IEEE
Advancing Technology for Humanity

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

2023 UPDATE

YIELD ENHANCEMENT

Table of Contents

List of Figures

List of Tables

Acknowledgments

This chapter was prepared by a group of experts representing broad spectrum of knowledge and activities associated with contamination control and yield analysis. The Yield Enhancement forum is represented by a number of leading advanced semiconductor manufacturing companies, most of major semiconductor EOMs, as well as many materials, components, metrology, and facility technology suppliers.

The Yield Enhancement roadmap described in this narrative is based on extensive data analysis, mathematical modeling, and experimental work conducted by the forum. This data correlates the criteria defining defect conditions on the surface of the critical substrates (wafer, lithography mask, lithography optics, etc.) with parameters of liquid chemicals, ultrapure water, air, gases, critical components, and thin film materials.

The Yield Enhancement leadership team acknowledges input provided by the More Moore IFT as well as resources and time of all contributors involved.

Joel Barnett, Greg Baumgart, Carlos Beitia, William Bozydaj, Kameron Brown, Will Byars, Mark Camenzind, Brett Clark, Kirk Chassaniol, Robert Clark, Nora Colligan, Patrick Connor, Dan Cowles, Tomasso Crisenza, John Croft, , Peter Egger, Majid Entezarian, Albert Escusa, Kim Farnsworth, , , Bob Gieger, Rick Godec, George Gonnella, Hugh Gotts, Andreas Eckl, Don Hadder, Jim Henry, Christoph Hocke, Hideaki Iino, Pratik Joshi, Jost Kames, Keith Kerwin, Kenji Kingsford, Alan Knapp, Kaoru Kondo, Cristian Landoni, Enrico Laurin, Ravi Laxman, Jae Seok Lee, Slava Libman, Jürgen M Lobert, Vanda Locati, Ruben Lopez-Trigo, Peter Maguire, Ulrich Mantz, Paul Mertens, Matt Milburn, Bob McIntosh, Tim Miller, Steve Moffatt, Sungin Moon, Chris Muller, Andreas Neuber, Rob Nine, Abbas Rastegar, Koichiro Saga, Akshey Sehgal, Simone Severi, Drew Sinha, Jim Snow, Deena Starkel, John Painter, Dave Roberts, Thomas Phely-Bobin, Marcel Teunissen, , Jan Rau, Gerd Reinig, Steffen Reyman, Sarah Riddle, Dan Rodier, Steve Rogers, Philippe Rychen, Jochen Ruth, Archita Sengupta, Tony Shucosky, Jonas Sundqvist, Joe Sweeney, Vincent Terracina, Ines Thurner, Gary Van Schooneveld, Rao Varanasi, Juliane Weise, Ulrich Wende, Daniel Wiederin, Dan Wilcox, Daun Wilcox, Hubert Winzig, Enghwa Wong, Bernie Zerfas

YIELD ENHANCEMENT

1. INTRODUCTION

The Yield Enhancement focus area is dedicated to activity ensuring that semiconductor manufacturing set up is optimized towards identifying, reducing, and avoiding yield-relevant defects and contamination.

Yield in most industries has been defined as the number of products made divided by the number of products that can be potentially made. In the semiconductor industry, yield is represented by the functionality and reliability of integrated circuits produced on the wafer surfaces. During the manufacturing of integrated circuits yield loss is caused, for example, by defects, faults, process variations, and design. The relationship of defects and yield, and an appropriate yield-to-defect correlation, is critical for yield enhancement.

The Yield Enhancement (YE) chapter will display the current advanced and next generation future requirements for high yielding manufacturing of More Moore as well as More than Moore products separated in "critical process groups" including microelectromechanical (MEMS), back-end processes, e. g., packaging. Consequently, an inclusion of material specifications for Si, SiC, GaN, etc., are considered.

In the manufacturing of integrated circuits yield loss is related to a variety of sources. During processes such as implantation, etching, deposition, planarization, cleaning, lithography, etc., failures responsible for yield loss occur. Several examples of contamination and mechanisms responsible for yield loss are listed in the following: a) airborne molecular contamination (AMC), b) airborne particular contamination (APC) of organic or inorganic matter caused by the environment, personnel or by the tools, c) process induced defects as scratches, cracks, and particles, overlay faults, and stress, d) process variations resulting, e.g., in differing doping profiles or layer thicknesses, e) the deviation from design, due to pattern transfer from the mask to the wafer, results in deviations and variations of layout and critical dimensions, and f) diffusion of atoms through layers and in the semiconductor bulk material.

The determination of defects and yield, and an appropriate yield to defect correlation are essential for yield enhancement. The specification of tools for defect detection and classification of defect for root cause analysis addresses the technology requirements for More Moore and More than Moore. Out of two typical types of defects, systematic and random, Yield Enhancement focuses on random ones, related to the areas of technology responsible for contamination control, as shown in Figure YE-1.

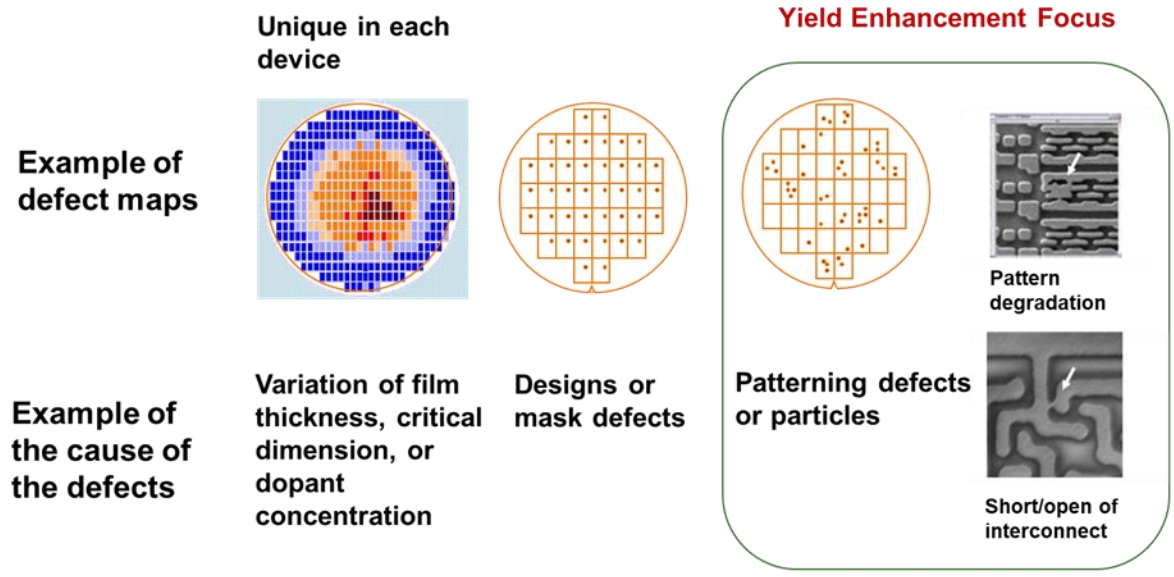


Figure YE-1 Random Yield Area of Focus

The YE chapter has two focus topics: "Substrate Environment Contamination Control" (SECC) and "Characterization, Inspection and Analysis (CIA)". These two topics crosscut front-end process technology, interconnect processes, lithography, metrology, design, process integration, test, and facility infrastructures."

YE is broken down into prevention of defects, focusing on random, and CIA (characterization, inspection and analysis). Current focus of YE is to add reliability enhancement to our focus, both of which focus on prevention of random defects that result in yield loss and reliability risk through proactive contamination control. The CIA portion will identify the challenge of not being able to measure defects but can correlate these defects to something that we can measure. This was agreed to be the area for collaboration between YE and FI (Factory Integration) chapter of IRDS. Specific topics to be addressed are (1) analysis of data at yield excursion events and (2) yield prediction using manufacturing big data and data analytics tools.

Definition of technology needs will depend on the approach to the big data application. Potential correlation between a measurable parameter and a target feature that is unmeasurable directly will likely become the only feasible way to predict yield loss due to manufacturing issues. FI considers the use of virtual metrology as a viable method to support the needs.

Refer to FI Chapter for more details on the technology needs in this space.

The focus of this chapter is enabling yield improvement through defect reduction in high-volume semiconductor manufacturing facilities via:

- Conducting ongoing risk analysis of the high purity materials, parts, utilities, and environments involved in advanced semiconductor manufacturing.
- Proposing potential solutions and risk mitigations associated with technology gaps that limit measurement and control of environmental wafer, mask, or substrate contamination.
- Initiating and conducting collaborative experimental studies and models to better define and quantify exposure of environmental contamination to wafer surfaces. Communicate results of the risks and their mitigation strategies to the industry in the form of the International Roadmap for Devices and Systems (IRDS) published roadmaps, conference presentations, and technical journal presentations.
- Initiating Semiconductor Equipment and Materials International (SEMI) standard development activities to address the risks.
- Supporting new technology trials through benchmarking studies.

Physical device dimensions and corresponding defect dimensions continue shrinking, while device complexity is increasing exponentially, posing new challenges to detection as well as tolerable contamination. The wafer edges and backside surface were identified to show significant impact on yield. Process variations and design are also factors impacting yield. Additional new challenges arise specifically for MEMS manufacturing as well as assembly lines using new material. Development of defect detection, defect review, and classification technologies showing highest sensitivity at high throughput solving those challenges is crucial for cost-efficient manufacturing. Furthermore, for efficient manufacturing the monitoring of contamination in the environment as well as on the critical surfaces requires appropriate analytical capabilities. Automated, intelligent analysis and reduction algorithms, which correlate facility, design, process, electrical and virtual metrology results, and their correlation to yield, test and work-in-progress data, will have to be developed to enhance root cause analysis and therefore enable rapid yield learning.

1.1. Current State of Technology

Yield Correlation/Data Mining—In the future the need for prediction will become even more important. The use of semi and unstructured data sources and unsupervised data mining will become necessary. Nonetheless, a high level of process knowledge will still be required.

Wafer Defect Metrology—Defect metrology continues to be important towards smaller nodes, especially considering new yield challenges like multiple patterning. The main way to detect yield impacting defects in production is defect inspection. Therefore, the requirements are defined together with the More Moore chapter.

Heterogenous Integration—3D integration is the challenge. Finding the right solutions for those inspection requirements will be the focus for future roadmap development.

Yield Management for MEMS—MEMS technology holds specific challenges for inspection and characterization based on structures at backside, capwafers, and a need of inspection and characterization of covered defects. The different MEMS technologies need to be separated in surface and bulk technologies for it causes different requirements to inspection and characterization.

Yield Management for Packaging and Assembly—As technology requirements in the assembly and packaging area increases, yield loss, and therefore yield improvement methodologies, become essential. Yet the most appropriate methodologies have to be selected and Front End (FE) yield tools need to be adapted to Back End (BE) requirements. This is a future opportunity to define a dedicated roadmap addressing Back End requirements.

Critical Surface Environment Control includes the ambient space around the wafer, lithography optics, lithography masks, and other critical substrates at all times. This includes tool environment consideration, cleanroom air, as well as storage of wafers in front opening unified pods (FOUPs). As the list of ambient contaminants to be controlled broadens, so must measurement capabilities. Affordable, accurate, repeatable, high capture rate, real-time monitoring equipment for non-particulate contamination are becoming increasingly necessary. The use of inert environments to transport, store, and even process wafers is expected to increase with process sensitivities. Pre-gate, pre-contact clean, salicidation, exposed copper, and reticle exposure are cited as processes that first require this capability. In addition, using inert environments offers the opportunity to reduce the introduction of moisture into vacuum load-lock tools, thereby decreasing contamination and load-lock pump-down times. Drier environments can contribute to static charging, so this needs to be considered. While closed-carrier purging systems currently exist, and wet-processing tool environments are evolving into enclosed, low-O_2 single wafer processing chambers needing to become increasingly inert, components such as needed wet-sink end-stations present a challenge. Safety when using inert purges must be carefully considered, including during maintenance. As wafer isolation technologies evolve, design and material selection of carriers and enclosures will be critical for performance in isolating the wafers from the ambient and in not contributing contaminants themselves. In addition, the materials and designs must not promote cross-contamination between processes. Seal technology, low-outgassing, and non-absorbing material development are key to an effective wafer and reticle isolation deployment.

There are three primary sources of process environment contamination. One is the impurities in the process materials as supplied. The second is the delivery system or the process itself. The third is reaction, such as contaminant- or thermally induced decomposition, by process such as reactive ion etch (RIE) contamination of FOUPs. These contamination sources are found throughout the pathway from the delivered gas or chemical to the substrate surface.

The current state of technology suggests significant gaps in contamination measurement capability. Complexity of the advanced semiconductor devices and continually shrinking geometrical scaling led to the situation when killer particle size became much smaller than capability of the most advanced metrology to detect those particles. This situation has been true in UPW (ultrapure water) for nearly a decade, with particle metrology providers investing into closing the gap, while the gap has been only increasing. Current definition of the killer size of the particles is based on half of the most critical dimension in logic devices.

As a result, the risk is high to continue monitoring particles of the sizes much larger than the killer size in an attempt to control killer particles. What makes the situation even more problematic are the following factors:

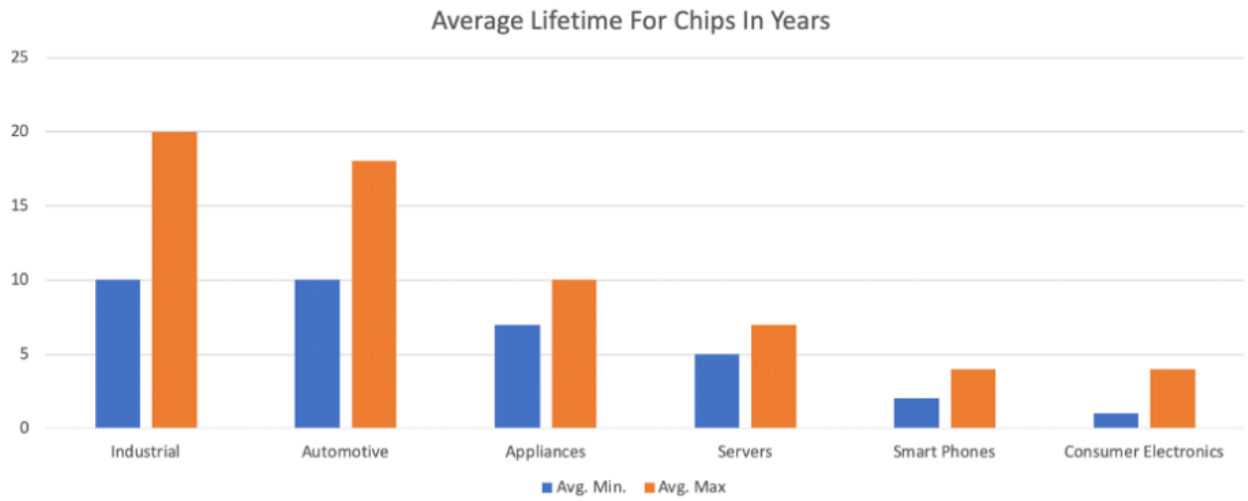
1. Most advanced particles filtration in UPW has reached its limits to control killer particles (the killer particles are significantly smaller than the smallest filter pore sizes).
2. There are indications that some high purity materials shed significant number of particles at current killer sizes or larger.
3. There is a concern that high molecular weight polymers may form killer size particle when they attach to the wafer and the water dries out.

It should be noted that particle control in UPW and liquid chemicals is not the only parameter that requires a proactive approach to Yield Enhancement. Particles are more critical than other types of contaminants, leading to yield and reliability problems and therefore used in this paper to illustrate the approach.

1.2. RELIABILITY—EMERGING TECHNOLOGY DRIVER FOR CONTAMINATION CONTROL

The Yield Enhancement (YE) chapter of the IRDS has been engaged in extensive collaboration with the More Moore (MM) chapter to ensure that the risk of reliability becomes a critical driver and focus in the development of the IRDS roadmap in 2021 and beyond. The importance of reliability is becoming more critical due to the changes in device development and complexity of application.

Today's complex applications require dramatic enhancements in communications and networking capabilities as well as real time human computer interfaces. Examples of this include intelligent edge devices such as augmented reality glasses, autonomous cars and navigation systems that collect, communicate, generate, and analyze data in real-time. These systems require the device to continuously process algorithms 24/7 either directly on the device or on a server that is near the device. This results in stringent workload profiles for the device, which if not properly managed, could lead to deterioration over time. The life expectancy of the device depends on its application or use, for instance a consumer electronic device, or smart phone may have an acceptable life span of 2–5 years and simply be replaced with a new model, where high-performance servers require a lifespan between 5 and 10 years before the datacenter expects to replace it (Figure-YE-2). This is further amplified with increased temperature because of shrinking feature sizes and 3D integration partitioning targeting high-density memory on logic. Regarding integration, many processes rely on highly conformal thin films constituted by new materials on high-aspect ratio and tight-pitch 3D structures. These three trends, namely stringent mission profiles, increased power density, and shrinking feature sizes on 3D structures, necessitate a focus on identifying roadmap for Yield Enhancement to enable adequate reliability.

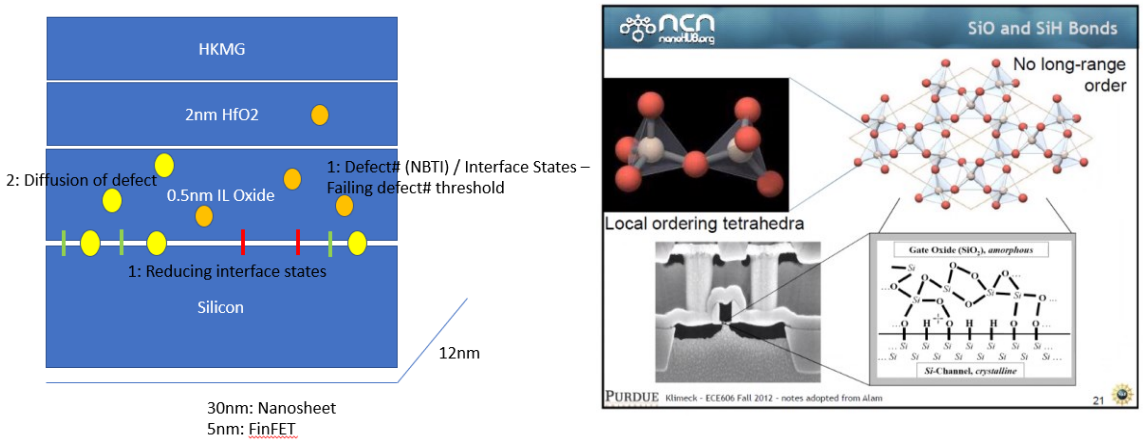


Source: https://semiengineering.com/making-chips-to-last-their-lifetime/, October 2020

Figure YE-2 Expected lifetime of chips in years.

