

INTERNATIONAL
TECHNOLOGY ROADMAP
FOR
SEMICONDUCTORS 2.0

2015 EDITION

YIELD ENHANCEMENT

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YIELD ENHANCEMENT

1. SCOPE

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, will be extended towards More Moore and More Than More yield considerations. The road mapping focus will move from a technology orientation to a product/application orientation. Thereby, all Yield Enhancement tables will be considerably reworked for ITRS 2.0. The Yield Enhancement section will display the current and future requirements for high yielding manufacturing of Moore More as well as Moore than Moore products separated in “critical process groups” including back-end processes, e. g. packaging. Consequently, an inclusion of material specifications for Si, SiC, GaN etc. will be considered.

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

As a result of the increased synergy of some of the Yield Enhancement topics with Factory Integration (e.g., big data, yield prediction and yield enhancement), the Yield Enhancement roadmap is now included in the FI Focus Area chapter. Due to the changed focus of the Yield Enhancement group several cross TWG activities are envisaged, connections with More Moore (MM), Heterogeneous Integration (HI) and Heterogeneous Components (HC) are necessary.

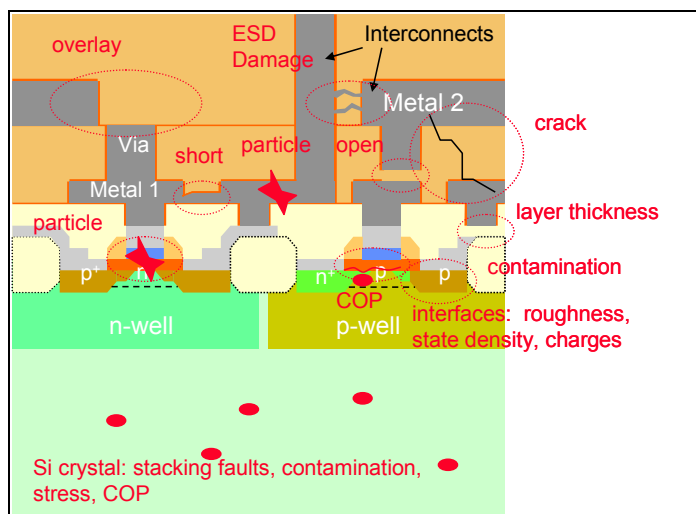


Figure YE1 Yield Enhancement Scope

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

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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.

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. Therefore, the yield enhancement chapter addresses not only the identification of tolerable contamination limits for processes and media, but also the tolerable budgets for particulate contamination of tools. The specification of tools for defect detection and classification of defects for root cause analysis addresses the technology requirements for detection and characterization of faults and failures.

The YE section has two focus topics: “Wafer 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.

Wafer Environment Contamination Control—Order-of-magnitude improvements in process critical fluid and gas impurity levels are not considered to be necessary in the foreseeable future. New materials and their precursors, however, 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 YE3. Table YE1 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 and references, such as the Semiconductor Equipment and Materials International (SEMI) Standards.

Table YE1 Definitions for the Different Interface Points

	<i>POS</i> <i>Delivery Point of Gas/Chemical Supplier</i>	<i>POD</i> <i>Outlet of Central Facility System</i>	<i>POC</i> <i>Submain or VMB/VMP Take off Valve</i>	<i>POE</i> <i>Entry to Equipment or Sub Equipment</i>	<i>POU</i> <i>Entry to the Process Chamber</i>	<i>POP</i> <i>Contact with Wafer</i>
<i>Interfaces</i>	<i>SEMI Standards Focus Area</i>	<i>ITRS Factory Integration Facilities Group Focus Area</i>		<i>ITRS Factory Integration Equipment Group Focus Area</i>		<i>ITRS Front End Processes, Lithography, Interconnect TWG Focus Area</i>
Ultrapure water	Raw water	Outlet of final filtration in UPW plant	Outlet of submain take off valve	Inlet of wet bench or subequipment	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/subequipment	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.

2. DIFFICULT CHALLENGES

The difficult challenges for the Yield Enhancement chapter are summarized in Table YE2. 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 also 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.

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

In 2011 the identification of Non-Visual Defects and Process Variations was set to the most important key challenge in the future. Data, test structures, and methods are needed for correlating process fluid

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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:

- In-line Defect Characterization and Analysis
- Next generation lithography

Table YE2 Yield Enhancement Difficult Challenges

<i>Difficult Challenges 2015-2020</i>	<i>Summary of Issues</i>
<p>It is a challenge to detect multiple killer defect types and to differentiate them simultaneously at high capture rates, low cost of ownership and high throughput. Furthermore, it is a dare to identify yield relevant defects under a vast amount of nuisance and false defects.</p>	<ul style="list-style-type: none"> • Existing techniques trade-off throughput for sensitivity, but at expected defect levels, both throughput and sensitivity are necessary for statistical validity. • Reduction of inspection costs and increase of throughput is crucial in view of CoO. • Detection of line roughness due to process variation. • Electrical and physical failure analysis for killer defects at high capture rate, high throughput and high precision. • Reduction of background noise from detection units and samples to improve the sensitivity of systems. • Improvement of signal to noise ratio to delineate defect from process variation. • Where does process variation stop and defect start?
<p>Process Stability vs. Absolute Contamination Level – This includes the correlation to yield test structures, methods and data that are needed for correlating defects caused by wafer environment and handling to yield. This requires determination of control limits for gases, chemicals, air, precursors, ultrapure water and substrate surface cleanliness.</p>	<ul style="list-style-type: none"> • Systematic Mechanisms Limited Yield (SMLY), resulting from unrecognized models hidden in the chip, should be efficiently identified and tackled through logic diagnosis capability designed into products and systematically incorporated in the test flow. It is required to manage the above models at both the design and the manufacturing stage. Potential issues can arise due to: <ol style="list-style-type: none"> a) Accommodation of different Automatic Test Pattern Generation (ATPG) flows. b) Automatic Test Equipment (ATE) architecture which might lead to significant test time increase when logging the numbers of vectors necessary for the logic diagnosis to converge. c) Logic diagnosis runs time per die. d) Statistical methodology to analyze results of logic diagnosis for denoising influence of random defects and building a layout-dependent systematic yield model. • Test pattern generation has to take into account process versus layout marginalities (hotspots) which might cause systematic loss, and has to improve their coverage. • Methodology for employment and correlation of fluid/gas types to yield of a standard test structure/product. • Relative importance of different contaminants to wafer yield. • Define a standard test for yield/parametric effect. • A possible work around is the use of NEXAF at a synchrotron radiation facility.
<i>Difficult Challenges Beyond 2020</i>	<i>Summary of Issues</i>

Table YE2 Yield Enhancement Difficult Challenges

<i>Difficult Challenges 2015-2020</i>	<i>Summary of Issues</i>
Next Generation Inspection – As bright field detection in the far-field loses its ability to discriminate defects of interest, it has become necessary to explore new alternative technologies that can meet inspection requirements beyond 13 nm node. Several techniques should be given consideration as potential candidates for inspection: high speed scanning probe microscopy, near-field scanning optical microscopy, interferometry, scanning capacitance microscopy and e-beam. This assessment should include each technique's ultimate resolution, throughput and potential interactions with samples (contamination, or degree of mechanical damage) as key success criteria.	<ul style="list-style-type: none"> Several techniques should be given consideration as potential candidates for inspection: high speed scanning probe microscopy, near-field scanning optical microscopy, interferometry, scanning capacitance microscopy and e-beam. This path finding exercise needs to assess each technique's ultimate resolution, throughput and potential interactions with samples (contamination, or degree of mechanical damage) as key success criteria.
In-line Defect Characterization and Analysis – Based on the need to work on smaller defect sizes and feature characterization, alternatives to optical systems and Energy Dispersive X-ray Spectroscopy systems are required for high throughput in-line characterization and analysis for defects smaller than feature sizes. The data volume to be analyzed is drastically increasing, therefore demanding for new methods for data interpretation and to ensure quality. [1]	<ul style="list-style-type: none"> Data volume + quality: strong increase of data volume due to miniaturization The probe for sampling should show minimum impact as surface damage or destruction from SEM image resolution. It will be recommended to supply information on chemical state and bonding especially of organics. Small volume technique adapted to the scales of technology generations. Capability to distinguish between the particle and the substrate signal.
Next generation lithography – Manufacturing faces several choices of lithography technologies in the long term, which all pose different challenges with regard to yield enhancement, defect and contamination control.	

2.1. WAFER ENVIRONMENTAL CONTAMINATION CONTROL

Wafer environmental contamination control requirements are categorized by manufacturing materials or environment, as shown in Table YE3.

Table YE3 Technology Requirements for Wafer Environmental Contamination Control

Year of Production	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
DRAM ½ Pitch (nm) (contacted)	24	22	20	18	17	15	14	13	12	11	10	9.2	8.4	7.7
Critical particle size (nm) based on 50% of DRAM 1/2 Pitch (nm) (contacted) [1]	12	11	10	9	8.5	7.5	7	6.5	6	5.5	5	4.6	4.2	3.9
Wafer Environment Control such as Cleanroom, SMIF, POD, FOUP, etc....not necessarily the cleanroom itself but wafer environment.														
Number of particles (/m ³) [1] [2]	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1	ISO CL1
Airborne Molecular Contaminants in Gas Phase (pptV, V for Volume) [3, 7, 12, 13, 14, 15, 33].														
Lithography: Point of entry (POE) to exposure tool [23]														
Total Inorganic Acids	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Total Organic Acids [30]	2000	2000	2000	2000	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Total Bases	20,000	20,000	20,000	20,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
PGMEA, Ethyl Lactate	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Volatile Organics (w/	26,000	26,000	26,000	26,000	26,000	26,000	26,000	26,000	26,000	26,000	26,000	26,000	26,000	26,000

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GCMS retention times \geq benzene, calibrated to hexadecane) [31]														
Refractory compounds (organics containing for example S, P, Si) [40] [43]	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Lithography: Point of entry (POE) to track & inspection tools; temporary reticle pod storage														
Total Inorganic Acids	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Total Organic Acids [30]	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Total Bases	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
PGMEA, Ethyl Lactate	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Condensable organics (definition to SEMI F21-95, bp 150 °C)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Refractory compounds (organics containing for example S, P, Si)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200
<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200
<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200	<200
< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100
tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
20000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500

Total Inorganic Acids	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Total Bases	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Total Organic Acids [30]	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Total other corrosive species [32]	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
H2S	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Total sulphur compounds	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Exposed Copper Wafer Environment (FOUP inside)														
Total Inorganic Acids	500	500	500	500	500	500	500	500	500	500	500	500	500	500
HCl	200	200	200	200	200	200	200	200	200	200	200	200	200	200
HF	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
HBr	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
HNOx	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Total Organic Acids [30]	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total bases	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Total other corrosive species [32]	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
H2S	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Total sulphur compounds	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
Moisture (ppb)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Exposed Aluminum Wafer Environment (FOUP inside)														
Total Inorganic Acids	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
HCl	100	100	100	100	100	100	100	100	100	100	100	100	100	100
HF	200	200	200	200	200	200	200	200	200	200	200	200	200	200
HBr	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
HNOx	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Total Organic Acids [30]	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Total other corrosive species [32]	1000	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Critical areas (Litho, Metrology)														
Temperature range in +/-K at POE [37]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Maximum short term temperature variation at POE in +/-K/5 min [37]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Maximum long term temperature variation in +/-K/hour at POE [37]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Humidity range in +/-% relative humidity r.H. at POE [37]	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Humidity range in +/-% relative humidity r.H. at POE [37]	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Maximum short term humidity variation in +/-r.H./5 min at POE [37]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Non-critical areas (others than Litho, Metrology)														
Temperature range on +/-K at POE [37]	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Humidity range in +/-% relative humidity r.H. at POE [37]	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Humidity range in +/-% relative humidity r.H. at POE [37]	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

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Ultrapure Water [29]														
Total organic carbon (ppb) [22] for immersion photolithography, POE	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Critical Organics as C (ppb) [22], POE	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Non-critical organics as C (ppb) [22], POE	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Reactive silica (ppb) as SiO ₂ [18], POC	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Total silica (ppb) as SiO ₂ [18], POC	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Number of particles >critical particle size (see above) (#/L) [26], POE	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Number of particles for EUV mask production >critical particle size (see above) (#/L) [26.3], POE	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Dissolved oxygen (ppb) (contaminant based) [16] POE	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Dissolved nitrogen (ppm) [10] POE	8–18	8–18	8–18	8–18	8–18	8–18	8–18	8–18	8–18	8–18	8–18	8–18	8–18	8–18
Hydrogen Peroxide (ppb) [42] POD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Metals (ppt each) (As, Ba, Cd, Mn, Pb, Sn, Sb, V) [39], POP	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Critical metals (ppt, each) (Al, Ca, Cr, Cu, Fe, K, Li, Mg, Na, Ni, Ti, Zn) [39], POP	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Other critical ions (ppt each) [24], POP	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
Phosphate as HPO ₄ (ppt), POP	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Boron (ppt) [24], POP	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
Temperature stability (K) [38], POE	± 1	± 1	± 1	± 1	± 1	± 1	± 1	± 1	± 1	± 1	± 1	± 1	± 1	± 1
Temperature gradient in K/10 minutes [38] for immersion photolithography, POE [38]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Liquid Chemicals														
All cleaning chemistries (aqueous and solvent): number of particles/ml >0.065um [1, calculation based on exponent of 3.0] [11]	0.19	0.15	0.11	0.080	0.067	0.046	0.037	0.030	0.024	0.018	0.014	0.011	0.0081	0.0062
All cleaning chemistries (aqueous and solvent): number of particles/ml >0.040um [1, calculation based on exponent of 3.0] [11]	0.81	0.62	0.47	0.34	0.29	0.20	0.16	0.13	0.10	0.078	0.059	0.046	0.035	0.027
All cleaning chemistries (aqueous and solvent): number of particles/ml >0.030um [1, calculation based on exponent of 3.0] [11]	1.9	1.5	1.1	0.81	0.68	0.47	0.38	0.31	0.24	0.18	0.14	0.11	0.08	0.06

