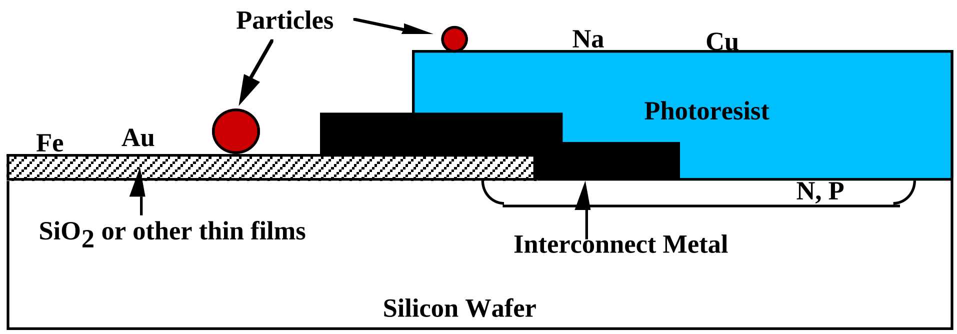
EE 212 FALL 1999-00

SEMICONDUCTOR MANUFACTURING - CLEAN ROOMS, WAFER CLEANING AND GETTERING- Chapter 4

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

Year of 1st DRAM Shipment	1997	1999	2003	2006	2009	2012
Minimum Feature Size	250nm	180nm	130nm	100nm	70nm	50nm
Wafer Diameter (mm)	200	300	300	300	450	450
DRAM Bits/Chip	256M	1G	4G	16G	64G	256G
DRAM Chip Size (mm^2)	280	400	560	790	1120	1580
Microprocessor Transistors/chip	11M	21M	76M	200M	520M	1.40B
Critical Defect Size	**125nm**	**90nm**	**65nm**	**50nm**	**35nm**	**25nm**
Starting Wafer Total LLS (cm^{-2})	**0.60**	**0.29**	**0.14**	**0.06**	**0.03**	**0.015**
DRAM GOI Defect Density (cm^{-2})	**0.06**	**0.03**	**0.014**	**0.006**	**0.003**	**0.001**
Logic GOI Defect Density (cm^{-2})	**0.15**	**0.15**	**0.08**	**0.05**	**0.04**	**0.03**
Starting Wafer Total Bulk Fe (cm^{-3})	**$3x10^{10}$**	**$1x10^{10}$**	**Under $1x10^{10}$**	**Under $1x10^{10}$**	**Under $1x10^{10}$**	**Under $1x10^{10}$**
Critical Metals on Wafer Surface After Cleaning (cm^{-2})	**$5x10^9$**	**$4x10^9$**	**$2x10^9$**	**$1x10^9$**	**$< 10^9$**	**$< 10^9$**
Starting Material Recombination Lifetime (µsec)	**≥ 300**	**≥ 325**	**≥ 325**	**≥ 325**	**≥ 450**	**≥ 450**



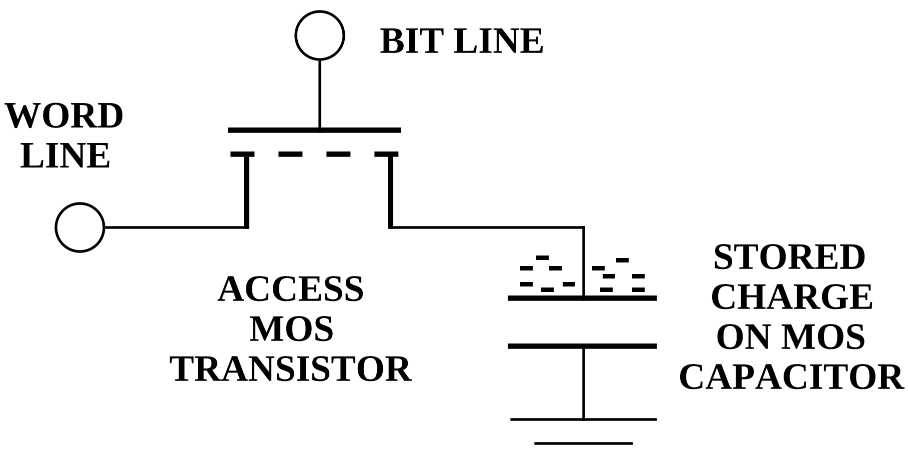
- **Contaminants may consist of particles, organic films (photoresist), heavy metals or alkali ions.**

