Advancing Technology for Humanity

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

2017 EDITION

ENVIRONMENTAL, SAFETY, HEALTH, AND SUSTAINABILITY

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ACKNOWLEDGMENTS

ESH/S members and adjunct participants: Mike Garner, David Harman, Francesca Illuzzi, Leo Kenny, Slava Libman, Supika Mashiro, Steve Moffatt, James Moyne, George Ndubuisi, Andreas Neuber, and Yaw Obeng

Contributors to the 2016 White Paper: Norm Armour, Nicole Becker, Hans-Peter Bipp, Peter Cobben, Christopher Dott, Terry Frances, Joji Hoshi, Thomas Huang, Chris Lee, Maty Lindgren, Joey Lu, Toshi Matsuda, Andreas Neuber, Alain Pardon, Brian Raley, Eric-Paul Schat, and Don Yeaman

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ENVIRONMENTAL, SAFETY, HEALTH, AND SUSTAINABILITY

1. INTRODUCTION

The Environmental, Safety, Health, and Sustainability (ESH/S) chapter of the IRDS serves to provide a long-range framework and process for all key stakeholders in the semiconductor and microelectronics industry, to develop proactive technical solutions to address critical ESH/S challenges up front, without gating industry R&D, mitigating cost, ensuring business continuity, and identifying key new markets and opportunities. This current version of the ESH/S chapter reflects that transitional nature of the technology roadmap itself, from the previous International Technology Roadmap for Semiconductors (ITRS) to the new scope and vision of the International Roadmap for Devices and Systems (IRDS).

There are several significant additions in this edition from 2016. First, we have formally added the area of Sustainability, given the increasing constraints posed by natural resources (water, energy), and materials usage. We will also include the topic of governance, in the context of how processes and systems are managed and reported. Note, that the broader sustainability topics typically included in standard reporting, such as fair labor practices and social responsibility that are not directly related to technology and operations, are considered out of the scope of this roadmap chapter.

1.1. CHARTER AND MISSION

The IRDS ESH/S long-term vision, direction, and scope for this edition of the roadmap will reflect the content developed in the 2016 white paper during the transition from the previous ITRS format. This will serve as a foundation and basis for the 2018 edition of the chapter, which will be a significant re-write.

From the previous work, we identified 13 core strategies, which represent our initial assessment of strategic improvements. These strategies are extensions and improvements of those in the former ITRS used by the semiconductor and electronics industries for several decades. This updated list reflects a broader context for the IRDS, specifically in regard to the full range of technology applications and devices envisioned in the time horizon to 2030. This is included as the starting point for the next chapter revision and will undoubtedly be dynamic and fluid going forward, given the rapidly changing environment and myriad of drivers in the ESH/S space. Here is an update list of strategic needs, based on the 2016 ESH white paper:

1. For the IRDS ESH/S vision, to revise and update the long-term direction for the semiconductor industry, to reflect the broader IRDS scope and focusing on new markets and opportunities, as well as risk mitigation and business continuity.
2. To enable LEAN engagement across the technology lifecycle, building on past ITRS learnings, re-establishing a framework process for ongoing collaboration by all key global stakeholders (from research consortia, and equipment and materials supply chain to the electronics industry), to facilitate dialogue and feedback on the impact of design changes.
3. Drive systems and processes that strengthen the effective connections between long-range technical challenges and medium-range technology development, to design near-term challenges (regulatory requirements, natural resource constraints, etc.), emphasizing the importance of developing technical forecast radar to comprehend the existing landscape as the foundation for forward-looking design for environment).
4. Promote governance practices, in the development of systems that enable more effective decision making, emphasize a systems integration approach to problem solving, addressing proactive risk mitigation, as well as forward-looking opportunities for the industry to perform ‘for the environment.’
5. Emphasize strategies that drive proactive engagement in the ESH/S space:
   a. Cross disciplinary and organizational collaboration: to provide proactive engagement with stakeholder partners and customers and reset strategic focus on the roadmap goals
   b. Design for ESH/S: process, products, and systems (equipment and facilities) that consume less raw materials and resources, to understand and characterize these with a long-term, lifecycle perspective

   c. Green chemistry and engineering processes, and the use of alternative assessment methodologies, promoting materials, equipment and process development design, that comprehend ESH/S long-term considerations, as part of the decision-making process across the entire technology lifecycle.

6. Understand and coordinate a forward-looking process and strategy that comprehends emerging regulations, rules and policies, to accurately capture the regulatory landscape; to enable effective technical strategies; and to address these issues in advance.
7. Proactively comprehend emerging materials (such as new metals and resists), as well as equipment challenges, emphasizing a collaborative, pre-competitive approach.

   Assist the predictions of impact of new materials requirements (codes and regulations) on chemical use and waste discharge and to collaborate on strategies and potential solutions.
8. Provide a clear global ESH/S perspective with regards to the introduction of new materials, and green chemistries used for making systems and devices. To assess, insofar as possible, impacts in measurable and quantitative ways. To provide forward-looking visibility of the key aspects to 2030.
9. Collaborate with appropriate key stakeholders and contribute to developing descriptions of the full lifecycle ESH/S outcomes and the full cycle costs associated with the introduction of new products and processes. To understand (characterize) processes and materials through the earlier pathfinding and early development phases, in order to better construct quantitative forward-looking roadmaps for the entire life of the technology operating inside the devices and systems envisioned within the time horizon.

   Provide proactive continuous engagement with stakeholder partners throughout the industry and help to reset strategic focus on the quantitative roadmap ESH/S goals.
10. Encourage the industrial use of materials that are less hazardous and whose byproducts are less hazardous.
11. Provide useful and helpful baseline information for the design of devices and systems (using equipment, materials, and facilities) that consume less raw materials and use resources more efficiently and sustainably (eco-efficiency).
12. Help describe manufacturing process optimization and minimize waste generation and/or to increase recycling and re-use rates. Early quantification of energy use, water consumption, and waste generation has been completed, the roadmap will continue in the goal of quantifying use further for more critical materials and additional facility parameters in the time horizon to 2030.
13. Fully comprehend nanotechnology standards through broader global collaboration.

