifically important in two areas highlighted previously in 2013 - nanomaterials and the significantly broader elemental range of emerging constructional materials and their compounds used in intregrated circuit manufacturing. Fab water and energy usage have become increasingly important issues in locations where such resources are not abundant. The adoption of EUV lithography, expanded use of single wafer cleans, and later beyond 2020, 450mm wafer processing will all exacerbate these sustainability issues and the scale of this challenge is clearly shown for the next 15 years. It becomes a bigger challenge for the industry to contain rises in energy and cooling sufficiently; accordingly more work will be needed to ensure future manufacturing sustainability consistent with cost, performance and local regulatory restrictions. One consequence of this is the need to significantly increase water recycling in Fabs, and more engineering efforts to monitor and optimize tool power usage.

The ESH 2015 Roadmap identifies challenges when new wafer processing and A&P technologies move through research and development phases, and towards manufacturing insertion in Table ESH1. Following the presentation of ESH Domains and Categories in Table ESH2, ESH technology requirements are clearly listed in Tables ESH3, 4 and 5. A greater focus has been placed on Sustainability and Green Chemistry in Tables ESH4-5 and the process explained in the separate figure ESH3. Potential technology and management solutions to meet these challenges are proposed in Figures ESH1 and ESH2. 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; chemical/material and tool suppliers; and academic and consortia researchers. ESH improvements must also support (or at minimum, not conflict with) enhanced technical performance, product timing, and cost-effectiveness. Further, ESH improvements must inherently minimize risk, public and employee health and safety effects, and environmental impact. For this purpose a new Figure ESH2 has been added to explain the necessary processes for Consensus Building of Stakeholders to Ensure Full Lifecycle Risk Assessment. Successful global ESH initiatives must be timely, yet far reaching, to ensure long-term success of the entire Semiconductor Technology Roadmap.

2. DIFFICULT CHALLENGES

The ESH Difficult Challenges (Table ESH1) serves two important purposes. First, the Difficult Challenges reflect inherent ESH science issues within the scope of evolving semiconductor technology (e.g., the need for nanomaterial assessment methodologies). Second, 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 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 and to minimize business impacts after processes are developed and introduced into high volume manufacturing (HVM), 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 integration between the emerging materials, process, equipment and device performance requirements in alignment with technology demands, while also reducing impacts on human health, safety, and the environment. Equipment design should minimize the potential for chemical/material exposures, the need for personal protective equipment (PPE), and ergonomic issues for equipment operators. Goals connected with the resource conservations are covered in the facility section. As shown by the device roadmaps, we are moving into a non-linear change in technology that introduces new materials and process integration requirements as well as the need for equipment modifications. Introduction of III-V compounds raises the need for detailed ESH controls and abatement modifications. New materials and processes require detailed process monitoring, equipment characterizations, metrology development and emission monitoring. Design for ease of maintenance and equipment end-of-life that align with the ESH issues defined by the new chemical compounds 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. Generally we have followed a strategy of moving these key parameters from a qualitative reference to a full model-based quantitative form. 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***	
	Summary of Issues
Overall Challenge	There is a need for conventional Roadmap quality goals and metrics to be defined for a substantial number of ESH technology requirements. Some improvents in Quantitative Analysis have been made, and this process is extended in 2015. More will be addressed in future revisions. The increasingly complex ESH, sustainability and product content challenges faced by the semiconductor and electronics industries and our chemical and equipment supply chain, require commitment in three key areas of focus: 1) renewed emphasis on technical roadmapping and consortia engagement; 2) adoption of green chemistry & engineering concepts, starting with the design phase; and 3) taking a holistic, full life cycle approach across the technology life cycle.
Chemicals and Materials Management and Efficiency	· *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 and policy differences, and the overall trends towards lower exposure limits and increased monitoring. The semiconductor industry must drive alignment on the use of accepted Alternative Assessment Methodologies, to drive consistency within the supply chain and with other industries, to increase influence with regulatory agencies; referencing the INEMI alternative assessment evaluation work, represents a good initial step toward standardization of approach.
	· *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. By effective utilization of Alternative Assesment Methodologies and tools, can proactively inform the practitioner, whether sufficient risk, exposure and hazard information is availble. If not, this should drirve the application of green chemistry principles in the development of more benign materials, if no alternatives are available.
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.Some practical efforts exist but there are no industry wide standards.
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	· *Design for ESH:* There is a need to make ESH a design-stage parameter for new facilities, equipment, processes and products. There is a need for methodologies to holistically evaluate and quantify the ESH impacts of facilities operations, processes, chemicals/materials, consumables, and process equipment for the total manufacturing flow.
	· *Sustainability Metrics:* There is a need for methodologies to define and measure sustainability by technology generation, as well as at the factory infrastructure level.
	· *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

Since the 2013 ESH Roadmap, we have re-assessed the structure of our analysis and in order to prioritize areas presenting the greatest 2015 ESH challenges or benefits, all ESH requirements have been placed in one of three Major 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 previous Roadmaps, 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.

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 facilities overall. Table ESH2 outlines these ESH goals for those items in the Critical and Important Categories.

Table ESH2 ESH Domains and Categories

Table ESH2 ESH Requirements by Domain and Category

Restricted Chemicals	C / I / U*	New chemicals	C / I / U*	Nanotechnology	C / I / U*
Assembly & Packaging		**Intrinsic**		**Intrinsic**	
3D via etch	C	Chemical risk assessments	U	Nanomaterials risk assessment methods	U
FEP		**ERM**		**ERM**	
Plasma Etch	C	Materials for novel logic & memory	C	Nanomaterials	C
CVD chamber clean	C	**FEP**			
Doping	C	High-k & gate materials	I		
3D via etch	C	Alternative surface preparation	U		
Interconnect		Non-silicon, active substrates [channel]	C		
Plasma etch	C	Novel memory materials	I		
CVD chamber clean	C	**Interconnect**			
3D via etch	C	Low-k materials	I		
Lithography		Copper dep processes	I		
PFOS/PFAS/PFOA materials	C	Advanced conductors	U		
		Planarization	I		
		Surface preparation	I		
		Lithography			
		Novel patterning chemicals/materials	I		
Utilization/Waste Reduction		**Energy**		**Green Fab**	
Intrinsic		**Intrinsic**		**Intrinsic**	
Surface preparation UPW use	I	Total fab tools energy usage	I	Safety screening methodologies for new technologies	U
Tool UPW usage	I	Total fab energy usage	I	Improve process chemical utilization	I
Assembly & Packaging		Total fab support systems energy usage	I	Reduce PFC, HFC, N2O, F-HTFs	C
Die thinning	U	**Factory Integration**		Liquid and solid waste reduction	I
Molding processes	U	Energy consumption	I	Reduce hazardous liquid waste by recycle/reuse	I
Waste & by-products	U	**Lithography**		Reduce solid waste by recycle/reuse	U
3D via etch	C	EUV	C	Define environmental footprint metrics for process, equipment, facilities, and products; reduce from baseline year	U
ERM				Integrate ESH priorities into the design process for new processes, equipment, facilities, and products	U
Nanomaterials	C			Facilitate end-of-life disposal/reclaim/recycle	U
Materials for novel logic & memory	C			**Factory Integration**	
Factory Integration				Fab eco-design	U
Non-hazardous solid waste	U			Process eco-design	I
Hazardous waste	I			Product eco-design	I
VOCs	I			Design for maintenance	U
PFCs, HFCs, N2O, F-HTFs	C			Water/utilities usage	I
FEP				Chemical usage	I
High-k & gate materials	U			Consumables usage	U
Doping	I			Equipment thermal management	U
Conventional surface prep	U			Design for End-of-Life	U
Alternative surface prep	U			Eco-friendly facility design	I
Non-silicon, active substrates [channel]	U			Total fab water consumption	I
Novel memory materials	I			Total site water consumption	U
Plasma and 3D via etch	C			Total UPW consumption	I
CVD chamber clean	C			UPW recycled/reclaimed	I
Lithography				Exhaust and abatement optimization	U
Mask making & clean	U			Carbon footprint	I
193 immersion	U			Ease of decommissioning and decontamination for equipment re-use/re-claim	U
Imprint	U				
Interconnect					
Low-k processing	U				
Copper dep processes	U				
Advanced metallization	U				
Planarization methods	I				
Plasma etch	C				
CVD chamber clean	C				
Surface preparation	U				
3D via etch	C				

*C = 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 ability to insert the technology into manufacturing, based on potential or existing policy/regulatory issues (whether internally or externally driven) in at least one of the ITRS member regions.

*I = 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 cost of ownership (CoO) of the technology in manufacturing; based on factors such as throughput, yield, and material and/or tool costs (including disposal/abatement).

*U = 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 ability to achieve the lowest ESH impact for the technology when inserted into manufacturing.

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 ESH3 and ESH4, 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. A recurring theme across all technical areas is the proliferation of new materials. Technologists have asked for guidance to choose the safest possible materials that meet process requirements. Appendix B provides that guidance.