Example #1: MOS V_{TH} is given by:

$$V_{TH} = V_{FB} + 2\phi_f + \frac{\sqrt{2\varepsilon_S q N_A (2\phi_f)}}{C_O} + \frac{qQ_M}{C_O} \qquad (1)$$

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

- Example #2: MOS DRAM



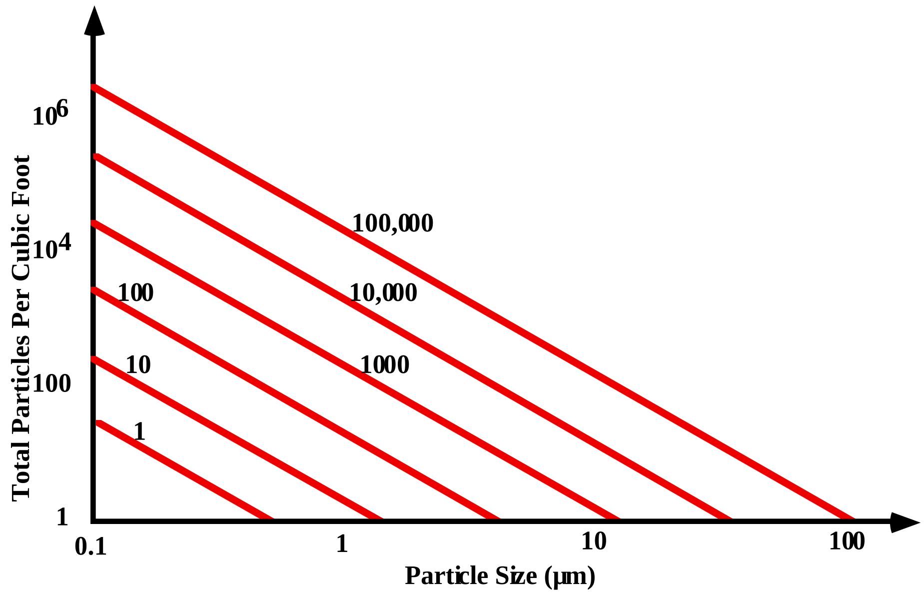
- Refresh time of several msec requires a generation lifetime of

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

- This requires $N_t \approx 10^{12}$ cm^{-3} or ≈ 0.02 ppb (see text).

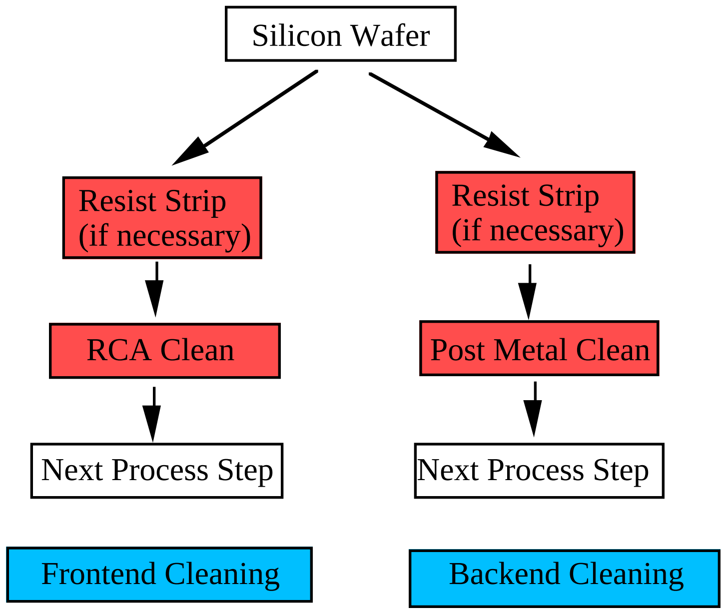
Level 1 Contamination Reduction: Clean Factories

• Air quality is measured by the "class" of the facility.

