INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

2016 EDITION

FACTORY INTEGRATION WHITE PAPER

FACTORY INTEGRATION

1. CHARTER AND MISSION

The Factory Integration (FI) focus area of the IRDS is dedicated to ensuring that the semiconductor manufacturing infrastructure contains the necessary components to produce items at affordable cost and high volume. Continuing to develop increasingly complex and advanced integrated circuits and devices and extending the historical performace vs. cost trends expressed by Moore's Law requires taking full advantage of device feature size reductions, new materials, yield improvement, wafer size increases, and other manufacturing productivity improvements in a safe and sustainable manner. This in turn requires a factory that can fully integrate all other manufacturing components and utilize these components collectively to deliver products that meet specifications determined by other IRDS focus areas.

Societal needs are driving development of new products and systems such as mobile devices and the internet of things (IoT) and these are impacting all areas of the IRDS, however, as shown in Figure 1, these factors impact the evolution of FI from two perspectives, namely:

(1) Requirements they place on product technologies that are delineated in roadmaps associated with other focus areas; these technology requirements indirectly influence FI in terms of tighter process requirements with acceptable yields, throughputs and costs.

(2) Enablers to FI technologies that directly impact FI in terms of aligning with these trends and effectively leveraging their associated capabilities.

An analysis of perspective (1) can be found by studying the roadmaps found in other focus groups as illustrated in Figure 1, and then determining how the FI roadmap addresses the related tighter process requirements. With respect to perspective (2), the following is an example of how some of these enablers directly impact FI:

- *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 IP protection, and performance.
- *Big Data*: The data explosion in FI provides both challenges and opportunities for FI; a section of the FI chapter describes these in detail.
- *Mobility*: Mobile devices have and will continue to enhance the capabilities of FI systems in terms of accessibility, ergonomics and human-machine interaction, flexibility, portability, etc., but also can present many security challenges as well as performance challenges.
- *Green Technology*: The movement towards greener technologies and subsequent requirements for reduction in energy costs and "carbon footprint" significantly impact FI. First and foremost, they require that facilities objectives such as energy consumption and ESH objectives such as contaminant waste reduction be an integral part of FI factory operation objectives.

The FI Focus team has addressed evolution of FI by providing an extensible roadmap that (1) focuses on the commonality of certain functional areas, (2) supports roadmaps for specific functional and physical areas, (3) addresses societal drives identified above, and (4) provides for improved integration with other roadmap focus areas. This white paper describes the scope of these functional areas and identifies key focus areas for 2016.

