EE M150: Introduction to Micromachining and MEMS

Lecture:
Chemical Safety, Yield, Clean Room Technology, and Wafer Cleaning Processes

Prof. Jack W. Judy

Lecture Outline

- Readings:
  - Chemical Safety Handbook: 1-46
  - Madou, Chapter 1: 10-14
  - Optional
    - Wolf and Tauber: Chapter 5: 119-148
- Topics:
  - Chemical Safety
  - Contamination
  - Device Yield
  - Clean Room Technology
  - Cleaning Processes
Chemical Safety: NFPA Diamond

- Identification system for chemical and material hazards
- Developed by the National Fire Protection Association
- 4 color-coded quadrants
- Numbers indicate severity: 0 = minimal, 4 = severe
- http://www.orcbs.msu.edu/chemical/nfpa/nfpa.html

NFPA Diamond

- **Blue Quadrant**: Health
  - 0: materials that on exposure during fire conditions would offer no hazard beyond that of an ordinary combustible
  - 1: materials that on exposure would cause irritation but only minor residual injury
  - 2: intense or continued exposure (not chronic) could cause temporary incapacitation or residual injury
  - 3: short exposure could cause serious temporary or residual injury
  - 4: short exposure could cause death or major injury

Gasoline = 1, Formaldehyde = 2, Cyanide = 3, Fluorine = 4
NFPA Diamond

• **Red Quadrant:** Flammability
  - 0: materials that will not burn
  - 1: materials that must be preheated before ignition can occur
  - 2: materials that must be moderately heated or exposed to relatively high ambient temperatures before ignition occurs
  - 3: liquids and solids that can be ignited under almost all ambient temperatures
  - 4: materials that will rapidly or completely vaporize at atmospheric pressure and normal ambient temperature or are readily dispersed in air and will burn easily

  Lubricating Oil = 1, Formic Acid = 2, Gasoline = 3, Propane = 4

NFPA Diamond

• **Yellow Quadrant:** Reactivity
  - 0: materials that are stable even under fire conditions and do not react with water
  - 1: normally stable but become unstable at high temperatures and pressures
  - 2: readily undergo violent chemical changes at elevated temperatures and pressures or react violently with water
  - 3: capable of detonation or explosive decomposition put require a strong initiating source, confined space, or explosive with water
  - 4: readily capable of detonation or explosive decomposition at normal temperatures and pressures

  Zinc = 1, Calcium = 2, Fluorine = 3, Nitroglycerine = 4
NFPA Diamond

- **White Quadrant**: Special
  - **W**: materials that demonstrate unusual water reactivity
  - **OX**: materials that possess oxidizing properties
    - oxidizers spontaneously evolve oxygen at room temperature or with slight heating

![Diagram of NFPA Diamond with Quadrants]

Material Safety Data Sheets

- **MSDS provides safety information**:
  - chemical breakdown (*what it is*)
  - methods of exposure (*how it gets in you*)
  - effects/risk of exposure (*what it does*)
  - permissible air concentration (*how much*)
  - any unusual chronic toxicity
  - flash point, autoignition temperature

- **MSDS is compiled by manufacturer**
  - required for shipping and storage
  - *no standard format*
Why Clean and Be Clean?

- Contamination can
  - ruin devices
    - a single ruined device in a complex circuit or MEMS structure can cause the whole chip to fail
      - leads to a lower yield of good chips per wafer
      - leads to higher costs and lower profits per chip
    - “poison” equipment
      - equipment must be removed from the manufacturing line
        - reduces production throughput and revenue
  - pose a health risk
    - endanger employees, customers, and environment
      - greatly increasing costs, possible litigation, etc...

Types of Contamination

- Particulates
  - Inorganic Dust
    - metallic, silicon, glass, quartz...
  - Organic Dust
    - dried skin, hair, clothing fibers, makeup, bacteria, ...

