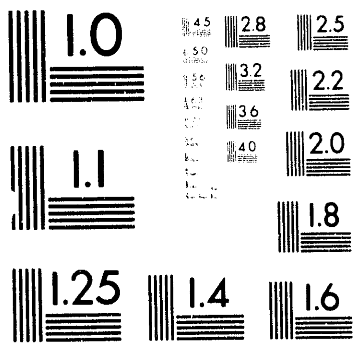
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Sensors For Process Control Focus Team Report *

CFM FTAB Meeting
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Background and Objective:

At the Semiconductor Technology Workshop, held in November 1992, the Semiconductor Industry Association (SIA) convened 179 semiconductor technology experts to assess the 15-year outlook for the semiconductor manufacturing industry. The output of the Workshop, a document entitled "Semiconductor Technology: Workshop Working Group Reports", contained an overall roadmap for the technology characteristics envisioned in integrated circuits (ICs) for the period 1992-2007 (Table 1). In addition, the document contained individual roadmaps for numerous key areas in IC manufacturing, such as film deposition, thermal processing, manufacturing systems, exposure technology, etc.

The SIA Report did not contain a separate roadmap for contamination free manufacturing (CFM). A key component of CFM for the next 15 years is the use of sensors for (1) defect reduction, (2) improved product quality, (3) improved yield, (4) improved tool utilization through contamination reduction, and (5) real time process control in semiconductor fabrication. The objective of this Focus Team is to generate a Sensors for Process Control Roadmap. Implicit in this objective is the identification of gaps in current sensor technology so that research and development activity in the sensor industry can be stimulated to develop sensor systems capable of meeting the projected roadmap needs.

Sensor performance features of interest include detection limit, specificity, sensitivity, ease of installation and maintenance, range, response time, accuracy, precision, ease and frequency of calibration, degree of automation, and adaptability to in-line process

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OVERALL ROADMAP TECHNOLOGY CHARACTERISTICS

	1992	1995	1998	2001	2004	2007
Feature size (μm)	0.5	0.35	0.25	0.18	0.12	0.10
Gates/chip	300K	800K	2M	5M	10M	20M
Bits/chip						
– DRAM	16M	64M	256M	1G	4G	16G
– SRAM	4M	16M	64M	256M	1G	4G
Wafer processing cost ($/cm^2)	$4.00	$3.90	$3.80	$3.70	$3.60	$3.50
Chip size (mm^2)						
– logic/μprocessor	250	400	600	800	1000	1250
– DRAM	132	200	320	500	700	1000
Wafer diameter (mm)	200	200	200–400	200–400	200–400	200–400
Defect density (defects/cm^2)	0.1	0.05	0.03	0.01	0.004	0.002
No. of interconnect levels — logic	3	4-5	5	5-6	6	6-7
Maximum power (W/die)						
– high performance	10	15	30	40	40–120	40–200
– portable	3	4	4	4	4	4
Power supply voltage (V)						
– desktop	5	3.3	2.2	2.2	1.5	1.5
– portable	3.3	2.2	2.2	1.5	1.5	1.5
No. of I/Os	500	750	1500	2000	3500	5000
Performance (MHz)						
– off chip	60	100	175	250	350	500
– on chip	120	200	350	500	700	1000

Table 1. SIA Overall Roadmap Technology Characteristics.

control applications. It is essential that the right kinds of sensors, monitoring the contaminants and particles of interest in process tools and supply lines, contribute to improvements in semiconductor products through defect reduction (with concomitant improvements in product quality), improved tool utilization through contamination reduction, and reduction in cost-of-ownership (COO) of process equipment. As an example, and using Table 1 as a reference, the use of sensors in real time process control must be able to contribute to the goal of achieving defect densities below 0.002 defects/cm2 by the year 2007. The goals stated above can be achieved by targeting the use of sensors in equipment and processes where defect reduction has high leverage.

