INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

2018 UPDATE

YIELD ENHANCEMENT

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

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

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Slava Libman, Dan Wilcox, David Blackford, Rick Godec, Steven Smith, Drew Sinha, Marcel Teunissen, Tim Miller, Steven Edmund, John Croft, Irina Belozerova, Bernie Zerfas, Jim Snow, Andreas Neuber, Abbas Rastegar, Alan Knapp, Deena Starkel, Sungin Moon, Brett Clark, Gary Van Schooneveld, Hideaki Iino, Philippe Rychen, Jochen Ruth

Peter Egger, Steffen Reyman, Carlos Beitia, Ulrich Wende, Juliane Weise, Simone Severi, Ines Thurner, Koichiro Saga, Ulrich Mantz, Andreas Eckl, Vanda Locati, Enrico Laurin

Akshey Sehgal, Joel Barnett, Paul Mertens, Martin Knotter

Rob Nine, Joe Sweeney, Matt Milburn, Enghwa Wong, Jonas Sundqvist, Ravi Laxman, Robert Clark, Steve Moffatt, Dave Roberts, Dan Cowles, Hubert Winzig, Ruben Lopez-Trigo, Keith Kerwin, William Bozydaj, Cristian_Landoni, Sarah Riddle, Greg Baumgart, Pratik Joshi, Greg Baumgart, Peter Maguire

Cesar M Garza, Christoph Hocke, Chris Muller, Hugh Gotts, Arnaud Favre, Guillaume Gallet, Mark Camenzind, Jürgen M Lobert, Albert Escusa, Jost Kames, John DeGenova, Markus PfeffeDon Hadder, Vincent Terracina, Kaoru Kondo, Tony Shucosky, Patrick Connor, Frank Flowers, Dan Rodier, Thomas Phely-Bobin, Majid Entezarian, Bob Gieger, Daniel Wiederin, Jae Seok Lee, Steve Rogers, Gerd Reinig, Kirk Chassaniol

Bob McIntosh, Rao Varanasi, Kim Farnsworth, Jan Rau, Kameron Brown, Kenji Kingsford, George Gonnella, Will Byars, Jim Henry, Tomasso Crisenza, John Painter, Archita Sengupta

YIELD ENHANCEMENT

1. INTRODUCTION

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

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

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

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 contamination and mechanisms responsible for yield loss are listed in the following: a) airborne molecular contamination (AMC), b) airborne particular contamination (APC) of organic or inorganic matter caused by the environment, personnel or by the tools, c) process induced defects as scratches, cracks, and particles, overlay faults, and stress, d) process variations resulting, e.g., in differing doping profiles or layer thicknesses, e) the deviation from design, due to pattern transfer from the mask to the wafer, results in deviations and variations of layout and critical dimensions, and f) diffusion of atoms through layers and in the semiconductor bulk material.

The determination of defects and yield, and an appropriate yield to defect correlation are essential for yield enhancement. The specification of tools for defect detection and classification of defect for root cause analysis addresses the technology requirements for More Moore and More than Moore.

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

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

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

Physical device dimensions and corresponding defect dimensions continue shrinking, posing new challenges to detection as well as tolerable contamination. The wafer edges and backside surface were identified to show significant impact on yield. Process variations and design are also factors impacting yield. Additional new challenges arise specifically for MEMS manufacturing as well as assembly lines using new material. Development of defect detection, defect review, and classification technologies showing highest sensitivity at high throughput solving those challenges is crucial for cost-efficient manufacturing.

Furthermore, for efficient manufacturing the monitoring of contamination in the environment and on the wafer surface requires appropriate analytical capabilities. Automated, intelligent analysis and reduction algorithms, which correlate facility, design, process, electrical and virtual metrology results, and their correlation to yield, test and work-in-progress data, will have to be developed to enhance root cause analysis and therefore enable rapid yield learning.

1.1. CURRENT STATE OF TECHNOLOGY

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

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

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

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

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

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

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

Current state of technology suggests significant gaps in contamination measurement technology. For example, the industry did not have adequate metrology for measuring killer particles in high purity liquids for the past several generations of semiconductor technologies. This gap continues to grow. As the result of these deficiencies, the Yield Enhancement chapter of IRDS is changing its direction from Reactive to Proactive Yield management. The sections below define specific proactive measures now undertaken to address these technology challenges.

1.1.1. ULTRAPURE WATER

Ultrapure water (UPW) is purified water with most of the quality parameters below or near the detection limits of the most advanced metrology. Current state of UPW technology generally can provide effective control of contamination. However, whereas some parameters are relatively easy to control, the effect of others requires further investigation.

Particle levels are reduced using the best available ultra-filtration (UF) technology, but today's particle detection and counting technology is not able to keep up with the fast-growing requirements for "killer" particle control due to continued scaling of critical semiconductor devices. Monitoring available for particles is limited to laser particle counters capable of monitoring 20nm particles with limited counting efficiency. There are new measurement devices for smaller particle sizes under development and commercialization, but their capabilities have not been demonstrated yet.

Lack of proven particle metrology limits the ability to confirm whether UF is effective in controlling particles down to the critical particle size. At the same time, it is apparent that the killer size of the particles has approached filtration capability of the most advanced final filters. Furthermore, there is test data suggesting the particle challenge concentrations in the feed to the final filters from UPW system components can be very high. Current definition of the killer size of the particles is based on half-pitch logic and is as small as 3.5 nm for the most critical electrically active particles (EAP). To address the metrology gaps and particle contamination risks, a new approach has been proposed. The details are described in the attached white paper (*"Proactive Particle Control in Ultrapure Water (UPW) in Silicon Wafer Cleaning Process, IRDS, 2018"*). New UPW IRDS parameters have been added to the Table YE03. This approach assumes no ability to monitor killer particles in UPW, but instead focuses on particle occurrence prevention by both reducing particle challenge to the UPW final filters as well as ensuring adequate performance of the filters.

Silica is one of more complex impurities in UPW. Silica may occur in UPW in a form of reactive (dissolved ionic) or colloidal silica. The main concern around colloidal silica is that its occurrence in UPW is highly probable, its retention by final filters is more difficult than other particles, and also because it may adsorb metal ions, thus becoming more detrimental on the wafer (these effects are based on published data).

While it is easy to control *reactive* silica (within defined sensitivities), *colloidal* silica is difficult to monitor at the level where it presents a problem. Traditionally colloidal silica has been measured as the delta between total and reactive silica in UPW. The killer particle size of currently considered generations has become very small, making it impractical to expect that the colloidal silica particles in critical concentration (posing risk to critical surface) could be measured as the delta of total and reactive silica, i.e., very small particles do not contain sufficient measurable amount of the silica compound. Since colloidal silica cannot be effectively monitored using state-of-the-art metrology as the compound, further consideration of colloidal silica will be done as part of particles monitoring. Given the criticality of this parameter, it is recommended to consider taking mitigation steps to prevent colloidal silica occurrence via improved treatment process control and use of higher purity materials.

