微纳光电子材料与器件工艺原理

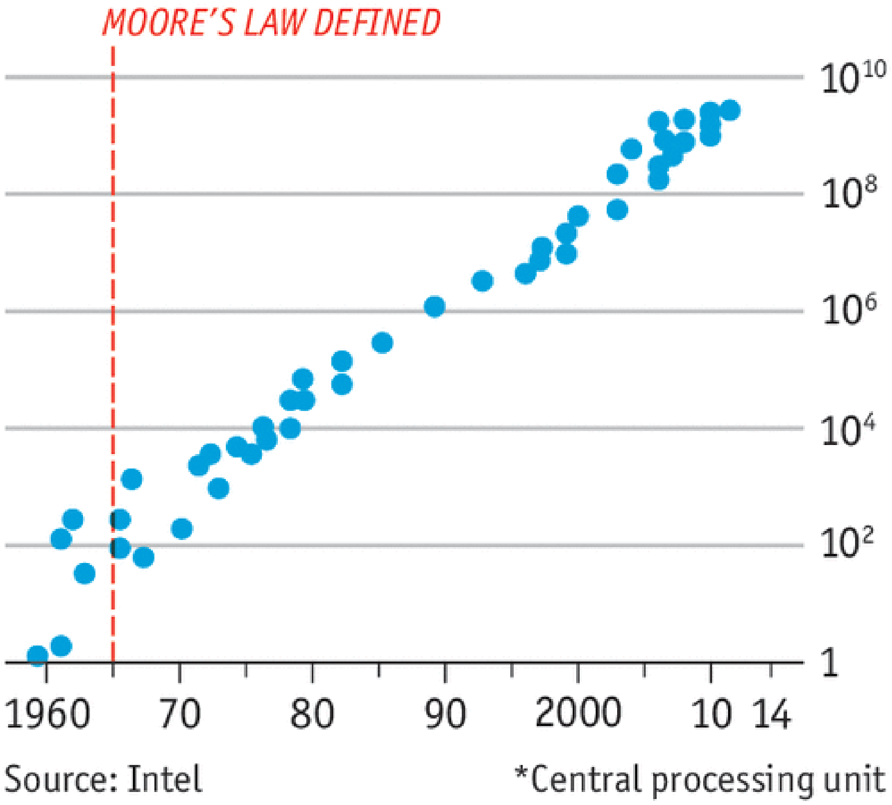
Cleanroom Environment and Wafer Clean

Xing Sheng 盛兴

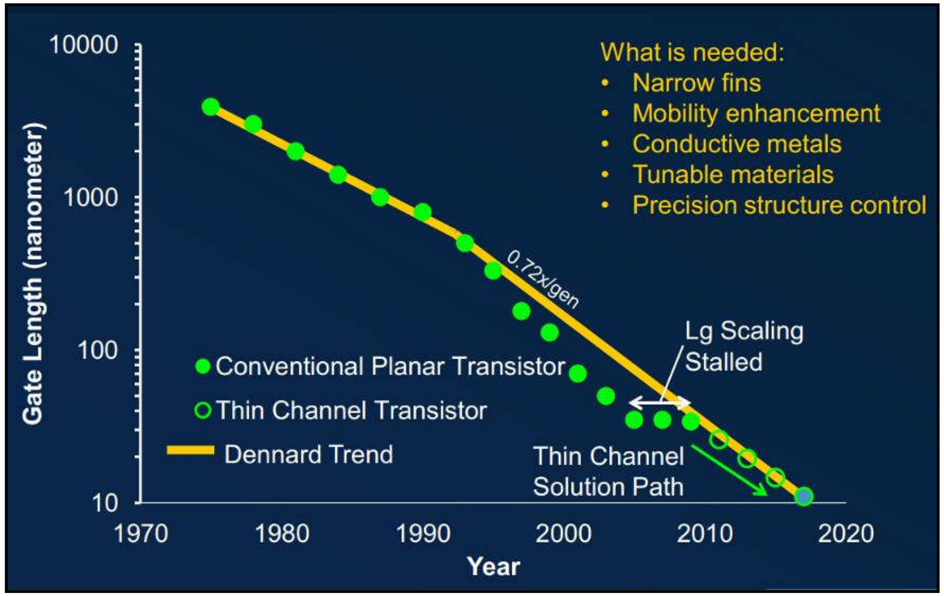
Department of Electronic Engineering
Tsinghua University
xingsheng@tsinghua.edu.cn