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

Table ESH3 Chemicals and Materials Management Technology Requirements

Table ESH3 Chemicals and Materials Management Technology Requirements

Chemical/Material	**MODULE TWG APPL**	**STATUS**	***2014***	***2015***	***2016***	***2017***	***2018***	***2019***	***2020***	***2021***	***2022***	***2023***	***2024***	***2025***	***2026***	***2027***	***2028***
Carbon Nanotubes (CNTs) [A]	I, FEP, ERM	CRITICAL	This entry refers to carbon nanotubes (CNTs) employed in an unbound state, primarily during manufacturing operations, wherein the exposure potential may be higher compared to bound nanomaterials. Specific technology requirements for unbound nanomaterials are as stated below under Emerging Research Materials and are described in ~~Section X~~.														
Graphene	I, FEP, ERM	CRITICAL	This entry refers to graphene deposited on a wafer in a single layer or in multilayers. Characterize graphene deposition process emissions and emissions from any subsequent process steps that could result in the release of graphene flakes. Determine potential worker and environmental exposures; develop treatment methods where required. Identify reaction byproducts.														
Spin on metal hard masks (oxides of Ti, Hf, Zr nanoparticles) [B]	L	CRITICAL	Develop processes that use the least hazardous chemical to meet process requirements. Characterize and, if warranted, treat resulting heavy metal-laden etch and CMP wastestreams. This entry refers to metal nanomaterials employed in an partially bound state. These NPs would be in a polymer matrix that would be spun on with a solvent and then heated to dry the solvent. Specific technology requirements for bound nanomaterials are as stated below under Emerging Research Materials and are described in ~~Section Y~~.														
New barrier and cap layers	I, ERM	CRITICAL	Develop processes that use the least hazardous chemical to meet process requirements. Characterize emissions and byproducts from all deposition processes (electroless plating, PVD, CVD, ALD) that use new metals, e.g., Co, CoWP, Mn, and Ru, and identify ESH implications. Determine potential worker and environmental exposures resulting from etch or CMP; develop treatment methods where required. Identify reaction byproducts.														
Planarization methods [A]	I, FEP	CRITICAL	This entry refers to nano-sized particles of alumina, ceria, and silica (< 100 nm) used in CMP (Chemical Mechanical Planarization) processes where they are in an unbound state. Specific technology requirements for unbound nanomaterials are described in ~~Section X~~.				This entry refers to other unbound nanomaterials (<100 nm), irrespective of source or chemical composition, used in CMP (Chemical Mechanical Planarization) processes, where the nanomaterials are in an unbound state and thus the exposure potential may be higher compared to bound nanomaterials. Specific technology requirements for unbound nanomaterials are described in ~~Section X~~.										
Plasma etch using fluorinated greenhouse gases (F-GHG)	I, FEP	CRITICAL	Characterize etch process emissions. Develop lower GHG emitting etch processes and chemistries, and more efficient abatement.														
CVD chamber clean (in-situ plasma, remote plasma and thermal) using fluorinated greenhouse gases (F-GHG)	I, FEP	CRITICAL	Characterize CVD process and chamber clean emissions. Develop lower GHG emitting chamber clean processes and chemistries, and more efficient abatement.														
Surface preparation	I, FEP	IMPORTANT	Characterize the quantity of clean chemistries used in single wafer processing.		Develop cleans processes which use less chemicals or lower hazard chemicals.												
Through-silicon via etch (e.g., 3D) using F-GHG	I, A&P	CRITICAL	Characterize TSV process emissions.		Reduce SF6 consumption through process optimization, recycling or abatement; develop lower GHG emitting alternative chemistries to replace SF6 and c-C4F8.												
Reactive materials (i.e. organometallics, hydrides, byproducts)	I, FEP	CRITICAL	Characterize precursor materials, process emissions and identify byproducts. Consider delivery system options, material compatibility; develop operating and maintenance protocols to mitigate energetic reactions in exhaust and abatement equipment.														
High-k and metal gate materials	FEP	IMPORTANT	Characterize processes that use new metals and identify ESH implications of new materials and processes.														
Non-silicon, active substrates (channel), or III-V processing	FEP, ERM	CRITICAL	Characterize III-V processes to determine potential worker and environmental exposures, especially for wet processing (e.g. CMP, wet etch); develop waste treatment methods and identify detection technologies for very dilute levels of III-V materials in effluents where required. Identify reaction byproducts; ensure safe storage and disposal of hazardous materials. Design indium processes that mitigate worker exposure to indium and indium compounds.														
Nanowires [A]	FEP, ERM	CRITICAL	This entry refers to nanowires employed in an unbound state, primarily during manufacturing operations, wherein the exposure potential may be higher than for bound nanowires. Arrays of nanowires will probably be patterned and etched (*i.e.,* extension of MuGFET), with conventional ESH concerns for such processes. Specific technology requirements for unbound nanomaterials are described in ~~Section X~~.														
Novel memory materials (RRAM, FERAM, PCRAM, MRAM)	FEP, ERM	IMPORTANT	Many materials including Oxide and Chalcoginide and a wide range of metals in Periodic Table being investigated. Identify ESH implications of new materials and processes. When choosing memory materials, assess alternative chemicals for potential risks and utilize the safer alternative chemistry that meet process performance. Design processes that maximize chemical utilization efficiency and minimize emissions. Characterize process emissions including byproducts. Evaluate and enable recycle/reclaim of process emissions.														
HfO2 nanocomposite resists [B]	L, ERM	CRITICAL	This entry refers to hafnium oxide nanoparticle polymer resists used in lithography (still in research stage). The particles would be in a polymer-solvent dispersion that would be dried so the NP would be in a polymer composite structure. After exposure, the NP in unexposed resist would be dissolved in the developer, so they would be in the waste in an unbound state. Specific technology requirements for nanomaterials are as stated below under Emerging Research Materials and are described in ~~Section Y~~.														
Self assembly block co-polymers	L, ERM	IMPORTANT	When choosing polymers and solvents, utilize ESH benign alternative chemistries that meet process performance requirements. Identify ESH implications of new polymers and solvents, new polymer brushes, and chemicals for neutral energy surfaces and processes such as solvent anneal. Design processes that maximize chemical utilization efficiency and minimize emissions.														
Advanced patterning chemicals/materials	L, ERM	IMPORTANT	Identify ESH implications of new materials, processes, and novel chemicals or polymer brushes to generate neutral surfaces. Reduce resource consumption for multi-patterning. Develop eco-friendly solvents with equal or better process performance.														
PFOS/PFAS/PFOA** chemicals	L	CRITICAL	PFOS/PFAS/PFOA alternatives researched.		Develop and implement safe non-PFAS/PFOA materials for critical uses in lithography. Phase out uses of PFAS/PFOA.												
Boron nitride (BN) nanoparticles and nanotubes in a composite [A,B]	A&P, ERM	CRITICAL	This entry refers to BN nanoparticles and nanotubes deployed in a semisolid or solid matrix and/or into a monolithic product. Specific technology requirements for such nanomaterials are described in ~~Sections X and Y~~. Micron-sized flakes of BN are currently used.				This entry refers to boron nitride nanotubes and nanowires deployed in a semisolid or solid matrix and/or into a monolithic product for thermal applications. Micron-sized flakes of BN are currently used and will prevail for multiple years. Future work will focus on improving polymer thermal conductivity and reducing thermal interface resistance between flakes, materials and the polymer. Specific technology requirements for such nanomaterials are described in ~~Sections X and Y~~.										
Cu or Ag nanoparticles in epoxies, nano-inks, and nano-solders [A,B]	A&P, ERM	CRITICAL	This entry refers to Cu or Ag nanoparticles deployed in a semisolid or solid matrix and/or into a monolithic product. Specific technology requirements for such nanomaterials are described in ~~Sections X and Y~~. Develop engineering controls for processes where				This entry refers to other nanomaterials deployed in a semi-solid or solid matrix and/or into a monolithic product. Specific technology requirements for such nanomaterials are described in ~~Sections X and Y~~.										
CNT's (in mold compounds or epoxies, inks and EMI shielding) [A,B]	A&P	CRITICAL	This entry refers to CNTs deployed in a semisolid or solid matrix and/or into a monolithic product. Specific technology requirements for such bound nanomaterials are described in ~~Sections X and Y~~.														
Graphene (multilayer in epoxy)	A&P	CRITICAL	Characterize graphene emissions from any process steps that could result in the release of graphene flakes. Determine potential worker and environmental exposures; develop treatment methods where required. Identify reaction byproducts.														
Ultra high K dielectrics	A&P, ERM	IMPORTANT	The Ultra high k dielectrics (dielectric constant >40) are deposited in a liquid or paste form and then annealed. Characterize processes that use new metals and identify ESH implications of new materials and processes.														
Emerging Research Materials																	
Green chemistry/alternative assessment	ALL	CRITICAL	Identify ESH safer alternative chemistries with equal or better process performance														
450mm Processing	ALL	CRITICAL	Characterize and quantify chemical and resource consumption, and process emissions; determine chemical utilization and byproduct formation rates; design processes that maximize chemical usage; develop reuse/recycle technology for process chemistries which are emitted from the process.								For new 450mm processes and equipment, characterize and quantify chemical and resource consumption, and process emissions. Determine chemical utilization and byproduct formation rates; design processes that maximize chemical utilization efficiency; develop reuse/recycle technology for process chemistries which are emitted from the process.						
Nanomaterials - bound [B]	ALL	CRITICAL	This entry refers to nanomaterials deployed in a semisolid or solid matrix and/or into a monolithic product. Considerations regarding materials handling, occupational exposures and controls, and environmental discharges and controls that need to be addressed for bound nanomaterials, as described in Section Y. Potential releases of unbound nanomaterials during disposal or recycling of electronic waste, particularly pertinent for assembly and packaging, are also described in ~~Section Y~~.														
Nanomaterials - unbound [A]	ALL	CRITICAL	This entry refers to nanomaterials employed in an unbound state, primarily during manufacturing operations. For unbound nanomaterials, there are important considerations regarding materials handling, occupational exposures and controls, and environmental discharges and controls that need to be addressed, as described in ~~Section X~~.														
Metrology	ALL	CRITICAL	There are numerous unsolved metrology challenges associated with the measurement of the materials listed in this table. Metrology equipment and methods are needed to characterize new materials and process byproducts in air, water and wastes, as well as in chemical mixtures and products. Metrology needs must be addressed in the near-term prior to incorporating new materials into HVM.														