By applying these ‘core strategies’ as the basis of our activities and further updating them for the 2018 edition of the IRDS ESH/S chapter, the roadmap international focus team (IFT) will in turn convey direction and strategies to other IRDS IFTs, to enable them to better manage their respective ESH/S challenges as a partnership with ESH/S.

This will be achieved through proactive continuous engagement with relevant institutional, governmental, regulatory, and industrial stakeholders to develop the information and the processes required so that ESH/S related lifecycle costs can be considered early in the equipment and process development cycles. The ESH/S IFT will continue to quantify energy use, water consumption, and waste generation reduction goals and their regional dependencies, as well as emphasize the critical importance of materials availability, usage, and efficiency and ESH/S implications across the technology lifecycle. For those challenges whose impacts and drivers are uncertain or inconsistent, flexible strategies and systems will be emphasized.

1.2. Current State of Technology

As the scope of the ESH/S chapter cuts across most facets of the semiconductor industry, and through the entire technology lifecycle, many of the other IRDS IFTs will have their own unique, respective technology challenges that the ESH/S shall partner with to address these issues and provide support to provide guidance, systems, and processes to proactively address them up front, in an integrated fashion. Each IFT will have a specific subsection addressing how their future technology needs will comprehend and address their EHS/S considerations. Several of the IFTs already refer to EHS/S in the 2017 IRDS, including Factory Integration, Emerging Research Materials, and Metrology.

For the areas of ESH/S, there are several over-arching technology themes that are of critical importance for semiconductor and electronics industries in the future and we will substantively address these in future roadmap editions. These high-value problems at a topical level include the natural resource constraints (water and energy), materials and equipment and design, usage, efficiency, treatment and reuse, and materials regulatory implications. A key technology gap existing today for choosing less ESH/S impactful materials is the lack of a universally applicable or accepted alternative assessment framework, methodology, or tool. This lack of a singular solution is likely a fundamental one, as materials' properties and impacts are also a function of use and exposure.

1.3. DRIVERS AND TECHNOLOGY TARGETS

Societal driving forces and trends such mobile devices and the internet of things (IoT) are impacting all areas of the IRDS; however, as shown in Figure ESH-1, these factors impact the evolution of ESH/S considerations from several different perspectives, namely:

1. Requirements on product and device technologies are defined by industries and roadmaps that have their own technology drivers and focus, but these technology requirements indirectly influence ESH/S in terms of product content, electromagnetic (EM) radiation, end of life recycling, and reuse challenges.
2. Insufficient coordination and communication on their respective future technology requirements to the semiconductor industry, where materials and fabrication decisions often have significant downstream implications, and whose decisions, if better informed, could be more effective in reducing risk and cost than those downstream in the electronics industry.

Following a similar approach by the Factory Integration IFT and their analysis, a pictorial of the key stakeholder engagements that have relevance to ESH/S considerations is shown in Figure ESH-1. This representation provides a high-level view of the complexities of influence and drivers that must be sufficiently comprehended to effectively design out these issues up front. Prevalent emerging technology trends are the following:

- *The Cloud:* The advent of the cloud and cloud-based technologies provides tremendous opportunities in terms of analytics, addressing data volumes, coordination, enterprise-wide sharing and commonality, and leveraging capabilities across industries. However; it also presents challenges in terms of security from attack, security for intellectual property (IP) protection, and performance, and all the collateral ESH/S implications that go with it.
- *Big Data:* The data explosion in manufacturing provides both challenges and opportunities for ESH/S with how novel sensing and its proliferation and data gathered for ESH/S can be effectively used to drive working solutions. This will require clear systems and robust processes to ensure intelligent discernment and information to enable valuable solutions, not just result in 'dark' data that is never utilized. Future ESH/S chapter editions will begin to tackle these key data issues.
- *Mobility:* The explosion of mobile devices, represent significant opportunities and risks, in terms of driving new technology (process and product requirements that will have collateral ESH/S implications) while providing novel capabilities for more effectively solving ESH/S impacts.
- *'Green' drivers:* The expansive (and often) diverse realm of ESH/S in how these issues are defined and the great range expectations from both external and internal stakeholders represents a fundamental challenge in defining long-term vision, goals, and strategies for the industry and beyond. Providing clear and succinct calibration on what ESH/S challenges is and how the industry defines their scope is critical to drive real solutions.
- *Internet of Things (IoT):* Defined as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies,"[1], IoT is identified as a clear industry driver. Ensuring that the full scope of future opportunities and capabilities associated with IoT, along with comprehending the critical risks associated with this area, is another key focus for the ESH/S chapter.
- *Supply Chain:* Given the increasing complexities of regulations, natural resource regional constraints, and technology drivers, the technology roadmap is an essential element in up leveling proactive technical solutions to enable more viable materials and equipment capabilities for driving cost-effective ESH/S solutions, as time-to-market demands increasingly do not afford sufficient time to address these issues reactively as in the past.