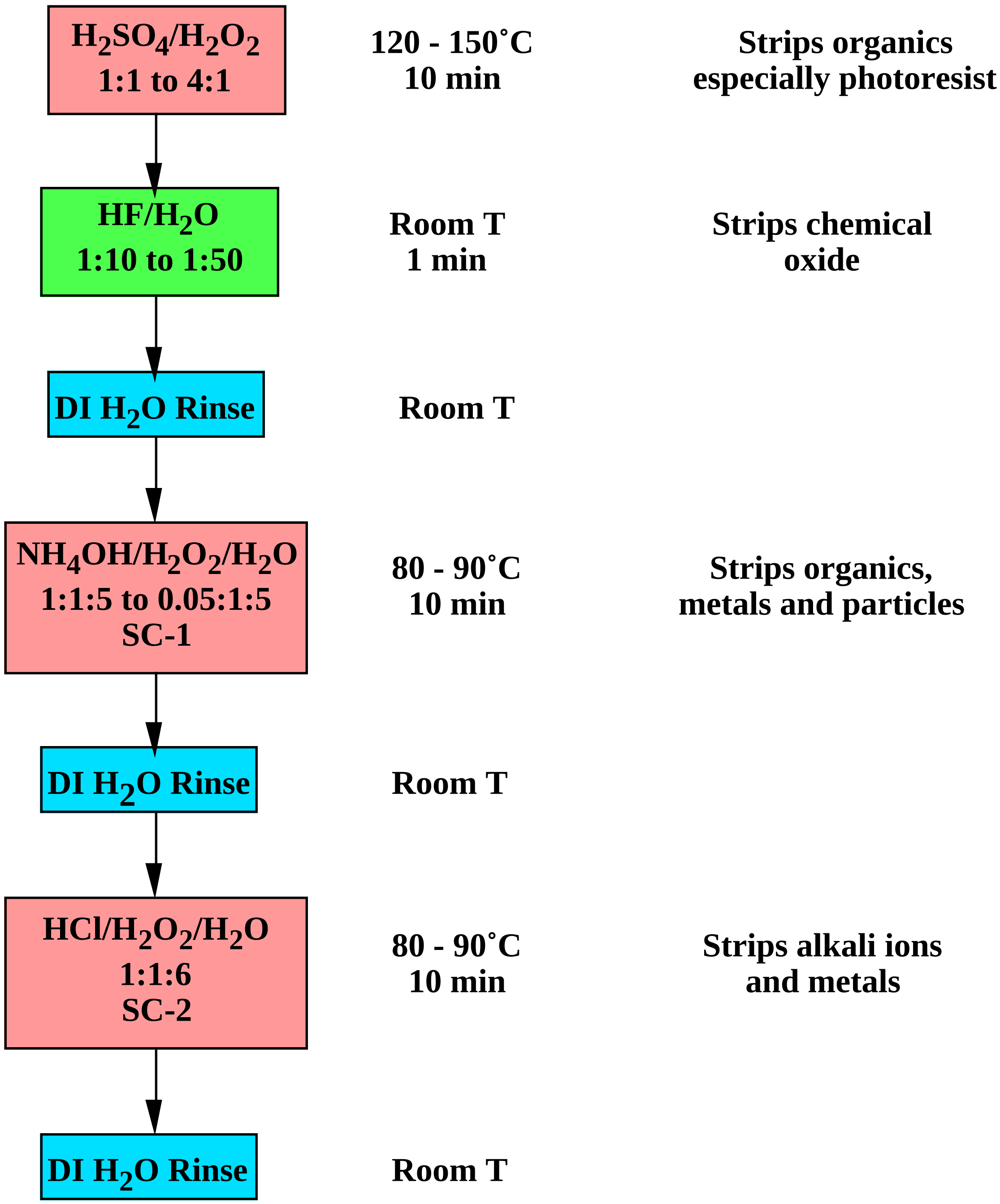


• Factory environment is cleaned by:
  - • Hepa filters and recirculation for the air,
  - • "Bunny suits" for workers.
  - • Filtration of chemicals and gases.
  - • Manufacturing protocols.

