Semiconductor Manufacturing Technology

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Chapter 6

Contamination Control in Wafer Fabs

Objectives

After studying the material in this chapter, you will be able to:

1. State and describe the five different types of cleanroom contamination and discuss the problems associated with each contamination.
2. List seven sources of contamination in a cleanroom and describe how each one affects wafer cleanliness.
3. Interpret and use the class number for cleanroom air quality.
4. State and discuss seven appropriate actions for technicians entering a cleanroom that follow acceptable protocol.
5. Describe the different aspects of a ultraclean cleanroom facility, including air filtering, electrostatic discharge, ultrapure DI water and process gases.
6. Explain how modern workstation design and a minienvironment contributes to contamination reduction.
7. State the chemistry of the two standard wet cleaning methods, explain the type of contamination removed by each, and discuss wet cleaning modifications and alternatives.
8. Describe the different types of wet cleaning equipment and state how each cleaning process contributes to wafer cleanliness.

Wafer Contaminants

- As the feature size on a chip shrinks, the need to control surface contamination becomes more critical.
- To achieve contamination control, all wafer fabrication is done in a cleanroom where contaminants are strictly controlled.

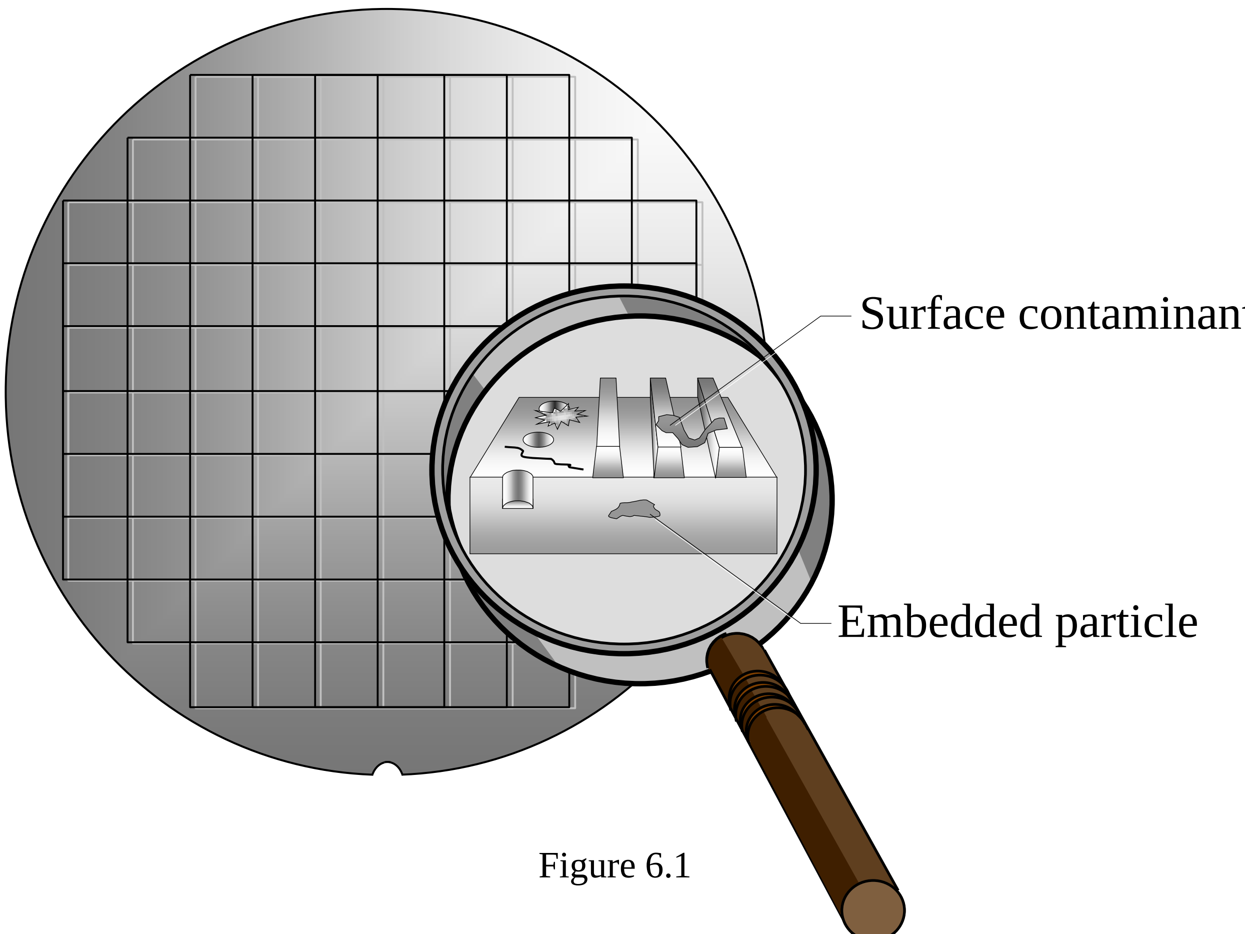


Figure 6.1

Wafer Fab Cleanroom

isolated from the outside environment and free of contaminants

The introduction of the high-efficiency particulate air filter (HEPA filter) in the 1960s was a first step toward significant particulate reduction in the wafer fab.

Photograph courtesy of Advanced Micro Devices, main fab corridor
Photo 6.1

Types of Contamination and The Problems They Cause

- Particles
- Metallic Impurities
- Organic Contamination
- Native Oxides
- Electrostatic Discharge

- Contamination often leads to a defective chip. Killer defects are those causes of failure where the chip on the wafer fails during electrical test.
- It is estimated that 80% of all chip failure are due to killer defects from contamination.

Relative Size of Particles

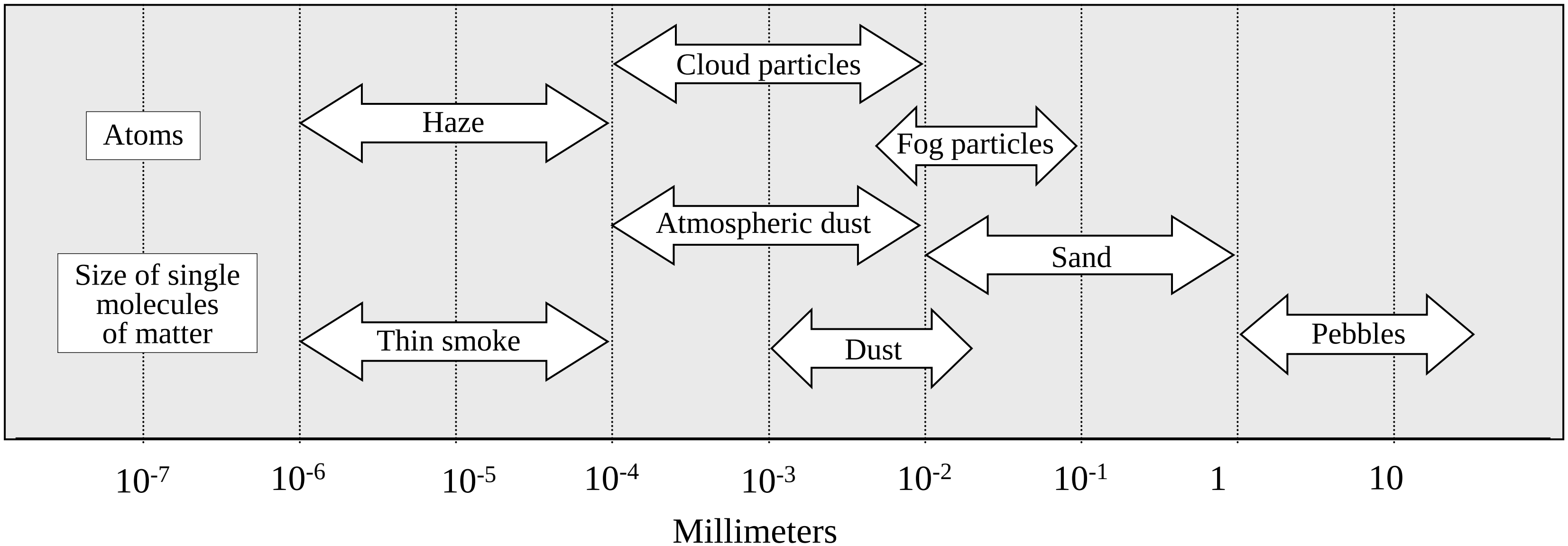


Figure 6.2

Defect from Particles: >1/2 CD

- The rule of thumb for an acceptable particle size in semiconductor manufacturing is that is must be less than **one-half** the minimum device feature size.
- For a 0.18-μm feature size cannot be exposed to 0.09 μm and larger particle.

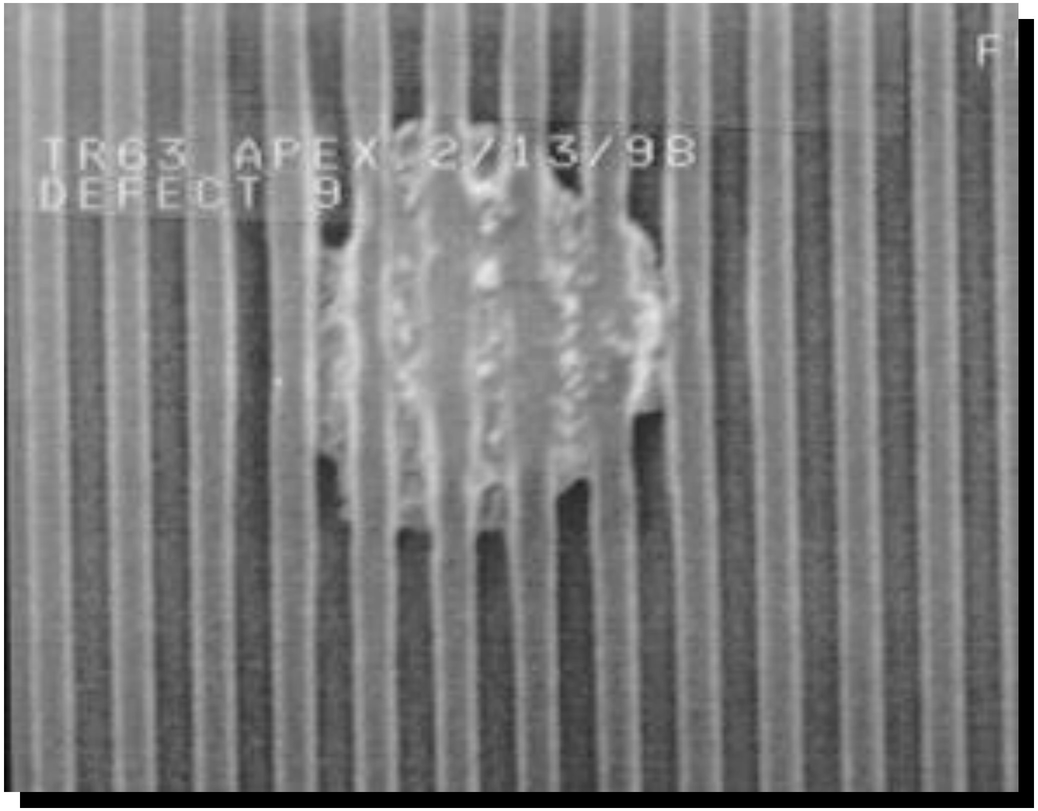
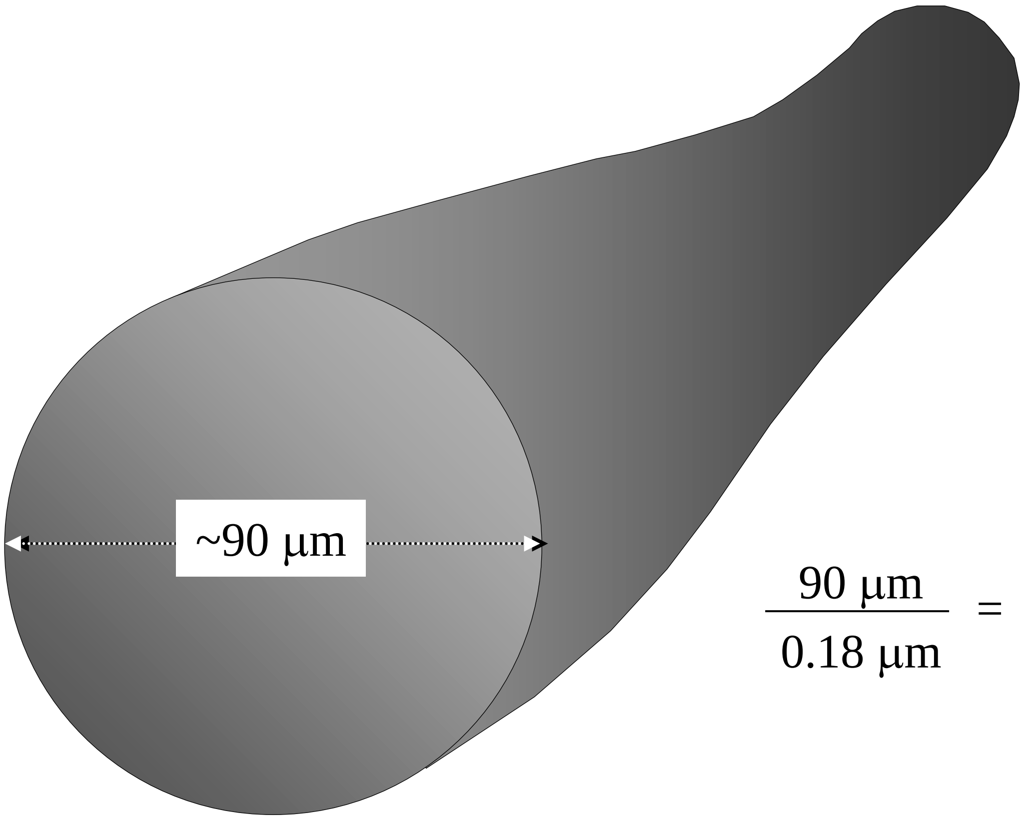


Photo 6.2

Micrograph courtesy of AMD, particle underneath photoresist pattern

Relative Size of Human Hair to 0.18 μm Feature Size

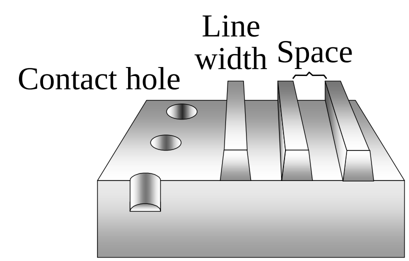


Cross section of human hair

The relative size of the human hair is approximately 500 times the size of the smallest feature size on an integrated circuit.

$$\frac{90\ \mu m}{0.18\ \mu m} = 500$$

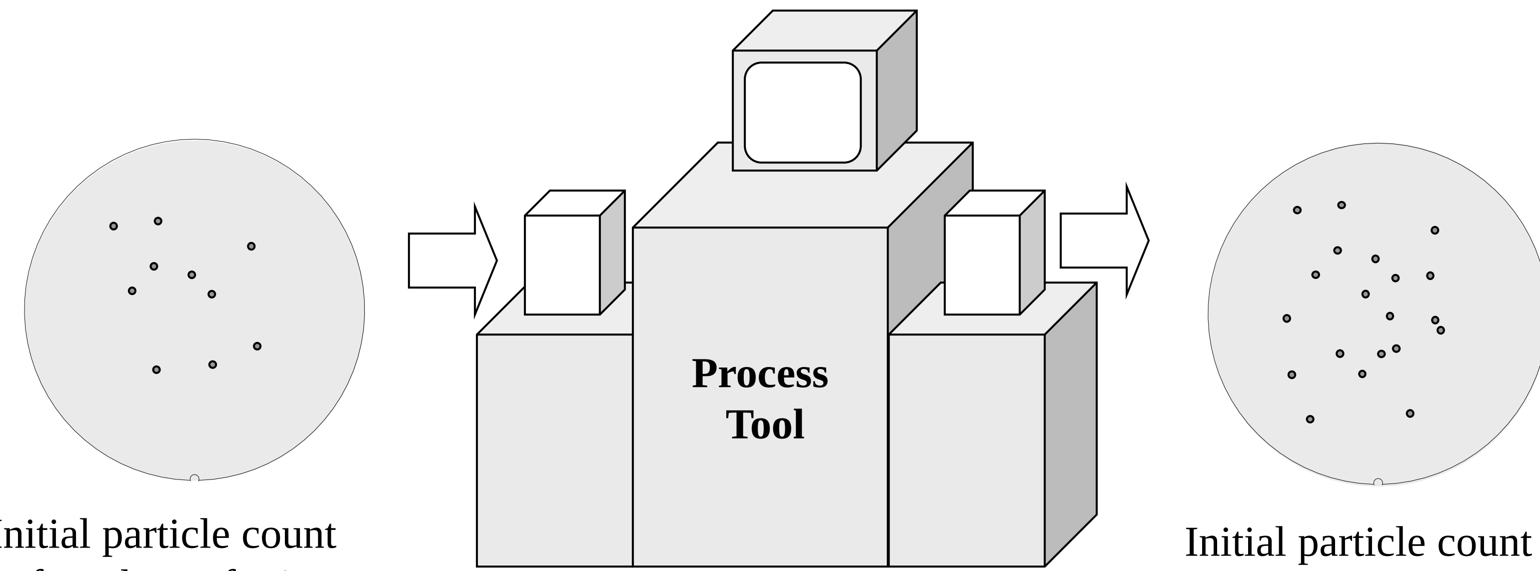
Minimum IC feature size = 0.18 μm



A small example of a segment from a larger integrated circuit.

Figure 6.3

Particles Per Wafer Per Pass on a Wafer



Initial particle count before the wafer is inserted in process tool.

Particles are added to the wafer by the process tool.