The most important modules for reliability are gate stack integrity, interconnect, and source/drain engineering. Bias temperature instability (BTI) in the gate stack, via-bottom voids in the interconnect, and source/drain EPI are also important concerns of reliability degradation in More Moore technologies. These are mostly induced by the initial defect density on the interfaces, which does not cause any electrical signature during wafer sort test but further enhanced during its operation by increased electrical field and/or diffusion of those defects causing shifts in device behavior, further leading to permanent device failure. BTI failure manifests itself by unacceptable threshold voltage shift causing irrecoverable timing failure causing functional failure, via void causing current crowding leading to blow of via, and source/drain EPI causing time-dependent-dielectric-breakdown (TDDB) of dielectric between the gate and source/drain and/or an increase of tunneling current at the junctions. BTI in the gate stack is a more critical one because of inspection difficulties for the quality check of the gate stack as well as the very small thickness of dielectric stack (down to 2nm). Typical sources of contamination are from airborne sources and ultrapure water used in last cleaning steps of the Si channel before oxide and high-k dielectric (e.g. HfO_2) deposition.

The images below illustrate the defect formation mechanisms.



Source: Based on communication with MM and reference to G. Klimeck (Purdue, ECE606: Solid State Devices).

Figure YE-3 Reliability Failure Mechanisms

Since an impact on reliability is expected to be caused by changes in the properties of the very thin films, it is understood that such defects would be inflicted by molecules and ions, as opposed to particles. Detailed knowledge of the manufacturing process steps, material reliability, and lifetime requirements are needed to determine defects that impact or will impact performance of the device during its lifetime. YE, in collaboration with MM is currently working on deconstructing the risks and quantifying the contamination limits for the roadmap. MM has developed the model (shown in Figure YE-4) that illustrates reliability projections that will be used to define the target limits along with other publications and supporting literature.

Figure YE-4 shows initial defect density causing a potential BTI failure at 10% shift threshold. Defect density numbers shown in the figure correspond to the critical area (e.g. active) of device, but not across the whole wafer. Wafer-level defect densities will be similar, since the effective active footprint is 3x the planar footprint, which is depreciated by the gate length being 1/3rd of the contacted gate pitch.

IRDS	BFF	BFF	GAA	GAA
	2022		2025	
Time (years)	0	10	0	10
Time (seconds)	0.00E+00	3.15E+08	0.00E+00	3.15E+08
Junction temperature (C)	25	125	25	125
Vdd (V)	0.70	0.70	0.65	0.65
Ns (1/cm3) - bulk+interface charge	1.00E+11	1.00E+11	1.00E+11	1.00E+11
Interface trap density (1/cm2-eV)~1/cm2	1.70E+10	1.70E+10	1.60E+10	1.60E+10
Power law exponent - n	0.16	0.16	0.16	0.16
Field exponent - m	0.1	0.1	0.1	0.1
Activation potential - Ea	0.49	0.49	0.49	0.49
Reliability constant - A	1.000	1.000	1.000	1.000
Interface trap adder	0.00E+00	4.66E+11	0.00E+00	4.36E+11
dVt (V)	0.005	0.027	0.005	0.026
dVt / (Vdd-Vt)	1%	10%	2%	10%

Source: More Moore, IRDS, 2021

Figure YE-4 Tolerable defect density in finFET (2022) and GAA (2025) for 10-year field operation.

Collaboration between Yield and MM teams will continue into 2023 to also address the defectivity issues impacting yield.

"Proactive approach" in the IRDS target parameters

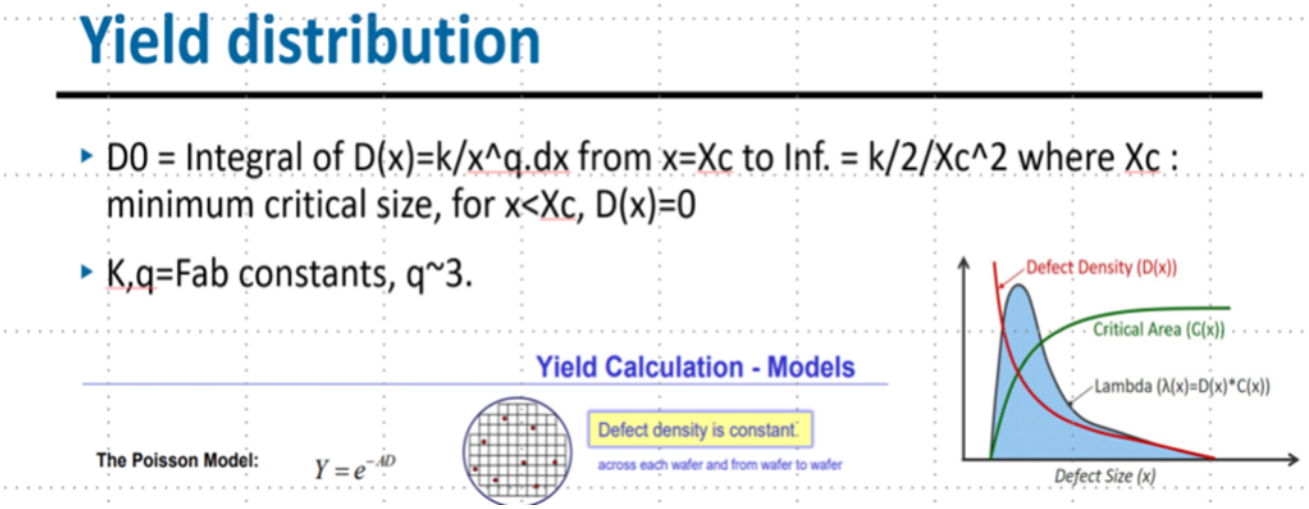
As the result of the above deficiencies, the YE chapter of IRDS has changed its direction from Reactive to Proactive Yield management in the cases where the previous approach cannot work. New IRDS parameters were added to the roadmap targets. This approach assumes no ability to monitor defect related parameters due to insufficient capability of the existing metrology. For example, when it is impossible to monitor killer particles in UPW and liquid chemicals, IRDS focuses on particle occurrence prevention by both reducing particle challenge to the final filters as well as ensuring enhanced performance of the filters. The new Proactive parameter added to the roadmap is shifting monitoring to the point in the treatment system where particle detection is feasible and meaningful, leveraging power-law correlation factor. At this location, the particle size distribution is not affected by filtration, the size distribution is typically normal, and power law correlation can be used to project the level of contamination to the target particle size. Knowing the efficiency of the final and point-of-use (POU) filters, relationship between the particle challenge to the filters and the level of particles at POE can be established.

In contrast with reactive approach, dependent on the measurement at the target point, proactive approach is focused on what is measurable and drives continuous improvement ignoring metrology deficiencies. Proactive approach also focuses on proactive risk analysis as opposed to corrective actions following reported yield excursions. This is particularly important in applications of semiconductor devices where reliability is critical.

Target particle size. The following image illustrates the level of discussion between YE IFT and the device experts (More Moore IFT) that helps to deconstruct the sensitivity of the device to particle related defects and determine the killer size of the particle, as defined in Table YE-3.

Target particle density. In addition to the killer particle size above, it is important to determine the target level of the defect density distribution of each layer, which meets required product yield which consists of every layer yield IRDS More Moore defines. This targeted defect density distribution is estimated using typical key parameters (such as k and q) in Yield projection formula. Yield calculation model below is an example that was referred from More Moore published method and agreed between Yield Enhancement and More Moore chapters of the IRDS.

	CRITICAL AREA								DEFECT DENSITY				YIELD IMPLICATIONS				
2022	Critical Dimension (nm)	Defect Size (nm)	Pitch (nm)	Density scale	Feature Density	Scaled Feature Density	Density @Chip	Critical Area (cm2) in 80mm2	k	q	Dx	Dx/wafer	Dxi	1/(A*Dxi)^n	1/(A*D0i)^n	Defect Mechanism	Process Type
Gate	18	9.0	45	1.00	80%	80%	32%	0.256	0.05	3.00	0.0071	5.0	0.032	0.994	0.978	Patterning, Gate stack	
Fin	6	3.0	24	1.15	40%	46%	12%	0.092	0.05	3.00	0.1926	136.1	0.289	0.980	0.978	Gate stack, EPI	
VC	18	9.0	45	1.15	7%	8%	3%	0.027	0.05	3.00	0.0071	5.0	0.032	0.999	0.978	Clean	
MetalC	18	9.0	45	1.15	80%	92%	37%	0.296	0.05	3.00	0.0071	5.0	0.032	0.979	0.978	Patterning, Metal	
Via0	12	6.0	34	1.15	5%	6%	2%	0.016	0.05	3.00	0.0241	17.0	0.072	0.999	0.978	Clean	
Metal0	12	6.0	24	1.15	80%	92%	46%	0.370	0.05	3.00	0.0241	17.0	0.072	0.906	0.978	Patterning, Metal	
Viax	16	8.0	45	1.15	3%	4%	1%	0.010	0.05	3.00	0.0102	7.2	0.041	0.999	0.978	Clean	
Metalx	16	8.0	32	1.15	80%	92%	46%	0.370	0.05	3.00	0.0102	7.2	0.041	0.935	0.978	Patterning, Metal	
Viay	40	20.0	113	1.15	2%	2%	1%	0.005	0.05	3.00	0.0007	0.5	0.007	1.000	0.978	Clean	
Metaly	40	20.0	80	1.15	80%	92%	46%	0.370	0.05	3.00	0.0007	0.5	0.007	0.994	0.978	Patterning, Metal	
							23%	0.181					Product	0.801	0.800		



Source – IRDS More Moore IFT

D_x—defect density value in the units of the number of defects per 300 mm wafer, based on the device complexity and defect characteristics for the given layer of the device manufacturing.

Figure YE-5 Defect Density Calculation

This calculation is based on well-known critical area-based yield forecasting model above published by More Moore IRDS Team which calculates critical area for each layer. The critical layers have different sensitivity to different type and sizes of the particles due to complexity, critical area distribution which is dependent on pattern design, and device critical dimensions.

1.2.1. ULTRAPURE WATER

Ultrapure water (UPW) is purified water with most of the quality parameters below or near the detection limits of the most advanced metrology. Current state of UPW technology generally can provide effective control of contamination. However, whereas some parameters are relatively easy to control, the effect of others requires further investigation. Recent development of the defectivity definitions suggests that some of the contaminants, such as particles, are going to affect yield, whereas others, such as non-particulate, may not affect yield but may impact reliability (see Section 1.1). There is ongoing effort to characterize the risk to reliability that has not been included in the 2022 roadmap.

Particle levels in UPW are reduced using the best available ultra-filtration (UF) technology, but today's particle detection and counting technology is not able to keep up with the fast-growing requirements for "killer" particle control due to continued scaling of critical semiconductor devices. Monitoring available for particles is limited to laser particle counters capable of monitoring 20nm particles with limited counting efficiency. There are new measurement devices for smaller particle sizes under development and commercialization, but their capabilities have not been fully qualified yet. The presence of particle precursors in UPW can interfere with response of some of these new instruments limiting their ability to accurately quantify sub-20 nm particles.

In recent years, the YE IRDS team together with the SEMI Standards organization developed a series of standards providing tools and methodologies to implement proactive particles control in advanced semiconductor facilities.

Figure YE-6 indicates the numbers of the UPW SEMI Standards supporting the effort. SEMI F104 is the method for testing critical components for particles. SEMI C79 drives filter performance by measuring ability of the filters to remove particles down to 4-nm size and ensuring low particle shedding by the filters. Ion exchange resin was found to be a major potential contributor of small particles. SEMI C93 measures contamination shedding by ion exchange resin.

Lack of proven particle metrology limits the ability to confirm whether UF is effective in controlling particles down to the critical particle size. At the same time, it is apparent that the killer size of the particles has approached filtration capability of the most advanced final filters. Furthermore, there is test data suggesting the particle challenge concentrations in the feed to the final filters from UPW system components can be very high. Current definition of the killer size of the particles is based on half-pitch logic and is as small as 3.0 nm for the most critical electrically active particles (EAP). To address the metrology gaps and particle contamination risks, a new approach has been proposed. The details are described in the white paper "*Proactive Particle Control in Ultrapure Water (UPW) in Silicon Wafer Cleaning Process, IRDS, 2023*". New "Proactive" UPW IRDS parameters have been added to Table YE-3. This approach assumes no ability to monitor killer particles in UPW, but instead focuses on particle occurrence prevention by both reducing particle challenge to the UPW final filters as well as ensuring adequate performance of the filters. Figure YE-6 illustrates application of the proactive approach in UPW, relying on SEMI standards and the supply chain to deliver solutions based on use of those standards.

Particle precursors. This is a new parameter added to UPW roadmap in 2021.

The critical particle size for the manufacture of semiconductors is now below 5 nm. The semiconductor industry has entered a region where particles, particle precursors and molecules in liquids begin to overlap. A particle precursor is defined as a dissolved molecular compound, which may form particles on the wafer. The ability to distinguish particle precursors from solid particles in UPW is becoming critical. While advanced filtration can remove nanometer sized solid particles, the same filter may have little or no ability to remove particle precursors. SEMI has recently developed a new standard (approved, pending publication) to measure particle precursors in UPW.

It was demonstrated that presence of high molecular weight organics may result in residue formation of the wafer, similar to particle of a size of approximately 8 nm and larger. The semiconductor industry is entering a region where dimensions of particles, particle precursors and molecules in liquids, begin to overlap. A particle precursor is defined as a dissolved molecular compound, which may form particles on the wafer. The ability to distinguish particle precursors from solid particles in UPW is becoming critical. While advanced filtration can remove nanometer sized solid particles, the same filter may have little or no ability to remove particle precursors. Experimental work has been conducted to determine relationships between the particle precursor concentration measured in UPW and the defect density formation on the wafer.

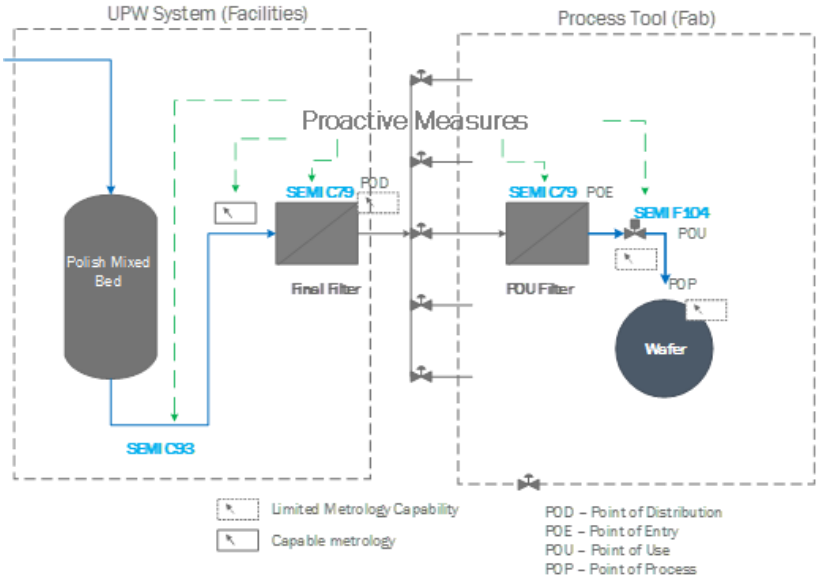


Figure YE-6 Proactive Particle Control

The conclusions of the experimental work are provided below. For more details, please refer to the Particle White Paper linked to this report.

1. Conducted series of experimental work suggest that the particle risk originating from precursors is real. All experiments conducted thus far indicate particle formation from all precursor materials tested.
    - The challenge solution used in the experiment involving IX resin leach-out, represents >1 order of magnitude higher concentration of such contamination than that of typical UPW. This produced >1000 particle per wafer on the surface of the sizes 10nm and larger, vs. concentration of at least 1E+7/ml as detected in solution by Liquid Nanoparticle Sizer (LNS). This means that in order to achieve the level of particles per Figure YE-7) of <5/wafer, the level of such precursors in UPW should be non-detect by Scanning Threshold Particle Counter (STPC) (online version of LNS). Typical STPC DL is ~1E+5/ml for the final polish loop.
2. This experimental work indicates that current ultrafiltration technology is not fully effective in mitigating ion exchange resin particle precursor passage. Continued improvements in the UPW final filtration technology is needed.
3. Different types of organic polymers that may occur in UPW may lead to different defect types and densities. And although mixed ion exchange leach-outs are used for quantification of the target precursor contamination level (due to the high probability of occurrence of such material), proactive minimization of all particle precursors is needed to support yield targets of the advanced existing and next generations of semiconductor technology.
    - Anion IX resin had much stronger affinity to the wafer surface vs. cation exchange resin, whereas mixed resin appears to produce lower contamination level than the two.
    - Synthetic polymer used in the 1st round of testing showed even higher tendency to adsorption and agglomeration of the formed particles.
    - The data indicate high potential of particle agglomeration, further increasing the risk to Yield.
4. The ratio of 3,300 LNS particles/ml forming one particle per 300mm wafer was chosen to calculate the allowed (target) level of UPW precursor contamination measured by LNS (or similar instrument based on nebulization/condensation particle counting technology). Referring to Figure YE-7, below suggesting that particles of the size of 7-10 nm range must be controlled at the level of less than 5 particles per wafer, the target level of the particle precursor (by LNS) is ~**20,000** particles/ml (rounded up).

