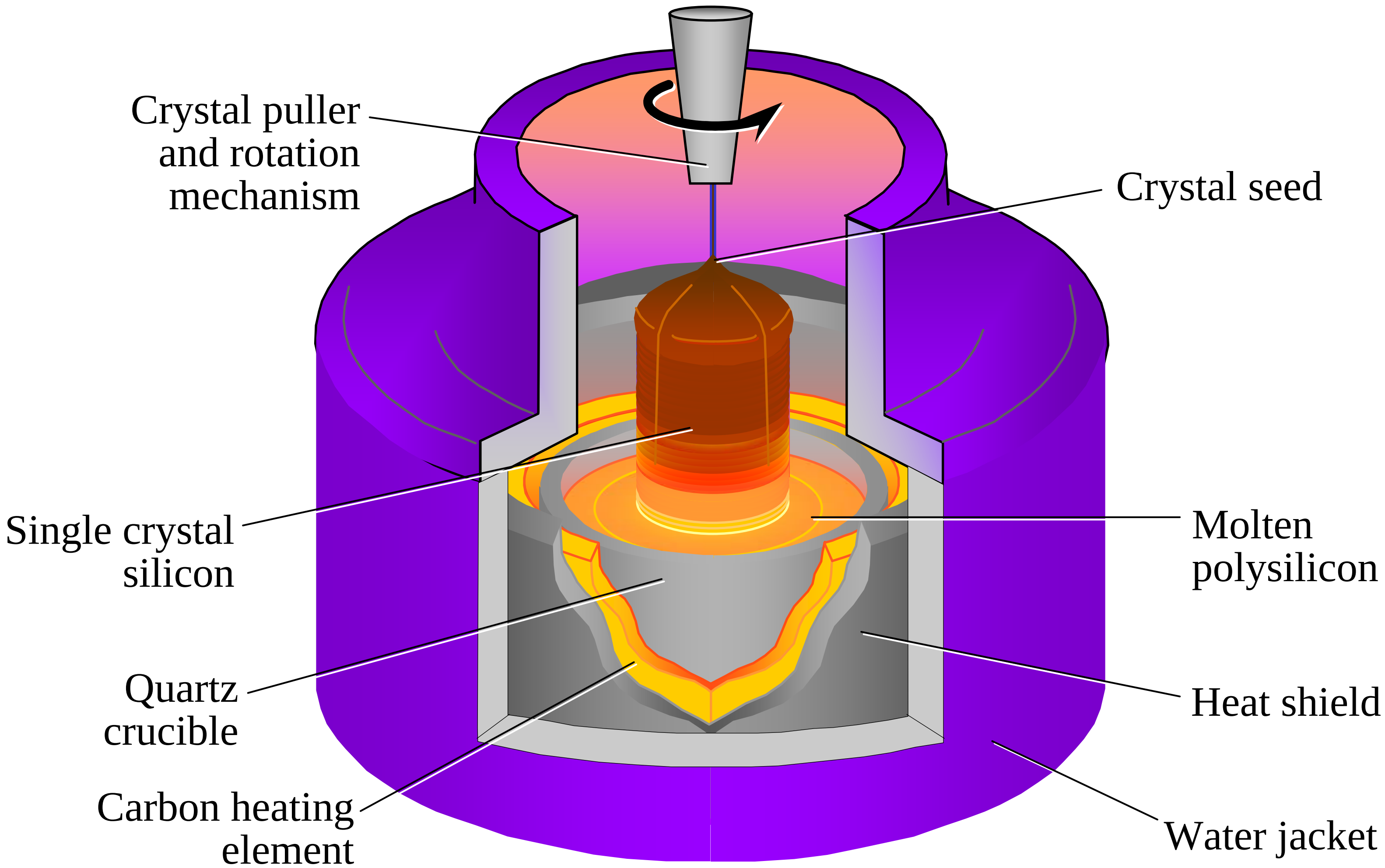
Semiconductor-Grade Silicon

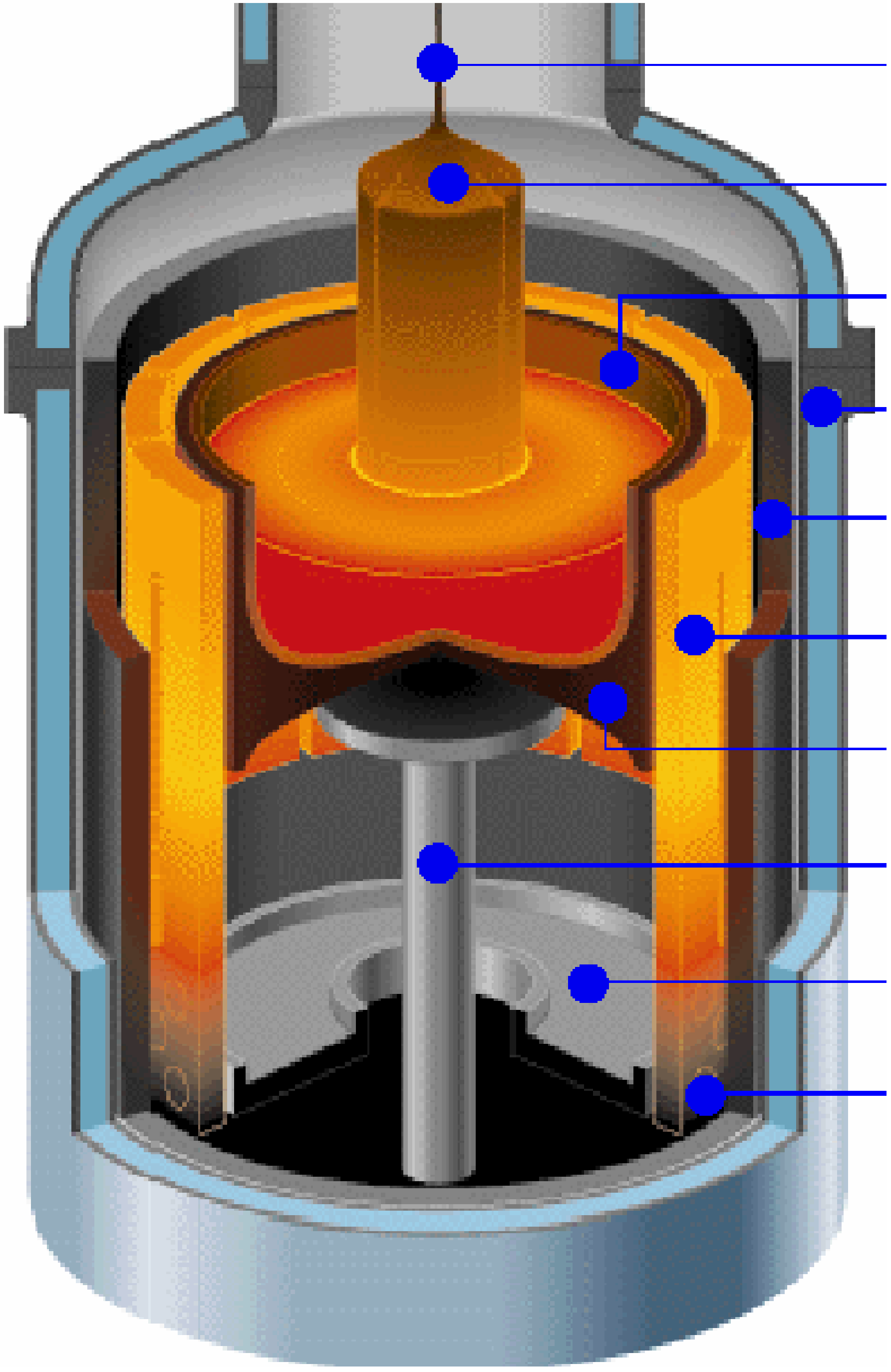
Steps to Obtaining Semiconductor Grade Silicon (SGS)		
Step	**Description of Process**	**Reaction**
1	Produce metallurgical grade silicon (MGS) by heating silica with carbon	$SiC\ (s) + SiO_2\ (s) \rightarrow Si\ (l) + SiO(g) + CO\ (g)$
2	Purify MG silicon through a chemical reaction to produce a silicon-bearing gas of trichlorosilane ($SiHCl_3$)	$Si\ (s) + 3HCl\ (g) \rightarrow SiHCl_3\ (g) + H_2\ (g)$ + heat
3	$SiHCl_3$ and hydrogen react in a process called Siemens to obtain pure semiconductor-grade silicon (SGS)	$2SiHCl_3\ (g) + 2H_2\ (g) \rightarrow 2Si\ (s) + 6HCl\ (g)$