Notes:
[A] See Appendix C, section 8.3.2 Unbound Nanomaterials
[A] See Appendix C, section 8.3.3 Bound Nanomaterials
[A,B] See Appendix C, sections 8.3.2 and 8.3.3

Manufacturable solutions exist, and are being optimized (white)
Manufacturable solutions are known (yellow)
Interim solutions are known (yellow, striped)
Manufacturable solutions are NOT known (red)

Table ESH4 Chemicals, Process, and Equipment Management Technology Requirements

Table ESH4 Chemicals, Process, and Equipment Management Technology Requirements				
Application	Processes	ESH Concerns	Earliest Intercept	ESH Metrology Needs
Memory Materials				
STT MRAM	Sputter deposition and sputter etch, Etch, Anneal and High Temperature Pinning	Etch chemistry byproducts, Chamber Cleaning, Corrosion Issues, Personal exposure, Abatement technology	**5-10 yrs**	Emission Characterization, Monitoring metrology, Exposure and Product life cycle metrics
RRAM Memory Cell	CVD,ALD	Chamber Cleaning	**3-5 yrs**	Emission Characterization. Exposure and Product life cycl
FERAM	PVD	Pb exposure paths, Chamber Cleaning	Current	Life cycle analysis of byproducts.
PCRAM	PVD	Se. Sb exposure paths , Chamber (	Current	Monitoring metrology, and life cycle analysis of byproducts.
Logic Materials				
Alternate Channel Material	MOCVD	InGaAs, InAlAs, InP and etch waste, Reactivity of precursor material, Delivery system design, exhaust and abatement management , Chamber Cleaning	**3-5 yrs**	Analytical techniques sensitivity to exposure limits, emission characterization, Exposure and Product life cycle metrics
	MOCVD	InGaSb, InAlAs, InP and etch waste, Reactivity of precursor material, Delivery system design, exhaust and abatement management, Sb handling issues ,Chamber Cleaning	**5-10 yrs**	Analytical techniques sensitivity to exposure limits, emission characterization, Exposure and Product life cycle metrics
	Epitaxy (CVD)	Safe handling procedures and abatement systems	**5-10 yrs**	
	Pattern and Etch process for nanowires	Silicon or Ge	**5-10 yrs**	
	CVD for Nanowire growth (catalyst)	Si, Ge, Handling and exposure issues need definition	**10-15 yrs**	
	CVD, Plasma CVD	Carbon Nanotubes exposure potential, Environmental discharge and controls	**10-15 yrs**	Analytical techniques sensitivity to exposure limits, emission characterization
	CVD	Graphene, Environmental discharge and controls , Cu Waste product	**10-15 yrs**	
	Integration of III-V and Ge, Epitaxy and MOCVD	InGaAs, InAlAs. InGaSb and etch waste, Reactivity of precursor material, Delivery system design, exhaust and abatement management, Chamber Cleaning	**3-5 yrs**	Analytical techniques sensitivity to exposure limits, emission characterization, Exposure and Product life cycle metrics
Novel 2D	CVD, MOCVD	Handling, Exposure and Environmental discharge controls are critical for these products	**10-15 yrs**	Abatement capture technology quantification
Lithography Materials				
Directed Self Assembly	Spin-on and anneal (thermal or solvent)	None	**3-5 yrs**	
Nano composite Resist	Spin Coating, Exposure, Track bake, Solvent develop, Plasma Etch, Post Etch Strip	Reactivity of Nanoparticles in organic matrix. Nanoparticle handling and exposure potential	**3-5 yrs**	Reactivity evaluation and analytical exposure path evaluati
Spin-On Hard mask	Spin-on and anneal (thermal or solvent)	exposure pathways, exhaust and waste disposal	**1-2 yrs**	Exposure characterization development
Front End Process				
Monolayer Doping	Wet	Sulfur Dopant Handling	**3-5 yrs**	
	Wet or ALD	Phosphorous Dopant handling and disposal	**3-5 yrs**	
	Wet or ALD	Boron Dopant Handling and disposal	**3-5 yrs**	
Interconnects				
Ultrathin Cu barrier layers	ALD, PEALD	Reactivity of precursor material, Delivery system design, exhaust and abatement management, Chamber Cleaning	**1-2 yrs**	Monitoring systems.
Interface Cu Barrier layers	CVD	Reactivity of precursor material, Delivery system design, exhaust and abatement management	**5-10 yrs**	Monitoring systems.
Low K ILD	CVD and Wet Processing	In Development	**5-10 yrs**	Monitoring systems.
Interconnects	CVD and Etch Processing	Personal exposure Paths	**3-5 yrs**	Monitoring systems.
CVD Chamber Clean	CVD	Abatement, GWP reduction, and Metals chemistries issues		
Thru -Si Vias	Etch	Material usage and GWP reduction		Emissions Characterization
Assembly and Package				
Chip Electrical Attach Materials	Liquid processing, Anneal	Graphene/CNT Hybrid	**5-10 yrs**	Monitoring systems

3.3.1. INTERCONNECT

Interconnect challenges are posed by new materials and continued concerns with high global warming potential (GWP) GHG used or emitted from chamber clean, plasma etch and deposition processes. Process emissions characterization is critical in the coming years to ensure Fabs can comply with increasing environmental regulations. It is anticipated with greater implementation of 3D and advanced packaging systems that greater needs to analyze this trend will become essential. The reader is referred also to the Packaging Chapter of this Roadmap that has further details on the methods.

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 electrochemical deposition (ECD), including extending copper plating bath life or recycling; changes in barrier composition and nucleation films especially if the dominant physical vapor deposition (PVD) processes move towards chemical vapor deposition/atomic layer deposition CVD/ALD processes; and the emergence of new capping layers and processes. For the dielectrics, increasingly porous films can involve new precursors and thus 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, fluorinated GHGs (F-GHGs) including perfluorocompounds (PFCs), hydrofluorocarbons (HFCs) and nitrous oxide (N_2O) are used extensively in interconnect dry etch, and chamber cleaning applications as well as interconnect and front end processing deposition processes. These process GHGs and fluorinated heat transfer fluids (FHTFs) have come under increased regulatory scrutiny. In interconnect, the residues of carbon-containing low-k films can produce F-GHG emissions (e.g., CF_4) during chamber cleaning. At present, dry etch processes for low-k dielectrics are all based on F-GHGs (whether or not they fall into the high GWP family), and so F-GHG emissions (as either byproducts or unreacted starting compounds) must be managed. The semiconductor industry's present goal is to reduce normalized PFC emissions by 30% from a 2010 baseline by 2020. To maintain this aggressive goal and to ensure that these chemicals remain available for industry use, the industry must strive to reduce process GHG emissions by process optimization, alternative chemistries, and/or abatement. Another high GWP process chemical to be addressed is N_2O (used in oxynitride deposition processes). FHTFs also have high GWP; FHTF emissions must be minimized and alternatives with lower GWP or no GWP should be considered.

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 2010 baseline. It is clear in this case that aggressive abatement strategies will be needed unless cost-effective alternatives can be found.

The USEPA now requires periodic reporting on the GHG emissions impact posed by new process technologies and finer line width processes, the introduction of new tool platforms, and 450mm wafer technology. As new processes and 450mm equipment are developed, it is imperative that GHG emissions be characterized from baseline processes.

To meet expected energy conservation goals, equipment (plasma-enhanced CVD, dry etch, and chemical mechanical planarization (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 (see Appendix C) and air-gap dielectrics. 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

Front End Processing challenges arise from the thrust's evolving use of new and novel chemicals, materials and processes for substrates, dopants, gate stacks, conductors and insulators. The new materials include reactive materials (i.e., organometallics, hydrides, byproducts), high-k and metal gates, non-silicon active substrates, III-V compounds, nanowires, carbon nanotubes (CNTs), graphene and novel memory (i.e., RRAM, FERAM, PCRAM, MRAM) materials. The introduction of rare and heavy metals into the process require evaluation of economic recovery and recycle techniques.

The introduction and use of these novel materials requires comprehensive assessment and understanding of ESH impacts to avoid harm to fab personnel and the environment. In addition efficient use of natural resources (e.g., water and energy) in tools and processes remains a continuing goal. These principles should be applied throughout this thrust, as outlined in the examples below.

ESH concerns for surface preparation focus on new clean techniques, chemical/material usage, and water and energy consumption. With the trend to more single wafer processing, single wafer tools should be fully characterized to determine the quantity of clean chemistries used per wafer. 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, sonic energy enhancement, DI water/ozone, gas phase, cryogenic, hot-ultrapure water (UPW) and simplified process flows) may reduce ESH hazards and chemical consumption. The impact of such alternative cleaning methods on energy consumption should be evaluated. Sustainable, optimized water use strategies (e.g., more efficient UPW production, reduced water consumption, and efficient rinsing) all can contribute to enhanced ESH performance. During the design of wet tools, attention should be paid to controlling process emissions, ergonomic and robotics safety principles, and ease and safety of equipment maintenance. Since there is an indication that single wafer tools use more chemicals and water, they should be designed to allow chemical and water recycle/reclaim (e.g., by providing drain segregation).

While there are generally fewer CMP steps in front end processing than in interconnect, CMP is still used 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) – are important here. Since the CMP slurries contain nano-sized (< 100 nm) particles of alumina, ceria, and silica in an unbound state, the potential hazards to fab personnel and the environment must be fully comprehended. For unbound nanomaterials, there are important considerations regarding materials handling, occupational exposures and controls, and environmental discharges and controls that need to be addressed. Also, the introduction of III-V materials into front end processes may introduce hazardous residues into the spent CMP slurries and rinse water, which may require special waste treatment. The ESH impact of this development should be fully understood. Implementation in 10nm and 7nm seems unlikely at this point in time, but this situation witll be reviewed continuously; the reader is refered to the Front End Processes Chapter of this Roadmap.

New gate stack materials (both high-κ and electrode) require assessing potential hazards associated with both the precursors, as well as their associated deposition (e.g., ALD) and etch processes. Since most high k materials have high leakage rates, new barrier layers will be required. Thus, the ESH properties of the precursors and the barrier materials as well as any process byproducts must be understood so that proper engineering controls and any needed personal protective equipment can be identified. These processes should be optimized for maximum chemical utilization and efficient energy use.