Initial particle count after the wafer passes through the process tool.

the smallest detectable diameter ~ 0.1 μm

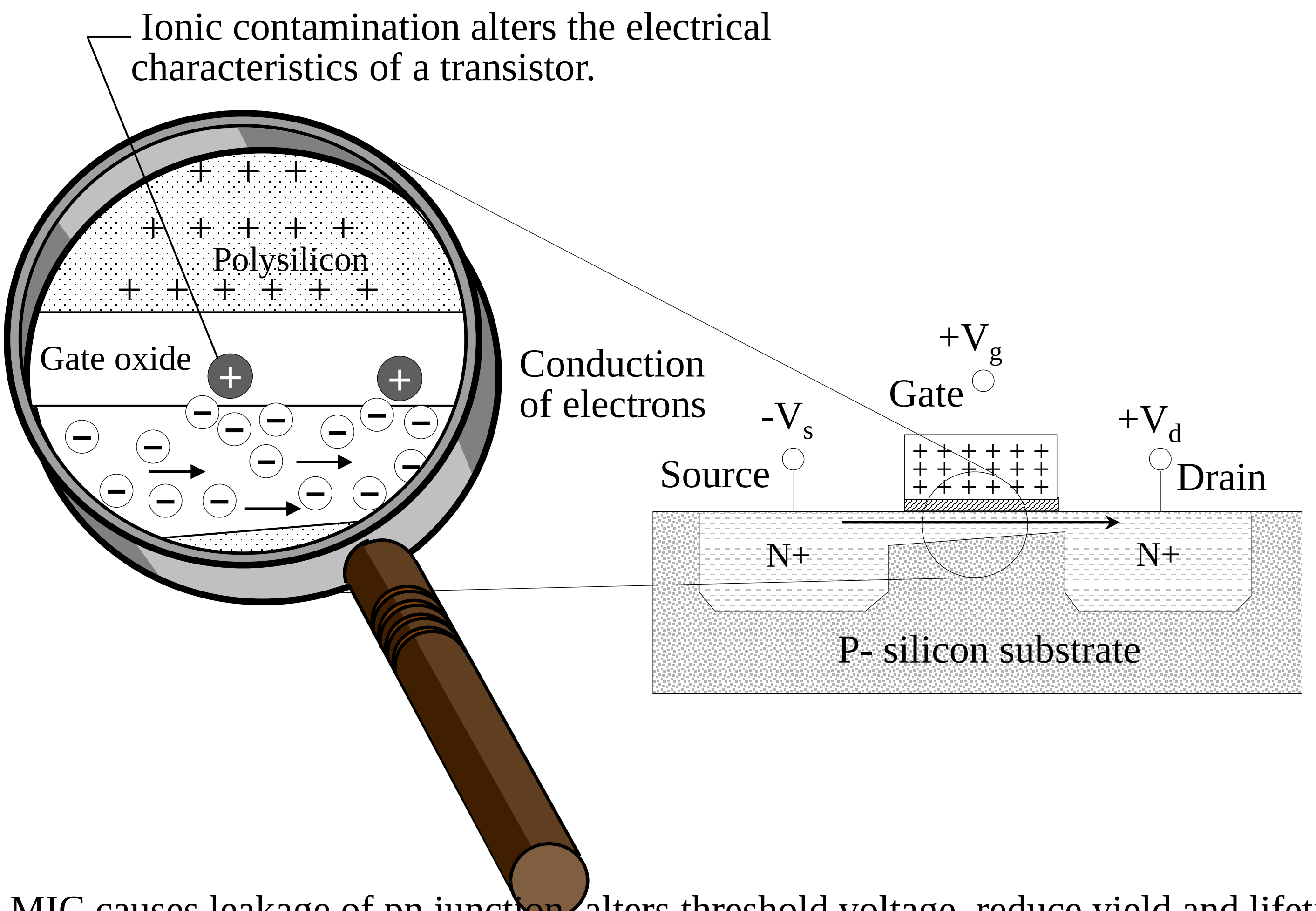
Figure 6.4

Typical Metal Impurities

Heavy Metals	**Alkali Metals**
Iron (Fe)	Sodium (Na)
Copper (Cu)	Potassium (K)
Aluminum (Al)	Lithium (Li)
Chromium (Cr)	
Tungsten (W)	
Titanium (Ti)	

- Two ways: one is to bind on the surface (not easy to remove); the other is to form in oxide (easy to remove by stripping the oxide)

Mobile Ionic Contaminant Altering Threshold Voltage



- MIC causes leakage of pn junction, alters threshold voltage, reduce yield and lifetime
- A single crystal of table salt (NaCl) contains enough sodium to deposit 10^{12} atoms per square centimeter on 5,000 (150-mm) wafers

Organic Contamination

- Organic contaminants are those that contain carbon and hydrogen
- Sources: bacteria, lubricants [潤滑油], vapor, detergents, photoresist [PR] .
- Equipment used in wafer fab today is designed with components that require no lubricants (oil-free pumps and bearings)

Native Oxide

- The surface of a silicon wafer will **oxidize** if exposed either to air at room temperature or to DI wafer that contains dissolved oxygen.
- To remove native oxide: using HF acid, or to inhibiting native oxide is to integrate multiple process steps into a multi-chamber with an evacuated, high-vacuum chamber so that the wafers are not exposed to ambient atmosphere and moisture. [page 43]

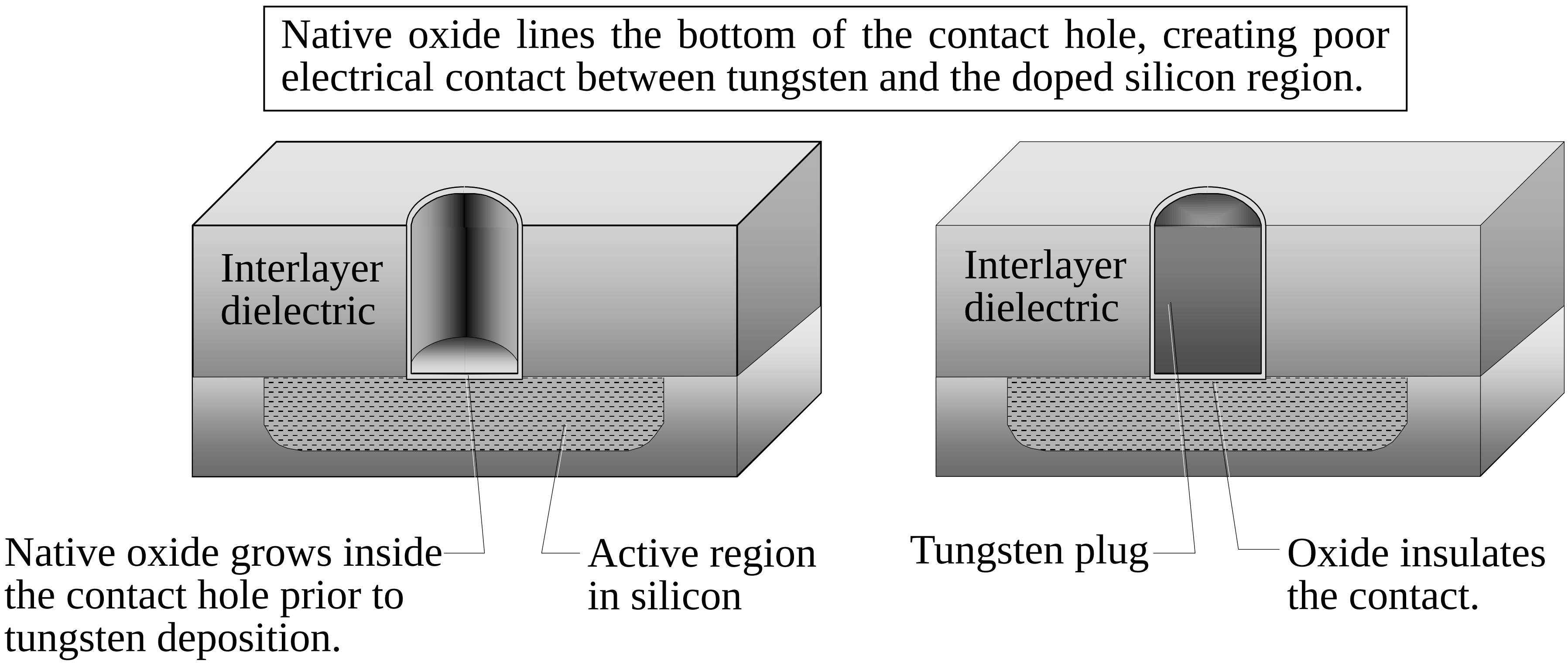


Figure 6.6

Particles Attracted to a Charged Wafer

- Electrostatic discharge (ESD) is a form transfer of static charge from one object to another that potentially damages the microchip.
- For 10^{-9} C, discharge in a few nanoseconds can generate peak current over 1 amp, literally vaporizing metal conductor lines or punching through oxide layer.
- Low humidity (~ 40%) in cleanroom increases static charge.
- The smaller the particle, the more particle attraction (TV screen attracts particles).

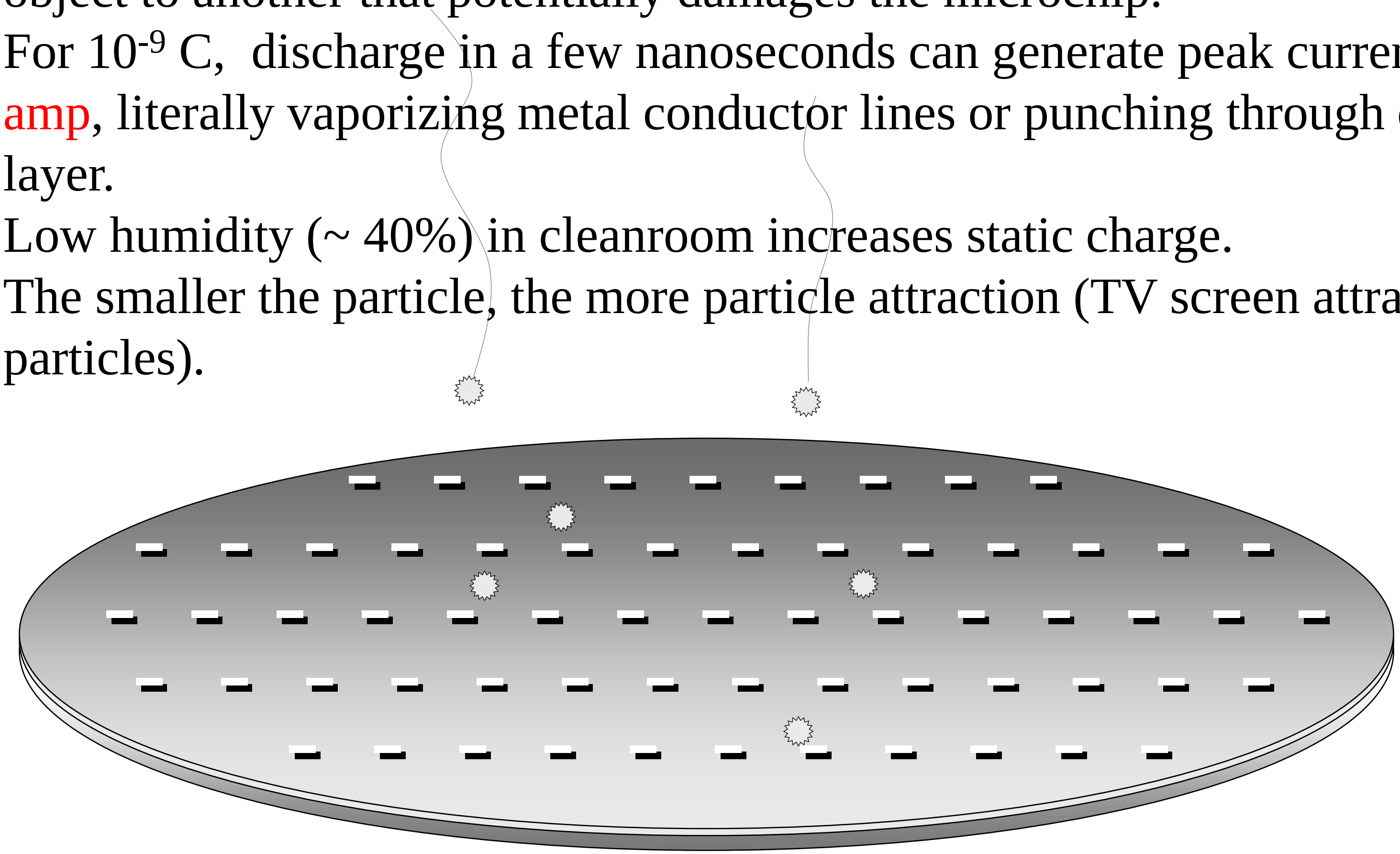


Figure 6.7

Sources and Control of Contamination

Seven Sources of Contamination in a Wafer Fab:

- Air
- Humans
- Facility
- Water
- Process Chemicals
- Process Gases
- Production Equipment

Table 6.1

Definition of Airborne Particulate Cleanliness Classes Per Federal Standard 209E

	Particles/ft^3				
Class	**0.1 µm**	**0.2 µm**	**0.3 µm**	**0.5 µm**	**5 µm**
1	3.50 x 10	7.70	3.00	1.00	0
10	3.50×10^2	7.50 x 10	3.00 x 10	1.00×10^1	0
100		7.50×10^2	3.00×10^2	1.00×10^2	0
1,000				1.00×10^3	7.00
10,000				1.00×10^4	7.00 x 10
100,000				1.00×10^5	7.00×10^2

Ultrafine particles: there recently has been usage of a class 0.1, with particle sizes down to 0.02 to 0.03 µm.

Table 6.2

Particles Emitted by Human Activities

Source of Particles	**Average Number of Particles per Minute > 0.3 μm**
Motionless (sitting or standing)	100,000
Moving hands, arms, trunk, neck and head	500,000
Walking at 2 miles per hour	5,000,000
Walking at 3.5 miles per hour	7,500,000
Cleanest Skin (per square foot)	10,000,000

- A human is a particle generator.
- People continually enter and leave cleanrooms and are the greatest source of contamination in a cleanroom.
- Particles come from hair and hair products (hair spray, gel), lint [皮棉] from clothes, flakes of dead skin, and so on.

Table 6.3

Technician in Cleanroom Garment

The goal of the cleanroom garment system is to meet these functional criteria: (bunny suit)

- Total containment of body-generated particles and aerosols [懸浮微粒].
- Zero particle release from the garment system. (0.1 μm>99.999%)
- Zero electrical charge buildup for ESD.
- No release of chemical or biological residues.
- Made: densely woven polyester fabric. [聚酯]

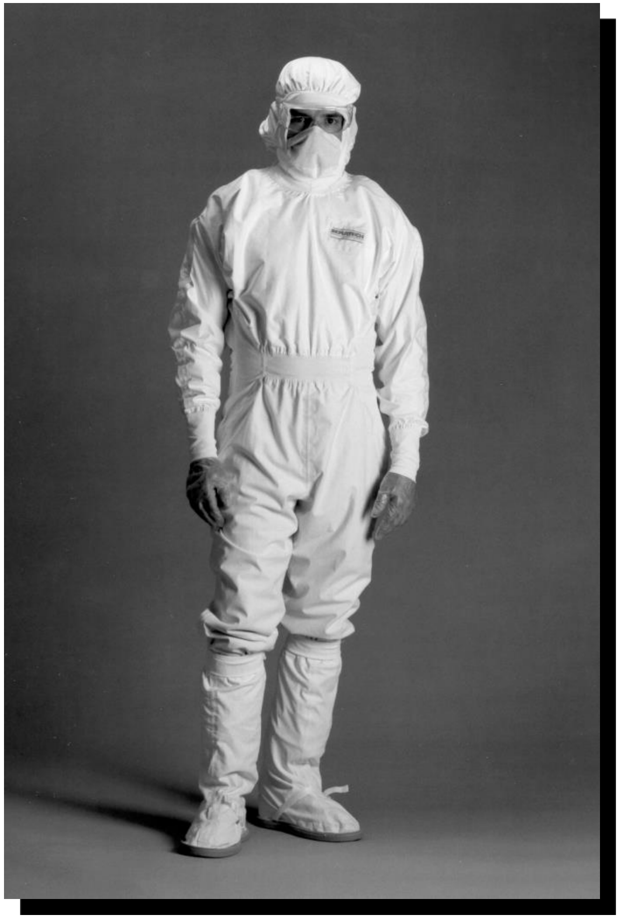


Photo courtesy of International SEMATECH, *James Minor (photographer) © 1990*

Photo 6.3

Proper Cleanroom Protocol

Should Do:	Should Not Do:	Why?
Entry into cleanroom by only authorized personnel.	Keep out unauthorized personnel.	Cleanroom's impose strict and demanding restrictions.
Take only what is necessary into the cleanroom.	Keep out all contaminants listed in the company's cleanroom policies and procedures.	To prevent entry of unwanted contamination sources.
Gown according to the company's cleanroom policies and procedures. From head to feet.	No bare street clothes allowed within the cleanroom. Do not touch garments with bare skin.	To keep cleanroom apparel free of contaminants that could be carried into the cleanroom.
Always make sure that all head and facial hair is covered.	Do not expose any facial or head hair.	Hair is a source of unwanted contaminants.
Follow procedures for entering the cleanroom, such as shoe cleaner, air shower (if required).	Do not open any door into the cleanroom until all procedures are complete.	Air showers may assist in removing contaminants from garments. Some companies have discontinued the use of air showers.
Keep cleanroom garment closed at all times while in the cleanroom.	Do not expose any street clothing. Do not touch anything in the cleanroom with bare skin.	Sources of unwanted contamination.
Move slowly.	Do not congregate or move quickly.	This disrupts the airflow pattern.

Table 6.4

Three Basic Strategies for Eliminating Particles from Cleanrooms

1. Start out with a cleanroom that is free of particles.
2. Minimize the introduction of particles into the cleanroom through equipment, tools, personnel and cleanroom supplies.
3. Continuously monitor the cleanroom for particles for timely response to cleaning maintenance.