Integrate Circuits

- **Moore's law**



Economist.com

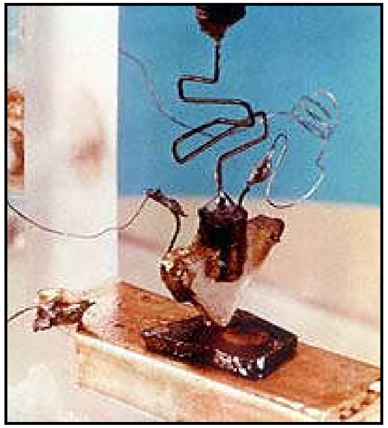


transistor number ↗

transistor size ↘

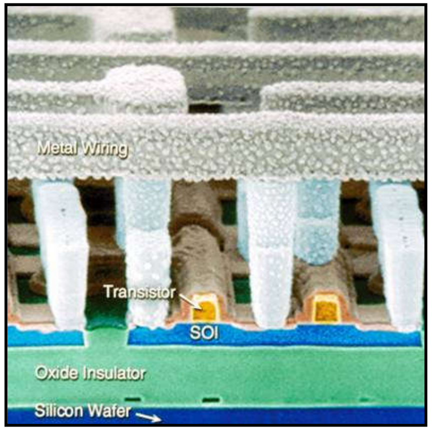
Factory Evolution

1947

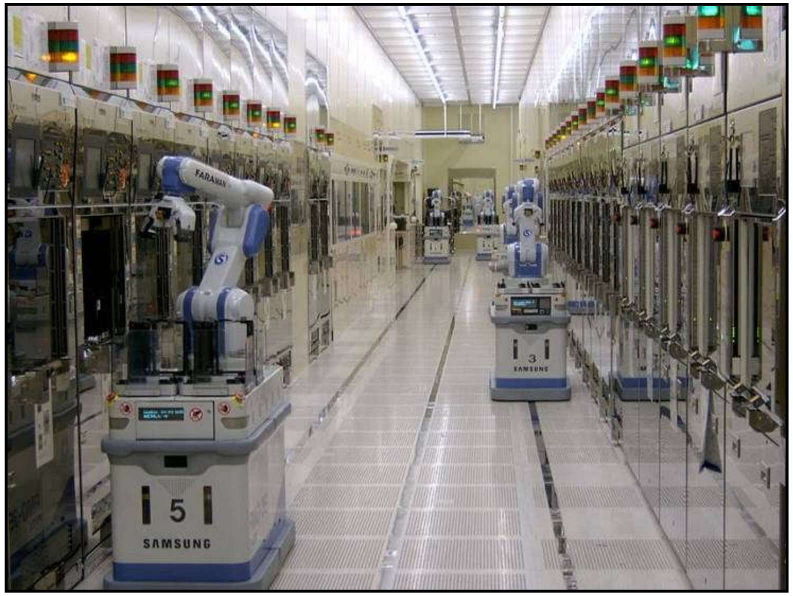


1 cm

today



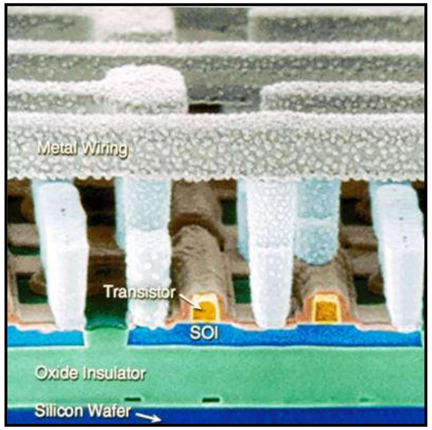
< 100 nm



Factory Evolution

- cost of new fab
  - 1967 2 million $
  - 2010 10 billion $

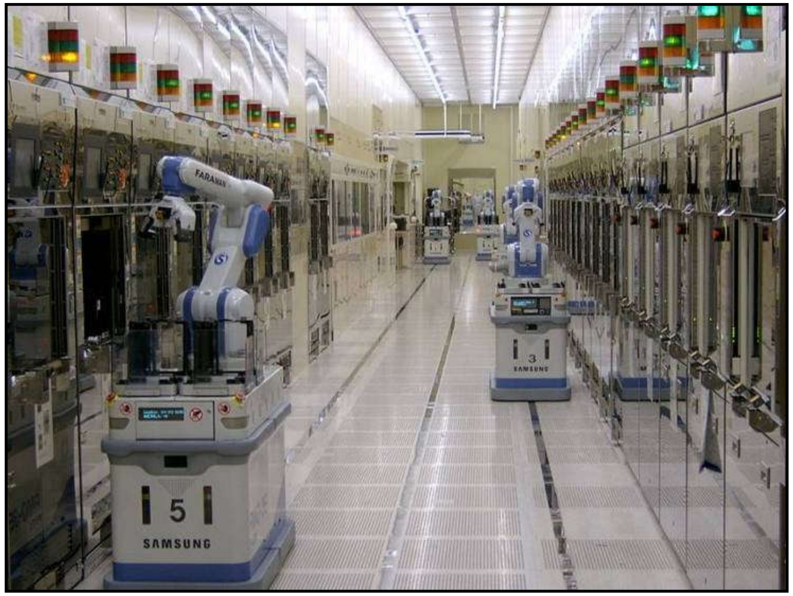
today



< 100 nm

Video TSMC

武汉新芯集成电路制造有限公司 厂区鸟瞰图



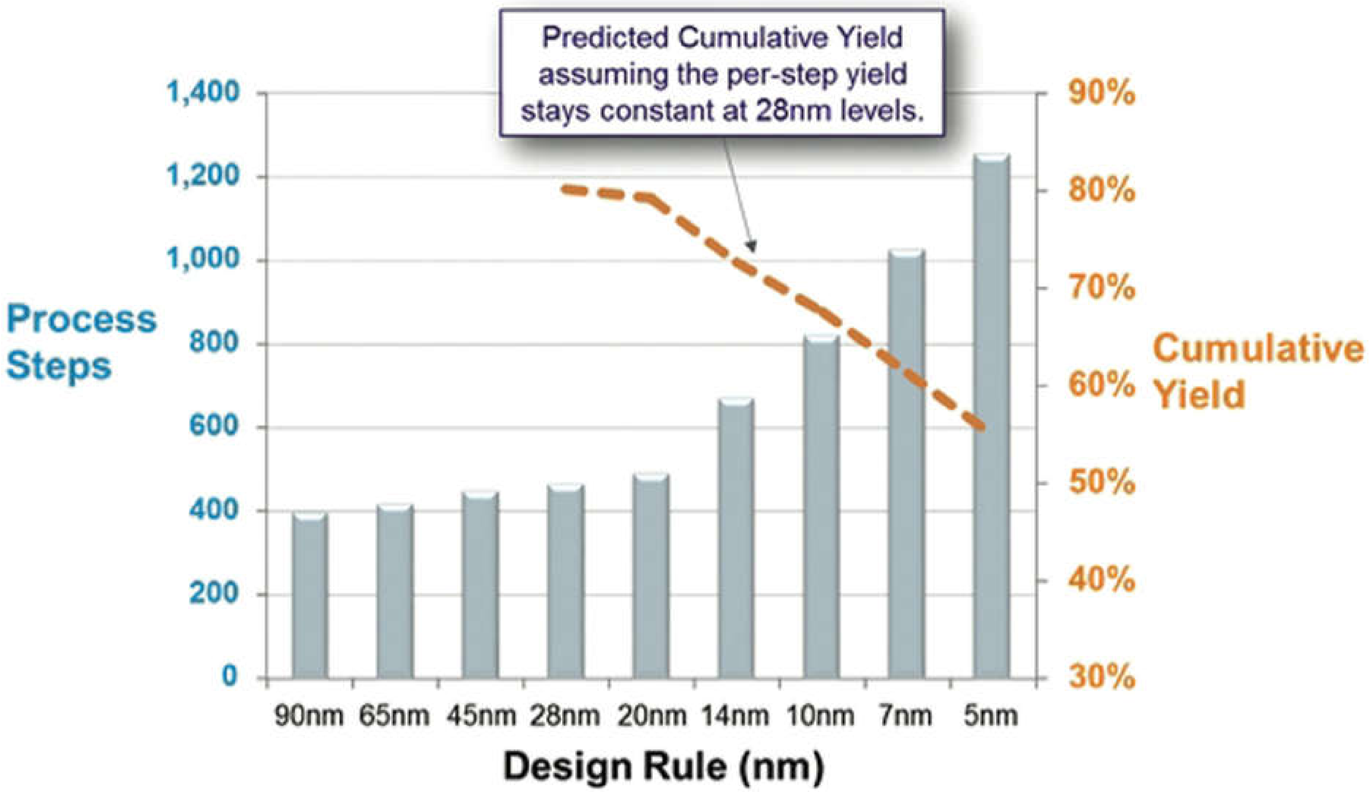
2016 武汉新芯
24 billion $$

Manufacturing Yield

- **Yield: rate of success**

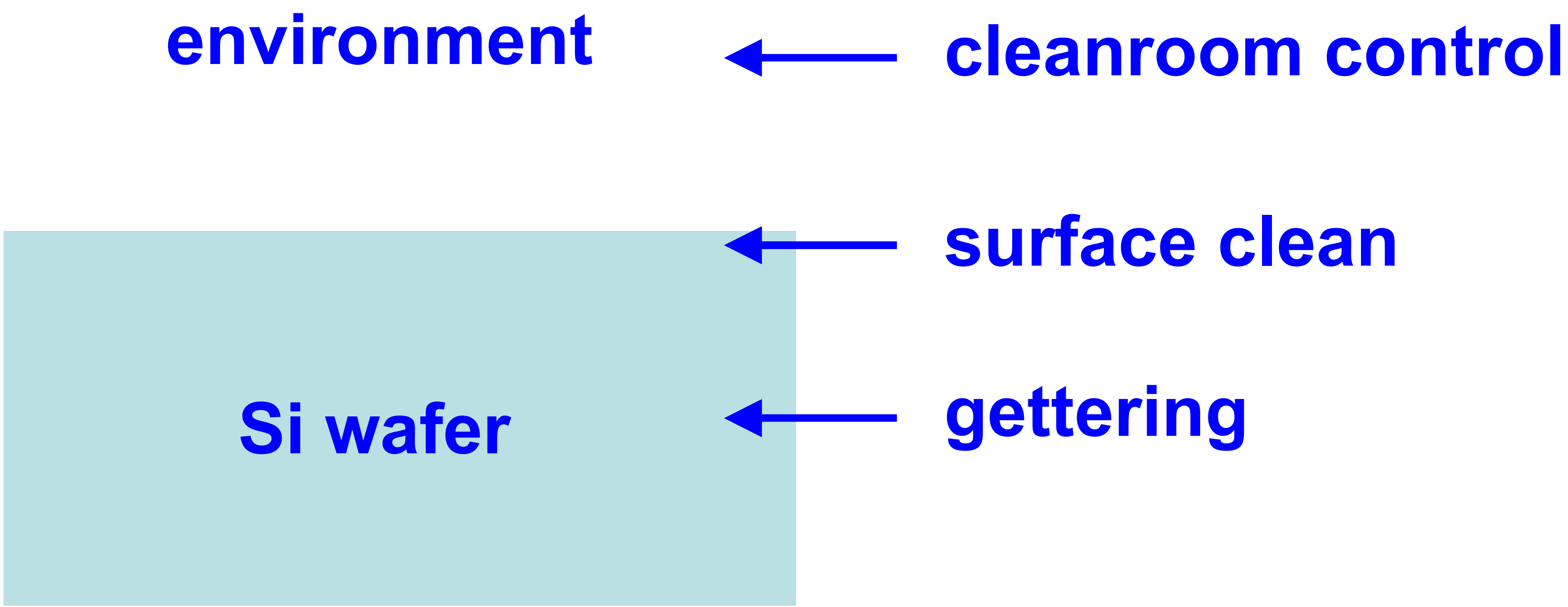
assume yield = 99% per step:

$$0.99^4 = 0.96$$
$$0.99^{400} = 0.02$$



every 1% yield increase = $$$

Defects Control

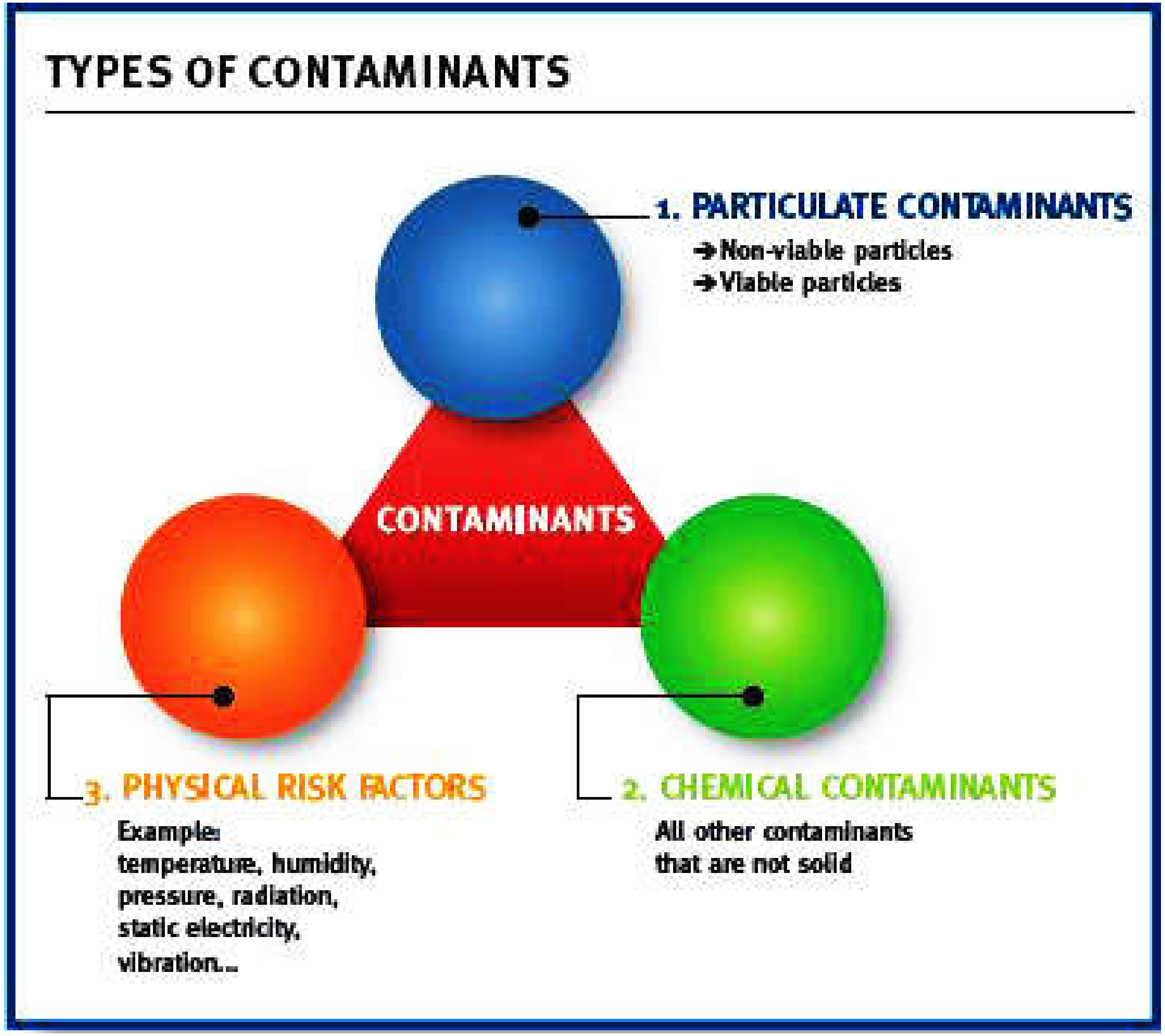


Cleanroom Orientation

Video 1 Video 2

always gown up!

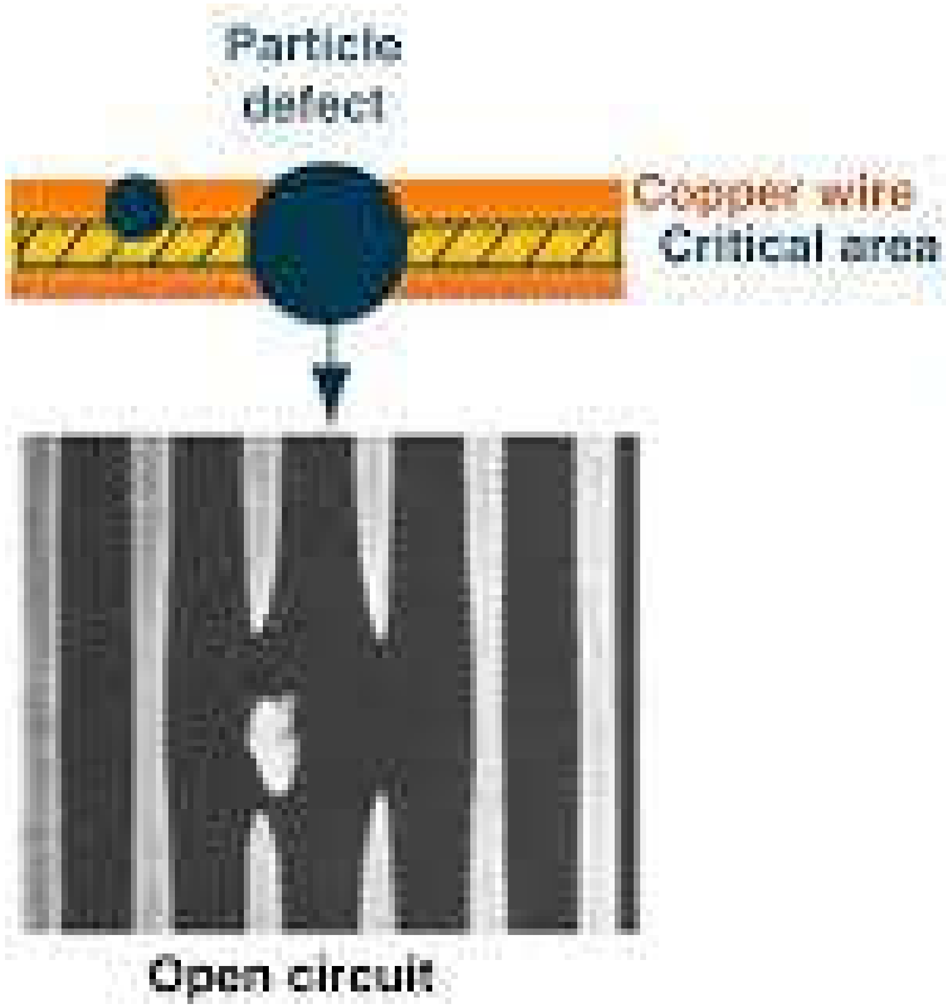
Contaminations

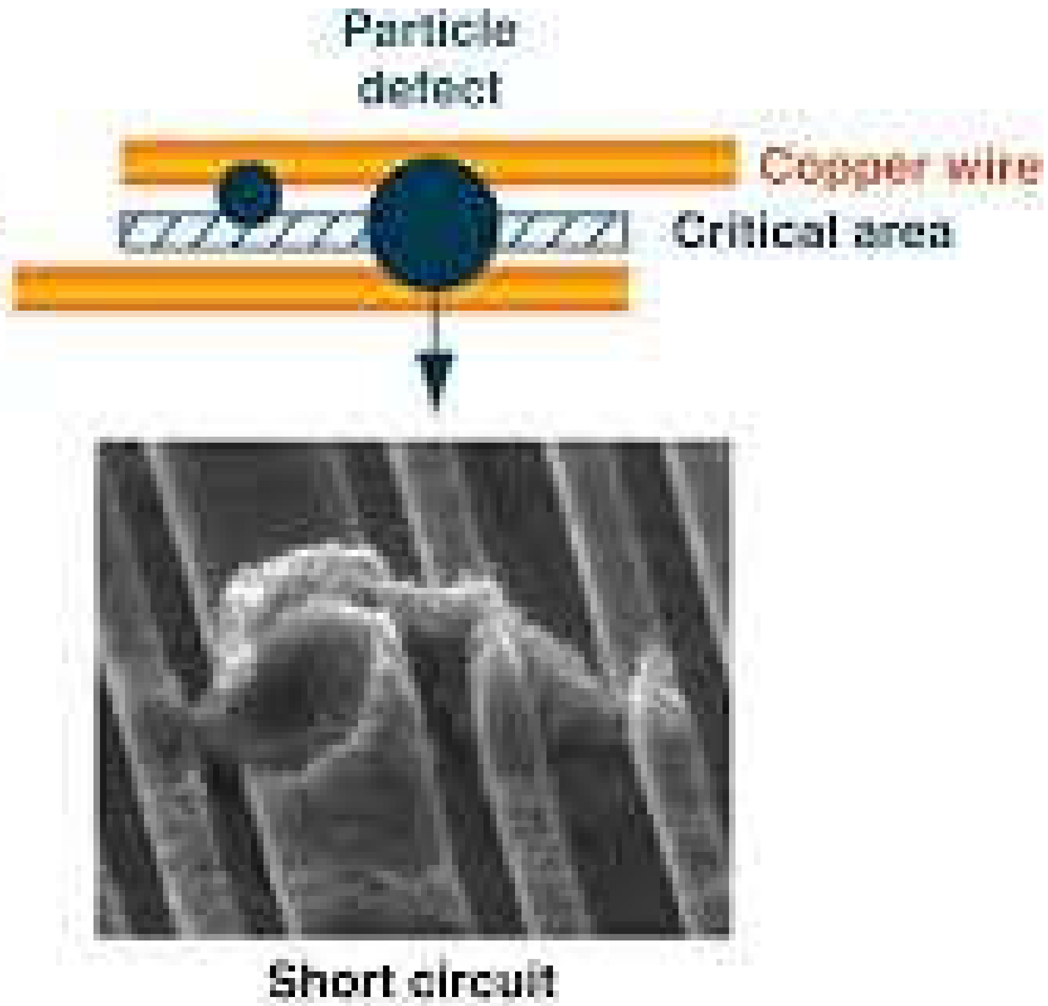


particles:
- hair
- pollen
- bacteria
- PM2.5
- ...

chemicals:
- organics
- Cu, Au
- Na, K
- ...