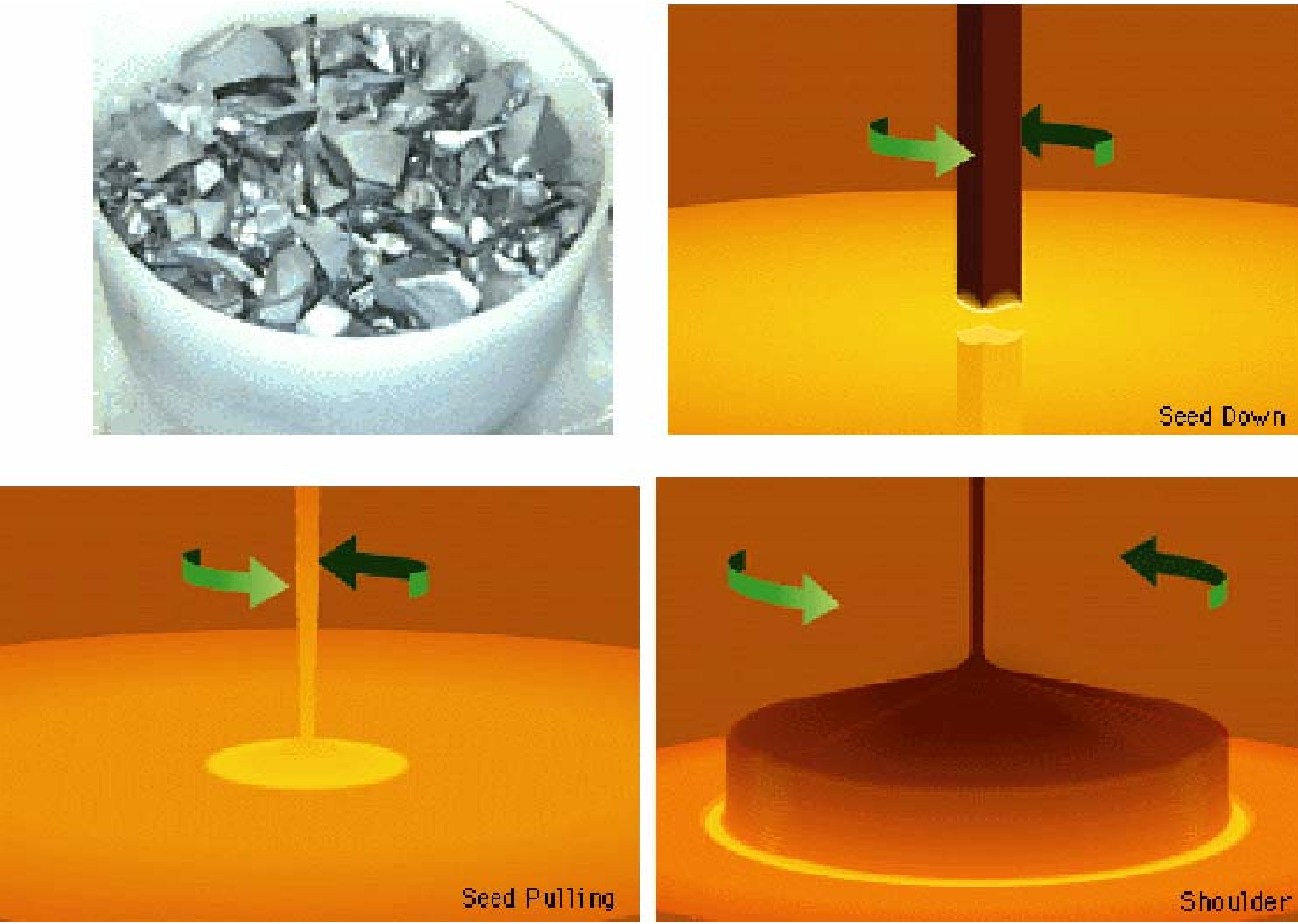
- Si is purified from SiO_2 (sand) by refining, distillation and CVD.
- It contains < 1 ppb impurities. Pulled crystals contain O (~10^{18} cm^{-3}) and C (~10^{16} cm^{-3}), plus dopants placed in the melt.