Cleanroom Facility Topics

- Cleanroom Layout
- Airflow Principles
- Air Filtering
- Temperature and Humidity
- Electrostatic Discharge

Early Ballroom Cleanroom Layout (Phase I)

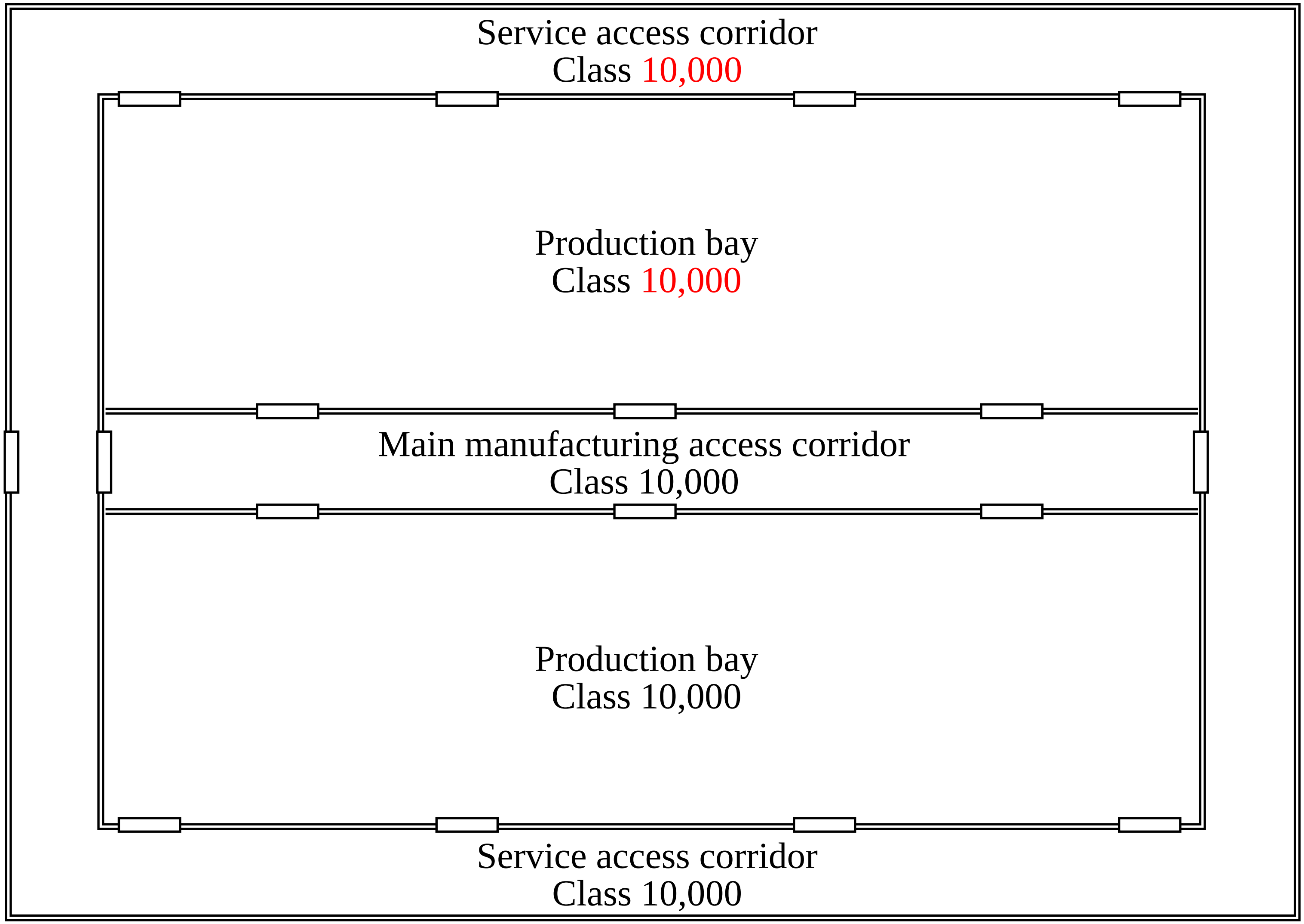


Figure 6.8

Bay and Chase Concept for Cleanroom (Phase II)

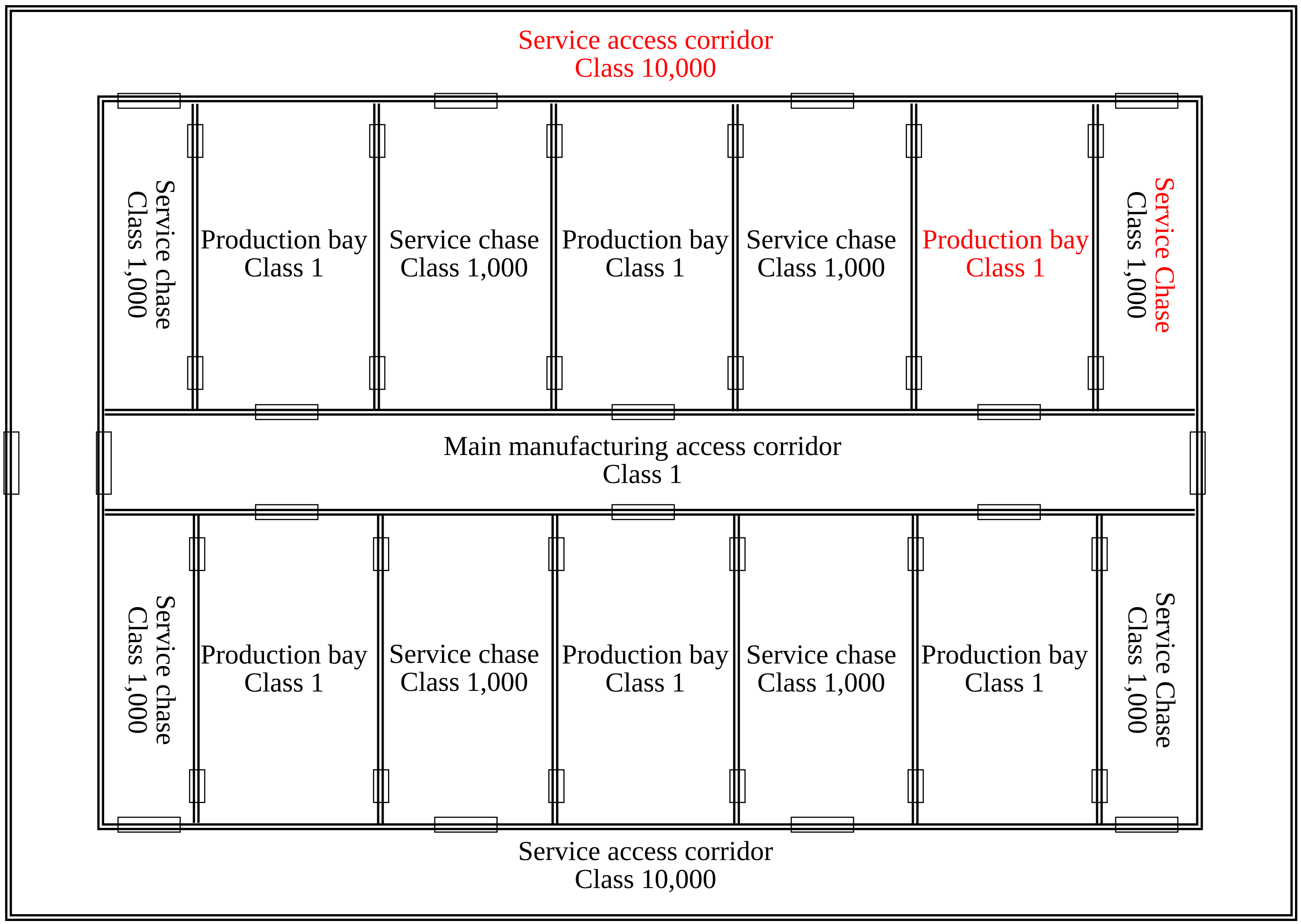
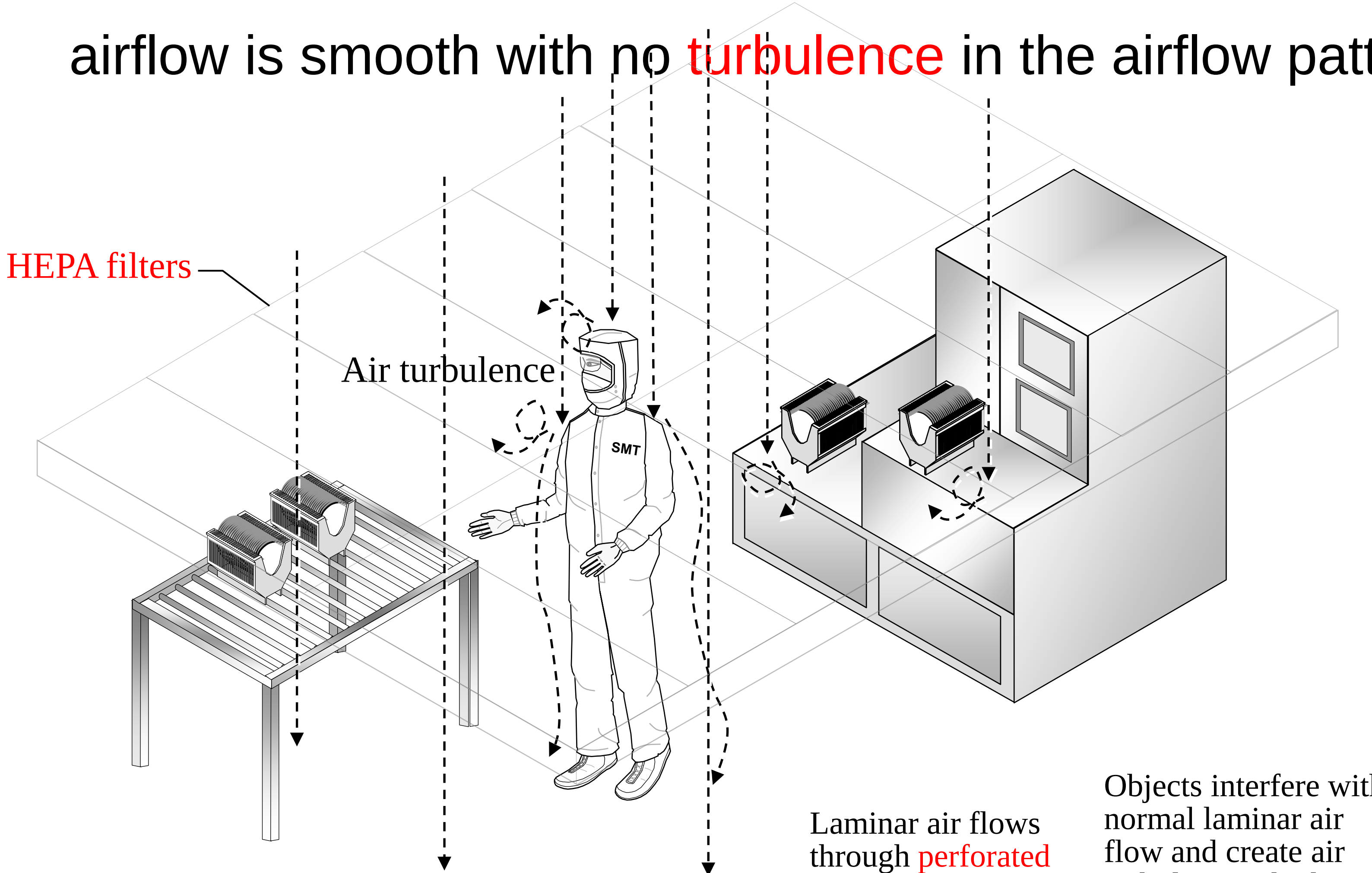


Figure 6.9

Laminar Air Flow

airflow is smooth with no turbulence in the airflow pattern

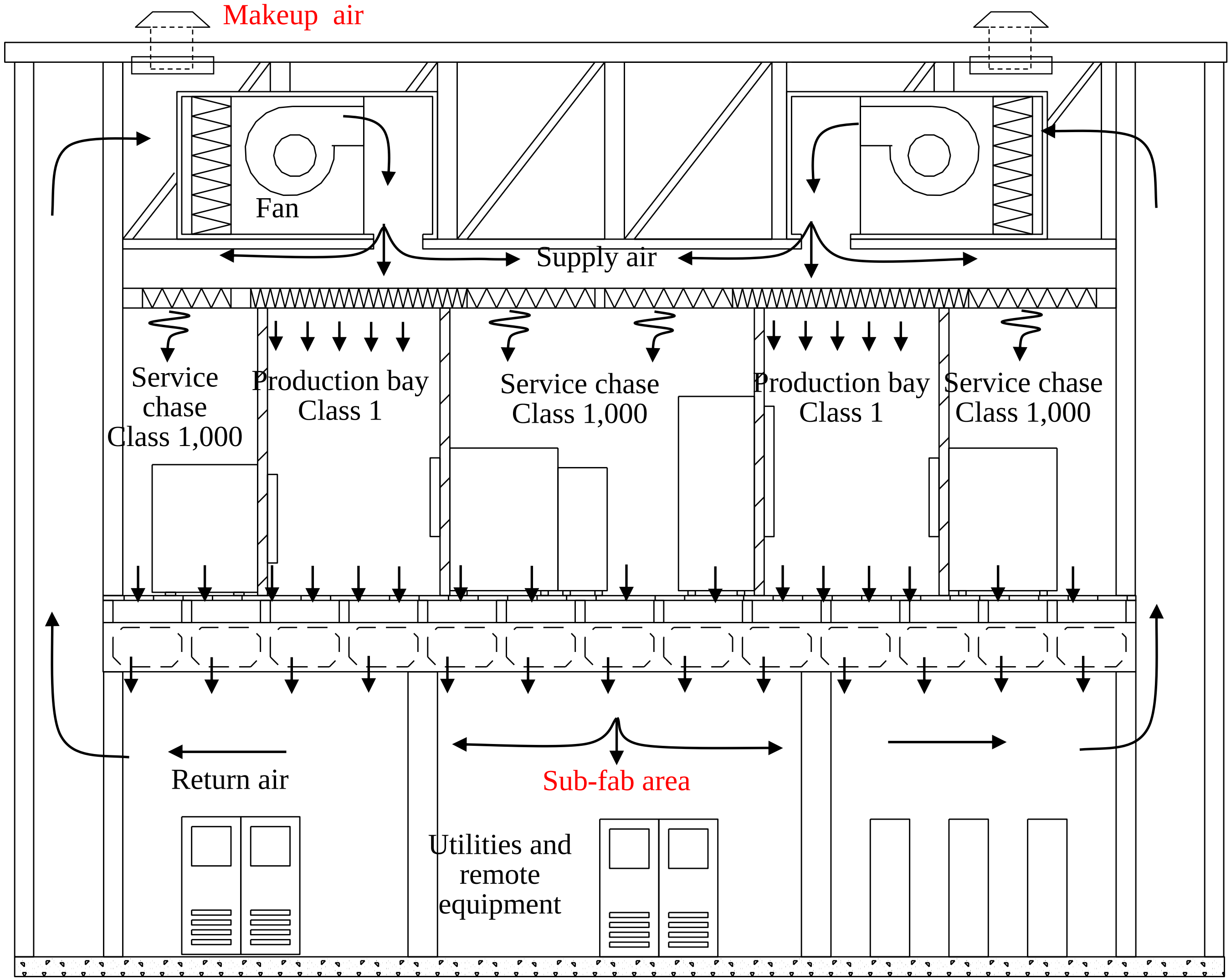


Laminar air flows through perforated floor.

Objects interfere with normal laminar air flow and create air turbulence which can dislodge and carry small particles.

Figure 6.10

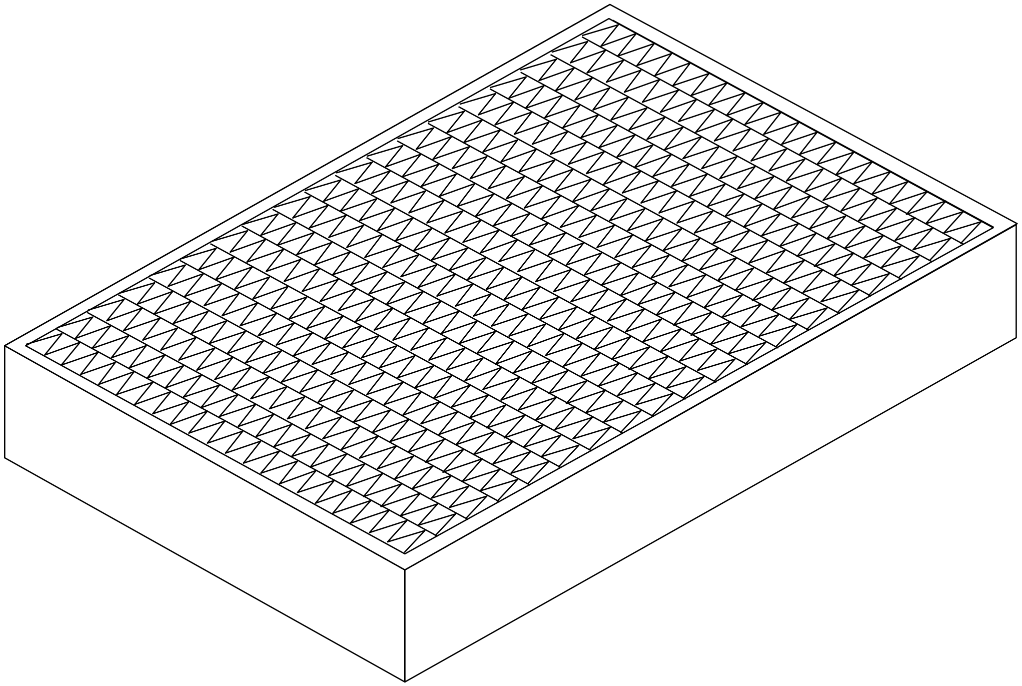
Wafer Fab Air Handling System



- Air may turn over every 6-sec to improve recovery of ultraclean conditions during disturbances.
- An exhaust system is used to remove undesirable heat and chemicals from process tools and work areas.

HEPA Filter

high-efficiency particulate air



ULPA: ultra low penetration air (fiberglass fibers, 99.9995% for 0.12 μm)

Figure 6.12

ESD, Temperature and Humidity

- Electrostatic Discharge
  - Static-dissipative cleanroom materials
  - ESD grounding
  - Air ionization
- Temperature and Humidity
  - $68 \pm 0.5^{\circ}$F and $40 \pm 10\%$ (RH)

Neutralizing Static Charge on a Surface with Air Ionization

- The surface attracts ions from the opposite polarity and neutralizes the electrostatic surface charge.
- Recently, soft-X-ray is used to generate large ion pairs.

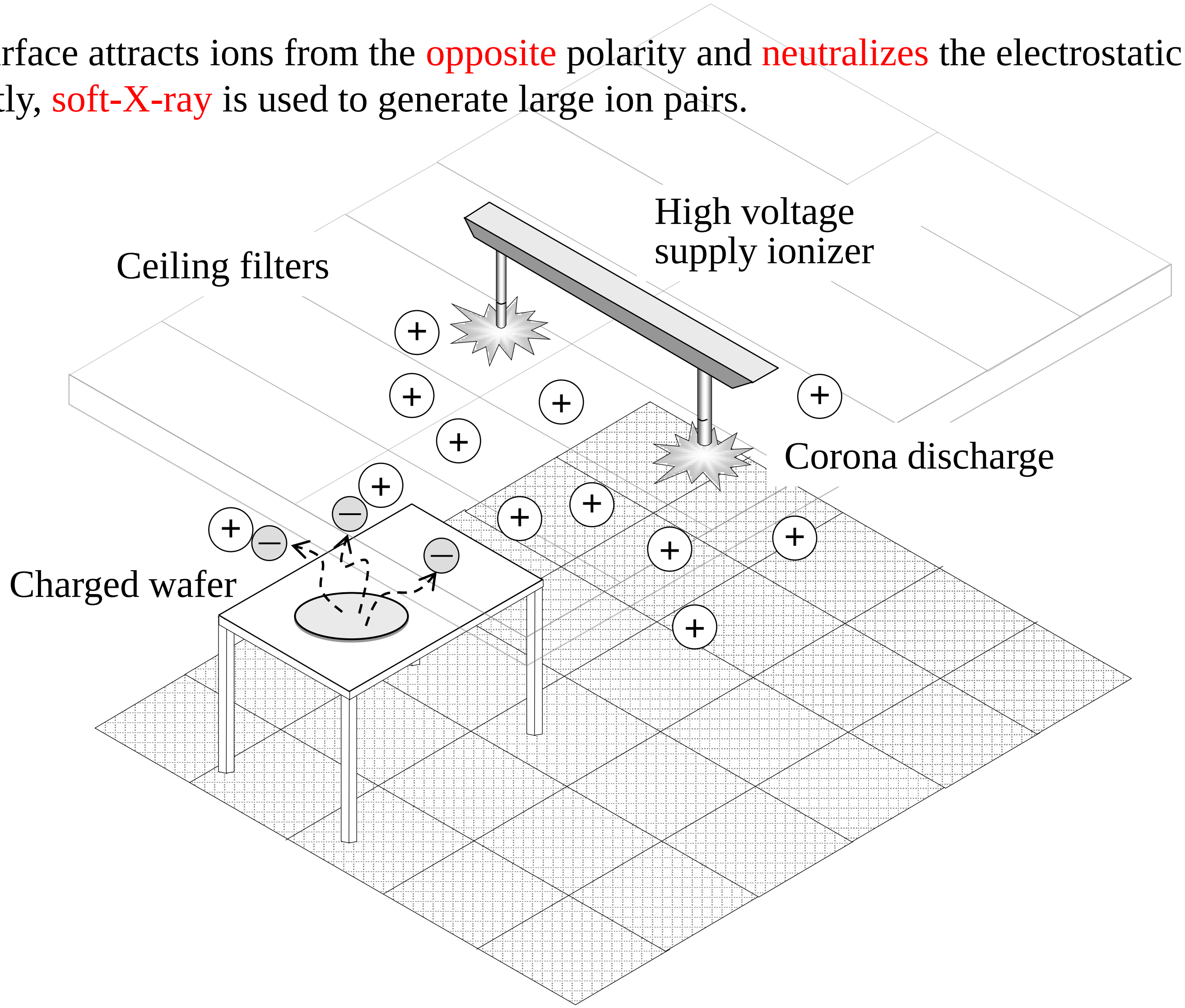


Figure 6.13

Water in the Wafer Fab

- DI Water Installation
- Deionization
- DI Water Filtration
- Zeta Potential
- Bacterial Control
- 2000 gallons for a 8-in wafer