Particles

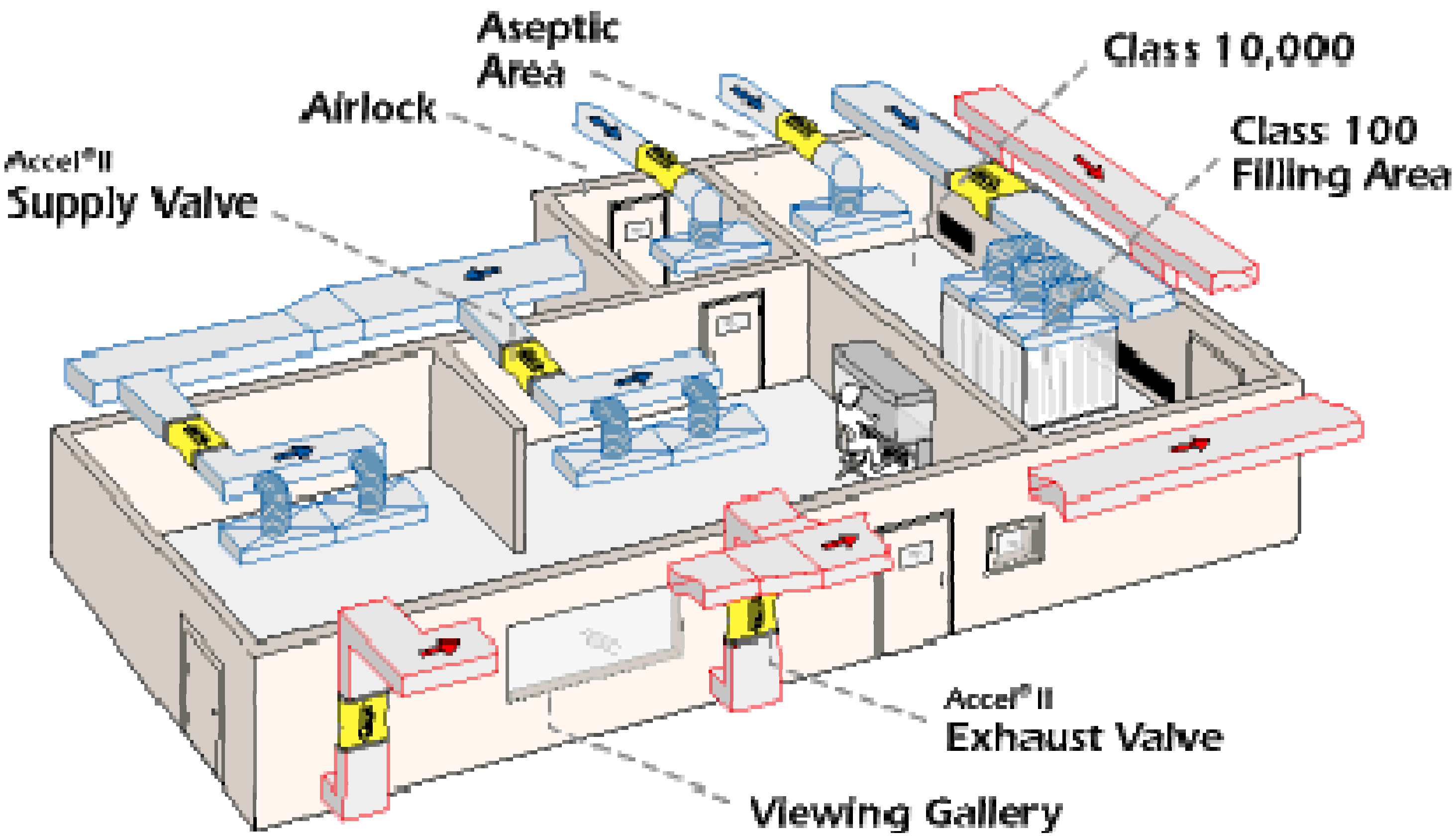

Particle defect
Copper wire
Critical area
Open circuit


Particle defect
Copper wire
Critical area
Short circuit

IC Roadmap

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})	**3×10^{10}**	**1×10^{10}**	**Under 1×10^{10}**	**Under 1×10^{10}**	**Under 1×10^{10}**	**Under 1×10^{10}**
Metals on Wafer Surface After Cleaning (cm^{-2})	**5×10^9**	**4×10^9**	**2×10^9**	**1×10^9**	**$< 10^9$**	**$< 10^9$**
Starting Material Recombination Lifetime (µsec)	**≥ 300**	**≥ 325**	**≥ 325**	**≥ 325**	**≥ 450**	**≥ 450**

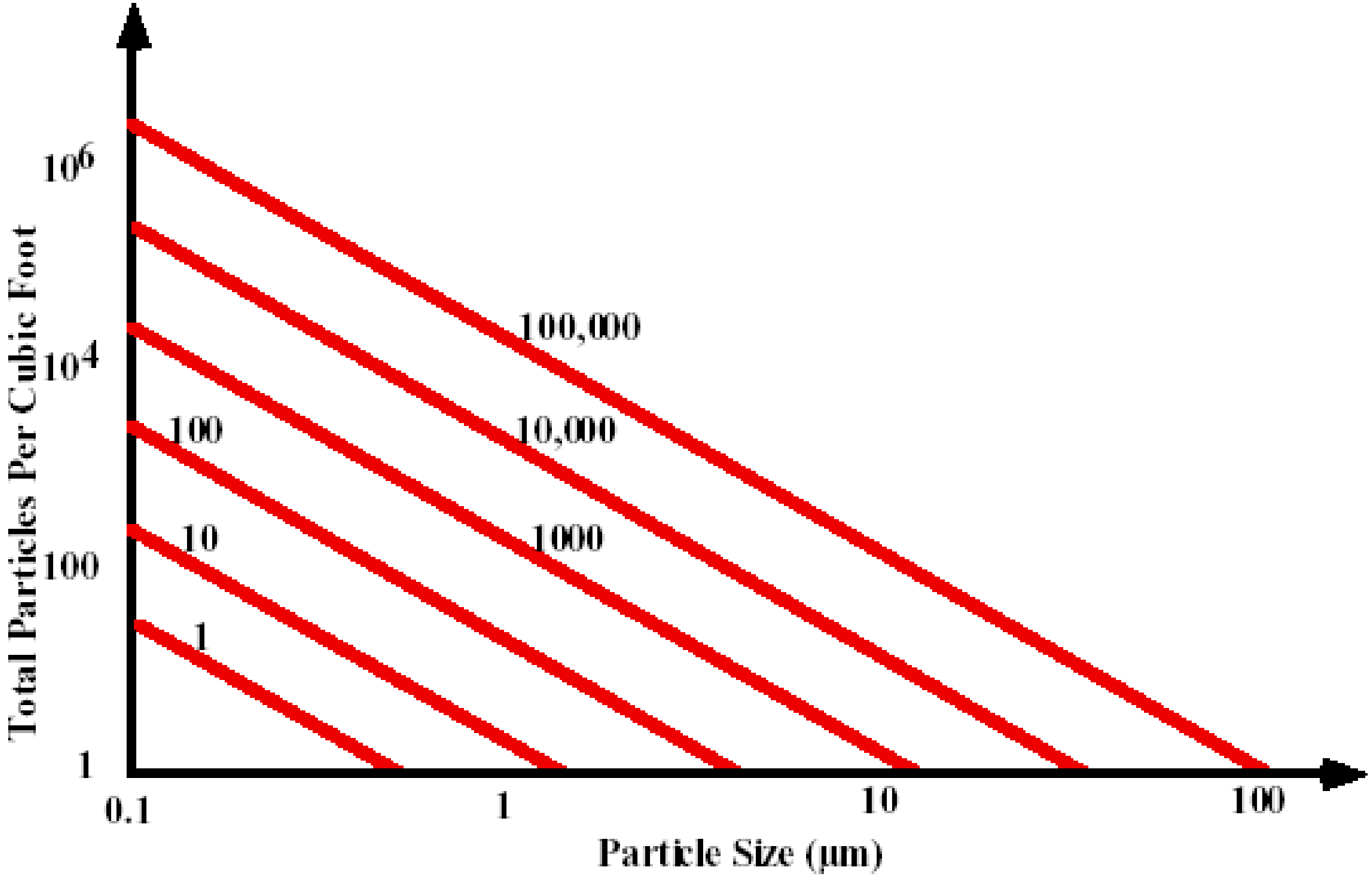
Cleanroom



class X:

less than X particles larger than 0.5 μm per cubic feet

Cleanroom



class X:

less than X particles larger than 0.5 μm per cubic feet

Cleanroom

Particle Diameter (um)				
Class	**0.1**	**0.3**	**0.5**	**5.0**
1	35	3	1	
10	350	30	10	
100		300	100	
1,000			1,000	7
10,000			10,000	70
100,000			100,000	700

'PM2.5 index' << 1 μg/m^3

class X:

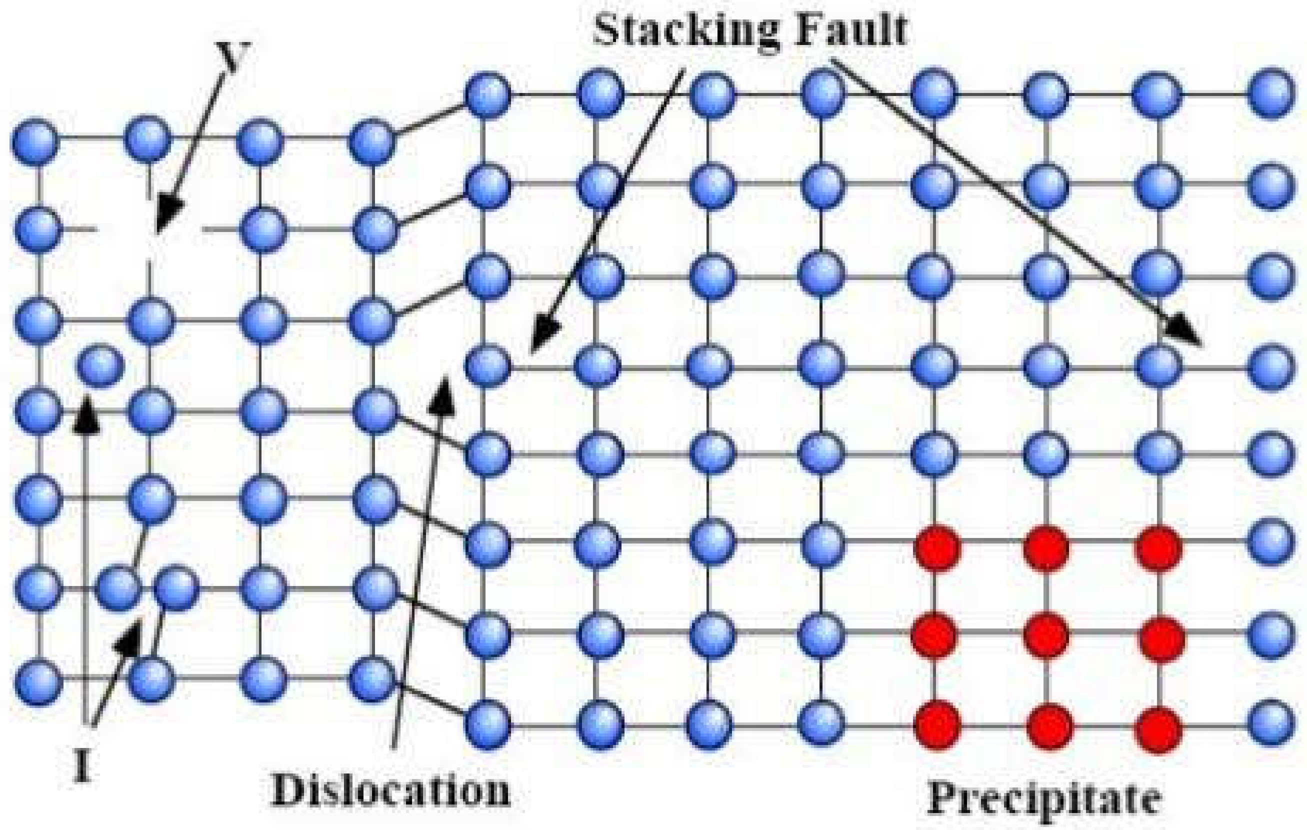
less than X particles larger than 0.5 μm per cubic feet

Defects

- Point Defects e.g. Vacancies (V), Interstitials (I)
- Line Defects e.g. Dislocations

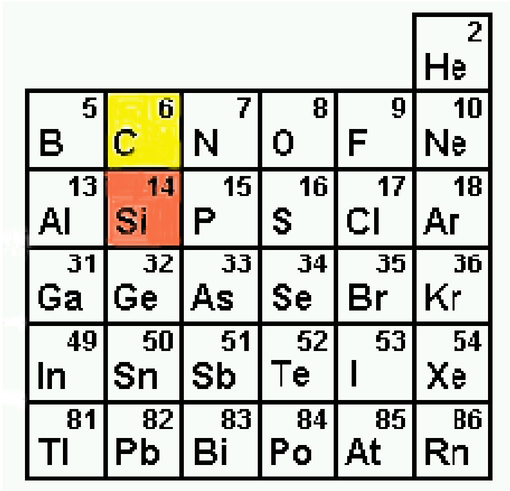
•Area Defects e.g. Stacking Faults ("extrinsic" or "intrinsic" form along {111} planes)