Measurement of the particles precursors still needs to be standardized to ensure high quality detection. A new SEMI specification, "*Guide for Evaluating Metrology for Evaluating Metrology for Particle Precursors in Ultrapure Water*," has been drafted and is in the review and balloting process with release anticipated late 2023. It is recommended that metrology combining nebulization/condensation is used for the analysis, given the capability of the measurements observed in research conducted by IRDS and others in the period of 2019-2022. The need for removal of particle precursors from UPW is being addressed by the SEMI UPW Task Force. A particle precursor challenge material is being developed for SEMI C79, "*Guide to Evaluate the Efficacy of Sub-15 nm Filters Used in Ultrapure Water (UPW) Distribution Systems*." The particle precursor challenge will be based on ion exchange extract. Presently, SEMI C79 uses a poly-dispersed silica with particles ranging from 5 to 35 nanometers to measure the effectiveness of a filtration device to remove particles. The particle precursor extract is being added as a complimentary challenge, not a replacement for poly-dispersed silica.

2020	2022	2025	2020	2022	2025	2020	2022	2025	2020	2022	2025
Defect Size (nm)	Defect Size (nm)	Defect Size (nm)	Dx/wafer	Dx/wafer	Dx/wafer	Cx, #/ml UPW	Cx, #/ml UPW	Cx, #/ml UPW	IRDS value, Cx' #/ml	IRDS value, Cx' #/ml	IRDS value, Cx' #/ml
10.0	9.0	7.0	5.7	5.0	6.6	3.8	3.3	4.4	1	1	1
3.5	3.0	3.5	133.5	136.1	52.8	122.9	125.6	43.9	100	100	10

Figure YE-7 UPW Roadmap Particle Development

Silica is one of more complex impurities in UPW. Silica may occur in UPW in a form of reactive (dissolved ionic) or colloidal silica. The main concern around colloidal silica is that its occurrence in UPW is highly probable, its retention by final filters is more difficult than other particles, and also because it may adsorb metal ions, thus becoming more detrimental on the wafer (these effects are based on published data). Recent data on particle precursors triggers additional concern of formation of high molecular weight polymeric dissolved silica (likely to be formed in the ion exchange media). While it is easy to control *reactive* silica (within defined sensitivities of metrology), *colloidal (including polymeric)* silica is difficult to monitor at the level where it presents a problem. Traditionally colloidal silica has been measured as the delta between total and reactive silica in UPW. The killer particle size of currently considered generations has become very small, making it impractical to expect that the colloidal silica particles in critical concentration (posing risk to critical surface) could be measured as the delta of total and reactive silica, i.e., very small particles do not contain sufficient measurable amount of the silica compound. Since colloidal silica cannot be effectively monitored using state-of-the-art metrology as the compound, further consideration of colloidal silica will be done as part of particles monitoring. Given the criticality of this parameter, it is recommended to consider taking proactive mitigation steps to prevent colloidal silica occurrence via improved treatment process control and use of higher purity materials. With the release of SEMI C79 and the use of colloidal silica as the test media, filter manufacturers have been able to significantly increase the retention of colloidal silica through filter design and functionalization. These improvements have been correlated to improve yield.[1] Characterizing filter retention performance using SEMI C79 is an effective pro-active management tool to reduce the risk from colloidal silica. Polish resin was demonstrated to have very little capacity to retain silica, while colloidal silica may be formed inside of the Polish beds from traces of reactive silica. This point is addressed in the roadmap (see Table YE-3) by adding a "proactive" silica control parameter in the feed to UPW tank. Pushing silica control upstream to the treatment process helps to reduce silica loads to the Polish loop.

Hydrogen peroxide has been reported to occur in final UPW as a by-product of 185 nm UV (ultraviolet) reactors used to decompose UPW organics. There are technologies available for removal of hydrogen peroxide in UPW; however, their implementation requires major system change and substantial investment. The UPW Roadmap defined H_2O_2 target at 3 ppb. This is based on the data suggesting that 10 ppb of H_2O_2 in UPW in pre-Epi cleans may affect wafer surface roughness. It is still unclear if a 3-ppb level may have similar detrimental effects. Additional study is needed to verify this concern. In the meantime, this target should allow for reducing H_2O_2 level, while possibly avoiding any major capital investments necessary to reach lower peroxide levels.

Metallic contamination in UPW is another important concern. Although metal control in UPW has never been a difficult challenge from the treatment process point of view, new technology drivers may put the entire technology supply chain in front of such challenges in the near future. Based on literature data "extremely low level of metal contamination is required for specific devices like CMOS image sensors". There are suggestions that some of the metals for such applications should be controlled at the level of two or even three orders of magnitude below the levels typically specified in most UPW systems. The supplemental white paper for this chapter titled "*Metal Contamination of Image sensors by Ultrapure Water in Silicon Wafer Cleaning Process*" (link is given in the Appendix) provides details of the literature data as well as how new specific metal targets (see Table YE-3) for UPW have been calculated for image sensors metal control. The ability to control some of the metals in UPW by current state-of-the-art treatment technology to such low levels may not be possible. This includes limitations of metrology and treatment technology, as well as materials purity of the critical components use in UPW Polish and delivery systems. For this reason, an additional parameter for proactive metal contamination control was added in the feed to the UPW tank.

Organic contamination is currently measured in terms of its total organic carbon content (TOC). This measurement of the organic content does not account for the types of organic comprising TOC; how it may react with various wafer surfaces, or how the reaction may impact device yield. While for most applications' organic compounds in UPW are categorized as critical and non-critical based on their boiling point, immersion lithography lens hazing is driven by factors besides boiling point. Although controlling organics at the target levels is difficult, both treatment and sensitive metrology solutions are available.

There is indication that residual amounts of TOC (less than 500 ppt) may be present as nm-size organic particles that can penetrate even the smallest pore size filter.

[1] *R. Pavlick, G Van Schooneveld, "Evaluating Three Generations of UPW Filtration Technology Using SEMI C79", Ultrapure Micro 2021*

UPW Recycling is a critical topic that the UPW IRDS team is currently prioritizing based on the input from the Environmental, Safety, Health & Sustainability (ESH/S) team. Advanced semiconductor manufacturing facilities need to achieve a relatively high water use efficiency, which is primarily driven by corporate Environmental, Social, and Governance (ESG) goals. Non-process water demand is less than the total available conservation opportunity at most facilities, as recently demonstrated by the Water and Energy Management IRDS group[2]. As a result, once non-process water demand is fully satisfied by reclaimed water, the only way to expand reclaim is to reuse water for UPW (process use). Drivers will force the industry to apply UPW recycling, reclamation, and reuse. From a technology need perspective, measures must be implemented to ensure the necessary UPW quality is maintained. Evidence is needed to help facilities gain confidence that UPW level recycling will not compromise production.

Point-of-use (POU) level recycle, adequate segregation, and targeted treatment will need be considered for UPW recycling. POU recycling will require design considerations as part of the tool itself. An adequate level of segregation will be necessary to maintain UPW quality. Recycling must consider limitations of the UPW treatment system and provide solutions necessary to compensate for those limitations. For example, the UPW system has limitations to treat low molecular weight neutral organic compounds (such as urea), therefore this stream will need to be segregated out. Another example is segregating slurry solids that may lead to clogging of the UPW pretreatment system. Any compounds that cannot be segregated but are not expected to be adequately controlled by existing UPW systems may require targeted treatment and risk mitigation measures. A potential approach may be to create a two-tiered UPW, define the margin of UPW quality for each categorized wet process (e.g., FEOL, BEOL, epi, CMP, scrubbing, etc.), and identify where a second tier UPW could be used. These tiers are described as follows:

Tier 1: Treating incoming city water

Tier 2: System treating a blend of incoming water and reclaim

Ongoing work within the UPW IRDS team will address risks associated with UPW recycling in the yield enhancement roadmap and collect data to help facilities make decisions related to water management.

Note: It is important to keep in mind that the SECC roadmap is focused on technology enablers, identifying the parameters that require new technologies for monitoring and control. For the practical purposes of UPW system design and operation, SEMI F63[3] and SEMI F61[4] provide guidance that can be used as a reference specification for the UPW quality, design, and operation of advanced semiconductor processes, considering feasibility of the existing technologies. The UPW IRDS team collaborates closely with the SEMI UPW Task Force to develop guides and test methods to mitigate existing risks and challenges.

1.2.2. AIRBORNE MOLECULAR CONTAMINATION

Airborne Molecular Contamination (AMC) first became an issue with the introduction of chemically amplified resists in the 1990s.[3]

A defect occurred once the photolytically initiated acids within the resist were neutralized by airborne ammonia from cleanroom air. This interaction is device defect relevant as it deteriorates line width and line structures.

More defect patterns with a strong relation to AMC root causes have been identified over the decades. Often AMC problems arose from revolutionary steps in manufacturing technology necessary to drive ahead *More Moore* feature shrinking or wafer throughput.

One example is the rapidly increasing formation of microcrystal contamination on masks and lenses from sulfurous AMC, such as sulfur dioxide that was photolytically activated by the 193 nm laser wavelength in ArF scanners. Another example is unwanted residues of strong acids, such as HF and HCl from dry etch processes attached to wafer surfaces, once FOUPs became the dominant technology for wafer transport and storage.

Meanwhile, technical solutions have since been developed to minimize the above cited defects and are available in production. However these solutions have been found in a “reactive way”. Their exploration has been driven by yield losses that were already impacting high volume manufacturing at the time any preventive solution was addressed.

---

[2] *International Roadmap for Devices and Systems: Water & Energy Management, 2023.*

[3] SEMI F063. Guide For Ultrapure Water Used In Semiconductor Processing

[4] SEMI F061. Guide To Design And Operation Of A Semiconductor Ultrapure Water System

The AMC section of the YE chapter takes a proactive approach and advance contamination control. The goal is to trigger research and close potential technology gaps in AMC control for the most defect-critical process steps of the next generation devices. For AMC, past experience shows that this could either be systematic and road blocking impacts, or random and event driven impacts. Yet they are both yield relevant.

For the IRDS YE AMC chapter, the team points out that effects, defects and technological solutions must not necessarily be feature size (line width) related. Device defects also often occur related to the introduction of new materials, metals or processes. Consequently, the proactive approach is needed to prevent the occurrence of major impact on transfers of technology from development to high volume production.

The continuous development of the AMC roadmap in the YE chapter is based on an ongoing exchange with experts from "More Moore" and "More than Moore" defectivity modelling and process integration. The assessment of the impact to the product includes the aspects of yield (% good dyes) as well as the aspect of device reliability (lifetime before failure). The most critical AMC related defects to next generation devices are identified and included in Table YE3, together with the AMC concentration limit information, as soon as they are available from research or experimental work. Citation of critical AMC and the limits is strictly related to the direct wafer environment contamination control (WECC) at the point where AMC (airborne molecular contamination) transfers into SMC (surface molecular contamination). AMC concentration limits are carefully evaluated and curated together with the typical expected time of impact to the sensitive wafer step. It can be shown that most AMC effects and defects are predominantly dose related (where dose = concentration x time of impact). Indications of the time of impact related to the AMC limit are included in Table YE3.

The 2023 update for the YE AMC section deals with documented or expected device defects manufactured in high-aspect FIN technology or GAA (gate all around) technology.

Requirements for wafer contamination control have been identified for gate oxide formation (gate oxide pre-clean), source drain contact module (trench etch and epi) and metallization (specifically copper metallization, via bottom filling).

The AMC subgroup started a modelling exercise in the year 2022 to quantitatively describe the transfer of AMC (airborne molecular contamination) to SMC (surface molecular contamination). This approach is supposed to support the revision of AMC limits for Table YE3 in the years to come and is outlined in Section 4.2 Surface Environmental Contamination Control. It is recognized that further tight control of the wafer environmental conditions in FOUPs is mandatory to prevent AMC conversion into SMC and subsequent defects, e.g., in metallization. This control involves more specific monitoring of critical AMC in FOUPs at short cycle times as well as efficient purge and clean technologies. The deteriorating effect to wafer surfaces spans all AMC classes. The group of experts still identified a technology gap in the availability of fast and reliable on-line monitoring technology to unambiguously quantify small levels of high-impact AMC. Once AMC can be quantified, technological solutions to prevent the impact of such AMC can be formulated.

Other next challenges for on-line clean room monitoring are solutions that would embed automated metrology means to check on the accuracy and repeatability of measurements, flexible software packages for alarm and data reporting and fab sampling line management to ensure measurement from more than one sampling area.

As the AMC chapter was restructured in 2021 and focused to device critical defects, the group acknowledges that there are fields of applications of AMC control which remain important but for which mature technological solutions exist. Such applications are, for example, the environmental cleanroom control of AMC in lithography zones to safely operate UV exposure tools. The AMC control limits for those tools are typically provided by the OEM device manufacturers.

The environmental cleanroom specifications span the entire range from acidic, basic AMC to condensable organics and Si-containing compounds, but also compounds such as reduced sulfur and ozone that have been added in recent years. Control of such compounds typically calls for concentration limits in the single digit parts per billion (ppb_v 10^{-9} moles per mole) range, and it is required to maintain operation of the optical systems in the interior of the tools. Beyond UV exposure tools, this also applies more and more to inspection tools with high energy light applications. The tool-based AMC control for inspection equipment is typically not yet at the advanced level of UV exposure tools. Consequently, it is recommended to keep control of AMC at the cleanroom location, specifically for acid and base contamination, at the level of 1 – 2 ppb_v. Alternatively, tool-based solutions can be applied that guarantee for these levels at the point of entry to the tool interior.

Furthermore, general AMC control limits exist, e.g., for cleanroom make-up air and cleanroom recirculation air. However, limits to support contamination control are highly dependent on the individual "shell" approach of the IDM and the location - from the outer environment to the wafer environment - and a generalized tabulation of standardized limits is less meaningful. In this context, the way to achieve the appropriate AMC control limit at wafer point of entry is an engineering and facility effort and allows—besides good practice considerations—many degrees of freedom. Consequently, cleanroom concentration limits were removed from Table YE3. The IRDS YE experts encourage managers responsible for cleanrooms to consult in-house and external expertise on appropriate concepts. For any such concepts, the occurrence of short term or event driven AMC excursions in cleanroom environments should be included in these considerations.

AMC on-line monitoring (selectivity, time-resolution, applicability)

AMC control deals with prevention of AMC release, impact and recirculation, for all of which a tight source control or mitigation is mandatory. To determine accurate AMC concentrations, there is clearly a need for better AMC monitoring instrumentation in the cleanroom and the wafer environment to determine AMC from the parts per billion (10^{-9}) to the part per trillion level (10^{-12}; by volume) in real time.

The availability of time-resolving and compound-resolving AMC monitoring technologies is a current need and the field of research as concentration totals for AMC classes have been identified to be less useful and could be misleading. Totals can both be masking the importance of individual, high-impact compounds and/or driving AMC control setups into non-effective positions along the process chain at unnecessary high cost. The main challenge is to combine high sensitivity with high specificity at manageable cost, maintenance and automated operation. Witness wafers have been used to link surface molecular contaminant (SMC) concentrations to specific defects. The surface concentrations are usually expressed in a maximum allowable number of molecules/cm^2, ions/cm^2, or atoms/cm^2 for elements or ng/cm^2 for organics. Witness wafers are capable methods, but they are run offline at small scale.

Supplemental information about on-line monitoring methods is found in the Appendix of this chapter on Table YE4 and YE4a for AMC monitoring programs. The evaluation of the technical demands for on-line monitoring technologies and their communication to potential suppliers will be a focus item for IRDS YE AMC over the next years.

1.2.3. GASES, LIQUID CHEMICALS, AND PRECURSORS

The targeted purity levels can be reached either by bulk delivery of a fluid with required purity or through use of local purification/filtration step. Care should be taken, at a minimum, to maintain the quality of the gas and chemicals coming from the source, ensuring that contamination is not added downstream, as may occur due to particle generation at components (such as valve switching), moisture outgassing, byproduct generation due to incompatible materials, etc. Particle filtration as close to the point of use (POU) or chamber entrance as possible is generally advisable for gases. For the most critical applications a local purifier may be used to enhance or ensure ultimate purity at the POU. In those cases, the prevailing approach is to seek levels that are adequate for the process and to view the purifier as "insurance." The challenge to the purifier is minimal, and long purifier lifetimes can normally be expected.

An important exception to this guidance is for some specialty materials that undergo a variation in composition as they are distilled from the cylinder or other delivery vessel in a bulk vapor delivery set up. For example, anhydrous HCl is known to form very stable hydrates with water that result in changes in the concentration in the water content in the cylinder and gas phase as the original specified contents are removed. In this case, a combination of rigid specifications on how much of the contents can be used before moisture becomes unacceptable requiring application of moisture removal devices is needed in the vapor transport path. Liquid anhydrous ammonia is another specialty gas with this potential issue. Within the realm of relatively volatile liquids that are delivered in bulk, i.e., not by direct liquid injection, volatilization, aqueous hydrogen peroxide, aqueous ammonia, and likely many of the amine-amide based chemical vapor deposition/atomic layer deposition (CVD/ALD) precursors, are expected to undergo similar distillative variation and/or thermal degradation under delivery conditions. Depending upon the process sensitivity this might be a source of poor film quality or process variability that can be addressed by attention to the delivery method. Reactivity of transport surfaces, impact of aging of bulk/spec gases within the delivery system, impact of perturbation of gases during transport as well as outgassing need to be considered, as well.

Point of use purifiers and filtration units are finding application in newer ALD techniques, for example, where the films are deposited as monolayer and incorporated impurities can be especially destructive. Purifiers must not add any new contaminants. A near- and medium-term challenge is filtration of the precursor vapor. The sources can be

sublimable solids or readily condensable vapors of low volatility liquids. These can re-solidify or re-liquefy causing plugging and instability in fluid transfer to the substrate surface.

1.2.3.1. BULK AND SPECIALTY GASES

Increased levels of purity requirements are expected in advanced processes. This type of improvement might be anticipated, based upon historical trends as design rules tightened, but there is again little objective evidence to support the need for improvements across the range of bulk gases. For very special applications where extraordinarily higher purities are critical, special purity grades or additional purification will be required.

The situation is similar for many of the specialty gases. Statistical process control (SPC), such as 3-sigma limits for process gases and liquids was implemented by most semiconductor manufacturer for critical process fluids, e.g., TEOS.