Unacceptable Contaminants in DI Water

- Dissolved Ions
- Organic Materials
- Particulates
- Bacteria
- Silica
- Dissolved Oxygen

Size of Particles in Water

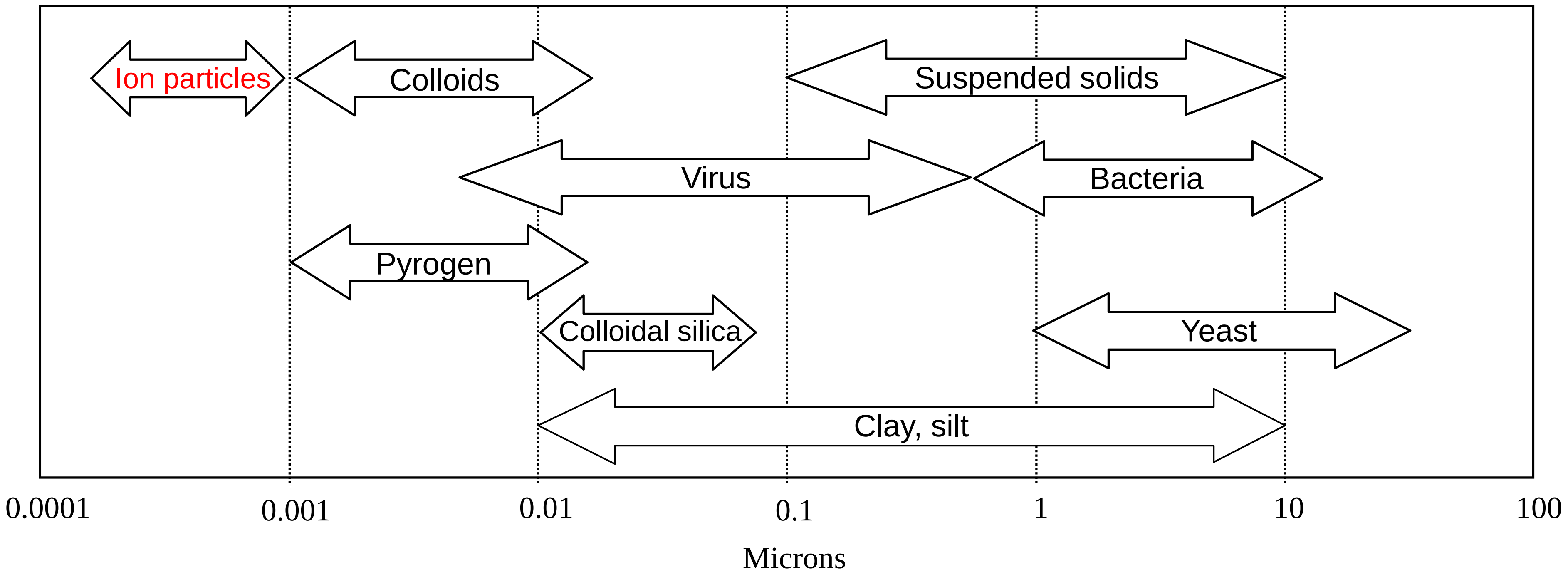


Figure 6.14

DI-Water Makeup and Polishing Loops

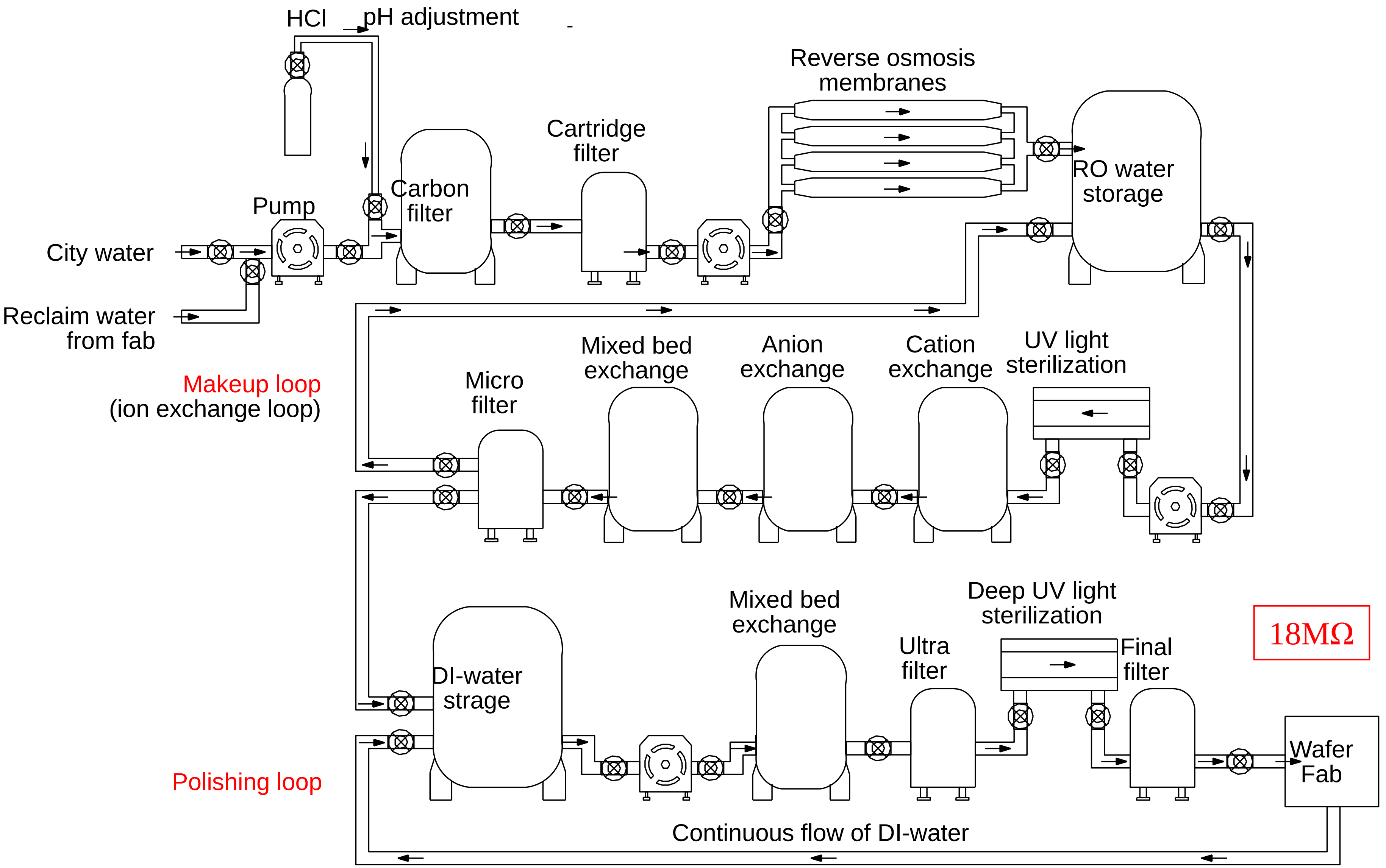


Figure 6.15

Principle of Reverse Osmosis Filtration

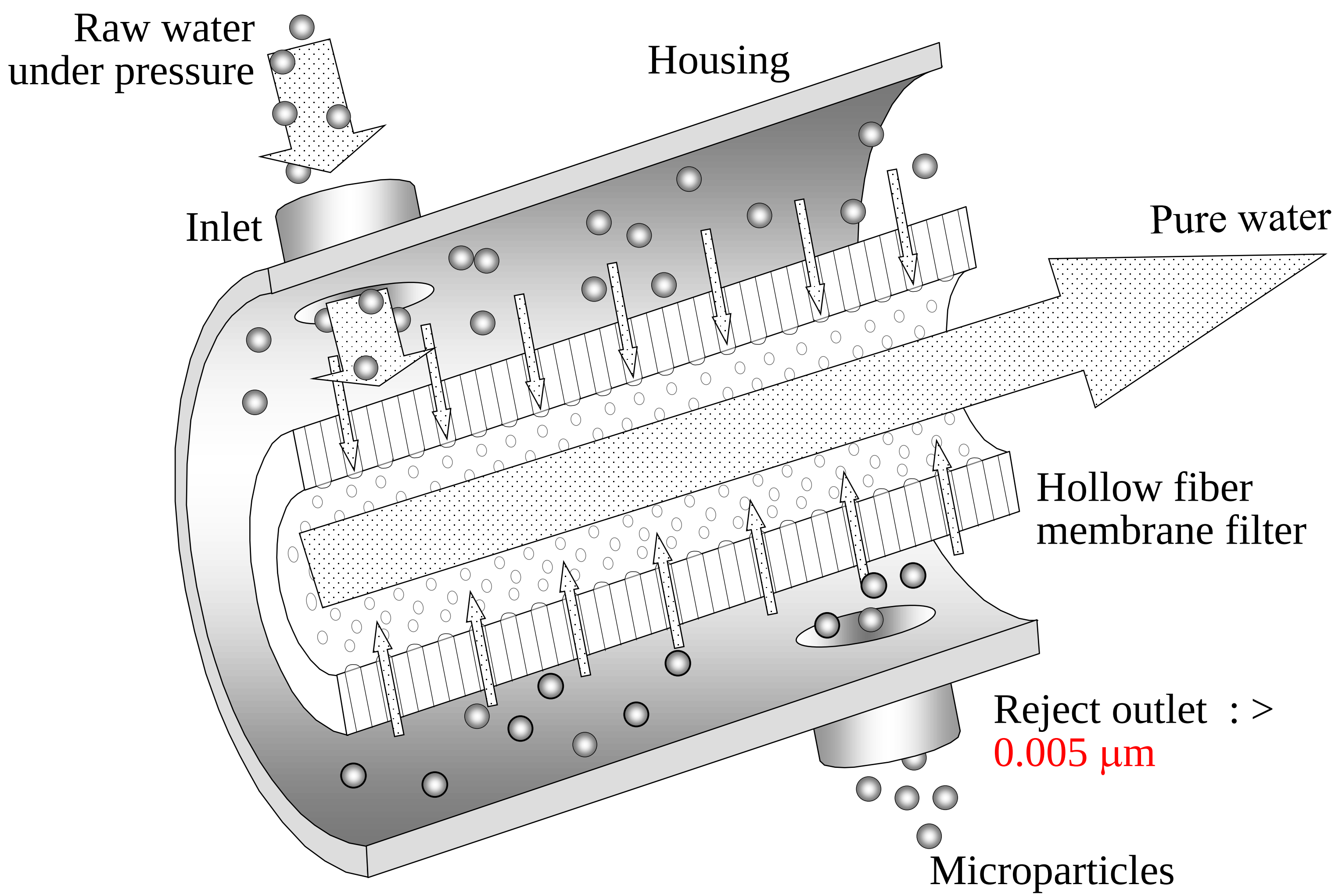
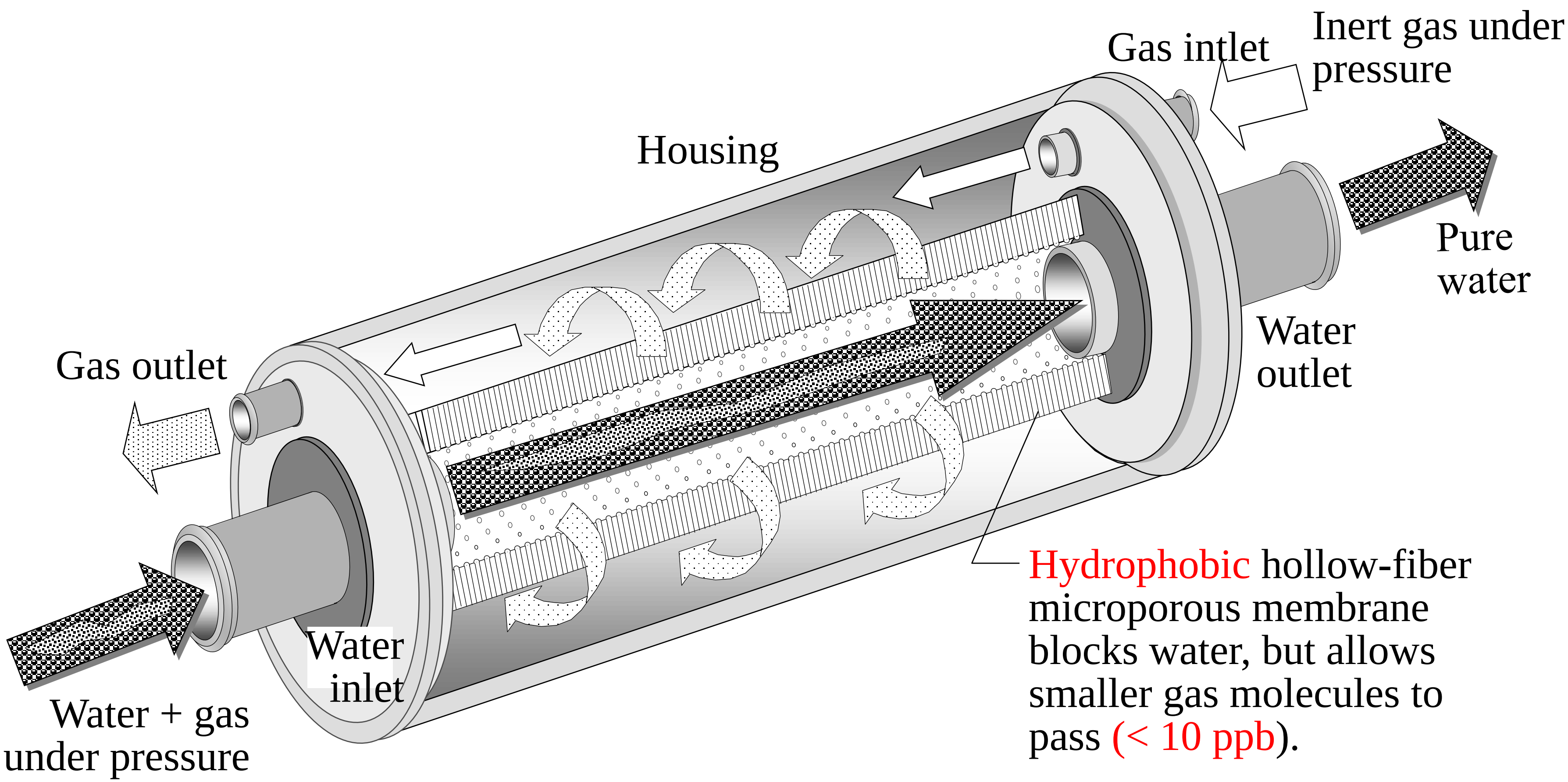


Figure 6.16

Membrane Contactor Filter



To remove gas in water (O_2)

Figure 6.17

Electrostatic Filtration Using the Zeta Potential

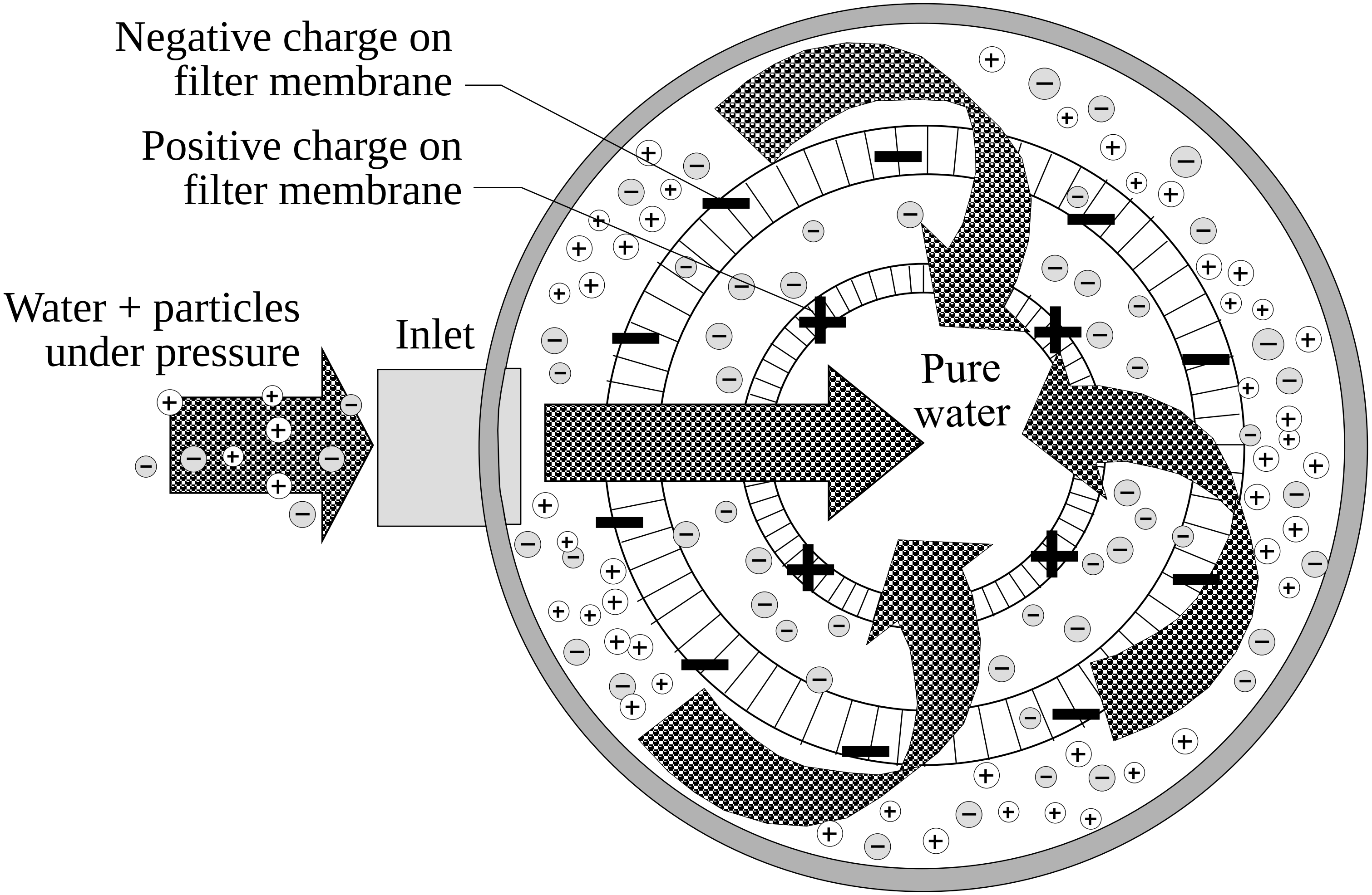


Figure 6.18

Process Chemicals

- Filter Types
- Process Gases
- Production Equipment
  - Sources of Contamination
- Workstation Design
  - Bulkhead Installation
  - Handling
  - Minienvironment

Filter Classifications

- **Particle filtration:** Depth type filtration (Figure 6.22) for particles from approximately 1.5 microns and larger.
- **Microfiltration**: Membrane filtration of a liquid that removes particles in range of 0.1 to 1.5 microns.
- **Ultrafiltration:** Pressure-driven membrane process that rejects large molecules from approximately 0.005 to 0.1 microns.
- **Reverse Osmosis:** Also called hyperfiltration. A pressure-driven solution process which transports liquid through a semi-permeable membrane with the exclusion of particles and metal ions as small as approximately 0.005 microns.