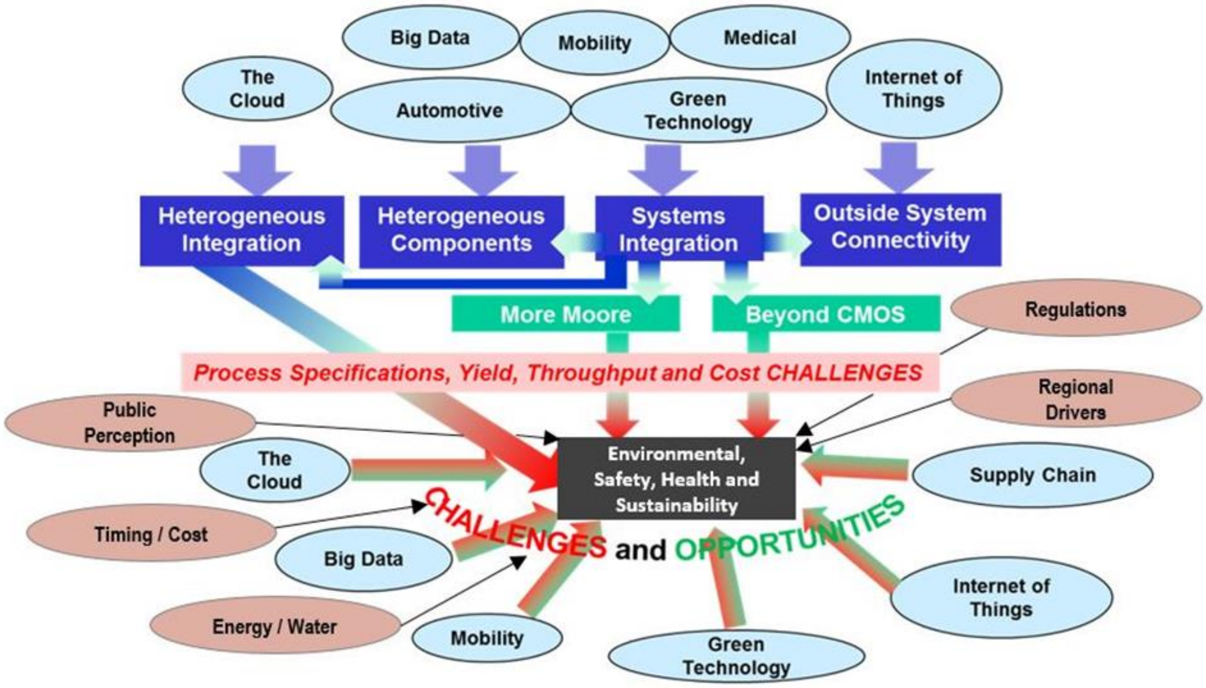

Figure ESH-1 Societal Forces Impacting Challenges and Opportunities in ESH/S

1.4. Background Information

Important information to help in the understanding of the ESH/S roadmap report is a listing of acronyms (found in the Acronyms section), and SEMI standards that have relevance to the scope of ESH/S considerations and are listed in the Appendix. Note that this list of standards is not meant to be comprehensive; for a complete listing of SEMI standards, refer to www.semi.org/standards.

2. Scope of Report

The Environmental, Safety, Health and Sustainability (ESH/S) IFT projects the principles of a successful, sustainable, long range, global, and industry-wide program. Execution remains largely independent of the specific technology thrust advances to which the principles are applied.

Historically the IFT managed the roadmap process through a well-defined set of six fully developed, quantitative tables and charts.

- Understand (characterize) processes and materials during the development phase
- Use materials that are less hazardous or whose byproducts are less hazardous
- Design products and systems (equipment and facilities) that consume less raw materials and resources
- Make the factory, and fundamental industry supply chain, safe for employees and the environment
- Provide clear global ESH/S perspective in regard to new materials, sustainability, and green chemistry
- Provide proactive engagement with stakeholder partners and customers and reset strategic focus on the roadmap goals.

In 2016 during the transition to IRDS, several key changes were made to the chapter. The new IFT reviewed and updated the ESH/S metrics and graphics to improve data linkages to much broader data sets, for a wider range of systems, applications, and devices. Accordingly, the scope of the chapter increased beyond the scale of its historic ITRS semiconductor origins and then consisted of eight charts. The ESH/S roadmap then identified challenges when new system manufacturing, wafer processing, and assembly and packaging technologies move through research and development (R&D) phases, and towards manufacturing insertion. Following the presentation of ESH/S domains and categories, ESH/S technology requirements will be updated and included in the 2018 edition, with an increased focus on sustainability and green chemistry.

Potential technology and management solutions to meet these challenges are proposed. Successful resolution of these challenges will best be realized when ESH/S challenges are an integral part of the technology design, development, and decision making for process, equipment, and facilities engineers, chemical/material and tool suppliers, and academic and consortia researchers. ESH/S solutions must also support (or at minimum, not conflict with) enhanced technical performance, product timing, and cost-effectiveness. Further, ESH/S improvements must inherently minimize risk, public and employee health and safety effects, and environmental impact. For this purpose, the 2016 IFT introduced a methodology to explain the necessary processes for consensus building of stakeholders to ensure full lifecycle risk assessment. Successful global ESH/S initiatives must be timely, yet far reaching, to ensure long-term success of the industry.

Scope additions in the 2016 white paper included specific new packaging and other technologies, such as:

- Photonics and its integration in the packaging aspects of devices
- More than Moore (MTM) and beyond CMOS applications such as power devices in SiC and GaN, sensors and advanced communications requirements.
- IoT devices including bio-based sensors.

3. Summary and Key Points

The 2017 ESH/S chapter of the IRDS is in a period of transition, and this current edition of this roadmap section is reflective of this state, where a significant portion of the content comes from the work of the provisional team in 2016. Note, that during the change from the ITRS and previous focus, the ESH/S technology roadmap became a subset of the Factory Integration roadmap effort during that time period. Now this change to the IRDS has been completed, the ESH/S roadmap is a separate chapter. As part of the future work of the group's efforts in redefining the vision, scope and long-term direction for ESH/S for the industry, a concerted focus in the near term will be to expand team membership to better support the new scope of the roadmap.

For this version of the ESH/S roadmap, several key elements have been introduced as new focus areas, including sustainability, as well as materials and equipment supplier engagement in promoting design for ESH/S (DFESH) increased support and visibility for research consortia driving technical solutions for energy and water usage. Among other critical areas of focus are materials challenges (design, utilization; long-term ESH/S implications across the technology lifecycle; better focus on future metrology needs; the concept of circular economy, and the importance of governance, systems integration and effective decision making in driving ESH/S solutions.

4. Challenges

The ESH/S roadmap white paper in 2016 delineated a number of challenges, from when new wafer processing and assembly and packaging technologies move through R&D to manufacturing insertion. Potential technology and management solutions to meet these challenges were then proposed by the 2016 ESH IFT and will be reevaluated in the context of the new ESH/S vision, direction, and scope for the 2018 ESH/S roadmap update. The successful resolution of these challenges will best be realized only when ESH/S concerns are integral in the thinking and actions of process, equipment, and facilities engineers; chemical/material and tool suppliers; and academic and consortia researchers, as part of their regular business, just as with quality. ESH/S improvements must also support (or at minimum, not conflict with) enhanced technical performance, product timing, and cost-effectiveness. Furthermore, such improvements (solutions) must inherently minimize risk, public and employee health and safety effects, and environmental impact.