All cleaning chemistries (aqueous and solvent): number of particles/ml >0.020um [1, calculation based on exponent of 3.0] [11]	6.5	5.0	3.8	2.7	2.3	1.6	1.3	1.0	0.81	0.62	0.47	0.37	0.28	0.21
All cleaning chemistries (aqueous and solvent): number of particles/ml >critical particle size [1] [11]	30	30	30	30	30	30	30	30	30	30	30	30	30	30
49% HF: Na, K, Fe, Ni, Cu, Cr, Co, Ca, (Ag, Au, Pd, Pt, Ru, Mo) (ppt, each) [21]	150	150	150	150	150	150	150	150	150	150	150	150	150	150
30% H ₂ O ₂ : Al, Na, K, Fe, Ni, Cu, Cr, Co, Ca, (Ag, Au, Ba, Cd, Mg, Mn, Mo, Pb, Pd, Pt, Ru, Sn, Ti, V, W, Zn) (ppt, each) [21]	150	150	150	150	150	150	150	150	150	150	150	150	150	150
29% NH ₄ OH: Al, Na, K, Fe, Ni, Cu, Cr, Co, Ca, (Au, Ba, Cd, Mg, Mn, Mo, Pb, Pd, Pt, Ru, Sn, Ti, V, W, Zn) (ppt, each) [21]	150	150	150	150	150	150	150	150	150	150	150	150	150	150
100% IPA: Al, Ba, B, K, Na, K, Fe, Li, Mg, Mn, Pb, Sn, Ti, Zn, Ni, Cu, Cr, Co, Ca (ppt, each) [28]	150	150	150	150	150	150	150	150	150	150	150	150	150	150
49% HF: All other metals not listed in row above (ppt, each) [20]	500	500	500	500	500	500	500	500	500	500	500	500	500	500
30% H ₂ O ₂ : All other metals not listed in row above (ppt, each) [21]	500	500	500	500	500	500	500	500	500	500	500	500	500	500
29% NH ₄ OH: all other metals not listed in row above (ppt, each) [21]	500	500	500	500	500	500	500	500	500	500	500	500	500	500
100% IPA: all other metals not listed in row above (ppt, each) [21]	500	500	500	500	500	500	500	500	500	500	500	500	500	500
IPA: High molecular weight organics (ppb)	500	500	500	500	500	500	500	500	500	500	500	500	500	500
100% IPA: Anions (ppb)	10	10	10	10	10	10	10	10	10	10	10	10	10	10
29% NH ₄ OH: Anions (ppb)	10	10	10	10	10	10	10	10	10	10	10	10	10	10
49% HF: Anions (ppb)	500	500	500	500	500	500	500	500	500	500	500	500	500	500
49% HF: Cl (ppb)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
96% H ₂ SO ₄ : Anions (ppb)	200	200	200	200	200	200	200	200	200	200	200	200	200	200
37% HCL: Anions (ppb)	300	300	300	300	300	300	300	300	300	300	300	300	300	300
30% H ₂ O ₂ : Anions (ppb)	10	10	10	10	10	10	10	10	10	10	10	10	10	10
30% H ₂ O ₂ : resin byproducts (ppb) e.g. total amines [41]	5	5	5	5	5	5	5	5	5	5	5	5	5	5
37% HCl: Ba, Cu, K, Pb, Li, Mn, Ni, Cu, Cr, Co, (ppt, each)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
96% H ₂ SO ₄ : Al, Ba, B, Ca, K, Pb, Li, Mg, Mn, Na, Sn, Ti, Zn, K, Ni, Cu, Cr, Co, (ppt, each)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
37% HCl: all other metals not listed in	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000

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row above (ppt, each) [20]														
96% H2SO4: all other metals not listed in row above (ppt, each) [20]	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
BE clean solvent: Critical ions (Cu, Au, Ag, Pt, Mo, Ru) (ppt each)	500	500	500	500	500	500	500	500	500	500	500	500	500	500
BE clean solvent: Other metal (ppt each)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
CMP slurries: scratching particles (/ml > key particle size) [9] [17]	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Post-CMP clean chemicals: particles >0.065 (/ml) [1] [9] [17]	< 10	< 10	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Post-CMP clean chemicals: elements TBD (ppt, each) [17]	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Plating chemicals: particles > critical size (/ml) [1] [9] [17]	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Bulk Gases (Contaminants, ppbv) [5]														
N2 (O2, H2, H2O, CO, CO2, THC) [34]	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
O2 (N2)	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
O2 (Ar)	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000
O2 (H2, H2O, CO, CO2, THC)	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Ar (N2, O2, H2, H2O, CO, CO2, THC) [34]	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
H2 (N2)	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
H2 (O2, H2O, CO, CO2, THC)	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
He (N2, O2, H2, H2O, CO, CO2, THC)	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
CO2 (CO, H2O, O2, THC)	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000
Lithography and Critical Metrology Purge Gases (ppbv)														
Critical clean dry air (H2O)	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000
Critical clean dry air (H2, CO)	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000
Critical clean dry air (organics (molecular weight > benzene) normalized to hexadecane equivalent)	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3
Critical clean dry air (total base as NH3)	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Critical clean dry air (NH3 (as NH3))	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Critical clean dry air (total acid including SO2 (as SO4))	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Critical clean dry air (SO4 (as SO4))	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03
Critical clean dry air (Each refractory compound (Organics containing S, P, Si)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Lithography nitrogen tool/maintenance purging gas supply (H2O, O2, CO2)	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500
Lithography nitrogen tool/maintenance purging gas supply	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000

(CO)														
Lithography nitrogen tool/maintenance purging gas supply (H2)	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000	<2000
Lithography nitrogen tool/maintenance purging gas supply (organics (molecular weight > benzene) normalized to hexadecane equivalent)	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3
Lithography nitrogen tool/maintenance purging gas supply (total base (as NH3))	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15
Lithography nitrogen tool/maintenance purging gas supply (total acid (as SO4) including SO2)	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025
Lithography nitrogen tool/maintenance purging gas supply (refractory compounds (organics containing S, P, Si, etc.) normalized to hexadecane equivalent)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Lithography helium tool/maintenance purging gas supply (H2O)	<3500	<3500	<3500	<3500	<3500	<3500	<3500	<3500	<3500	<3500	<3500	<3500	<3500	<3500
Lithography helium tool/maintenance purging gas supply (O2, CO2)	<4000	<4000	<4000	<4000	<4000	<4000	<4000	<4000	<4000	<4000	<4000	<4000	<4000	<4000
Lithography helium tool/maintenance purging gas supply (CO, H2)	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0	<1000 0
Lithography helium tool/maintenance purging gas supply (organics(molecular weight > benzene) normalized to hexadecane equivalent)	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3
Lithography helium tool/maintenance purging gas supply (total base (as NH3))	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15
Lithography helium tool/maintenance purging gas supply (total acid including SO2 (as SO4))	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025	< 0.025
Lithography helium tool/maintenance purging gas supply (refractory compounds (organics containing S, P, Si, etc.) normalized to hexadecane equivalent)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Number of particles > critical size (/M3) [1]	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Number of particles > 0.1 μm (/M3) [1]	0.40	0.29	0.20	0.14	0.10	0.07	0.05	0.036	0.025	0.018	0.013	0.009	0.009	0.009
Etchants (Corrosive, e.g., BCl3, Cl2, HBr)														
O2, H2O (ppbv)	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500
Critical specified metals/total metals	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0	<1/100 0

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(ppbw) [19]														
Etchants (Non-corrosive, e.g., C5F8, C4F8, C4F6, CH2F2, SF6)														
O2, H2O (ppbv)	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000
Etchants (e.g. Xe)														
O2, H2O (ppbv)	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000
ALD/CVD blanket / purge/ delivery gases														
Sweep and bubbler gases for ALD/CVD volatile chemical delivery e.g., N2 (O2, H2, H2O, CO, CO2, THC) (ppb) [34]	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
CVD/ALD Thin Film Process Fluids														
CVD/ALD Thin Film Process Fluids - High k Dielectrics														
High k Gate Dielectrics e.g., Al2O3 and LaAlO3														
High k Gate Dielectrics - TMA [75-24-1] (Assay)	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5
High k Gate Dielectrics - TMA (O2 ppm)	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
High k Gate Dielectrics - TMA Metals each element (ppb)	<150	<150	<150	<150	<150	<150	<150	<150	<150	<150	<150	<150	<150	<150
High k Gate Dielectrics - TMA (Silicon ppm)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
High k Gate Dielectrics - TMA (Hydrocarbons ppm)	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
High k Gate Dielectrics - La(FMD)3 (Lanthanum tris(N,N'-isopropylformamidinate) (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Gate Dielectrics - Hf oxides, silicates or aluminates														
High k Gate Dielectrics - Hf-HTB [2172-02-3] (assay)	99	99	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Gate Dielectrics - Hf-HfCl4 [13499-05-3] (assay)	99.9	99.9	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Gate Dielectrics - Si source - Metal Silicates														
Si source - Metal Silicates - 3DMAS [15112-89-7] (assay)	99.9	99.9	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Si source - Metal Silicates - 4DMAS [1624-01-7] (assay)	99.9	99.9	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Va High k Gate Dielectrics - MgO														
High k Gate Dielectrics - MgO-Mg(EtCp)2 [114460-02-5] (assay)	98	98	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd

High k Capacitor Dielectrics e.g., Al ₂ O ₃ and LaAlO ₃	NA	NA												
High k Capacitor Dielectrics - TMA [75-24-1] (see High k Gate Dielectrics - TMA above)														
High k Capacitor Dielectrics - TDEAA [32093-39-3] (assay)	99	99	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - La(thd) ₃ [14319-13-2] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - Ta ₂ O ₅	tbd	tbd												
High k Capacitor Dielectrics - Ta(OC ₂ H ₅) ₅ [6074-84-6] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - Hf oxides														
High k Capacitor Dielectrics -HfCl ₄ [13499-05-3] (assay)	Yes	Yes	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - HfCl ₄ (Zr -ppm)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - HfCl ₄ (Metals each element -ppb)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - HfCl ₄ (Hydrocarbons - ppm)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics -HfCl ₄ (Hydrolysis product Hf oxides -ppm)	Yes	Yes	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics Hf metal organics - TDEAH [19824-55-6] (assay % by NMR)	99	99	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics -TDEAH (Zr -ppm)	2000	2000	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics -TDEAH (Metals each element -ppb)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics -TDEAH (Hydrocarbons -% by NMR)	1	1	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics -TDEAH (Chloride ppm)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics -TDEAH (Hydrolysis product alkylamine -ppm)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics -Hf metal organics , TEMA [352535-01-4] (same as TDEAH)														
High k Capacitor Dielectrics - Zr metal organics - TEMA [175923-04-3] (assay % by NMR)	99	99	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - TEMA - (Hf ppm)	2000	2000	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd

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Dielectrics - TEMAZ (Metals each element ppb)															
High k Capacitor Dielectrics - TEMAZ (Hydrocarbons (% by NMR))	1	1	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - TEMAZ (Chloride ppm)	5	5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - TEMAZ (Hydrolysis product (alkylamine) ppm)	Yes	Yes	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - SrTiO3	99	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - Sr(DPM)2 (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - Ti(OiPA)4 [546-68-9] (assay)	150	150	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High k Capacitor Dielectrics - Ti(O)dpm)2 [152248-67-4] (assay)	<10	<10	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Spacers; misc. FEOL dielectric Films	<20	<20													
Spacer Dielectric - SiCN															
Spacer Dielectric - BTBAS [186598-40-3] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
CVD/ALD Thin Film Process Fluids - Low k Dielectrics															
Interconnect Dielectrics- Barrier / Etch Stops															
Barrier / Etch Stops - SiC															
Barrier / Etch Stops - DMDMOS [1112-39-6] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Barrier / Etch Stops - 3MS [993-07-7] (Assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Barrier / Etch Stops - 4MS [75-76-3] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Barrier / Etch Stops SiN / SiO2	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Barrier / Etch Stops SiN / SiO2 - SiH4 [7803-62-5] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Barrier / Etch Stops SiN / SiO2 SiCN	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Barrier / Etch Stops SiN / SiO2 - 4MS [75-76-3] (assay)	>99	>99													
Barrier / Etch Stops SiN / SiO2 - 3MS [993-07-7] (assay)	>99	>99	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Barrier / Etch Stops - SiCO															
Barrier / Etch Stops - SiCO - Alkylsilanes (e.g., Trimethylsilane [993-07-7], Tetramethylsilane [75-76-3], DMDMOS [1112-39-6], OMCTS [556-67-2]) [25] - ILD															
SiCO - Alkylsilanes (Metals except B,	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd

Au, Ag (ppb, each))														
SiCO - Alkylsilanes (B, Au, Ag (ppb, each))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
SiCO - Alkylsilanes (H2O (ppm))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
SiCO - Alkylsilanes (CO, CO2 (ppm))	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
SiCO - Alkylsilanes (Non-methane hydrocarbons C2-C4 (ppm))	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4
SiCO - Alkylsilanes (Nitrogen (ppm))	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
SiCO - Alkylsilanes (Ar+O2 (ppm))	<5	<5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
SiCO - Alkylsilanes (Chloride (ppm))	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
SiCO - Alkylsilanes - 3MS [993-07-7] (assay)	>99	>99	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
SiCO - Alkylsilanes - DEMS [2031-62-1] (assay)	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
SiCO - Alkylsilanes -OMCTS [556-67-2] (assay)	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
SiCO - Alkylsilanes - DMDMOS [1112-39-6] (assay)	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Interconnect Bulk Low k dielectrics	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Interconnect Bulk Low k dielectrics - FSG / FOSG	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
FSG / FOSG - SiF4 [7783-61-1] (assay)			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
FSG / FOSG - TEOS [78-10-4] (assay)	99.99	99.99	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
FSG / FOSG - SiH4 [7803-62-5] (assay)			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
FSG / FOSG - 3MS [993-07-7] (assay)	>99	>99	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Interconnect Bulk Low k dielectrics - OSG / SiCO (k = 3.0 to k = 2.7)														
OSG / SiCO - 3MS [993-07-7] (assay)	>99	>99												
OSG / SiCO - DEMS [2031-62-1] (assay)	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
OSG / SiCO - TMCTS [2370-88-9] (assay)	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
OSG / SiCO - DMDMOS [1112-39-6] (assay)	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
OSG / SiCO - OMCTS [556-67-2] (assay)	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Interconnect Ultra low k Porous OSG / SiCO (k < 2.7 to 2.2)														
Ultra low k Porous OSG / SiCO -DEMS [2031-62-1] (assay)	>99.5	>99.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Ultra low k Porous OSG / SiCO - DEMS (Organic Porogen (%))			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
CVD/ALD Thin Film Process Fluids - Metal Gate Electrodes														
Metal Gate														