Polish resin was demonstrated[12] to have very little capacity to retain silica, while colloidal silica may be formed inside of the Polish beds from traces of reactive silica. This point is addressed in the 2018 roadmap (see Table YE03) by adding a "proactive" silica control parameter in the feed to UPW tank. Pushing silica control upstream to the treatment process helps to reduce silica loads to the Polish loop.

Hydrogen peroxide has been recently reported to occur in final UPW as a by-product of 185 nm UV (ultraviolet) reactors used to decompose UPW organics[12]. There are technologies available for removal of hydrogen peroxide in UPW; however, their implementation requires major system change and substantial investment. The 2018 UPW Roadmap further reduced the H_2O_2 target from 10 ppb to 3 ppb. This change was triggered by new data suggesting that 10 ppb of H_2O_2 in UPW in pre-Epi cleans may affect wafer surface roughness[12]. While the new target is substantially lower than the previous one, it is unclear if a 3-ppb level may have similar detrimental effects. Additional study is needed to verify this concern. In the meantime, a new target should allow for reducing H_2O_2 level, while possibly avoiding any major capital investments necessary to reach lower peroxide levels.

Metallic contamination in UPW is another important concern. Although metal control in UPW has never been a difficult challenge from the treatment process point of view, new technology drivers may put the entire technology supply chain in front of such challenges in the near future. Based on literature data "extremely low level of metal contamination is required for specific devices like CMOS image sensors"[12]. There are suggestions that some of the metals for such applications should be controlled at the level of two or even three orders of magnitude below the levels typically specified in most UPW systems. The attached white paper "*Metal Contamination of Image sensors by Ultrapure Water in Silicon Wafer Cleaning Process*" provides details of the literature data as well as how new specific metal targets (see YE03 table) for UPW have been calculated for image sensors metal control. The ability to control of some of the metals in UPW by current state-of-the-art treatment technology to such low levels may not be possible. This includes limitations of metrology and treatment technology, as well

as materials purity of the critical components use in UPW Polish and delivery systems. For this reason, an additional parameter for proactive metal contamination control was added in the feed to the UPW tank.

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

There is indication that residual amounts of TOC (less than 500 ppt) may be present as nm-size organic particles that can penetrate even the smallest pore size filter. *Note: It is important to keep in mind that the SECC roadmap is focused on technology enablers, identifying the parameters that require new technologies for monitoring and control. For the practical purposes of UPW system design and operation, SEMI F63[1] and SEMI F61[2] provide guidance that can be used as a reference specification for the UPW quality, design, and operation of advanced semiconductor processes, considering feasibility of the existing technologies.* The UPW IRDS team collaborates closely with the SEMI UPW Task Force to develop guides and test methods to mitigate existing risks and challenges.

1.1.2. AIRBORNE MOLECULAR CONTAMINATION

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

The number of AMC contaminants has increased as the industry has reduced the feature size, as shown in Figure YE1 below:

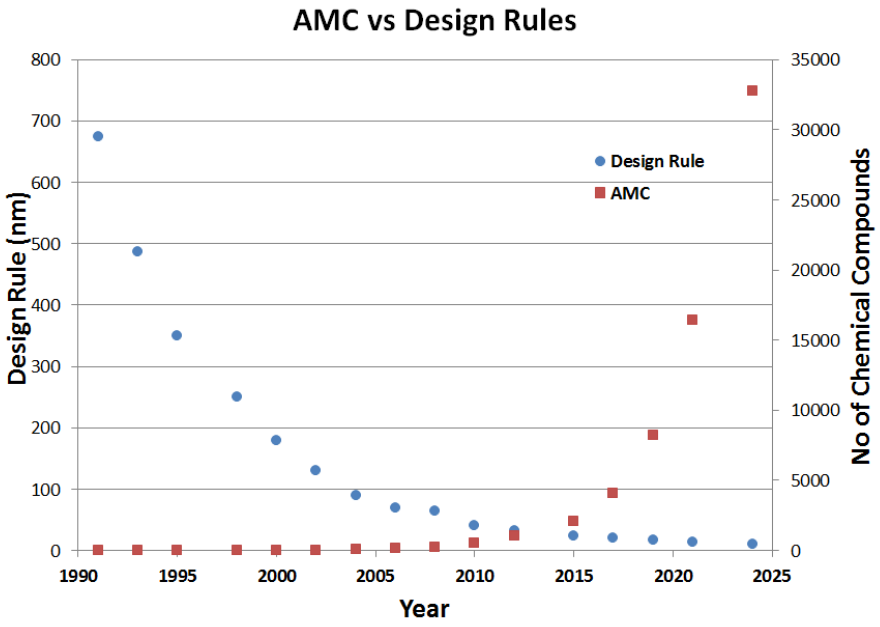

Figure YE1 Increasing Sensitivity of New Generations of Semiconductor Technologies to AMC

One reason is that the exposure wavelength needs to decrease in order to improve resolution. But as the wavelength decreases, the energy increases and the greater the energy of the exposure beam, the greater the number of reactions it can induce from chemical substances present in the environment. This leads to deposition onto optical elements and/or chemical attack on antireflecting coatings in the optical elements of the exposure and metrology tools.

Another reason is that as the features decrease, the ratio of surface-to-bulk increases. The surface of materials is more energetic because of dangling bonds, and this promotes undesirable chemical reactions on the surface of the structures formed in the manufacturing process.

There is need for a new classification for contaminants. The International Roadmap for Semiconductors (ITRS) formally introduced a roadmap for AMC in 2007. It recognizes the following categories: Molecular Acids, Molecular Bases, Refractories, Dopants, and Condensables.

A new approach is required for several reasons. For one, there are some contaminants that don't follow in any of the categories mentioned above. Another reason is that the current classifications is not rigorous but grew out of terms used in the semiconductor industry. For instance, "refractory" is a term used to describe a class of metals that have an extraordinarily resistant to heat and wear; whereas in the previous classification it is meant to describe those substances that change the index of refraction of optical elements.