•Volume Defects e.g. Precipitates, Collection of Vacancies

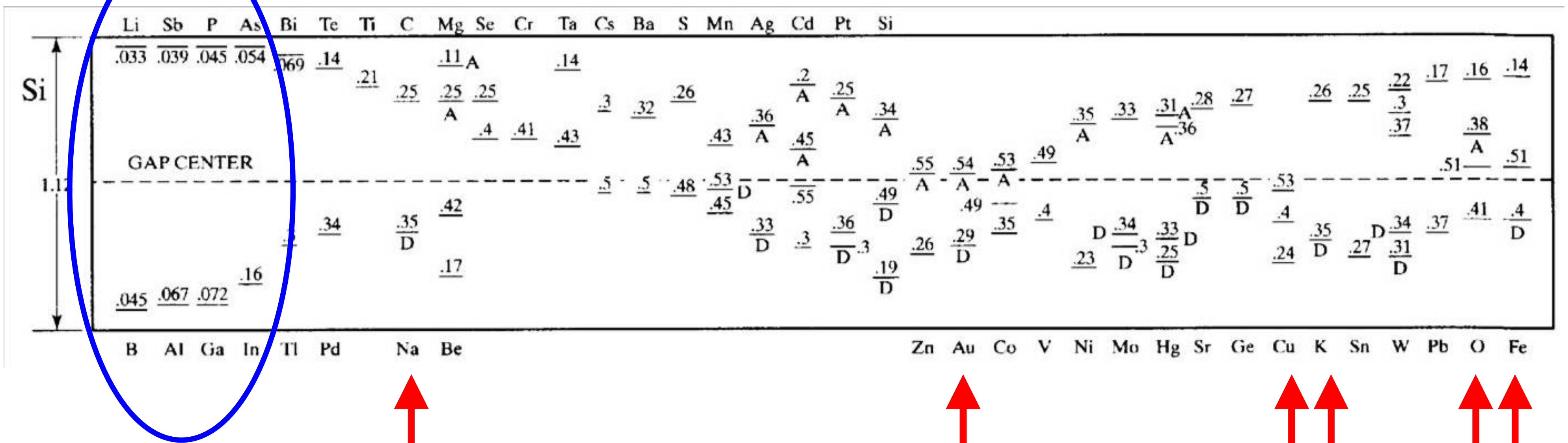


Defects

Q: why?



dopants



deep level defects

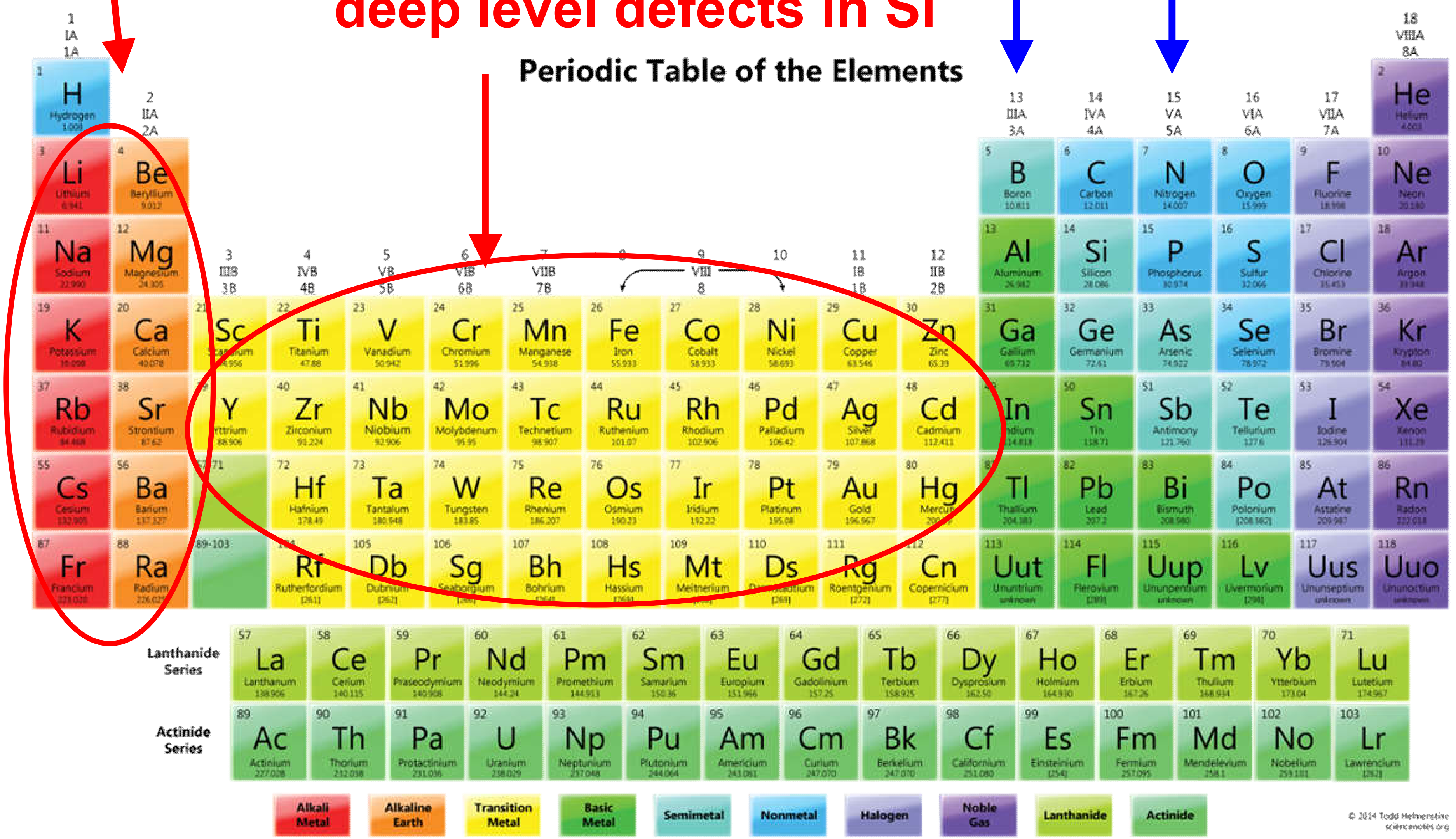
Na, K, Au, Cu, Fe, O, ...

Defects

ions in gate oxide

deep level defects in Si

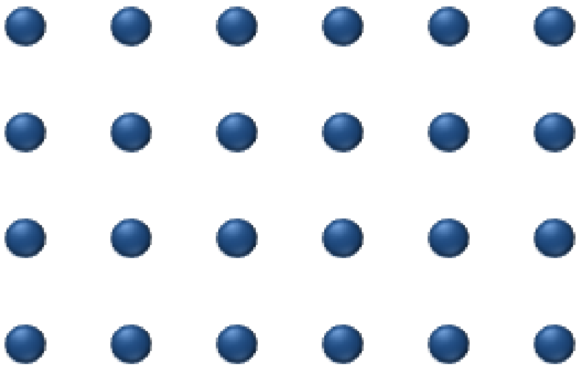
dopants



Diffusion of Defects

Liquid

Solid



C **concentration (mol/m^3)**

J **diffusion flux (mol/m^2/s)**

D **diffusivity (m^2/s)**

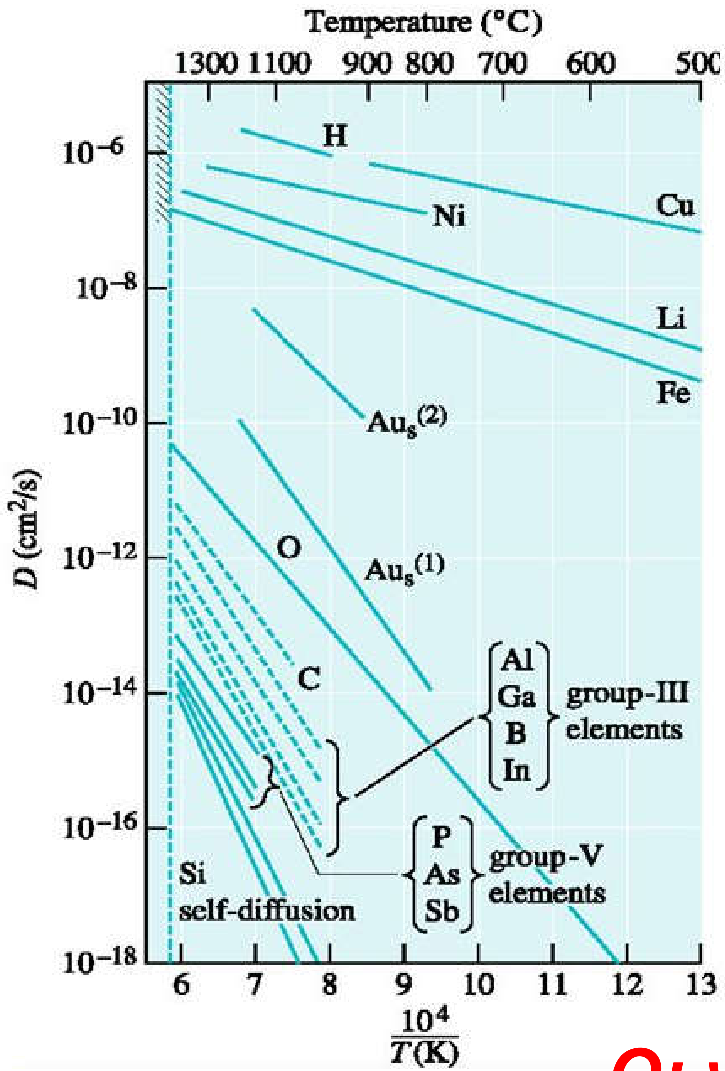
Diffusion of Defects

- **Diffusivity (扩散系数) *D***
  - rate of spread
  - unit: cm^2/s

$$D = D_0 \exp(-\frac{E_A}{kT})$$

- **Diffusion length *L***

$$L = \sqrt{Dt}$$



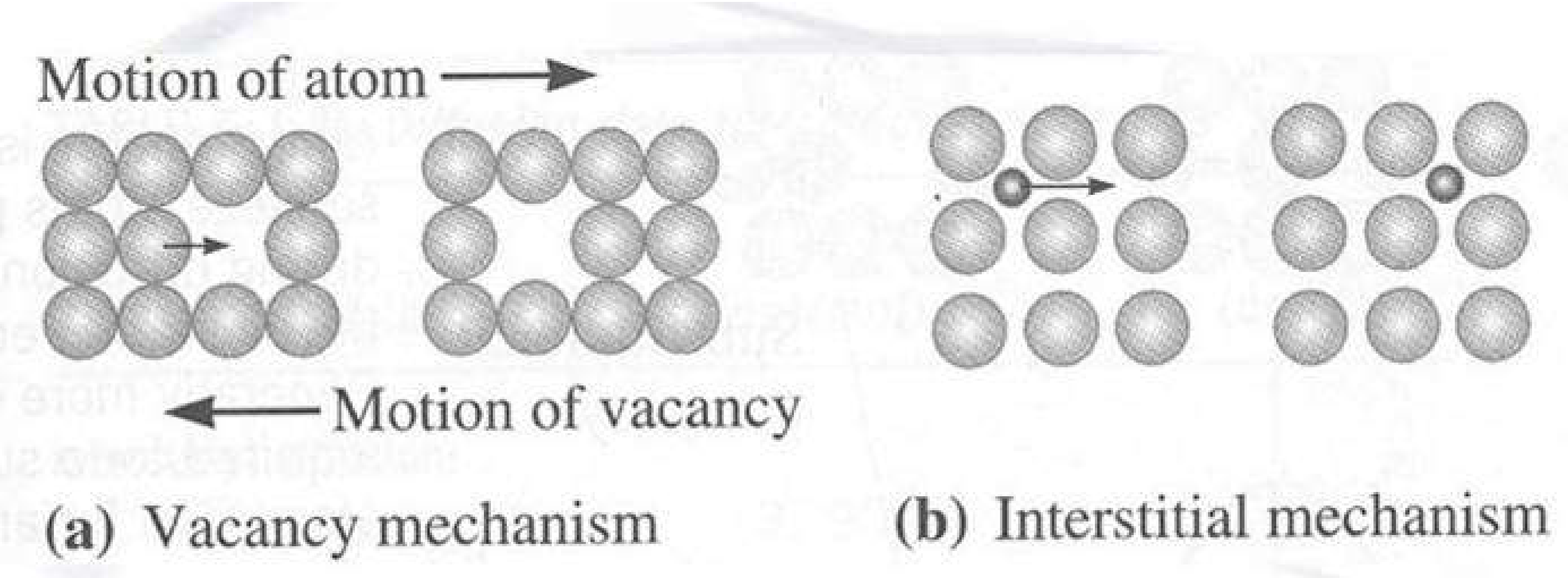
fast

slow

Q: why?

diffusivity of defects in Si

Defect Diffusivity in Silicon



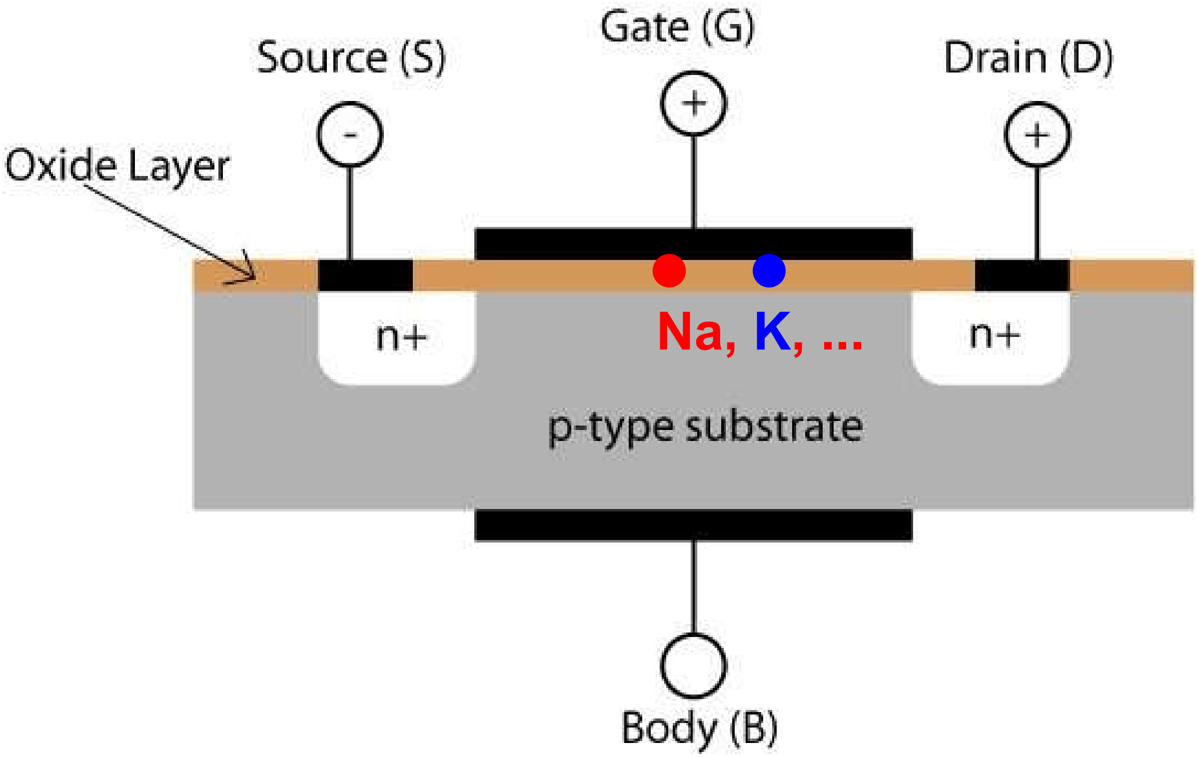
B, P, As, Sb, Si, ...

