Modern IC factories employ a three tiered approach to controlling unwanted impurities:  
1. clean factories 2. wafer cleaning 3. gettering

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Minimum Feature Size</td>
<td>250nm</td>
<td>180nm</td>
<td>130nm</td>
<td>100nm</td>
<td>70nm</td>
<td>50nm</td>
</tr>
<tr>
<td>Wafer Diameter (mm)</td>
<td>200</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>DRAM Bits/Chip</td>
<td>256M</td>
<td>1G</td>
<td>4G</td>
<td>16G</td>
<td>64G</td>
<td>256G</td>
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<tr>
<td>DRAM Chip Size (mm²)</td>
<td>280</td>
<td>400</td>
<td>560</td>
<td>790</td>
<td>1120</td>
<td>1580</td>
</tr>
<tr>
<td>Microprocessor Transistors/Chip</td>
<td>11M</td>
<td>21M</td>
<td>76M</td>
<td>200M</td>
<td>520M</td>
<td>1.40B</td>
</tr>
<tr>
<td>Critical Defect Size</td>
<td>125nm</td>
<td>90nm</td>
<td>65nm</td>
<td>50nm</td>
<td>35nm</td>
<td>25nm</td>
</tr>
<tr>
<td>Starting Wafer Total LLS (cm⁻²)</td>
<td>0.60</td>
<td>0.29</td>
<td>0.14</td>
<td>0.06</td>
<td>0.03</td>
<td>0.015</td>
</tr>
<tr>
<td>DRAM GOI Defect Density (cm⁻²)</td>
<td>0.06</td>
<td>0.03</td>
<td>0.014</td>
<td>0.006</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Logic GOI Defect Density (cm⁻²)</td>
<td>0.15</td>
<td>0.15</td>
<td>0.08</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Starting Wafer Total Bulk Fe (cm⁻³)</td>
<td>3x10¹⁰</td>
<td>1x10¹⁰</td>
<td>Under 1x10¹⁰</td>
<td>Under 1x10¹⁰</td>
<td>Under 1x10¹⁰</td>
<td>Under 1x10¹⁰</td>
</tr>
<tr>
<td>Critical Metals on Wafer Surface After Cleaning (cm⁻²)</td>
<td>5x10⁹</td>
<td>4x10⁹</td>
<td>2x10⁹</td>
<td>1x10⁹</td>
<td>&lt; 10⁹</td>
<td>&lt; 10⁹</td>
</tr>
<tr>
<td>Starting Material Recombination Lifetime (µsec)</td>
<td>≥ 300</td>
<td>≥ 325</td>
<td>≥ 325</td>
<td>≥ 325</td>
<td>≥ 450</td>
<td>≥ 450</td>
</tr>
</tbody>
</table>

Contaminants may consist of particles, organic films (photoresist), heavy metals or alkali ions.
Example #1: MOS $V_{TH}$ is given by:

$$V_{TH} = V_{FB} + 2\phi_f + \sqrt{2\epsilon_S q N_A (2\phi_f)} \frac{C_T}{C_o} + \frac{q Q_M}{C_o} \quad (1)$$

- If $t_{ox} = 10 \text{ nm}$, then a 0.1 volt $V_{th}$ shift can be caused by $Q_M = 6.5 \times 10^{11} \text{ cm}^{-2} (< 0.1\% \text{ monolayer or } 10 \text{ ppm in the oxide}).$

- Example #2: MOS DRAM

  ![MOS DRAM Diagram]

- Refresh time of several msec requires a generation lifetime of

$$\tau_G = \frac{1}{\sigma v_{th} N_t} \approx 25 \text{ \mu s} \quad (2)$$

- This requires $N_t \approx 10^{12} \text{ cm}^{-3}$ or $\approx 0.02 \text{ ppb}$ (see text).
Level 1 Contamination Reduction: Clean Factories

- Air quality is measured by the “class” of the facility.

- Factory environment is cleaned by:
  - Hepa filters and recirculation for the air,
  - “Bunny suits” for workers.
  - Filtration of chemicals and gases.
  - Manufacturing protocols.
Level 2 Contamination Reduction: Wafer Cleaning

- RCA clean is “standard process” used to remove organics, heavy metals and alkali ions.
- Ultrasonic agitation is used to dislodge particles.
Level 3 Contamination Reduction: Gettering

- Gettering is used to remove metal ions and alkali ions from device active regions.

- For the alkali ions, gettering generally uses dielectric layers on the topside (PSG or barrier Si$_3$N$_4$ layers).
- For metal ions, gettering generally uses traps on the wafer backside or in the wafer bulk.
- Backside = extrinsic gettering.
- Bulk = intrinsic gettering.
• Heavy metal gettering relies on the facts that:
  • Metals diffuse very rapidly in silicon.
  • Metals segregate to “trap” sites.
• “Trap” sites can be created by SiO$_2$ precipitates (intrinsic gettering), or by backside damage (extrinsic gettering).

• In intrinsic gettering, CZ silicon is used and SiO$_2$ precipitates are formed in the wafer bulk through temperature cycling at the start of the process.