A classification of AMC contaminants based on their chemical families is being proposed. Such classification is justified because chemical families exhibit a similar pattern of chemical reactions. Figure YE2 below summarizes this new classification proposal:

	Impact				
Chemical Family	Process	Equipment	Device		
			FEOL	MOL	BEOL
Roadmap Term.	POU	POE	POP	POP	POP
Inorganic Acids	Yes	Yes	No	Yes	Yes
Inorganic Bases	Yes	No	Yes	Yes	Yes
Carboxilic Acids	Yes	Yes	Not Known	Not Known	Yes
Organic bases	Yes	Yes	Yes	Yes	Yes
Esters	Not Known	Yes	Not Known	Not Known	Not Known
Aldehyde/Ketones	Not Known	Yes	Not Known	Not Known	Not Known
Phenolic/Alchohol	Yes	Not Known	Not Known	Not Known	Not Known
Aromatics	Not Known	Yes	No	No	No
Plastizers	Yes	No	Yes	No	No
Aliphatics	No	Yes	No	No	No
Heterocycles	Not Known	Yes	Not Known	Not Known	Not Known
Siloxanes	Not Known	Yes	Not Known	Not Known	Not Known
Fluorinated	Not Known	Yes	No	No	No
Sulfurous	Yes	Not Known	Not Known	Not Known	Not Known
Halocarbons	Not Known	Not Known	Not Known	Not Known	Not Known

Figure YE2 Proposed New Classification of AMC Contaminants

FigureYE2 also points towards its impact: process, equipment, and device. In some instances, the impact is not known and requires further investigation. The sources of AMC contamination can be outgassing from materials of construction in the cleanroom, wafer processing equipment, post processed wafers, wafer pods, and wafer environmental enclosures, as well as inadequate exhaust and fugitive emissions from chemicals used in wafer processing. The presence of humans in these environments are the main sources of AMC. Makeup air is also a significant source for AMC. The FOUP itself is a source of contamination because of materials outgassing and because it can trap AMC outgassing from process steps such as etch. Some defects are also linked to humidity and temperature conditions. As a result, the measurement and control of the contamination inside FOUPs are key challenges for integrated device manufacturers (IDMs) and foundries.

AMC can also create shortfall in productivity because of the impact of AMC to production tools, such as exposure tools, reticles, metrology, or corona ionizers. AMC is in many cases a highly dynamic phenomenon, particularly in confined environments such as FOUPs and (point of distribution) PODs, where critical surface chemistry interacts with the environment surfaces. It should be noted that there is not a certain critical level of contamination for each AMC. This is always seen in connection with the contact time of AMC and the materials. Ultimately a dose (concentration × time) of the AMC is to be considered.

AMC control deals with prevention of AMC release for which a tight source control is mandatory as well as mitigation and continuous removal through air recirculation. There is clearly a need for better AMC monitoring instrumentation in the clean room to measure AMC at the part per trillion level (by volume) in real time. Ion mobility spectrometry techniques (IMS), cavity ring-down spectroscopy (CRDS), Fourier transformer infrared (FTIR), ultraviolet (UV) chemiluminiscence instruments and various atmospheric pressure ionized mass spectroscopy (APIMS) have been used to measure low level AMC, but the

former is too unspecific, the latter too involved. A larger variety of online methods and instrumentation is still needed, but current technology appears to lag behind technology needs. The main challenge is to combine high sensitivity with high specificity at manageable cost, maintenance, and automated operation. Witness wafers have been used to link surface molecular contaminant (SMC) concentrations to specific defects. The surface concentrations are usually expressed in a maximum allowable number of molecules/cm^2, ions/cm^2, or atoms/cm^2 for elements or ng/cm^2 for organics. Supplemental information is found in the Appendix of this chapter for AMC monitoring programs.

Clean room ambient conditions are regarded at point of entry (POE) to critical process steps that may involve further tool related measures of AMC protection and reduction, including relative humidity, to achieve proper process control. FOUP and reticle POD 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, wafer surface, or backside and edge of wafers.

1.1.3. Gases, Liquid Chemicals, and Precursors

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

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

Point of use purifiers and filtration units are finding application in newer ALD techniques, for example, where the films are deposited as monolayer and incorporated impurities can be especially destructive. Purifiers must not add any new contaminants. A near- and medium-term challenge is filtration of the precursor vapor. The sources can be sublimable solids or readily condensable vapors of low volatility liquids. These can resolidify or reliquify causing plugging and instability in fluid transfer to the substrate surface.

1.1.3.1. Bulk and Specialty Gases

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

The situation is similar for many of the specialty gases. Statistical process control (SPC) for process gases and liquids was implemented 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, but 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.

For some processes, such as advanced lithography (especially 193 nm), very small quantities of "high molecular weight/high boiling point" (e.g., C_6-C_{30}) hydrocarbons in supply gases 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 C_6 are considered detrimental if they result in refractory deposits. For the same reason, other potential impurities such as siloxanes or organophosphates can also be very detrimental in extremely small quantities. In order to detect such species with sufficient sensitivity, it is necessary to directly detect the relevant species and calibrate the analyzer with the appropriate standard near the quantitation limit. The methods used are analogous to those for AMC, such as thermal desorption (TD) gas chromatography (GC), mass spectrometry (MS) or TD GC with flame ionization detector (FID), photo ionization detector (PID), or ion mobility spectrometry (IMS). 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, if not optimized. For methods using adsorbent traps, it is very important to determine the trap efficiency. Using atmospheric pressure ionized mass spectroscopy (APIMS) to provide real-time measurement of individual hydrocarbons is possible in principle, but very involved and calibration is difficult, because larger hydrocarbons may be collisionally dissociated in the ionization process.

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

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

For specialty gases, contaminant values in etchants, dopants, and deposition gases have been expanded in Table YE3 to reflect the increased number of different materials in use, and to better delineate the processes in which they are used. Particulate contamination is omitted since online monitoring of particle concentrations is not commonly practiced and the efficacy of POU particle filters is well established. Whereas there is evidence that the most demanding applications, such as low temperature epi and its cleaning gases, will continue to benefit from improvements in purity as deposition temperatures are lowered, this is expected to be reflected in wider use of the best available purity rather than substantial improvements of those levels.

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

More detailed consideration of the impurity levels found in the growing number of novel materials used in processing will be increasingly important. Requisite purity levels for critical materials such as novel metal oxides, chemical mechanical planarization (CMP) slurries, low/high κ dielectric materials, precursor materials (used in CVD, ALD, and electroplating solutions) for barrier and conductor metals (such as Cu, Ta) have not been widely studied, and many of these materials have not been called out in Table 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 is often required to prevent decomposition that can contribute detrimental molecular and particulate impurities. Traditionally bulk purifiers were used in the bulk gas delivery systems to remove particles and other homogeneous chemical contaminations like oxygen, or moisture present in the supply gases. However, with the development and commercial availability of POU purifiers, there is a strong interest from end users to utilize POU purifiers particularly for specialty gases needed for critical process steps with very critical level of contamination control. These point-of-use purifiers POU are highly effective to remove chemical contaminants to extreme low level (~ ppt), easy to use, easy to replace, with low cost-of-ownership. The capability of placing those POU purifiers very close to inlet of process chamber, assures least travel path (less contamination) for process gases after chemical purification and filtration.