Cu, Fe, Li, H, Au, ...

Defects

defect density

$$V_{th} = V_{FB} + 2\Phi_f + \frac{\sqrt{2\varepsilon_s q N_A (2\Phi_f)}}{C_{ox}} - \frac{qQ_M}{C_{ox}}$$



alkali ions (Na, K, ...) in gate oxide

Defects

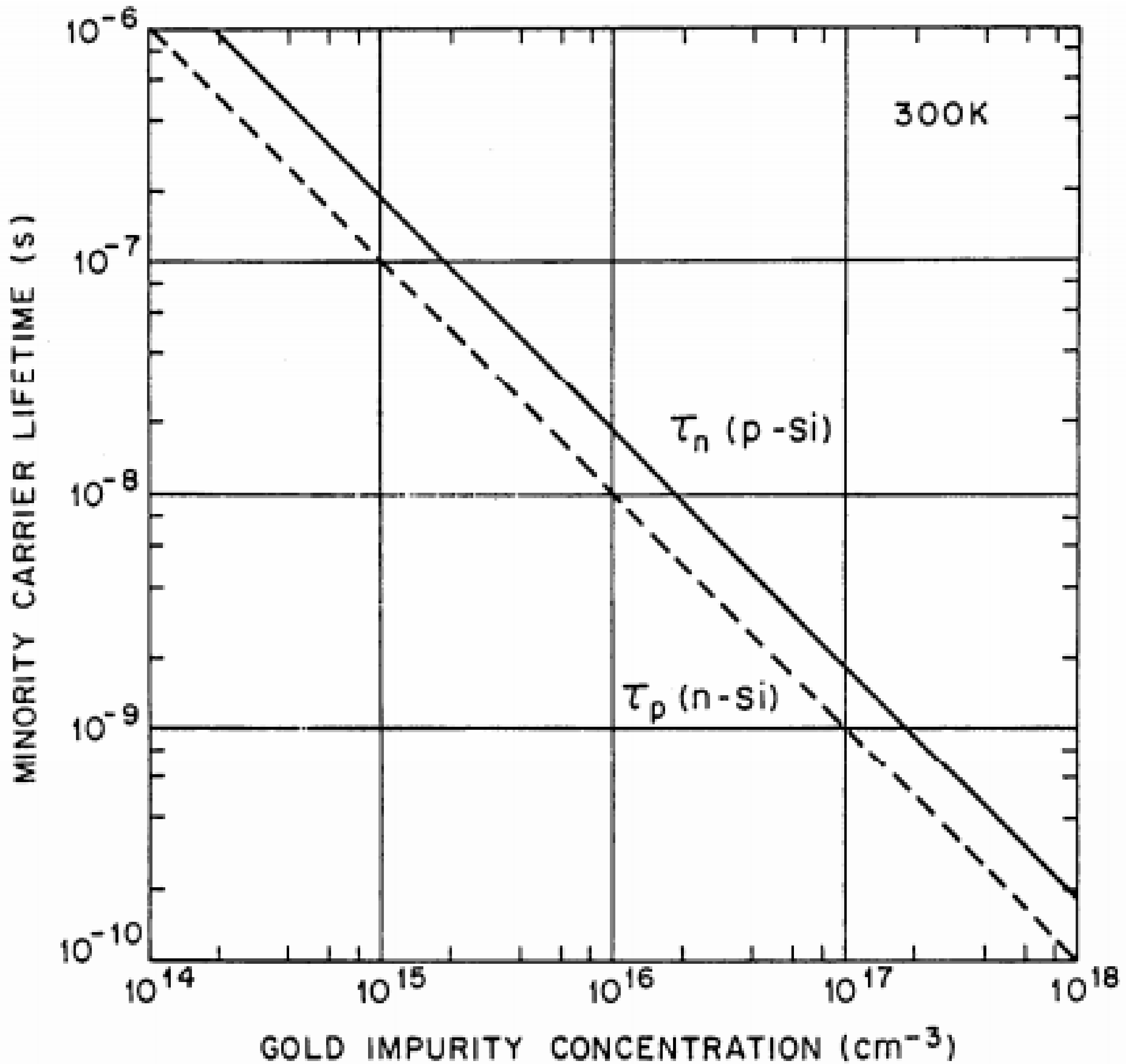


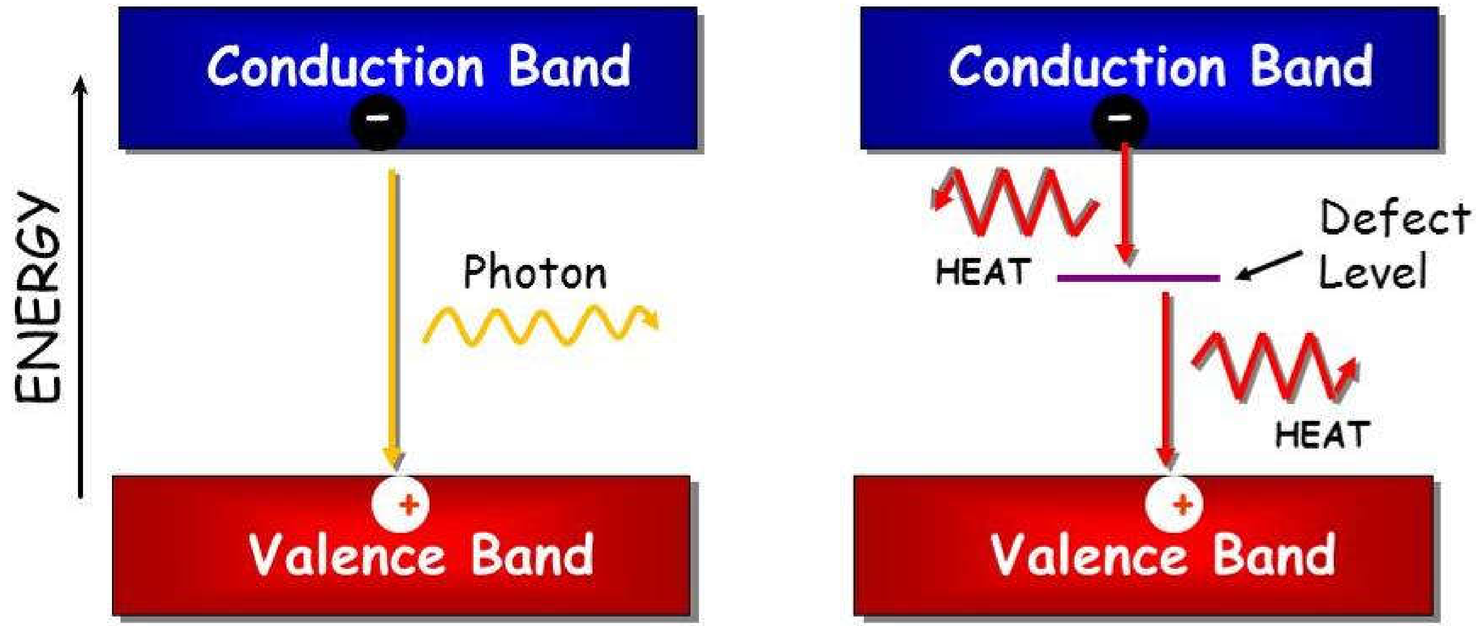
Fig. 16 Recombination lifetime versus gold impurity concentration in silicon.[8]

Deep level defects (e.g. Au) reduce minority carrier lifetime

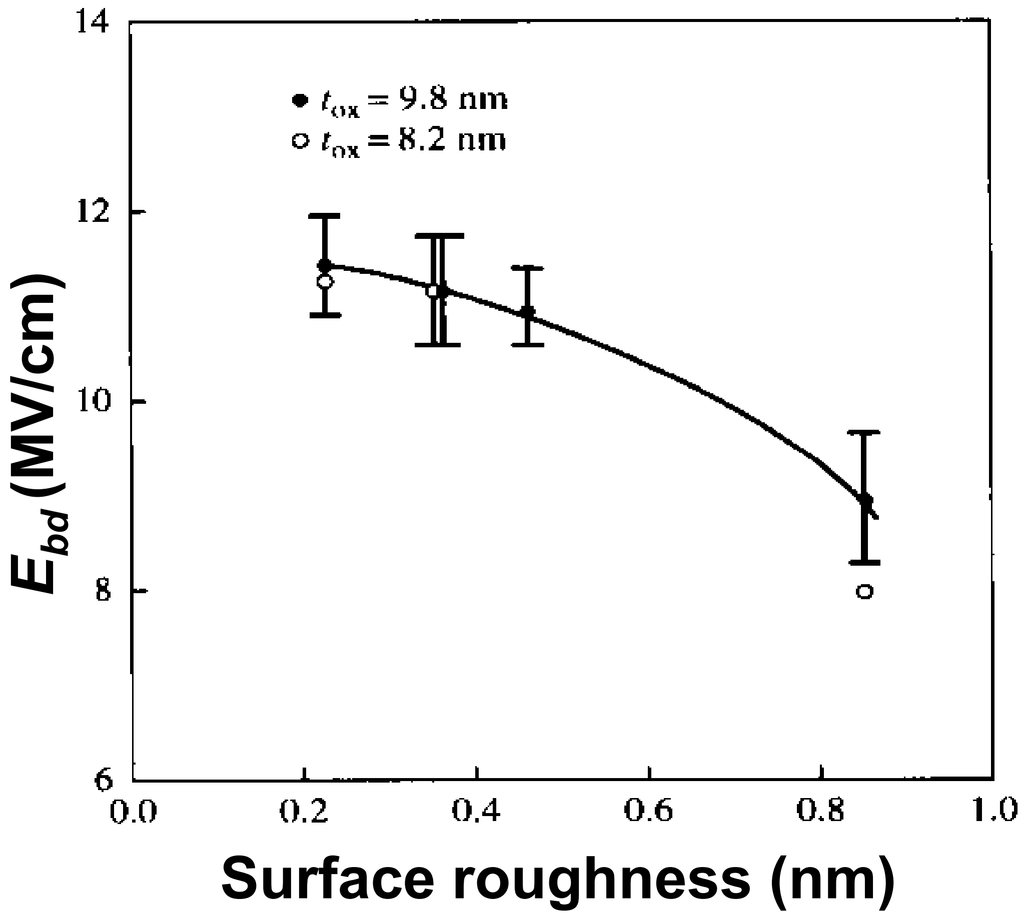
bad for solar cells

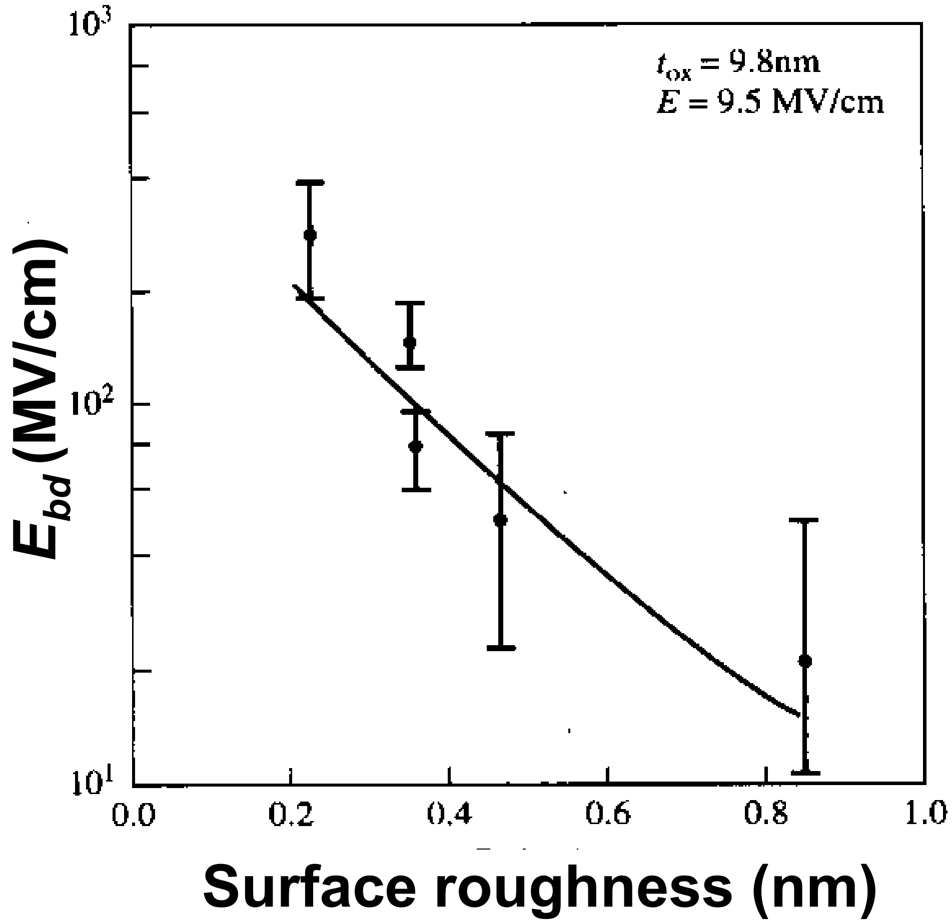
Defects

recombination at defect sites
reduce efficiencies of LEDs / solar cells



Defects





Surface roughness reduces breakdown voltages (E_{bd})