The expanded introduction of low-vapor pressure pyrophoric liquids within the fab structure requires rigorous design and certification of new delivery systems.

3.3.3. LITHOGRAPHY

For the lithography chemicals/materials and consumables, there are two principal issues. The first issue is the need for developers, etchants, anti-reflective coatings (ARCs), and photoacid generators (PAGs) in chemically amplified resists free of any PFOS/PFAS/PFOA species. The second issue pertains to novel patterning chemicals/materials includes a number of areas, such as spin on metal hard masks, HfO_2 nanocomposite resists, self-assembly block co-polymers and advanced patterning chemicals. The ESH concerns associated with the new materials and processing of the materials must be addressed. More information on the range of materials can be found in the Lithography Chapter of this Roadmap.

In the process area, the key concern is the onset of 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. Historically, fab electrical consumption has been relatively stable with equipment accounting for 40-60% of the total fab electrical budget of approximately 100MW. The introduction of EUV will significantly change that balance. Each EUV stepper will take 800kW-1MW compared with <100kW for an existing DUV stepper/scanner and, depending on the number of layers adopting EUV exposure, and throughput of the tools, the percentage and total fab electrical usage will rise according to the number of EUV steps. It is difficult to determine exactly how many EUV steps will be adopted and precisely when. But for sake of discussion we can assume that this might happen in the next 5 years. Reference to the Lithography chaper of this roadmap will indicate that large scale of EUV exposure may commence for 5nm for several mask layers. However, assuming EUV lithography starts with two steps at that time, when the throughput of EUV exposure tools is about one fifth of that of DUV exposure tools, then the tool portion of electrical usage will rise significantly, by about 10%, to about 40% of the total fab supply. If the throughput problems are suitably addressed, then this may reduce electrical consumption somewhat, but the end result will always be greater tool usage of electricity and matching tool cooling.

3.3.4. ASSEMBLY AND PACKAGING

ESH goals for Assembly and Packaging largely focus on the need to identify the ESH ramifications of nanomaterials usage during manufacturing as well as the incorporation of nanomaterials in products. As with other applications involving nanomaterials, needs of the semiconductor industry include development of metrology to detect and measure nanomaterials in relevant media, establishment of thresholds for workplace exposure and environmental discharge, and cost effective treatment or controls. Further elaboration on these needs is included in Appendix C for nanomaterials at the end of this section.

For Assembly and Packaging in particular, consideration must be given to nanomaterials which remain present at nano-scale in the final product. Semiconductor packaging is subject to evolving regulatory requirements around product safety and electronic waste which may restrict the use of certain materials. These materials are not intended to be released, nor is any discernible degree of exposure anticipated during typical consumer use. However, the presence of nanomaterials in the final product should be comprehended, and the extent to which bound nanomaterials may leach from discarded products or be released during mechanical actions such as cutting, grinding, drilling, or etching should be validated.

With respect to specific applications, several nanomaterials are being evaluated as a component of epoxy or solder used in die attach, the mechanical support between the die and substrate. The advantages of these nanomaterials—including metallic nanoparticles, CNTs, graphene, and boron nitride (BN) nanotubes and nanoparticles—are primarily enhanced heat dissipation as a thermal interface material or enhanced electrical conductivity as fillers. ESH impacts may vary. BN nanotubes and nanoparticles, which offer electrical insulation in combination with thermal dissipation, are likely to be applied as micron-sized flakes within a compounded die attach epoxy paste, but use of nano-sized materials in the future is possible. In this case as well as in the case of CNTs and graphene, nanomaterials would be expected to remain trapped in the polymer matrix, unless the matrix were to be degraded or damaged, pointing to the need to evaluate any such processes, e.g., e-waste dispositioning, where that might occur.

As for metallic nanoparticles (e.g. nano-Cu and nano-Ag), their anticipated use as a Pb-free, low temperature solder or electrically conductive adhesive is as a sintered material, whereby dispersed nanoparticles form micron-sized agglomerates, rendering the presence of any nano-scale particles in the final product inapplicable. Therefore, any exposure potential would be for nanoparticles from the pre-sintered paste, whether while in use or from residues on tools. This would also apply to the emerging use of metallic nanoparticles as conductive materials employed in printed electronics.

For assembly of "System-in-Package," nanomaterials may be used as 3D interconnect materials, either as nanoparticle-based solders, CNT interconnects, or thermally conducting nanocomposite polymers in manners similar to those described above. Stacked devices have also driven the use of through silicon vias (TSV). For Assembly and Packaging, the ESH concern for TSV is one shared with Interconnect, namely the use of sulfur hexafluoride as a high etchrate process gas and c-C_4F_8 in the well-known Bosch process. In light of continued global focus on GHG emissions and potential emission limits as well as the industry's PFC reduction goals, alternatives gases with lower GWPs need investigation.

Finally, the use of high-k dielectrics in advanced packaging processes to create embedded passive devices introduces new complex metal oxides. The ESH implications of material delivery, byproduct formation, and waste discharge need to be identified so that any impacts to emissions or waste discharge may be characterized.

3.3.5. EMERGING RESEARCH MATERIALS

ESH goals for Emerging Research Materials (ERMs) largely focus on the need to identify the ESH ramifications of new materials including metals and nanomaterials usage during manufacturing as well as the incorporation of metals and nanomaterials within products.

Many processes used in manufacturing semiconductors require reactive chemistry, and therefore some of the materials used are naturally unstable and/or have energetic properties. Some also can produce byproducts which may be reactive under certain conditions. Control mechanisms are in place to mitigate these material hazards; however, new and emerging materials, some with unknown properties, are continuously being introduced into research and manufacturing. Incidents involving reactive materials occasionally occur in the industry; therefore, focus on hazards identification and controls are a continuing priority. Development of best-known methods and/or guidelines for identifying, assessing and controlling energetic material hazards is a priority.

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. For example, indium compounds are under consideration for use in the channel and a recent NIOSH paper concludes, "Research is needed to evaluate the adequacy of the current REL for protecting workers from indium-related disease and whether indium exposure limits, including biological exposure limits, should apply to all indium compounds or be compound-specific."[1] It is important that the industry understands and addresses the hazards posed by the various forms of metal compounds.

Nanotechnology, including nanomaterials, nanostructured materials, and nanoscale structures, will play an increasingly important role in semiconductor technology. Of these three nanoscale entities, the only one being considered by regulatory agencies to have potential ESH risks is nanomaterials. The term engineered nanomaterials (ENMs)—materials that have been purposely synthesized or manufactured to have at least one external dimension of approximately 1 nm–100 nm and that exhibit unique properties determined by this size[2]—is widely used in the field to distinguish such "man-made" nanomaterials from "incidental" nanomaterials, *e.g.*, those formed from combustion processes. Throughout the ITRS, ENMs are referred to simply as nanomaterials. As shown in Table ESH3, there are various nanomaterials in the form of nanoparticles, nanotubes, nanowires, and thin sheets (graphene) being considered for introduction in a number of semiconductor process applications from now through 2028. Full ESH evaluation of the potential risks of any nanomaterial is predicated on a comprehensive knowledge base of the physico-chemical properties, toxicity (human and

[1] *Journal of Occupational and Environmental Hygiene (2013): Use of and Occupational Exposure to Indium in the United States, Journal of Occupational and Environmental Hygiene.* *http://dx.doi.org/10.1080/15459624.2013.836279*

[2] *National Nanotechnology Initiative Environmental, Health, and Safety Research Strategy, 2011, http://nano.gov/sites/default/files/pub_resource/nni_2011_ESH_research_strategy.pdf*

environmental), and exposure of the nanomaterial during all lifecycle stages—manufacturing, consumer use, and end-of life (disposal or recycling). Such an evaluation must be conducted for both a nanomaterial and a product containing the nanomaterial in relevant media (*e.g.*, air, water, and biological matrices). Despite years of research, a comprehensive knowledge base for science-based risk assessment of any nanomaterial or product containing a nanomaterial is lacking. The semiconductor industry is already funding research on physico-chemical and toxicological properties of some nanomaterials; however, it is beyond the scope and capability of the semiconductor industry to undertake or fund studies to obtain complete knowledge. Thus, the ITRS seeks to identify essential ESH knowledge for each nanomaterial relevant to the semiconductor industry.

For simplicity, the nanomaterials of relevance to the industry as shown in Table ESH3 may be broadly characterized as ***unbound*** (*i.e.*, free or dispersed in a fluid, including water and epoxy formulations) or ***bound*** (*i.e.*, embedded in a solid matrix such as a polymer-based composite). ESH requirements for these two types of nanomaterials are discussed in Appendix C. Note that it is critical that manufacturing and discharge conditions be specified to the greatest extent possible for each processing step.

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 to address the unique ESH challenges nanomaterials may present. In addition, the small sizes of new nanomaterials may make standard ESH controls (e.g., emission control equipment) less than optimal. As a result, the following ESH considerations must be addressed for future technology development:

- Validated metrology to detect the presence of nanomaterials in the workplace, waste streams, and the environment;
- Validated and cost-effective occupational exposure controls, including PPE and engineering controls.
- Scientific basis for determining protective discharge levels, including knowledge of key parameters for eco-toxicity and transport, partitioning, and fate of nanomaterials (requires validated metrology); and
- Cost-effective air, water, and waste treatment technology for achieving protective discharge levels, when they are known.

Additional information on nanomaterials can be found in Appendix C.

3.3.6. ESH CONCERNS FOR E-WASTE

There are growing regulatory concerns world-wide regarding potential releases of toxic metals and unbound nanomaterials from electronic products during disposal or recycling processes (e.g., grinding) that may result in environmental and occupational (workers handling e-waste) exposures. If research studies indicate such releases of toxic metals or unbound nanomaterials can occur, then ESH needs must be identified and addressed by disposal and recycling companies, with guidance from the semiconductor industry. The considerations for E-Waste are also discussed in the Factory Integration Chapter of this Roadmap.