CZ Crystal Puller

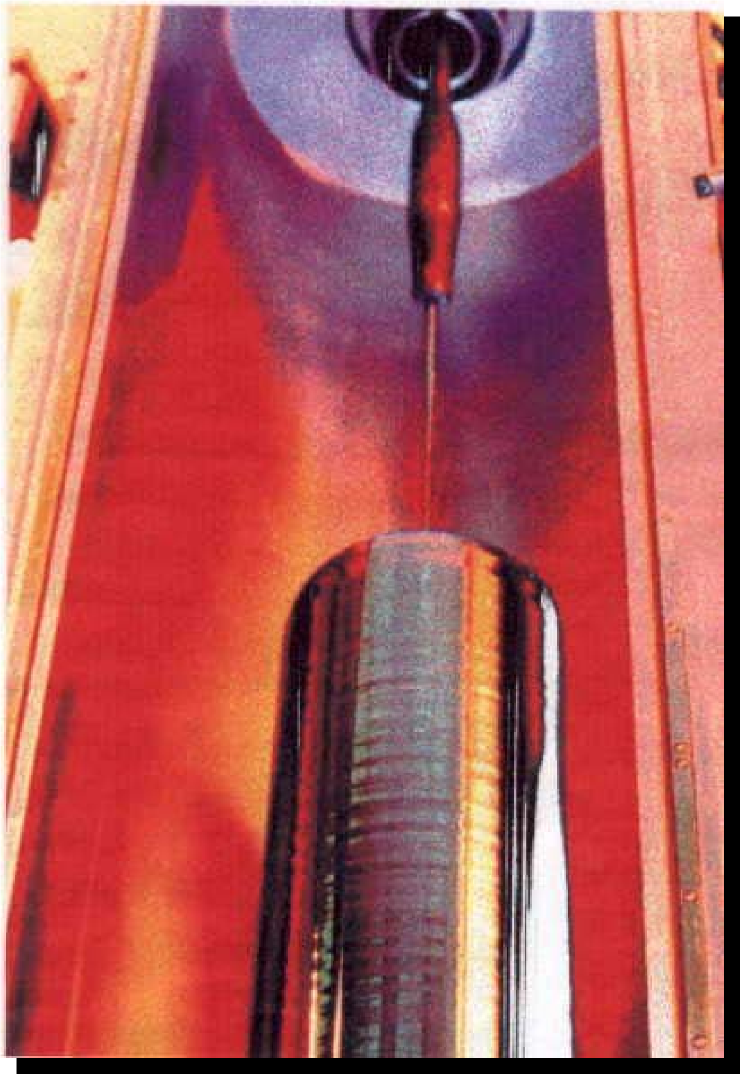


- All Si wafers come from "Czochralski" grown crystals.
- Polysilicon is melted, then held just below 1417 °C, and a single crystal seed starts the growth.
- Pull rate, melt temperature and rotation rate control the growth