We have based the requirements for different sensor technologies on (1) the various SIA Roadmaps expected to be impacted by development of improved sensor systems, and (2) the Microcontamination Roadmap developed at the MICRO TECH 2000 Workshop held in April 1991 (Table 2). The roadmap presented here can serve as a guide to new research and development activities by providing a basis for new technologies (or a basis for extending the limits of existing technologies) as well as establishing the criteria for new calibration procedures and standards. There is also the obvious need to drive the cost of sensors down by simplifying sensor designs, and improving modularity, interchangeability, and data communication.

Our focus in the remainder of this paper is to provide definitions outline the needs and requirements in the area of sensors for process control, and make initial recommendations as to how these needs can be addressed in an efficient manner.

Definitions:

A **transducer** is a device that converts one form of energy to a second form of energy that is useful for measurement purposes. In this manner, transducers can be used to detect acoustic energy, biological properties, chemical species, electrical properties, magnetic fields, mechanical properties, optical energy, radiation, thermal properties, and particulates, to name a few. A **sensor** consists of one or more transducers connected to the first level of electronic drive and signal processing circuitry. For the purpose of this study, the Focus Team considers sensors to be small in size and suitable for use in in-line and in situ monitoring. A sensor is also considered to be inexpensive in order to distinguish it from analytical instrumentation, which is capable of multi-species analyses and is generally used off-line in a laboratory setting. It is necessary to further define what is meant by inexpensive. It is expected that the types of sensors required to meet future microcontamination and IC technology roadmap goals will be in the $5,000-$80,000 range; however, the most important measure of the cost effectiveness of the sensor is the return on investment (ROI). It is believed that the targeted ROI will have to be in the 6 month time frame to make the sensor attractive for purchase. ROI will be realized in the form of increased yield, better product quality, elimination of the need for monitor wafers, etc.

Monitors are instruments that contain sensors and their associated electronics and can

TABLE II. Microcontamination Roadmap

Year Required	1991	1994	1997
Cleanroom	35 particles.ft^3 at 0.1 μm	1 particle/ft^3 at 0.08μm	1 particle/ft^3 at 0.03μm
Liquids	<50 particles/ft^3 at >0.5μm	<50 particles/ft^3 at 0.007μm	<2 particles/ft^3 at>0.03μm
Gases	<10 particles/ft^3 at >0.03 μm	<0.1 particle/ft^3 at >0.03μm	<0.05 particles/ft^3 at >0.03μm
Cationic Species	<10 parts per billion	<100 parts per trillion	<5 parts per trillion
Trace Impurities in Gases (N_2)	<10 parts per billion	<100 parts per trillion	1 part per trillion
% Vapor vs. Liquid Cleaning	0%	30%	60%
Contamination Level (Fe per cm^2, after clean)	$<5 \times 10^{11}$	$<1 \times 10^{10}$	$<1 \times 10^{8}$

Table 2. Microcontamination Roadmap

These levels are detection limits of "pure" fluids (gases, chemicals, air, etc.) as in the bottle, cylinder, distribution piping, or cleanroom. These levels do not represent levels inside process equipment and hence are not applicable to process control. In addition, the roadmap needs to meet both process and sensor requirements. Several of the specifications in this table are not realistic because it will take hours of testing to sample a cubic foot or in some cases even a milliliter. There is a need in process control for quick results.

be interfaced to the process to provide real time process control (e.g., alarm, feedback to the operator, automatic process parameter change, etc.). As a rule of thumb, monitoring system cost can be > $50,000 but the cost to monitor any individual process equipment should be < $100,000. It should be noted here that some point-of-use (POU) analytical monitors will fit the above definition of sensors and will be included in this roadmap.

Needs:

According to the SIA Roadmap, sensors will be needed to support technologies in the following "Working Group" areas. In every case, the status of the technology will require careful assessment as to current availability, return on investment, impact on yield, and crucial areas for future research, development, commercialization, and implementation. This Focus Team, as well as the SEMATECH CFM FTAB, should provide guidance and prioritize recommendations in order to shorten the time required for commercialization of new sensor technologies for process control.

* In the following categories, an asterisk indicates areas where sensors are utilized but are not included in sensors for process control roadmap.