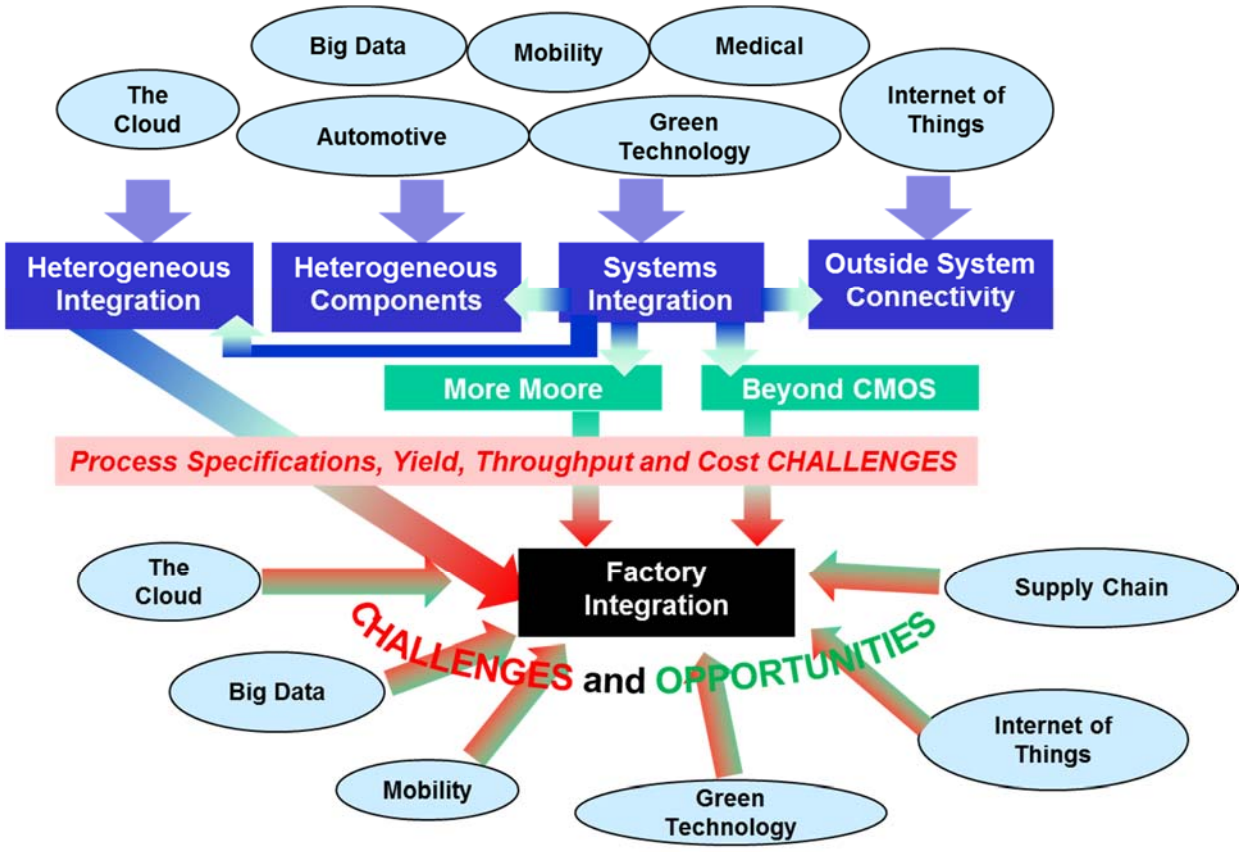

Figure 1: Societal forces impacting challenges and opportunities in FI

2. SCOPE

The Factory Integration Focus Area scope is summarized in terms of functional areas in Figure 2. A total of eleven functional areas are defined including six common functional areas (Augmenting Reactive with Predictive—ARP, Big Data—BD, Control System Architectures—CSA, Environment Safety and Health—ESH, Factory Operations—FO, and Yield Enhancement—YE) and five physical-system corollary areas (Production Equipment—PE, Material Handling Systems—MHS, Factory Information and Control Systems—FICS, Facilities, and Assembly & Test Integration—ATI—Proposed for future roadmap versions). Each of these areas has a dedicated section in the Focus Area chapter and is summarized as follows:

- **Common functional areas**
    - *Augmenting Reactive with Predictive (ARP)* covers augmenting of existing reactive technologies with predictive technologies while retaining the reactive capabilities. These predictive technologies include Predictive Maintenance (PdM), Fault Prediction (FP) Virtual Metrology (VM), predictive scheduling, yield prediction and augmenting predictive capabilities of the factory with simulation and emulation.
    - *Big Data (BD) and the Cloud* identifies the challenges and potential solutions associated with the increases in data generation, storage and usage, and capabilities for higher data rates and additional equipment parameter data availability. It specifically addresses the Big Data attributes of: volume, velocity, variety, veracity and value. The cloud aspect addresses the centralization of capabilities to support re-use and

distribution; while this capability extends big data capabilities it also brings with it issues of data partitioning and security.

- Control Systems Architectures (CSA) covers general trends in control that are common across the FI space. Control inside the equipment is generally not within the CSA scope. Trends addressed include the move to more granular control (e.g., lot-to-lot, to wafer-to-wafer, to within wafer), higher speed control, higher quality control methods, increase in control systems capabilities, the advent of new control paradigms such as fully distributed (autonomous) control and machine learning, and new control platforms such as cloud-based.
- *Environmental Safety and Health (ESH)* projects the principles of a successful, sustainable, long range, global, industry-wide ESH program. 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, remain similar to those presented in earlier Roadmaps.
- *Factory Operations (FO)* provides many of the key drivers of requirements and solutions to address fab productivity, agility and flexibility. It covers the hierarchical operation of the factory, integration of factory component operations such as facilities and assembly/test, methods for overall factory productivity improvement, waste reduction and cycle time metrics, operational paradigms related to 450mm and smaller lot sizes, the emerging need for integration with supply chain, and future manufacturing paradigms.
- *Yield Enhancement (YE)* has two focus topics: "Surface Environment Contamination Control" and "Characterization, Inspection and Analysis." These two topics crosscut front end process technology, interconnect processes, lithography, metrology, design, process integration, test, and facility infrastructures.

- **Physical-system functional areas**
  - *Production Equipment (PE)* covers process and metrology equipment and their interfaces to other factory elements. It also focuses on addressing equipment related productivity losses.
  - *Material Handling Systems (MHS)* covers transport, storage, identification, tracking carrier and/or lot-level movement, and control of direct and indirect materials. MHS covers requirements for the automated MHS hardware and control systems.
  - *Factory Information and Control Systems (FICS)* includes computer hardware and software, manufacturing execution and decision support systems, factory scheduling, traceability of process and production materials, control and diagnostics associated with control of equipment and material handling systems, and process control. FICS also covers decision making support systems for the productivity waste visualization and reduction.
  - *Facilities* include the infrastructure of buildings, utilities and monitoring systems. Examples of challenges addressed include contamination control, understanding of electrostatic problems and how to mitigate them, and implementation of green technologies.