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Electrodes - Titanium nitride/carbonitride														
Titanium nitride - TiCl4 - Purity based upon metals (ppbv total)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Metal Gate Electrodes - Ru/RuO2														
Metal Gate Electrodes - Ru/RuO2 - RuO4 [20427-56-9] (assay)	tbd	tbd												
CVD/ALD Thin Film Process Fluids - MIM capacitor Electrodes			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
MIM capacitor Electrodes - Ru / RuO2														
MIM capacitor Electrodes - Ru(EtCp)2 [32992-96-4] (assay)	tbd	tbd												
MIM capacitor Electrodes- TiN														
MIM capacitor Electrodes- TiN - TiCl4 [7550-45-0] (assay)	>99.7	>99.7	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
MIM capacitor Electrodes - TiCl4 (Metals Purity (ppbv total))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
MIM capacitor Electrodes - TaN			>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7
MIM capacitor Electrodes - TaN - PDMAT [19824-50-0]	tbd	tbd												
MIM capacitor Electrodes -TaN - TAIMATA [629654-53-1] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
MIM capacitor Electrodes - TaN - TBTEMT [511292-99-2] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
MIM capacitor Electrodes - WN	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
MIM capacitor Electrodes - WN - WF6 [7783-82-6] (assay)	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7
CVD/ALD Thin Film Process Fluids - Interconnect Conductive Films			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
conductive barriers- strike layers -Etch Stops- Caps - etc. (cmos and tsv's)														
conductive barriers - TaN - Tantalum Amides (e.g., PDMAT [19824-50-0], TBTDET [169896-41-7]; TAIMATA; TBTEMT)														
Tantalum Amides - (Critical specified metals/total metals (ppbw))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Tantalum Amides (O2, H2O (ppbv))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Tantalum Amides	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd

(Hydrocarbons (ppm))															
conductive barriers - Titanium Nitride Precursors - halides and Amides ; TiCl4; TDMAT; TEMAT; TDEAT; TiCp(X)3															
Titanium Nitride Precursors (Critical specified metals/total metals (ppbw))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Titanium Nitride Precursors (O2, H2O (ppbv))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Titanium Nitride Precursors Hydrocarbons (ppm)	<100	<100	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000
Titanium Nitride Precursors -	< 1000	< 1000													
TDMAT [3275-24-9] (assay % by NMR)			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
TDMAT - (Purity (based on metals analyzed (ppmv))			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
TDEAT [4419-47-0] (assay % by NMR)	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000
TiCl4 [7550-45-0] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
TiCl4 Purity based upon metals (ppbv total)	Yes	Yes	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
TEMAT [308103-54-0] (assay % by NMR)	< 10	< 10	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Tantalum Nitride Precursors - Tantalum Amides (e.g., PDMAT [19824-50-0], TBTDET [169896-41-7]; TAIMATA; TBTEMT)															
Tantalum Nitride Precursors - (Nb (ppm))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Tantalum Nitride Precursors - (Metals each element (ppb))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Tantalum Nitride Precursors - (Hydrocarbons (ppm))	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Tantalum Nitride Precursors - (Chloride (ppm))	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7	>99.7
Tantalum Nitride Precursors - (Hydrolysis product (alkylamine))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
PDMAT [19824-50-0] (assay % by NMR)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
TBTDET [169896-41-7] (assay % by NMR)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
TAIMATA [629654-53-1] (assay % by NMR)	<100	<100	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
TBTEMT [511292-99-2] (assay % by NMR)	<10	<10	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
conductive barriers - Ruthenium metal/ RuO2 - Ru carbonyls; Ru amidinates e.g.,															

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Ru(EtCp)2 [47, 48] [32992-96-4]; RuO4 [20427-56-9]														
Ru(EtCp)2 [32992-96-4] (assay)	NA	NA	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
RuO4 [20427-56-9] (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Bulk Metal Interconnects - vertical - horizontal wiring - tsv's	Yes	Yes	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Tungsten metal - Tungsten Hexafluoride (WF6) [7783-82-6] (assay)	99.9	99.9	99.9	99.9	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Tungsten Hexafluoride (Critical specified metals/total metals (ppbw)) [19]	<1/1000	<1/1000	<1/1000	<1/1000	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Tungsten Hexafluoride (O2 (ppbv))	<10	<10	<10	<10	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Copper metal - Cu(hfac)(tmvs) [139566-53-3] (assay)			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
CVD/ALD Thin Film Process Fluids - Semi-conducting Thin Films														
Epitaxial Si and Ge - including SiGe alloys														
Epitaxial Si and Ge - Disilane [1590-87-0] (assay)	99.999	99.999	99.999	99.999	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High Temperature Si Epitaxy - SiHCl3 [59] [10025-78-2] (assay)	99.95	99.95	99.95	99.95	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High Temperature Si Epitaxy - SiHCl3 (O2 (ppb))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High Temperature Si Epitaxy - SiHCl3 (H2O (ppb))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High Temperature Si Epitaxy - SiHCl3 (Hydrocarbons (ppb))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High Temperature Si Epitaxy - SiHCl3 (Inboard He Leak Rate (atm cc/sec))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High Temperature Si Epitaxy - SiHCl3 (Dopants B, Al, P, As (ppb))	<0,5	<0,5	<0,5	<0,5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High Temperature Si Epitaxy - SiHCl3 (Metals like Fe (ppb))	<1	<1	<1	<1	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High Temperature Si Epitaxy - SiHCl3 (Carbon (ppb))	<500	<500	<500	<500	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
High Temperature Si Epitaxy - SiH4 [7803-62-5] (assay)			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si and Ge - GeH4 [7782-65-2] (assay)			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si and Ge - GeH4 (Carbon Dioxide (ppmv))	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Epitaxial Si and Ge - GeH4 (Carbon Monoxide (ppmv))	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Epitaxial Si and Ge - GeH4 (Digermane (ppmv))	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100

Epitaxial Si and Ge - GeH4 (Nitrogen (ppmv))	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9	<10E-9
Epitaxial Si and Ge - GeH4 (Methane(ppmv))			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si and Ge - GeH4 (Oxygen + Argon (ppmv))			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si and Ge - GeH4 (Trigermane(ppmv))	<2	<2	<2	<2	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si and Ge - GeH4 (Water(ppmv))	<1	<1	<1	<1	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si and Ge - GeH4 (Chlorogermanes(ppmv))	<20	<20	<20	<20	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si and Ge - GeH4 (Germoxanes(ppmv))	<2	<2	<2	<2	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si and Ge - GeH4 (Hydrogen(ppmv))	<1	<1	<1	<1	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
CMOS Channel Materials														
Epitaxial Si Channel Replacement films	<0.5	<0.5	<0.5	<0.5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si Channel Replacement - GaAs / InGaAs	<1	<1	<1	<1	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
GaAs / InGaAs - Ga(CH3)3 (TMG) [1445-79-0] (assay)	<1	<1	<1	<1	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Ga(CH3)3 (TMG) (Metals each element(total ppb))	<5	<5	<5	<5	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
GaAs / InGaAs - In(CH3)3 (TMI) [3385-78-2] (assay)	<50	<50	<50	<50	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
GaAs / InGaAs - arsine (AsH3) [7784-42-1] (assay)			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si Channel Replacement - GaN														
Epitaxial Si Channel Replacement - GaN - TMG [1445-79-0] (assay)	99.999	99.999	99.999	99.999	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si Channel Replacement - GaN - NH3 [7664-41-7] (assay)	99.999 9	99.999 9	99.999 9	99.999 9	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
GaN - NH3 (Iron (ppbw))	<100	<100	<100	<100	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Epitaxial Si Channel Replacement - SiC			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Channel Replacement - SiC - SiH4 [7803-62-5] (see above)	99.999 9	99.999 9	99.999 9	99.999 9	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Channel Replacement - SiC - C3H8 (propane) [74-98-6] (assay)	99.999	99.999	99.999	99.999	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
SiC - C3H8 (propane) - (Total metals (ppbw))	<100	<100	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Channel Stress-Strain Management Films														
Strain Management Films - SiGe alloys														
Low Temperature Si/Ge Epitaxy														

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Low Temperature Si/Ge Epitaxy - Dichlorosilane (DCS), dilute B₂H₆, dilute PH₃, dilute monomethylsilane														
Low Temperature Si/Ge Epitaxy (O ₂ (ppb))	<500	<500	<500	<500	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Low Temperature Si/Ge Epitaxy (H ₂ O (ppb))	<200	<200	<200	<200	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Low Temperature Si/Ge Epitaxy (Hydrocarbons (ppb))	<1000	<1000	<1000	<1000	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Low Temperature Si/Ge Epitaxy - Inboard He Leak Rate (atm cc/sec)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Point of Use Purification														
<i>POUF - SiH₄, Si₂H₆, GeH₄, process and purge H₂, process and purge N₂</i>														
POUF - SiH ₄ , Si ₂ H ₆ , GeH ₄ (O ₂ (ppb))	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
POUF - SiH ₄ , Si ₂ H ₆ , GeH ₄ (H ₂ O (ppb))	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
POUF - SiH ₄ , Si ₂ H ₆ , GeH ₄ (Hydrocarbons (ppb))	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
POUF - SiH ₄ , Si ₂ H ₆ , GeH ₄ (Inboard He Leak Rate (atm cc/sec))	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10
<i>POUF - Deposition gases - GeH₄ [7782-65-2]</i>			No	No	No	No	No	No	No	No	No	No	No	No
POUF - GeH ₄ (O ₂ , H ₂ O (ppbv))	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
POUF - GeH ₄ (Other dopants (ppbv))	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Mixing tolerance for mixtures	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
GeCl ₄ [10038-98-9]	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10	<10E-10
GeH ₄ [7782-65-2]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SiH ₂ Cl ₂ [4109-96-0]			tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Si ₂ H ₆ [1590-87-0]	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500
Vic2 Si ₃ N ₄	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
SiH ₄ [7803-62-5]	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%	+/-1%
Si ₂ H ₆ [1590-87-0]	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Other available High purity volatile liquid precursors available for Electronic Thin film applications (General)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Deposition Gases CVD/PECVD/ ALD (General)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Deposition Gases CVD/PECVD/ ALD (General) (O ₂ , H ₂ O (ppbv))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Deposition Gases CVD/PECVD/ ALD (General) (Critical specified metals/total metals (ppbw)) [19]	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd

Deposition Gases CVD/PECVD/ ALD (General) (Dopants (ppbv))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Metal Dopants (e.g., FeCp2, MgCp2) (assay)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Amorphous Carbon (Double Patterning) e.g., propylene [9003-07-0] and acetylene [74-86-2]	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Amorphous Carbon (Double Patterning) (Other hydrocarbons (ppmv))	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Amorphous Carbon (Double Patterning) (Total metals (ppbw))	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000	< 1000
Deposition gases (e.g. NH3)														
Deposition gases (e.g. NH3) (O2, H2O (ppbv))	<500	<500	<500	<500	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Deposition gases (e.g. NH3) (Critical specified metals/total metals (ppbw)) [19]	<100	<100	<100	<100	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Deposition gases (e.g., N2O, NO)	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Deposition gases (e.g. NH3) (O2, H2O (ppbv))	<100	<100	<100	<100	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Deposition gases (e.g. NH3) (Critical specified metals/total metals (ppbw)) [19]	<200	<200	<200	<200	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Deposition gases - electrical dopants (e.g. AsH3, PH3, B2H6)														
electrical dopants (O2, H2 (ppb)) [36]	< 100	< 100	< 100	< 100	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Other dopants (ppbv)	<1	<1	<1	<1	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Other Dopants (Mixing tolerance for mixtures (relative variance))	+/- 1%	+/- 1%	+/- 1%	+/- 1%	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
Implant gases - AsH3, PH3, BF3														
Implant gases (O2, H2O (ppbv))	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500	< 500
Implant gases (Other dopants (ppbv))	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Implant gases (Mixing tolerance for F2 (relative variance))	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%	+/- 4%
Implant gases (Other constituents (ppbv))	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0	< 2500 0
Laser gases - Litho, (e.g. F2/Kr/Ne)														

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Laser Gases (O ₂ , H ₂ O (ppbv))	< 500	< 500	< 500	< 500	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
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Notes for Table YE3

[1] Critical particle size is based on ½ design rule. Killer particle sizes are based on the most demanding particle level. That has been determined to be ½ the DRAM ½ pitch. It's typically less than Logic. Again, because it's a 'roadmap' to the smallest required particle level, and not a specification, we don't include the required logic particle levels – we know they will be higher and bigger than DRAM.

[2] Airborne particle requirements are based on ISO 14644-1 at "at rest".[3]

[3] Ion/species indicated is basis for calculation. Exposure time is 60 minutes with starting surface concentration of zero. Basis for lithography projections is defined by lithography tool suppliers. Metals and organics scale as defined in the surface preparation roadmap for metallics and organics. Values listed in table are based on experience, however, all airborne molecular contaminants can be calculated as $S = E \cdot (N \cdot V / 4)$; where S is the arrival rate (molecules/second/cm²), E is the sticking coefficient (between 0 and 1), N is the concentration in air (molecules/cm³); and V is the average thermal velocity (cm/second). The following sticking coefficients have been proposed; $SO_4 = 1 \times 10^{-5}$, $NH_3 = 1 \times 10^{-6}$, $Cu = 2 \times 10^{-5}$. The sticking coefficients for organics vary greatly with molecular structure and are also dependent on surface termination.

[4] Includes P, B, As, Sb

[5] Contaminant targets apply up to POE (point-of-entry). POE is defined as the entry point to the equipment or subequipment, see also the text. Benchmark data has been collected both at Point of Delivery (POD) or Point of Entry (POE), which typically show only minor differences.

[6] Critical metals and ions may include: Al, As, Ba, Ca, Co, Cu, Cr, Fe, K, Li, Mg, Mn, Na, Ni, Pb, Sn, Ti, Zn. Three different case studies were reviewed where the levels of Ca, Fe, and Ni in the UPW resulted in levels of problem densities (atoms/sq cm) on the wafer. These were reduced to acceptable levels by reducing the level of these elements in the UPW to levels well below 10 ppt. In only one case does the data exist that showed success by obtaining values below 0.5 ppt. These results drive the 1.0 ~ 0.5 ppt values.