The promise of providing "in control" process fluids is anticipated to improve process yields by either minimizing the overall variability of the manufacturing process or in simply reducing the likelihood of a process crash resulting from large variations in material quality that would still nominally have met a more standard specification.

For some processes, such as advanced lithography (especially 193 nm and EUV), very small quantities of "high molecular weight/high boiling point" (e.g., C_6-C_{30}) hydrocarbons in supply gases are detrimental because of a tendency to adhere to the exposed surfaces, and potential for photochemical degradation to leave non-volatile residues that impact optical characteristics on lenses, masks, mirrors, etc. However, any organics, even ones with lower molecular mass than C6-organic compounds are considered detrimental if they result in refractory deposits. For the same reason, other potential impurities such as siloxanes or organophosphates can also be very detrimental in extremely small quantities. In order to detect such species, e.g. siloxanes and organophosphates with sufficient sensitivity, it is necessary to directly detect the relevant species and calibrate the analyzer with the appropriate standard near the quantitation limit. The methods used are analogous to those for AMC, such as thermal desorption (TD) gas chromatography (GC), mass spectrometry (MS) or TD GC with flame ionization detector (FID), photo ionization detector (PID), or ion mobility spectrometry (IMS).

New developments include reaction steps and time-of-flight (TOF) measurements. These approaches may still miss some heavier hydrocarbons and/or polar species that tend to remain in the column or emerge as very broad peaks, if not optimized. For methods using adsorbent traps, it is very important to determine the trap efficiency, which are used as sampling techniques. Using atmospheric pressure ionized mass spectroscopy (APIMS) to provide real-time measurement of individual hydrocarbons is possible in principle, but very involved and calibration is difficult, because larger hydrocarbons may be collisionally dissociated in the ionization process.

An approach that has gained some acceptance is to use TD GC/MS and sum all peaks corresponding to C_6 and higher. The instrument is usually calibrated with a multi-component standard and results are reported as "toluene" or "hexadecane" for wafers or as toluene for clean dry air (CDA) or gases. While the quantization provided by this method is approximate, and some species may be overlooked, it does at least provide a metric for contamination level and a straightforward calibration.

Historically, applications for both O_2 and H_2 generally tolerate higher levels of N_2 contamination than other contaminants; however, H_2 as a carrier for epitaxy now requires more stringent N_2 levels and the table reflects this observation. Requirements for critical CDA with stricter control of organics and refractories, lithography purge gases, and supercritical CO_2 supply are included. Whereas critical CDA may not always be conveniently or cheaply available, there is no technological barrier to its production. Analytical methods are usually the same as used for airborne molecular contamination in clean room air, such as bubbling through ultra-pure water (for metals, acids, amines, etc.) or trapping on an adsorbent trap for organics. In each case, the sampler concentrates impurities so that requisite sensitivities are achieved when the sample is introduced to the analyzer inductively coupled plasma - mass spectrometry (ICP-MS) or ion chromatography for aqueous samples, GC-MS for desorption of organics). Such methods are time consuming by nature, and direct methods would be preferred if available. However, there is no apparent pressing need for real-time analysis. For SO_2 there are convenient online methods, e.g., UV fluorescence.

For specialty gases, contaminant values in etchants, dopants, and deposition gases emphasize in Table YE-3 the increased number of different materials in use, and to better delineate the processes in which they are used. Particulate contamination is omitted since online monitoring of particle concentrations is not commonly practiced and the efficacy of POU particle filters is well established. Whereas there is evidence that the most demanding applications, such as low temperature epi and its cleaning gases, will continue to benefit from improvements in purity as deposition

temperatures are lowered, this is expected to be reflected in wider use of the best available purity rather than substantial improvements of those levels indicated in the table, which reflects the most critical application.

Tighter control over the variation in purity in both bulk and specialty gases is more important than improvement in absolute purity levels. However, the often more chemically reactive specialty gases present a more formidable challenge for maintaining of point of supply (POS) purity levels throughout the delivery to the point of process. Selected specialty gases, e.g., HCl are now commonly under statistical process control at the POS.

More detailed consideration of the impurity levels found in the growing number of novel materials used in processing will be increasingly important. Requisite purity levels for critical materials such as novel metal oxides, chemical mechanical planarization (CMP) slurries, low/high κ dielectric materials, precursor materials (used in CVD, ALD, and electroplating solutions) for barrier and conductor metals (such as Cu, Ta) have not been widely studied, and many of these materials have not been called out in Table YE-3. An early attempt to start to catalogue and characterize the properties of the thin film precursors utilized in semiconductor processing is found in the supplementary material for this chapter.

Deposition precursors for thin film materials are often sensitive to moisture, air and high temperatures. Control over the delivery process from the POS to the reaction chamber is critical to high yielding performance. The use of very high purity carrier and purge gases in these systems is often required to prevent decomposition that can contribute detrimental molecular and particulate impurities. Traditionally bulk purifiers were used in the bulk gas delivery systems to remove particles and other homogeneous chemical contaminations like oxygen, or moisture present in the supply gases. However, with the development and commercial availability of POU purifiers, there is a strong interest from end users to utilize POU purifiers particularly for specialty gases needed for critical process steps with very critical level of contamination control. These point-of-use purifiers POU are highly effective to remove chemical contaminants to extreme low level (~ ppt), easy to use, easy to replace, with low cost-of-ownership. The capability of placing those POU purifiers very close to inlet of process chamber, assures least travel path (less contamination) for process gases after chemical purification and filtration.

By analogy with the definition of UPW particle precursors, The IRDS YE Gas Team defines particle precursors as contaminants in the gas in molecular form may generate particles by reaction or agglomeration.

1.2.4. LIQUID CHEMICALS

Pre-diffusion cleaning and EUV mask blank cleaning requirements drive the most aggressive impurity levels. Liquid particle level requirements are expected to become tighter with each technology generation. These target values are derived from the purity requirements on a wafer as calculated by the surface preparation experts assuming a linear relationship between the concentration in the liquid and on the wafer. Particle counters are currently only capable of measuring down to 30-40 nanometers (nm) in liquid chemicals. By assuming a particle size distribution, it should be possible to infer particle concentrations to smaller particle sizes, but this will be influenced by the level of filtration utilized. Another measurement challenge for several chemicals is the differentiation between foreign particles, micelles, and bubbles, which is currently not possible, although solutions can be degassed and/or pressurized to dissolve gases and bubbles into solution. The ability to differentiate between damaging foreign particles and intentionally created micelles is also important for any effort to impart filtration that is effective but does not interfere with the chemical functional properties.

Liquid chemicals can be separated into the two main categories of “Functional Chemistry” and “Cleaning Chemistry”. Functional Chemistry is used to modify the wafer surface by removing material (Etch, CMP) or depositing a new film onto the surface (plating, coating). Whereas Cleaning Chemistry is used to remove contaminates from any previous processing step or modify the surface charge of the wafer surface to facilitate particle removal. This distinction is important to understand what is important in controlling the quality of the chemistry to minimize the defect contribution from it. For Functional Chemistry, assay control is key to the process in making sure the proper amount intended material is removed without removing material not intended. Either situation will result in a feature on the wafer surface that is measured by any subsequent defect metrology inspection step as a defect. For Cleaning Chemistry, the controls for preventing any foreign material or unintentional compounds in the chemistry is key to ensuring the ability to remove surface defects without contributing to additional ones.

For this reason, the two categories were specifically listed out in the Liquid Chemicals section of the tables so that appropriate requirements can be considered and specified based on their application in the manufacturing process. The "Cleaning Chemistry" (or "critical cleans") will have a longer list of parameters and much more restrictive limits as compared to their "Functional Chemistry" counterpart. For example, HF cleaning chemistries may have less

restrictions on contamination type parameters as compared to HF being used as an etchant. Conversely, HF etchant may be more restrictive on assay variance than its counterpart for use as a cleaner. Often many chemical cleaners are blended with other chemistries or diluted with water, which further highlights the need for strict controls on all of the constituents used in these blends to maintain contamination levels where they need to be to protect wafer yield. This is also why new categories were created to include proprietary chemistries and etchants to incorporate the diverse products in use that are provided by chemical suppliers or are blended at the IDM site. The number of these proprietary chemistries is growing such that they have become more dominant in number as compared to the general and historical standard list of processing chemistries and do require some level of guidance for maintaining quality control.

As the need for precise photolithography process control continues to become more critical, the quality control for the associated process chemistries also needs to more restrictive. With the proliferation with EUV in various process nodes the need for more consistent developers of high quality is necessary. As a result, placeholder sections have been added to signify the ongoing characterization and future development of established quality criteria for these emerging technologies.

The ability to accurately analyze organic, anion, and cation contamination in process chemicals is becoming more critical to successful wafer processing. With the increased use of CMP and plating chemicals, there is critical need for a better understanding of purity requirements for the delivered chemicals that considers the wide variety of ingredients used to make them.

The performance characteristics of many of the process chemicals that are used for etching, plating, CMP and cleaning depend heavily on the amount and type of foreign material present as well as the consistency from batch to batch that is used in the process. The integrated effects of variability in the performance of these chemistries will play a significant role in the defect control within the manufacturing process. The process flow is designed based on the premise that each process step is stable and repeatable. Any deviations from these integrated design parameters will most likely have adverse effects of other process steps in the process flow which includes wafer defect impacts.

For the control of metal ions in liquid chemicals, the processing and control of these contaminants at the supplier (POS) is an important first step. However, with the exposure of the chemistry to the shipping containers and various process and delivery equipment before it reaches the wafer process (POP); additional purification steps may be warranted to maintain the necessary purity levels. These additional purification steps can occur at the distribution system (POD), connection point to the distribution system (POC), entry into the processing equipment (POE) or even inside the wafer processing tool itself (POU). The critical nature of the specific processing step should dictate whether that specific chemistry should have additional purification employed.

The ability to detect, control, and protect the process from adverse defect conditions relies on both the sensitivity of liquid defect metrology to detect the critical size of particle but also in the ability for the various metrologies to have the same or similar response to a change in the population and size distribution of these particles. Too often particle distribution baseline shifts occur at the end user's detection point with no signal observed at the chemical source location. By the time the chemical distribution system has detected this change, it is too late to protect the manufacturing process from the impacts of this increased defect level. Furthermore, many defect elevations occur in the wafer process with no detectable shift in any of the online liquid particle counting systems due to a mismatch in the sensitivity of the liquid particle counting metrology and the wafer defect sensitivity.

1.2.4.1. ALD/CVD Precursors

At recent nodes ALD processes have been adopted aggressively and that proliferation is expected to accelerate in the future. ALD processes will therefore constitute a growing subset of the processes used in high volume manufacturing (HVM) and some discussion of common/unique aspects of ALD processes with respect to SECC is warranted.

For the clear majority of semiconductor processes, gaseous reactants are delivered to the processing chamber at atmospheric or super atmospheric pressures. However, for most ALD processes, the precursor is delivered at pressures typically in the range of 5 Torr to 100 Torr (667 Pa to 13.3 kPa) to the reactor, which is typically processing less than 1 Torr (133 Pa). To minimize precursor deposition/condensation within a delivery system, the equipment is typically heated to 100°C or greater. At such conditions, the gas flow through many of the delivery system sub-components is in the slip flow regime. In the slip flow regime, there is a non-zero boundary velocity at solid surfaces and a thinner boundary layer. This significantly alters both the fluid dynamics and heat transfer properties of the system. Additionally, ALD precursors can readily form particles in the precursor delivery system through both condensation and reaction with residual oxygen-containing species. With solid precursor sources, there is an added risk that source material particulate can be entrained by the carrier gas.

Furthermore, metallic impurities in inorganic, metalorganic, organometallic or organometalloid precursors are typically orders of magnitude higher in concentration than in most non-metal containing gas streams and can be a source of metallic contamination in the resulting films. In addition, thermal decomposition of precursors on the wafer or in the gas phase can produce particles or provide another source of in-film contamination. Original equipment manufacturers (OEMs) and precursor suppliers should keep these complexities in mind when designing or modifying precursor delivery sub-components and systems. Semiconductor manufacturers should consult with their suppliers if they are interested in re-engineering or adapting their precursor delivery systems since changing the pressure drop or flow dynamics of a vapor delivery system for a sensitive precursor may have unintended negative consequences.

Due to the low vapor pressure of many ALD precursors, the process canisters are usually kept at elevated temperature (>90°C) at the point of use in the tool gas box. Many ALD precursors will have a slow rate of decomposition at these temperatures and extra care should be taken to adjust the size of the on-board source canister to consume the source before process deteriorating decomposition starts. In many cases smaller heated onboard source canister that is refilled by a bulk deliver system or a liquid injection system without tank are preferred solutions.

When supplying the precursor from a bulk delivery system in the sub fab, extra care should be taken to avoid release of bubbles from the push gas into the liquid precursor. The bubbles are released due to the pressure drop going from the point of push gas insertion (sub fab) up to the tool. These bubbles will typically disturb the liquid flow controllers in the tool gas box or direct liquid injection systems resulting in a disturbed fluctuating delivery flow of precursor into the reaction chamber and possible particle generation in the injection system if the injection is over flown with precursor above it is optimal working conditions.

Downstream of the ALD reactor, the relatively low vapor pressure ALD precursors and process by-products tend to condensate at the first point of temperature drop. Therefore, the pump stack and pressure control should be heated above the condensation temperature and all the way to preferably a cold trap that condensate the precursor in a controlled manner to avoid back streaming particles into the reactor.

Finally, semiconductor manufacturers should conduct due diligence audits of any analytical methods or techniques used to screen precursor quality with the understanding that many of the possible errors made while analyzing the precursors (e.g. incomplete digestion, failing to account for sample matrix effects, etc.) can lead to results that under-report the true impurity level. Many manufacturers are adopting ship to control standards individually with their suppliers in order to minimize any precursor variation associated yield loss in their factories.

1.2.5. CRITICAL COMPONENTS

Critical Components are defined as the high-purity polymer materials used in the manufacture, storage and conveyance of process chemicals that are a liquid at room temperature and up to 85°C. This includes UPW and the broad range of chemicals used in the semiconductor manufacturing process. As such they should not contribute more than a certain portion of the allowed contamination per the individual liquid specifications. Typically, it is based on “50%” of the concentration contributed by all the critical components making up the distribution system. These polymeric materials are made by high temperature and high-pressure molding or extrusion. It is critical that the starting materials (raw polymer pellets) be as clean and meet the same specification as the finished products (pipe or tubing or fitting or valve, etc.). Gaskets and seals have not been included in the list to date. This is primarily due to the extremely low surface area of exposure to the fluid. They are included in SEMI F57 for extractables. There is no practical way to assess the particle contribution for gaskets and seals due to the requirement to have them included in a flowing system where it would be very difficult to determine what any particle source is. The component manufacturing process is mechanical and thermal in nature (i.e., there are no chemicals involved).

Critical Components are essential to the delivery of clean chemicals to the wafer. There is a large surface area exposure and there can be a long exposure time as well. The knowledge of the end user’s challenges is essential in defining the material requirements. The impact of particles, metals and organics on the wafer is the prime concern of the roadmap. Further as the particle size gets very small (<10 nm), the make-up of the “particle” becomes more difficult to determine. They are not hard, optically visible items anymore. They will more likely be large organic molecules or amorphous silicon compounds that could agglomerate into a larger mass or individually end up as a defect on the wafer surface. We have added a category called Non-Volatile Residue (NVR) which is defined as matter that remains on the wafer after a clean and/or rinse step. It is likely that for Critical Components that these materials will be an organic compound from materials of construction. There is the possibility of “new” contaminants (like organics that are particle precursors) that may not be removed by the re-treatment system.

In Critical Components we have added an alternate definition to the UPW definition for critical organics. In the UPW section critical organics are actually particle precursors. For Critical Components it will be related to compounds that have properties similar to cyclohexanone or cyclohexanol in terms of molecular weight and boiling point, (approximately 99 molecular weight and about 160oC boiling point). These organics are known to have an impact on wafer production and as such are considered critical organics. These organics can remain on the wafer surface as a film or a splotch or can agglomerate into a particle. There are now three different definitions of critical organics. One each for UPW, HP chemicals and critical components. For critical components there needs to be an assessment of what the effect of organics coming from critical components is on the wafer so we can establish both a definition of these and target concentrations for the roadmap. This will be first for UPW and then for various classes of HP chemicals.

The model developed by Mustafa Badaroglu in the More Moore chapter of the IRDS was used as the method to establish the permitted particle contribution from Critical Components. This value for critical components is based on a percentage of the value calculated for UPW. There are four different particle categories: static and dynamic before the final filter and static and dynamic post final filter. Static components (like tubing or non-actuated valves) are allowed a smaller fraction of the UPW target than dynamic (components that actuate and move during use like an on-off final dispense valve). There are values per actuation for dynamic components. The particle targets for chemicals are the same as for UPW. The post filter value is for any chemical that is last step.

Generally, the specification for metals is more restrictive for UPW because UPW is generally cleaner than chemicals and is mostly the final rinse step after a chemical process step. The requirements for extractables in UPW, particularly at ambient temperature, are typically easier to achieve in UPW than in certain chemicals. The aggressive nature of the chemical environment will tend to extract more metals than UPW. Further the conveyance (and containment) of organics used in the wafer process may extract different organics from the material matrix than UPW. The aggressive nature of the chemicals used in the wafer process places an extra emphasis on the quality and nature of the materials of construction. Due to the very small size of particles that can affect the device and the limitation of current metrology, we have to use a “proactive” means to measure particles, i.e., we use current methodology to measure larger particles and then using the statistical Power Law relate that to smaller particle concentration. This allows us to list measurable particles into the roadmap.

While we have included filters in the list of Critical Components, we have not addressed the many varieties of configurations and materials of construction of filters. Further the manufacturing of filters is much more complex than the manufacture of those made of one raw material. There is also a myriad of different surface preparations used in filters to provide for a specific performance feature. These are typically chemical in nature (a functional group type of treatment) that further complicates the nature of filters. In addition, there is the pore sizing and type of filtration (e.g., surface vs depth filtration) that also adds complexity. We have included in the Critical Components calculation methodology the use of filters in the chemical distribution systems. This was done to account for the total surface area of everything that touches the fluid as accurately as possible. For any pre-final filter the same logic applies, i.e., it is a static pre-filter component. We also caution that operation of POU filters can be problematic if these are not operated at stable conditions of flow and pressure, because filters have the potential to shed particles if not operated properly. There is still work to be done to assess the ability of final filters to remove very small particles (<10nm) and to determine how this information could be used in the allocation of particle contribution from critical components before and after a final filter.