Some specific ESH/S challenges that were identified in the previous 2016 ESH white paper are included below. Given the IRDS transition, these topics will be addressed more fully in the2018 edition of the ESH/S roadmap:

- Rework of the quantitative calculations for water based on current external inputs
- Spray cleaning delivers all particles to wafer, so achieving defects is the deciding factor
- F-GHG reduction is defined by world semiconductor council (WSC), but we keep this target in the tables
- For ESH/S, new restrictions of use from US EPA sometimes appear for existing materials; we consider this not to be a roadmap issue.

- We use green chemistry principle for bringing on ALL new materials
- No changes in toxic wastes, total waste, or chlorofluorocarbon (CFC)
- Need to analyze volatile organic compounds (VOC)- increasing solvent use in assembly. Include assembly in analysis and assessment as they can be major potential sources
- Compare water consumption, energy use, CFC metrics, from fab-level to mass-level calculations
- Nanomaterials require a new section in the roadmap
- New elements and precursors
- Add additional metrology and more data with specific cases
- New energetic materials
- Green chemistry
- New lithography: new mask, new lasers (light source efficiency), and energy safety, etc., in EUV adoption.
- Full lithography supply chain
- Eco and resource efficiency, water, hydrogen, overall facilities, etc.
- Industry 4.0 (for more information, refer to the 2017 Factory Integration roadmap report)

Difficult challenges associated with ESH/S (along with materials issues) are ubiquitous in their relevance across the entire technology lifecycle, cutting across all disciplines, organizations, and functional areas, and are summarized in the Tables ESH-1 below (Factory Integration IFT-related topics for ESH/S can be found in the Factory Integration 2017 roadmap report). While we segment these difficult challenges in terms of near and long-term focus, it should be noted that the greatest hurdle to proactively addressing these ESH/S issues is structural and organizational, not just topical. Designing out issues up front requires a dedicated focus and commitment within a technology roadmap framework, as a matter of continuous improvement across the technology lifecycle. Therefore, for the industry to accept and tangibly engage in the roadmap process, adopting this commitment to design for ESH/S (DFESH) in practice is the primary industry challenge and will require a fundamental shift in how the industry approaches these challenges.

From an industry and technology perspective, the once regular cadence of introducing a new technology generation every two years has moved to ~4 years due to the slowing of Moore's Law and the proliferation of many new device types. This has affected the overall industry approach to adopt cohesive, precompetitive ESH/S solutions. This drives fabs to need to use more power, materials and water to make more wafers at existing process technology nodes on the roadmap. This effect is being strongly felt in semiconductor foundries. Secondly, the 'lifecycle' for all silicon, chemicals and gases is pressed into a more rapid rise to achieve improvement within narrower process windows than was originally forecasted a decade ago. The industry also has to contend with the diminished ability to shrink die size; an extended delay in transitioning to a larger wafer size; and rapidly increasing materials and treatment costs. In the context of these complex drivers, new technology development is being done at 'half nodes', with these triggered by individual company and product needs for improvement.

Moreover, we have a more fractured and geographically diverse manufacturing base; a more numerous and conflicting regulatory; and regionally different natural resource diverse set of constraints as well. These factors all contribute to the challenges we observe in developing clear long-term technical solutions and cohesive global policy to address key ESH/S issues. Finally, the significant decline in industry support for pre-competitive systems (SRC, ERC, IRDS) and the demise of SEMATECH, significantly impact the supply chain, research consortia, and even manufacturers to substantively meet future industry challenges, which are much more globally impactful than they have been historically. Unless these gaps are met, it will have serious consequences to the long-term business continuity of the industry. This has irony, in that the semiconductor industry historically has developed systems and processes that have had tangible success in addressing these big challenges and can again if adequate resourcing and technical leadership is applied.

Table ESH-1 ESH/S Difficult Challenges

Near-Term Challenges: 2017–2024	*Description*
Alignment on a common vision, scope, and strategy	• Expansive scope of ESH/S extends across the technology lifecycle and interdependence with adjacent industries • Divergence in drivers (technology, regulations, supply chain and lifecycle, regional natural resource constraints, materials present challenges in developing unified, cohesive solutions • Relying on compliance to a myriad of regulations that are not harmonized does not fundamentally address long term ESH/S challenges
Team reset (resourcing, support, organizational commitment)	• Team membership has been significantly diminished during the transition from ITRS to IRDS, and with temporarily being part of another IFT, resulting in significantly reduced resources • Pre-competitive industry associations and entity resourcing, and scope have either been significantly reduced or eliminated (i.e., SEMATECH), limiting the research, development, and implementation of solutions for ESH/S challenges • Industry support of ESH/S forward looking DFESH initiatives has been reduced, with diminished support of technology roadmap and related efforts
Materials challenges	• Emerging/novel materials, i.e., III-V (GaN, InP, InGaP, etc.), nano and energetic materials (assessing their ESH/S impacts, along with social responsibility implications) • Utilization challenge (materials efficiency of incoming fab materials is <2%) • Treatment and abatement solutions to meet current and future regulatory requirements can gate development ramp, and increased costs • Restrictions on recycling, repurposing, and reuse are significant due to technology and regulatory hurdles • There is no universally accepted or applicable alternative assessment (frameworks, methods, and tools) strategy, nor are there clear guidelines or standards for how these should be applied for picking less ESH/S impactful materials.
Electromechanical exposure	• Stimulate research for potential biological interactions: mmWave (28–330 GHz), ID, and reconcile regulatory direction
DFESH gap across the technology lifecycle	• Insufficient engagement across industry segments (materials, equipment, semiconductor manufacturing, and electronics), to ensure that ESH/S factors are considered to enable effective decision making
Future metrology capabilities	• Advanced forecasting and time for identifying future needs for materials and environmental emissions analysis, sample preparation, chemical characterization instruments, and method development is critical to quantify ESH/S impact assessments • Defining future chemical sensor capabilities and continuous effluent monitoring?
Natural resource issues (sustainability)	• Fab energy and water usage (availability); regulations are introduced stepwise • Water recycling (difficulties due to segregation); with higher costs driving need for affordable solutions

5. TECHNOLOGY REQUIREMENTS

The practices of ESH/S have been well established and historically proven to be effective over the past five decades of incredible growth in the semiconductor industry. However, as the complexities (both internal and external) associated with ESH/S have greatly increased, a fundamental change in how we approach these challenges has become a necessity. Luckily, there have been significant advances in the development of proactive systems and processes to address ESH/S challenges through technical solutions, so the industry has demonstrated strategies to build on. With the advent of technologies beyond CMOS (MTM, IoT, sensors, heterogeneous, photonics, biochips, RF, and power), a deeper comprehension and further quantitative analysis is needed with the increasing reliance on novel organics materials, polymers, nanoparticles, etc.