[7] Units on all contaminants in WECC Table are often given as ppb (or ppm or ppt, we use ppb here solely for demonstration purposes). The reader should be aware that these units of parts per billion (ppb) may be ppb by mass, volume, or molar ratios. Where not designated, the following guidelines apply: Chemicals and UPW are typically ppb by mass, while gases and clean room are typically ppb by volume. In the case of the fluid acting as an ideal gas, ppb by volume is equal to ppb molar. The notable exception to the above is metals in gases that are ppb by mass. In UPW, ppb is used based on mass of water. Since 1 liter of water equals ~1 kg, 1 ppb is equal to 1 µg/l.

Some parameters in the tables may be considered process variables rather than contaminants in the classical meaning. They are marked by an asterisk. The limits are sometimes fluent.

[8] Detection of metals at the levels indicated will be dependent on sampling time and flow rate. Sticking Coefficients vary widely for metals. It is generally believed that Cu has a sticking coefficient 10x of other metals, and therefore the guideline for Cu could be lower.

[9] Key particle size for scratching particles depends on mean particle size of slurry. Target level will be specific to slurry and wafer geometry sensitivity.

[10] The Dissolved Nitrogen range is solely for the physical process needs of megasonics cleaning. Processes without megasonics cleaning can ignore the line item. The concentration is process specific and needs to be determined by the end user. Factors to consider include UPW temperature, partial pressure in the gas phase and megasonic energy input at the tool. Other gases, such as oxygen and hydrogen, may be used with different optimum levels. Process enhancements through chemistry associated with the other gases or other chemicals are outside of the scope of this chapter. While a relatively wide range of dissolved nitrogen values may be acceptable based on other process variables it is important to note that tight control at the desired value is warranted.

DN2 spec is considered at POE, taking into account possibility that N2 control inside the tool.

[11] As of the current year's update the finest production available sensitivity liquid particle sensor for chemicals is 0.040 µm, although measurement technology is being developed at 0.020µm. Values obtained by these particle counters are not directly comparable to the roadmap values and need to be normalized to critical particle size values in the roadmap using the equation and methods of Footnote A above. Interim solution to higher sensitivity particle counter is to collect data over longer time period to provide greater precision in the data near the threshold sensitivity of the counter. Most benchmark data has been collected at Point of Delivery (POD) or Point of Entry (POE) and is the basis for parameters. This particle counting efficiency is not taken into account, which may vary with particle counter model, particle materials, chemical, etc.. It is based on actual data reported.

[12] SMC Organics: Single wafer shall be oxidized to make organic-free, then wafer shall be exposed for 24 hours and top side analyzed by TD-GC-MS with 400°C thermal desorption, and quantitation based on hexadecane external standard. TIC response factor per SEMI

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MF 1982-1103 (formerly ASTM 1982-99).[4] Limits determined by above method are a guideline for many organics. Note higher limits can be used for process wafers oxidized or cleaned prior to subsequent process step. Processes such as gate oxide formation, or polysilicon deposition, may be more sensitive to organics, especially high boilers such as DOP. Silicon nitride nucleation may also be more sensitive than above for some processes. Please note dopants requirement is covered in earlier section. Contamination levels are time based, and samples should be exposed for a weeks time for better sensitivity; ng/cm²/week. Total contamination level on reticles that cause problems also vary with energy exposure. These guidelines subject to change with new data currently being generated.

[13] SMC Dopants: Single wafer is first stripped with HF to yield dopant-free surface and than exposed for 24 hours. Topside of wafer is analyzed by methods known to give reliable recovery of boron. This is a guideline for dopants based on sampling in operating running fabs. Lower specifications may be required for key FEPs, especially for smaller geometries, lower thermal budgets, and for lightly-doped devices. If wafers are stripped with HF or BOE immediately prior to next thermal process, then steps may become less sensitive to surface molecular dopants, and higher limits apply. Note that BEPs tend to be orders of magnitude less sensitive to dopants than FEPs.

[14] SMC Metals: Single wafer known to meet the ITRS FEP spec of 1E10 atoms/cm², *from the Starting Materials table, is exposed to a clean environment for 24 hours. Subsequent analysis of top surface by VPD-ICP-MS or VPD-GFAA. Lower specifications may be required for key FEPs, especially for smaller geometries. If wafers are cleaned prior to the next thermal process, then air exposure during earlier steps may be less of an issue. Note that majority of environmental metallic contaminants are particles, not molecular. If total particles on wafers are kept in spec than majority of metals, most metals from the environment should be within specifications. Back-end processes (BEPs) tend to be less sensitive to metals that FEPs provided not particles. Specs of twice the incoming wafer specs are readily achievable and readily measurable in case of wafers exposed for 24 hours.*

[15] SMC General: A 24-hour exposure will accentuate the contamination per wafer as wafers are often exposed too much shorter times in actual processing. The above SMC (surface molecular contamination) limits are preliminary, and no single value applies to all process steps or types of organics, dopants or metals. The SMC limits can vary substantially from process to process, and local air purification or purges may be needed to control contaminant levels.

[16] Dissolved oxygen (DO) has an effect on pre-gate oxide cleaning and the etch rate of non H-passivated SiO₂ and copper structures. The level in the table is that of the most stringent. It is expected that slightly higher levels within the same order of magnitude would not have any significant effect on manufacturing processes. If the water for a specific processes need to remain at low oxygen concentrations lower levels of dissolved oxygen could provide somewhat larger process time windows before critical concentration levels are reached. It is known that some fabs consider DO a process variable and operate at DO levels 3 orders of magnitude higher than stated in the table. Corrosion rates as a function of DO are not a linear relationship for all materials, specifically copper etch rates are near a maximum at 300 ppb DO.

DO spec is considered at POE, taking into account possibility that N₂ blanketing may be provided at the tool level.

[17] Uncertain at this time what target levels might be set given the variety of chemistries used in the industry and unknown sensitivity of the wafer to particles or ionic contamination in the chemical. This parameter is identified as a potentially critical one that should be considered and work is ongoing to define the correct levels.

[18] Silica may occur in UPW in a form of reactive (dissolved) or colloidal silica. Colloidal silica is considered detrimental for the semiconductor manufacturing. However, the killer particle size of currently considered generations became so small, making it impracticable to expect that the colloidal silica might be measured as delta between total and reactive silica in UPW. Hence, colloidal silica is considered to be controlled as particles down to non-detectable (as silica) level. As a result only reactive silica may occur in UPW. For practice purposes either of the tests total or reactive silica can be used. However, measuring both total and reactive silica may be considered to confirm no presence of colloidal silica. Dissolved Silica is a potential cause for water spotting.

When boron is controlled below or near limits of boron detection the level of dissolved silica is usually bellow the limits of detection as well. The silica specification is considered at POC (point of connection) based on the industry experience - no water marks were reported at the specified level. It is expected that the wafer will leach silica, adding silica level on the top of UPW level.

[19] The list of critical metals (e.g., Al, Ca, Cu, Fe, Mg, Ni, K, Si, Na) varies from process to process depending on the impact on electrical parameters such as gate oxide integrity or minority carrier lifetime as well as mobility of the metal in the substrate. The metals listed in note [G] for liquid process chemicals are of concern but the issues around metals in specialty gases are primarily around the potential for corrosion to add metal particles to the gas flow (e.g., Fe, Ni Co, P). The potential for volatile species containing metals must be considered for each specialty gas but are generally not present in the bulk gases.

[20] The following is a complete list of metal ions of concern in certain liquid chemicals: Ag, Al, As, Au, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Pd, Pt, Ru, Sb, Sn, Sr, Ti, V, W, Zn.

[21] Elements listed that are not in parentheses may cause high or some risk to device quality and may often be present in process chemicals. Elements listed that are in parentheses may cause high risk to device quality but are not typically present in process chemicals.

[22] TOC on-line measurement remains the reference detection method for the presence of total organics in UPW. Users of this roadmap are encouraged to speciate organics in their UPW. For the practical purposes, the on-line TOC measurement may be considered as critical organics, unless non-critical fraction is determined. Less than 1ppb of Total Organic Carbon was proven successful for immersion lithography operation, concerned about lens hazing.

Total Organic Carbon in UPW is defined as equivalent amount of CO₂ produced from UV oxidation at 185nm wavelength inside of the UV reactor of a TOC monitoring device. Currently used online, TOC analyzers are non-specific in their measurement of organic contaminants. Some organics are expected to have higher impact to the semiconductor manufacturing than others, hence TOC specification has been replaced with critical and non-critical organics for all applications, except for immersion photolithography. Critical Organics are those with the highest boiling point. Organics with high boiling points could deposit on the wafer surface in a high temperature furnace and result in the formation of silicon carbide. This is considered a fatal defect at levels of 1.0E+12 atoms per cm² as C. The boiling point of organic compounds is used to categorize them as a "critical". At this time, any organic compound with a boiling point higher than 200°C is considered critical. Based on past experience acceptable concentration of total critical organic compounds is <1.0ppb (as measured by on-line instrumentation). Non critical organics is proposed to be as high as 3.0 ppb. Modeling and experimental analysis are in progress to validate correlations of critical organic compounds to device defects. The end user may want to consider POU solutions for immersion litho if 1 ppb water quality is chosen to be controlled for the immersion lithography tools, independently of the type of the organics comprising TOC. The color in the ITRS table is provided to indicate the need of metrology development for online measurement of critical organics, as well additional work needed to better define the critical organics via FMEA. The organics specification is defined at the POE (Point of Entry) to the manufacturing tools, assuming that control of the organics level is provided outside of the tools, whereas the manufacturing process technology takes into account contribution by the tool materials and chemistry used.

[23] The photolithography AMC guidelines are for tools with ArF lasers only, and are based on inputs from the Litho TWG. The critical metrology guidelines are from the metrology TWG. All photolithography tools and some metrology equipments have chemical filters on the makeup air to the internals of the tools. These filters have a finite lifetime, which is dependent on the contaminant loading. Providing a chemically cleaner environment will extend the life of these filters.

[24] Other critical ions may include inorganic ions such as Fluoride, Chloride, Nitrate, Nitrite, and Bromide, Sulfate as well as ammonium. However no reference was currently found that these ions in typical concentrations found in ultrapure water up to 50 ppt have any impact on the process. Phosphate specification level was defined at 20 ppt based on FMEA analysis. Also for organic anions such as acetate, formate, propionate, citrate, and oxalate no harmful levels have been established up to now.

The ions specification is considered at POP (point of process) due to assumption that both UPW system as well as POU filters may be used to control metals, while tool environment may contribute metal contamination. Ammonium, sulfate, and nitrite can be contributed by air.

[25] The variety of CVD and ALD precursors is continuously increasing as well as their applications. The contaminant types and levels vary widely due to the different chemical behavior. An overview about typical precursors is therefore given in attachment Precursor table.

[26.1] The maximum allowed particle concentration in UPW has been updated based on the following assumptions and considerations:
 A. The maximum concentration of particles in UPW is a function of the allowed defect level on the wafer as defined in the FEP Surface preparation table and particle deposition from UPW to the wafer surface. The concentration per wafer will remain constant and will only change with the wafer size (300 mm to 450 mm). The reference point will be the critical particle size. The relationship between acceptable particle concentrations on the wafer and that in UPW is based on experimental data and theoretical modeling. The user of this part of the table is encouraged to refer to the supplemental materials for specific details of the calculations.
 B. The definition of the "killing" particle size uses the roadmap's definition of DRAM ½ Pitch (nm). Significant metrology issues for particles at the critical size still exist. Given the fact that the metrology gap is growing and has not been addressed for last several years, the risk management for particle control is being shifted towards the effective particle filtration and reduction of the particle challenge to the final filters. This work together with a SEMI task force produced a guide ([5] SEMI C079) for filter performance validation, as a method to control the particles on the wafer surface and mitigate the risk of particle contamination impacting yield. Similar task force has developed a test method for evaluation of the cleanliness of the virgin ion exchange resin. This document can be found in supplemental materials [6].

[26.2] Colloidal silica was previously added to emphasize higher criticality of colloidal silica particles in UPW, than the currently measured reactive and total Si in water. Existing UPW metrology is not sensitive enough to allow the detection of silica particles at the specified size as a chemical. silica particles are believed to have the ability to adsorb metals and act as a transport mechanism to potentially deposit metals on the surface of a wafer. Such metal deposition could seriously impact yield. There is no metrology that can effectively detect colloidal silica directly. And therefore, the colloidal silica specification was merged with the particles.

[26.3] An additional particle requirement has been specified for EUV mask production, which requires even tighter particle control. Critical particle size remains equal to the DRAM ½ Pitch (nm). However the allowed concentration is an order of magnitude lower than that specified for high volume manufacturing facilities (refer to supplemental information for additional details).

[26.4] All particles are considered equally critical independently of their material of construction and their properties.

The particles specification is considered at POP (point of process) due to assumption that both UPW system as well as tool environment have to control particles, taking into account capabilities of both UPW system (including POU filters) and the tool environment contribution. However, for the practical purposes, the assumption is that most particles will be contributed by the tool, thus requiring even higher UPW quality targets at POE. Out of 12 particles per wafer (currently allowed by FEP), all 12 can be contributed by the tool (inlet valve and wafer environment). This means that UPW should contribute < 1 particle per wafer at POE.

[27] It needs to be considered that the total H₂O₂ anion concentration will impact the life time of the solution. Also the fluoride in the ppm range of the total chemical mixture can etch the wafer.

[28] Concentrations higher than 100 ppb could cause corrosion especially in back end of line processes.

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[29] The ultrapure water parameters provided in this table are applicable for the most critical process unless otherwise identified by additional footnotes. Further information can be found in the Supplementary tables

[30] Typical Organic Acids found in cleanroom environments that may be of concern include Acetate, Citrate, Formate, Glycolate, Lactate, Oxalate, and Propionate. Others may also be of concern. These acids can be a significant load on acid removal filters.

[31] Ideally, continuous monitoring using online instrumentation would be preferred when practical since this can give both long term averages and catch excursions. When online monitoring is not available, an average grab sample for at least 4 hours, and not more than 24 hours is recommended, to get an average, increase sensitivity of the analysis, and avoid short term transient effects

[32] Other corrosive species include contaminants such as chlorine. Humidity is also of major concern, as it exacerbates corrosion. The humidity should be kept as low as possible in corrosive environments.

[33] Calculations for expressing ng/L into ppt are: $[(\text{ng}/(\text{L of Air})) * (24.4 \text{ L of Air}) / \text{mol Air} / \text{MW}(\text{ng}/\text{nmol})) * 1000 \text{ picomol}/\text{nmol}] = \text{picomol}/\text{mol of Air} = \text{ppt molar and/or ppt volume.}$

[34] For certain processes such as sputtering POE purifiers may be required for N2 and Ar

[35] CO2 here is assumed to be used for wet cleaning and other equipment, not for super critical CO2 applications or dry etching.