Seed Down
Seed Pulling
Shoulder

Silicon Ingot Grown by CZ Method

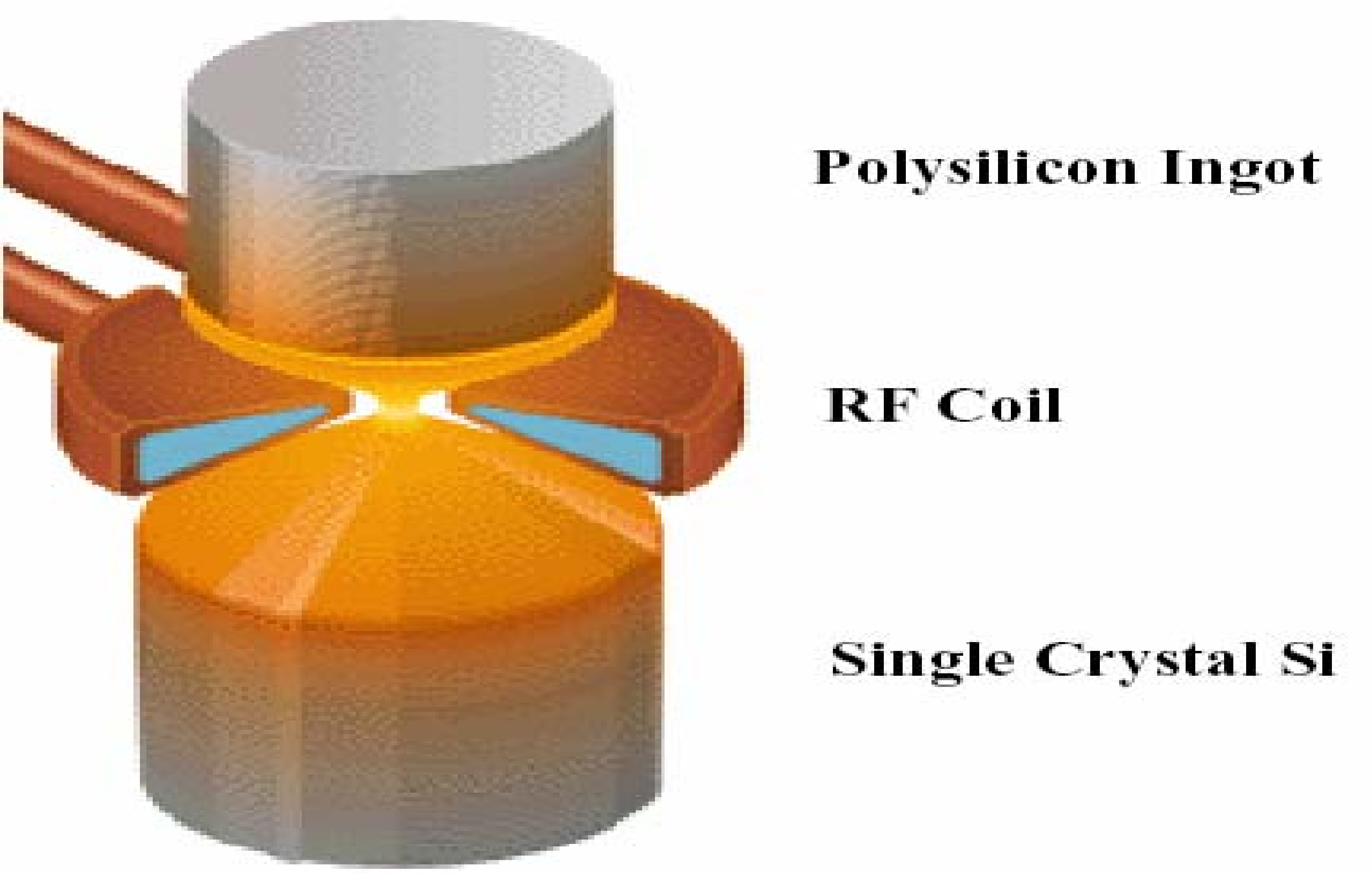


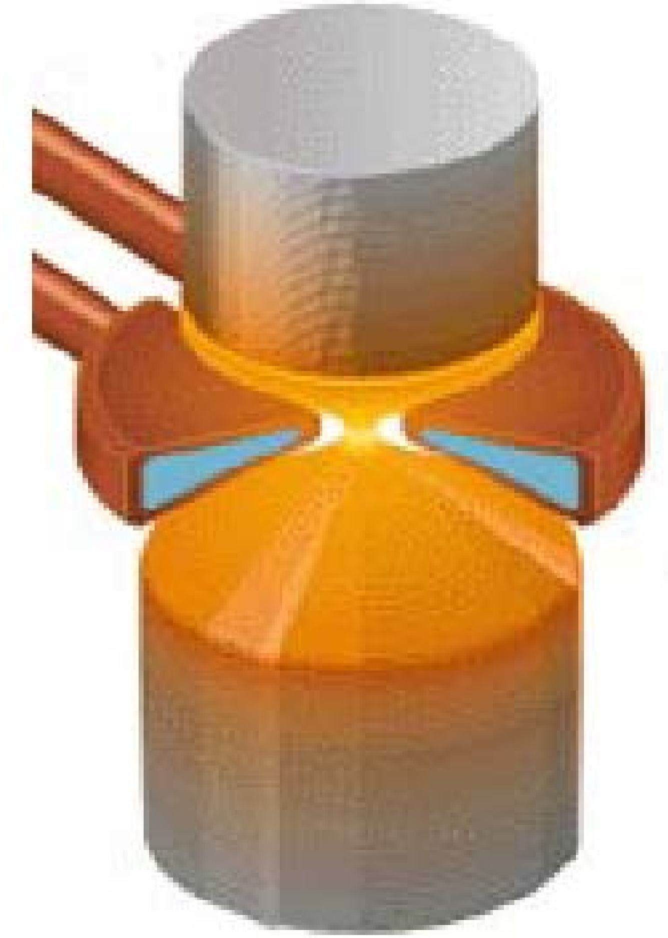
Photograph courtesy of Kayex Corp., 300 mm Si ingot

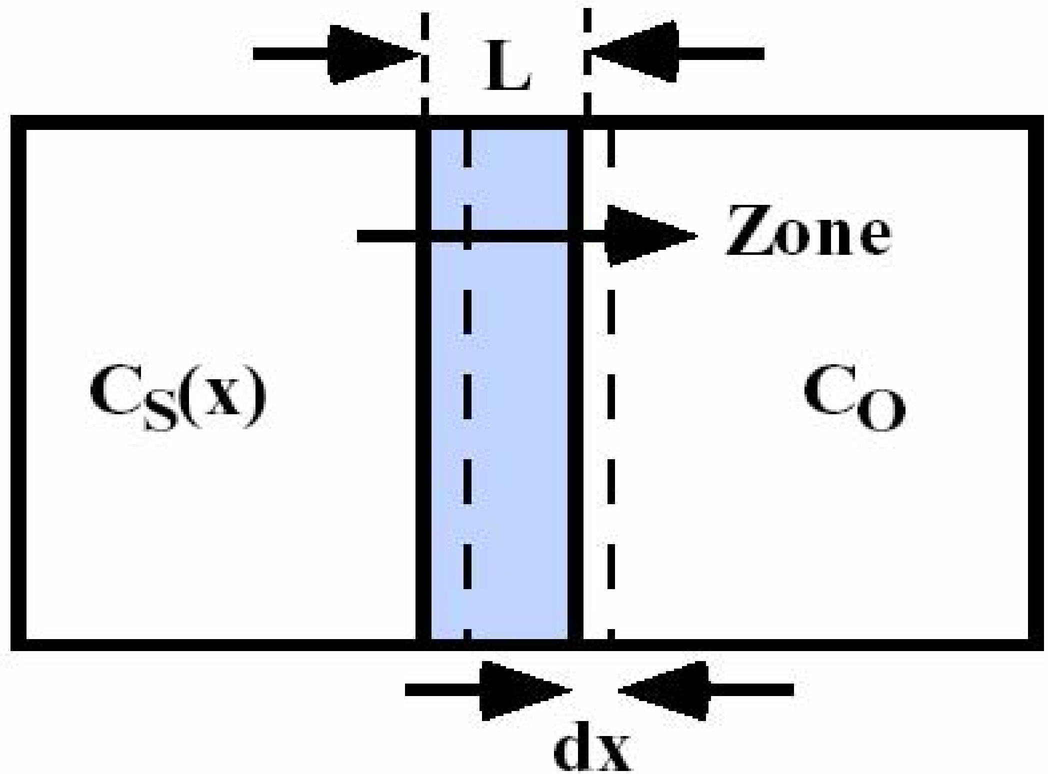
CYLINDER OF MONOCRYSTALLINE

- The Silicon Cylinder is Known as an Ingot
- Typical Ingot is About 1 or 2 Meters in Length
- Can be Sliced into Hundreds of Smaller Circular Pieces Called Wafers
- Each Wafer Yields Hundreds or Thousands of Integrated Circuits

An alternative process is the “Float Zone” process which can be used for refining or single crystal growth.