1.3. Drivers and Technology Targets

Yield technology drivers are changing. While in past memory was the primary driver of the Yield Enhancement roadmap due to smaller critical dimension, now Logic has become and will likely continue to be the leading driver in the future. Logic was chosen to be a driver for Yield roadmap for the following reasons (refer to the IRDS More Moore chapter for additional information):

- It has tighter pitch size than that of other types of semiconductor products
- Advanced Flash manufacturing is transitioning to 3D structure where the pitch equivalent is almost an order of magnitude larger than that of Logic
- Logic has significantly more metal layers and higher complexity, increasing risks to yield
- Logic has less redundancy compared to Flash memory

- Flash has self-alignment – that is not available for logic

This year roadmap effort conducted extensive analysis of the possible defect occurrence as function of the device structure. New defectivity drivers are based on the device driven definitions, supporting critical dimensions of the advanced logic devices (for particles) and device sensitivity to the molecular and ionic contamination (see Figure YE-5).

1.4. Vision of Future Technology

Given significant limitation of particle and other metrology as outlined in the following sections, the vision for future technology involved in Yield Enhancement is based on the effort of proactive and systematic defect control throughout the entire supply chain. The IRDS Yield Enhancement Chapter will continue focusing on definition of the technology needs while the technology providers and SEMI Standards will focus on delivering optimized process control and material purity independently of the ability of direct monitoring of those defects. Electrical characterization methods, Big Data and modeling will become more and more important for yield learning and yield prediction.

It should be noted that the vision of future technology in the space of Yield Enhancement is limited to a few next generations, as uncertainty of the future device design limits the ability to adequately anticipate and project the needs. There are those who believe that future of shrinking beyond 5 nm node may be limited by ability to enable high enough production Yield.

As indicated in the More Moore roadmap, geometrical scaling is approaching its limits that means that if the near-term challenges are resolved, it will likely support the technology needs for the longer term than what is currently covered by YE roadmap.

2. Scope of Report

Yield in most industries has been defined as the number of products that can be sold divided by the number of products that can be potentially made. In the semiconductor industry, yield is represented by the functionality and reliability of integrated circuits produced on the wafer surfaces. During the manufacturing of integrated circuits yield loss is caused for example by defects, faults, process variations, and design. The relationship of defects and yield, and an appropriate yield to defect correlation, is critical for yield enhancement.

The previous scope of the Yield Enhancement group, which was More Moore driven front end processing, was extended towards More Moore and More than Moore yield considerations. The roadmap focus moved from a technology orientation to a product/application orientation. The Yield Enhancement section displays the current and future requirements for high yielding manufacturing of More Moore as well as More than Moore products separated in “critical process groups” including MEMS, back-end processes, e. g. packaging.

Airborne molecular contamination (AMC), packaging, liquid chemicals and ultra-pure water were identified as the main focus topics for the next period. Electrical characterization methods, big data, and modeling will become increasingly important for yield learning and yield prediction. Here Yield Enhancement benefits from the big data activities within the Factory Integration IFT. Regarding AMC, liquid chemicals, and ultra-pure water a close link to Environmental Safety and Health IFT is already indicated.

The scope of the report is to provide an overview of the needs of next generation semiconductor technology with respect to the measures needed to enable high manufacturing yield of future technologies. Yield enhancement chapter focuses on next two generations of technologies due to the urgency of dealing with the challenges of next two generations. There are experts who believe that the More Moore roadmap may soon be constrained by Yield. In this case, higher focus should be provided on near term roadmap.

This report provides narrative in support to the enclosed excel document delivering key parameters and their values helping to specify quantitative technology targets. This reports also provides an appendix with additional supporting information that is used to justify certain definitions in the roadmap table.

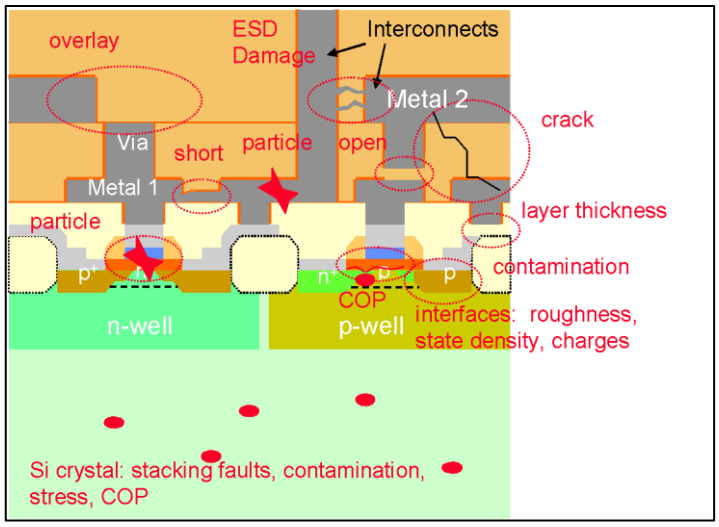


Figure YE-8 Yield Enhancement Scope

In the manufacture of integrated circuits yield loss is related to a variety of sources. During processes such as implantation, etching, deposition, planarization, cleaning, lithography, etc. failures responsible for yield loss occur. Several examples of contaminations and mechanisms responsible for yield loss are listed in the following: a) airborne molecular contamination (AMC) or particles of organic or inorganic matter caused by the environment or by the tools; b) process induced defects as scratches, cracks, and particles, overlay faults, and stress; c) process variations resulting, e.g., in differing doping profiles or layer thicknesses; d) the deviation from design, due to pattern transfer from the mask to the wafer, results in deviations and variations of layout and critical dimensions; and e) diffusion of atoms through layers and in the semiconductor bulk material. Figure YE-8 illustrates the YE scope.

The determination of defects and yield, and an appropriate yield to defect correlation are essential for yield enhancement. This correlation is of major importance, because not all defects change device properties or cause failure of devices or integrated circuits.

The YE section 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.

Surface Environment Contamination Control—Although most of the parameters in Table YE-3 table do not require significant improvements, nor indicate challenges in process critical fluid and gas impurity control, some parameters present a serious technology challenge. New materials and their precursors introduce challenges that require continuous study. Clarification of potential contamination from point-of-supply to point-of-process will define control systems necessary for delivered purity. There are several locations in the pathway from the original delivery package, *i.e.*, the Point of Supply (POS) of a liquid or gas to the location where that material contacts the wafer, *i.e.*, the Point of Process (POP), for ascertaining purity. This has led to a considerable amount of confusion and ambiguity in discussing the quality of process fluids, including the data found in Table YE-3. Table YE-1 summarizes the major fluid handling and/or measurement nodes found along the typical systems supplying process fluid. This table is an effort to create a common language for the discussion of attributes and requirements at these different node points. Further information regarding pathway nodes can be found in the supplementary materials in the Appendix and sources in the References section, such as the Semiconductor Equipment and Materials International (SEMI) Standards.

Table YE-1 Definitions for the Different Interface Points

	POS *Delivery Point of Gas/Chemical Supplier*	*POD* *Outlet of Central Facility System*	*POC* *Submain or VMB/VMP Take off Valve*	*POE* *Entry to Equipment or Sub Equipment*	*POU* *Entry to the Process Chamber*	*POP* *Contact with Wafer*
Ultrapure water	Raw water	Outlet of final filtration in UPW plant	Outlet of submain take off valve	Inlet of wet bench or sub-equipment (downstream POU filter, if available)	Inlet of wet bench bath, spray nozzle, or connection point to piping, which is also used for other chemicals	Wafer in production
Process chemicals	Chemical drum/tote/bulk supply	Outlet of final filtration of chemical distribution unit	Outlet of VMB valve	Inlet of wet bench or intermediate tank	Inlet of wet bench bath or spray nozzle	Wafer in production
Specialty gases	Gas cylinder or bulk specialty gas systems	Outlet of final filtration of gas cabinet	Outlet of VMB valve	Inlet of equipment	Inlet of chamber (outlet of MFC)	Wafer in production
Bulk gases	Bulk gas delivered on site or gas generator	Outlet of final filtration/purification	Outlet of submain take off valve or VMB valve	Inlet of equipment/ sub-equipment	Inlet of chamber (outlet of MFC)	Wafer in production
Cleanroom and AMC	Outside air	Outlet of make-up air handling unit	Outlet of filters in cleanroom ceiling	Inlet to mini-environment or sub equipment for AMC, outlet of the tool filter for particles	Gas/air in vicinity to wafer/substrate	Wafer/substrate in production (AMC/ SMC)

POD—point of delivery POC—point of connection POE—point of entry POP—point of process POU—point of use
VMB— valve manifold box VMP—valve manifold post UPW—ultra pure water MFC—mass flow controller
AMC—airborne molecular contamination SMC—surface molecular contamination

Characterization, Inspection and Analysis—Physical device dimensions and corresponding defect dimensions continue shrinking, posing new challenges to detection as well as tolerable contamination. The wafer edges and backside were identified to show significant impact on yield as well as process variations and design. Development of defect detection, defect review, and classification technologies showing highest sensitivity at high throughput is crucial for cost efficient manufacturing. Furthermore, for efficient manufacturing the monitoring of contamination in the environment and on the wafer, surface requires appropriate analytic capabilities. Automated, intelligent analysis and reduction algorithms, which correlate facility, design, process, electrical and virtual metrology results, and their correlation to yield, test and work-in-progress data, will have to be developed to enhance root cause analysis and therefore enable rapid yield learning.

3. SUMMARY AND KEY POINTS

It is recommended that the reader of the IRDS Yield Enhancement Chapter reviews this narrative along with other materials and particularly Table YE-3, including associated notes. It is important to keep in mind that although the values in the roadmap were defined based on empirical data and modeling, there is no sufficient ground to justify specific technological decision, which are expected to be made by the technology end users based on the process specific sensitivities and requirements.

It is also important to note that definition of the semiconductor technology needs in the roadmap does not take into account feasibility of existing facility technology and metrology capability. Applying the roadmap values for facility systems specifications may pose execution challenges. Instead, it is recommended to refer to definitions of most current SEMI standards (if available) where the feasibility issues are taken into account and solutions are recommended, under consideration of the roadmap definitions.

Given limitations of the metrology used in material, environment, and process control, it is recommended to focus on proactive measures related to technology management. Such approach should lean on standardization, data mining, and process performance optimizations related to all aspects of the facility, materials, and other technologies involved in the Yield enabling and enhancement. Particles control in liquid chemicals and UPW is an example of such challenge.

4. CHALLENGES

4.1. NEAR-TERM CHALLENGES —CIA

Currently, one of the important key challenges will be the detection of multiple killer defects and the signal-to-noise ratio. It is a challenge to detect multiple killer defects and to differentiate them simultaneously at high capture rates, low cost of ownership and high throughput. Furthermore, it is difficult to identify yield relevant defects under a vast amount of nuisance and false defects. As another challenge with high priority the requirement for 3D inspection was identified. This necessitates for inspection tools with the capability to inspect high aspect ratios but also to detect non-visuals such as voids, embedded defects, and sub-surface defects is crucial. The demand for high-speed and cost-effective inspection tools remains, especially in the area of 3D inspection as the importance of 3D defect types increases. In subchapter to Characterization, Inspection and Analysis another key challenge was identified: detection of organic contamination on surfaces – the detection and characterization of non-volatile organics on surfaces is currently not possible in the fab. There are few laboratories or fab scale instrumentation available or implemented except ToF-SIMS, and XPS.

MEMS technologies have different challenges. Inspection and review tools need to be able to handle a broad range of wafer thicknesses. Infrared inspection is required as an automatic and full wafer scan option, which is available in principle but has not yet proven to meet the required throughput requirements. Review options need to be able to have solely edge grip handling and an automatic focus adjustment for a considerable wafer bow.

Traditional yield management focuses on adequate inline inspection capabilities to detect and control all relevant defect types to set up short feedback loops as well as enable correlation to yield and test fails. To move to a more proactive approach, a complete range of inline-produced data needs to be used, with the ultimate goal to get signals before hardware is affected. Therefore, a system for yield prediction to achieve a proactive yield perfection based on a full fab data transparency is needed. The data used are MES/wafer tracking data, trace (streaming data from machines), metrology, defectivity, PCM data, yield data (wafer probe, binsort, final test), consumables/raw material data, facility data, environment data, material release data, device and product data, failure analysis data, reliability data, and equipment/maintenance (log files).

The goal will be the improvement of process stability, yield and reliability through a holistic approach for data analysis. Major challenges are the connection of all relevant data sources, Continuous learning from unknowns, how to incorporate subject matter expertise (SME), the definition of a way to structure and facilitate the capture of relevant information (e.g., FDC trace data) to bring value for analysis, traceability, ownership and responsibility on data (overcome ownership siloing)

Other topics challenging the Yield Enhancement community are listed as follows for the focus in the near term:

- Process stability versus absolute contamination level
- Wafer edge, backside and bevel monitoring and contamination control
- Development of sub 10 nm water and chemical liquid particle counter as well as tight particle control technologies (new, tighter filters with low particles shedding and minimal contribution of metal and organic species)
- Correlation yield and contamination levels

Data, test structures, and methods are needed for correlating critical tool parts quality as well as process fluid contamination types and levels to yield and to determine the required control limits. The issues for this challenge are to define the relative importance of different contaminants to wafer yield, a standard test for yield/parametric effect, and a maximum process variation (control limits). The fundamental challenge is to understand the correlation between impurity concentration in key process steps and device yield, reliability, and performance. This correlation will determine whether further increases in contamination limits are truly required. The challenge increases in complexity as the range of process materials widens and selection of the most sensitive processes for study will be required for meaningful progress.

Furthermore, in the long term the following key challenges were identified:

- Inline defect characterization and analysis

The difficult challenges for the Yield Enhancement chapter are summarized in Table YE-2. Currently, the most important key challenge will be the detection of multiple killer defects and the signal-to-noise ratio. It is a challenge to detect multiple killer defects and to differentiate them simultaneously at high capture rates, low cost of ownership and high throughput. Furthermore, it is difficult to identify yield relevant defects under a vast amount of nuisance and false defects. As a challenge with second priority the requirement for 3D inspection was identified. This necessitates for inspection tools the capability to inspect high aspect ratios but also to detect non-visuals such as voids, embedded defects, and sub-surface defects is crucial. The demand for high-speed and cost-effective inspection tools remains, especially in the area of 3D inspection as the importance of 3D defect types increases. In 2011 and with the change of the scope of the subchapter to Characterization, Inspection and Analysis a new key challenge was identified: Detection of organic contamination on surfaces – the detection and speciation of non-volatile organics on surfaces is currently not possible in the fab. There is no laboratory or fab scale instrumentation available or implemented. In 2020 IRDS studied organic precursor deposition on the wafer surface. These studies were done to determine the risks associated with organic contamination on the wafer surface. Results were published in 2021.

Other topics challenging the Yield Enhancement community are prioritized as follows in the near term:

- Process Stability versus Absolute Contamination Level
- Wafer Edge, Backside and Bevel Monitoring and Contamination Control
- Development of sub 10 nm water and chemical liquid particle counter
- Correlation Yield and Contamination Levels

Furthermore, in the long term the following key challenges were identified:

- Inline defect characterization and analysis
- Next generation lithography

Table YE-2 Yield Enhancement Difficult Challenges

Near-Term Challenges: 2022-2028	***Description***
Challenge #1 Control of Electrically Active and other particles in Ultrapure Water and Liquid Chemicals for advanced semiconductor manufacturing (logic key driver)	Insufficient metrology and marginal treatment technology capability
Challenge #2 Control of Electrically Active and other particles in UPW of EUV mask production	Insufficient metrology and marginal treatment technology capability
Challenge #3 Critical Organics in UPW	Insufficient metrology for online speciation of organics
Challenge #4 Metals in H_2O_2	Insufficient metrology capability. Characterization needed for specific critical metals for key process steps and segments.
Challenge #5 Slurry particle characterization and other impurity monitoring	Insufficient metrology capability
Challenge #6 Plating chemicals: particles > critical size (>0.150 µm) (#/ml)	Need reliable monitoring of large particles
Challenge #7 Liquid Chemicals: particles > critical size (#/ml)	Need reliable monitoring of particles <10 nm. Need Filtration technology that is reliable at the stated retention rating and that has minimal "rise up" contributions at the time of install into the process.