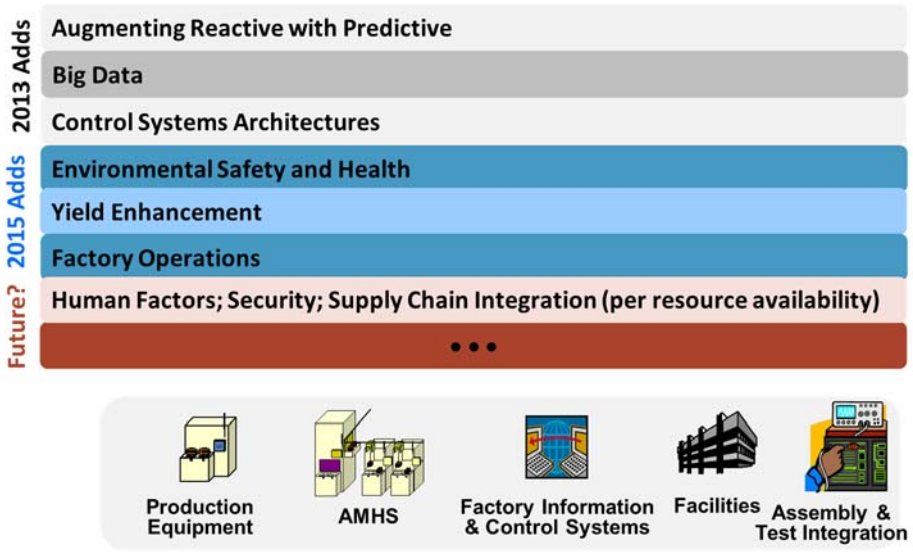

Figure 2: 2016 Factory Integration Focus Area scope and structure

3. CROSS TEAM INTERACTIONS

The interaction with other IRDS efforts is summarized in Figure 1 and Figure 2. The following is a summary of the more prominent interactions

- *Environmental Health and Safety (ESH):* ESH continues to play a very important role in factory design and operation. Decisions made at the earliest stages of factory planning will have a dramatic impact on the ability of that factory to meet rigorous safety and environmental requirements economically. The FI chapter provides a summary of the synergy between ESH and FI, and references the full ESH IRDS chapter where appropriate.
- *Yield Enhancement (YE):* Development of good yield management strategies reduces costs and investment risks. The FI chapter provides a summary of the synergy between YE and FI focusing on areas of big data, yield prediction and yield enhancement, and references the full YE IRDS chapter where appropriate. For YE challenges that are identified in the YE chapter, FI may provide potential solution alternatives or enhancements. For example if metrology is not available for a particular yield problem, YE may be achievable using FI techniques to predict the yield metric of concern and mitigate the problem.
- *Lithography:* Key lithography related challenges that need to be addressed by the Factory Integration Thrust area are to ensure the building and facilities infrastructure (e.g., power and cooling water) is ready for EUVL, support the improvment of Advanced Process Control (APC) for lithography equipment (e.g., tighter control is needed for overlay and edge roughness), and to improve predictive scheduling/dispatch potential solutions for lithography as it is usually the bottleneck process. Other issues to be addressed include Design for Manufacturing (DFM) and temperature variation inside the tools, and Airborne Molecular Contamination (AMC) impact on reticles and wafers.
- *Metrology:* Metrology systems must be fully integrated into the factory to facilitate run-to-run process control, wafer tracking to support traceability, yield analysis, and other off-line analysis. The scope of cross-team interaction with metrology includes this integration as well as data management and big data, virtual metrology, review and classification tools integrated measurement (IM), and leveraging metrology strategies to reduce cycle time and wafer-to-wafer process variance.

- *Test:* Big data and prediction requirements and solutions will impact and provide solutions for Test.
- *Emerging Research Materials (ERM)*: The introduction of new materials may result in the need for new processes and/or process requirements and constraints, and additional requirements for factilities (e.g., to support abatement and environmental/sustainability considerations such as recycling). The FI capabilities must provide a roadmap so that these new materials can be successfully introduced into the manufacturing process and meet the requirements of productivity, cost and quality.
- *Design:* The era of "Smart Manufacturing" and "Industry 4.0" has led to a tighter coupling between design and production using tools such as design for manufacturability and cyber-physical systems. The FI roadmap must support linkage between emerging design capabilities and manufacturability. This support should include identifying the need for and supporting feedback back to design to optimize the design to manufacture process.