1.1.3.1.1. LIQUID CHEMICALS

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

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

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

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

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

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

1.1.3.2. ALD/CVD PRECURSORS

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

For the clear majority of semiconductor processes, gaseous reactants are delivered to the processing chamber at atmospheric or super atmospheric pressures. However, for most ALD processes, the precursor is delivered at pressures typically in the range

of 5 Torr to 100 Torr to the reactor, which is processing typically less than 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. Original equipment manufacturers (OEMs) and precursor suppliers should keep these complexities in mind when designing or modifying precursor delivery sub-components and systems. Semiconductor manufacturers should consult with their suppliers if they are interested in re-engineering or adapting their precursor delivery systems since changing the pressure drop or flow dynamics of a vapor delivery system for a sensitive precursor may have unintended negative consequences.

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

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

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

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

1.1.3.3. CRITICAL COMPONENTS

The roadmap for cleanliness of critical components does not currently exist. The technology related to critical components focuses on the semiconductor manufacturing process. The cleanliness requirements have not been effectively standardized. SCIS defined the need to improve definitions for the cleanliness and establish adequate standards.

1.2. DRIVERS AND TECHNOLOGY TARGETS

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

- It has tighter pitch size than that of other types of semiconductor products
- Advanced Flash manufacturing is transitioning to 3D structure where the pitch equivalent is almost an order of magnitude larger than that of Logic
- Logic has significantly more metal layers and higher complexity, increasing risks to yield
- Logic has less redundancy compared to Flash memory
- Flash has self-alignment – that is not available for logic

This year roadmap effort conducted extensive analysis of the possible defect occurrence as function of the device structure. As a result, the term EAP (electrically active particle) was introduced. Although critical particle size is still based on 50% of ½ pitch design rule, this rule is applied for electrically active particles only, assuming that "bridging" can be caused by particles smaller than the ½ pitch size. All other particles are not expected to become a device "killer" until their size exceeds ½ pitch.

1.3. VISION OF FUTURE TECHNOLOGY

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

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

2. SCOPE OF REPORT

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

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

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

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

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

This report also provides continuity with the relevant details of the previously published 2015 ITRS 2.0 materials as well as connection between the IRDS roadmap and SEMI Standards.

Logic technologies have more disruptive nature in their development and therefore typically follow bi-annual cycle. Hence Yield Enhancement Table YE3 shows technology change every two years. This means that in between those years of change, we will show frozen state of technology requirements.

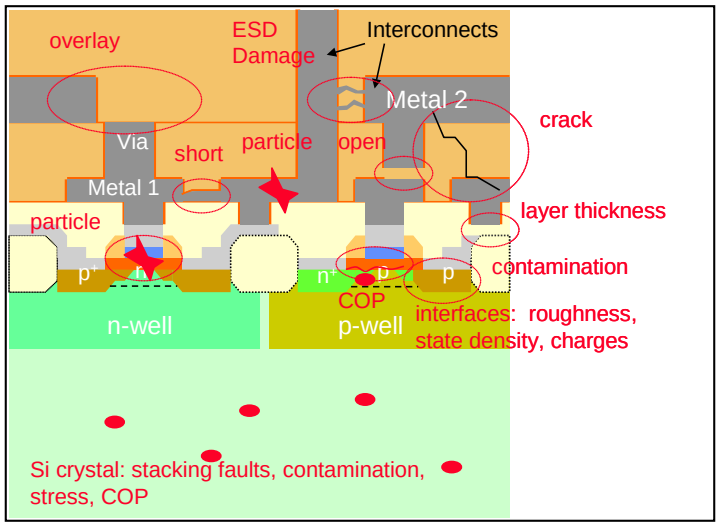

Figure YE3 Yield Enhancement Scope

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

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

The YE section has two focus topics: “Surface Environment Contamination Control” and “Characterization, Inspection and Analysis.” These two topics crosscut front end process technology, interconnect processes, lithography, metrology, design, process integration, test, and facility infrastructures.

Surface Environment Contamination Control – Although most of the parameters in Table YE3 table do not require significant improvements, nor they indicate challenges in process critical fluid and gas impurity control, some parameters present a serious technology challenge. New materials and their precursors introduce challenges that require continuous study. Clarification of potential contamination from point-of-supply to point-of-process will define control systems necessary for delivered purity. There are several locations in the pathway from the original delivery package, *i.e.*, the Point of Supply (POS) of a liquid or gas to the location where that material contacts the wafer, *i.e.*, the Point of Process (POP), for ascertaining purity. This has led to a considerable amount of confusion and ambiguity in discussing the quality of process fluids, including the data found in Table 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 in the Appendix and sources in the References section, such as the Semiconductor Equipment and Materials International (SEMI) Standards.

Table YE1 Definitions for the Different Interface Points

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

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

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

3. SUMMARY AND KEY POINTS

It is recommended that the reader of the IRDS Yield Enhancement Chapter reviews this narrative along with other materials and particularly Table YE3, including associated notes. It is important to keep in mind that although the values in the roadmap were defined based on empirical data and modeling, there is no sufficient grounds to justify specific technological decision, which are expected to be made by the technology end users based on the process specific sensitivities and requirements.

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

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

4. CHALLENGES

4.1. NEAR-TERM CHALLENGES—CIA

Currently, one of the important key 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 another challenge with high priority the requirement for 3D inspection was identified. This necessitates for inspection tools with the capability to inspect high aspect ratios but also to detect non-visuals such as voids, embedded defects, and sub-surface defects is crucial. The demand for high-speed and cost-effective inspection tools remains, especially in the area of 3D inspection as the importance of 3D defect types increases. In subchapter to Characterization, Inspection and Analysis another key challenge was identified: detection of organic contamination on surfaces – the detection and characterization of non-volatile organics on surfaces is currently not possible in the fab. There are few laboratories or fab scale instrumentation available or implemented except ToF-SIMS, and XPS.

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

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

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

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

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

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

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

- Inline defect characterization and analysis

The difficult challenges for the Yield Enhancement chapter are summarized in Table 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 contamination types and levels to yield and to determine the required control limits. The issues for this challenge are to define the relative importance of different contaminants to wafer yield, a standard test for yield/parametric effect, and a maximum process variation (control limits). The fundamental challenge is to understand the correlation between impurity concentration in key process steps and device yield, reliability, and performance. This correlation will determine whether further increases in contamination limits are truly required. The challenge increases in complexity as the range of process materials widens and selection of the most sensitive processes for study will be required for meaningful progress.