Several key technology requirements that can influence future materials challenges are of particular note here:

Green Chemistry and Engineering—Through the last few iterations of the ESH/S chapter of the ITRS, the authors have introduced the concepts of green chemistry, as developed by Anastas and Warner, in their seminal 1998 book.[2[1] Although written from a synthetic chemistry perspective, the core 12 principles delineated there are relevant and vital to any industry sector, though the relative importance of each may vary based on the application. However, while green chemistry has been integrated qualitatively into the roadmap and experienced some measure of adoption by semiconductor manufacturers and suppliers, much work needs to be done in achieving widespread integration and implementation across the industry.

Given the volume, sources, and complexity of regulation, materials availability and downstream implications, as well as diversity of products and supply chain, the need for a long term (lifecycle) approach that proactively develops and drives technical solutions that address ESH/S challenges up front is a critical necessity. The roadmap provides an ideal framework for taking a long view on technology development, employing the requisite systems integration approach that is vital in creating comprehensive solutions and processes for the industry in the future. Applying green chemistry and engineering concepts and tools across the technology lifecycle, from materials and equipment research through development to ongoing manufacturing, and providing the appropriate tools (i.e., alternative assessment methodologies to drive materials replacements) and systems at each key decision point along the way, is the only viable path forward in addressing ESH/S challenges. Reacting to existing regulations is simply no longer possible, given the R&D time required in the development of new technologies. The focus going forward for the roadmap, will be setting goals and direction for driving widespread understanding and awareness for green chemistry and engineering, and a path toward the development of tangible implementation strategies across the technology lifecycle. Figure ESH-2 highlights the importance of integrating these methodologies early on in the design phase (for process or products), to improve decision making effectiveness and to avoid risk and cost, which is more probable as you approach the present, when reacting to regulation and natural resource constraints delays technology insertions and increases cost.

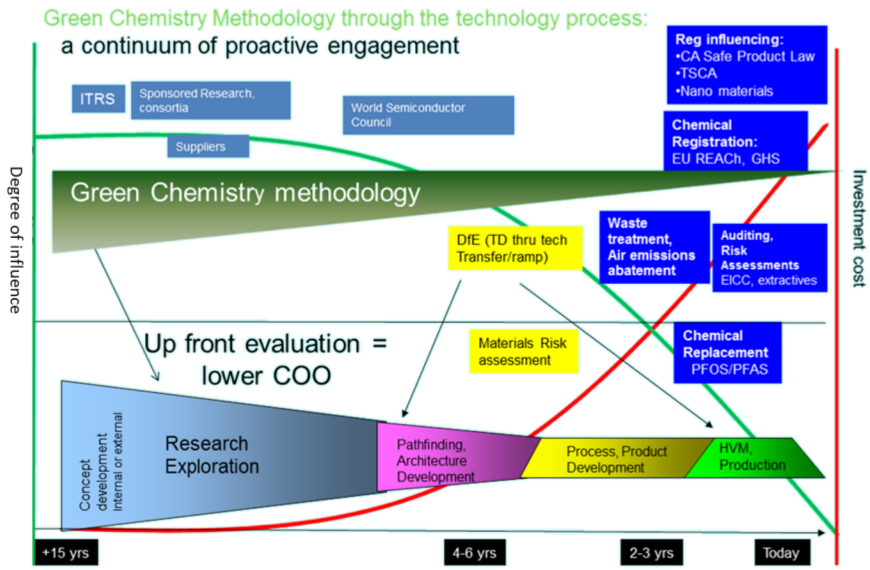

Figure ESH-2 ESH/S Engagements Across the Technology Lifecycle

5.1.1. ALTERNATIVE ASSESSMENT METHODOLOGIES

Consistent with the principles and concepts of green chemistry, is the application of alternative assessment methodologies, which enable the selection of less ESH/S impactful materials, proactively. Such methods can be viewed as a practical implementation vehicle for green chemistry. In the fall 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 microelectronics 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 IRDS does this for the microelectronics 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 that enable the selection of more benign materials.

As part of this effort, the project team examined existing environmental/toxicology assessment tools, methods and frameworks that have been developed by various sources (industry, non-governmental organizations (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[3]. Moreover, the 14 alternative assessment tools that were evaluated represented tools that have been shown to have future potential regulatory interest and can be used in the context of the aforementioned framework. These were also grouped into similar categories, which can be useful to electronics manufacturers and upstream by the microelectronics industry.

Utilization of these tools by microelectronics 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 was planned but has not yet been implemented. This represents another key technology gap, in better selecting less impactful ESH/S materials.

5.1.2. LITHOGRAPHY

ESH/S continues working on the sustainability aspects of "new" lithography: new mask, new lasers (light source efficiency), energy safety, etc., in EUV adoption. Introduction of EUV exposure has major fab impacts in terms of power and water usage. Examination of the full lithography supply chain, including new resist chemistries, is underway. The adoption of EUV is expected to significantly increase the energy consumption of a given wafer fab. Since the EUV tools are still under 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 are increasingly being utilized in HVM.
- Each EUV tool uses on average 810 kWatts (and up to 1MW, in the most recent configuration).
- The throughput of the EUV tools is 20% that of 248/193 nm scanners (single pass) and this is rising to 50%. But electrical power and cooling water will also increase.
- The assumption of number of mask levels that use the EUV tool starts at 2 and increases over time is being calculated fully into the model.