3.3.7. PROCESS AND EQUIPMENT MANAGEMENT

Previous versions of the ITRS included a table highlighting process and equipment technology needs. This table is not included in the 2015 roadmap but consideration should be given to including this table in future years. We are entering a non-linear transitory stage in semiconductor technology development and roadmap focus that reflects these changes is critical. The chemicals, materials, processes and equipment listed in Tables ESH3 and ESH4 are needed to achieve the requirements identified in the roadmap by the technical thrusts. The combination of chemicals, materials, equipment and processes define the ESH risk factors that need to be controlled, monitored and treated. To address the challenges associated with new chemicals, materials, equipment and processes requires metrology, detailed process characterizations, enhanced equipment state metrics, emission characterization and metrology and, potentially, development of new waste treatment and recovery technologies. Many semiconductor processes are transformative, i.e., chemicals and materials that are input into the process undergo chemical reactions that result in formation of byproducts and emissions. It is imperative that baseline processes be characterized and that this information be communicated along the supply chain so that safety and environmental risks are proactively addressed. Modifications of equipment for recovery optimization are needed in terms of hardware and equipment recipe modifications that do no impact the process performance. While on-tool recycle is not always economically feasible, it may be applicable for specific circumstances. Expanded introduction of low-vapor pressure pyrophoric liquids within the fab requires a rigorous design and certification process and development of new delivery systems. The introduction of rare and heavy metals into the process require evaluation of recovery and recycle techniques; additionally, ex-situ and in-situ cleaning of the equipment must be evaluated to insure that appropriate ESH factors are addressed. Appropriate procedures for equipment end of life will require further investigation.

3.4. FACTORY INTEGRATION

Factory planning, design, and construction considerations are integral to the industry's responsible ESH performance. Towards that end in ITRS 2.0 ESH considerations are entirely presented in the Factory Integration Focus. Table ESH5 establishes such goals for factory design and operation.

Table ESH5 Facilities Technology Requirements

Table ESH5 Facilities Technology Requirements																
Year of Production	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*
Facilities Design																
Facilities Design **Important**	Meet established goal and metrics						Meet established goal and metrics									
Water																
Total fab* water consumption (liters/cm^2) [1]																
300mm/450mm fabs	7.8	7.8	7.3	7.0	6.4	6.4	5.8	5.5	5.5	5.3	5.0	5.0	5.0	4.6	4.6	4.6
200mm fabs	7.6	7.6	7.0	6.4	5.8	5.8	5.0	4.8	4.8	4.3	4.1	4.1	3.9	3.5	3.5	3.5
Important																
Total UPW consumption (liters/cm^2) [1] **Important**	6.5	6.5	6.5	6.0	6.0	6.0	5.0	5.0	5.0	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Site water recycled/reclaimed** (% of use) **Important**	50%	50%	60%	60%	70%	70%	70%	75%	75%	75%	80%	80%	80%	90%	90%	90%
Energy (electricity, natural gas, etc.)																
Total fab energy usage (kWh/cm^2)																
Non EUV	1.0	1.0	1.0	0.9	0.9	0.9	0.8	0.8	0.8	0.7	0.7	0.7	0.6	0.6	0.6	0.6
EUV			1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Important																
Waste																
Hazardous waste (g per cm^2) [1] **Important**		8			7.5		7.2	7.2	7.2	7.2	6.5	6.5	6.5	6	6	6
Air Emissions																
Volatile Organic Compounds (VOCs) (g per cm^2) [1] **Important**		0.06			0.055		0.05	0.05	0.05	0.05	0.045	0.045	0.045	0.045	0.045	0.045
Fluorinated greenhouse gases, fluorinated heat transfer fluids, and nitrous oxide **Critical**	Normalized emission rate (NER) to be 0.22 kg CO_2 equivalent/cm^2 by 2020 -- as agreed to by the World Semiconductor Council (WSC)			Normalized emission rate (NER) to be 0.22 kg CO_2 equivalent/cm^2 by 2020 -- as agreed to by the World Semiconductor Council (WSC).						Normalized emission rate (NER) <0.22 kg CO_2 equivalent/cm^2						

Manufacturable solutions exist, and are being optimized	(white)
Manufacturable solutions are known	(yellow)
Interim solutions are known	◆ (yellow)
Manufacturable solutions are NOT known	(red)

Notes for Table ESH5:

**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

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 and equipment maintenance (fall protection and heavy lift), especially for 450 mm wafers and associated process tools.

The industry faces increasing permit, code, and emissions limitations. Future factory planning (and 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 ESH5, 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.

Roughly 50% of the water incoming to a fab site ends up as UPW used by the process tools; the rest is rejected during the UPW generation process or is used by various facility systems such as the cooling towers and scrubbers. Since UPW production requires large chemical quantities, any increase in UPW consumption and quality results in greater chemical consumption (and UPW production cost).

One trend in integrated circuit (IC) manufacturing is the migration from batch wet processing tools to single wafer systems. This is currently occurring in 300mm fabs and is expected to be even more widely adopted when 450mm wafer processing goes into HVM. The throughput of a single wafer wet tool is less than batch systems and single wafer wet tools use more UPW per wafer pass. Both of these trends increase the UPW consumption of a given fab. The only way to reverse this trend is for the fab to recycle / reuse a larger percentage of the incoming water. 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). Note that when the power requirements for the process tools are reduced, the amount of heat those tools generate goes down and therefore the size of the utility systems deployed to remove that heat (chillers, cooling towers, etc.) can also be reduced in size so the effective power savings is doubled.

As stated above, the adoption of EUV is expected to significantly increase the energy consumption of a given wafer fab. Since the EUV tools are still in the early stages of development, it is unclear what their average power consumption will be and what wafer throughput each tool will provide. The power consumption roadmap is based on the following assumptions;

- EUV tools start to be utilized in Manufacturing from 2015, possibly reaching significant usage by 2019
- Each EUV tool uses on average 810 kwatts (the requirement may rise to 1MW to facilitate higher source power and wafer thrughput, these factors are being studied)
- The throughput of the EUV tools is 10% that of 248/193nm scanners (single pass) and this is rising to 20%
- The assumption used here of number of mask levels that use the EUV tool starts at 2 and increases over time.

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. 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

Previous versions of the ITRS included a table (ESH7) highlighting sustainability technology needs; this table has been removed based on the assumption that the primary roadmap sections on chemicals/materials, process and equipment, and facilities and resources should take revision precedence because they form the foundation of the ESH roadmap upon which sustainability would be based. Consideration should be given to develop and include a sustainability table in future versions of the ITRS.

As we look forward to these upcoming revisions for sustainability, we are mindful of the value of viewing our roadmap and technology developments in this broader context, given their far reaching implications (both in terms of opportunity and risk), and the many touch points and impacts these topics have for our industry and beyond. It has become clear that global challenges such as climate change, natural resource usage, and materials availability must be addressed in an integrated, life cycle approach, mindful of both the opportunities that our industry can derive from ESH technology expertise as well as the necessity for mitigating operational risks. As previously mentioned, many instances exist where no quantitative ESH goal or metric will be possible. Despite this reality, we can nonetheless set expectations for driving toward common methodologies and tools to ensure consistency across our industry and beyond, emphasizing the importance of continuous improvement.

To develop effective and meaningful sustainability guidance for the industry will require the inclusion of proactive anticipation of future regulatory trends, employing methodologies of life cycle assessment (LCA), green chemistry and green engineering, and Design for ESH (DFESH). Each serves to identify gaps and provide direction and focus to the industry on how to best develop technology solutions for sustainability challenges. As we move toward revising our approach to sustainability, several topics must be addressed:

- Climate change implications (PFC, N_2O, fluorinated heat transfer fluids, carbon footprint)
- Green chemistry, green engineering and alternatives evaluation, LCA tools (how to best integrate the principles and methodologies)
- DFESH (for facilities, equipment and products including ease of disassembly and re-use at end of life), and how factories are best integrated more broadly in their environment (materials efficiency, re-purposing of waste, etc.)

3.6. PRODUCT STEWARDSHIP

Due to the wide variety of semiconductor devices and their myriad end-use applications, the key areas of focus and requirements for product stewardship do not have explicitly defined, quantitative goals associated with them and Table ESH8 has been removed. However, product aspects such as materials content, material sourcing and attributes of product use are of critical importance. Thus, the emphasis here is on establishing consistent methodologies and approaches across the industry, wherever possible, especially when quantitative targets and metrics cannot be readily defined.

Climate change is recognized as a critical 21st century global environmental challenge, driving international efforts to not only reduce total carbon dioxide emissions but also much smaller sources of emissions, such as semiconductor manufacturing GHGs (e.g., F-GHGs, N_2O and fluorinated heat transfer fluids). Carbon footprint (a means to track a product’s or process’ impact on global climate) is defined as the total GHG emissions over a product's life cycle. Reducing carbon footprint is vital to the industry's sustainability; therefore, carbon footprint methodologies and metrics should be developed to track progress.

In previous iterations of the Roadmap, we have called out the importance of DFESH, 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. Specific attention was also emphasized, on the critical importance of design of facilities, equipment, and products for ease of disassembly and re-use at end of life.