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

- Inline defect characterization and analysis
- Next generation lithography

Table YE2 Yield Enhancement Difficult Challenges (CIA)

Difficult Challenges 2019–2023	*Summary of Issues*
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.	• 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?

Table YE2 Yield Enhancement Difficult Challenges (CIA)

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.	• 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: 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.
Difficult Challenges Beyond 2023	*Summary of Issues*
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.	• 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.
Inline 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 inline 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]	• 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.	

Table YE2a Yield Enhancement Difficult Challenges-2018- SECC

Near-Term Difficult Challenges: 2019–2023	*Description*
Challenge #1 Control of electrically active and other particles in ultrapure water and liquid chemicals for advanced semiconductor manufacturing (logic key driver)	Insufficient metrology and marginal treatment technology capability
Challenge #2 Control of electrically active and other particles in UPW of EUV mask production	Insufficient metrology and marginal treatment technology capability
Challenge #3 Critical organics in UPW	Insufficient metrology for online speciation of organics
Challenge #4 Metals in H2O2	Insufficient metrology capability. Characterization needed for specific critical metals for key process steps and segments.
Challenge #5 Slurry particle characterization and other impurity monitoring	Insufficient metrology capability
Challenge #6 Plating chemicals: particles > critical size (>0.150um) (#/ml)	Need reliable monitoring of large particles
Challenge #7 Liquid chemicals: particles > critical size (#/ml)	Need reliable monitoring of particles <10 nm. Need Filtration technology that is reliable at the stated retention rating and that has minimal "rise up" contributions at the time of install into the process.
Challenge #8 CMP slurries: large particles > MPS (#/ml)	Need reliable LPC metrology that can measure targeted particles sizes and concentrations that ignore the MPS sizes and do not require sample dilution to obtain the measurement.
Challenge #9 Post-CMP (pCMP) cleans particles	Some pCMP cleans will have volatile or highly reactive ingredients that form bubbles in solution, therefore; new metrology and new techniques will be needed to differentiate between bubbles and real particles for contamination control. The pCMP cleans that contain surfactants will have micelle particles and structures that are necessary for the chemistry to perform the intended function. The need is for reliable and accurate metrology to distinguish micelles from other foreign particles in solution.
Challenge #10 Particle measurement for ISO class 1	Need more efficient and effective laser particle counters with detection limit << 100 nm or CPC with sample flow >> 0,1 cfm
Challenge #11 AMC metrology	Need of more sensitive gas analyzers for HCl, HF, HNO_3, HBr, NH_3, Total Acids, H_2S, SO_2, organic acids, sulphuric acids and Total bases with detection limit << 100 ppt
Challenge #12 Particle contribution by critical components and its control	Insufficient analytical capability and unknown level of cleanliness
Challenge #13 Critical metals in UPW for CMOS image sensors	Insufficient metrology sensitivity beyond 200 ppq concentration

4.2. SURFACE ENVIRONMENTAL CONTAMINATION CONTROL

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

Table YE3 Technology Requirements for Surface Environmental Contamination Control

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

Airborne molecular contamination (AMC)—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, O_3) 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 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 in the Appendix. Table YE4 and YE4a provide more detail for AMC monitoring and on-line methods.

Table YE4 AMC Monitoring Methods

Table YE4a Supporting Table for On-line Methods

Numerous studies related to AMC outgassing from the materials of construction of environmental enclosures and FOUPs have been performed to guide material selection for these enclosures. Beyond proper material choice the need for pumping and nitrogen purging of wafer environment enclosures is further investigated for critical process steps to diminish cross-over of contamination from different process steps by FOUPs. The potential for AMC to impact new processes should be considered in all process integration studies.

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

This is specifically true where disruptive, revolutionary techniques are introduced into the manufacturing chain. For example, future lithography systems require vacuum processing and are not expected to impose new AMC control requirements in the clean room environment. However new challenge compounds are identified for the tool interior that may require novel air and purge gas treatments.

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 ± 0.03 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 optical 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 sub-fab and not in the main cleanroom.

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.
- 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 week's 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".

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

The FOUP is a plastic container that stores and carries 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/cm^2. 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. Table YE3

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 the following: 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 regard 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

4.2.2. 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 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—Despites 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 FOUP 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 1× 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 arrive 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 form 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.

4.2.3. 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 193 nm 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 is 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 depends 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.

4.2.4. CRITICAL COMPONENTS

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

The challenge of such particle quality control is due to the limitations of the existing analytical techniques and related metrology to qualify high purity components. Currently used SEMI F057[5] and SEMI F104[6] methods only measure particles of the size of 100 nm and larger. There is a need for 10nm particle measurement of the components shedding. Metrology for such analysis does not currently exist, although new non-optical particle detection techniques are being developed for detecting 10nm and smaller particles. Application of the Power Law from 100 nm to 10 nm and less has not been demonstrated and hence cannot be assumed to hold true. Ability to measure 10nm particles is critical to gaining actual understanding of particle performance for critical components.

4.2.5. ULTRAPURE WATER QUALITY

Ultrapure water – Specific definitions of the water quality requirements to enable future technology are presented in the Table YE3. Critical challenges are summarized in Table YE2a.

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. Section 1.1.1 provides an explanation of the proactive approach used in UPW.

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

More stringent criteria beyond 2018 are only projected where there is evidence that manufacturing process requirements demand improvements. UPW is generally the cleanest fluid available in the manufacturing process. Limited data is currently available to correlate contamination level to device yield. For this reason, the UPW Roadmap for contamination tolerance is relatively stable over time.

The UPW section of Table YE3 considers some parameters as process variables rather than contaminants. The stability of the wafer processing environment can be as important as the level of contaminants present for some parameters. For example, some semiconductor manufactures treat dissolved oxygen (DO_2) in this way, while others consider it a contaminant. Stability of temperature continues to be important for immersion lithography.

For 2018 some commonly monitored parameters such as resistivity and bacteria are not included in the table, as they do not represent technology challenges and are only used for monitoring operational performance of the UPW systems. These parameters are critical for the water quality, but non-critical for the future technology enabling. Bacteria can be controlled down to a level of non-detect and the resistivity has become not sensitive enough to monitor water quality variation within the ranges targeted for the ionic species in UPW.

UPW parameters were reviewed for the 2018 roadmap for the specific location where they are critical to maintaining semiconductor yield. The notes to the Table YE3 contain definitions for these parameters. Some parameters are specified for point of process (POP), while the others are specified in different locations. The definitions are driven by the consideration of whether the tool environment may further contribute to changes in those parameters.