Materials and Bulk Processes

1. Starting material dimension and temperature sensors.
   a. Optical sensor for silicon boule diameter (may already exist in an acceptable form).
   b. Optical temperature sensor for silicon boule during growth (may already exist in an acceptable form).
   c. Trace metal contamination sensor to monitor growth melt.
   d. Atomic crystallographic defect monitors for growth melt.
   e. Epitaxial layer crystallographic quality monitor.

2. Doping technologies and thermal processes
   a. Sensors for trace contaminants in dopant gases and process gases, both in the supply system and in the chamber during wafer processing.
   b. Sensor for particles in chamber or on wafer.
   c. Mass flow monitors (may already exist in an acceptable form).
   d. Monitors for spatial variations in dopant gas concentrations in a process chamber.
   e. Monitors that can spatially resolve temperature with a precision of 1 C° over the entire front-side surface area of a wafer and that have a dynamic response capable of responding to rapid thermal processing conditions.
   f. Monitors for precise and accurate measurement of wafer-to-wafer temperature variations (may already exist in an acceptable form).

g. Composition and contamination monitors for plasma deposition and plasma etch processes. Chemically-selective gaseous contaminant monitors for moisture, atmospheric contaminants, etc., and particle monitors. Composition monitors capable of determining mole ratios of reactant gases within process chambers. Quadrupole mass spectrometers, currently used in sputtering and ion implantation, could have applications in chemical vapor deposition (CVD) and plasma etch systems.

3. Real-Time Monitors for Film Deposition and Etching Processes
   a. Monitors for deposited film thickness and film quality (dielectric density, dielectric stoichiometry, alloy composition, etc.). (may already exist in an acceptable form).
   b. Monitors for etch rate, etch depth, aspect ratio, uniformity, and surface quality for both plasma and wet chemical etch processes.
   c. Particulate monitors. Bubbles formed by chemical degradation of some liquid baths interfere with particle counting. Need alternatives to light scattering techniques, which have limitations.
   d. Composition and contamination monitors for wet chemical etch, DI water insignia, and POU chemical generation processes. Included here are concentration monitors for acids, bases, peroxides, and mixtures and contamination monitors for metal ions, anions, organics, particulates, and oxygen. Research in the area of kinetics of metal plating onto silicon (and in particular at p/n junctions) is necessary to further define acceptable metal ion concentrations in liquids. Sensors may have to endure high temperatures and corrosives and oxidizers, some at high concentrations. Composition monitoring may require dilution to be suitable for some analytical techniques. Creation of a waste stream or the use of reagents for the analysis will not be desirable, but may be unavoidable in some cases. HF concentration monitoring (via ionic conductivity) is currently available.
   e. Monitors for patterned wafers.

4. Surface Preparation
   a. Monitors for planarization of starting wafers and in-process wafers to maintain wafer within lithography depth-of-field constraints.
   b. Trace metal contamination monitors.
   c. Surface particulates monitors.

Environmental, Safety and Health *

1. Material input monitors
   a. Monitors for leaks and material loss in supply lines to process tools. Low cost in-situ component level liquid detection is currently available.

2. Product output monitors
   a. Precision, high throughput balances to measure accumulated mass on wafers.

b. Monitors for thickness of deposited materials on walls of process chambers.

3. Laboratory safety monitors (hazardous gases)
   a. Trace (ppb) monitors for phosphine, arsine, silane, etc., near equipment, supply lines, and exhaust. There are currently groups working on in-situ component level gas detection in the ppm range.

4. Detoxification monitors
   a. Monitors to verify and control neutralization processes (e.g., scrubbers, acid neutralization systems). These monitors would indicate long before a potential accident that the neutralization process is malfunctioning.

Manufacturing Facilities (building systems, product handling, raw materials) *

1. Real-time monitors for deposition and etching processes.
2. Contamination monitors for input gases and liquids.
3. Monitors for impurity evolution during processing.
4. Electrical device performance monitors for evaluating test structures (short loop quality control).

Packaging *

1. Assembly test chip monitoring of package integrity (may already exist in an acceptable form).

Equipment Design and Modeling *

1. Monitors for 3-dimensional mapping of deposition/etching equipment processes.
2. Monitors for thermal distribution in the equipment and across the front surface area of the wafer.
3. Monitors for gas flow dynamics based on equipment input and output gas supply lines.