[36] Epi – need to purify @ 45 nm; currently must add purifiers from B2H6/Germane/PH3/AsH3 – need 100 ppb

[37] The variation is defined at one location over time in at rest conditions. As reference point for the POE a location is chosen 0.3 m below the ceiling panels. Common sense requires that sensitive equipment are not installed heat sources within the cleanroom, since they may impact the temperature control between the reference point and the actual inlet to the mini-environment/tool filter.

[38] This temperature stability requirement is for immersion photolithography tools, using UPW as an immersion fluid, and based upon utility requirements projected by some tool manufacturers in 2005. It represents the maximum rate of change and stability of the temperature of the cold UPW supplied to the tool in order for the tool to maintain process required temperature stability.

[39] Values based on FMEA Risk Priority Number of 625. Users of the Table are strongly encouraged to review the FMEA and adjust as necessary for local UPW and Wafer monitoring frequency. *Metals are considered to be particularly important for CMOS sensors.*

The metal specification is considered at POP (point of process) due to assumption that both UPW system as well as POU filters may be used to control metals, while tool environment may contribute metal contamination.

[40] Value of 100 pptv refractory compounds is not to be seen as an absolute limit but a recommended value derived from total dose considerations. Based on experience bottom lens deterioration from refractories is prevented for 7-10 years if an annual integral dose of $8.8\text{E}+5$ ppth of refractories is not exceeded. This calculates back to an average permanent sum concentration of 100 pptv. Actual concentrations can vary in a bandwidth of factor 3–5 around this value.

[41] The resin by-products are only a small part of the organics in H2O2, but have shown the most serious effects on the wafer. The organics leached out from the resins are different depending on the type of resin, but have shown a much higher sticking potential than the other solvents in the H2O2. Total amines are mentioned here as an example only. Measurement of these organics is possible, e.g. by ion chromatography or liquid chromatography with mass spectrometer, but there a variety of problems, such as the sample preparation since these compounds can be very volatile/sensitive.

[42] Hydrogen peroxide (H2O2) was confirmed to be produced by UV (ultraviolet) lamps in the polish loop at the levels of up to 30 ppb, the level exceeding dissolved oxygen, which is also considered to be an oxidant. The effect of specific level of H2O2 to the wafer has not been validated yet. At this point H2O2 parameter has been added to the roadmap to indicate risks and possible need to reduce its level. Further research is needed to confirm UPW spec levels. H2O2 control is considered at POD (point of distribution) based on the assumption that no H2O2 production is expected downstream that point.

[43] More than one IDM regards the combination of 0.1 ppb limit value and the refractory compounds definition as not supported by own experience on lens integrity; General opinion is that light boiling perfluorated compounds (normally from chiller thermofluids) (e.g. Galden LT) do not have lens effects due to their lens sticking probability; A severeness rating is requested stating that Silanol and Siloxane compounds are of high importance in their contribution, S- and P- compounds following and of least importance perhalogenated compounds

[44] There is an opinion that the limit value of 0.5 ppbv total inorganic acids is too strict; Experience exists that 2 ppbv would be an acceptable limit value maintaining good yield/no or low defect conditions

- [1] Cooper, D. W., "Comparing Three Environmental Particle Size Distributions," Journal of the IES, Jan/Feb 1001, 21–24
- [2] Pui, D. Y. H. and Liu, B.Y.H., "Advances in Instrumentation for Atmospheric Aerosol Measurement," TSI Journal of Particle Instrumentation, Vol 4. (2) Jul-Dec 1989, 3–2.
- [3] ISO 14644-1 Cleanrooms and Associated Controlled Environments-Part 1: Classification of Air Cleanliness.
- [4] SEMI MF1982-1103 (previously ASTM F 1982-99e1), Standard Test Methods for Analyzing Organic Contaminants on Silicon Wafer Surfaces by Thermal Desorption Gas Chromatography, SEMI.
- [5] SEMI C79-0113 GUIDE TO EVALUATE THE EFFICACY OF SUB-15 nm FILTERS USED IN ULTRAPURE WATER (UPW) DISTRIBUTION SYSTEMS. www.semi.org
- [6] SEMI DRAFT: Document 5621A
NEW STANDARD: GUIDE FOR DETERMINING THE QUALITY OF ION EXCHANGE RESIN USED IN POLISH APPLICATIONS OF ULTRAPURE WATER SYSTEM

End of Notes for Table YE3

Wafer environment control—The wafer 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)—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. Only in some highly congested areas, makeup air is a significant yet temporarily important source for AMC. Oxygen and water vapor as well as low concentration atmospheric contaminants (e.g., CO, O₃) can also be considered as part of the AMC burden. Acid vapors in the air have been linked to corrosion, as well as with the release of boron from HEPA filters. The impact of amines on deep ultraviolet (DUV) photoresists are well known examples of AMC affecting wafer processing. Hydrocarbon films of only a few monolayers may lead to loss of process control, especially for front-end processes. Other areas of concerns for AMC are IPA from semiconductor cleaning equipment and corrosion when Cu is exposed. The impact of AMC on wafer processing can only be expected to become more deleterious. This is not only driven by device dimensions decreasing but also by the introduction of new chemistry and recipes for future technical nodes that exhibit new defect schemes. Besides AMC creating defects to the wafer surface or bulk material Yield Enhancement group engages on defects or shortfalls in productivity that originate from the impact of AMC to production tools as reticles, metrology or exposure tools. AMC is in many cases - as for excursions - a highly dynamic phenomenon. AMC control deals mainly with prevention of AMC release for which a tight source control is mandatory. There is clearly a need for better AMC monitoring instrumentation in the clean room to measure

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AMC at the part per trillion level (by volume) in real time. Surface acoustic wave (SAW) devices and atmospheric pressure ionized mass spectroscopy (APIMS) have been used to measure low level AMC, but a larger variety of on-line methods and instrumentation is needed and expected to be available in the future, see also the link for *AMC monitoring programs*. Table YE4 and YE4a provide more detail for AMC monitoring and on-line methods.

Table YE4 AMC Monitoring Methods

Year of Production	2012	Measurement methods																			
Flash ½ Pitch (nm) (un-contacted Poly)(f)	25	Online Monitoring		Wet or Dry Impinger Sampling [11]					Passive/Diffusive Sampling (Beaker/Dry trap) [12]				TD GC-MS				Surface analysis	L D L			
	DRAM ½ Pitch (nm) (contacted)	36	Method	LDL	Method	LDL (pptV)	Sample volume (L)	Sample flow rate (LP M)	Sample frequency	Method	LDL	Sample duration (d)	Sample frequency	Method challenges	LDL (pptV)	Volume (L)	Sample flow rate (mL/min)		Sample frequency	Method	
MPU/ASIC Metal 1 (M1) ½ Pitch (nm)	32	Lithography: Point of entry (POE) to exposure tool [23]																			
MPU Printed Gate Length (nm) ††	31	Limits from YE3 table																			
MPU Physical Gate Length (nm)	22	Wafer Environment Control such as Cleanroom, SMIF POD, FOUUP, etc....not necessarily the cleanroom itself but wafer environment.																			
Critical particle size (nm) [1]	22.5	ISO CL1																			
Number of particles (m ³) [1] [2]	ISO CL1																				
Total Inorganic Acids	5,000	PWPD -IC ₁ [2]	10	IC-Conductivity [13,14]	10-100	1500-200	1-5	Every 2 months	IC-Conductivity [13,14,16]	100	7-90	quarterly									
		CRDS [3] †	100																		
		UV-F [4] †	500																		
		IMS [1]	1,000																		
Total Organic Acids [30]	2,000	PWPD -IC ₁ [2]	30	IC-Conductivity [13,14]	10-100	1500-200	1-5	Every 2 months	IC-Conductivity [13,14,16]	100	7-90	quarterly	Use special GC column	100	20 to 40	50 to 200	Every 2 months				
		PTR-MS ₃ [5]	200																		
Total Bases	20,000	PWPD -IC ₁ [2]	10	IC-Conductivity [13,14,15]	10-100	1500-200	1-5	Every 2 months	IC-Conductivity [13,14,15,16]	100	7-90	quarterly	For organic amines only (not total bases). Cut at C28.	100	20 to 40	50 to 200	t.b.d				
		PAS [6] *	20																		
		IMS [1]	1,000																		
		CRDS [3] *	4,000																		
PGMEA, Ethyl Lactate	5,000	PTR-MS ₃ [5]	800										None	100	20 to 40	50 to 200	t.b.d				
		IMS [1]	1,000																		
		PID [8]	1,000																		
Volatile Organics (w/ GCMS retention times ≥ benzene, calibrated to hexadecane) [31]	26,000	PID [8]	1000										Cut at C28	100	20 to 40	50 to 200	t.b.d				
Refractory compounds (organics containing for example S, P, Si)	100	PTR-MS ₃ [5]	50										Breakthrough to be studied for low boiling point S or Si compounds. Cut at C28.	100	20 to 40	50 to 200	t.b.d				
Lithography: Point of entry (POE) to track & inspection tools; temporary reticle																					

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pod storage																	
<u>Total Inorganic Acids</u>	2,000	PWPD -IC [2]	10	IC-Conductivity [13,14]	100	200-500	1-5	Every 6 months	IC-Conductivity [13,14]	100	7-90	quarterly					
		CRDS [3]	100														
		UV-F [4]	500														
		IMS [1]	1,000														
<u>Total Organic Acids [30]</u>	2,000	PWPD -IC [2]	30	IC-Conductivity [13,14]	100	200-500	1-5	Every 6 months	IC-Conductivity [13,14]	100	7-90	quarterly	Use special GC column	100	20 to 40	50 to 200	2x annual
		PTR-MS [5]	200														
<u>Total Bases</u>	2,000	PWPD -IC [2]	10	IC-Conductivity [13,14, 15]	100	200-500	1-5	Every 6 months	IC-Conductivity [13,14, 15]	100	7-90	quarterly					
		PAS [6]	20														
		IMS [1]	1,000														
<u>PGMEA, Ethyl Lactate</u>	5,000	PTR-MS [5]	800										None	100	20 to 40	50 to 200	t.b.d
		IMS [1]	1,000														
		PID [8]	1,000														
<u>Condensable organics (definition to SEMI F21-1102, bp 150 °C)</u>	1,000	PTR-MS [5]	50										Cut at C28	100	20 to 40	50 to 200	t.b.d
<u>Refractory compounds (organics containing for example S, P, Si)</u>	tbd	PTR-MS [5]	50										Breakthrough to be studied for low boiling point S or Si compounds. Cut at C28.	100	20 to 40	50 to 200	t.b.d
		L-IMS [9]	800														
		PID [8]	1,000														
Reticle Storage (inside stocker, inside pod, inside exposure tool library, inside inspection tool)																	
<u>Total Inorganic Acids</u>	<200	PWPD -IC [2]	10	IC-Conductivity [13,14]	10	1500-200	1-5	Every 6 months	IC-Conductivity [13,14]	100	7-90	quarterly					
		SRI-MS [7]	50														
		CRDS [3]	100														
<u>Total Organic Acids [30]</u>	<200	PWPD -IC [2]	30	IC-Conductivity [13,14]	10	1500-200	1-5	Every 6 months	IC-Conductivity [13,14]	100	7-90	quarterly	Use special GC column	100	20 to 40	50 to 200	2x annual
		PTR-MS [5]	200														
<u>Total Bases</u>	<200	PWPD -IC [2]	30	IC-Conductivity [13,14, 15]	10	1500-200	1-5	Every 6 months	IC-Conductivity [13,14, 15]	100	7-90	quarterly					
		PAS [6]	20														
<u>Condensable organics (definition to SEMI F21-1102, bp 150 °C)</u>	≤ 100	PTR-MS [5]	50										Cut at C28. Does not apply to inside POD sampling	100	20 to 40	50 to 200	t.b.d
<u>Refractory Compounds</u>	tbd	PTR-MS [5]	50										Breakthrough to be studied for low boiling point S or Si compounds. Cut at C28.	100	20 to 40	50 to 200	t.b.d
		L-IMS [9]	800														
Gate/Furnace area wafer environment (cleanroom FOUNDRY ambient/tool ambient)																	

Total metals [8] (E+10 atoms/cm2/week)	10																	Witness wafer + VPD ICP-MS [17] or TXRF [18] (but not for light elements Li, Na, Al & Mg) or equivalent. SEMI E45-1101.	10E+09 atoms/cm2
Dopants [4] (E+10 atoms/cm2/week; front end of line only)	10	PTR-MS [5]	50															Witness wafer + DSE ICP-MS [19] (TOF-SIMS [20] also or equivalent). SEMI E45-1101.	10E+09 atoms/cm2
Volatile Organics (w/ GCMS retention times ≥ benzene, calibrated to hexadecane) [31]	20000	PID [8]	1000							Cut at C28	100	20 to 40	50 to 200	t.b.d					
Gate/Furnace area wafer environment (FOUP inside)																			
Total metals [8] (E+10 atoms/cm2/day)	0.5																	Witness wafer + VPD ICP-MS [17] or TXRF [18] (but not for light elements Li, Na, Al & Mg) or equivalent. SEMI E45-1101.	10E+09 atoms/cm2
Dopants [4] (E+10 front end of line only)	0.5	PTR-MS [5]	50															Witness wafer + DSE ICP-MS [19] (TOF-SIMS [20] also or equivalent). SEMI E45-1101.	10E+09 atoms/cm2
Volatile Organics (w/ GCMS retention times ≥ benzene, calibrated to hexadecane) [31]	tbd									Cut at C28. Be aware that the FOUP is not tight and will be replenished with gases from outside the FOUP. Make sure the surrounding environment is clean	100	10 to 20 but always identical volumes, temperature and background	50 to 200	t.b.d					