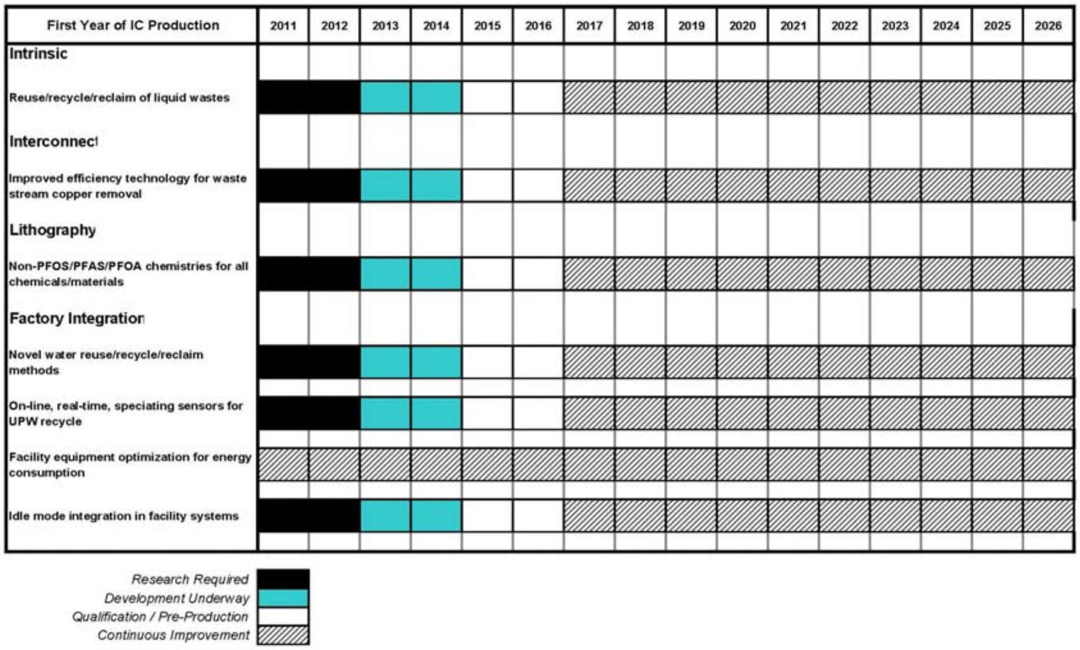
With this latest edition of the Roadmap, a concerted effort was made to integrate the concept of 'green chemistry' and 'green engineering' into the ITRS. This edition aims to emphasize the vital importance of working toward a standard, consistent and productive approach to alternative assessment methodologies and tools, as they apply to product design, and in concert with the broader electronics industry. Alignment on a common approach is key, as a systematic methodology will enable the ability to proactively address product content issues during product design.

In addition to pursuing environmental initiatives, the global electronics industry (including semiconductor manufacturers) is collaborating to address social concerns regarding the extraction of minerals that may contribute to armed conflict in the Democratic Republic of Congo and adjoining countries. In particular, through the efforts of the Conflict-free Sourcing Initiative, a systematic due diligence process has been established to evaluate the origins of designated "conflict minerals" (tantalum, tungsten, tin and gold). Much progress has been made, and a concerted effort is underway to certify smelters used by materials suppliers as "Conflict-free". In 2013, the World Semiconductor Council established a "Conflict-free Supply Chain" policy intended to support these efforts through the use of common tools and methods.

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.

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 microelectromechanical systems (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 World Semiconductor Council (WSC) PFC emission reduction commitments, any expanded PFC use in MEMS applications must be carefully considered against the established reduction goals.

6. OTHER CONSIDERATIONS

The 2015 Roadmap guidance indicates 450 mm wafer processing in R&D pilot line operation continues in the next five years, with a delayed scaling up of energy and resources until earliest in the nect decade. This is clearly explained in Factory Automation Chapter. One such item is single wafer clean versus wet bench. For chemicals/materials, the goal is to remain constant, and the aim is 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, for 450 versus 300 mm wafers) will need to be reassessed in future Roadmap editions. It is not clear today that equivalence will be met. The challenges of a vastly increased set of materials, with a large group of new materials being added specifically in emerging devices, along with exposure steps with EUV and the consequent inflection point of 450mm, indicate very significant challenges in recycling, waste, energy and abatement. The combination of 450mm, EUV exposure and rapid addition of new materials over the next 5 years poses significant challenges.

7. CONCLUSIONS

The increasing number and complexity of chemical regulations around the globe, coupled with adding many new materials into emerging devices, results in major ESH Challenges. This is further exacerbated by EUV with significantly greater energy and water per wafer and the shift to 450nm. Rigorous quantitative models have been built to address these aspects. We seek, generally, to better quantify all ESH activities. These challenges have been described in this chapter. A deeper process of consensus building from a larger range of stakeholders has been implemented to provide full lifecycle risk assessment. Figure ESH2 illustrates this concept below.

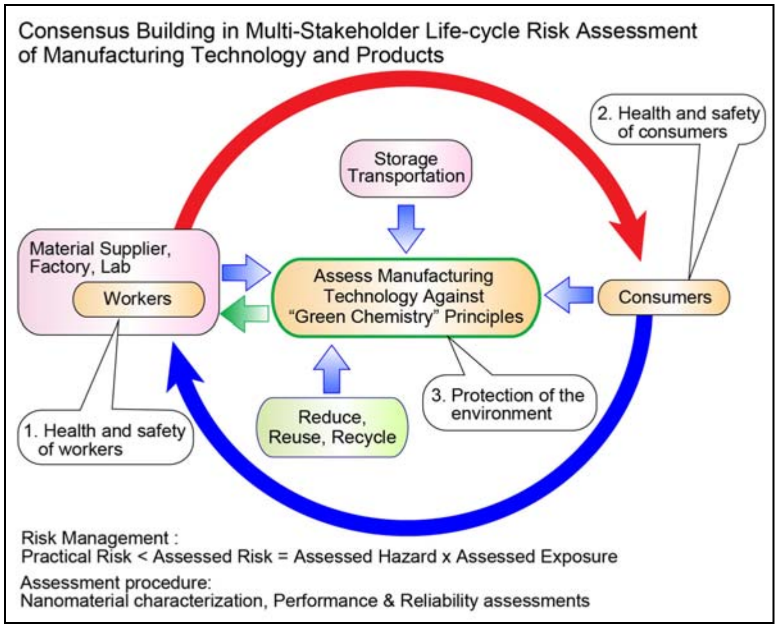


Figure ESH2 Consensus Building Process for Lifecycle Risk Assessment

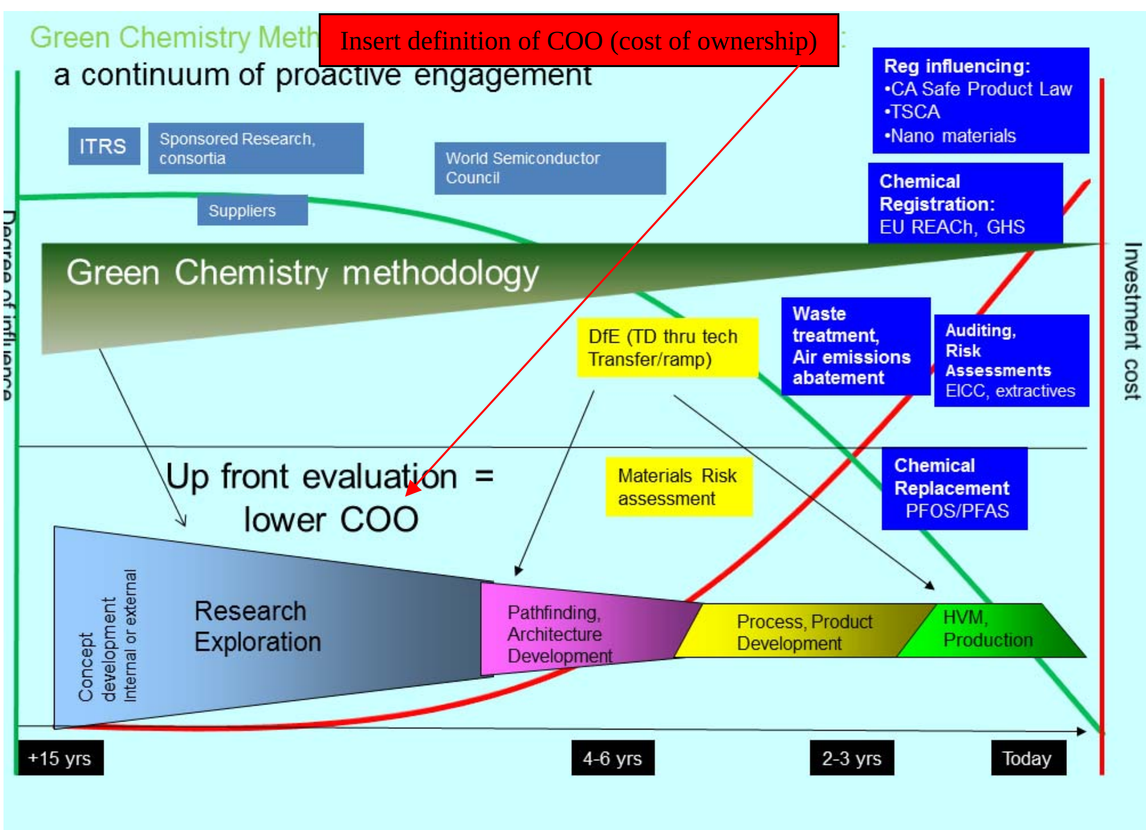


Figure ESH3 Consensus Building Green Chemistry Methodology

APPENDICES

7.1. APPENDIX A: ACRONYMS

A&P	assembly and packaging		LCA	life cycle assessment
ALD	atomic layer deposition		MEMS	microelectromechanical system
ARC	anti-reflective coating		MRAM	magnetoresistive random-access memory
BN	boron nitride		NIOSH	National Institute of Occupational Safety and Health
CMP	chemical mechanical planarization		NIST	National Institute of Standards and Technology
CMR	carcinogenic, mutagenic, toxic for reproduction		OSHA	Occupational Safety and Health Administration
CNT	carbon nanotube		PAG	photoacid generator
CoC	cost of ownership		PBT	persistent, bioaccumulative, and toxic
CVD	chemical vapor deposition		PCRAM	phase-change resistive random-access memory
DFESH	design for environment, safety and health		PFAS	Perfluoralkylsulfonate
DI	deionized water		PFC	Perfluorocompound
DSA	direct self-assembly		PFOA	perfluorooctanoic acid
ECHA	European Chemicals Agency		PFOS	perfluorooctanesulfonic
ECD	electrochemical deposition		POP	persistent organic pollutant
ENM	engineered nanomaterial		POU	point-of-use
ERM	emerging research material		PPE	personal protective equipment
ESH	environment, safety and health		PVD	physical vapor deposition
EU	European Union		REACH	registration, evaluation, and authorization of chemicals
EUV	extreme ultraviolet		REL	recommended exposure limit
FE RRAM	ferroelectric resistive random-access memory		RoHS	restriction of hazardous substances
FEP	front end processing		RRAM	resistive random-access memory
F-GHG	fluorinated greenhouse gas		SRC	Semiconductor Research Corporation
FHTF	fluorinated heat transfer fluid		STI	shallow trench isolation (STI)
GHG	greenhouse gas		SVHC	substances of very high concern
GWP	global warming potential		TSV	through silicon vias
HAR	high-aspect ratio		UPW	ultrapure water
HFC	hydrofluorocarbon		USEPA	United States Environmental Protection Agency
HVM	high-volume manufacturing		vPvB	very persistent and very bioaccumulative
I	interconnect		WSC	World Semiconductor Council
IC	integrated circuit		VOC	volatile organic compound
IPCC	International Panel on Climate Change		3D	three-dimensional
L	lithography			