Process Control Sensors

Environmental safety & health, manufacturing facilities, and equipment design and modeling would not be included as sensors for process control. These areas are very important to the success of the SIA roadmap and sensors will play a significant role. Since the concerns and focus of each of these areas are different, a focus team would benefit each area. It is also obvious sensors developed for one application can be utilized in other areas. Therefore, the different sensor focus groups could feed its recommendation to one central sensor team which would coordinate research & development.

The sensor for process control has three major categories which would matrix through the SIA categories of materials & bulk processes, packaging, doping technologies, thermal processes and film deposition, and etching processes. Sensor environments are basically gaseous, plasma, partial vacuum, at atmospheric pressure or greater, and liquid chemical.

Requirements:

There are two approaches that can be considered in defining the sensor attributes necessary for meeting SIA Roadmap objectives. The first approach would be to identify the critical process parameters for the approximately 600 process steps currently used in IC manufacturing and for the approximately 1200 process steps projected for the year 2005, and then attempt to define quantitative requirements for the sensor technologies needed for measurement and control of each parameter. The second approach, which appears to be more tractable, is to attempt to identify generic parameters (metal concentrations in liquids, particles on wafers, trace contaminants in plasma deposition chambers, etc.) that should be monitored for process control and set quantitative targets for sensor technologies required for these parameters. Quantitative targets that would be defined include detection limit, specificity, sensitivity, range, response time, accuracy, precision, ease and frequency of calibration, degree of automation, and adaptability to in-line process control applications. In this second approach, we would focus on processes that have high leverage for defect reduction and yield improvement. Once the targets have been identified, it will be necessary to validate their importance on device performance, defect densities, and yield so that it is clear that real time process control, using advanced sensor technologies, could assist in meeting SIA Roadmap objectives. This Focus Team, as well as the SEMATECH CFM FTAB, would review the targets and assist in prioritizing sensor research and development activities.

It is clear that there will have to be compromises made by the process engineers based on the limitations of new sensor technologies, particularly in the development and early implementation phases. However, it is instructive to list all the desired attributes of a sensor for use in a high-volume manufacturing environment.

1. Reliability and maintainability
   a. Continuous, on-line diagnostics of sufficient number of parameters to ensure 100% confidence in performance. Diagnostics should appear in data file to allow for understanding of behavior over time. They should also be readily referenced for periodic checks by maintenance personnel.
   b. Sensor maintenance must not be required more frequently than scheduled tool maintenance.
   c. Sensor has designed-in flexibility for quick and simple exchange of parts for sensor maintenance by floor personnel.
   e. Sensors must not add contamination to the process stream or bath.
   f. Sensor must be functional in the hostile environments of process tools.

If no source is available consider R&D effort.

- This process will identify development required and stimulate development of needed sensors.
- Center for Sensor Research should pick target, then develop or apply, then improve, then proliferate, then pick new target.

Key processes for gas and partial vacuum environments

- Gate oxide
- Polysilicon
- Metal PVD
- Metal etch
- ILD CVD
- Metal CVD
- ILD etch

Key measurements for gas and partial vacuum sensors.

- Particles in gases coming in.
- Particles in exhaust.
- Particles in volume surrounding wafers.
- Particles on wafer.
- Chemically selective measurements of composition of and contamination in gases coming in and in exhaust.