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<u>Total bases</u>	<u>tbd</u>	PWPD -IC [2] 200 ^[23]	200	IC-Conductivity [13, 14, 15]	100	200-500	1-5	as needed	IC-Conductivity [13, 14, 15]	100	7-90	as needed	Cut at C28. Be aware that the FOUP is not tight and will be replenished with gases from outside the FOUP. Make sure the surrounding environment is clean enough.	100	10 to 20 but always identical volumes, temperature and background	50 to 200	t.b.d
		PAS [6]*	20														
		IMS [1]	1,000														
		CRDS [3]*	4,000														
<u>Total other corrosive species</u> [32]	<u>tbd</u>	IMS [1]	1,000	IC-Conductivity [13, 14]	100/1000	200-500	1-5	as needed	IC-Conductivity [13, 14]	100	7-90	as needed					
<u>H2S</u>	<u>tbd</u>	UV-F [4] [†]	500														
		IMS [1]	1,000														
<u>Total sulphur compounds</u>	<u>5000</u>	UV-F [4] [†]	500														
		IMS [1]	1,000														
		PTR-MS [5]	1000														
Exposed Aluminum Wafer Environment (FOUP inside)																	
<u>Total Inorganic Acids</u>	<u>tbd</u>	PWPD -IC [2] 200 ^[23]	200	IC-Conductivity [13, 14]	100	200-500	1-5	as needed	IC-Conductivity [13, 14]	100	7-90	as needed					
		CRDS [3] [†]	100														
		UV-F [4] [†]	500														
		IMS [1]	1,000														
<u>HCl</u>	<u>100</u>	PWPD -IC [2] 200 ^[23]	200	IC-Conductivity [13, 14]	100	200-500	1-5	as needed	IC-Conductivity [13, 14]	100	7-90	as needed					
<u>HF</u>	<u>200</u>	PWPD -IC [2] 200 ^[23]	200	IC-Conductivity [13, 14]	100	200-500	1-5	as needed	IC-Conductivity [13, 14]	100	7-90	as needed					
		CRDS [3] [†]	100														
<u>HBr</u>	<u>tbd</u>	IMS [1]	1,000	IC-Conductivity [13, 14]	100	200-500	1-5	as needed	IC-Conductivity [13, 14]	100	7-90	as needed					
<u>HNOx</u>	<u>tbd</u>	PWPD -IC [2] 200 ^[23]	200	IC-Conductivity [13, 14]	100	200-500	1-5	as needed	IC-Conductivity [13, 14]	100	7-90	as needed					
		CLD [10]	200														
<u>Total Organic Acids</u> [30]	<u>tbd</u>	PWPD -IC [2] 400 ^[23]	400	IC-Conductivity [13, 14]	100	200-500	1-5	as needed	IC-Conductivity [13, 14]	100	7-90	as needed	Use special GC column	100	10 to 20 but always identical volumes, temperature and background	50 to 200	as needed
		PTR-MS [5]	200														
<u>Total other corrosive species</u> [32]	<u>1000</u>	IMS [1]	1,000	IC-Conductivity [13, 14]	100/1000	200-500	1-5	as needed	IC-Conductivity [13, 14]	100	7-90	as needed					

Methods and instruments are known and are being optimized

Methods and instruments are known and in preparation for production

Methods and instruments are in beta tool status under qualification



Footnotes from first row : Please refer to YE3 table footnotes.

[23] note amendment: entry to scanner has two applications: supply gas with 10 ppt LDL and filtered ambient air with 100 ppt LDL.

Footnotes

- [1] IMS Ion Mobility Spectrometry; for method key features and capabilities please refer to the methods overview table (YE 4a)
- [2] PWPD-IC Parallel Wet Plate Denuder Ion Chromatography; for method key features and capabilities please refer to the methods overview table (YE 4a)
- [3] CRDS Cavity Ring Down Spectroscopy; for method key features and capabilities please refer to the methods overview table (YE 4a)
- [4] UV-F UV Fluorescence; for method key features and capabilities please refer to the methods overview table (YE 4a)
- [5] PTR-MS Proton Transfer Mass Spectrometry; for method key features and capabilities please refer to the methods overview table (YE 4a)
- [6] PAS Photoacoustic Spectrometry; for method key features and capabilities please refer to the methods overview table (YE 4a)
- [7] SRI-MS Switchable Reactive Ion MS (matrix nitrogen or inerts); for method key features and capabilities please refer to the methods overview table (YE 4a)
- [8] PID Photoionization Detektor; for method key features and capabilities please refer to the methods overview table (YE 4a)
- [9] L-IMS Laser Induced Ion Mobility Spectrometry; for method key features and capabilities please refer to the methods overview table (YE 4a)
- [10] CLD Chemiluminescence Detection of NO_y compounds, for method key features and capabilities please refer to the methods overview table (YE 4a)
- * Method is capable to detect and quantify individual compounds. Sum values are therefore the results of summing up individual concentrations
- ** LDL calculated from LDL of unrestricted volume & sampling time (clean room) to restricted volume & sampling time (FOUP)
- [11] Impinger sampling for FOUP and other micro-environments is only applicable for continuous purge outgas testing, not for static volume testing, due to the limited volume of the device.
- [12] Due to its long sampling time, passive sampling (formerly beaker sampling) is recommended only for long-term averaging of AMC concentrations.
- [13] Ion Chromatography Mass Spectrometry (IC/MS) may be used to identify unknown species
- [14] Capillary electrophoresis mass spectrometry (CE/MS) may be used with probable higher detection limits
- [15] Liquid chromatography mass spectrometry (LC/MS) may be used for organic bases
- [16] Open beakers are not suitable for compressed gas analysis. Dry passive samplers would work.
- [17] VPD ICP-MS: Vapor phase deposition inductively coupled plasma mass spectrometry
- [18] TXRF: Total reflectance X ray spectroscopy
- [19] DSE ICP-MS: Drop scan extraction inductively coupled plasma mass spectrometry
- [20] TOF-SIMS: Time of flight secondary ion mass spectrometry

Temperature and humidity specifications have been added to Table YE3 this year for the most critical applications, *e.g.*, lithography for several reasons.

- 1) The strictest requirements are driven by the lithography process, which is protected by an environmental chamber. The specifications in the Table YE3 reflect the inlet condition to each individual environmental chamber. Here especially, the maximum variation over time is important, which the environmental chamber must be able to compensate. At the POP lower specifications down to $\pm 0.03^\circ \text{K}$ are maintained.
- 2) But also in the coater/developer track temperature and humidity specifications must be guaranteed to maintain stable conditions for the resist.
- 3) The temperature variation is also important for the stepper itself, since minor temperature variations can result due to different thermal extension coefficients in misalignments between the stepper foundation/wafer stage and the lens column. Steppers need up to a week to stabilize after a temperature change.
- 4) Another critical requirement is driven by metrology equipment which depend either on laser beams (the air density depend on temperature and humidity) and by measurements where misalignments are important.

The temperature and humidity stability over different locations within critical areas is less important. Also in other areas temperature and humidity variations shall be controlled to less strict limits since it may have an impact on the surface (native oxide formation) or alignments. Some companies choose not to have different specifications for critical and non-critical areas to allow flexibility in the cleanroom use as well as simplify the temperature and humidity control and the associated segregation.

These specifications are variational specifications and set points can be chosen in a wide range. A recent benchmarking study between fabs has shown values between 19.5 and 24°C for temperature and values between 35% and 48% for the relative humidity. There are different drivers for establishing environmental conditions. The temperature set point is normally chosen based on comfort level and climatic conditions and the resulting energy consumption. The set point for relative humidity takes into consideration higher electrostatic charges at lower humidity and higher corrosion/native oxide formation at higher relative humidity. Capacity of AMC filters also depends on the humidity.

Another process area with temperature/humidity control as well as AMC control requirements is the location of the lithography excimer lasers, if they are installed in the subfab and not in the main cleanroom.

2.1.1. TABLE YE3 STRUCTURAL CHANGES FOR 2015

The revision of Table YE3 is taking into account the immediate wafer and masks environment and enclosures (FOUPs, reticle Pods). The revision aligns the table structure and content with actual manufacturing concepts involving clean room control, high purity storage environments as (bare) wafer and mask stockers and enclosures. Each process segment listed is split into information that is referring to the clean room ambient conditions and limits that are referring to the interior environment and atmosphere of FOUPs, reticle Pods or bare material storage environment. Clean room ambient conditions are regarded as POE conditions to critical process steps that may involve further tool related measures of AMC protection and reduction, yet require controlled entry conditions to achieve proper process control. FOUP and reticle Pods interior limits are not only influenced by clean room environmental contamination but are depending heavily on remaining active material outgassing or re-evaporation of AMC attached to the containment walls. Other structure changes are as follows:

- For reasons of transparency and comparability process limits for clean room environment and containments (FOUPs and reticle Pods) are posted side-by-side per process.

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- The revision of AMC limits in Table YE3 performed in 2011 has been based on a structured investigation and inquiry process that involved front-end manufacturing companies, institutes and academia, and included their published information on defects and yield.
- The deduced tabulated recommendations for AMC limits consider integrated concepts of clean room limits and wafer/reticle environment limits at actual standard sit times or operation and service times for materials and tools that are regarded as acceptable under yield requirements and factory integration processes.

Example of Tabulated Values in Table YE3:

Gate/Furnace Area Wafer Environment (Cleanroom FOUP Ambient/Tool Ambient)	
Total Metals [A] (E+10)	< 10 atm/cm ² /week
Dopants [B] (E+10, front end of line only)	< 10 atm/cm ² /week
Volatile Organics (w/ CGMS retention times ≥ benzene, calibrated to hexadecane) [C]	20,000
Gate/Furnace Area Wafer Environment (FOUP Inside)	
Total Metals [A] (E+10)	< 0.5 atm/cm ²
Dopants [B] (E+10, front end of line only)	< 0.5 atm/cm ²
Volatile Organics (w/ CGMS retention times ≥ benzene, calibrated to hexadecane) [C]	20,000
SMC organics on wafers, ng/cm ² /day [D]	NA
Total SM on wafer, E+10 atoms/cm ² /day	< 0.5 atm/cm ²

SMC--surface molecular condensable, SM--surface metals

[A] Detection of metals at the levels indicated will be dependent on sampling time and flow rate. Sticking Coefficients vary widely for metals. It is generally believed that Cu has a sticking coefficient 10x of other metals, and therefore the guideline for Cu could be lower.

[B] Includes P, B, As, Sb

[C] Ideally, continuous monitoring using online instrumentation would be preferred when practical since this can give both long term averages and catch excursions. When online monitoring is not available, an average grab sample for at least 4 hours, and not more than 24 hours is recommended, to get an average, increase sensitivity of the analysis, and avoid short term transient effects

[D] SMC Organics: Single wafer shall be oxidized to make organic-free, then wafer shall be exposed for 24 hours and top side analyzed by TD-GC-MS with 400°C thermal desorption, and quantitation based on hexadecane external standard. TIC response factor per SEMI MF 1982-1103 (formerly ASTM 1982-99).[4] Limits determined by above method are a guideline for many organics. Note higher limits can be used for process wafers oxidized or cleaned prior to subsequent process step. Processes such as gate oxide formation, or polysilicon deposition, may be more sensitive to organics, especially high boilers such as DOP. Silicon nitride nucleation may also be more sensitive than above for some processes. Please note dopants requirement is covered in earlier section. Contamination levels are time based, and samples should be exposed for a weeks time for better sensitivity; ng/cm²/week. Total contamination level on reticles that cause problems also vary with energy exposure. These guidelines subject to change with new data currently being generated.

The structure and tabulated values in Table YE3 (process segment Furnace/thermal treatment): AMC limits for clean room ambient environmental control are listed side-by-side with AMC limits recommended for the wafer environment inside FOUPs. Tabulated values are derived from front-end manufacturing defect analysis and scientific work of academia.

New line item in Table YE3: Moisture: In order to reflect the impact of moisture to the wafer- and reticle environment, moisture has been introduced as additional line item to Table YE3, starting with “exposed copper”.

2.1.2. NEW AMC TOPICS RELATED TO FACTORY INTEGRATION (AMC INTEGRATED CONCEPT)

The FOUP is a plastic container that stores and carry 25 wafers from tool to tool. During storage, wafers may outgas chemicals and by-products of previous processes inside the FOUPs. As a consequence, the concentration of some critical AMC inside FOUPs may be higher than inside the cleanroom by several orders of magnitude.

The FOUP itself may be a source of contamination because of residues from its own manufacturing process, and also because it can trap AMC coming from contaminated wafers which will then be further outgassed. The defects due to AMC are a result of a combination of critical contamination inside the FOUP, type of substrate

and storage time. Some defects are also linked with humidity and temperature conditions. As a result, the measurement and control of the contamination inside FOUPs are key challenges for the IDMs and foundries.

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/cm². Sticking coefficients (s) for different molecules are found in the literature and help us to relate SMC to AMC concentrations in the air. AMC concentrations which will generate surface defects on the wafer are also depending on time of exposure at a given humidity and temperature. The general formula relating SMC to AMC is as follows: $C = N / (s \times V \times t)$, where C is the AMC concentration in the air, N the SMC concentration on the wafer, s the sticking coefficient, V the mean speed of the AMC and t the exposure time. The YE3 table is reporting recommended AMC concentrations in ppt(v) for 24 hours exposure time inside FOUPs. For lower exposure times, new AMC values can be calculated using the formula above. A simple consequence is that the allowable concentrations in air are higher for shorter exposures (linear relationship according to this equation). Sticking coefficient are not strictly constant for different exposure times and the approach above only represent a simplified version of a more advanced theory using the kinetic laws of contamination (more details can be found in the literature).

The Yield Enhancement group has been working on the different issues related to FOUP contamination and therefore proposes a new table describing the potential solutions. Factory Integration is dealing with the whole process flow including: cycle time, q-time constraints, layout and consumption. As a consequence the integration of the measurement and control of contamination inside FOUPs was handled as a common project between YE and FI. In the frame of this common work, Factory Integration has the role to evaluate the validity of each solution in regards to cycle time and throughput. FOUP cleaning is increasingly more important to mitigate the FOUP contamination particularly from pores due to outgassing from the wafers. This can be mitigated by using a FOUP with lower porosity and more frequent FOUP swap and subsequently cleaning the FOUP before reintroduction into production.

In 2011, YE defined the potential solutions for the following 3 main topics:

- - Outgassing of new FOUP
- - Outgassing of “in production“ FOUP
- - Cross-contamination on wafers inside FOUP

2.1.3. NEW AMC TOPICS RELATED TO 450 MM

There are several considerations for critical contamination control specifications (CCCS) for the clean room environment and wafer environment in 450 mm wafer sub 1× nm technical node high volume manufacturing.

A transition in production from 300 mm wafer substrate to 450 mm diameter substrates is driven by output per wafer and time and therefore by cost. Yield loss would affect the overall output of the 450 mm production line which is subjected to be more productive than current 300 mm lines. Consequently this would affect the return on investment (ROI) on 450 mm investments which are right now assumed to be wafer diameter specific and therefore comparatively massive.