Level 2 Contamination Reduction: Wafer Cleaning



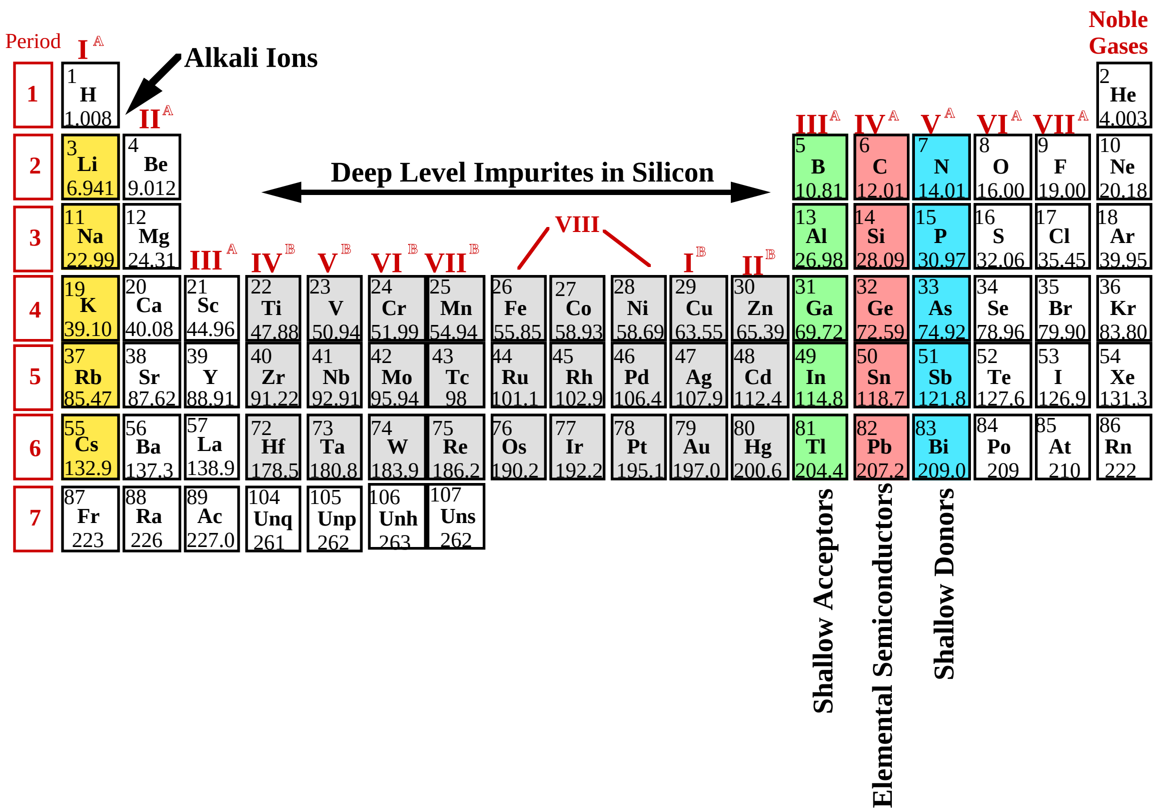
- **RCA clean is "standard process" used to remove organics, heavy metals and alkali ions.**