Key processes using liquid environment

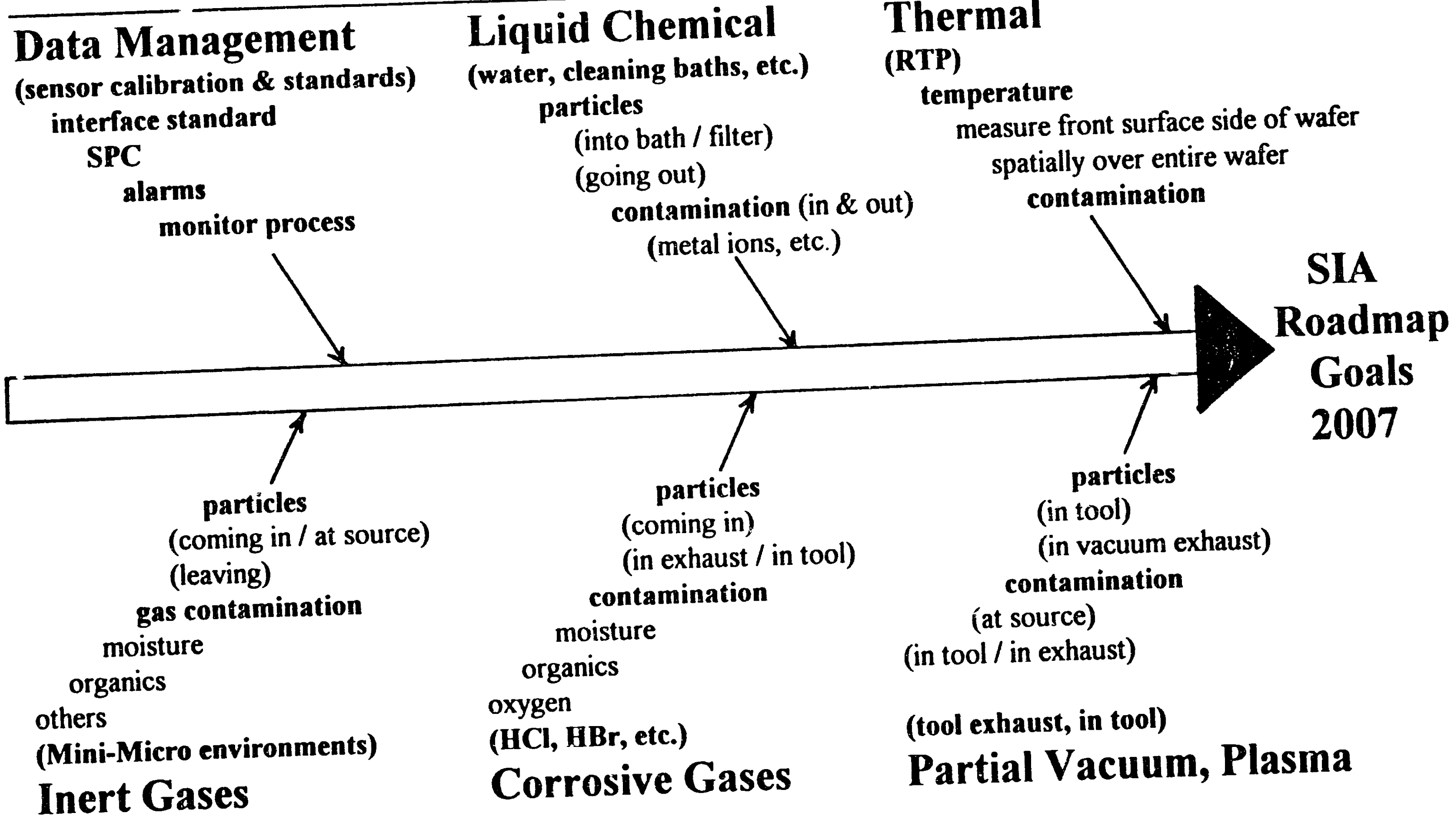
- Wafer cleaning - piranha/SC-1/SC-2
- Wafer rinsing - Pure water
- Photoresist removal
- Etching - PSG, BPSG, Metallization, etc.
- Immersion techniques

Key measurements for liquid sensors

- Acid / base composition & contamination
- Water purity
- Trace metals in wafer bath
- Trace anions & cations
- Dissolved gases & bubbles
- H_2O_2 concentration
- Particle concentration
- Organic concentration
- Chemical selective (Na, Pb, Cu, Cl^{-1}, SO_4^{-2}, etc.)

The following is the initial roadmap proposed by the focus team for process control sensors. The focus team feels that we have fulfilled the assignment given to us at the president's day meeting.

Sensors for Process Control Roadmap



Note: temperature, flow, and pressure of liquids and gases are sufficient to obtain SIA goals. Multi-species determination of contamination determination by inexpensive sensors or sensor arrays is important. Concentration sensors need to measure / monitor concentration of component gas / liquids and concentration of trace contamination.

CFM Research Center

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