Critical contamination control specifications for the wafer level have to be put forward as projections for 450 mm wafer size together with the sub 1× nm node. Current know-how and information on wafer processing speed, wafer defect budget, handling modes and foreseeable fab space structure have to be taken into account. From this information CCCS for the clean room environment and the wafer environment need to be derived.

Contamination control specifications for the production of sub 1× nm structured chips products on 450 mm wafers experience in some parts influences that come with the technical node and materials used. Other parts are influenced by the projected influences from wafer size and possible countermeasures.

Based on know-how from current 300 mm high volume manufacturing (HVM) at 28 nm node in some segments, conservative, steady projections of the requirements can be proposed for specification. Such steady

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specification for the clean room environmental level can often only be maintained due to permanent technical improvements and active contamination control (counter) measures on the tool level. Such examples for foreseeable unchanged specifications on the clean room level are the specifications for the following:

Vibration—The mere increase in wafer size would pose significant challenges with regard to wafer handling due to higher masses of tool structures, lower stiffness and an unwanted reduction in resonance frequency. This shift – if not actively addressed – could increase the risk of coupling of natural background into the tool operation. Yet the actual perspective is that 450 mm production could further be possible in clean rooms respecting vibration class VC-D supported by active vibration control on tool-level

Particle cleanliness—Despite the model-related shrinking of the critical particle diameter together the shrinking of the line structures there is little evidence that significant tighter requirements for particle cleanliness in the clean room environment (class 4 or class 5 to ISO 14644-1) or mini-environments (class 1 to ISO 14644-1) would come along with the introduction of 450 mm wafers. Uncertainties exist based on the expected broad implementation of FOUN purge with XCDA or dry nitrogen that could enhance ESA (electrostatic attraction) based on increased surface charges.

For two contamination categories tighter specifications are foreseeable which are mainly due to the technological node expected on the onset of 450 mm production

ESD—The requirements to prevent ESD (Electrostatic discharge) induced defects will get more stringent with reduced line width but are supported by active countermeasures on the tool side

EMI—It can be expected that EMI (Electromagnetic interference) will gain more attention and may need enhanced preventive action. This is mainly related to the expectation that for sub 1x nm node both e-beam and TEMS may become production relevant tools thus requiring that standard production floor space may be capable to accommodate such EMI-sensitive tools

AMC—In the case of AMC (Airborne molecular Contamination) an alignment of requirements for various tools sharing the same fab space and experiencing the same threat to wafer yield should result in a simplification of the contamination control model and a higher ability to achieve yield safely. Currently AMC control strategies for the different processes vary widely based on the preparedness or unpreparedness of the tools for non-ideal contamination situations of the clean room environment. This leads to relaxed clean room environmental standards in case tools come with a well-defined AMC protective interface and stringent requirements if the tools arrives unprepared creating either a demand to adapt the clean room condition or the minienvironments conditions.

Considering that AMC effects to wafers do generally not originate from concentrations but from doses related to sit-times the migration to 450 mm wafers can have an impact on the contamination burden if processing speed would not scale up proportional to wafer size. Currently the WECC group would expect this effect to be most pronounced for metrology tools. The progress on processing speed needs to be monitored to decide whether AMC control limits for WECC would need scaling in the coming years due to the wafer size effect.

2.1.4. NEW AMC TOPICS RELATED TO INTERACTIONS OF AIR IONIZERS WITH AMC

Corona based air ionizers may be used to neutralize charge to prevent electrostatic discharge damage and electrostatic particle attraction to wafers, masks or other surfaces.

The hot emitter tip, UV light, energetic electrons and ions formed can interact with AMC's (Airborne Molecular Contaminants) that have Si, S, P, B, Cl, Sn or other selected elements to make nm non-volatile particles such as oxides, and larger deposits or dendrites on the tips up to millimeters, that can throw the ionizer out of balance or lead to ionizer faults. While presumably rare, if this happens, the deposits call attention to the unusual presence of specific excess AMC's that can react with also with other energy sources to, not only deposit onto ionizer tips, but possibly onto other surfaces, due to interaction with excess energy such as 193nm lithography, lasers and inspection tools or hot surfaces. The compounds might degrade optics, masks, scanners, or other surfaces. Analysis of the ionizer tip deposits by SEM-EDS, ICP-MS (especially for boron) or other methods can indicate what elements are present in air, aiding selection of methods to look for possible sources of a limited number of contaminants, instead of large sections of the periodic table. This

method can be used to more rapidly find some AMC issues for which no other test are currently available, such as ppbv and higher leaks of some hydrides, silicones, silanols, halogens, organometallics, O=C=S, TEOS, organophosphates, ammonia, acids, etc.

Process critical materials—Additional experimental investigation is required to support our understanding of impurity specifications in novel materials, such as Cu plating solutions, CMP slurries, or chemical vapor deposition (CVD) precursors to high/low- κ dielectrics and other thin film materials. For many years the critical particle size concept was used to judge whether particles will have an impact on yield or not. This concept has to be rethought since particles do not impact the process yield alone by their physical size but also by their chemical composition. The allowable particle concentration thereby depend also on product parameters such as cell size and have therefore been aligned with the particle concentration on the surface as derived by the Front End Processes (FEP) TWG surface preparation group calculation model.

2.1.5. ULTRAPURE WATER QUALITY

Ultrapure water—UPW is purified water with most of the quality parameters below or near their detection limits of the most advanced metrology. Specific definitions of the water quality requirements to enable future technology are presented in the Table YE3. 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 YE3.

It is important to remind that the roadmap is focused on technology enabling, 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. More stringent criteria beyond 2015 are only projected where there is evidence that manufacturing process requirements demand improvements. UPW is generally the cleanest fluid available in the manufacturing process. As such there is only selective data currently available correlating contamination level and device yield.. For this reason the UPW Roadmap for contamination tolerance is relatively stable over time. Over the past several years the UPW and Chemical groups have worked closely together to develop a failure mode and effect analysis (FMEA) to evaluate the risk of known contaminants of the wafer.

The UPW section of Table YE3 considers some parameters as process variables rather than contaminants. It is clear that the stability of the wafer processing environment can be as important as the level of contaminants present for some parameters. For example; some semiconductor manufactures treat dissolved oxygen (DO₂) in this way, while others consider it a contaminant. Stability of temperature continues to be important for immersion lithography.

For 2015 some commonly monitored parameters such as resistivity and bacteria are not included in the table, as they do not represent technology challenge and 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 zero level and the resistivity became non-sensitive to the water quality variation within the ranges targeted for the ionic species in UPW.

UPW parameters were reviewed for the 2015 roadmap for the specific location where they are critical to maintaining semiconductor yield. The notes to the Table YE3 contain definitions for these parameters. Some parameters are specified for POP (Point of Process), while the others are specified in different locations. The definitions are driven by the consideration of whether the tool environment and measurement location may affect those parameter values

2.1.5.1. PARTICLE CONTAMINATION IN UPW

The focus will turn 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 reducing line widths.. On-line metrology for particles in liquid does not address killer particle size, and therefore, filtration efficiency for killer particles provides limited information.. At the same time it is

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apparent that the killer size of the particles has approached filtration capability of the most advanced final filters, while there is some test data suggesting the particle challenge concentrations to the final filters from UPW system components can be very high. (Refer to ion exchange particle shedding data in the published supporting materials).

The 2015 edition includes specifically a category for the particles in EUV mask operation. This is to emphasize the importance of the particle control specific to this area. Electrically active particles (mostly metallic) were removed from the table based on feedback from FEP, suggesting that all particles are equally critical to future technology. The colloidal silica parameter has been removed from the table. Colloidal silica will now be considered as a particle, subject to the particle specification in the table. If colloidal silica particles are controlled to the particles specification, all measurable silica in UPW will be in the form of dissolved. 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 work around 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. We are continuing to investigate selective defect density in the critical areas that require better understanding. This includes particle deposition modeling based on a thorough literature review and experimental data. Experimental data is included in supplemental materials.

2.1.5.2. METAL CONTAMINATION IN UPW

The UPW team is currently reviewing previous categorizing critical as 1ppt and non-critical metals as 10 ppt). This is based on the fact the concentration of metal on the wafer is function of UPW concentration and deposition ability. Instead we are considering defining the UPW spec based on device impact (XE+Y at/cm²) and deposition as a function of metal concentration in the bulk liquid. We propose the target levels based on the device impact and the deposition efficiency.. We have updated the FMEA accordingly and suggested maximum concentration of metals with changes based on our calculation.

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. As a result of this, the ITRS UPW team removed TOC from the table in the 2013 publication. 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<1.0ppb.

The 2015 Yield roadmap maintains a separate line for immersion litho 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 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 > 200C
 - 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
 - Non- Polar Organics - have very little attractive strength to have any direct device impact. Non-polar organics may adhere to a hydrophobic wafer surface as foreign material (FM) via VanderWaals forces which are relatively weak and are easily removed in chemical cleans.

- Critical carbon atoms on wafer related to TOC in bulk fluid
 - Defined by FEP as 1×10^{-12} atoms/cm² for Si-C defect in furnace.
 - Breakdown of organic compounds particularly at higher temperature (>200 C) 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 defined by FEP as 200°C
 - UPW ITRS group is looking at compounds with lower boiling point that may be related to other defects

We continue to use failure mode effects analysis (FMEA) approach to determine the overall risk of each subgroup to the wafer manufacturing process. In 2013 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 give us baseline data to identify typical organic compounds in semiconductor UPW systems and can be used for occurrence risk factor in the FMEA review.

It is critical that further experimental analysis is completed in the next few years to determine the correlation between failures in the semiconductor devices and level/type of organic contaminant. Research will continue in 2016 to investigate this further.

UPW measurement methodologies—General test methodologies for monitoring contaminants in UPW are indicated in the Figure YE2 below. Over the past few years the ITRS UPW 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.

<i>Parameter</i>	<i>Measured (POD/POC)</i>	<i>Test Method</i>
<i>TOC</i>	<i>Online</i>	<i>Conductivity/CO₂</i>
<i>Organic ions</i>	<i>Lab</i>	<i>Ion chromatography</i>
<i>Other organics</i>	<i>Lab</i>	<i>LC-MS, GC-MS, LC-OCD</i>
<i>Total silica</i>	<i>Lab</i>	<i>ICP-MS or GFAAS</i>
<i>Reactive Silica</i>	<i>Lab</i>	<i>Colorimetry</i>
<i>Particle monitoring</i>	<i>Online</i>	<i>Light scatter</i>
<i>Particle count/characterization</i>	<i>Lab</i>	<i>SEM—capture filter at various pore sizes</i>
<i>Cations, anions, metals</i>	<i>Lab</i>	<i>Ion chromatography, ICP-MS</i>
<i>Dissolved O₂</i>	<i>Online</i>	<i>Electric cell</i>
<i>Dissolved N₂</i>	<i>Online</i>	<i>Electric cell</i>

ICP-MS—inductively coupled plasma mass spectrometry
GFAAS—graphite furnace atomic absorption spectrometry
SEM – scanning electron microscope

Figure YE2 General Test Methodology for Ultrapure Water

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. Measurements of these nanoparticles are made difficult by the low scattering efficiency of them. 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.

2.1.6. THE SENSITIVITY PROBLEM

As of 2015, the highest sensitivity 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. Experiments have shown that small particles may even deposit preferentially [M. Knotter] and therefore the impact is increased even further. 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 the optically based particle counters To estimate the concentration of smaller particles in chemicals currently an extrapolation assumes a $1/d^3$ 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. Further discussion is needed on validity of the power law extrapolation, e.g., effect of filtration on extrapolation (filter rating/detection size).

2.1.7. 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 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 particle counts that are detected during the sample interval. Follow this link for more details on particle monitoring.

Although the gas/liquid chemical section of Table YE3 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 [1]. 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, however, 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 YE3 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 YE1 describes the several interfacial points of process materials with equipment found along these paths and associates them with the various TWGs within the ITRS 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 very difficult to obtain with the exception of 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 YE3 are intended to represent those at the Point of Entry, POE, defined as the inlet to the process tool as described in Table YE1. There are sufficient measurement data on bulk gases and aqueous fluids to provide guidance with regard to 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.

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. Anhydrous HCl for example is known to form very stable hydrates with water that results in concentration in the water content in the cylinder 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 and the application of moisture gettering purification devices somewhere in the vapor transport path. Liquid anhydrous ammonia are another specialty gas with this potential issue [3], 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 amide based CVD/ALD precursors are expected to undergo similar distillative variation and/or thermal degradation under delivery conditions [4], 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 or the application of POUP .

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 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 YE3 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., POU purification, POUP).

Bulk and Specialty Gases—The major bulk gases are listed separately in Table YE3. 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 polling 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 YE3 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 YE3 have been left at current levels, unless an objective justification for increased purity can be identified. Although changes to the current Table YE3 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. More details with regard to bulk and specialty gases are provided in the gas supplemental documents.

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.

Liquid chemicals—Table YE3 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. In the supplementary links an ion table and a mixing calculation are provided that show for which chemicals which ions are important and in which chemicals they could actually occur/have been observed. With the increased use of CMP and plating chemicals, there must be a better understanding of purity requirements for the delivered chemicals.

ALD/CVD Precursors: At recent nodes Atomic Layer Deposition (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 HVM and some discussion of common/unique aspects of ALD processes with respect to Wafer and Environmental Contamination Control (WECC) is warranted.

For the vast majority of semiconductor processes, gaseous reactants are delivered to the processing chamber at atmospheric or superatmospheric pressures. However, for most ALD processes, the precursor is delivered at pressures typically in the range of 5 Torr to 100 Torr to the reactor, which is processing typically below <1 Torr. 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. 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

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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.

Down stream of the ALD reactor, the relatively low vapor pressure ALD precursors and process by-products tend to condensate at 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.

Table YE3 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. 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 N₂ specification was changed to eliminate Ar as a critical impurity, although it was left in the O₂ specification. Even so, the 50 ppbv limit given in 2005 was raised to an Ar limit of <1000 ppbv. The ongoing requirement in O₂ derives from the potential for uncontrolled Ar impurities to impact plasma etching processes, although typical Ar specifications for O₂ used for etching is more consistent with the <1000 ppbv level.