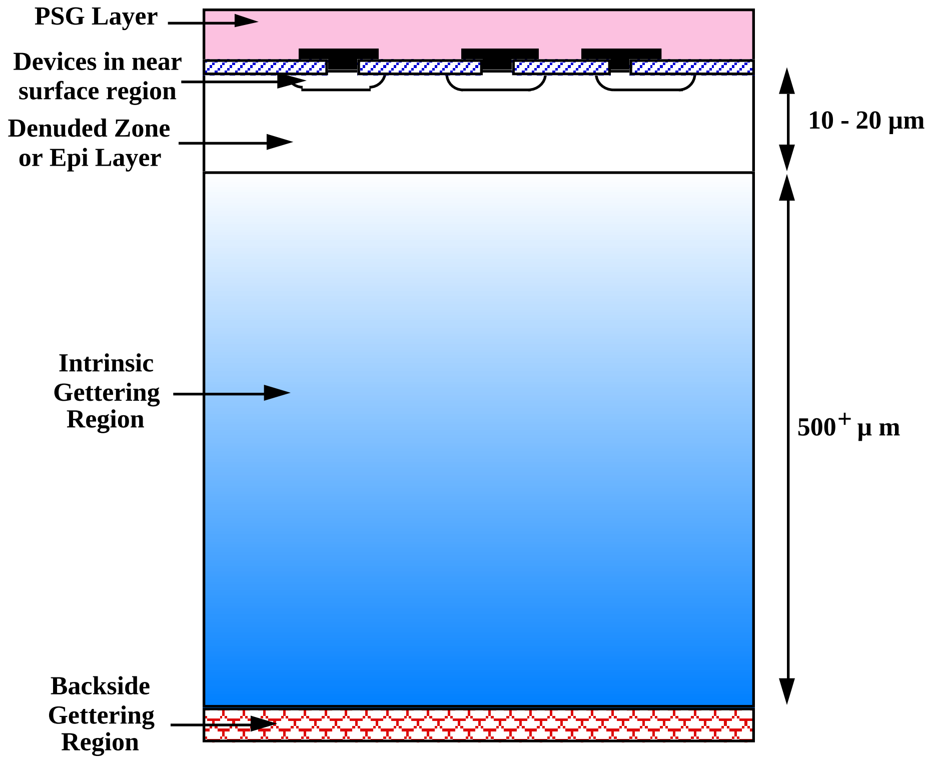
- **Ultrasonic agitation is used to dislodge particles.**

Level 3 Contamination Reduction: Gettering

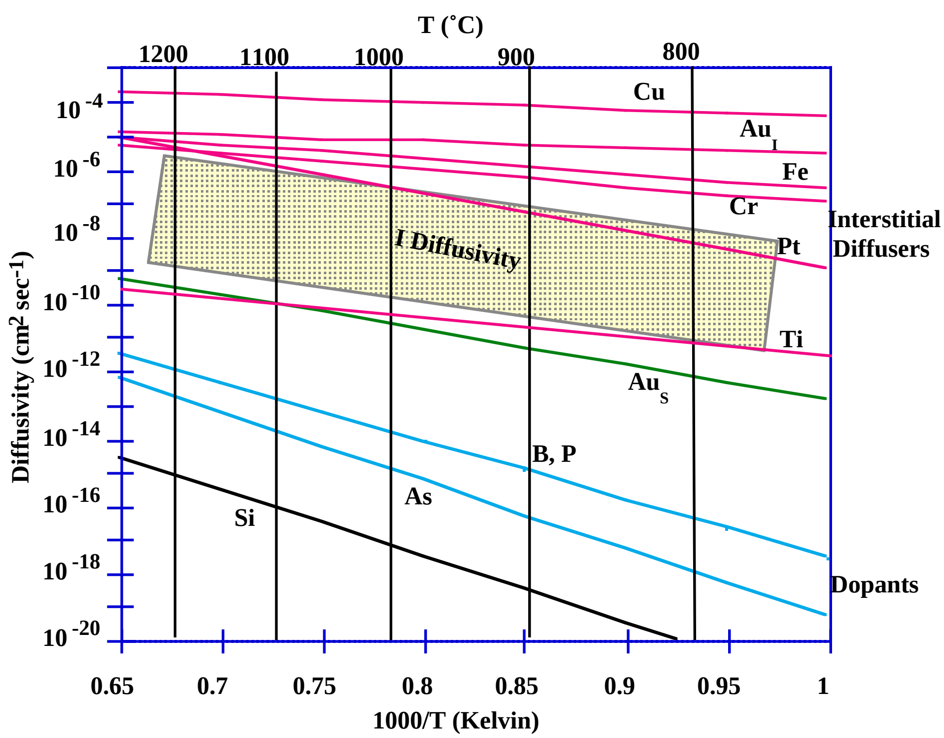
- Gettering is used to remove metal ions and alkali ions from device active regions.