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/S programs require water reuse in process and non-process applications, energy efficient facilities equipment, improved facilities system design, and new facilities operating strategies.

5.1.3. MANUFACTURING AND FACILITIES CONSIDERATIONS

The following considerations are shared with the IRDS Factory Integration IFT effort and are more fully addressed in that chapter:

- Energy Savings and Factory Environment
- Resource Conservation Considerations

- Industry Collaboration for Facilities

5.1.4. AUGMENTING REACTIVE WITH PREDICTIVE NEEDS

The scope of augmenting reactive with predictive (ARP) is an ongoing focus for FI technologies that can have a predictive component. A number of the key elements being considered by the 2017 Factory Integration chapter (predictive maintenance, equipment health monitoring, virtual metrology, predictive scheduling, etc.), all have significant ESH/S implications and relevance. In future ESH/S chapter revisions, we will focus on providing additional context and content to these efforts, to leverage and integrate into ongoing efforts. This is another key theme—to make ESH/S a key element to all industry design thinking to drive proactive technical solutions.

6. POTENTIAL SOLUTIONS

Since the ESH/S IFT was in transition during the development of the 2017 edition, potential solutions will be explored in the 2018 edition of the IRDS.

7. CROSS TEAMS

ESH/S Team technology requirements are often driven by other IRDS IFT teams' requirements. In order to understand the crosscut issues fully, the ESH/S IFT interfaces with other adjacent groups and puts together a list of key crosscut challenges and requirements as shown in Table ESH-2. This is followed by a discussion of interactions with specific groups or interactions around specific issues. ESH/S will continue to address these key crosscut challenges and requirements. Note, beyond these core group of partner work groups (emerging research materials, factor integration and metrology), regular engagement with the other IFT groups will also continue around specific issues.

Table ESH-2 Crosscut Issues Relating to Environmental, Safety, Health, and Sustainability

Crosscut Topic	*Counterpart IFT(s)*	*ESH/S-related key challenges*
Addressing analytic characterization issues for emerging ESH/S challenges	*Metrology*	Drive the development of novel sensors and supporting IoT systems and tools to better address emissions (PFCs, hazardous air pollutants (HAPS), VOCs, waste water metals, and organics), and to assist in more effective waste segregation and treatment.
Sustainable Manufacturing Green Chemistry and Engineering	*Factory Integration*	• ESH/S to identify required Fab/equipment capabilities to measure resource consumption and release/emission to environment. • FI to provide necessary metrics, methodology, data systems, and infrastructure to accommodate ESH/S objectives • Yield Enhancement (YE) to benefit from yield excursion detection and analysis and ultimately yield prediction provided as part of FICS, ARP and BD capabilities.
New materials	*Emerging Research Materials*	• Ongoing joint engagement on new materials table to evaluate potential ESH/S impacts and downstream lifecycle considerations
Other IFT Team Engagements: More than Moore, Packaging Integration, and Lithography		

7.1.1. ESH/S STAKEHOLDERS

ESH/S is impacted in all that we do as an industry in devices and systems and the entire lifecycle of devices and systems. In terms of stakeholders internal to the IRDS, the ESH/S IFT is mostly connected with the following seven categories. A large part of what we do is extensive open communication with a very wide range of globally collaborating stakeholders:

1. Internal IRDS Roadmap: Roadmap Management, Factory Integration, Metrology, Device and Assembly/Packaging, Lithography, ERM, FEP. Emerging new structures under IEEE guidance.

2. Semiconductor Industry: associations (WSC, SIA, JEITA, KSIA, TSIA, ESIA), and WSC (policy), SEMI
3. Research consortia: Imec, ITRI, Fraunhofer, Leti and SRC/ERC, CNSE, Tyndall
4. Adjacent industry (technology lifecycle): ACC, ACS/GCI, INEMI, MEMS, Sensors
5. Government Agencies: OCED? ECCA, US EPA, NIST
6. Regional Co-coordinators: IEEE, NEREID/SiNANO, SDRJ
7. Industry Associations, primarily: WSC, SIA, JEITA, KSIA, TSIA, ESIA, WSC (policy), SEMI, iNEMI

Our significant stakeholders for the ESH/S roadmap IFT include all the active stakeholders for Factory Integration roadmap, including all solution manufacturers and suppliers that cover all manufacturing sectors including front-end, back-end, facilities and linkage to the upstream and downstream supply chain. Stakeholders also include *all* device designers especially from the perspective of the tighter linkage between design and manufacturing via design for manufacturability innovations and the increased use of cyber-physical systems. Within the IRDS, the ESH/S has strong cross linkage to FEP, Packaging Integration, Yield Enhancement, Lithography, Metrology, and ERM. Stakeholders also include local communities wherever semiconductor manufacturing operation takes place, and the related government groups associated with manufacturing. One major issue with ESH/S in IRDS is the vast breadth of interactions. This is a major challenge in itself.

8. Emerging Concepts and Technologies

Table ESH-3 Emerging Technologies and Issues

Challenges	*Category*	*Short description*	*Comments*
Nanomaterials	New materials	Significantly broader elemental range of emerging materials and their compound	First introduction in Assembly and Packaging: TSV, filler materials, etc.
Energetic materials	New materials	ESH/S Impact, such as organometals, safety issues at interfaces between supply/process and effluent treatment, e.g., supply of liquid materials	
III/V materials	New materials	ESH/S Impact, e.g., AsH_3 outgassing (e.g., during cleaning)	
Availability of materials	New materials	Availability, reuse, and recycling	e.g., Xe
Fab energy and water usage	Resources	Energy and water availability	Continuous effort, regulations are introduced step by step
Water recycling in fabs	Resources	Trends in water recycling based on segregation	Costs is high and therefore an obstacle, need for affordable solutions
EUV lithography	Resources	Energy and utility consumptions	Major challenge
Expanded use of single wafer cleans	Resources	Increase in chemical and water consumption instead of reduction, insufficient segregation	Still a concern
450 mm wafer processing	Resources	Energy and utility consumptions	
Power monitoring	Metrology	Methodologies and instrumentation: More engineering efforts to monitor and optimize tool power usage needed	
Continuously effluent monitoring	Metrology	Methodologies and instrumentation	
Materials risk assessment and selection	Process development	General, material selection roadmap, sustainability and green chemistry, avoidance of secondary costs, conflict materials	
Molecular efficiency (e.g. ALD)	Process development	Effluents, material conversion efficiency	