Defects

defects in water

effects of water cleaning on transistor performance

water resistivity (MΩ*cm, at 25 °C)	leakage current (A/μm²)
5	$12*10^{-9}$
10	$10*10^{-9}$
13	$5*10^{-9}$
15	$1*10^{-9}$

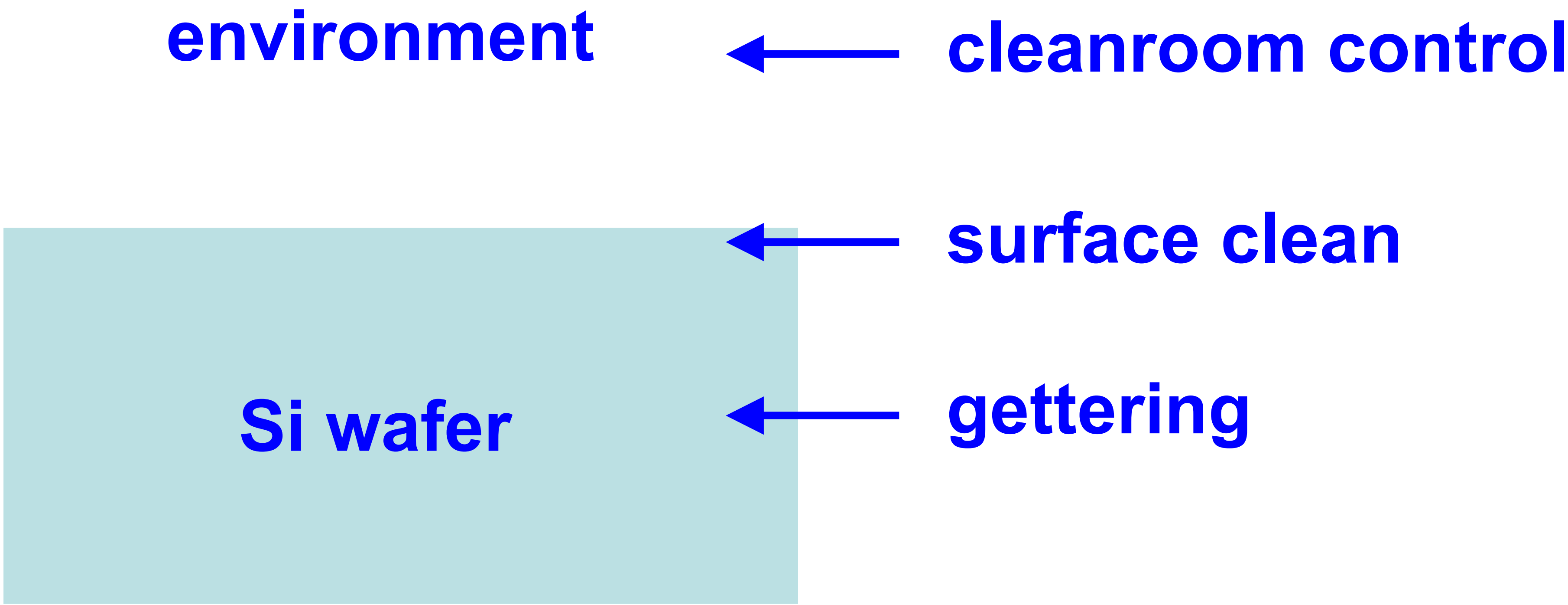
Water

- Types
  - purified water, distilled water, tapping water, ...
  - 自来水，矿泉水，纯净水，超纯水，蒸馏水，...
- In cleanroom, deionized (DI) water (去离子水) is used
  - free of any mineral ions
  - only H^+, OH^-

$$H_2O \leftrightarrow H^+ + OH^-$$

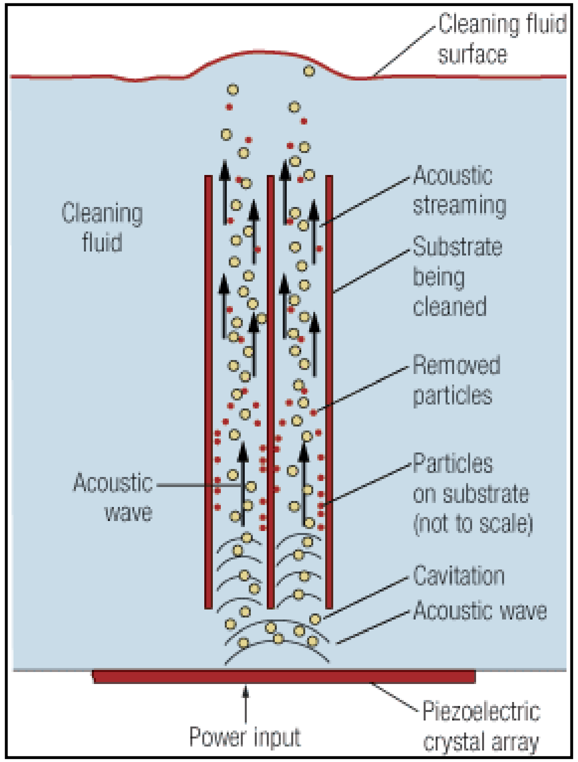
- In water, at 25 °C
  - $[H^+]*[OH^-] = K_w = 10^{-14}$ (mol/L)^2
  - in DI water, $[H^+] = [OH^-] = 10^{-7}$, pH = 7.0
  - resistivity = 18.5 MΩ*cm

Defects Control



Si Wafer Clean

- **Ultrasonic / megasonic clean in DI water**



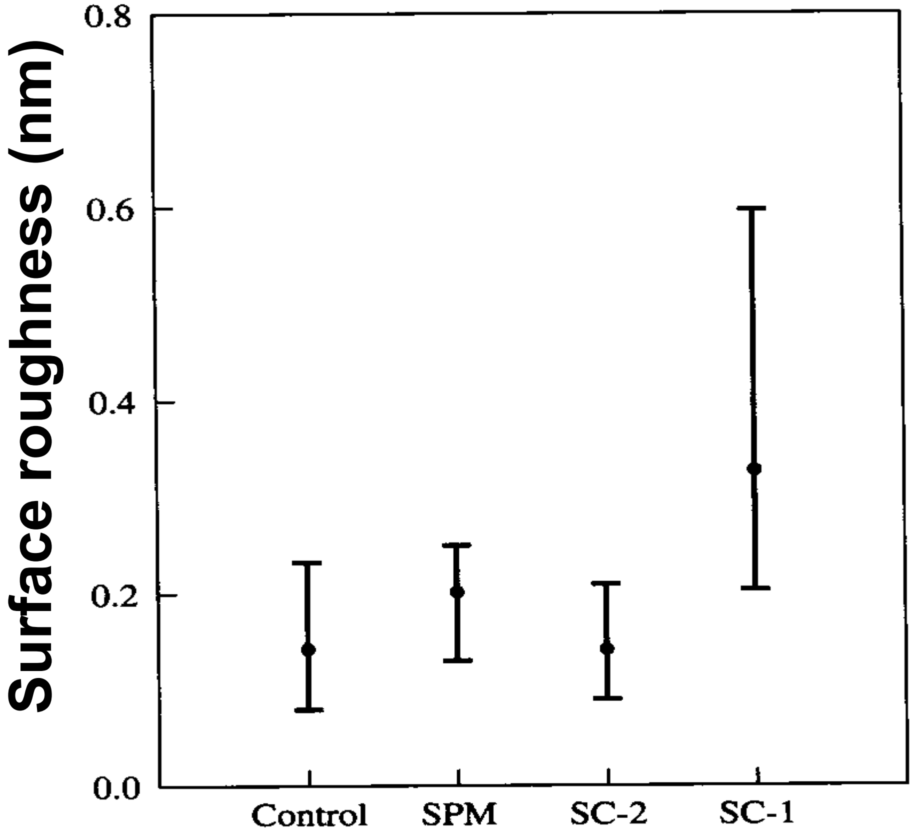
remove: large particles,
water soluble ions (Na, K, Cl, ...)

Standard Si Wafer Clean (RCA)

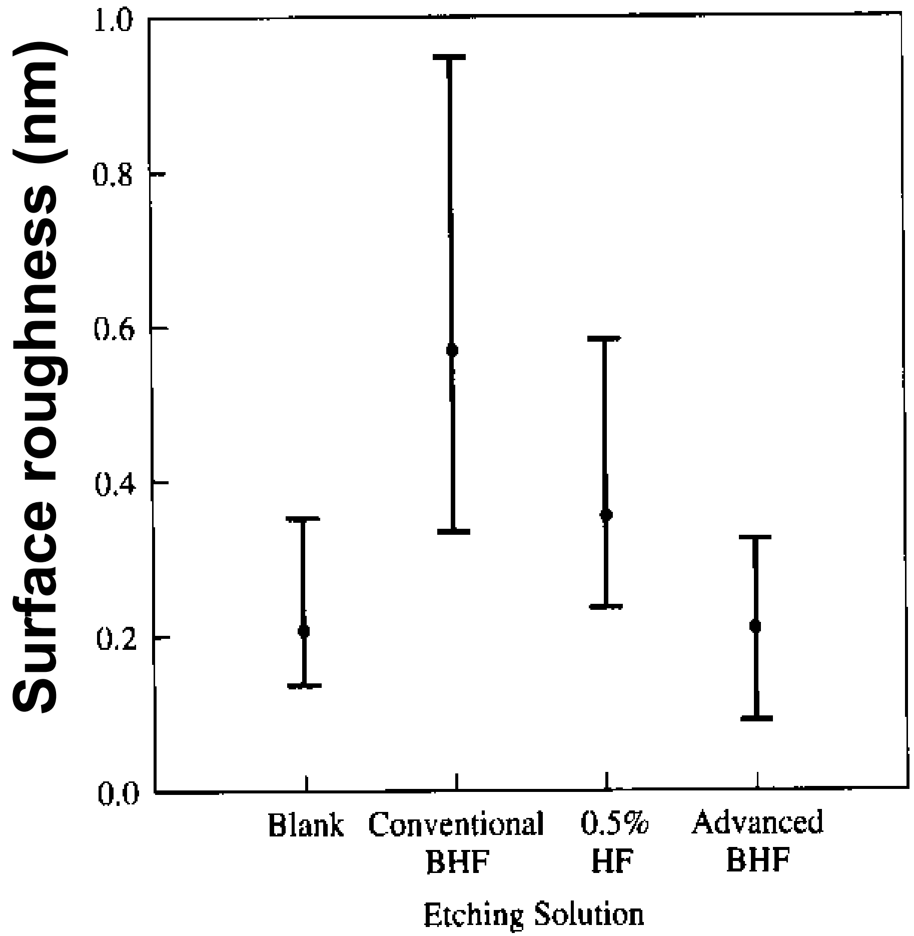
- **Step 1 (SC-1)**
  - $NH_4OH : H_2O_2 : H_2O$ = 1:1:5, at 80 °C, 10 mins
  - remove organic residues
- **Step 2**
  - $HF : H_2O$ = 1:50, at 25 °C, 20 secs
  - remove native SiO_2
- **Step 3 (SC-2)**
  - $HCl : H_2O_2 : H_2O$ = 1:1:6, at 80 °C, 10 mins
  - remove metals
- **Step 4**
  - clean in DI water

https://en.wikipedia.org/wiki/RCA_clean

Surface Roughness



SPM: H_2SO_4–H_2O_2 cleaning
SC-1: NH_4OH–H_2O_2–H_2O cleaning
SC-2: HCl–H_2O_2–H_2O cleaning



Surface Roughness of Si after cleaning
ammonia (NH_4OH) and HF slightly etches Si

Metal Removal

Table 4–3 Oxidation-reduction reactions for a number of species of interest in silicon wafer cleaning

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	$H_2O + H_2SO_3 \leftrightarrow H_2SO_4 + 2H^+ + 4e^-$
Cu^{2+}/Cu	−0.34	$Cu \leftrightarrow Cu^{2+} + 2e^-$
O_2/H_2O	−1.23	$2H_2O \leftrightarrow O_2 + 4H^+ + 4e^-$
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	$O_2 + H_2O \leftrightarrow O_3 + 2H^+ + 2e^-$

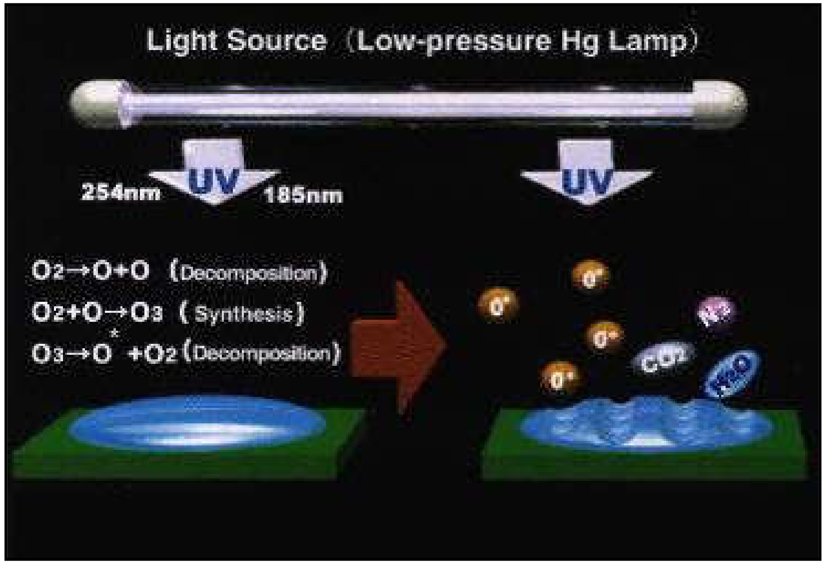
Other Si Clean Recipes

- **Piranha clean**
  - SPM: Sulfuric-Peroxide Mixture
  - $H_2SO_4 : H_2O_2 = 3:1$, 10–30 mins
  - extremely exothermic, self heating up to 80 °C
  - remove organic residues and some metals
- **Ozone (O_3) clean**
  - $H_2O + O_3$
  - remove organic residues
- **Organic solvent**
  - Acetone / Isopropanol / DI water
  - remove organic residues
  - not used for standard CMOS process!