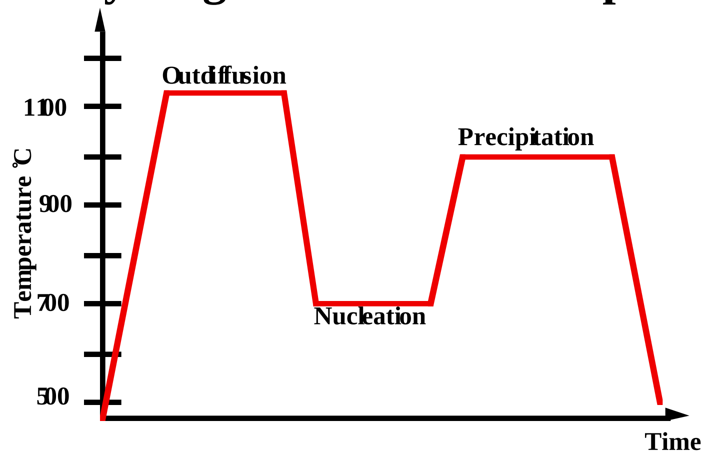
- For the alkali ions, gettering generally uses dielectric layers on the topside (PSG or barrier Si_3N_4 layers).
- For metal ions, gettering generally uses traps on the wafer backside or in the wafer bulk.
- Backside = extrinsic gettering.
- Bulk = intrinsic gettering.



- **Heavy metal gettering relies on the facts that:**
  - **Metals diffuse very rapidly in silicon.**
  - **Metals segregate to "trap" sites.**

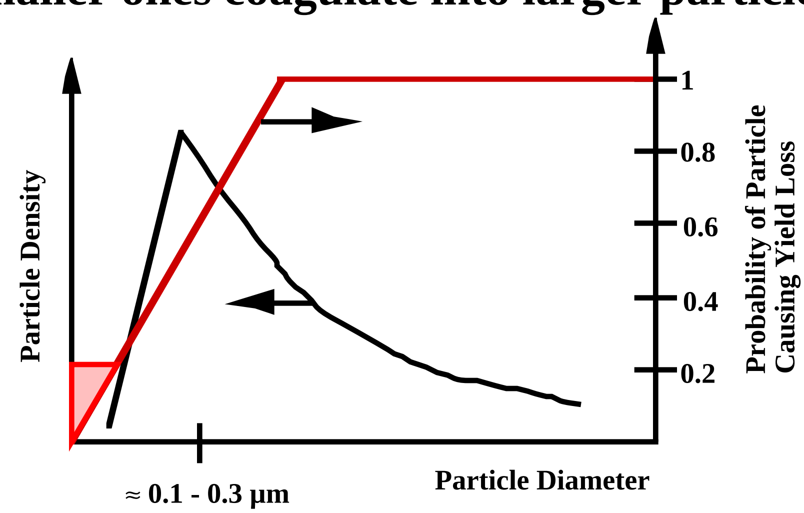


- "Trap" sites can be created by SiO_2 precipitates (intrinsic gettering), or by backside damage (extrinsic gettering).
- In intrinsic gettering, CZ silicon is used and SiO_2 precipitates are formed in the wafer bulk through temperature cycling at the start of the process.



Modeling Particle Contamination and Yield

- ≈ 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 µm are the most troublesome:
  - larger particles precipitate easily
  - smaller ones coagulate into larger particles