Depth-Type Filter

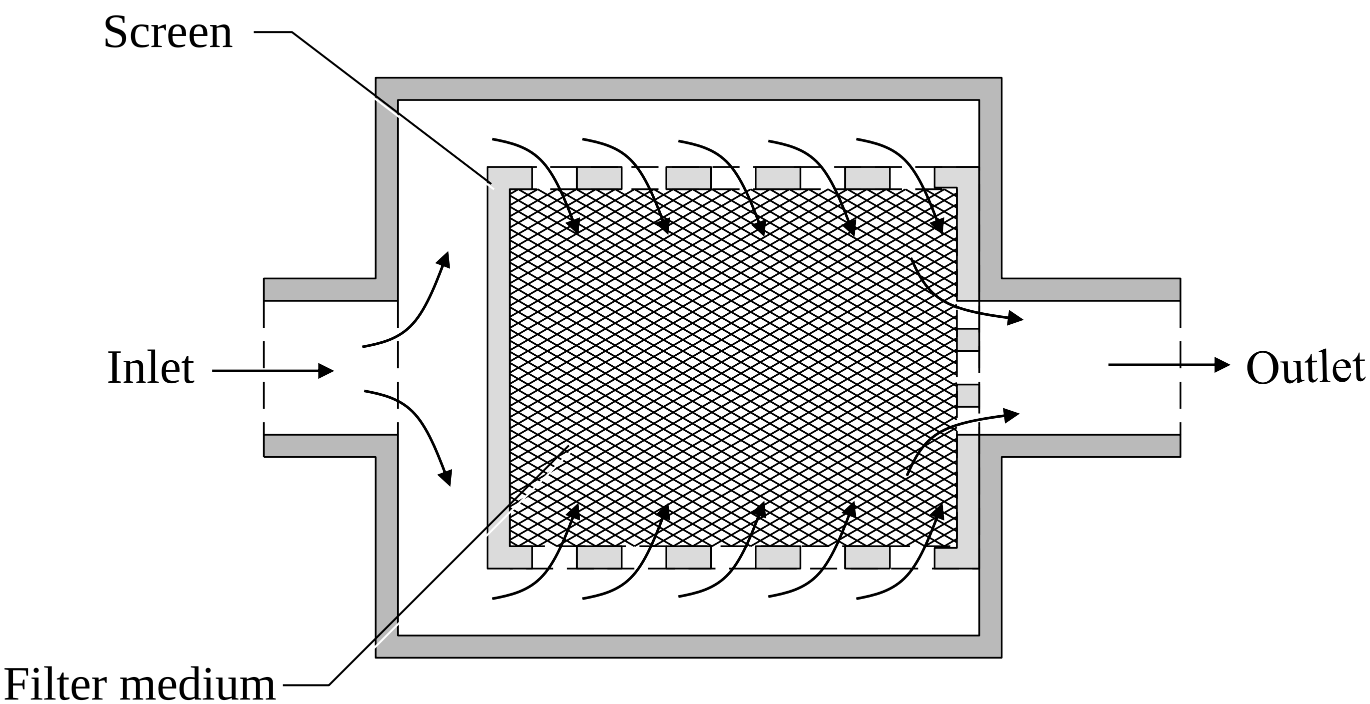


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Figure 6.19

Membrane Filter
99.9999999% of 0.02 um

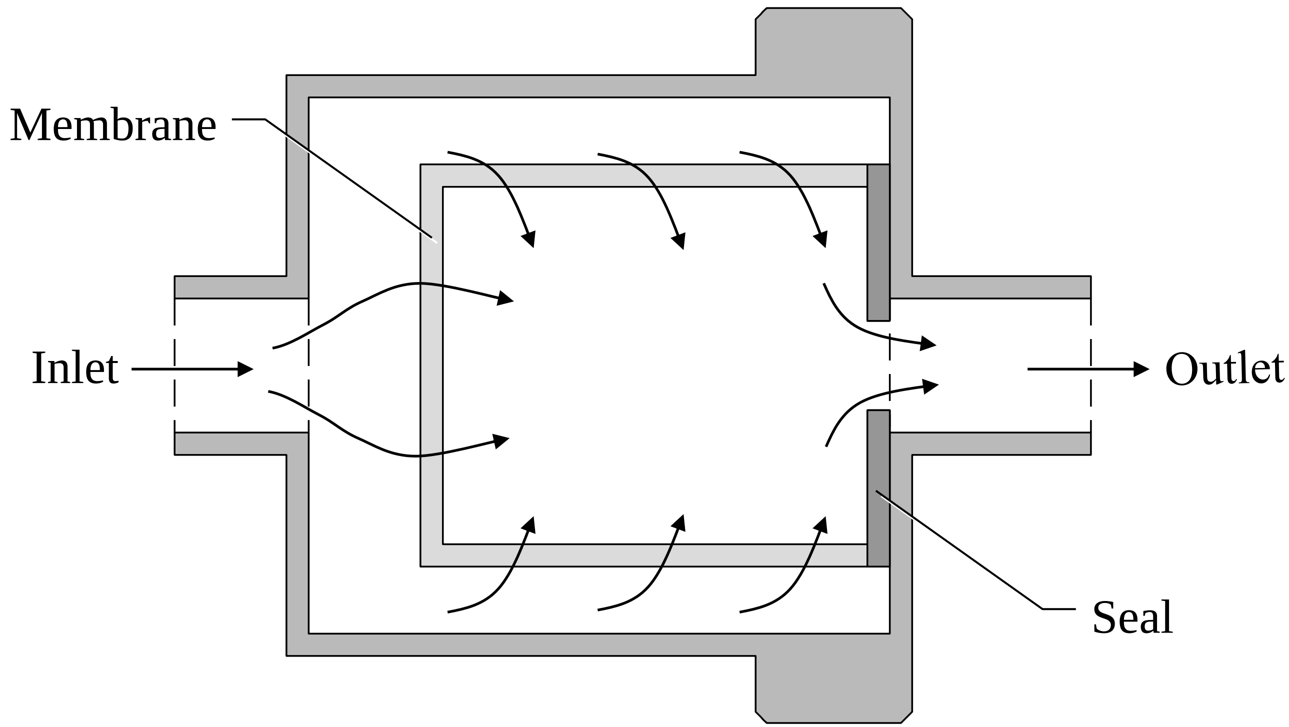

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Figure 6.20

Sources of Contamination from Process Tools

- Flaking of by-products built up on chamber walls.
- Automated wafer handling, transporting and chucking/clamping.
- Mechanical operations such as shaft (軸) rotation and valve opening or closing.
- Pumping and venting in vacuum environments.
- Cleaning and maintenance procedures.

Wafer Surface Particles as a Function of Process Steps

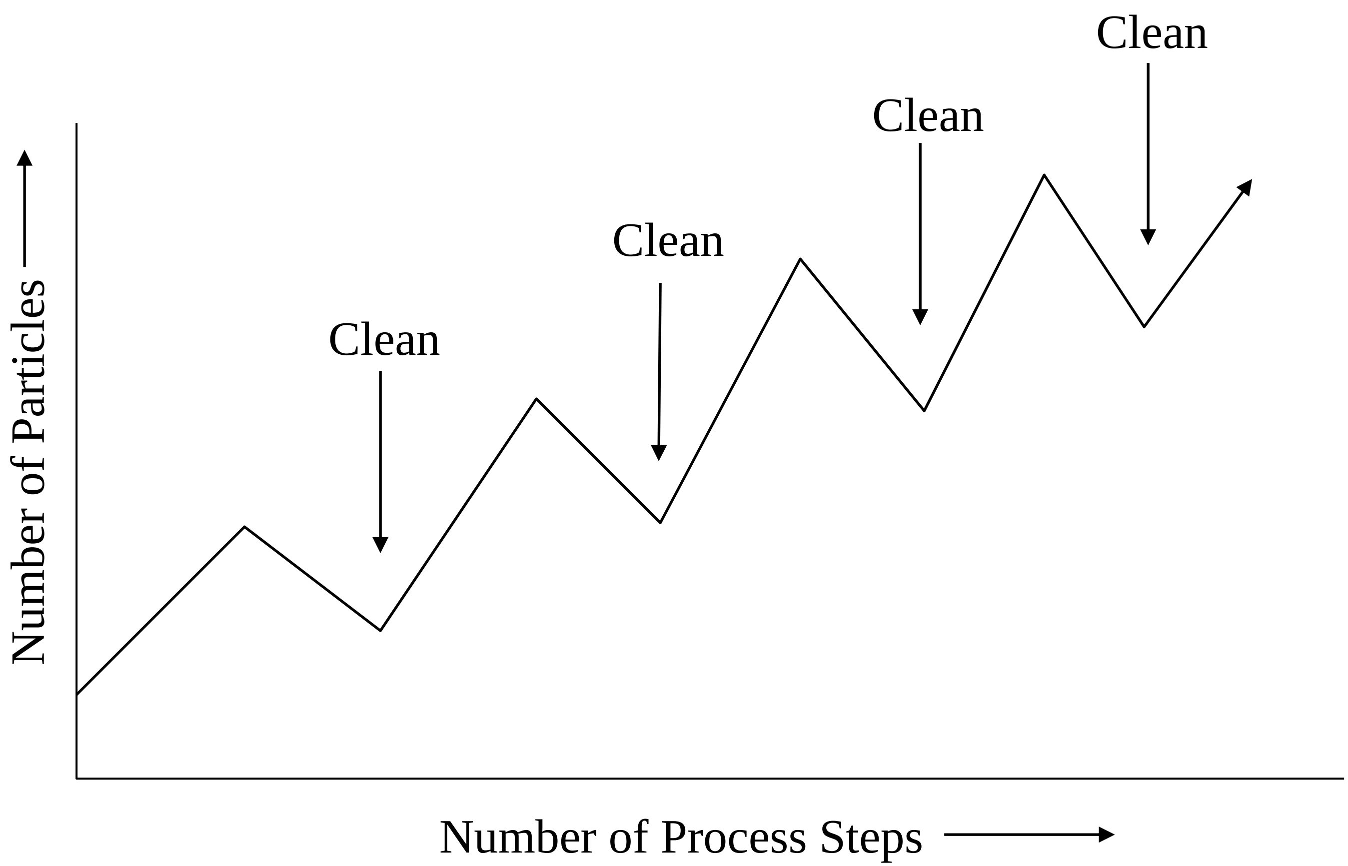


Figure 6.21

Bulkhead [分壁] Installation

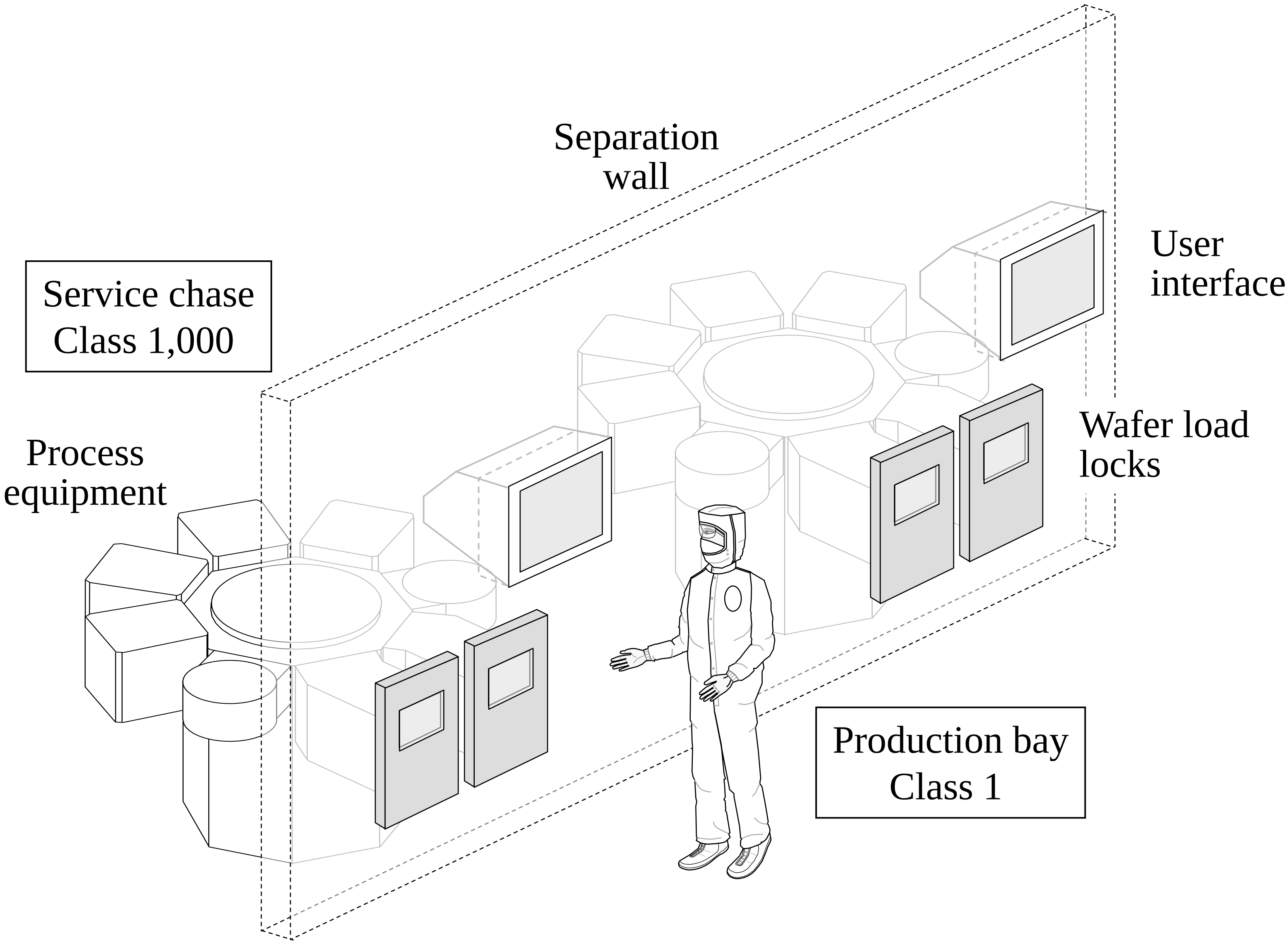
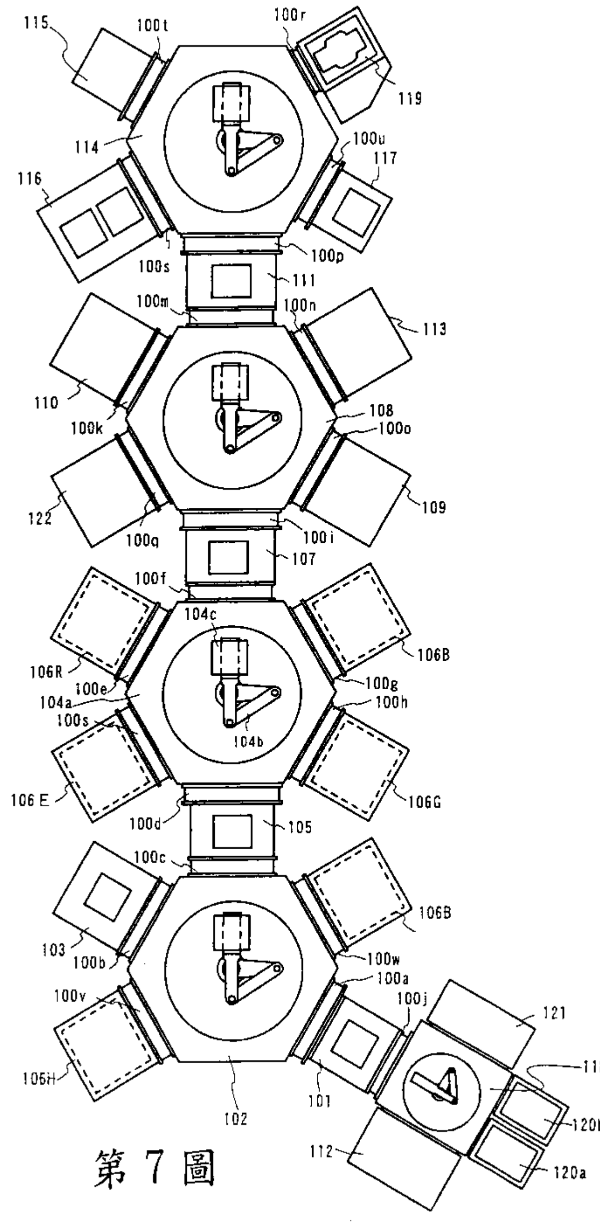


Figure 6.22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Wafer Cassette

- Wafer cassette is used to transport wafer between tools with conveyors and elevators as a way to pick up and transfer wafer into and out of the tool.
- Robotic wafer handlers do load and unload wafer from cassette to reduce wafer particulate contamination over manual handling.