INEMI (***International Electronics Manufacturing Initiative)***,
GEC (Green Electronic Council), GC3 (Green Chemistry Council),
ACC (American Chemical Council),
NAS (National Academy of Sciences) and
HESI (Health & Environmental Sciences Institute)

7.2. Appendix B: Screening Table for Potential Chemical Bans/Restrictions

States, regions and countries continue to enact regulations that limit or ban the use of highly hazardous chemicals. Additional regulations aim to minimize or eliminate the quantity of certain toxic chemicals in articles or products. Prior versions of the ITRS included a screening table, which listed specific chemicals potentially subject to restrictions. Because chemical regulations expand and evolve rapidly, it has become impractical to keep such a list current. The approach taken in the 2015 2.0 Roadmap, as with the previous revision, is to identify classes of chemicals subject to current or future limits or bans and to provide links to the most current chemical lists. Within certain regulatory jurisdictions such as the European Union (EU), chemical manufacturers or users can access websites that contain updated listings of regulated chemicals. In other jurisdictions, chemicals are listed in specific regulations or on documents posted to the web; changes to a regulation or document must be monitored over time. In both cases, it is easier to monitor changes by accessing updated information on the Internet.

Potentially controlled, restricted or banned chemicals fall into the following categories:

- Class I[3] or Class II[4] Ozone Depleting Substances
- Carcinogens, Mutagens or Reproductive Toxins[5]
- Persistent, Bioaccumulative and Toxic5
- Very Persistent and Very Bioaccumulative5
- Persistent Organic Pollutants[6]
- Anthropogenic GHGs

This list of regulations or treaties is intended to be used as an aid to identify existing or potential limitations on the use of particular substances and to identify potential bans or concentration limitations for substances in articles or products. This list helps to identify banned, restricted, controlled and/or substances subject to potential future regulations. It is the expectation that the industries' supply chain work in partnership to ensure that the most benign, technologically feasible substances are being selected. When more hazardous substances are required, it is imperative that workplace and environmental risks are identified and addressed. Organizations involved in the early phases of chemical research can use Table A1 can serve as a screening tool for understanding risks associated with raw materials chosen for R&D. This table focuses only on the potential for legal limitations on the use of a substance, and is not meant to substitute for the broader risk assessment used to approve materials for production or for the more thorough ESH review performed as part of chemical use approval. By encouraging the industry (researchers, suppliers, manufacturers, customers) to reference common approaches in alternative assessment, specifically the INEMI sponsored project on Alternative Assessment Methodology Tool Evaluation, which is completing the first phase of this project by end of 2015, this will drive consistency of approach amongst stakeholders. This project work was co-authored by representatives of the semiconductor, chemical and electronics industry technical representatives, along with those relevant government, NGO and academic interests. The objective of this work was to define a recommended alternative assessment framework, based on current work from the NAS and other key industry associations, with the intent of driving a consistant starting point, for directing which methodologies and tools should be used for a specific user’s application (a function of industry and use). The group then selected a group of alternative assessment tools that were of potential, future regulatory interests, and a set of descriptors and criteria that would define the value of these tools. The resulting matrix was then populated, by looking at 3 key materials of interest for each assessment tool, selected, for their importance to the semiconductor and electronics industries. The completed evaluation matrix, will serve as an objective reference for the pros and cons of these key alternative assessment tools, as a guide for the industry and a starting point for establishing

standards around alternative assessment.

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[3] *http://www.epa.gov/ozone/title6/phaseout/classone.html*
[4] *http://www.epa.gov/ozone/science/ods/classtwo.html*
[5] *http://www.reachonline.eu/REACH/EN/REACH_EN/article57.html*
[6] *http://chm.pops.int/TheConvention/ThePOPs/tabid/673/Default.aspx*

Issues	*Show Stopper*	HIGH RESTRICTION POTENTIAL	MEDIUM RESTRICTION POTENTIAL
List of Chemicals or Raw Materials Subject to Actual or Potential Manufacture or Use Restrictions	Asbestos Materials Certain glycol ethers Polychlorinated biphenyls Fully halogenated chlorofluorocarbons (CFCs) Carbon tetrachloride 1,1,1 trichloroethane Halons 1211, 1301, 2402 Hydrobromofluorocarbons (HBFCs) HCFC 141b Polybrominated biphenyls (PBBs) and their ethers/oxides (PBDEs) Cadmium compounds Lead compounds Mercury compounds Hexavalent Chromium compounds Polychlorinated Biphenyls (PCB)/ Terphenyls (PCT) Polychlorinated Naphthalene (PCN) Short Chain Chlorinated Paraffins (C10-13, Cl >50%) Tributyl tin (TBT) and, Triphenyl tin (TPT) compounds, including Bis(tributyltin)oxide (TBTO) (NB: TBTO is black in Japan) Certain Azo Colorants	Hydrochlorofluorocarbons (HCFCs) Perfluorooctyl sulfonates (PFOS) Perfluorooctanoic acid (PFOA) and its salts Cadmium compounds Lead compounds Mercury compounds Hexavalent Chromium compounds Other chlorinated organic compounds Other brominated organic compounds	Perfluorocompounds (PFCs) - SF6 - C4F10 - C2F6 - C5F12 - CF4 - C6F14 - NF3 - CHF3 - C4F8 - C3F8 Hydrofluorocarbons (HFCs) Certain phthalates Phenols Perfluoroalkyl sulfonates (PFAS) Ethylene Oxide Ethylene Dichloride Polyaromatic hydrocarbons Antimony Trioxide Beryllium Polyvinyl chloride (PVC) Other brominated flame retardants Triethyl arsenate Anthracene Cobalt dichloride Diarsenic pentaoxide Diarsenic trioxide Sodium dichromate Alkanes, C10-13, chloro (Short Chain Chlorinated Paraffins)

Red - restriction only applies to product content; if the material is not ultimately contained in the final product, there is no use restriction.
Blue – restriction applies both for process use and containment in final product, but restriction level is higher if material is ultimately contained in final product.

Black - Restriction level is the same regardless of whether the material is included in the final product or merely used in the process.

The tool is meant to focus only on the potential for legal limitations on the use of a substance, and is not meant to substitute for the broader risk assessment or for the more thorough EHS review performed as part of chemical use approval.

7.3. APPENDIX C: NANOMATERIALS

INTRODUCTION

Nanotechnology, including nanomaterials, nanostructured materials, and nanoscale structures, will play an increasing important role in semiconductor technology. Of these three nanoscale entities, the only one considered by regulatory agencies to have potential ESH risks is nanomaterials. The term engineered nanomaterials (ENMs)—materials that have been purposely synthesized or manufactured to have at least one external dimension of approximately 1 nm–100 nm and that exhibit unique properties determined by this size7—is widely used in the field to distinguish such "man-made" nanomaterials from "incidental" nanomaterials, e.g., those formed from combustion processes. Throughout the 2013 Roadmap, ENMs are referred to simply as nanomaterials. As shown in Table ESH4, there are a plethora of various nanomaterials in the form of nanoparticles, nanotubes, nanowires, and thin sheets (graphene) slated for introduction in front-end processing, interconnect , lithography, and assembly and packaging from now through 2028. The only known current use of nanomaterials in high volume semiconductor manufacturing is alumina, ceria, and silica nanoparticles for CMP processes.

Full ESH evaluation of the potential risks of any nanomaterial is predicated on knowledge of the physico-chemical properties, toxicity (human and environmental), and exposure of the nanomaterial during all lifecycle stages—manufacturing, consumer use, and end-of life (disposal or recycling). Such an evaluation must be conducted for both a nanomaterial and a product containing the nanomaterial in relevant media (e.g., air, water, and biological matrices). Despite years of research, such complete knowledge for any nanomaterial or products containing nanomaterials is lacking, and it is beyond the scope and capability of the semiconductor industry to undertake or fund studies to obtain

[7] *National Nanotechnology Initiative Environmental, Health, and Safety Research Strategy, 2011, http://nano.gov/sites/default/files/pub_resource/nni_2011_ESH_research_strategy.pdf*

such complete knowledge. Thus, the ITRS seeks to identify essential ESH knowledge for each nanomaterial in Table ESH4, with regard to manufacturing processes, environmental discharges, and handling of e-waste (e.g., grinding).

For simplicity, the nanomaterials of relevance to the semiconductor industry as shown in Table ESH4 may be broadly characterized as unbound (i.e., free or dispersed in a fluid, including water and epoxy formulations) or bound (i.e., embedded in a solid matrix such as a polymer-based composite). ESH requirements for these two types of nanomaterials are discussed below. Note that it is critical that manufacturing and discharge conditions be specified to the greatest extent possible for each processing step.