Challenges	*Category*	*Short description*	*Comments*
Ensure Full Lifecycle Risk Assessment, exposure risk	General	Evaluate risks, carbon footprint, standardized model, data	Combine with material risk assessment
# of regulations	General	Rapidly increasing # provides challenge for compliance	
Sustainability	General	Methodologies: selection of KPI, reports to what standards	
Air emissions	Regulations	Requirements for VOC, NOx etc. & testing methods require improvements	
GHG emissions	Regulations	Regulatory requirements F-GHG, N_2O	
Materials regulations	Regulations	Regulatory requirements, e.g. ban on PFOS, PFOA; PFAS etc. in articles	
TMAH	Regulations	Regulatory requirements for concentrated chemicals	
CE certified equipment	Tools	Costs for small innovative companies for compliance certification	

9. Conclusions and Recommendations

Significant new challenges are being faced in device and systems manufacturing with respect to ESH/S. The increasing number and complexity of chemical regulations around the globe, coupled with adding many new materials into emerging devices, results in major ESH/S Challenges. This is further exacerbated by EUV and single wafer cleaning processes with significantly greater energy use and water consumption per wafer. Rigorous quantitative models have been built to address these aspects. We seek, generally, to better quantify all ESH/S 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 as shown below.

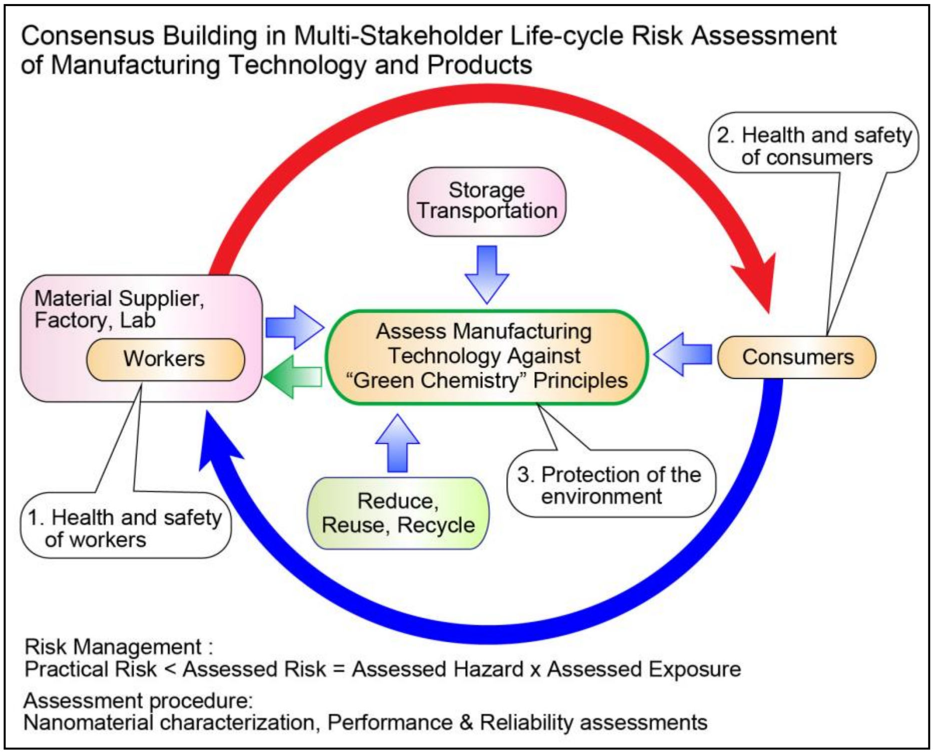

Figure ESH-3 Stakeholder Engagement and Lifecycle Risk Assessment

Successful resolution of these challenges will best be realized when ESH/S concerns are integral in all the thinking and actions of process, equipment, and facilities engineers; chemical/material and tool suppliers; and academic and consortia researchers. ESH/S improvements must also support (or at minimum, not conflict with) enhanced technical performance, product timing, and cost-effectiveness. Further, ESH/S improvements must inherently minimize risk, public and employee health and safety effects, and environmental impact. For this purpose, Figure ESH-3 represents the necessary processes for "Consensus Building of Stakeholders to Ensure Full Lifecycle Risk Assessment". Successful global ESH/S initiatives must be timely, yet far reaching, to ensure long-term success of the entire IRDS. Accordingly, a new Difficult Challenges table has been assembled.

As we move to a new era for the devices and systems roadmap, this association reflects the broader, more expansive implications of today's technology landscape and the complex interrelationships across the lifecycle of devices and systems. Despite this broader view of the roadmap, the critical importance of the core mission and work in the semiconductor industry remains, as the fundamental industry segment where proactive integration of technical solutions can most effectively address ESH/S challenges, with advances in materials, equipment and process development.

Further quantitative analyses of new metrics will be presented in several more tables.

Ultimately, the ongoing success of the roadmap, will depend on the active engagement of all key stakeholders, in how we address ESH/S challenges, from equipment and materials research, through process development and device fabrication, transitioning into the electronics industry and end of life. Going forward, the sustainability and impacts of use, as well as the value of how novel devices can work 'for the environment', and how to design out waste through the lifecycle, represent the new frontiers in these areas.

10. OTHER CONSIDERATIONS

Despite the extended postponement of the 450 mm wafer development program, increases in materials, energy and water consumption represent significant challenges to the semiconductor industry. Given the negative resource impacts to pre-competitive industry organizations focusing on research and development, roadmapping and cross-industry alignment with increasing concerns of IP leakage and security, the challenge for developing broad, strategic and holistic solutions has become even more acute. Past industry experience has repeatedly demonstrated that a dedicated, long-term focus and strong stakeholder engagement is requisite to developing viable solutions to ESH/S challenges. In fact, the postponement of 450 mm places a larger burden on 200/300 mm manufacturing, since many ESH/S-related solutions that were under development for 450 mm will now have to be implemented in the 200/300 mm environment.