- **Yields are described by Poisson statistics in the simplest case:**

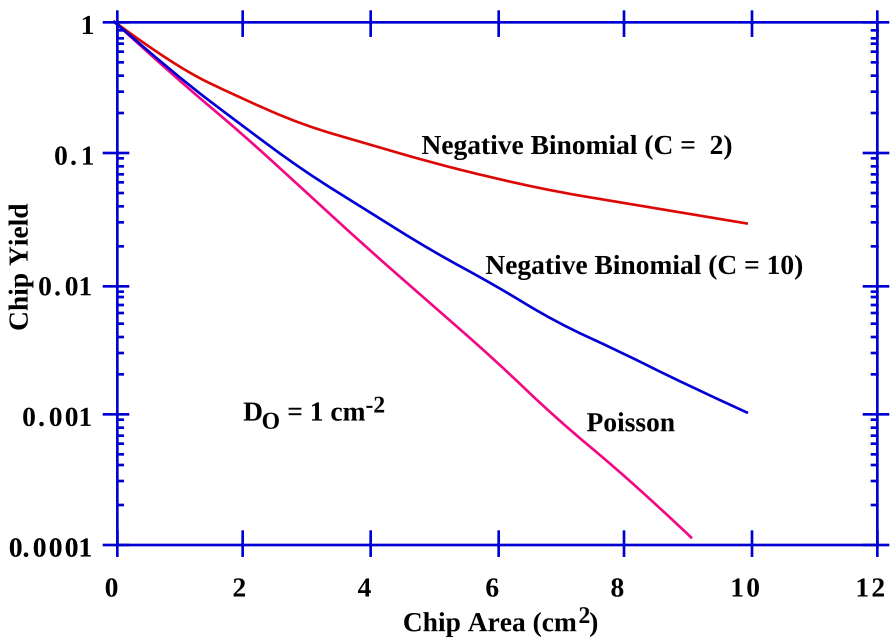
$$\mathbf{Y = \exp^{-A_C D_O}} \qquad (3)$$

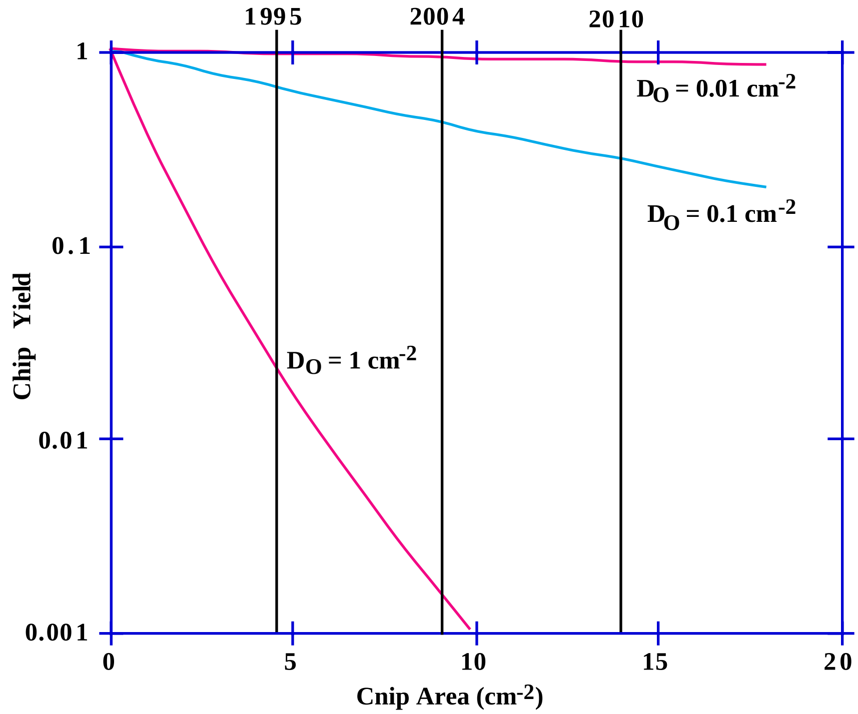
where A_C is the critical area and D_O is the defect density.

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

$$\mathbf{Y = \frac{1}{\left(1 + \frac{A_C D_O}{C}\right)^C}} \qquad (4)$$

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_2 plasma or in H_2SO_4/H_2O_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.**