- Films
  - Residues
    - oil, grease, finger prints, incomplete etch, ...
    - solvent residues (acetone, IPA, ...), photoresist developer residue, inadequate rinsing, water stains, ...
  - Oxides
    - grown by thermal, chemical, or electrochemical processes

- Atomic Contamination
  - Absorbed / Adsorbed Atoms or Ions
    - in / on the films or substrate (Na, K, Ca, Au, Cu, Fe, Ni, Cr, ...)
Sources of Contamination

• Humans
  – cause most of the contamination
  – dirt, oils, etc. tracked into labs on shoe soles
  – bodies continuously exfoliate skin, replace hair, …
  – widespread use of make-up, perfume, hair gels, …
    • spread throughout lab by central air system
  – use of mechanical tweezers
    • scratch and chip wafer edge and surface

• Machines
  – abrasion during automated wafer handling
  – mechanical mechanism wear and lubrication
  – aging plastic and rubber parts

Contamination Induced Problems

• Mobile ions in oxides
  – can change electric fields and voltages at Si surface
    • mostly an issue for MOSFETs (Δ threshold voltage) but also
      exploited for anodic wafer bonding (covered in EE M250A)

• Impurities in silicon
  – act as recombination centers for electron-hole pairs
    and impact carrier concentration / distribution

• Particles on surface or in release etchant
  – create numerous problems during photolithography
  – can jam micromechanical structures

• Unintentional films between layers
  – create open circuits or short circuits between layers
  – impede adhesion between films (release etch)
Effects of Particulates

- Photolithography
  - create defects (cuts or protrusions)

- Microstructures

  ![Feature Size vs Year Graph](image)

Device Yield

- Yield is the fraction of functional parts
- Defect densities $D_o$
  - $n$ defects on wafer, $N$ chips, chip area $A$
  - larger die are more likely to be defective
  - might or might not be uniform from wafer to wafer
- Poisson yield (worst case): $Y_{\text{poisson}} = \exp(-D_o \cdot A)$
Impact of Device Yield

- Reduce die size for fixed defect density increase yield
- Consider 25 200-mm wafers/day and profit $1/chip
  - 100% yield = profit of $5M/year
  - 80% yield = loss profit of $1M/year
  - reduce chip size by 2X increases profits by 4X

Clean Room Air Filters

- High Efficiency Particulate Air (HEPA) Filters
  - most common type of clean room air filter
  - high efficiency, low pressure drop, good loading characteristics
  - uses glass fibers in a paper-like medium
  - are rated by their particle retention:
    - A true HEPA-rated filter, by definition, will retain 99.97% of incident particles of with a diameter of 0.3 µm or larger
Clean Room Designs

**FIGURE 5**
Cleanroom with axial fan units installed sideways connecting the air-supply plenum at the top and the air-return plenum at the bottom.

**FIGURE 6**
Hallroom-type cleanroom with process and service areas located on the same floor.
Clean Room Classification

- **Temperature** is controlled: 68 to 72 °F
- **Humidity** is controlled: 40 to 46 % RH
- **Room is held at positive pressure to blow dust OUT**
  - 0.1 inch of H₂O (3.6 mpsi) for Class 100, 1000, and 10,000
  - 0.3 to 0.4 inch of H₂O for Class 1 and 10
  - doors open inward, so room pressure closes them shut

- **Biohazard rooms operate at negative pressure to keep bugs IN**

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**Clean Room Classification**

<table>
<thead>
<tr>
<th>Class</th>
<th># 0.5 μm particles per ft³</th>
<th># 5.0 μm particles per ft³</th>
<th>air changes per hour</th>
<th>ceiling filter coverage (%)</th>
<th>air velocity (fpm)</th>
<th>max. vibration (μm/s)</th>
<th>temp. tolerance</th>
<th>RH tolerance</th>
<th>approx. capital cost per ft³</th>
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<td>office</td>
<td>12-18</td>
<td>10</td>
<td>3</td>
<td>10</td>
<td>±3 °F</td>
<td>±5%</td>
<td>$10</td>
<td>$50</td>
<td>$350,000</td>
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<tr>
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<td>100,000</td>
<td>65</td>
<td>30</td>
<td>10</td>
<td>±3 °F</td>
<td>±5%</td>
<td>$200,250</td>
<td>$50</td>
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<tr>
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<td>65</td>
<td>50</td>
<td>30</td>
<td>±2 °F</td>
<td>±5%</td>
<td>$300,000</td>
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<tr>
<td>100</td>
<td>100</td>
<td>65</td>
<td>50</td>
<td>30</td>
<td>±2 °F</td>
<td>±5%</td>
<td>$3,000</td>
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<tr>
<td>10</td>
<td>10</td>
<td>65</td>
<td>50</td>
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<td>$50</td>
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Laminar Flow Benches

- Use HEPA filtering to provide local clean air conditions
  - can drop the Class rating by a factor of 100 in a local area
    - Class 100 laminar bench and in a Class 10,000 Clean Room
- Vertical style used above free standing equipment
- Horizontal style used behind microscopes