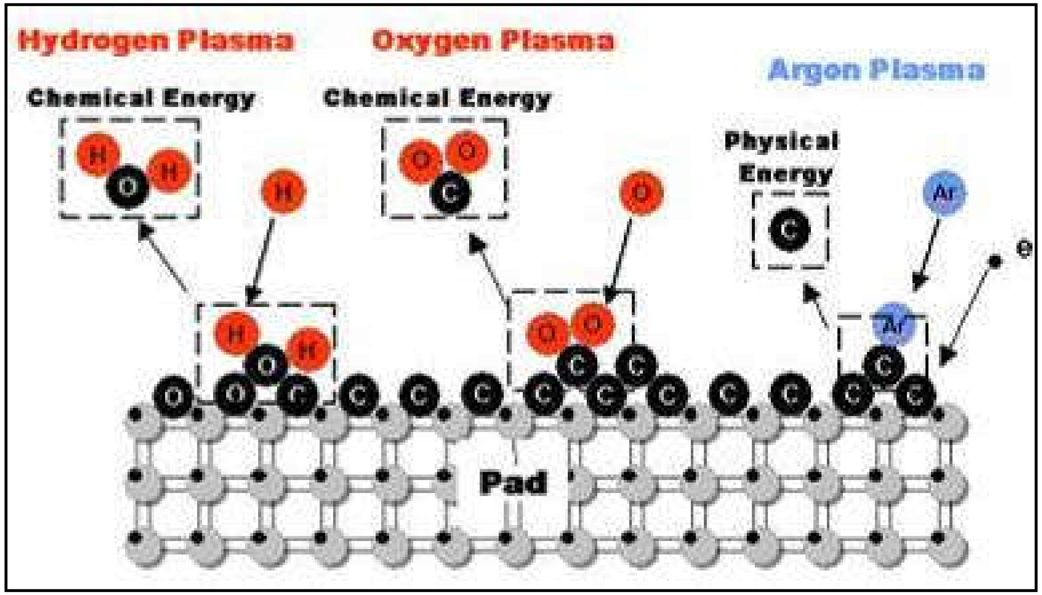
'wet' method

Other Si Clean Recipes

- UV Ozone clean
  - clean organic residues



- Plasma clean
  - clean organic residues

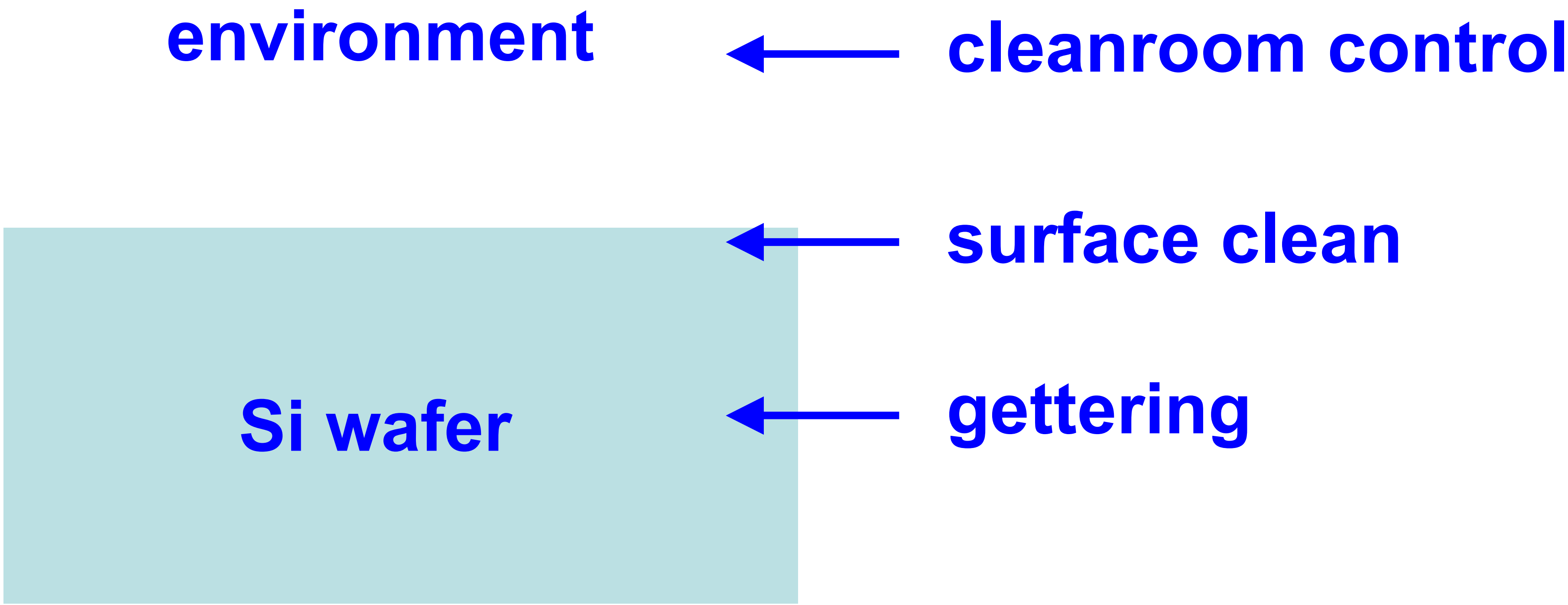


'dry' method

Clean other Materials

- SiO_2 (glass, quartz, ...)
  - piranha clean, H_2SO_4 : H_2O_2 = 3:1, 10–30 mins
- GaAs
  - NH_4OH : H_2O = 1:10, for stoichiometric surface (Ga/As 1:1)
  - H_3PO_4 or HCl, for As rich surface
- Acetone / Isopropanol / DI water
  - generally works well for most non-CMOS process

Defects Control

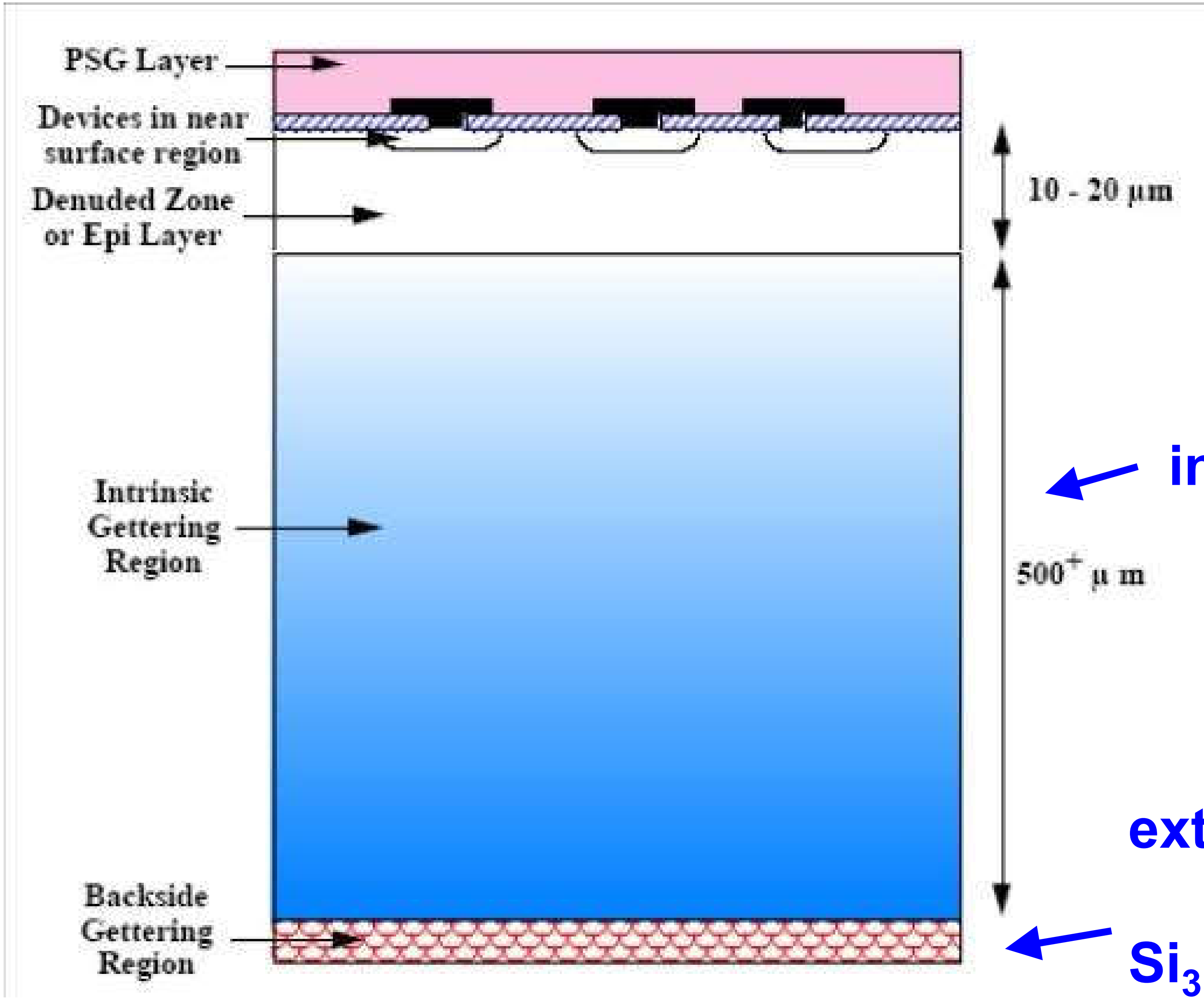


Si Wafer Gettering（吸杂）

- 'gettering' in vacuum
  - use titanium to absorb gases in vacuum tubes

titanium

Si Wafer Gettering（吸杂）



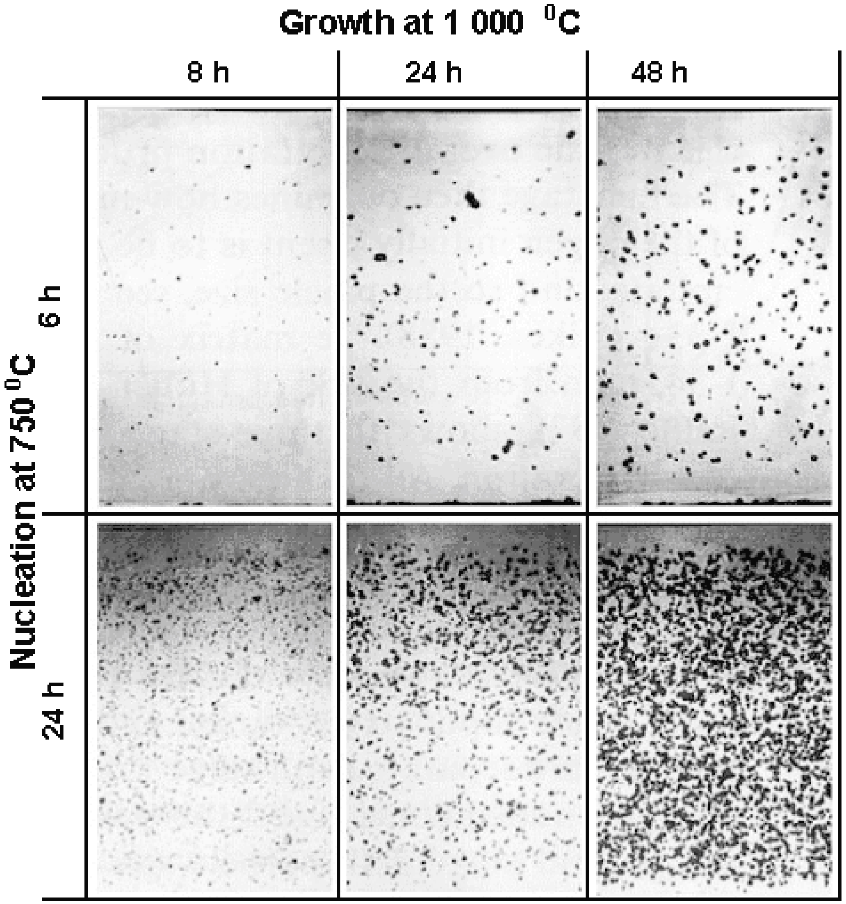
intrinsic gettering

extrinsic gettering:

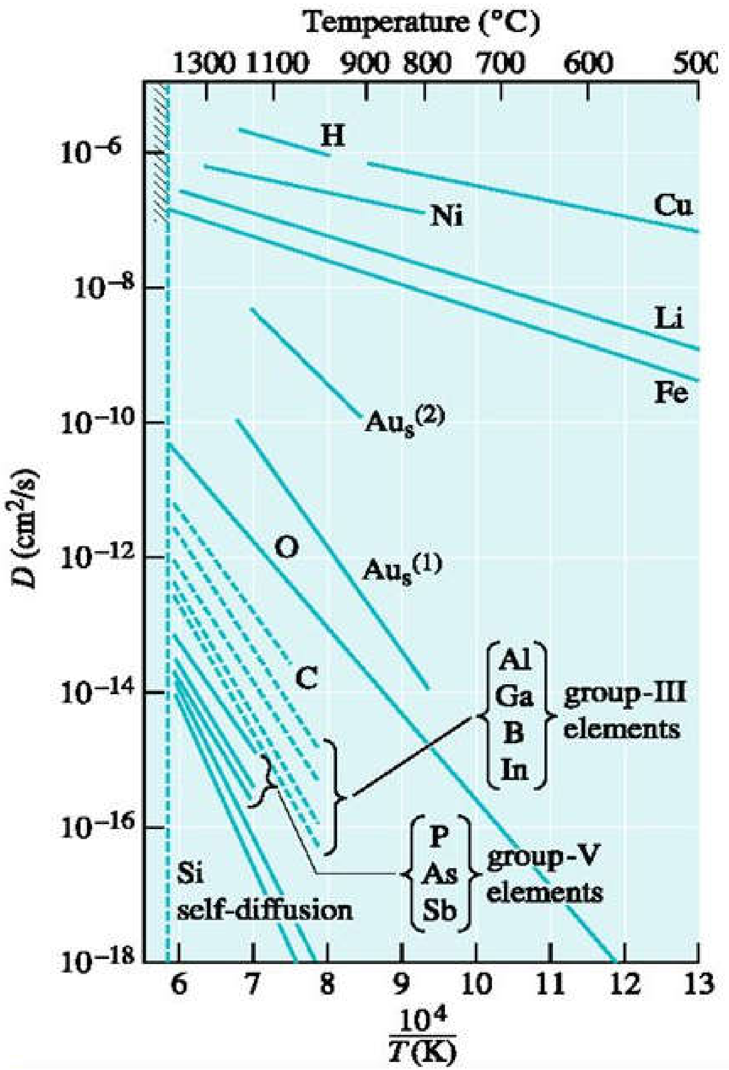
Si_3N_4, P_2O_5, ...

Si Wafer Gettering（吸杂）

- **intrinsic gettering**



O defects in Si



easy

hard

diffusivity of defects

Si Wafer Gettering（吸杂）

- **Minority carrier lifetime**

Au doped Si: 10^{-9} s

Typical Si: 10^{-6} s

Gettered Si: 10^{-3} s

Lab Safety

- Chemicals
  - HF, H_2SO_4, ...
  - KOH, NH_4OH, ...
  - Acetone, ...
- Electricity
  - instruments, ...
- Fires
  - Acetone, Alcohol, ...
- Sharps
  - silicon, glass, ...
- ...

Lab Safety

- Lab orientation
  - exits, showers, ...
- Proper protection
  - gloves, goggles, aprons, ...
- Materials Data Safety Sheets (MSDS)
- ...

Lab Safety

- **Materials Data Safety Sheets (MSDS)**

Material Safety Data Sheet
Hydrofluoric Acid, 48% MSDS

Section 1: Chemical Product and Company Identification

Product Name: Hydrofluoric Acid, 48%

Catalog Codes: SLH2227

CAS#: 7664-39-3

RTECS: Not applicable.

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Section 3: Hazards Identification

Potential Acute Health Effects:
Very hazardous in case of skin contact (corrosive, irritant, permeator), of eye contact (irritant, corrosive), of ingestion. Liquid or spray mist may produce tissue damage particularly on mucous membranes of eyes, mouth and respiratory tract. Skin contact may produce burns. Inhalation of the spray mist may produce severe irritation of respiratory tract, characterized by coughing, choking, or shortness of breath. Severe over-exposure can result in death. Inflammation of the eye is characterized by redness, watering, and itching. Skin inflammation is characterized by itching, scaling, reddening, or, occasionally, blistering.

Chemical Safety

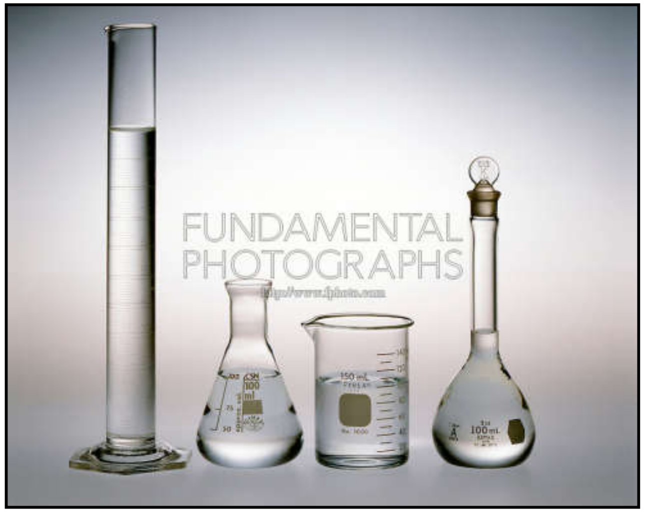
- **NFPA diamond**
  - **0: no harzard**
  - **4: highest risk**

HF

acetone

H_2O_2

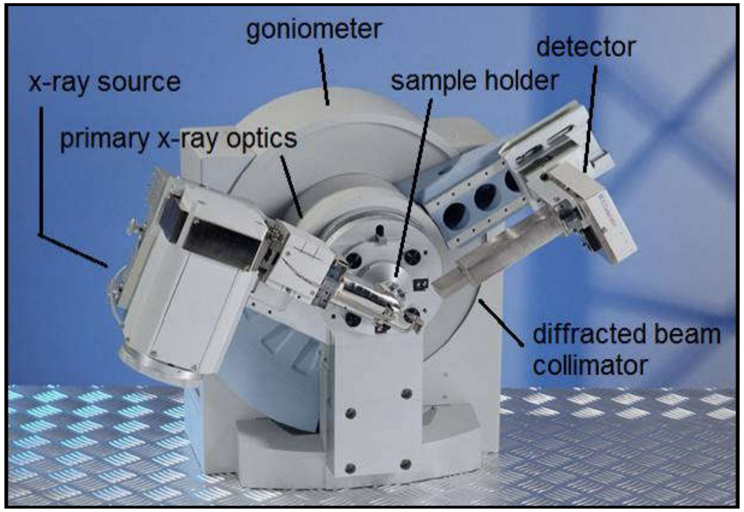
Chemical Safety

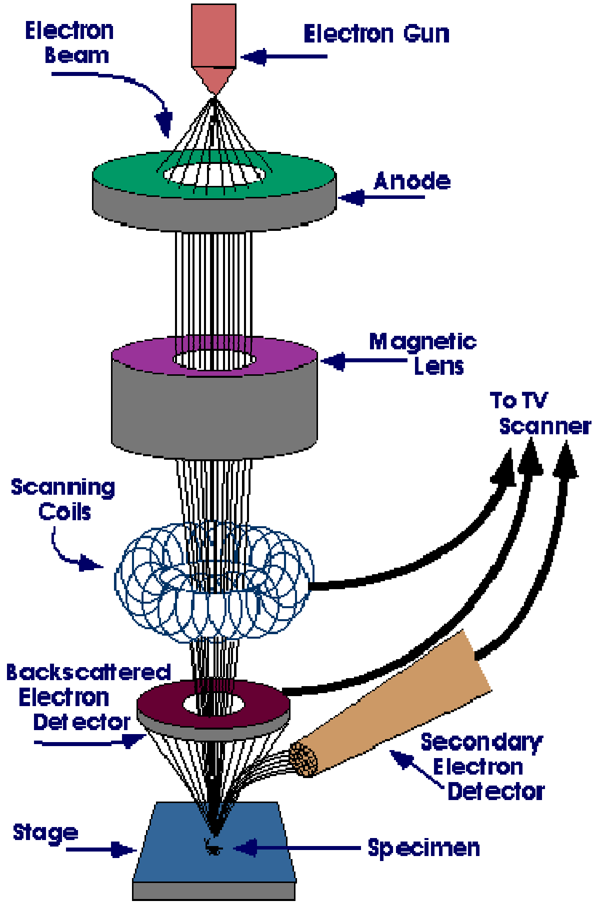


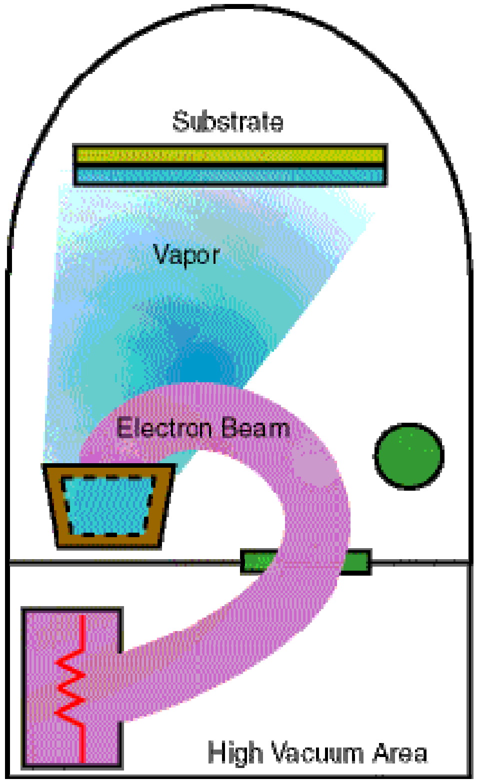
- Choose proper containers
- Most solvents
  - glass, Teflon, ...
- Be careful
  - alkali (NaOH, etc) slowly etches glass
  - HF strongly etches glass!

glass art by HF etch

Radiation Safety





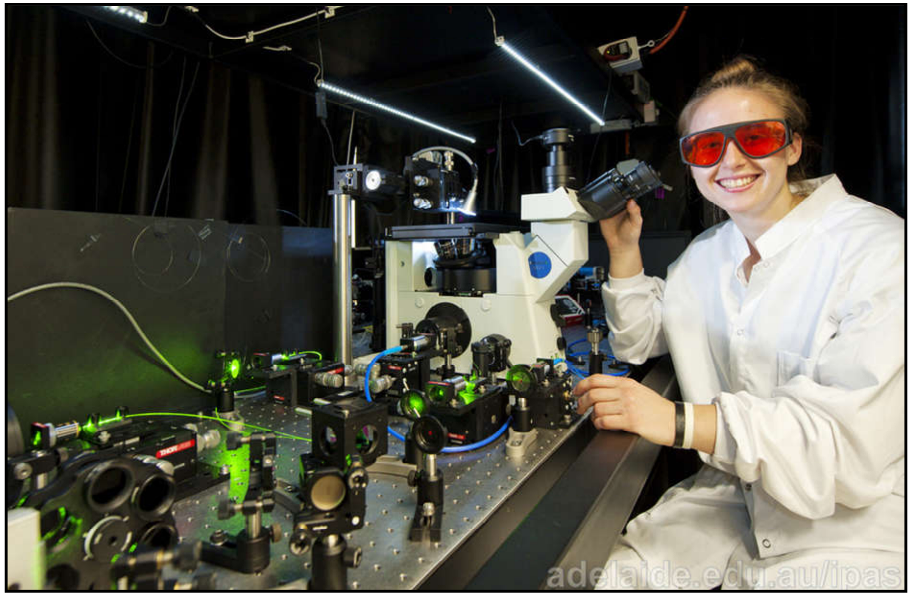


XRD **SEM & TEM** **Ebeam Evaporator**

Laser Safety

Class 1	CD/DVD Player/Recorder, Laptop or Personal Computer
Class 2	Presentation Laser Pointer, Barcode Reader
Class 3R	Some Measuring & Targeting Devices, Higer Power Pointers
Class 3B	Higher power laser products intened for professional applications
Class 4	Medical Lasers, Industrial Cutting/Welding, Scientific Applications and most *Laser Light Show* Equipment

wear goggles



Biological Safety

Basic Facility

- BSL-1
  - Safe microorganisms
  - Not known to cause disease in healthy adult humans
- BSL-2
  - Moderate-risk microorganisms
  - Potentially hazard to humans and the environment
  - e.g. inactivated virus that Causes Foot and Mouth Disease

Containment Facility

- BSL-3, BSL-3 Enhanced & BSL-3 Ag
  - High-risk microorganisms, foreign and emerging agents
  - Serious and potential lethal consequences for livestock
  - Not harmful to humans because of protective measures
  - e.g. live virus that Causes Foot and Mouth Disease
- BSL-4
  - High-risk agents microorganisms
  - No known vaccine or therapy
  - e.g. Nipah and Hendra viruses

Thank you for your attention