UNBOUND NANOMATERIALS

Unbound nanomaterials present much greater exposure potential than bound nanomaterials. Both occupational exposures of workers and environmental exposures due to discharges from various processes must be addressed. Specific high-priority needs for occupational exposures for each nanomaterial in Table ESH3 are: (1) validated metrology for measuring exposure levels; (2) a scientific basis and data for establishing exposure threshold limits; and (3) validated and cost-effective occupational exposure controls, including PPE and engineering controls. Similarly, the needs for environmental exposures due to discharges are: (1) validated metrology for measuring nanomaterialconcentrations and key properties in air, water, and waste; (2) validated metrology for distinguishing nanomaterials from natural or incidental nanomaterials in air, water, and waste; (3) a scientific basis for determining protective discharge levels, including knowledge of key eco-toxicity parameters and transport, partitioning, and fate of nanomaterials (requires validated metrology); and (4) cost-effective air, water, and waste treatment technology for achieving protective discharge levels, when they are known. Nanomaterials dispersed in a high-viscosity fluid such as an epoxy formulation used in spin-on processes will be purchased from vendors, so occupational exposure is not expected to occur. However, unbound nanomaterials may be released in the waste stream; thus, the environmental exposure needs described above need to be addressed.

BOUND NANOMATERIALS

Nanomaterials embedded in solid matrices will be purchased from vendors, so the occupational exposure needs described above for unbound nanomaterials are not relevant. One exception is potential releases of nanomaterials if a composite piece undergoes mechanical processes such as cutting and grinding; it is anticipated that this scenario is unlikely as nanomaterial-composites will be purchased as final components. Environmental discharge of nanomaterials in solid matrices is only relevant for the exception noted above.

ESH CONCERNS FOR E-WASTE

There are growing regulatory concerns world-wide regarding potential releases of unbound nanomaterials from electronic products during disposal or recycling processes (e.g., grinding) that may result in environmental and occupational (workers handling e-waste) exposures. If studies indicate such releases of unbound nanomaterials, then ESH needs must be identified and addressed by disposal and recycling companies, with guidance from the semiconductor industry.

EXISTING ESH GUIDANCE AND REGULATIONS

At this time, there are no US regulations in place for specific nanomaterials or products containing nanomaterials, with the exception of sprays for agricultural use. It is imperative that the semiconductor industry monitor and follow future guidance set forth by the regulatory agencies (e.g., ECHA, OSHA and EPA), other agencies such as NIOSH, and nanomaterial manufacturers.

THE PATH FORWARD

Once the highest priority nanomaterials and processes have been identified, the semiconductor industry can sponsor research, leverage existing physico-chemical property−toxicity−exposure studies, and establish partnerships with federal agencies and nanomaterial manufacturers to address ESH needs specific to the industry. For example, NIOSH has conducted over 40 site visits to evaluate workplace exposures to nanomaterials and recommend engineering and PPE controls to mitigate such exposures, and has released guidance documents such as Current Intelligence Bulletin 65, Occupational Exposure to Carbon Nanotubes and Nanofibers8. Further, for implementation of the 2013 Roadmap, it is important to ensure facilitated, deliberate communication of information needs and time schedules among SEMATECH, SRC, government agencies (e.g., EPA for environmental regulations, NIOSH for exposure studies, and NIST for metrology and standards in the US), and academic institutions world-wide.

[8] *http://www.cdc.gov/niosh/docs/2013-145/*

7.4. APPENDIX D: GREEN CHEMISTRY

The 2015 Roadmap continues in emphasizing the importance integrating the principles of green chemistry, to proactively addressing environmental, health, safety, sustainability and product content issues in the semiconductor industry. This significant shift in strategy was prompted by several key drivers, including the complexity and volume of emerging regulations, an accelerated diversification in the industry, longer lead times for novel material, process and equipment development to address future technology challenges, etc. Additionally, broad global challenges such as climate change, natural resource and materials resource usage and availability, potentially can constrain the path of the technology roadmap.

To proactively address the challenges above, as well as develop a comprehensive treatment of ESH challenges that cut across many facets of our industry, the concepts of green chemistry (also known as sustainable chemistry) and green engineering are being integrated into the technology roadmap. Sustainable chemistry builds upon the principles of green chemistry and engineering by integrating economic viability and social benefits across the lifecycle for a given application. More sustainable products and processes must not only be more efficient in their use of materials and resources, but must also be profitable, saleable and useful to society. This must be accomplished across the lifecycle of the product and in comparison to alternatives which could provide the same application or service.

Referencing the US EPA website, Green chemistry "is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, and use". This definition, as well as the establishment of 12 Principles of Green Chemistry, comes from the text originally published by Paul Anastas and John Warner in ***Green Chemistry: Theory and Practice*** (Oxford University Press: New York, 1998), which establishes a methodology framework, within which to implement green chemistry in the context of a particular application, use or industry.

The Green Chemistry principles as defined in the Warner & Anastos publication listed above are:

1. **Prevention**
   It's better to prevent waste than to treat or clean up waste afterwards.
2. **Atom Economy**
   Design synthetic methods to maximize the incorporation of all materials used in the process into the final product.
3. **Less Hazardous Chemical Syntheses**
   Design synthetic methods to use and generate substances that minimize toxicity to human health and the environment.
4. **Designing Safer Chemicals**
   Design chemical products to affect their desired function while minimizing their toxicity.
5. **Safer Solvents and Auxiliaries**
   Minimize the use of auxiliary substances wherever possible make them innocuous when used.
6. **Design for Energy Efficiency**
   Minimize the energy requirements of chemical processes and conduct synthetic methods at ambient temperature and pressure if possible.
7. **Use of Renewable Feedstocks**
   Use renewable raw material or feedstock rather whenever practicable.
8. **Reduce Derivatives**
   Minimize or avoid unnecessary derivatization if possible, which requires additional reagents and generate waste.
9. **Catalysis**
   Catalytic reagents are superior to stoichiometric reagents.
10. **Design for Degradation**
    Design chemical products so they break down into innocuous products that do not persist in the environment.
11. **Real-time Analysis for Pollution Prevention**
    Develop analytical methodologies needed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. **Inherently Safer Chemistry for Accident Prevention** Choose substances and the form of a substance used in a chemical process to minimize the potential for chemical accidents, including releases, explosions, and fires.

Analogously, the US EPA references the definition for Green Engineering, as "the design, commercialization, and use of processes and products, which are feasible and economical while minimizing 1) generation of pollution at the source and 2) risk to human health and the environment. Green engineering embraces the concept that decisions to protect human health and the environment can have the greatest impact and cost effectiveness when applied early to the design and development phase of a process or product". This definition preceded that for Green Chemistry, and was defined in the Green Engineering: Defining the Principles Conference, held in Sandestin, Florida in May of 2003, and from an ACS publication in that same year by Anastos & Zimmerman. Coming out of this work, the following principles of Green Engineering were defined:

1. Engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools.
2. Conserve and improve natural ecosystems while protecting human health and well-being.
3. Use life-cycle thinking in all engineering activities.
4. Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.
5. Minimize depletion of natural resources.
6. Strive to prevent waste.
7. Develop and apply engineering solutions, while being cognizant of local geography, aspirations, and cultures.
8. Create engineering solutions beyond current or dominant technologies; improve, innovate, and invent (technologies) to achieve sustainability.
9. Actively engage communities and stakeholders in development of engineering solutions.

The intent for these principles was to create a framework of guidance in the design of equipment and processes "within the constraints dictated by business, government and society such as cost, safety, performance and environmental impact."

To begin the process of integration of these green chemistry and engineering principles to the semiconductor (and electronics) industry, several key elements are worth noting:

- Many of the systems and processes developed and used within the industry for many years (pollution prevention, DFESH, materials risk assessment evaluations, etc.), exemplify the principles of green chemistry and engineering, regardless of whether they had been defined as such. They serve as a solid foundation upon which the industry can build going forward.
- A key vehicle to take the principles and drive improvement in the overall 'green' content of technology development is in the application of 'alternatives evaluation' type tools.
- Today, there is no single, universally applicable alternative evaluation tool available. Therefore, an objective assessment of existing tools—and their relative merits and applicability—is needed to better define and implement a consistent approach across the industry. The INEMI sponsored project evaluating alternative assessment methodologies (first phase completed in Fall 2015), will be a valuable reference for the semiconductor and adjacent industries, as a guide to selecting more benign alternative materials, and as a means for identifying key gaps in information, as well as a catalyst for novel, green chemistry materials design. The project defined an overall hierarchical framework, which directs the practitioner to the appropriate types of materials and tools, based on the specific application, and will also serve as a starting point, for establishing standards of approach in materials evaluations.
- It is important to identify appropriate milestones and decision points where the alternatives evaluation tool(s) may be utilized. In this way, technology development decisions can be made within a broader LCA/LEAN perspective. This strategy will mitigate risk, improve decision making, and build upon existing industry best practices in ESH, sustainability, and product stewardship.
- Incorporation of Green Chemistry and Engineering (through appropriate alternatives evaluation tool selection), has several key aspects:
    - Education: significant changes in approach for adoption of these concepts, require a commensurate change in how we approach materials, process and equipment design. This will require a broad industry effort to support modifications of learning requirements, changes in curricula and a more proactive view in addressing 'green' issues.
    - Software: setting an expectation for development of a suite of risk based tools, which employ commonly used systems, compatibility, and ease of use, flexibility and customization.

- Comprehension of hazard and toxicity must be commensurate with use and application, to fully understand exposure and risk of a material, in the context of the equipment and process utilization.

The unique characteristics of the semiconductor and electronics industry present special challenges in addressing ESH issues, including:

- New technology processes and products introduced every few years (resulting in new materials, process and equipment changes and providing a means for driving ESH improvement);
- Use of novel materials with (in some cases) with less than ideal ESH properties due to technical requirement drivers and basic device physics;
- Complex set of regulatory and technology drivers, coupled with increasing challenges for performance, requiring long lead time for R&D.