Clean Room Clothing

<table>
<thead>
<tr>
<th>CLASS 1</th>
<th>CLASS M 1.5</th>
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<td>Hood</td>
<td></td>
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<tr>
<td>Hair Cover</td>
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</tr>
<tr>
<td>Coverall</td>
<td></td>
</tr>
<tr>
<td>Intersuit</td>
<td></td>
</tr>
<tr>
<td>Boots</td>
<td></td>
</tr>
<tr>
<td>Facial Cover</td>
<td></td>
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<tr>
<td>Gloves</td>
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</tr>
<tr>
<td>Safety Glasses</td>
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<tr>
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<tr>
<td>Coverall or Frock</td>
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</tr>
<tr>
<td>Boots or Footwear</td>
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<tr>
<td>Facial Cover (Optional)</td>
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<tr>
<td>Gloves</td>
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<tr>
<td>Safety Glasses</td>
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<tr>
<td>Boots or Footwear</td>
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<td>Facial Cover (Optional)</td>
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<td>Gloves (Optional)</td>
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<table>
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<tr>
<td>Safety Glasses</td>
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**Gowning Sequence**

1. **Intersuit**
   - Needed for cleanest classes

2. **Shoe Cover**
   - May be needed before entering gowning area

3. **Cap**
   - Make sure to Contain ALL hair

4. **Hood**
   - Check for snug fit good face seal

5. **Face Mask**
   - Bend nose piece for a snug facial fit

6. **Coverall**
   - Keep off floor and bench, tuck in hood before zipping

7. **Boots**
   - Put on over the leg of the coverall

8. **Safety Glasses**
   - Remember to put on safety glasses

9. **Gloves**
   - Pull hem of glove over coverall sleeve

Taken from [http://www.uniclean.com/technical/gowning-sequence.htm](http://www.uniclean.com/technical/gowning-sequence.htm)

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**Clean Room Dos and Don’ts**

- **Do:**
  - change gloves whenever dirty or torn
  - use a fresh pair of gloves whenever handling wafers
  - wipe down wafer handling areas with isopropanol
  - use clean room paper and dust-free ball point pens
  - remove all rings and bracelets from fingers and wrists
  - use special lint-free paper and pens or markers

- **Don’t:**
  - touch your face or skin with gloves
  - touch oily machinery or hot elements
  - lean on equipment
  - wear cosmetics, powders, or colognes
  - use normal paper and pencils
Wafer Cleaning

• Clean wafers are needed for high device yield
• Must remove particles, residues, contamination
• Cleaning process must not generate particles

• Semiconductor Industry Association Roadmap:
  – for ICs of 0.25 µm in size:
    • Metal Contamination: $10^9$ atoms/cm$^2$
    • Organic Contamination: $10^{14}$ atoms/cm$^2$
    • Oxide Contamination: $10^{14}$ atoms/cm$^2$
    • Particle Contamination: 0.2 particles/cm$^2$ (125 nm in size)
    • Surface Roughness: < 0.1 nm

Defect Detection Methods

• Particles:
  – optical microscope: good down to 1-2 µm
  – automated laser and e-beam scanners

• Residues:
  – Synchrotron radiation total-reflection x-ray fluorescence (SR-TXRF)
    • can detect contamination down to $8 \times 10^7$ atoms/cm$^2$
Wafer Cleaning Processes

• Remove chemically bonded films
• Vital before high-temperature steps (furnaces)
• Popular cleaning sequence by Kern at RCA (~1960’s)
  – Remove thick organic films
    • immersion in Piranha (5:1 H₂SO₄:H₂O₂) or O₂ plasma
    • rinse in DI water until resistivity is >10 to 18 MΩ-cm
    • optional use of an ultrasonic bath to agitate particles off surfaces
  – Remove residual organics and some metals
    (Standard Clean 1: SC1)
    • 1:1:5 of NH₄OH : H₂O₂ : DI at 75 to 80º for 10 to 15 min, rinse
  – Strip hydrous oxide film formed in prior step
    • 10:1 of HF:H₂O, then a quick rinse (skipped for SiO₂ film)
  – Desorb remaining atomic / ionic contamination
    • 6:1:1 of H₂O:HCl:H₂O₂ at 75 to 80º for 10 to 15 min, rinse
  – Dry wafers with spin dryer

Next Lecture

• Readings for next lecture:
  – Jaeger: 13-28
  – Madou, Chapter 1: 1-10, 13-32, 38-41
  – Optional:
    • Madou: 33-76
    • Wolf and Tauber: Chapter 12: 488-544