4. STAKEHOLDERS

Stakeholders for the Factory Integration include *all* solution manufacturers and suppliers and covers *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 the tighter linkage between design and manufacturing via design for manufacturability innovations and the increased use of cyber-physical systems. Within the IRDS, the FI chapter has strong cross working group linkage to ESH, YE, Lithography, Metrology, Test, ERM and Design, ESH, and thus FI stakeholders would include the stakeholders defined for these IRDS efforts.

5. TECHNOLOGY STATUS, NEW REQUIREMENTS AND POTENTIAL SOLUTIONS

5.1. TECHNOLOGY STATUS AND UPDATE

Challenges and potential solutions for FI are provided in the FI Focus area chapter organized into the areas shown in Figure 2. The FI area continues to evolve rapidly with new challenges in existing areas such as big data capabilities to support yield prediction and fab-wide control to yield and throuput objectives; and prioritization in new areas such as security and supply chain integration, and new paradigms such as artificial intelligence. The FI Focus chapter is structured to be extensible to support emerging challenge areas currently being defined or potentially defined in the future, so that the roadmap can respond quickly to evolution and revolutions in FI.

In the 2016 roadmap the following are key areas where efforts are being focused:

- *Big Data:* The current Big Data section of the FI chapter addresses challenges and potential solutions associated the "5 Vs" of data Volume, Velocity, Variety (merging), Veracity (quality) and Value (analytics). Efforts in 2016 are focused on (1) quantifying these challenges by leveraging results from a survey conducted by the Yield Enhancement group, as well as discussions at the Advanced Process Control conference with big data experts, and (2) providing more information on the evolution of Big Data analytics (e.g., algorithms).
- *Security:* This is an area that is rapidly growing in importance in FI and is receiving increased attention in 2016. Information security will be more challenging with the increase of data shared across the factory integration space. Challenges include protection of data and IP, and system protection against malicious attacks. Solutions in other industries should be heavily leveraged. While it is expected that a security roadmap in semiconductor manufacturing will rely heavily on advancements in other manufacturing areas, a framework for security in semiconductor manufacturing factory integration is still needed; this framework needs to incorporate the fact that security in this environment must cover the actual control of physical entities (e.g., equipment) that can be responsible for safety events (e.g., danger to product, equipment or

people). The current FI roadmap summarizes basic security challenges and solution areas. Future roadmap versions will seek to better define an evolving FI security framework.

5.2. New Requirements, Difficult Challenges and Potential Solutions Paths

The following are topics that explored in the current FI Focus area chapter that may be delegated as functional areas in future versions of the FI roadmap:

- *Assembly and Test Integration (ATI)* includes the FI aspects of the "backend" production including any integration with front-end processing. With the advent of More-than-Moore, heterogeneous integration and the related impacts on yield and need for single device traceability, tighter integration with assembly and test is now required. Further, many of the IRDS FI concepts defined for front-end processes can be extended to assembly and test. The FI chapter is evolving to capture this increased importance of integration of assembly and test. In the current roadmap, key challenge and solution areas for assembly and test integration are overviewed; in the future it is expected that "Assembly and Test Integration" will become a function area of FI.
- *Security*: As noted above, information security will be more challenging with the increase of data shared across the factory integration space. Future roadmap versions will seek to better define an evolving FI security framework as part of an FI section dedicated to security.
- *Supply Chain Integration:* Tighter integration of FI with the supply chain, both upstream and downstream, will be required to better achieve directives of productivity, quality and cost reduction, by supporting concepts such as lean manufacturing, yield correlation, part tracking (e.g., to pursue warranty recall isolation), and coordinated ESH directives. As the importance of supply chain integration grows, its specification in the IRDS FI chapter is increasing accordingly. In the current roadmap, key challenge and solution areas for supply chain integration are overviewed; in the future it is expected that "Supply Chain Integration" will become a function area of FI. Current efforts that will be leveraged include output the SEMI Components Instruments and Subsystem (SCIS) special interest group.

6. Summary

The Factory Integration Focus area chapter of the IRDS focuses on integrating all the factory components needed to efficiently produce the required products in the right volumes on schedule while meeting cost targets. This chapter provides the technical requirements categorized by functional areas and also the proposed potential solutions. It also provides Factory Integration related challenges from the crosscut issues and key focus areas that need to be addressed in order to keep up with the technology generation changes, productivity improvements and at the same time maintaining decades-long trend of 30% per year reduction in cost per function.

As mentioned earlier, the scope of the FI Thrust includes Augmenting Reactive with Predictive, Big Data, Control Systems Architectures, Environmental Safety and Health, Factory Operations, Yield Enhancement, Production Equipment, Material Handling Systems, Factory Information and Control Systems, and Facilities. Emerging areas that are beginning to be addressed include Assembly and Test Integration, Security and Supply Chain Integration. Primary focus areas for 2016 include Big Data and security.

7. REFERENCES

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8. ACKNOWLEDGMENTS

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