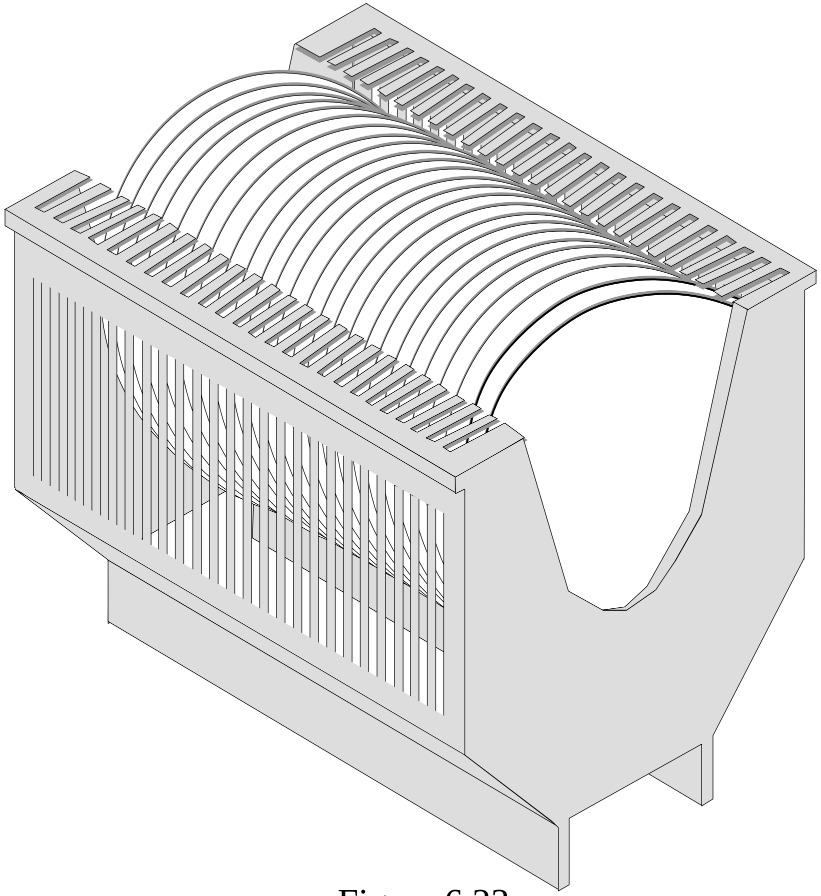

Figure 6.23

Electrostatic Wafer Chuck (ESC)

- Phase I: mechanical clamp
- Phase II: vacuum chuck, but leads to distort the shape of the wafer
- Phase III: ESC generates minimum particles and holds the wafer flat

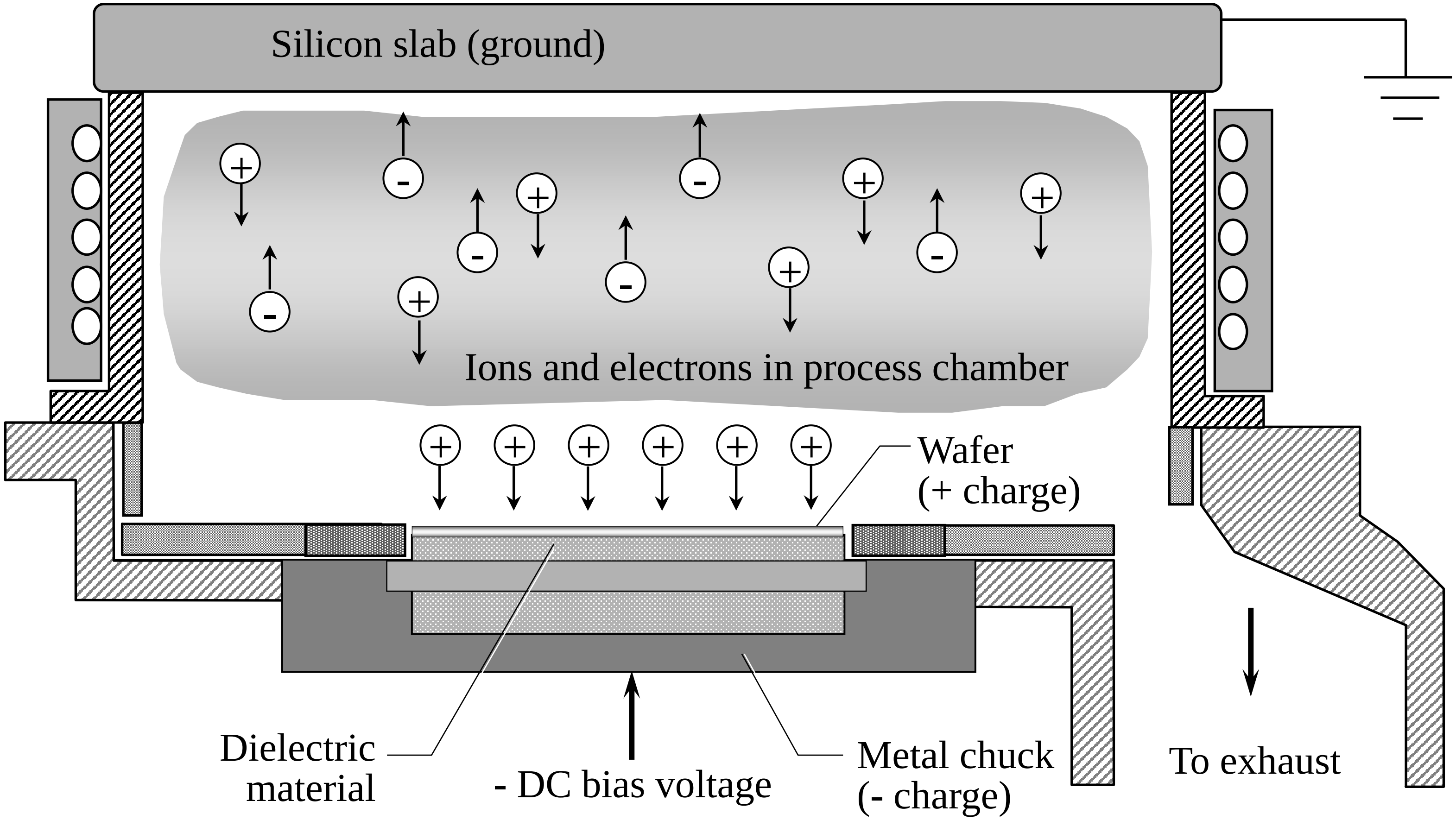

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Figure 6.24

Minienvironment Concept

- SMIF: standard mechanical interface
- It reduces wafer exposure to water vapor during the nitrogen purge, which serves to inhibit native-oxide growth

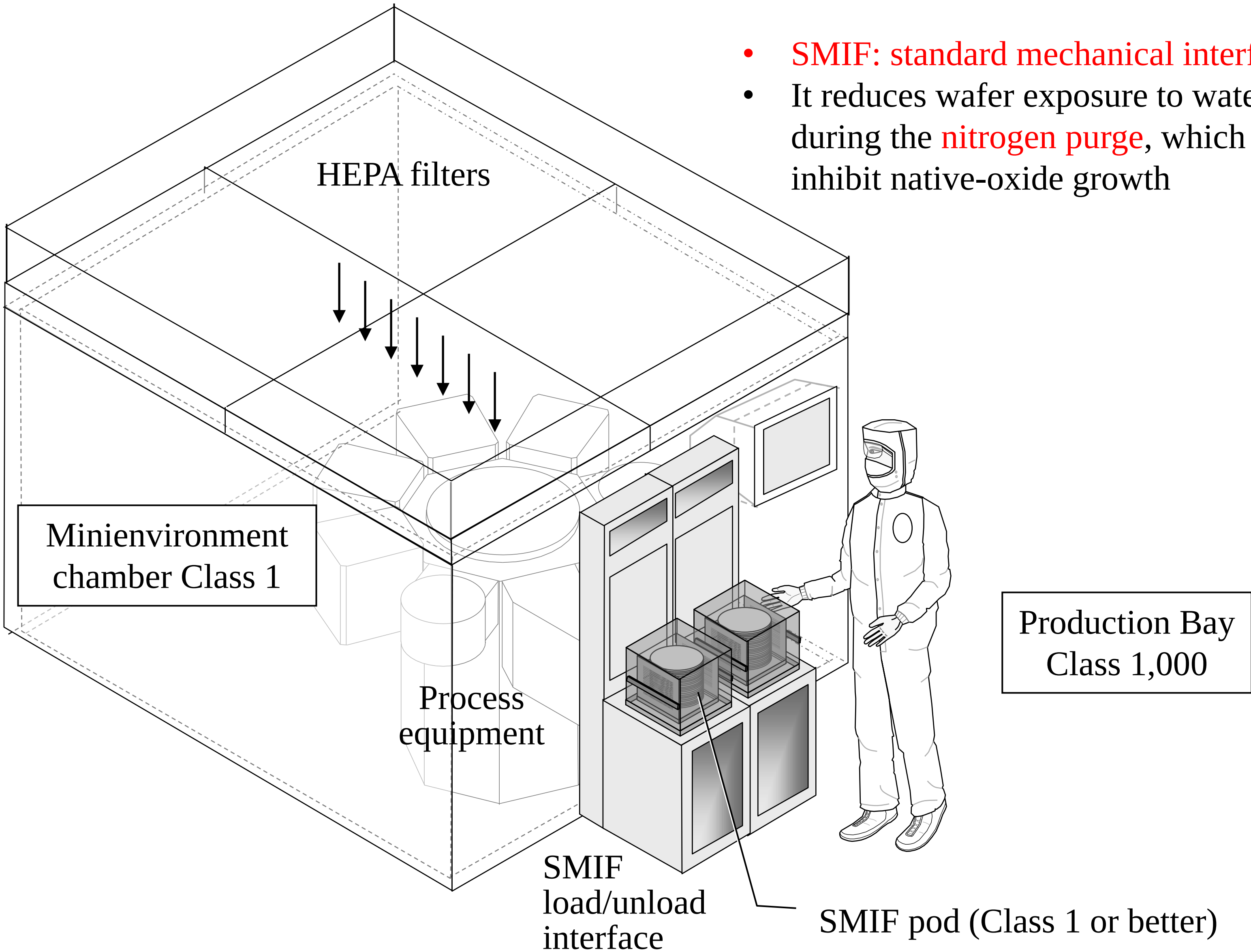


Figure 6.25

FOUP: for 12-in wafer, the cassette and pod will become one.

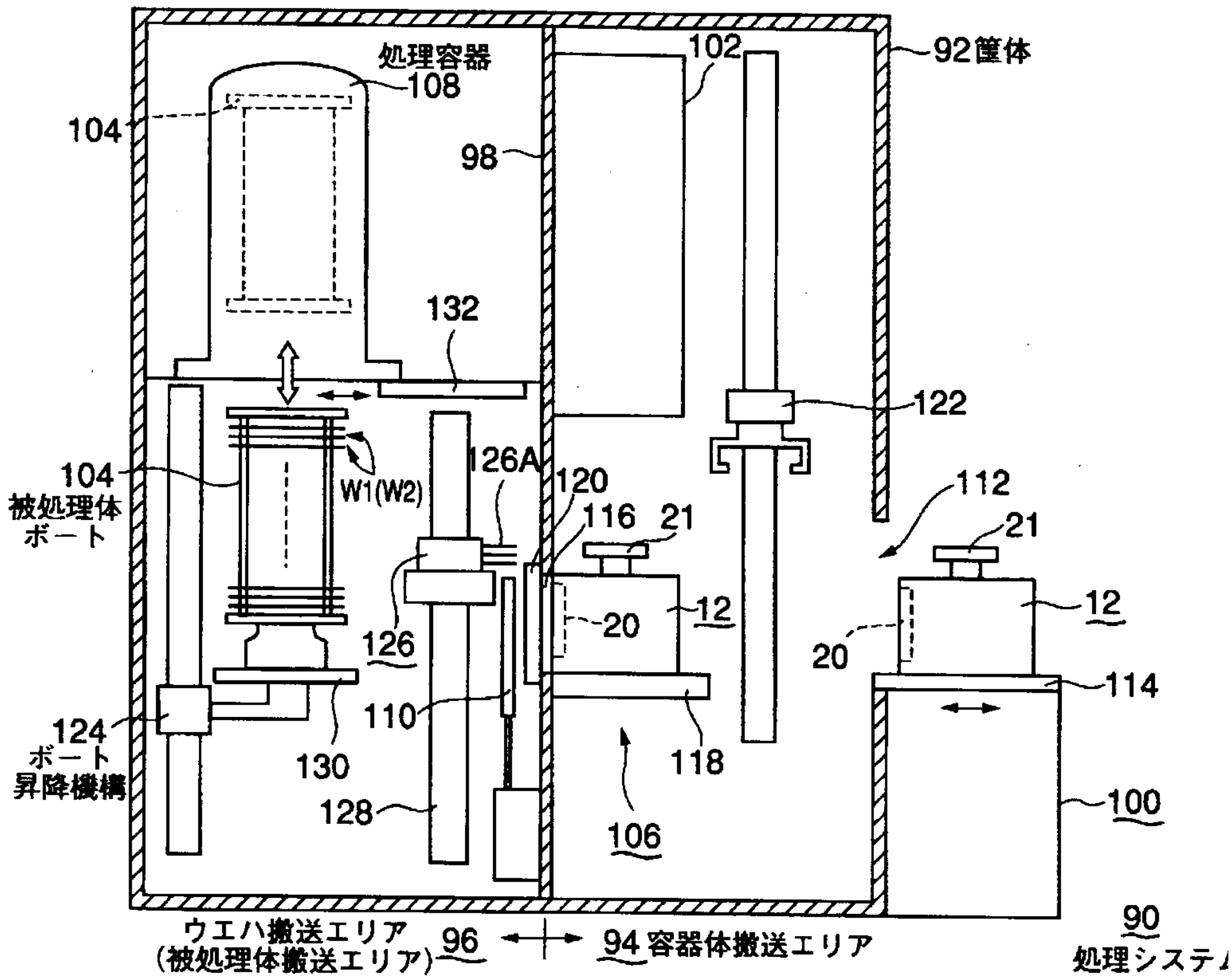
Front-opening unified pod

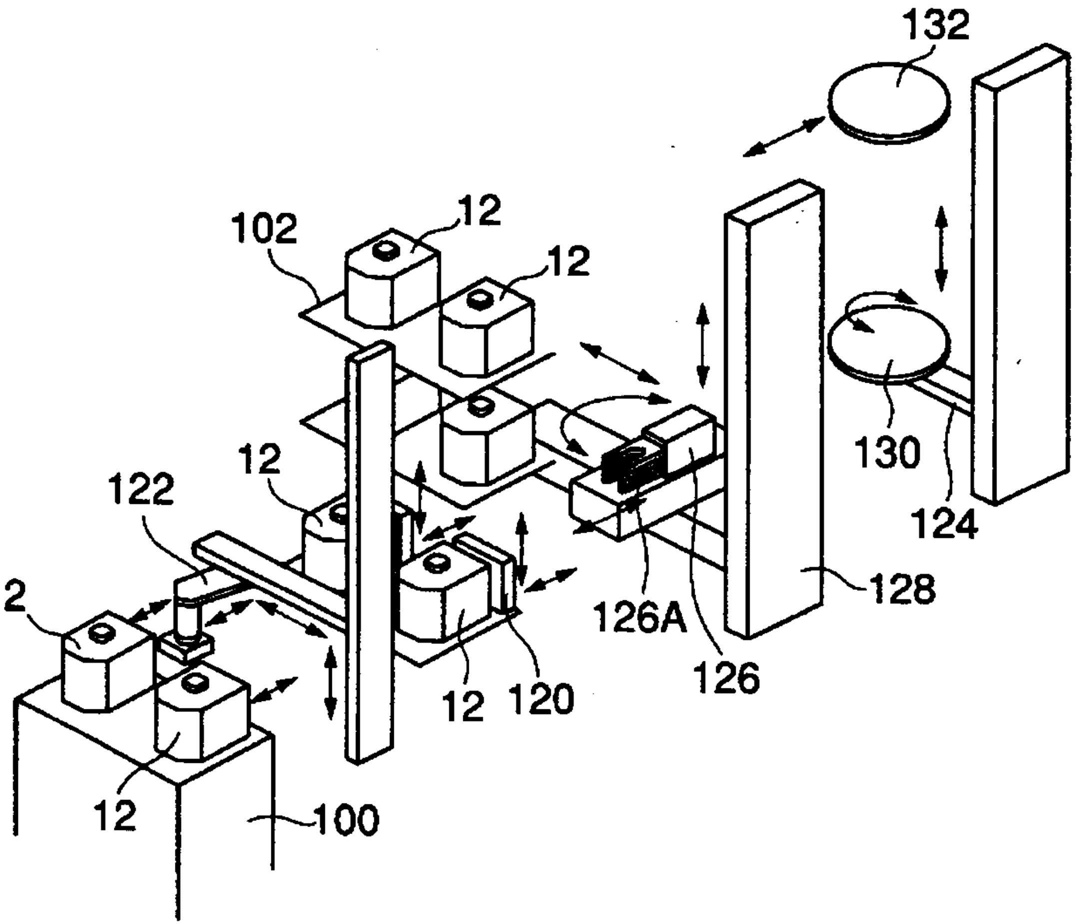
SMIF Pod Interface

Photograph courtesy of Applied Materials, Centura 5300 SMIF pod interface

Photo 6.4

SMIF for Vertical Furnace





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Wafer Wet Cleaning

- Wet-Cleaning Overview
- Wet Clean Equipment
- Alternatives to RCA Clean

Wafer Wet-Cleaning

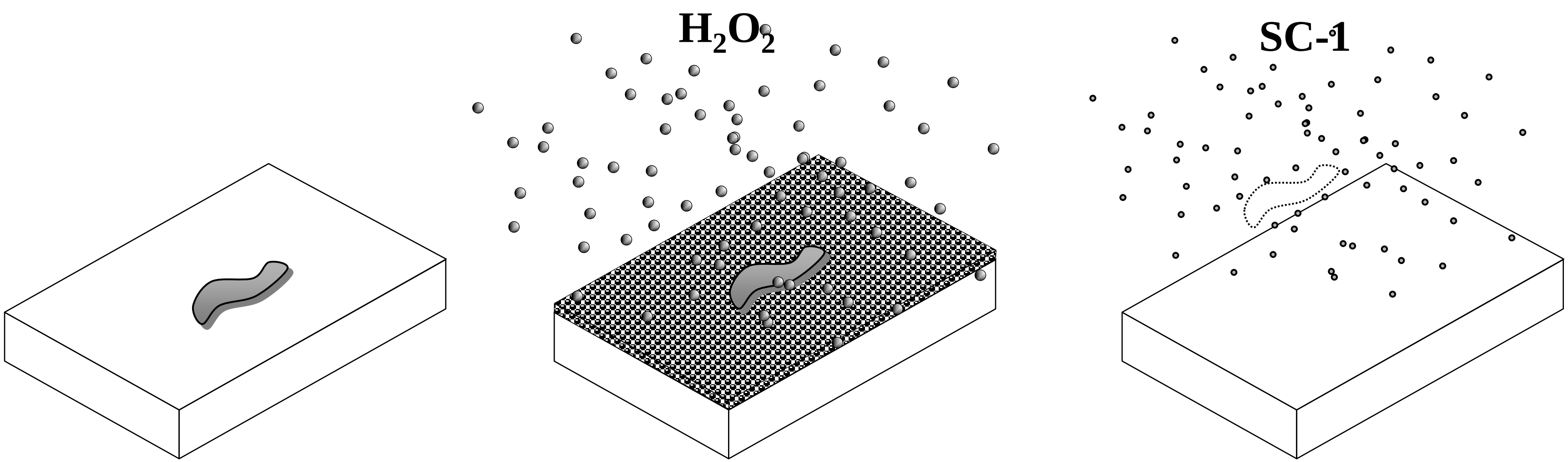
- RCA Clean
  - Standard Clean 1 (SC-1)
  - Standard Clean 2 (SC-2)
- Modification to RCA Clean
  - Piranha Mixture
  - HF Last Step
  - Chemical Vapor Cleaning
- Wafer Cleaning Steps