11. APPENDIX

11.1. RELEVANT STANDARDS

A number of industry standards have specific relevance to the scope of ESH/S considerations, which are listed below. Note that this list is not meant to be comprehensive; for a complete listing of SEMI standards, refer to www.semi.org/standards.

Standards of Relevance to ESH/S

Number	*Title*
IEST-RP-CC012.2	Considerations in Cleanroom Design
ISO 14644-1	Cleanrooms and controlled environments, Part 1: Classification of air cleanliness
SEMI E10	Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM) and Utilization
SEMI E116	Specification for Equipment Performance Tracking
SEMI E120	Specification for the Common Equipment Model
SEMI E125	Specification for Equipment Self Description
SEMI E126	Specification for Equipment Quality Information Parameters
SEMI E129	Guide to Assess and Control Electrostatic Charge in A Semiconductor Manufacturing Facility
SEMI E132	Specification for Equipment Client Authentication
SEMI E133	Specification for Automated Process Control
SEMI E134	Specification for Data Collection Management
SEMI E138	XML Semiconductor Common Components
SEMI E147	Guide for Equipment Data Acquisition
SEMI E148	Specification for Time Synchronization and Definition of the TS-Clock Object
SEMI E151	Guide for Understanding Data quality
SEMI E160	Specification for Communication of Data Quality
SEMI E163	Guide for the Handling of Reticles and Other Extremely Electrostatic Sensitive (EES) Items Within Specially Designated Areas
SEMI E164	Specification for EDA Common Metadata
SEMI E167	Specification for Equipment Energy Saving Mode Communications (EESM)
SEMI E169	Guide for Equipment Information System Security
SEMI E170	Specification for Secured Foundation of Recipe Management Systems (SFORMS)
SEMI E171	Specification for Predictive Carrier Logistics (PCL)
SEMI E175	Specification for Subsystem Energy Saving Mode Communication (SESMC)

Number	*Title*
SEMI E176	Guide to Assess and Minimize Electromagnetic Interference (EMI) in a Semiconductor Manufacturing Environment
SEMI E30	Specification for the Generic Model for communications and Control of Manufacturing Equipment (GEM)
SEMI E33	Specification for Semiconductor Manufacturing Facility Electromagnetic Compatibility
SEMI E37	High-Speed SECS Message Services (HSMS) Generic Services
SEMI E43	Guide for Measuring Static Charge on Objects and Surfaces.
SEMI E5	SEMI Equipment Communications Standard 2 Message Content (SECS-II)
SEMI E51	Guide for Typical Facilities Services and Termination Matrix
SEMI E54	Specification for Sensor/Actuator Network
SEMI E58	Specification for Automated Reliability, Availability, and Maintainability (ARAMS)
SEMI E6	Guide for Semiconductor Equipment Installation Documentation
SEMI E78	Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment
SEMI S2	Environmental, Health, and Safety Guideline for Semiconductor Manufacturing Equipment
SEMI S23	Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment

12. Acronyms

A&P	assembly and packaging
AA	Alternatives Assessment
ACC	American Chemical Council
ACS	American Chemical Society
ACS GC&E	American Chemical Society, Green Chemistry & Engineering
ALD	atomic layer deposition
AMC	Airborne Molecular Contamination
ARC	anti-reflective coating
BN	boron nitride
CE	circular economy
CMP	chemical mechanical planarization
CMR	carcinogenic, mutagenic, toxic for reproduction
CNT	carbon nanotube
CoO	cost of ownership
CVD	chemical vapor deposition
DFESH	design for environment (safety and health)
DI	deionized water
DSA	direct self-assembly
ECHA	European Chemicals Agency
ECD	electrochemical deposition
ENM	engineered nanomaterial
EPEAT	Electronic Product Environmental Assessment Tool)
ERM	emerging research material
ESH	environment, safety and health
EU	European Union
EUV	extreme ultraviolet
FE RRAM	ferroelectric resistive random-access memory
FEP	front end processing
F-GHG	fluorinated greenhouse gas
FHTF	fluorinated heat transfer fluid
GaN	gallium nitride
GEC	green electronics council
GHG	greenhouse gas
GWP	global warming potential
HAPs	hazardous air pollutants
HAR	high-aspect ratio
HESI	Health & Environmental Sciences Institute
HFC	hydrofluorocarbon

HVM	high-volume manufacturing
I	interconnect
IC	integrated circuit
INEMI	International Electronics Manufacturing Initiative
IoT	internet of things
IPCC	International Panel on Climate Change
L	lithography
LCA	life cycle assessment
LEAN	efficient manufacturing
MEMS	microelectromechanical system
MOCVD	metal organic chemical vapor deposition
MRAM	magnetoresistive random-access memory
NAS	National Academy of Sciences
NIST	US National Institute of Standards
NGO	non government agency
NIOSH	National Institute of Occupational Safety and Health
NIST	National Institute of Standards and Technology
OSHA	Occupational Safety and Health Administration
PAG	photoacid generator
PBT	persistent, bioaccumulative, and toxic
PCRAM	phase-change resistive random-access memory
PFAS	perfluoroalkyl sulfonate
PFC	perfluoro compound (or
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic
POP	persistent organic pollutant
POU	point-of-use
PPE	personal protective equipment
PPH	pollution prevention hierarchy
PVD	physical vapor deposition
REACH	registration, evaluation, and authorization of chemicals
REL	recommended exposure limit
RoHS	restriction of hazardous substances
RRAM	resistive random-access memory
SIA	semiconductor industry association
SEMI	global industry association serving the manufacturing supply chain for the micro- and nano-electronics industries,
SESHA	Semiconductor Environmental, Safety & Health Association
SRC	Semiconductor Research Corporation
STI	shallow trench isolation (STI)
SVHC	substances of very high concern

TLC	technology life cycle
Tsensors	trillions of sensors
TSV	through silicon vias
UPW	ultrapure water
USEPA	United States Environmental Protection Agency
vPvB	very persistent and very bioaccumulative
WSC	World Semiconductor Council
VOC	volatile organic compound
3D	three-dimensional

13. REFERENCES

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