Modeling Particle Contamination and Yield

• $\approx 75\%$ of yield loss in modern VLSI fabs is due to particle contamination.
• Yield models depend on information about the distribution of particles.
• Particles on the order of 0.1 - 0.3 $\mu$m are the most troublesome:
  • larger particles precipitate easily
  • smaller ones coagulate into larger particles
• Yields are described by Poisson statistics in the simplest case:

\[
Y = \exp^{-ACDO}
\]

where \( AC \) is the critical area and \( DO \) is the defect density.

• This model assumes independent randomly distributed defects and often underpredicts yields.
• Negative binomial statistics eliminates these assumptions and is more accurate.

\[
Y = \frac{1}{\left(1 + \frac{ACDO}{C}\right)^C}
\]

where \( C \) is a measure of the particle spatial distribution (clustering factor).
• Note that defect densities will need to be extremely small in the future.

Modeling Wafer Cleaning

• Cleaning involves removing particles, organics (photoresist) and metals from wafer surfaces.
• Particles are largely removed by ultrasonic agitation during cleaning.
• Organics like photoresists are removed in an O\textsubscript{2} plasma or in H\textsubscript{2}SO\textsubscript{4}/H\textsubscript{2}O\textsubscript{2} solutions.
• The “RCA clean” is used to remove metals and any remaining organics.
• Metal cleaning can be understood in terms of the following chemistry.

\[
\text{Si} + 2\text{H}_2\text{O} \leftrightarrow \text{SiO}_2 + 4\text{H}^+ + 4\text{e}^- \quad (5)
\]
\[
\text{M} \leftrightarrow \text{M}^{z+} + z\text{e}^- \quad (6)
\]
• If we have a water solution with a Si wafer and metal atoms and ions, the stronger reaction will dominate.
• Generally (6) is driven to the left and (5) to the right so that SiO\(_2\) is formed and M plates out on the wafer.
• Good cleaning solutions drive (6) to the right since M\(^+\) is soluble and will be desorbed from the wafer surface.

<table>
<thead>
<tr>
<th>Oxidant/Reductant</th>
<th>Standard Oxidation Potential (volts)</th>
<th>Oxidation-Reduction Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn(^{2+}/\text{Mn})</td>
<td>1.05</td>
<td>Mn (\leftrightarrow) Mn(^{2+}) + 2e(^-)</td>
</tr>
<tr>
<td>SiO(_2)/Si</td>
<td>0.84</td>
<td>Si + 2H(_2)O (\leftrightarrow) SiO(_2) + 4H(^+) + 4e(^-)</td>
</tr>
<tr>
<td>Cr(^{3+}/\text{Cr})</td>
<td>0.71</td>
<td>Cr (\leftrightarrow) Cr(^{3+}) + 3e(^-)</td>
</tr>
<tr>
<td>Ni(^{2+}/\text{Ni})</td>
<td>0.25</td>
<td>Ni (\leftrightarrow) Ni(^{2+}) + 2e(^-)</td>
</tr>
<tr>
<td>Fe(^{3+}/\text{Fe})</td>
<td>0.17</td>
<td>Fe (\leftrightarrow) Fe(^{3+}) + 3e(^-)</td>
</tr>
<tr>
<td>H(_2)SO(_4)/H(_2)SO(_3)</td>
<td>-0.20</td>
<td>H(_2)O + H(_2)SO(_3) (\leftrightarrow) H(_2)SO(_4) + 2H(^+) + 2e(^-)</td>
</tr>
<tr>
<td>Cu(^{2+}/\text{Cu})</td>
<td>-0.34</td>
<td>Cu (\leftrightarrow) Cu(^{2+}) + 2e(^-)</td>
</tr>
<tr>
<td>O(_2)/H(_2)O</td>
<td>-1.23</td>
<td>2H(_2)O (\leftrightarrow) O(_2) + 4H(^+) + 2e(^-)</td>
</tr>
<tr>
<td>Au(^{3+}/\text{Au})</td>
<td>-1.42</td>
<td>Au (\leftrightarrow) Au(^{3+}) + 3e(^-)</td>
</tr>
<tr>
<td>H(_2)O(_2)/H(_2)O</td>
<td>-1.77</td>
<td>2H(_2)O (\leftrightarrow) H(_2)O(_2) + 2H(^+) + 2e(^-)</td>
</tr>
<tr>
<td>O(_3)/O(_2)</td>
<td>-2.07</td>
<td>O(_2) + H(_2)O (\leftrightarrow) O(_3) + 2H(^+) + 2e(^-)</td>
</tr>
</tbody>
</table>

• The strongest oxidants are at the bottom (H\(_2\)O\(_2\) and O\(_3\)). These reactions go to the left grabbing e\(^-\) and forcing (6) to the right.
• Fundamentally the RCA clean works by using H\(_2\)O\(_2\) as a strong oxidant.

**Modeling Gettering**

• Gettering consists of:
  1. Making metal atoms mobile.
  2. Migration of these atoms to trapping sites.
  3. Trapping of atoms.
• 1 generally happens by kicking out the substitutional atom into an interstitial site. One possible reaction is:

\[ \text{Au}_S + \text{Si}_I \leftrightarrow \text{Au}_i \]  

(7)

• 2 usually happens easily once the metal is interstitial since most metals diffuse rapidly in this form.

• 3 happens because heavy metals segregate preferentially to damaged regions or to N\(^+\) regions or pair with effective getters like P (AuP pairs). (See Chapter 4.)

• In intrinsic gettering, the metal atoms segregate to dislocations around SiO\(_2\) precipitates.