Near-Term Challenges: 2022-2028	*Description*
Challenge #8 CMP Slurries: large particles > MPS (#/ml)	Need reliable LPC metrology that can measure targeted particles sizes and concentrations that ignore the MPS sizes and do not require sample dilution to obtain the measurement.
Challenge #9 Post-CMP (pCMP) Cleans particles	Some pCMP cleans will have volatile or highly reactive ingredients that form bubbles in solution, therefore; new metrology and new techniques will be needed to differentiate between bubbles and real particles for contamination control. The pCMP cleans that contain surfactants will have micelle particles and structures that are necessary for the chemistry to perform the intended function. The need is for reliable and accurate metrology to distinguish micelles from other foreign particles in solution.
Challenge #10 Particle measurement for ISO class 1	Need more efficient and effective laser particle counters with detection limit << 100 nm or CPC with sample flow >> 0,1 cfm
Challenge #11 AMC metrology	Need of more sensitive gas analyzers for HCl, HF, HNO_3, HBr, NH_3, Total Acids, H_2S, SO_2, organic acids, sulphuric acids and Total bases with detection limit << 100 ppt
Challenge #12 Particle contribution by critical components and its control	Insufficient analytical capability and unknown level of cleanliness
Challenge #13 Critical metals in UPW for CMOS image sensors	Insufficient metrology sensitivity below 200 ppq concentration
Challenge #14 Low concentration particle measurement in the 10-100nm range to check the cleanliness of gases and to judge the contribution to particle cleanliness from hardware present in the gas delivery system (upstream or downstream from POD).	Preferably these measurements should be possible at a freely selectable flowrate instead of fixed 1 cfm or 0.1 cfm
Challenge #15 Composition and/or structural information for <100nm particles, especially when present in small numbers.	Low amounts of particles have the potential of creating issues. Having excess to techniques that can learn about elemental composition and/or chemical structures can help a lot in root cause finding of observed issues.
Challenge #16 Particulate precursor metrology < 10 nm	Need better understanding of particle precursors and critical concentrations to form particles. Important to determine relationship between species/concentrations and particle size.
Challenge #17 Removing particles < 30 nm	Overcoming the static/van der Waals forces that make particles adhere to critical surfaces is much more difficult for particles < 30 nm.
Long-Term Challenges: 2029–2037	***Description***
OUT OF CURRENT SCOPE OF YIELD ENHANCEMENT	

4.2. SURFACE ENVIRONMENTAL CONTAMINATION CONTROL

Surface environment control—The surface environment control includes the ambient space around the wafer at all times, whether the wafers are open to the cleanroom air or stored in PODs/FOUPs. As the list of ambient contaminants to be controlled broadens so must measurement capabilities. Affordable, accurate, repeatable, high capture rate, real time sensors for non-particulate contamination are becoming increasingly necessary. The use of inert environments to transport and store wafers is expected to increase with process sensitivities. Pre-gate, pre-contact clean, salicidation, exposed copper, and reticle exposure are cited as processes that first require this capability. In addition, using inert environments offers the opportunity to reduce the introduction of moisture into vacuum load-lock tools, thereby decreasing contamination and load-lock pump-down times. While closed carrier purging systems exist and are evolving, tool environments that may need to become inert, such as wet sink end-stations, present a challenge. As wafer isolation technologies evolve, design and material selection of carriers and enclosures will be critical for performance in isolating the wafers from the ambient and in not contributing contaminants themselves. All carriers and enclosure materials must meet factory one specifications. In addition, the materials and designs must not promote cross-contamination between processes. Seal technology, low-outgassing, and non-absorbing materials development are key to an effective wafer and reticle isolation deployment.

Airborne molecular contamination (AMC)— Fugitive emissions from chemicals used in wafer processing and inadequate exhaust are the main sources of AMC. Only in some highly congested area, makeup air is a significant yet temporarily important source for AMC. Outgassing from materials of construction in the cleanroom, wafer processing equipment, post processed wafers, and wafer environmental enclosures as well as inadequate exhaust and fugitive emissions from chemicals used in wafer processing are the main sources of AMC. Oxygen and water vapor as well as low concentration atmospheric contaminants (e.g., CO, O_3) can also be considered as part of the AMC burden.

The cooperation with the More Moore group in IRDS initiated an evaluation of the significance of AMC after their conversion into SMC in relation to the influences on the reliability of the semiconductor structure. For this purpose, IRDS More Moore defined threshold values for SMC, beyond which the long-term safe function of transistors is no longer ensured (for details see chapter More Moore).

AMC become SMC when they hit the exposed surface or chip structure and remain there permanently. This process is a multi-stage process consisting of transport steps and at least one phase transition (from the gas phase to a sorbed state on the surface) that is influenced by the AMC concentration, the characteristics of the boundary layers and the solid surface, among other factors.

The AMC group in the IRDS YE chapter had newly evaluated various model approaches in 2022 to be able to describe this process in a model-like manner and to be able to calculate various scenarios. The model includes contributions for the transport process to the surface, the phase transfer process of attachment, and contributions that take into account the influence of surface saturation and possible back transport. [20]

With reference to a limiting deposition of carbon atoms to key process steps (source/drain and gate stack formation), first results for critical AMC concentrations or - more precisely - critical AMC doses (as ct product of concentration and exposure time) could be calculated for model substances.

Surface environmental contamination control requirements are categorized by manufacturing materials or environment, as shown in Table YE-3.

Table YE-3 Technology Requirements for Surface Environmental Contamination Control

Table YE-3a Limit values for interfering atoms on surfaces; avoidance of critical defect densities, various process stages (from the chapter More Moore)

Contaminants	Type	Module	Process Step	Mechanism	Defect Density as measured	Model substance	Comments & potential failure mechanism
Carbon	atomic carbon, post thermal treatment	Source drain & gate stack	Dry etch	Surface damage blocking the dopant (B,P) diffusion in the extension region	5 e^{13} at/cm^2	DEP, DBP, DOP, Ethyl-propionate	Can occur on air break after cleaning. Deterioration of device performance is explained by means of positively ionized carbons at the interface actin as additional positive charges affecting the inversion to n-channel
Organics	Molecular	Gate stack	Standard clean	Carbon compounds induces the expansion of the silicon oxide lattice, deteriorating the silicon oxide layer, resulting in the device failure	5 e^{11} at/cm^2	DEP, DBP, DOP, Ethyl-propionate	Sources of organic contamination are chemical surface modification (i.e. hexamethyldisilazane priming), wafer box storage and extended vacuum exposure. Major organic molecules in the cleanroom air are volatiles outgassing from polymeric materials. They are affecting subsequent CVD steps controlling the film thickness.
Oxidizers	H_2O_2, O_2, O_3	SD/MOL, metal	Air break thermal anneal	Si and/or metal oxidation	1 e^{10} at/cm^2	ozone	Oxygen and moisture in the ambient air. Si-O-Si, Si-H and Si-OH species; very dilute solutions of HF, in de-ionized water, DI, or dilute solutions of ammonium fluoride, NH_4F, HF and DI water (buffered oxide etch, BOE) completely remove silicon native oxide, leaving a hydrogen-terminated clean silicon surface a

Table YE-3b Model results critical times (t_{crit}) to reach the limit values for impurity atoms for different process stages; model substances

Model substance	Defect density limit	Impact concentration c_0	Critical time t_{crit}
DEP (Diethyl phtalate)	5e^{11} at C/cm^2	1000 ppt_v	22 sec
		100 ppt_v	228 sec
		10 ppt_v	∞
	5e^{13} at C/cm^2	1000 ppt_v	∞
		100 ppt_v	∞
		10 ppt_v	∞
DOP (Dioctyl phtalate)	5e^{11} at C/cm^2	1000 ppt_v	14 sec
		100 ppt_v	143 sec
		<< 1 ppt_v	∞
	5e^{13} at C/cm^2	1000 ppt_v	1’430
		100 ppt_v	15’500
		18 ppt_v	∞

The results show that the concentrations for which the model substances do not reach the critical limits due to their properties, even with very long exposure times, are generally very small and their compliance can be a problem in the manufacturing process.

Similarly, the model results show that for common concentrations of AMC, as can occur in the cleanroom and in the FOUP, the time periods until the critical SMC coverage is reached can be very short.

The summary of the model results shows the necessity of an effective AMC control, e.g., in FOUPs, by suitable measures such as FOUP purging and AMC control in the area of atmospheric wafer handling. In any case, however, the verification of very small AMC levels is underlined by fast and sufficiently sensitive on-line measurement procedures.

The model developed in 2022 is universally applicable and can be extended to other limit descriptions if the necessary parameter sets for components and surfaces are available. The AMC Group will continue to work on this.

AMC remains to be in many cases—as for excursions—a highly dynamic phenomenon. AMC control deals mainly with prevention of AMC release for which tight source control is mandatory. Since there is clearly a need for better AMC monitoring instrumentation in the clean room to measure AMC at the part per trillion level (by volume) in real time, in the recent past academia and industry engaged much in making breakthrough technology options available for AMC measurements.

Table YE-4 and YE-4a provide more details on AMC monitoring and on-line methods. In the same moment Table 4 outlines the current AMC-gaps to assure seamless control of AMC-limits.

Table YE-4 AMC Monitoring Methods

Table YE-4a Supporting Table for On-line Methods

Numerous studies related to AMC outgassing from the materials of construction of environmental enclosures and FOUPs have been performed to guide material selection for these enclosures. Progress has been made by proper material choice and pump-and-purge steps for FOUPs support reducing AMC induced wafer defects. The potential for AMC to impact new processes should be considered in all process integration studies.

While not specifically mentioned, charged defects are also an area of concern where ion control is critical in areas such as lithography, particularly EUV. Wafer charging must also be managed to avoid attracting charged particles to the wafer.

4.2.1. CRITICAL COMPONENTS

One of the biggest challenges of contamination affecting Yield is due to our limited ability to control particles. In both high purity liquid chemicals and UPW, the particles originate mostly from the materials of construction of the components used in the respective liquid delivery systems. The following sections discuss the implications and additional controls needed to maintain sufficiently low level of particles. However, it is important to make sure that the materials used in those systems are of adequate quality to mitigate the risk of particles occurrence.

The challenge of such particle quality control is due to the limitations of the existing analytical techniques and related metrology to qualify high purity components. Currently used SEMI F057[5] methods only measure particles of the size of 100 nm and larger. There is a need for 10nm particle measurement of the components shedding. Metrology for such analysis does not currently exist, although new non-optical particle detection techniques are being developed for detecting 10nm and smaller particles. Application of the Power Law from 100 nm to 10 nm and less has not been demonstrated and hence cannot be assumed to hold true. Ability to measure 10nm particles is critical to gaining actual understanding of particle performance for critical components.

[5] *SEMI F057- Specification for Polymer Materials and Components Used in Ultrapure Water and Liquid Chemical Distribution Systems*

4.2.2. ULTRAPURE WATER QUALITY

Ultrapure water – Specific definitions of the water quality requirements to enable future technology are presented in the Table YE-3. Critical challenges are summarized in Table YE-2b

Particle levels are reduced using the best available ultra-filtration (UF) technology, but today's particle counting technology is not able to keep up with critical particle node due to continued scaling of critical semiconductor devices. Lack of proven particle metrology limits the ability to confirm whether UF is effective in controlling killer size particles down to the critical particle size referenced in Table YE-3. Section 1.1.1 provides an explanation of the proactive approach used in UPW.

It is important to note that the roadmap is focused on technology enabling, thus identifying the parameters that require new technologies for monitoring and control. For the practical purposes, SEMI F063 provides a guide that can be used as a reference specification for the UPW quality in design and operation of advanced semiconductor processes, considering feasibility of the existing technologies. UPW SEMI standards are in process of alignment with the new direction of the UPW roadmap for proactive technology management.

More stringent criteria beyond 2021 are only projected where there is evidence that manufacturing process requirements demand improvements. UPW is generally the cleanest fluid available in the manufacturing process. Limited data is currently available to correlate contamination level to device yield. For this reason, the UPW Roadmap for contamination tolerance is relatively stable over time.

The UPW section of Table YE-3 considers some parameters as process variables rather than contaminants. The stability of the wafer processing environment can be as important as the level of contaminants present for some parameters. For example, some semiconductor manufacturers treat dissolved oxygen (DO_2) in this way, while others consider it a contaminant. Stability of temperature continues to be important for immersion lithography.

Since 2018 some commonly monitored parameters such as resistivity and bacteria were no longer included in the table, as they do not represent technology challenges and are only used for monitoring operational performance of the UPW systems. These parameters are critical for the water quality, but non-critical for the future technology enabling. Bacteria can be controlled down to a level of non-detect and the resistivity has become not sensitive enough to monitor water quality variation within the ranges targeted for the ionic species in UPW.

UPW parameters were reviewed for the 2018 roadmap for the specific location where they are critical to maintaining semiconductor yield. The notes to the Table YE-3 contain definitions for these parameters. Some parameters are specified for point of process (POP), while the others are specified in various locations. The definitions are driven by the consideration of whether the tool environment may further contribute to changes in those parameters.

4.2.2.1. PARTICLE CONTAMINATION IN UPW

The focus has turned more to critical parameters such as particles, metals, and organic compounds. Particles remain a high and growing risk, critical for implementing future semiconductor technology due to its high sensitivity to decreasing line widths. On-line metrology for particles in liquid does not address killer particle size, and therefore, filtration efficiency for killer particles is not known. At the same time, it is apparent that the killer size of the particles has approached filtration capability of the most advanced final filters. Furthermore, there is some test data suggesting the particle challenge concentrations to the final filters from UPW system components can be much higher than previously believed (Refer to SEMI C79[6] and SEMI C93[7] for filter performance test data and UPW Polish ion exchange particle shedding, respectively).

Detailed analysis provided with input from More Moore suggested the higher criticality of the electrically active particles (EAP) compared to other particles. This difference is reflected in Table YE-3.

Particles continue to be important for EUV mask operation because the EUV mask defect has in semiconductor manufacturing, replicating of thousands of times during the lifetime of the mask. The mask is expected to be defect free, which requires particularly tight particle control in mask production. It is important to note that the killer size of the particles on mask is independent of the device pitch size, but a function of the EUV wavelength (refer to the sizes of killer particles in Table YE-3).

[6] *SEMI C79-0113 - Guide to Evaluate the Efficacy of Sub-15 nm Filters Used in Ultrapure Water (UPW) Distribution Systems*
[7] *SEMI C93-0217 - Guide for Determining the Quality of Ion Exchange Resin Used in Polish Applications of Ultrapure Water System*

Colloidal silica, long considered as delta between total and reactive silica, has been removed from the roadmap, even though experimental work further confirmed high criticality of this material. Colloidal silica is now considered and treated as a particle, subject to the particle specification in the table. If colloidal silica particles are controlled to the specification, all measurable silica in UPW will be in the form of dissolved silica. Hence the value for a total silica specification remains (total silica = dissolved/reactive silica). Reactive silica concentration is limited due to its negative impact on device yield, forming water marks on the wafer. In this case, reactive silica specification can be measured using either total silica analyses methods (i.e., ICP-MS) or as reactive silica (by colorimetric method) to the level specified in the table. For practical purposes, measuring total and reactive silica may be considered to confirm no presence of colloidal silica.

As a workaround to the particle metrology gap, the UPW forum has worked with SEMI to develop a filter performance validation standard (SEMI C079) as a risk mitigation measure. The UPW Task Force of SEMI has also developed a document for ion exchange resin testing, thus helping to mitigate significant particle shedding from the resin. It is believed that ion exchange resin sheds different forms of organic materials between low (LMW) and high molecular weight (HMW); these organic materials are dissolved as well as undissolved materials (particles). It is now believed (based on experimental data) that HMW dissolved organics may permeate through the UPW final filters and form particles on the wafers due to the drying mechanism. This adds further complexity to particle monitoring in UPW as current optical particle counters target suspended solids particles and are incapable of detecting these organic, or soft particles. Even sub-ppb levels of very HMW organics may form particles on the wafer surface. Additional experimental work is discussed in the next section and its results have verified this concern.

4.2.2.2. Particle Precursors

The smallest critical particle size for the manufacture of semiconductors is now 3.5 nm. The semiconductor industry is entering a region where particles, particle precursors and molecules in liquids, begin to overlap. Particle precursors are defined as a dissolved or suspended nanomaterial that when dried could result in a particle of critical size. The ability to distinguish particle precursors from solid particles in UPW is becoming critical. While advanced filtration can remove nanometer sized solid particles, the same filter may have little or no ability to remove particle precursors.

A primary source of particle precursors in UPW are thought to be high-molecular weight organics that rinse off ion-exchange resins. As part of the development of SEMI C93 “Guide for Determining the Quality of Ion Exchange Resin used in Polish Applications for Ultrapure Water System”, a benchmark study was initiated. The benchmark study consisted of monitoring the “particles” rinsing off a number of virgin polish resins using the particle detection technique “Nebulization and Condensation Particle Counting”. Particles were detected as high as 1E9 particles per mL. Using the Focused Aerosol Deposition technique, these particles were found to contain sulfur, supporting the thesis that this material came from the resin.

Further benchmarking studies using the high molecular weight organic Poly (sodium 4-styrenesulfonate), Mw approximately 70,000da, have been deposited on one inch silicon wafer. Analysis of the silicon wafer surface by SEM and surface scan metrology have indicated the presence of a high concentration of nanometer sized particles attributed to the high-molecular weight organic. This confirms the ability of particle precursors in the form of high molecular polymers to become killer particles and presents a problem to the future manufacture of advanced semiconductors.

Series of experiments were performed in 2022 using High Molecular Weight (HMW) Organic compounds and ion exchange resin leach-outs deposited on wafer surfaces. The results confirmed higher concentrations of these compounds in the UPW sample showed notable correlation to higher particle counts on wafer surfaces. This was measured on wafer surface scan metrology and comparable results were found using an alternative method with particle detection to 8nm. Particle distribution was similar in bulk liquid sample and both surface detection methods.

4.2.2.3. Metal Contamination in UPW

The IRDS roadmap has revisited its approach to metal specification. The details of the new approach are provided is the white paper linked in the Appendix. The current approach includes special considerations for CMOS image sensors. New parameters for critical metals for image sensors have been introduced. Target levels of critical metals is redefined. For some metals, this target level is below limits of detection of most advanced metrology.

4.2.2.4. Organic Contamination in UPW

There has been an increased interest in the past few years to understand how organic contamination of UPW may affect semiconductor devices. Organic contamination is currently measured in terms of its total organic carbon content or TOC. This measurement of the organic content does not account for the type of organic and how it may react with

various wafer surfaces or how the reaction may impact device yield. In place of TOC, we are now categorizing organic compounds in UPW for critical and non-critical based on their boiling point. Immersion lithography lens hazing was previously a driver of UPW TOC<1.0 ppb.

The Yield roadmap includes a separate line for immersion lithography TOC (<1.0 ppb), implying that this may be required as POU definition, while the rest of the water quality spec was relaxed to 3 ppb of non-critical organics. We continue working on a new definition of critical organics, based on polar strength as quantified using boiling point. The definition of the critical organics was included in the table notes, which recommend end users to consider characterization of the UPW organics in their own specs. New metrology is needed for on-line detection of the critical organics.

- Critical Organics – non-volatile polar organic compounds with boiling point >200°C
  - Critical organic compounds should be controlled to <1 ppb
  - Organic compounds are categorized as critical with respect to its ability to form a hydrogen bond with any oxide surfaces including gate, tunnel, or native oxide
  - Total non-critical organic compounds should be controlled to <3 ppb
- Critical carbon atoms on wafer related to TOC in bulk fluid
  - Defined by FEP as $1x10^{12}$ atoms/cm^2 for Si-C defect in furnace.
  - Breakdown of organic compounds particularly at higher temperature (>200ºC) is an important consideration for the formation of Si-C defect. The level proposed is considered to be adequate to mitigate such risk of such defect formation.
  - Critical boiling point of organic compounds previously defined by FEP as 200ºC
  - UPW IRDS group is looking at compounds with lower boiling point that may be related to other defects

In addition to the above definition of the critical organics, there is special attention to HMW organics; their mechanism of impact to wafers may be due to killer size particle formation. This aspect is a growing focus of the UPW team.