Wafer Wet-Cleaning Chemicals

Contaminant	Name	Chemical Mixture Description (all Cleans are followed by a DI Water Rinse)	Chemicals
Particles	Piranha (SPM)	▪ Sulfuric acid/hydrogen peroxide/DI water	$H_2SO_4/H_2O_2/H_2O$
	SC-1 (APM)	• Ammonium hydroxide/hydrogen peroxide/DI water	$NH_4OH/H_2O_2/H_2O$
Organics	Piranha (SPM)	• Sulfuric acid/hydrogen peroxide/DI water	$H_2SO_4/H_2O_2/H_2O$
Metallics **(not Cu)**	SC-2 (HPM)	• Hydrochloric acid/hydrogen peroxide/DI water	$HCl/H_2O_2/H_2O$
	Piranha (SPM)	▪ Sulfuric acid/hydrogen peroxide/DI water	H_2SO_4/H_2O_2
	DHF	• Hydrofluoric acid/water solution (will not remove copper)	HF/H_2O
Native Oxides	DHF	• Hydrofluoric acid/water solution (will not remove copper)	HF/H_2O
	BHF	• Buffered hydrofluoric acid	$NH_4F/HF/H_2O$

Table 6.5

Oxidation and Solubility of Particle in SC-1



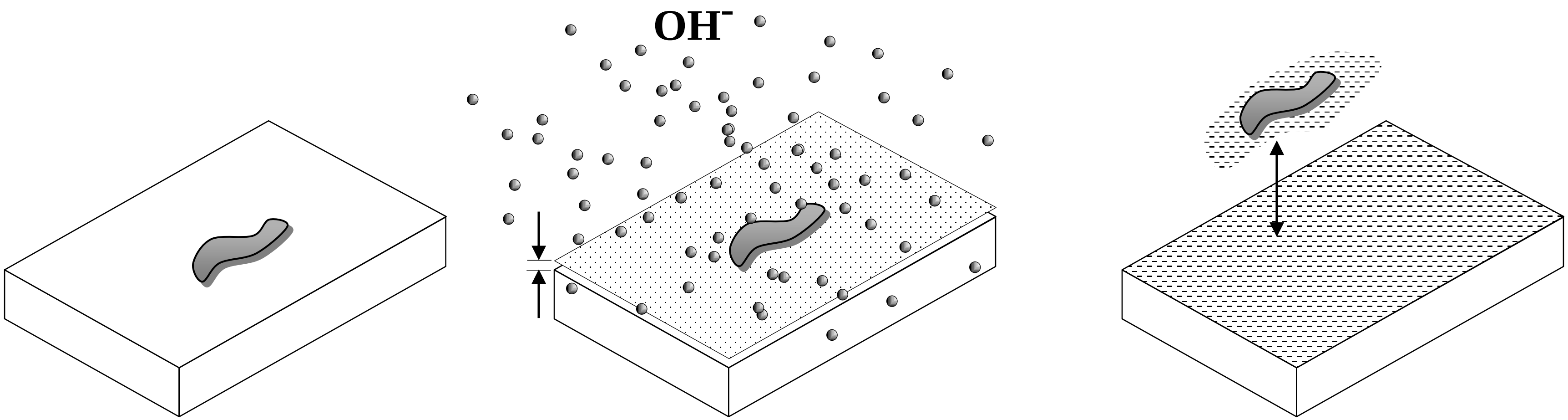
(1) Particle attaches to silicon.

(2) Oxidation of silicon by H_2O_2 helps lift particle.

(3) Particle dissolves in SC-1 solution.

Figure 6.26

Particle Removal Through Negative Charge Repulsion



(1) Particle attaches to silicon.

(2) OH^- from NH_4OH etches surface.

(3) HO^- builds up a negative charge on the surface that repels the particle away.

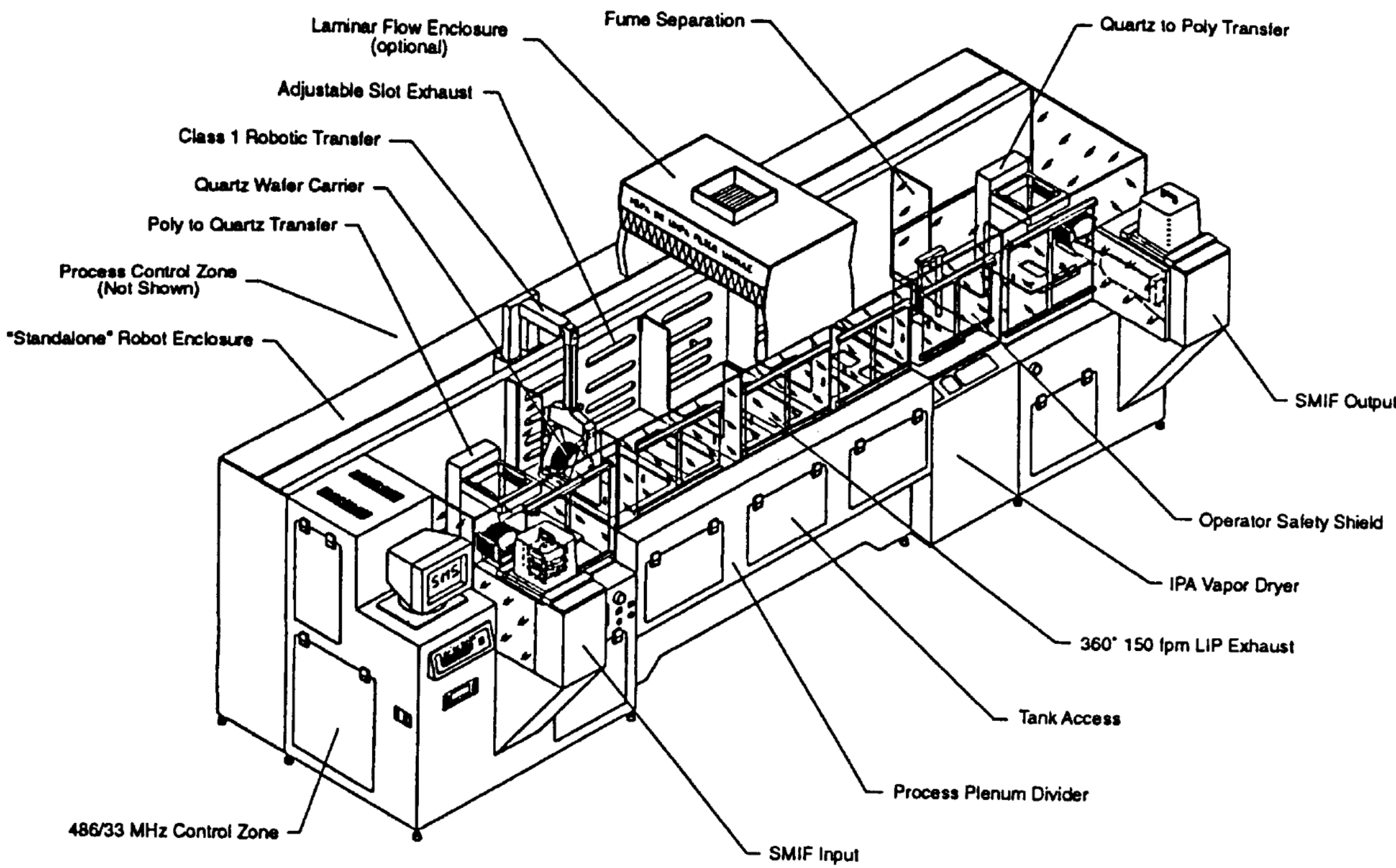
Figure 6.27

Typical Wafer Wet-Cleaning Sequence

Cleaning Step	What it Cleans
H_2SO_4/H_2O_2 (piranha)	**Organics & metals**
UPW rinse (ultrapure water)	Rinse
HF/H_2O (dilute HF)	Native oxides
UPW rinse	Rinse
$NH_4OH/H_2O_2/H_2O$ (SC-1)	**Particles**
UPW rinse	Rinse
HF/H_2O	Native oxides
UPW rinse	Rinse
$HCl/H_2O_2/H_2O$ (SC-2)	**Metals**
UPW rinse	Rinse
HF/H_2O	Native oxides
UPW rinse	Rinse
Drying	Dry

Table 6.6

Wet Bench for Immersion Processing



Wet-Cleaning Equipment

- Megasonics
- Spray Cleaning
- Scrubbers
- Wafer Rinse
  - Overflow Rinsers
  - Dump Rinse
  - Spray Rinse
  - Hot DI-Water Rinsing
- Wafer Drying
  - Spin Dryers
  - IPA Vapor Dry

Megasonic Cleaning

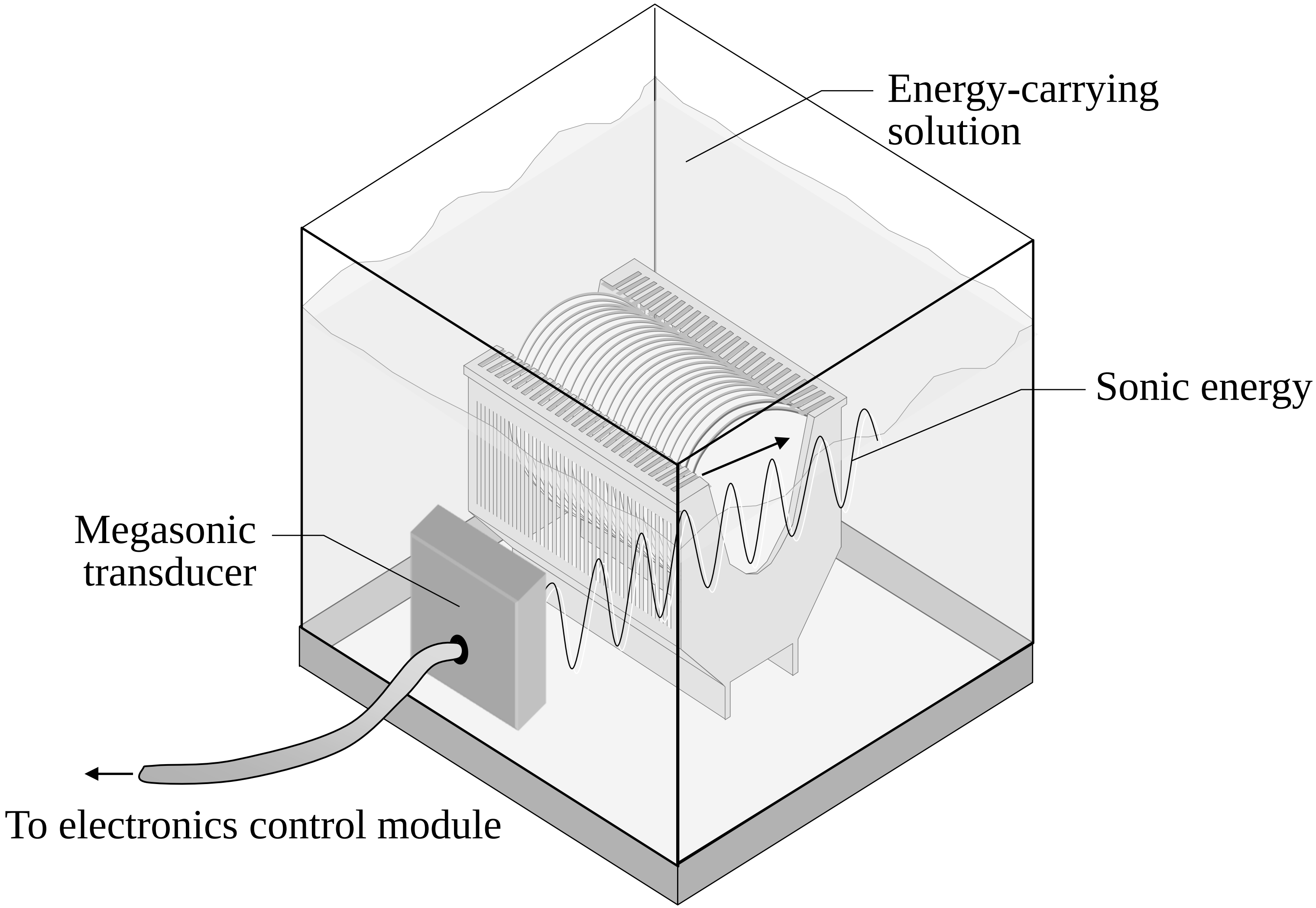


Figure 6.28

Megasonic Cleaning

- Using ultrasonic energy with frequencies near 1-M Hz.
- Achieves much more effective particle removal at lower bath temperatures (30°C vs. RCA 80°C)
- This fact is important because of the difficulty in removing smaller particles, more force is needed.
- Mechanisms: (a) cavitation (formation of bubbles, 渦凹) and (b) acoustic streaming.
- (a) Cavitation: transducer creates pressure waves, bubbles form in the low-pressure, bubbles collapse to enhance particles removal without damage to silicon wafer.
- (b) Acoustic streaming is the steady flow of liquid induced in the megasonic tank from the ultrasonic energy.
- Flowing liquid has more cleaning action than stationary water because it transports the particle away from the surface.
- When frequency < 100 kHz, it is called ultrasonic, cavitation-induced pitting on silicon wafers occurs that have not been found in the megasonic frequency range (800-1200 kHz)

Spray Tool Designs for Wafer Cleaning

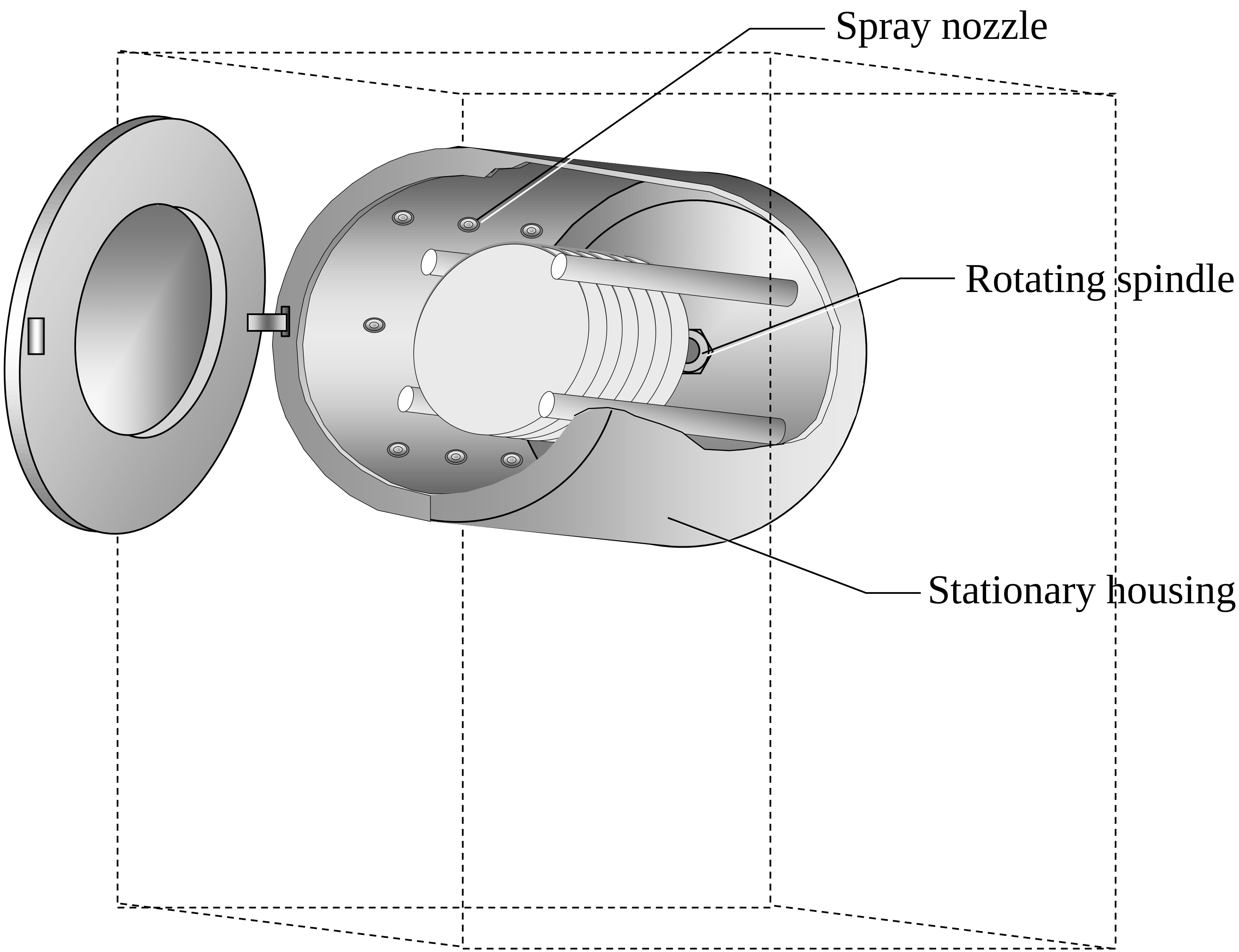


Figure 6.29

Spray Cleaning

- The wet-cleaning chemicals are sprayed onto wafers.
- A DI-water rinse is sprayed on the wafers after each cleaning step.
- The DI water's resistivity is monitored to determine when all the chemicals are removed.
- After completion of the cleaning and rinsing cycles, the chamber is purged with hot nitrogen and the spin rate is accelerated to dry the wafers.
- Advantage is a continuous supply of premixed, freshly blended chemicals sprayed on the wafer.
- The use of spray and centrifugal force from the rotating wafer ensures effective rinsing at a reduced chemical and water usage rate.
- Center of wafer is not turning at the high velocity, worse with larger diameter wafers.

Wafer Brush Scrubber

- Widely used following wafer chemical mechanical planarization (CMP).
- Brush scrubbing is able to remove particles one micron in diameter and smaller.
- PVA (聚醋酸乙烯酯) brushes are effective at removing particles without wafer damage.