$$Si + 2H_2O \leftrightarrow SiO_2 + 4H^+ + 4e^- \qquad (5)$$

$$M \leftrightarrow M^{z+} + ze^- \qquad (6)$$

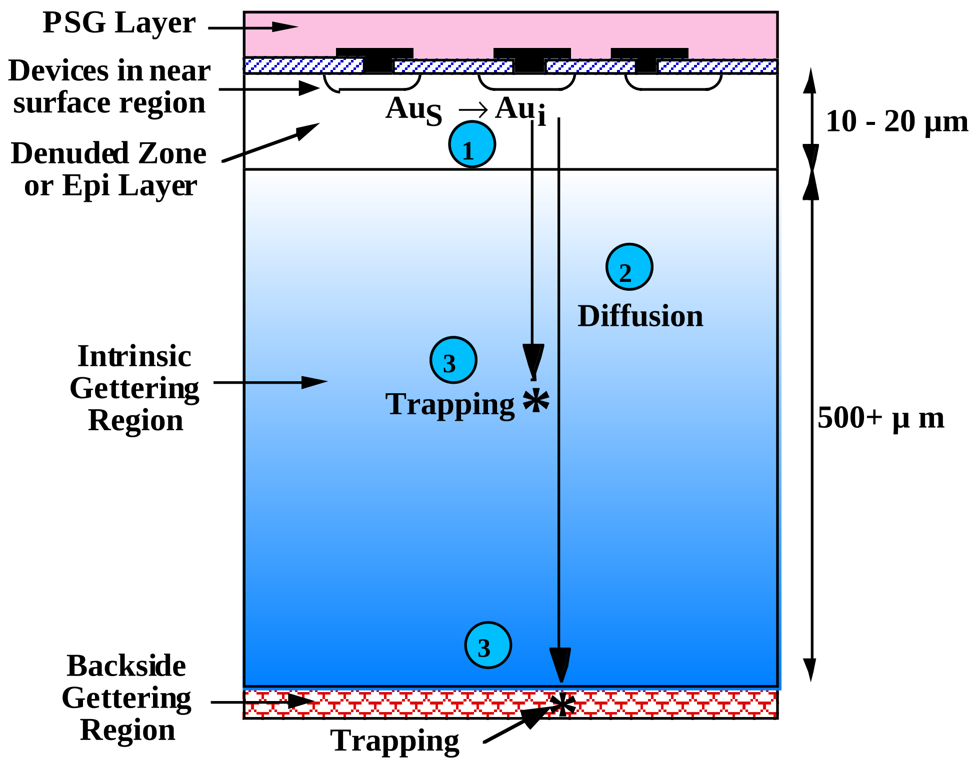
- **If we have a water solution with a Si wafer and metal atoms and ions, the stronger reaction will dominate.**
- **Generally (6) is driven to the left and (5) to the right so that SiO_2 is formed and M plates out on the wafer.**
- **Good cleaning solutions drive (6) to the right since M^+ is soluble and will be desorbed from the wafer surface.**

Oxidant/ Reductant	Standard Oxidation Potential (volts)	Oxidation-Reduction Reaction
Mn^{2+}/Mn	1.05	$Mn \leftrightarrow Mn^{2+} + 2e^-$
SiO_2/Si	0.84	$Si + 2H_2O \leftrightarrow SiO_2 + 4H^+ + 4e^-$
Cr^{3+}/Cr	0.71	$Cr \leftrightarrow Cr^{3+} + 3e^-$
Ni^{2+}/Ni	0.25	$Ni \leftrightarrow Ni^{2+} + 2e^-$
Fe^{3+}/Fe	0.17	$Fe \leftrightarrow Fe^{3+} + 3e^-$
H_2SO_4/H_2SO_3	-0.20	$H_2O + H_2SO_3 \leftrightarrow H_2SO_4 + 2H^+ + 2e^-$
Cu^{2+}/Cu	-0.34	$Cu \leftrightarrow Cu^{2+} + 2e^-$
O_2/H_2O	-1.23	$2H_2O \leftrightarrow O_2 + 4H^+ + 2e^-$
Au^{3+}/Au	-1.42	$Au \leftrightarrow Au^{3+} + 3e^-$
H_2O_2/ H_2O	-1.77	$2H_2O \leftrightarrow H_2O_2 + 2H^+ + 2e^-$
O_3/O_2	-2.07	$O_2 + H_2O \leftrightarrow O_3 + 2H^+ + 2e^-$

- **The strongest oxidants are at the bottom (H_2O_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_2O_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:

$$Au_S + Si_I \leftrightarrow Au_i \qquad (7)$$

• 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.