We continue to use failure mode effects analysis (FMEA) approach to determine the overall risk of each subgroup to the wafer manufacturing process. Previously the UPW team completed an organic speciation benchmarking study which used LC-OCD analysis to speciate-organic compounds in UPW used at ten advanced technology facilities. This information is available as supporting documents and will provide baseline data to identify typical organic compounds in semiconductor UPW systems and can be used for occurrence risk factor in the FMEA review.

UPW measurement methodologies—General test methodologies for monitoring contaminants in UPW are indicated in the Figure YE-9 below. Over the past few years, the UPW IRDS team has benchmarked many advanced UPW systems to determine water quality. Past benchmark efforts have identified the inadequacy of some measurement methodologies to quantify contaminants in the UPW. Sensitivity of the following methods is presently adequate: viable bacteria, dissolved gasses, ions, total organic, and metals. While particle measurement is not adequately sensitive to validate quality at the critical dimension it continues to be a valuable tool to detect filtration failures.

Parameter	*Measured (POD/POC)*	*Test Method[A]*
TOC	*Online*	Membrane-Conductivity/CO_2, Conductivity/CO_2
Organic ions	*Lab*	*Ion chromatography*
Other organics	*Lab*	*LC-MS, GC-MS, LC-OCD*
Total silica	*Lab*	*ICP-MS or GFAAS*
Reactive Silica	*Lab*	*Colorimetry*
Particle monitoring	*Online*	*Light scatter (additional new methods are being qualified)*
Particle count/characterization	*Lab*	*SEM—capture filter at various pore sizes*
Cations, anions, metals	*Lab*	*Ion chromatography, ICP-MS*
Dissolved O_2	*Online*	*Electric cell*
Dissolved N_2	*Online*	*Electric cell*

Figure YE-9 General test methodologies for monitoring contaminants in UPW

ICP-MS—inductively coupled plasma mass spectrometry GFAAS—graphite furnace atomic absorption spectrometry SEM—scanning electron microscope
Note: [A] See SEMI F63 and F75 for additional information about UPW metrology

UPW and liquid chemicals particle measurement—Problem Definition and Goals: The sensitivity limit of particle counters for UPW and liquid chemicals has not kept pace with critical particle size (the size of particles which are thought to be detrimental to wafer yield). Although this concept needs to be discussed again since particles not only impact yield because of their physical dimensions, but even more by the chemical composition, e.g., as spot Fe contamination. Optical measurements of these nanoparticles are made difficult by their low scattering efficiency. Low particle concentrations and small sample volumes of current particle monitors can result in large sample-to-sample variability. More sensitive particle measurement methodology with adequate measurement statistics is needed to meet projected purity goals.

4.2.3. THE PARTICLE SENSITIVITY PROBLEM

The highest sensitivity laser on-line particles counter commercially available for both UPW and liquid chemicals is 0.02 microns. Even at this size the detection efficiency is only 2–5%, so most particles at 0.02 microns and smaller go undetected. Improvements in particle counter sensitivity for UPW have been accomplished by increases in laser power. While improvements in sensitivity for liquid chemical particle counters are viable, further sensitivity improvements for UPW using this approach are unlikely, due to the significant cost implications. There is an ongoing effort to develop alternative technologies to the optically based particle counters.

To estimate the concentration of smaller particles in chemicals, currently an extrapolation is made that assumes a 1/d3 relationship between particle counts and particle size in liquid chemicals. The further away the particle size of interest gets from actual measurement capabilities, the higher the potential for error-error being defined as the difference in the projected value compared to the true value. Moreover, the power law coefficient may be significantly affected by the actual filtration capability of the final filters used upstream to the particle measurement, making projections impossible. Therefore, it is important for the industry to develop a more sensitive method that can measure particle concentrations at greater sensitivity to validate the particle count versus particle size relationship so that the

relationship can continue to be reliably used. This power law is not currently used/recommended for specification of the critical liquid chemical and UPW quality. However, the use of power law is considered to be effective for the critical components as particles contributes by those components are not affected by filtration (in contrast with UPW and chemicals).

4.2.4. THE MEASUREMENT PRECISION PROBLEM

Statistical process control is increasingly being used to monitor the consistency of process parameters. Process variation of fluid purity can be as critical to wafer yield as the absolute purity of the fluids. Therefore, it is important that measurement methods detect a sufficient number of events to ensure confidence in measured particle concentrations. Development of other statistically significant particle counting methods, or a higher sample volume particle counter is needed to improve confidence in reported particle counts. The sample volume (volume of fluid measured) will determine the number of particles that are detected during the sample interval. Refer to SEMI F063 for additional information on particles monitoring in UPW.

Although the gas/liquid chemical section of Table YE-3 shows an essentially flat purity trend, there is likelihood that specific process steps may require higher purity. In some cases, yield improvements may be achieved more by reducing variations in purity than by reduction of average contamination levels. Hence, there is a need for improved statistical process control of contamination levels during manufacturing and delivery of these process materials. In 2008, SEMI released the results of a comprehensive effort to create a standard set of guidelines for defining "in control" specialty gases[8]. A coincident effort by several large semiconductor manufacturers began for the purchase of selected specialty gases. Although the number of companies that have started utilizing in control guidelines for the purchase of consumable raw materials has increased, along with the breadth of the offering for in control materials, the industry has not yet settled on one standard set of criteria.

Overview for gases and liquid chemicals—The recommended contaminant values for gases and chemicals in Table YE-3 represent typical gas/liquid chemical quality requirements at the point of entry to the process tool (POE) for the more demanding manufacturing processes in the roadmap. In many applications, the requirements for the contaminants in these gases and/or liquid chemicals may be relaxed as dictated by the specific process requirements. On the other hand, some manufacturers have claimed benefits from lower contaminant levels. Considering that a given process can be run successfully within a "window" defined by a range of material purity and also by ranges in other parameters (purging time, etc.), it follows that, in practice, trade-offs exist between imposed purity requirements, process throughput, etc. Pushing a process to the upper limit of its "purity window" may require significant investment of time and effort in optimizing other parameters, and the economics of pursuing that effort will depend on the environment. It may also be that benefits attributed to low contaminant levels are more attributable to the reduction in contaminant variations achieved with high-purity process gases and chemicals. This topic is addressed in more detail below regarding the push for the adoption of statistical process control, SPC, for specifying process fluid purity.

There are three primary sources of process environment contamination: One is the impurities in the process materials as supplied. The second is the delivery system or the process itself. The third is decomposition, which may be caused thermally or by reaction with adventitious contaminants e.g., moisture. These contamination sources are found throughout the pathway from the delivered gas or chemical to the wafer surface. Table YE-1 describes the several interfacial points of process materials with equipment found along these paths and associates them with the various chapters within the IRDS and other organizations such as SEMI that focuses on them. This helps to clarify the relationship of these organizations with the WECC while also removing ambiguity about the definition of various points along the process path.

While purity measurements at the Point of Process, POP (that is, in the processing chamber itself), would provide the most direct correlation between gas or liquid quality and process performance, these measurements are often exceedingly difficult to obtain except for certain fluid properties in wafer immersion baths. Examples include both particulate generation during plasma processes and wafer out gassing. The latter is the most important source of water vapor contamination in many processes, often obscuring moisture contributions from the process fluid. Measurements at the POU provide the most direct information of the quality of process fluids going directly into the process chamber, but these are also not available for many of the common processes.

Because of these difficulties, the values in Table YE-3 are intended to represent those at the Point of Entry, POE, defined as the inlet to the process tool as described in Table YE-1. There are sufficient measurement data on bulk

[8] SEMI. Standard Practices for the Development of Ship to Control Process Limits, 2008.

gases and aqueous fluids to provide guidance regarding POE impurity levels for many applications, although measurements on these fluids are often performed at the POS, POD, or POC. For these materials, which are relatively unreactive and delivered in large volume, the extrapolation to POE is generally very reasonable. In the case of Specialty Gases and other reactive process fluids, such extrapolation is more delicate because delivered volumes are smaller, increasing sensitivity to contamination effects, and degradation in the distribution system related to materials of construction, atmospheric contamination, thermal degradation, etc. is more likely. These factors are minimized with normal best construction and operations practices, and therefore the best guidance available is often regarding POS specification and to a lesser extent POD or POC measurements, which are interpreted as equivalent to POE. In summary, while the intention is to recommend POE purity levels for all gases and liquids, in practice, the supporting data has more often been collected at POS, POD, or POC.

The targeted levels can be reached either by bulk delivery of a fluid with requisite purity or through use of a local purification/filtration. Care should be taken, at a minimum, to maintain the quality of the gas coming from the source, ensuring that contamination is not added downstream of the POS, as may occur due to particle generation at components, moisture out gassing, byproduct generation due to incompatible materials, etc. Particle filtration as close to the POU as possible is generally advisable for gases. For the most critical applications a local purifier may be used to enhance or ensure ultimate purity at the POU. In those cases, the prevailing approach is to seek POC levels that are adequate for the process and to view the purifier as "insurance." The challenge to the purifier is minimal, and long purifier lifetimes can normally be expected.

Point of use purifiers and filtration units are finding application in newer atomic layer deposition techniques, ALD, for example where the films are deposited by the monolayer and incorporated impurities can be especially destructive. A near/medium term challenge is filtration of the precursor vapor. The sources can be sublimable solids or readily condensable vapors of low volatility liquids. These can resolidify or reliquify causing plugging and instability in fluid transfer to the substrate surface. In addition, these vapor delivery systems are typically low pressure (<100 Torr) which can change the fluid dynamics and hence filtration efficiency dramatically. One additional limitation with the POUP (POU purification) systems in particular is endpoint monitoring to determine when the purifier matrix is exhausted. Practically this is handled by routine change out of the purifier units at a frequency that typically results in no problems.

Specific purity challenges will be discussed below, but generally there is little objective evidence to suggest that the purity levels listed in Table YE-3 are not suitable for multiple generations of semiconductor manufacturing. Yield improvements are expected to be achieved by reducing variations in purity. Statistical process control (SPC) on incoming materials will reduce variation at the POS. Inconsistencies at the POU may remain due to variations in downstream contributions, e.g., when the flow in a distribution system is decreased, moisture contamination due to out gassing tends to increase. Elimination of these variations may again require purification at the appropriate point (e.g., POUP).

Bulk and Specialty Gases—The major bulk gases are listed separately in Table YE-3. The 2007 roadmap had indicated an increase in purity requirements post 45 nm. This type of improvement might be anticipated, based upon historical trends as design rules tightened, but there is again little objective evidence to support the need for improvements across the range of bulk gases. Informal poling of several large semiconductor manufacturing organizations suggests that an increase above current purity requirements for the majority of bulk gases is not necessary to meet post 45 nm design rule manufacturing. For very special applications where extraordinarily higher purities are critical, special purity grades or additional purification will be required. As exemplified above, downstream POUP might also be utilized as an additional means of removing variability in POS gases. Therefore, Table YE-3 has been modified from 2005 to remove many of the step improvements scheduled for future manufacturing nodes except where specific information has been identified to justify the change.

The situation is similar for many of the Specialty Gases, although several additional categories of applications have been added to better identify needs for specific processes, *e.g.*, etch, deposition, doping and laser applications. Like the Bulk gases, the values in Table YE-3 have been left at current levels, unless an objective justification for increased purity can be identified. Although changes to the current Table YE-3 values for gases are small, the introduction of so many new materials and the process innovations required to meet future design rules, *e.g.*, atomic layer deposition, will require close monitoring.

Statistical process control for process gases and liquids was implemented circa 2005 by large semiconductor manufacturer for a selection of critical process fluids, e.g., TEOS. Rather than simply meeting specification values for a set of quality control parameters, the materials were selected against specifications dictated by statistical control of

variability of the materials. The utilization of SPC selection criteria continues and has expanded, however, there are still no standards accepted across the industry that define the SPC process.

The promise of providing "in control" process fluids is anticipated to improve process yields by either minimizing the overall variability of the manufacturing process or in simply reducing the likelihood of a process crash resulting from large variations in material quality that would still nominally have met a more standard specification.

An informal survey of several large semiconductor manufacturing companies on their implementation of statistical process control requirements for their bulk and specialty gas purchases indicates that SPC processes are already being applied to many of the materials utilized in manufacturing or will be shortly. However, the criteria that form the basis of "in control" varies substantially. Survey responses suggest that customer expectation is that the application of process control for the preparation of POS materials will improve their semiconductor manufacturing process stability and are critical for high yield manufacturing. Initial implementation will likely focus on specialty gases that exhibit the greatest potential for causing semiconductor process variability, *e.g.*, anhydrous HCl but will be used on new and existing products for both memory and microprocessors. See Table YE-4b.

Liquid chemicals—Table YE-3 summarizes the purity requirements for liquid chemicals delivered to process tools. Pre-diffusion cleaning and EUV mask blank cleaning requirements drive the most aggressive impurity levels. Liquid particle level targets are shown to become purer each technology generation. These target values are derived from the purity requirements on a wafer as calculated by the FEP surface preparation group assuming a linear relationship between the concentration in the liquid and on the wafer. Particle counters currently are capable of measuring only to 40 nm for liquid chemicals. By assuming a particle size distribution, it should be possible to infer particle concentrations to smaller particle sizes, but this will be influenced by the level of filtration utilized. Another measurement challenge for several chemicals is the differentiation between particles and bubbles, which is currently not possible.

The ability to accurately analyze organic, anion, and cation contamination in process chemicals is becoming more critical to successful wafer processing. ALD/CVD precursors: At recent nodes Atomic Layer Deposition (ALD) processes have been adopted aggressively and proliferation is expected to accelerate in the future. ALD processes will therefore constitute a growing subset of the processes used in HVM and some discussion of common/unique aspects of ALD processes with respect to Surface Environmental Contamination Control (SECC) is warranted.

Table YE-3 contains information only for very few CVD/ALD precursors. The variety of layers and the respective contaminants is enormous.

Therefore, a link to the precursor table is provided in the Appendix. The precursor table provides information by application as to which precursors are potential candidates at different technology generations, and the nature of contamination that can be expected. A major challenge is the development of accelerated yield learning for critical processes that introduce new precursors that will only be used for one or two generations.

Bulk/specialty gases—There were only a few changes to the bulk gas purity requirements. The measurement of organic refractory components at <0.1 ppb is a detect ability challenge for both nitrogen and helium used in lithography applications. The roadmap indicates these areas as orange from 2007 to 2010 because this is at the limit of detection for current analytical methods.

In addition, changes were made to better delineate the need to control Ar as an impurity. The N_2 specification was changed to eliminate Ar as a critical impurity, although it was left in the O_2 specification. Even so, the 50 ppbv limit given in 2005 was raised to an Ar limit of <1000 ppbv. The ongoing requirement in O_2 derives from the potential for uncontrolled Ar impurities to impact plasma etching processes, although typical Ar specifications for O_2 used for etching is more consistent with the <1000 ppbv level.

Novel materials—More detailed consideration of the impurity levels found in the growing number of novel materials used in processing will be increasingly important. Requisite purity levels for critical materials such as novel metal oxides, CMP slurries, low/high k dielectric materials, precursor materials (such as CVD and electroplating solutions) for barrier and conductor metals (such as Cu, Ta) have not been widely studied, and many of these materials have not been called out in Table YE-3. An early attempt to start to catalogue and characterize the properties of the thin film precursors utilized in semiconductor processing is found in the supplementary material for this chapter.

Deposition precursors for thin film materials are often sensitive to moisture, air and high temperatures. Control over the delivery process from the POS to the reaction chamber is critical to high yielding performance. The use of very high purity carrier and purge gases in these systems are often required to prevent decomposition that can contribute

detrimental molecular and particulate impurities. Traditionally bulk purifiers were used in the bulk gas delivery systems to remove particles and other homogeneous chemical contaminations like oxygen, or moisture present in the supply gases. However, with the development and commercial availability of point-of-use (POU) purifiers, there is a strong interest from end users to utilize point-of-use (POU) purifiers particularly for specialty gases needed for critical process steps with very critical level of contamination control. These point-of-use purifiers (POU) are highly effective to remove chemical contaminants to extreme low level (~ ppt), easy to use, easy to replace, with low cost-of-ownership. The capability of placing those point-of-use (POU) purifiers very close to inlet of process chamber, assures least travel path (less contamination) for process gases after chemical purification and filtration.

Novel measurement techniques and impact studies are needed to ensure that these materials are produced with the impurity specifications that meet technology requirements. Additional detail on the variety of thin film precursors under consideration can be found in Liquid Chemicals section of Table YE-3 and the supplementary precursor table.

4.3. Characterization, Inspection and Analysis

The following section of the near-term challenges remains unchanged from 2020 publication.

This subchapter focuses on equipment requirements to perform the characterization inspection and analysis tasks. This is facing the demands of nowadays yield enhancement in a broad application as *e.g.* 'More than Moore' technologies but also power electronics and mechatronics and MEMS applications. Furthermore, the characterization, inspection and analysis demands of e.g., packaging and assembly could be taken into account.

The More Moore requirements for defect detection on un-patterned wafers as well as patterned wafers are the most challenging. Therefore, those requirements are directly integrated in the More Moore chapter for Logic. As Logic was defined to be the technology driver see chapter 1.2.

A specific MEMS expert group is defining the specific requirements of inline control in MEMS production. The different MEMS technologies need to be separated in surface and bulk technologies for it causes different requirements to inspection and characterization. Surface technology is defined for structures till 30 µm depth. Any stacked technologies and those with depth more than 30 µm are considered bulk technology.

The detailed requirements are presented in Table YE-5.

Table YE-5 Yield Requirements for MEMS Production

4.4. Long-term Challenges

This section is not included in the Yield chapter due to the focus on near term challenges.