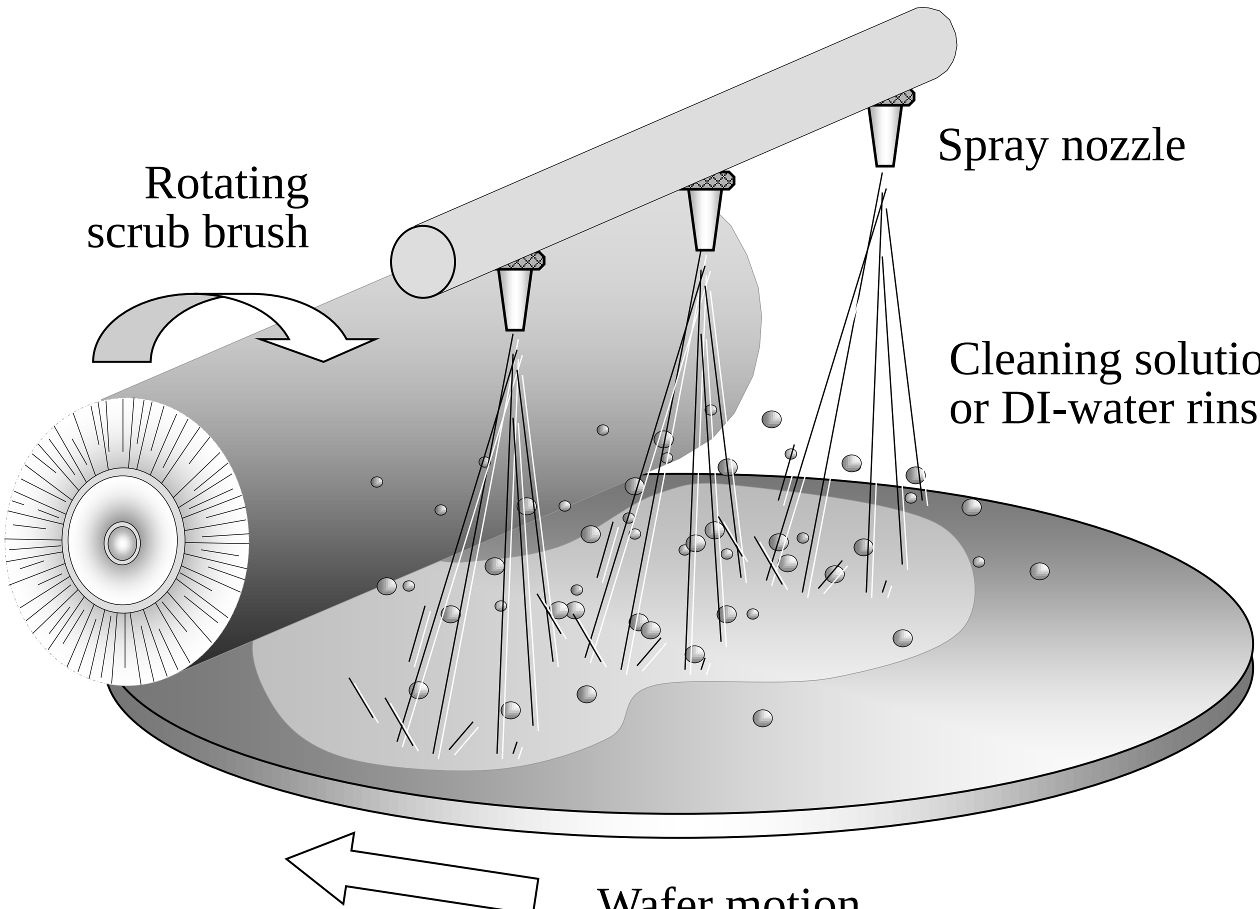
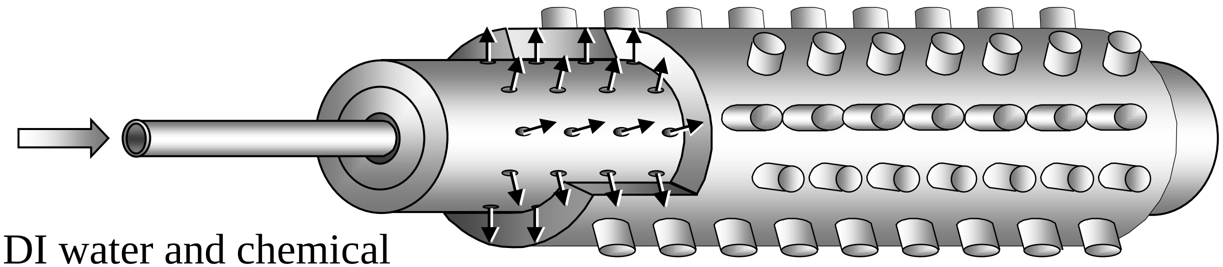
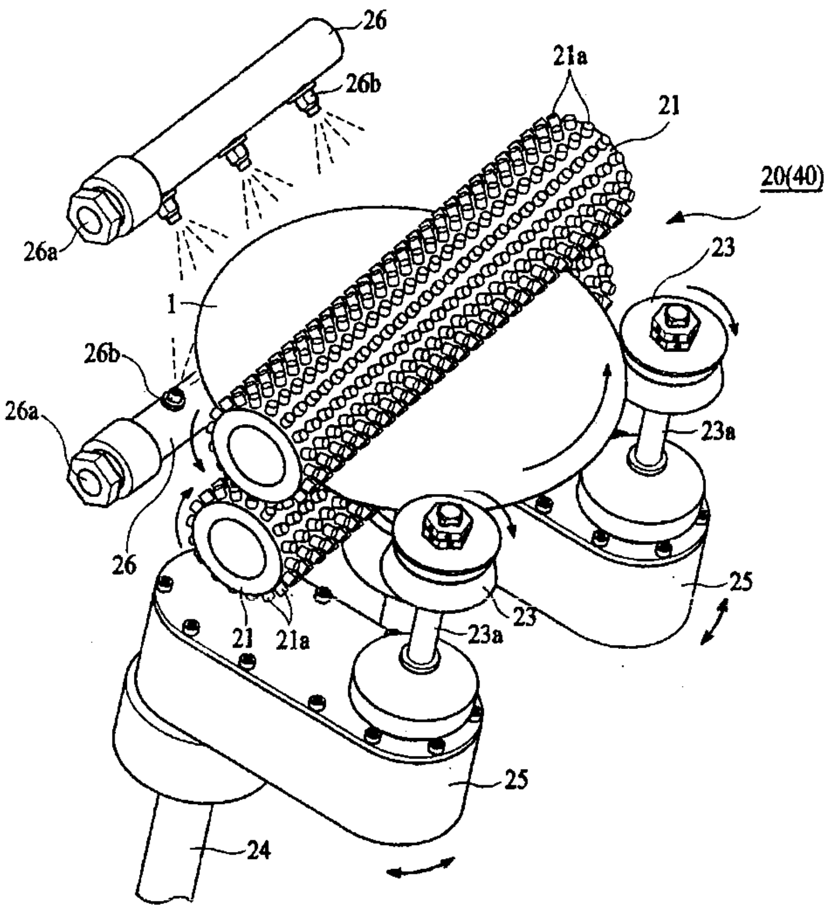


Figure 6.30

Double-side Scrubber





Overflow Rinser

- Chemical residues must be removed from the wafer after cleaning.
- Every wet-clean process step is followed by an DI water rinse.
- Overflow rinsers are the conventional system, but they consume a large amount of DI water.

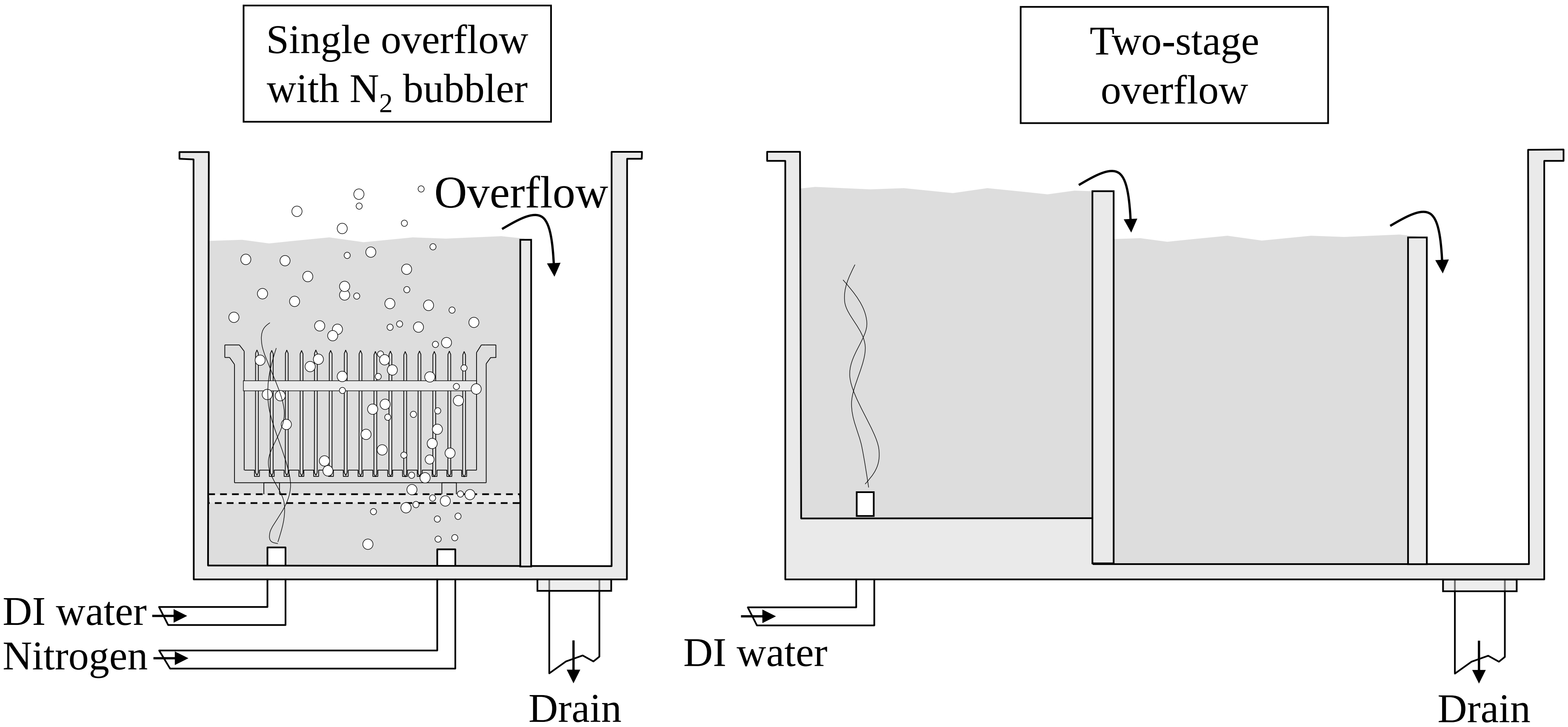


Figure 6.31

Dump Rinse

- Hot DI-water rinsing (70~80°C) has become widely used for rinsing the wafer.
- Benefits are that is aids in the removal of residual chemicals and it improves the performance of the dry wafer.
- Some reports show that the use of DI-water rinse at elevated temperatures creates a etching silicon surface.

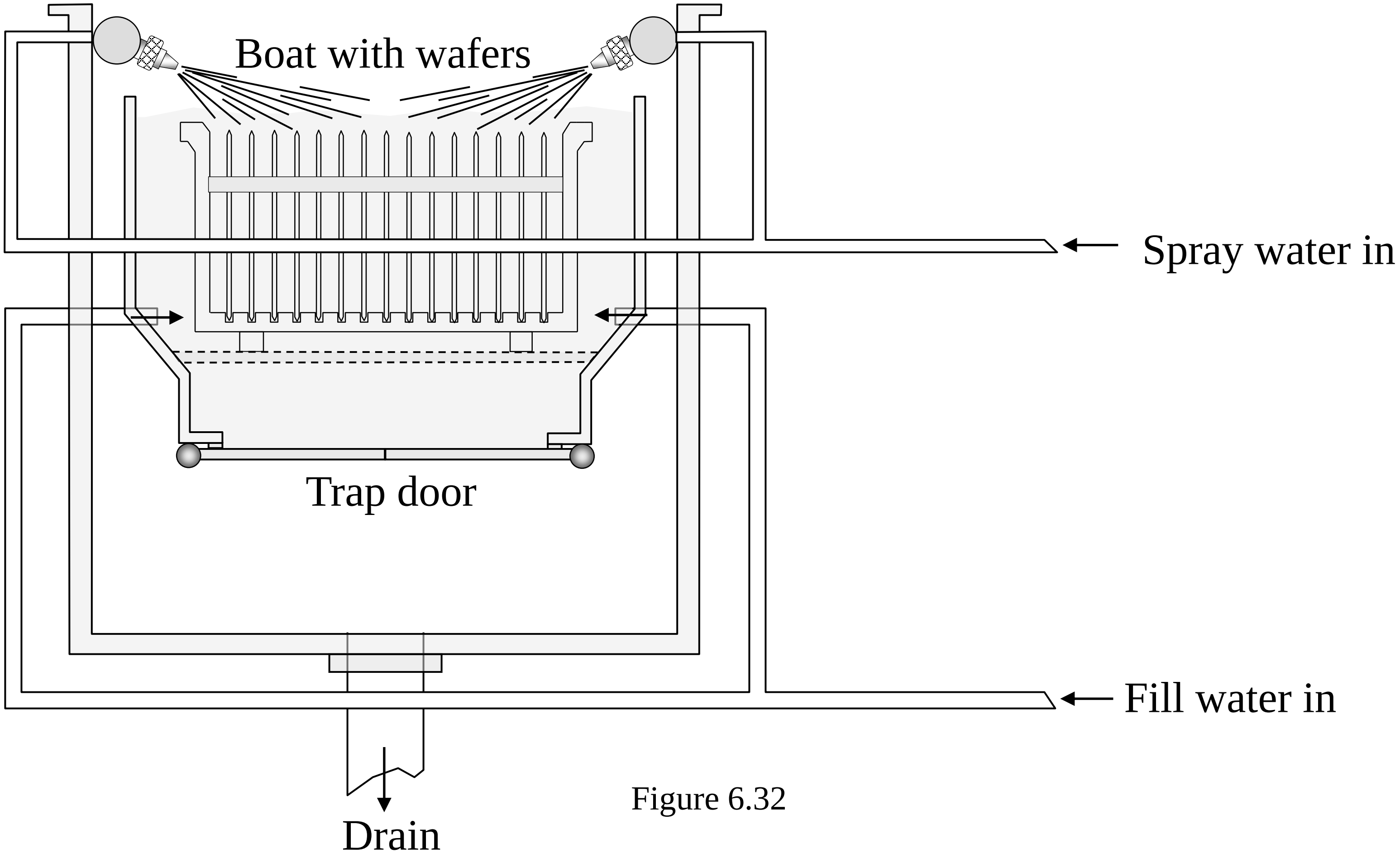
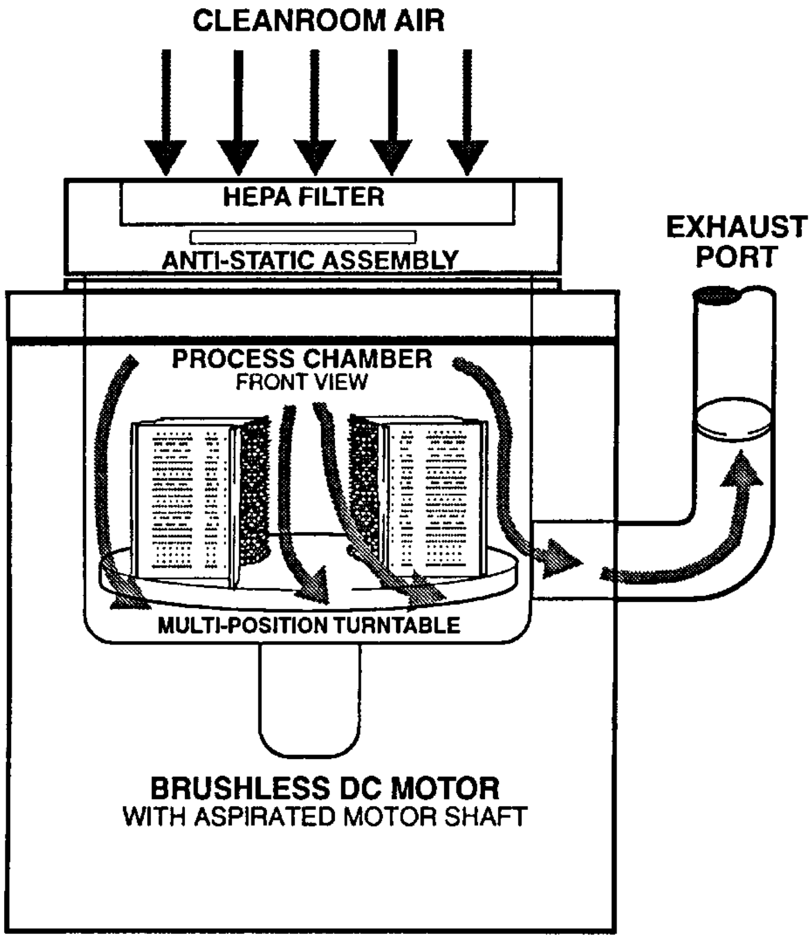


Figure 6.32

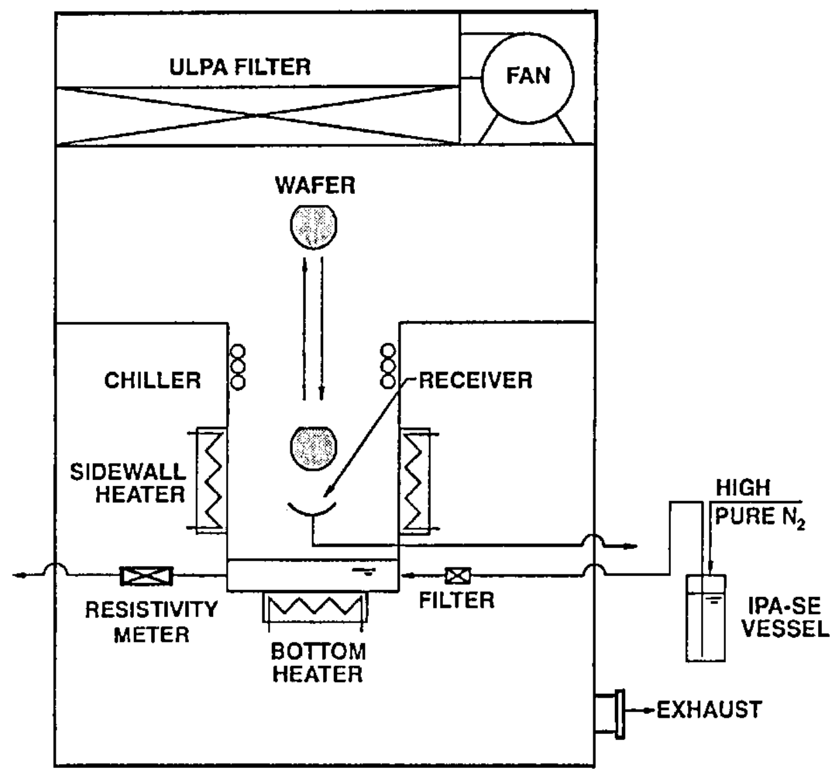
Wafer Drying

- It is important to dry the wafer with no drying spots.
- Wettability: water will either adhere to a clean hydrophilic wafer or bead up on a hydrophobic surface.
- Oxide-coated and RCA-cleaned wafer surfaces are hydrophilic.
- Oxide-free surfaces that have been hydrofluoric acid (HF) etched and hydrophobic due to the hydrogen-terminated surface.
- (a) Spin dryers [Fig.6.29]: high-speed rotation removes moisture while wafers are sprayed with heated nitrogen
- (b) IPA vapor dry: a displacement of water by heated solvent vapors of isopropyl alcohol (IPA).

Wafer Drying



Downflow centrifugal dryer



Isopropyl alcohol vapor dryer

Alternatives to RCA Clean

- Dry Cleaning
  - Plasma-Based Dry Cleaning (HF-vapor or ashing)
- Chelating Agents (EDTA)
- Ozone: remove light organic
- Cryogenic Aerosol Cleaning (inject cool Ar as solid ice particles)