4.2.5.1. PARTICLE CONTAMINATION IN UPW

The focus has turned more to critical parameters such as particles, metals, and organic compounds. Particles remain a high and growing risk, critical for implementing future semiconductor technology due to its high sensitivity to decreasing line widths. On-line metrology for particles in liquid does not address killer particle size, and therefore, filtration efficiency for killer particles is not known. At the same time, it is apparent that the killer size of the particles has approached filtration capability of the most advanced final filters. Furthermore, there is some test data suggesting the particle challenge concentrations to the final filters from UPW system components can be much higher than previously believed (Refer to SEMI C79[7] and SEMI C93[8] for filter performance test data and UPW Polish ion exchange particle shedding, respectively).

Detailed analysis provided with input from More Moore suggested that the higher criticality of the electrically active particles (EAP) compared to other particles. This difference is reflected in Table YE3.

Particles continue to be important for EUV mask operation due to the effect the EUV mask defect has in semiconductor manufacturing, replicating dozens of thousands of time during life of the mask. The mask is expected to be defect free that requires particularly tight particle control in mask production. It is important to note that the killer size of the particles on mask is independent of the device pitch size, but rather a function of the EUV wavelength (refer to the sizes of killer particles in Table YE3).

Colloidal silica, long considered as delta between total and reactive silica has been removed from the roadmap. This is despite the fact that experimental work further confirmed high criticality of this parameters. Colloidal silica is now considered and treated as a particle, subject to the particle specification in the table. If colloidal silica particles are controlled to the particles specification, all measurable silica in UPW will be in the form of dissolved silica. Hence the value for a total silica specification remains (total silica = dissolved/reactive silica). Reactive silica concentration is limited due to its negative impact on device yield, forming water marks on the wafer. In this case, reactive silica specification can be measured using either total silica

analyses methods (i.e., ICP-MS) or as reactive silica (by colorimetric method) to the level specified in the table. For practical purposes, measuring total and reactive silica may be considered to confirm no presence of colloidal silica.

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

4.2.5.2. METAL CONTAMINATION IN UPW

The 2018 IRDS roadmap has revisited its approach to metal specification. The details of the new approach are provided is the white paper linked in the Appendix. The current approach includes special considerations for CMOS image sensors. New parameters for critical metals for image sensors have been introduced. Target levels of critical metals is redefined. For some metals this target level is below limits of detection of most advanced metrology.

4.2.5.3. ORGANIC CONTAMINATION IN UPW

There has been an increased interest in the past few years to understand how organic contamination of UPW may affect semiconductor devices. Organic contamination is currently measured in terms of its total organic carbon content or TOC. This measurement of the organic content does not account for the type of organic and how it may react with various wafer surfaces or how the reaction may impact device yield. In place of TOC we are now categorizing organic compounds in UPW for critical and non-critical based on their boiling point. Immersion lithography lens hazing was previously a driver of UPW TOC<1.0 ppb.

The 2018 Yield roadmap maintains a separate line for immersion lithography TOC (<1.0 ppb), implying that this may be required as POU definition, while the rest of the water quality spec was relaxed to 3 ppb of non-critical organics. We continue working on a new definition of critical organics, based on polar strength as quantified using boiling point. The definition of the critical organics was included in the table notes, which recommend end users to consider characterization of the UPW organics in their own specs. New metrology is needed for on-line detection of the critical organics.

- Critical Organics – non-volatile polar organic compounds with boiling point >200°C
  - Critical organic compounds should be controlled to <1 ppb
  - Organic compounds are categorized as critical with respect to its ability to form a hydrogen bond with any oxide surfaces including gate, tunnel, or native oxide
  - Total non-critical organic compounds should be controlled to <3 ppb
- Critical carbon atoms on wafer related to TOC in bulk fluid
  - Defined by FEP as $1xE\text{-}^{12}$ atoms/cm^2 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 previously defined by FEP as 200°C
  - UPW IRDS group is looking at compounds with lower boiling point that may be related to other defects

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

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

UPW measurement methodologies—General test methodologies for monitoring contaminants in UPW are indicated in the Figure YE2 below. Over the past few years the UPW IRDS team has benchmarked many advanced UPW systems to determine

water quality. Past benchmark efforts have identified the inadequacy of some measurement methodologies to quantify contaminants in the UPW. Sensitivity of the following methods is presently adequate: viable bacteria, dissolved gasses, ions, total organic, and metals. While particle measurement is not adequately sensitive to validate quality at the critical dimension it continues to be a valuable tool to detect filtration failures.

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

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

Figure YE4 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.

4.2.6. THE PARTICLE SENSITIVITY PROBLEM

The highest sensitivity laser on-line particles counter commercially available for both UPW and liquid chemicals is 0.02 microns. Even at this size the detection efficiency is only 2–5%, so most particles at 0.02 microns and smaller go undetected. Improvements in particle counter sensitivity for UPW have been accomplished by increases in laser power. While improvements in sensitivity for liquid chemical particle counters are viable, further sensitivity improvements for UPW using this approach are unlikely, due to the significant cost implications. There is an ongoing effort to develop alternative technologies to the optically based particle counters. To estimate the concentration of smaller particles in chemicals, currently an extrapolation is made that assumes a $1/d^3$ 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. Power low is not currently used/recommended for specification of the critical liquid chemical and UPW quality. However, the use of power law is considered to be effective for the Critical components as particles contributes by those components are not affected by filtration (in contrast with UPW and chemicals).

4.2.7. 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. Refer to SEMI F063 for additional information on particles monitoring in UPW.

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[9]. 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 chapters within the IRDS and other organizations such as SEMI that focuses on them. This helps to clarify the relationship of these organizations with the WECC while also removing ambiguity about the definition of various points along the process path.

While purity measurements at the Point of Process, POP (that is, in the processing chamber itself), would provide the most direct correlation between gas or liquid quality and process performance, these measurements are often 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[10], 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[11], 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 poling of several large semiconductor manufacturing organizations suggests that an increase above current purity requirements for the majority of bulk gases is not necessary to meet post 45 nm design rule manufacturing. For very special applications where extraordinarily higher purities are critical, special purity grades or additional purification will be required. As exemplified above, downstream POUP might also be utilized as an additional means of removing variability in POS gases. Therefore, Table 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.

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. 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 Surface Environmental Contamination Control (SECC) is warranted.

For the vast majority of semiconductor processes, gaseous reactants are delivered to the processing chamber at atmospheric or super atmospheric pressures. However, for most ALD processes, the precursor is delivered at pressures typically in the range of 5 Torr to 100 Torr 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 decomposition at these temperatures and extra care should be taken to adjust the size of the on-board source canister to consume the source before process deteriorating decomposition starts. In many cases smaller heated onboard source canister that is refilled by a bulk deliver system or a liquid injection system without tank are preferred solutions.