5. Technology Requirements

5.1. Summary

The Technology Requirements section deals with the issues outlined in the Critical Challenges section.

The Yield Enhancement Technology Requirements include definitions of the yield characterization, inspection, and analysis, as well as definitions of the level of impurities of the materials and environments used in semiconductor manufacturing. Table YE-3 provides a list of the parameters and their level that needs to be controlled to ensure minimum of 80% yield. Those parameters define both the technology necessary to achieve those level (i.e., purification) and metrology necessary to monitor those parameters. In cases where metrology does not exist, it is required that the yield will be ensured by either tighter process control measures or by tight material quality control throughout associated supply chain, based on SEMI Standards.

6. Potential Solutions

6.1. General

For pattern wafer inspection the requirements for the next years will be to overcome issues of detection of the defects within the nuisance signal. This is correlated to the issue to obtain high sensitivity at high throughput. Major

breakthroughs are required to achieve the required throughputs at roadmap sensitivities for yield ramp and volume production. The high aspect ratio inspection is still requiring for high yield at high throughput due to the high cost of ownership of the inspection tools. This also requires a good separation of the defect signals from the noise. The introduction of advanced lithography process using high energies has a potential to initiate chemical reactions and layer modification on the surface. Therefore, the detection of volatile and non-volatile organics is crucial. Currently, only synchrotron radiation-based facilities have the potential to analyze traces of non-volatile organic surface contamination. This is with respect to qualification and quantification.

Critical Components—There is currently no means to measure particles smaller than 20nm from Critical Components. The intent is to measure larger particles using existing technology and apply the Power Law to extrapolate smaller particle population. The basis for the Power Law is the established relationship of particle size to population (concentration). In statistics, a *power law* is a functional relationship between two quantities, where a relative change in one quantity results in a proportional relative change in the other quantity, independent of the initial size of those quantities: one quantity varies as a *power* of another. In particles it is a logarithmic relation of size as particles get smaller. There is a SEMI task force working on measurement and results interpretation for 10nm particles. There will need to be ongoing work for <10nm particles.

6.2. Surface Environmental Contamination Control

Surface Environment Control—As the list of ambient contaminants to be controlled broadens so must measurement capabilities. Affordable, accurate, repeatable, real-time sensors for non-particulate contamination are becoming increasingly necessary.

Process Equipment—Defect reduction in process equipment remains paramount to achieving defect density goals. Solutions and technology developments are required to provide major enhancement capabilities in the next years and continue to enable cost-effective high-volume manufacturing for device dimensions below 14 nm. New cleaning chemistries, *in situ* chamber monitoring, materials development, and other techniques including improved techniques of parts cleaning can help maintain chamber cleanliness run-to-run and dramatically reduce the frequency of chamber wet cleans. These developments will also act to increase equipment utilization. Reduced backside wafer contamination control must drive both measurement technology and fundamental changes in equipment. Metal/particle cross contamination from backside to next wafer front-side, hot spots/depth of focus in lithography, and punch through on electrostatic chucks are all examples of issues that must be addressed in future tools. Particle avoidance techniques (O-ring material selection, gas flow/temperature management, wafer chuck optimization) will continue to play a key role in meeting defect densities. It is believed that a more fundamental understanding of reactor contamination formation, transport, and deposition will be required to enhance current equipment and process design and aid in the placement and interpretation of data from *in situ* sensors. Fundamental physical, chemical, and plasma reactor contamination models must be employed. *In situ* process control will become increasingly important to reduce process-induced defects and to minimize requirements for post-measurements. Intelligent process control at a tool requires a fundamental understanding of how parameters impact device performance. Open tool control systems that allow both users and equipment suppliers to easily integrate new sensor and new control software will be necessary to enable intelligent process control.

Process critical materials— Further studies into device impact are necessary to validate any need for increased purities. System concerns such as corrosion potential may lead process concerns in seeking higher purities.

In order to accelerate yield enhancement for processes that incorporate new materials, it is very desirable that development studies include purity data as much as is practical. Studies of new materials (*e.g.*, for gate dielectrics) are initially concerned with basic process performance, and later with integration issues. During those stages of development contamination is a relatively minor concern. However, if no information is collected, later yield enhancement efforts proceed with inadequate technical basis. Collecting and reporting both environmental and material contamination data whenever practical will lead to long-term benefits.

UPW—Effect of UPW quality to wafer defects for most advanced device geometries is unknown. Particles (including colloidal silica) are considered to be high risk. Potential solution for the particle control is due to reduction of the particle challenge in the final filters and application of the POU filtration, providing an additional layer of protection. Use of SEMI C079 and SEMI C093 guides are recommended for the particle challenge reduction. Proactive colloidal silica control using frequent regeneration of the makeup water ion exchange resin is also recommended.

Although updated target levels for hydrogen peroxide have been defined, additional study is needed to better correlated process related issues with the level of H_2O_2 in UPW.

Recycling and reclaiming initiatives must drive improvements in rapid online analytical technology, especially detection of organics, to ensure that POU-recycled UPW is equal or better than single-pass water.

Chemicals—Figure YE-1 also shows various technological areas that may be required to enhance and measure the purity of delivered chemicals to the wafer manufacturing process.

Wafer environment control—The use of inert environments to transport and store wafers is expected to increase with process sensitivities. Pre-gate and pre-contact clean and salicidation are cited as processes to first require this capability. In addition, using inert environments offers the opportunity to reduce the introduction of moisture into vacuum load-lock tools, thereby decreasing contamination and load-lock pump-down times. While closed carrier purging systems exist and are evolving, tool environments that may need to become inert, such as wet sink end-stations, present a challenge. As wafer isolation technologies evolve, design and material selection of carriers and enclosures will be critical for performance in isolating the wafers from the ambient and in not contributing contaminants themselves. In addition, the materials and designs must not promote cross-contamination between processes. Seal technology, low outgassing, and non-absorbing materials development are key to effective wafer isolation deployment.

6.3. Characterization, Inspection and Analysis

For the challenges of MEMS production, the potential solutions for infrared inspection of metal wafers will be to switch to other technologies like thermography, photoacoustic, or ultrasonic in the future. Possible solutions for critical dimension (CD) scanning electron microscopy (SEM) measurements under angle on silicon on glass could be the use of special structures, the use of reduced beam intensity, or the use of gas as an option to discharge.

7. Cross Teams

Yield Enhancement forum interacts with the teams that either provide definitions about defects and factors affecting manufacturing yield or can benefit from the information generated by the forum for their respective roadmap development. SECC forum of Yield Enhancement provides input into SEMI Standards development by triggering new standards development or existing standard updates in the areas associated with the respective technology challenges. The following diagram illustrates the cross-team linkage.

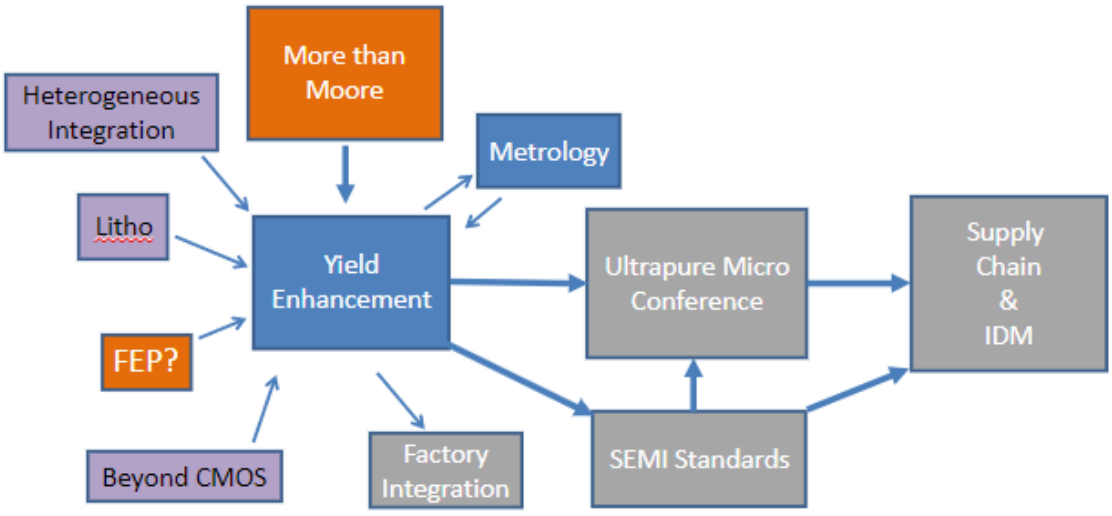


Figure YE-10 Yield Enhancement IFT Cross Team Linkage Diagram

Currently, most of the input into Yield Enhancement is coming from the More Moore IFT, helping to define defects for the most advanced and tightest critical dimension technologies. Additionally, Yield Enhancement works with the Metrology IFT to align on definitions of the required metrology sensitivity.

Yield Enhancement IFT provides input to Factory integration, helping to define conditions in the factory enabling high yield production.

8. Emerging/Disruptive Concepts and Technologies

8.1. Directed Self Assembly

An emerging and disruptive technology that is expected to be increasingly important is directed self-assembly (DSA) and utilizing structured nano-materials. The impact for yield would be more emphasis on defects associated with nonuniformity in structure than in foreign materials or molecular impurities.

9. Conclusions and Recommendations

Most advanced semiconductor technologies and particularly logic (the new yield technology driver) have reached the point when yield may become a constraining factor of the future shrinkage of the critical dimensions. This is because the defect metrology of both critical substrates (wafer, mask, lithography optics, etc.) and materials has reached their limits. This affects the ability to prevent, predict, and control defects in the manufacturing facility. This requires new systematic approaches to continue enabling future technology in accordance with the IRDS roadmap definitions. Such new approaches should include combination of the following measures:

- Proactive measurement of contamination control of the critical materials used throughout the supply chain.
- Leveraging data analytics to correlate process variation in production with any deviations in critical parameters.
- Employ prediction modeling and experimentation to help with decisions on the choice of the technologies and method of their applications at all levels of the manufacturing facility.
- Standardize quality control using SEMI and other standards.
- Take advantage of collaborative development in the industry via IRDS, SEMI, and other research institutions to drive most productive technology solutions related to the SECC. Assist emerging metrology to commercialize via benchmarking studies and independent third-party qualifications.

For next steps, the Yield Enhancement IFT will continue focusing on the areas of the technology challenges as defined in this chapter. More detailed definition of the technology needs and challenges should help to address those needs. There is an increasing need in collaborative development that will require tighter interaction between the roadmap group within Yield IFT and other forums external to Yield.

10. Appendices

10.1. Appendix A—Supplemental Materials

Below is the list of supplemental materials and the links to them:

Title	File Name
Proactive Particle Control in Ultrapure Water (UPW) in Silicon Wafer Cleaning Process, IRDS, 2022	WP_Proactive_Particle_Control_in_Ultrapure_Water_2023.pdf
Metals Spec in UPW, White Paper by Drew Sinha and Slava Libman	Metals_WP.pdf
Metal Contamination of Image sensors by Ultrapure Water in Silicon Wafer Cleaning Process White Paper by Drew Sinha and Slava Libman	Me_WP_Image_Sensor_9_18_18.pdf
Precursor Table	1403_14rev2master_precursor_table.pdf

10.2. APPENDIX B—ACRONYMS

Acronym/Abbreviation	*Definition*
ALD	atomic layer deposition techniques
AMC	airborne molecular contamination
APC	airborne particular contamination
APIMS	atmospheric pressure ionized mass spectroscopy
ATE	automatic test equipment
ATPG	automatic test pattern generation
BE	back end
CCCS	critical contamination control specifications
CDA	clean dry air
CIA	characterization, inspection and analysis
CMOS	complementary metal-oxide semiconductor
CMP	chemical mechanical planarization
CoO	cost of ownership
CPC	condensation particle counter
CRDS	cavity ring-down spectroscopy
CVD	chemical vapor deposition
DSA	directed self assembly
DUV	deep ultraviolet
EAP	electrically active particle
EMI	electromagnetic interference
ESA	electrostatic attraction
ESD	electrostatic discharge
ESG	Environmental, Social, and Governance
EUV	extreme ultraviolet
FE	front end
FEP	front end processes
FID	flame ionization detector
FMEA	failure mode and effects analysis
FOUPs	front opening unified pods

Acronym/Abbreviation	*Definition*
FTIR	Fourier transform infrared spectroscopy
GC	gas chromatography
GCMS	gas chromatography–mass spectrometry
GFAAS	graphite furnace atomic absorption spectroscopy
HEPA	high-efficiency particulate arrestance
HMW	high molecular weight
HVM	high volume manufacturing
ICP-MS	inductively coupled plasma mass spectrometry
IMS	ion mobility spectrometry
IRDS	International Roadmap for Devices and Systems
ISO	International Standards Organization
LCOCD	liquid chromatography: organic carbon detection
LMW	low molecular weight
LPC	laser particle counter
MEMS	microelectromechanical system
MFC	mass flow controller
MPS	mean particle size
MS	mass spectrometry
NEXAF	near edge x-ray absorption fine structure
O=C=S	type of chemical compound containing oxygen, carbon, and sulfur
OEMs	original equipment manufacturer
pCMP	post-CMP or post chemical mechanical planarization
PID	photo ionization detector
POD	point of delivery or point of distribution
POE	point of entry
POP	point of process
POS	point of supply
POU	point-of-use
POUP	POU purification

Acronym/Abbreviation	*Definition*
ROI	return on investment
SECC	surface environment contamination control
SEM-EDS	scanning electron microscopy - energy-dispersive x-ray spectroscopy
SEMI	Semiconductor Equipment and Materials International
SMC	surface molecular contaminant
SMLY	systematic mechanisms limited yield
SPC	statistical process control
TD	thermal desorption
TEOS	Tetraethyl-orthosilicate
TOC	total organic carbon content
ToF-SIMS	time-of-flight - secondary ion mass spectroscopy
UF	ultra-filtration
UPW	ultrapure water
UV	Ultraviolet
VC-D	vibrational circular dichroism
VMB	valve manifold box
VMP	valve manifold post
WECC	wafer environment contamination control
XCDA	Extreme clean dry air
XPS	x-ray photoelectron spectroscopy
YE	Yield Enhancement

11. REFERENCES

1. S. Libman, S. Edmund, B. McIntosh, et al. UPW IRDS and SEMI: Reinforced Process of Enabling Advanced Existing and Future Semiconductor Technologies. UPW Micro Conference. Portland, OR. (2017).
2. S. Libman, G. Van Schooneveld, B. McIntosh, et al. UPW IRDS and SEMI: Reinforced Process of Enabling Advanced Existing and Future Semiconductor Technologies. UPM Conference. Phoenix, AZ. (2019).
3. Yield Enhancement, International Roadmap for Devices and Systems, 2018 edition (2019). IEEE. White Paper: Proactive Particle Control in Ultrapure Water (UPW) in Silicon Wafer Cleaning Process. Supplemental Materials, YE IRDS, 2018 (2019).
4. SEMI F104 – Particle Test Method Guide for Evaluation of Components Used in Ultrapure Water and Liquid Chemical Distribution Systems. SEMI, 673 S. Milpitas Blvd., Milpitas, CA.
5. SEMI C79-0113 - Guide to Evaluate the Efficacy of Sub-15 nm Filters Used in Ultrapure Water (UPW) Distribution Systems. SEMI, 673 S. Milpitas Blvd., Milpitas, CA.
6. SEMI C93-0217 - Guide for Determining the Quality of Ion Exchange Resin Used in Polish Applications of Ultrapure Water System. SEMI, 673 S. Milpitas Blvd., Milpitas, CA.
7. P. Herrling, P. Rychen, D, Starkel, and Keanan Cassidy. Nanoparticle profiling in a UPW Polishing Section by Different Monitoring Systems: Advanced Understanding of Sources and Sinks. UPM Conference. Austin, TX. (2018).
8. G. Van Schooneveld and B. McIntosh, Understanding Particle Contribution from Components Used in Ultrapure Water and High-Purity Chemical Systems and Their Impact on Industry-Driven Particle Requirements. Ultrapure Micro 2019, Phoenix, AZ (2019)
9. G. Van Schooneveld, SEMI C79 Task Force Technical Review, CT Associates, Eden Prairie, MN 55344 (2018)
10. Proactive Contamination Control for Sub 10nm Particle in Advanced Semiconductor Manufacturing. 236th ECS Meeting. October 13-17, 2019, | Atlanta, GA
11. SEMI F063. Guide For Ultrapure Water Used In Semiconductor Processing. SEMI, 673 S. Milpitas Blvd., Milpitas, CA.
12. SEMI F061. Guide To Design And Operation Of A Semiconductor Ultrapure Water System. SEMI, 673 S. Milpitas Blvd., Milpitas, CA.
13. Thompson, L. F.; Willson, C. G.; Bowden, M. J. Introduction to microlithography, 2nd ed.; American Chemical Society: Washington, DC, 1994.
14. SEMI MF 1982-1103 (formerly ASTM 1982-99
15. SEMI F057 – Specification for Polymer Materials and Components Used in Ultrapure Water and Liquid Chemical Distribution Systems
16. SEMI. Standard Practices for the Development of Ship to Control Process Limits, 2008.
17. Alvarez Jr, D.; Spiegelman, J.; Heinlein, E.; Ramos, C.; Holmes, R. J.; Shamsi, Z., New Chemical Vapor Delivery Systems for Surface Cleaning. Solid State Phenomena 2013, 195, 25–29.
18. Norton, E. T.; Amato-Wierda, C., Kinetic and Mechanistic Studies of the Thermal Decomposition of Ti (N (CH3) 2) 4 during Chemical Vapor Deposition by in Situ Molecular Beam Mass Spectrometry. Chemistry of materials 2001, 13 (12), 4655–4660.
19. Libman S., McIntosh B., Hadder D., Van Schooneveld G., UPW IRDS and SEMI Standards: Enabling Yield by Wet Processing Defect Control in Advanced Semiconductor Technologies. May/June 2018, Austin TX.
20. Hocke, C., Sosedowa, Y., Kames, J., YE sub-team report-out, AMC; A model to quantify the transfer from AMC to SMC; evaluation of AMC risks against SMC limit values; 2022 7th IRDS Yield workshop; 2nd of September 2022