For some processes, such as advanced lithography, very small quantities of “high molecular weight/high boiling point” (e.g., C₆-C₃₀) hydrocarbons are detrimental because of increased adherence to the exposed surfaces, and potential for photochemical degradation to leave non-volatile residues on lenses, masks, mirrors, etc. However, any organics, even ones with retention times less than C₆ are considered detrimental if they can 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 with ultimate sensitivity, it is necessary to directly detect the relevant species and calibrate the analyzer with the appropriate standard. The methods used are analogous to those for AMC, such as TD gas chromatography (GC)/mass spectroscopy (MS) (TD = thermal desorption) or TD GC/FID, or ion mobility spectroscopy (IMS). Even these approaches may miss some heavier hydrocarbons and/or polar species that tend to remain in the column or emerge as very broad peaks. For methods using adsorbent traps, it is very important to determine the trap efficiency. Using APIMS to provide real time measurement of individual hydrocarbons is possible, in principle, but calibration is difficult, because larger hydrocarbons are collisionally dissociated in the ionization process.

A compromise approach that has gained some acceptance is to use TD GC/MS and sum all peaks corresponding to C₆ and higher. The instrument is usually calibrated with a multi-component standard and results are reported “hexadecane”. While the quantization provided by this method is approximate, and some species may be overlooked, it does at least emphasize the heavier hydrocarbons while providing a straightforward calibration.

Historically, applications for both O₂ and H₂ generally tolerate higher levels of N₂ contamination than other contaminants, however, H₂ as a carrier for Epitaxy now requires more stringent N₂ levels and the table reflects this observation. Requirements for critical clean dry air (CDA), lithography purge gases, and supercritical CO₂ 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, sulfates, 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 (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 SO₂ there are convenient on line methods, *e.g.*, UV fluorescence.

For specialty gases, contaminant values in etchants, dopants, and deposition gases have been expanded in Table YE3 to reflect the increase number of different materials in use, and to better delineate the processes they are used for. 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.

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 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.

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 YE3. 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 YE3 and the supplementary precursor table.

2.2. CHARACTERIZATION, INSPECTION AND ANALYSIS

In 2011 the subchapter was defined to be extended to characterization, inspection and analysis. During the previous years the sub chapter was limited to inspection capabilities. 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.

2.2.1. ELECTRICAL CHARACTERIZATION METHODS AND VIRTUAL METROLOGY FOR YIELD CONTROL

In order to overcome the problems of missing sensitivity and high effort consuming metrology for yield control one focus of the YE group will be the partial replacement of physical based metrology to electrical diagnosis and virtual metrology wherever feasible. The use of all available data sources and approaches for data analysis will be further elaborated for yield monitoring. Hereby, a better balance of defect/contamination detection and fault diagnostics/control of electrical characteristics should be established by including statistical and systematic approaches into YE activities.

Furthermore, virtual metrology becomes more and more essential for yield considerations. Virtual metrology is defined as the prediction of post process metrology variables (either measurable or non-measurable) using process and wafer state information that could include upstream metrology and/or sensor data. Refer to Yield Enhancement Chapter for more information.

2.2.2. WAFER DEFECT METROLOGY

Defect metrology continues to be important towards smaller nodes specially considering new yield challenges like multiple patterning. The main way to detect yield impacting defects in the production is defect inspection. Therefore the most important requirements for inspection and review are now incorporated in the *More Moore chapter*. For Heterogeneous Integration not small dimensions but 3D integration is the challenge. To find the right solutions for those inspection requirements and challenges will be the focus.

2.2.3. 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. In this situation a clear benefit can be drawn from the experience in the FE.

Yet the most appropriate methodologies have to be selected and FE yield tools need to be adapted to BE requirements. The task will be to define a dedicated roadmap.

Due to the changed focus of Yield Enhancement several cross TWG activities are envisaged, connections with More Moore (MM), Heterogeneous Integration (HI) and Heterogeneous Components (HC) are necessary.

3. POTENTIAL SOLUTIONS

3.1. WAFER ENVIRONMENTAL CONTAMINATION CONTROL

Process Equipment—Defect reduction in process equipment remains paramount to achieving defect density goals. Solutions and technology developments are expected to provide major enhancement capabilities in the next 15 years and continue to enable cost-effective high volume manufacturing for device dimensions below 90 nm. Refer to Figures YE3 and YE4. Equipment defect targets are primarily based on horizontal scaling. Vertical faults, particularly as they apply to the gate stack, metallic, and other non-visual contaminants, and parametric sensitivities need to be understood. 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. These 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—Figure YE4 illustrates the set of potential solutions for prevention and elimination of defects. 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—UPW systems meeting specifications do not appear to be large defect drivers for current device geometries. Based on this the Roadmap does not predict that significant changes are required for future geometries. As a Roadmap priority, specific defect mechanisms related to UPW are required to drive significant changes. The current focus is to understand the impact of the tool upon water quality, specifically particles, bacteria, and dissolved gasses, as well as to identify species that are suspected to be in UPW but are below the detection limit of available measurement methods. Improved measurement methodologies are required for organics, and organic ions to specify low-level contaminants 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 YE4 also shows various technological areas that may be required to enhance and measure the purity of delivered chemicals to the wafer manufacturing process. Technology areas:

Wafer 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. 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.

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First Year of IC Production DRAM 1/2 Pitch	SUBSTRATE		SUBSTRATE LOCATION			2013	2014	2015	2016	2017	2018	2019
	WAFER	RETICLE	STORAGE	PROCESS	TRANSPORT	32nm	28nm	25nm	22nm	20nm	18nm	16nm
New FOUF Outgassing / Contamination												
Off line AMC measurement in laboratory	X	0	X	0	0	[Shaded]						
Inline AMC measurement inside FOUF in fab	X	0	X	X	X	[Shaded]						
Inline AMC measurement inside 450mm FOUF and MAC in fab	X	0	X	X	X	[Black]	[Blue]	[White]	[White]	[White]	[White]	[Shaded]
Used FOUF Outgassing / Contamination (no wafer inside)												
Off line AMC measurement in laboratory	X	0	X	0	0	[Shaded]						
Inline AMC measurement inside FOUF in fab	X	0	X	X	X	[Shaded]						
Inline AMC measurement inside 450mm FOUF and MAC in fab	X	0	X	X	X	[Black]	[Blue]	[White]	[White]	[White]	[White]	[Shaded]
Vacuum purge and heating	X	0	X	0	0	[Shaded]						
Wafer Cross Contamination Inside FOUF (e.g acids after dry etch, oxygen or humidity before EPI clean)												
Inline AMC measurement inside FOUF in fab	X	0	X	X	X	[Shaded]						
Integrated AMC measurement inside load port	X	0	0	X	0	[Black]	[Blue]	[White]	[White]	[White]	[White]	[Shaded]
Vacuum purge : outgass the FOUF with wafers under vacuum and fill it with N2	X	0	X	0	X	[Shaded]						
N2 purge station : injection of N2 inside FOUF with wafer	X	0	X	0	X	[Shaded]						
N2 purge station integrated in stocker : injection of N2 inside FOUF with wafers	X	0	X	0	0	[Shaded]						
FOUF change : wafer transfer in a clean FOUF during q-time	X	0	X	0	X	[Shaded]						
Purgeable load port : injection of N2 when the FOUF is connected to the EFEM	X	0	0	X	0	[Shaded]						
Outgassing chamber integrated in process equipment	X	0	0	X	0	[White]	[White]	[White]	[Shaded]	[Shaded]	[Shaded]	[Shaded]
Wafer transfer under vacuum	X	0	0	X	X	[Black]	[Blue]	[White]	[White]	[White]	[White]	[Shaded]
<i>This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.</i>												
Research Required			[Black]									
Development Underway			[Blue]									
Qualification / Pre-Production			[White]									
Continuous Improvement			[Shaded]									

Figure YE3 Wafer Environment and Reticle Environment Contamination Measurement and Control Potential Solutions (last updated in 2013)

<i>Wafer Environment Contamination Control Potential Solutions- UPW</i>								
<i>First Year of IC Production</i>	2015	2016	2018	2020	2022	2024	2026	2028
<i>DRAM 1/2 pitch, nm (contacted)</i>	24	22	18	15	13	11	9.2	7.7
GENERAL								
Fluid purity impact on device yield / performance								
Contaminant based process control								
Ultra Pure Water								
Particle online metrology 10 nm [A]								
Particle online metrology 5 nm [A]								
Effective Filtration at 10nm particle size [A]								
Effective Filtration at 5nm particle size [A]								
Improved components to reduce particle generation (IX resin, coated pumps, etc.) [C]								
Off-line test for particle filtration performance validation [A]								
Correlation of specific organic functional groups to wafer defects via Failure Mode and Effect Analysis [D]								
Correlation of specific organic functional groups to wafer defects via Failure Mode and Effect Analysis [D]								
On-line detection of the critical organics (non-volatile) needs development [D]								
Need to develop organic deposition model (sticking, removable, etc.) [D]								
Use on-line TOC as way to control total organics (assuming that all is critical) [D]								
Need to define effect of UPW borne H2O2 to manufacturing process								
Drivers:								
[A] killer particle control								
[B] critical particle effect								
[C] critical particles and organics								
[D] critical organics								
<i>This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.</i>								
Research Required 								
Development Underway 								
Qualification/Pre-Production 								
Continuous Improvement 								

Figure YE4 Wafer Environmental Contamination Control Potential Solutions-UPW

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Wafer Environment Contamination Control Potential Solutions - Liquid Chemicals								
First Year of IC Production	2015	2016	2018	2020	2022	2024	2026	2028
DRAM 1/2 pitch, nm (contacted)	24	22	18	15	13	11	9.2	7.7
GENERAL								
Fluid purity impact on device yield / performance								
Contaminant based process control								
CHEMICALS - Metrology								
Development of 40 nm particle counter [A]								
Development of 20 nm particle counter [A]								
Development of 10 nm particle counter [A]								
Particle characterization to identify source of contamination [A], (for components and systems)								
Bubble discrimination of reactive chemistries [A]								
Improved metrology for concentration measurements[B]								
Surfactant concentration measurement and control [B]								
Anion & cation measurement in process chemicals, e.g. cleaning chemicals [A]								
Organic measurement (TOC and speciation) in process chemicals, e.g. H2O2, IPA [A]								
Contaminant characterization in CMP slurries, e.g. zeta potential, large particle size [A]*								
Contaminant characterization in CMP slurries, e.g. H2O2 concentration [B]								
Characterization of CMP slurries, e.g. Particle size distribution [B]								
On-line contaminant and constituent measurement in plating chemicals, e.g. copper sulfate, organic additives [A],[B]								
Improved blend accuracy taking into account incoming chemical concentration changes (closed loop control capability) [B]								
Closed loop point of use blending improvements [B]								
CHEMICALS - Components and Systems								
Filtration 0.02/0.04 μ m w ith high flux (1 gpm/0.5 psi/10"/1cP) [A]								
Filtration sub 0.02 μ m with high flux (1 gpm/0.5 psi/10"/1cP) [A]								
Filtration sub 0.01 μ m with high flux (1 gpm/0.5 psi/10"/1cP) [A]								
Ionic POU purifiers (<1 ppt metals) [A]								
Inline End point detection for Ionic POU purifiers [A]								
Improved components to reduce particle generation, e.g. tubing, valves, pumps, fittings, etc. [A]								
Improved system startup & flushing methodology to more quickly reach particle target and reduce chemical usage [A]								
Improved flow capacity and increased pressure for pumps [C]								
Improved flow capacity increased pressure and temperature for piping components [C]								
Reduced pressure fluctuations by improved BCD system performance and by better pressure and flow control [A], [B]								
Improved connection technology (reduce leakages and increase reliability) [A], [D]								
Decrease permeation of piping components (eg HCl permeation) [A], [D]								
Higher purity resins and components (metals, organics, anions, cations, surface smoothness, permeability) [A]								
Elimination of particle sources in chemical distribution system including POU (particle prevention in chemical conditions) [A], (for EUV mask cleaning)								
*Slurries are also looked at in terms of changes in active components (e.g., H2O2)								
Driver:								
[A] Purity								
[A] Purity - components and systems								
[B] Process control								
[C] Capacity								
[D] Maintenance								
This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.								
<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;"> <p>Research Required</p> <p>Development Underway</p> <p>Qualification/Pre-Production</p> <p>Continuous Improvement</p> </div> <div style="text-align: center;"> <p>■</p> <p>■</p> <p>■</p> <p>■</p> </div> </div>								

Figure YE5 Wafer Environmental Contamination Control Potential Solutions-Liquid Chemicals

3.2. CHARACTERIZATION, INSPECTION AND ANALYSIS

For pattern wafer inspection the requirements 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. . 3 d inspection capability will become very important for More than Moore technologies. The introduction of multi layer patterning will increase the importance of wafer inspection in lithography.

New solutions and roadmap for characterization and inspection in the packaging and assembly will be incorporated.

First Year of IC Production	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Pattern Wafer Inspection														
High sensitivity at high throughput														
High signal to noise ratio														
High Aspect Ratio Inspection														
High sensitivity at high throughput														
High signal to noise ratio														
Detection of volatile and non-volatile organic surface contamination														
laboratory scale quantification and qualification														
development of in line method														
in line monitoring														
<i>This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.</i>														
Research Required														
Development Underway														
Qualification / Pre-Production														
Continuous Improvement														

Figure YE6 Characterization, Inspection and Analysis Potential Solutions (last updated in 2011)

4. YIELD ENHANCEMENT SUPPLEMENTAL LINKS

- Industry Goals for Particle Measurements In Liquid Chemicals (updated June 2015) - Set LPC goals for the future Feb2015 Liquid Chems.doc
- Ion Table - ITRS-UPW+Chem Ion FMEA 07-28-2015.xlsx
- Mixing Calculation - ITRS_MixingCalc_HPM_100207.xls
- Advanced Analytical Methods for Particle Control in the Wafer Environment - Particles Libman SPCC rev2.pdf
- SEMI 5621A new standard (draft) "Guide for determining the quality of ion exchange resin used in polish applications of Ultrapure Water System" - 6521A Draft for Ballot Cycle 8 11092014.pdf:
- Organic Speciation Benchmark Study Summary April 2013.pdf
- AMC monitoring programs - AMC_MonitoringProgram_090730_NBR.xls
- AMC definitions - AMC_ITRS_Definitions_090724_AN.xls
- Bulk and Specialty Gases - ITRS_SG_ContList_070913_NBR.xls
- Precursor Table – 1403-14 rev 2 master precursor table 2013.doc
- Precursors in production - 1403-14 precursors in prodn 2013.doc

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