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

Downstream of the ALD reactor, the relatively low vapor pressure ALD precursors and process by-products tend to condensate at 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 in the Appendix. The precursor table provides information by application as to which precursors are potential candidates at different technology generations, and the nature of contamination that can be expected. A major challenge is the development of accelerated yield learning for critical processes that introduce new precursors that will only be used for one or two generations.

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

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

For some processes, such as advanced lithography, very small quantities of “high molecular weight/high boiling point” (*e.g.*, C_6-C_{30}) 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 C_6 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 C_6 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 O_2 and H_2 generally tolerate higher levels of N_2 contamination than other contaminants, however, H_2 as a carrier for Epitaxy now requires more stringent N_2 levels and the table reflects this observation. Requirements for critical clean dry air (CDA), lithography purge gases, and supercritical CO_2 supply are included. Whereas critical CDA may not always be conveniently or cheaply available, there is no technological barrier to its production. Analytical methods are usually the same as used for airborne molecular contamination in clean room air, such as bubbling through ultra-pure water (for metals, 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 SO_2 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 increased 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.

4.3. Characterization, Inspection and Analysis

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

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

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

The detailed requirements are presented in Table YE5.

Table YE5 Yield Requirements for MEMS Production

4.4. Long-term Challenges

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

5. Technology Requirements

5.1. Summary

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

The Yield Enhancement Technology Requirements include definitions of the yield characterization, inspection, and analysis, as well as definitions of the level of impurities of the materials and environments used in semiconductor manufacturing. Table YE3 provides a list of the parameters and their level that needs to be controlled to ensure minimum of 80% yield. Those parameters define both the technology necessary to achieve those level (i.e., purification) and metrology necessary to monitor those parameters. In cases where metrology does not exist, it is required that the yield will be ensured by either tighter process control measures or by tight material quality control throughout associated supply chain, based on SEMI Standards.

6. POTENTIAL SOLUTIONS

6.1. GENERAL

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

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 critical device dimensions for advanced semiconductor manufacturing. 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. 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—Studies into device impact are necessary to validate any need for increased purities. System concerns such as corrosion or haze 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.

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

Surface Environment Control—As the list of ambient contaminants to be controlled broadens so must measurement capabilities. Affordable, accurate, repeatable, real time sensors for non-particulate contamination are becoming increasingly necessary. 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. Wet clean and etch, tool environments have also transitioned that may need to single-wafer and use of closed processing systems are becoming more prevalent for corrosion sensitive layers 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 of volatile contaminants, and non-absorbing materials development are a key to effective wafer isolation deployment.

6.2. 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 YE5 and YE6. 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 YE5 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—Effect of UPW quality to wafer defects for most advanced device geometries is unknown. Particles (including colloidal silica) are considered to be high risk. Potential solution for the particle control is due to reduction of the particle challenge in the final filters and application of the POU filtration, providing additional layer of protection. Use of SEMI C079 and SEMI C093 guides are recommended for the particle challenge reduction. Proactive colloidal silica control using frequent regeneration of the ion exchange resin is also recommended.

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

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

Chemicals—Figure YE5 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:

Substrate 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.

	SUBSTRATE		SUBSTRATE LOCATION								
First Year of IC Production DRAM 1/2 Pitch	WAFER	RETICLE	STORAGE	PROCESS	TRANSPORT	2017 20nm	2018 18nm	2019 16nm	2020 14nm	2021	2022
New FOUP Outgassing / Contamination											
Off line AMC measurement in laboratory	X	0	X	0	0						
Inline AMC measurement inside FOUP in fab	X	0	X	X	X						
Inline AMC measurement inside 450mm FOUP and MAC in fab	X	0	X	X	X						
Used FOUP Outgassing / Contamination (no wafer inside)											
Off line AMC measurement in laboratory	X	0	X	0	0						
Inline AMC measurement inside FOUP in fab	X	0	X	X	X						
Inline AMC measurement inside 450mm FOUP and MAC in fab	X	0	X	X	X						
Vacuum purge and heating	X	0	X	0	0						
Wafer Cross Contamination Inside FOUP (e.g acids after dry etch, oxygen or humidity before EPI clean)											
Inline AMC measurement inside FOUP in fab	X	0	X	X	X						
Integrated AMC measurement inside load port	X	0	0	X	0						
Vacuum purge : outgass the FOUP with wafers under vacuum and fill it with N2	X	0	X	0	X						
N2 purge station : injection of N2 inside FOUP with wafer	X	0	X	0	X						
N2 purge station integrated in stocker : injection of N2 inside FOUP with wafers	X	0	X	0	0						
FOUP change : wafer transfer in a clean FOUP during q-time	X	0	X	0	X						
Purgeable load port : injection of N2 when the FOUP is connected to the EFEM	X	0	0	X	0						
Outgassing chamber integrated in process equipment	X	0	0	X	0						
Wafer transfer under vacuum	X	0	0	X	X						
Wafer environment (outside of pod)											
Off line AMC measurement in laboratory	X	0	X	0	X						
Inline AMC measurement of WE	X	0	X	X	X						

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Research Required
Development Underway
Qualification / Pre-Production
Continuous Improvement

Figure YE5 Wafer Environment and Reticle Environment Contamination Measurement and Control Potential Solutions

First Year of IC Production	2017	2018	2019	2020	2021
Logic 1/2 pitch, nm (contacted)	18	18	14	14	12
GENERAL					
Fluid purity impact on device yield / performance					
Contaminant based process control					
Critical Components					
Particle quality analysis of the critical components, 10 nm [A]					

Drivers:
[A] killer particle control
[B] critical particle effect
[C] critical particles and organics
[D] critical organics

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Research Required
Development Underway
Qualification/Pre-Production
Continuous Improvement

Figure YE6 Substrate Environment Contamination Control Potential Solutions—Critical Components

First Year of IC Production	2017	2018	2019	2020	2021
Logic 1/2 pitch, nm (contacted)	18	18	14	14	12
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]					
Mitigation measures to control EAP (electrically active particles) [A]					
Mitigation measures to control High Molecular Weight Polymers [C]					
On-line detection of the critical organics (non-volatile) needs development [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					
Need to better define effect of Metal in UPW to image sensors					

Drivers:
[A] killer particle control
[B] critical particle effect
[C] critical particles and organics
[D] critical organics

This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Research Required	
Development Underway	
Qualification/Pre-Production	
Continuous Improvement	

Figure YE7 Substrate Environment Contamination Control Potential Solutions—UPW

First Year of IC Production	2017	2018	2019	2020	2021
Logic 1/2 pitch, nm (contacted)	18	18	14	14	12
GENERAL					
Fluid purity impact on device yield / performance. Requirements are specific to the chemistry and the Process step that it is used for.					
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)					
Micelle particle size and concentration characterization [B] for surfactant containing chemistries.					
Bubble discrimination of reactive chemistries [A]					
Improved metrology for concentration measurements [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. (Agglomertaes, Foreign Material) [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 µm with high flux (1 gpm/0.5 psi/10"/1cP) [A]					
Filtration sub 0.02 µm with high flux (1 gpm/0.5 psi/10"/1cP) [A]					
Filtration sub 0.01 µm 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 reliabilitiy) [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.

Research Required
Development Underway
Qualification/Pre-Production
Continuous Improvement

Figure YE8 Substrate Environment Contamination Control Potential Solutions—Liquid Chemicals

6.3. CHARACTERIZATION, INSPECTION AND ANALYSIS

For the challenges of MEMS production, the potential solutions for infrared inspection of metal wafers will be to switch to other technologies like thermography, photoacoustic, or ultrasonic in the future. Possible solutions for critical dimension (CD)

scanning electron microscopy (SEM) measurements under angle on silicon on glass could be the use of special structures, the use of reduced beam intensity, or the use of gas as option to discharge.

7. CROSS TEAMS

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

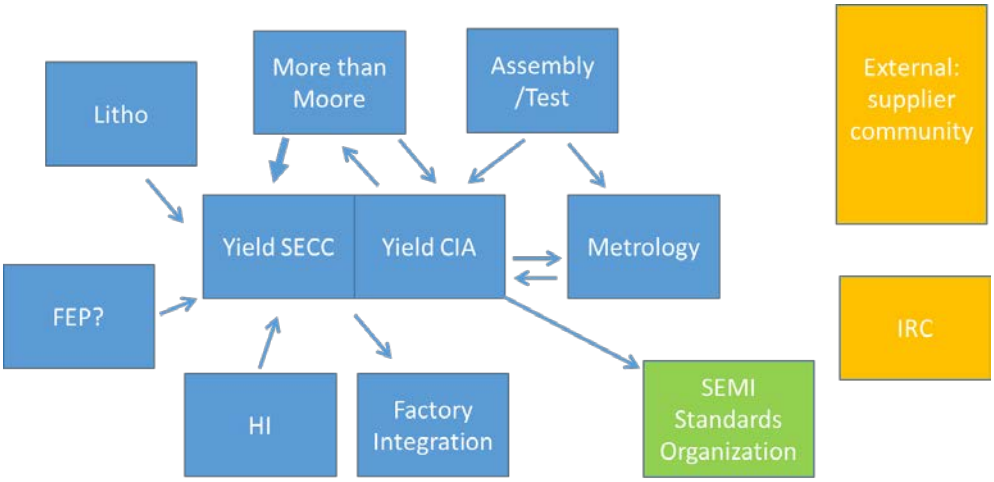

Figure YE9 Yield Enhancement IFT Cross Team Linkage Diagram

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

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

8. EMERGING/DISRUPTIVE CONCEPTS AND TECHNOLOGIES

8.1. DIRECTED SELF ASSEMBLY

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

9. CONCLUSIONS AND RECOMMENDATIONS

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

- Proactive measurement of contamination control of the critical materials used throughout the supply chain;
- Leveraging data analytics to correlate process variation in production with any deviations in critical parameters;

- Employ prediction modeling and experimentation to help with decisions on the choice of the technologies and method of their applications at all levels of the manufacturing facility.
- Standardize quality control using SEMI and other standards
- Take advantage of collaborative development in the industry via IRDS, SEMI, and other research institutions to drive most productive technology solutions related to the SECC. Assist emerging metrology to commercialize via benchmarking studies and independent third-party qualifications.

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

10. APPENDICES

10.1. APPENDIX A—SUPPLEMENTAL MATERIALS

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

Title	File Name
Metals Spec in UPW, White Paper by Drew Sinha and Slava Libman	Metals_WP.doc
AMC Monitoring Program	AMC_MonitoringProgram_011209AG
AMC Integrated Concept	FI_AMC_Integrated_concept_052510.ppt
Precursor Table	1403_14rev2master_precursor_table_2013.doc

10.2. APPENDIX B—ACRONYMS

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

Acronym/Abbreviation	*Definition*
HMW	high molecular weight
HVM	high volume manufacturing
ICP-MS	inductively coupled plasma mass spectrometry
IMS	ion mobility spectrometry
IRDS	International Roadmap for Devices and Systems
ISO	International Standards Organization
LCOCD	liquid chromatography: organic carbon detection
LMW	low molecular weight
LPC	laser particle counter
MEMS	microelectromechanical system
MFC	mass flow controller
MPS	mean particle size
MS	mass spectrometry
NEXAF	near edge x-ray absorption fine structure
O=C=S	type of chemical compound containing oxygen, carbon, and sulfur
OEMs	original equipment manufacturer
pCMP	post-CMP or post chemical mechanical planarization
PID	photo ionization detector
POD	point of delivery or point of distribution
POE	point of entry
POP	point of process
POS	point of supply
POU	point-of-use
POUP	POU purification
ROI	return on investment
SAW	surface acoustic wave
SECC	surface environment contamination control
SEM-EDS	scanning electron microscopy - energy-dispersive x-ray spectroscopy
SEMI	Semiconductor Equipment and Materials International
SMC	surface molecular contaminant
SMLY	systematic mechanisms limited yield
SPC	statistical process control
TD	thermal desorption
TEOS	Tetraethylorthosilicate
TOC	total organic carbon content
ToF-SIMS	time-of-flight - secondary ion mass spectroscopy
UF	ultra-filtration
UPW	ultrapure water
UV	Ultraviolet
VC-D	vibrational circular dichroism
VMB	valve manifold box
VMP	valve manifold post
WECC	wafer environment contamination control
XCDA	Extreme clean dry air
XPS	x-ray photoelectron spectroscopy
YE	Yield Enhancement

11. REFERENCES

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

[3] Thompson, L. F.; Willson, C. G.; Bowden, M. J. Introduction to microlithography, 2nd ed.; American Chemical Society: Washington, DC, 1994.

[4] SEMI MF 1982-1103 (formerly ASTM 1982-99

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

[6] SEMI F104 – Particle Test Method Guide for Evaluation of Components Used in Ultrapure Water and Liquid Chemical Distribution Systems

[7] SEMI C79-0113 - Guide to Evaluate the Efficacy of Sub-15 nm Filters Used in Ultrapure Water (UPW) Distribution Systems

[8] SEMI C93-0217 - Guide for Determining the Quality of Ion Exchange Resin Used in Polish Applications of Ultrapure Water System

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