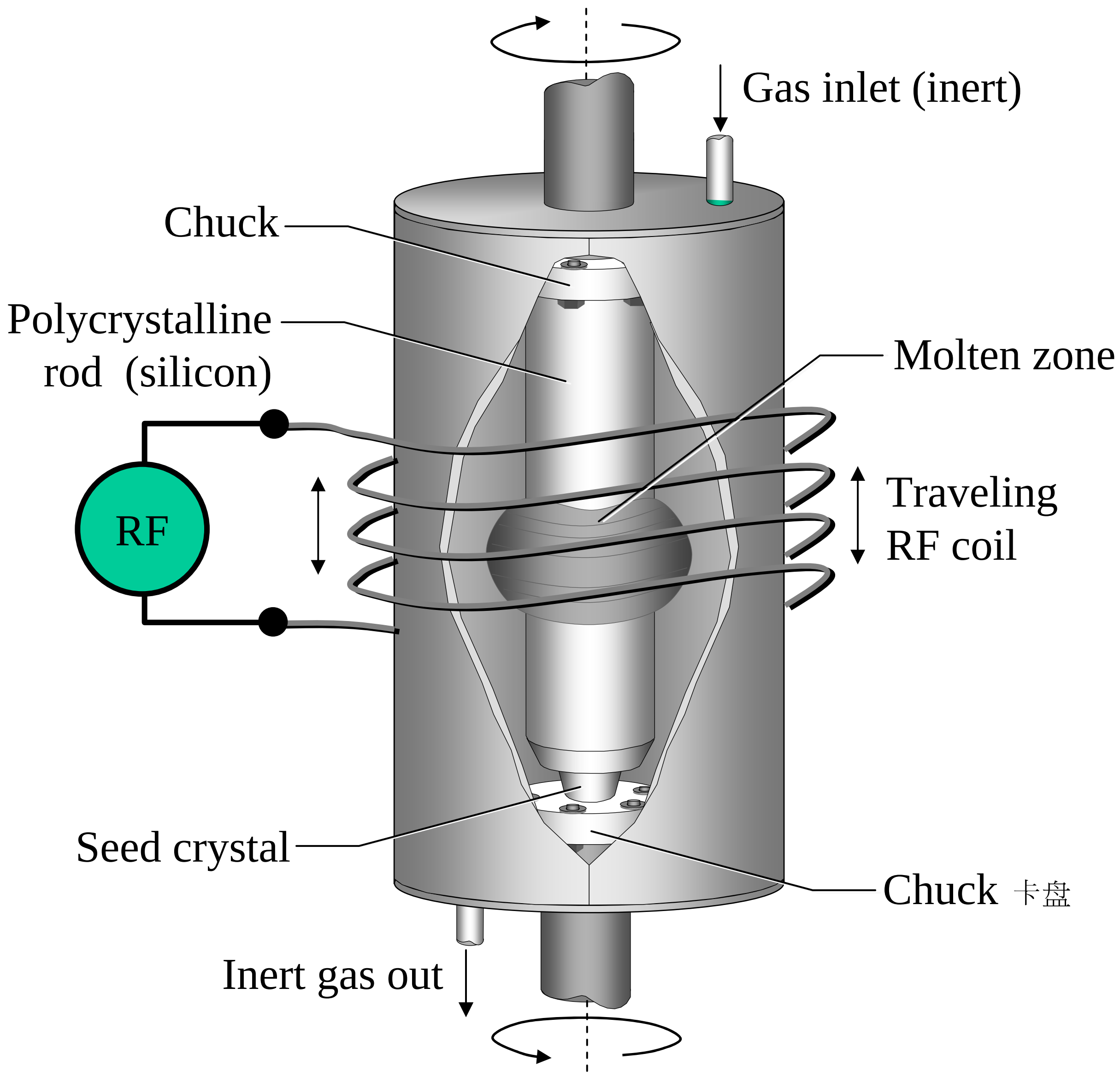






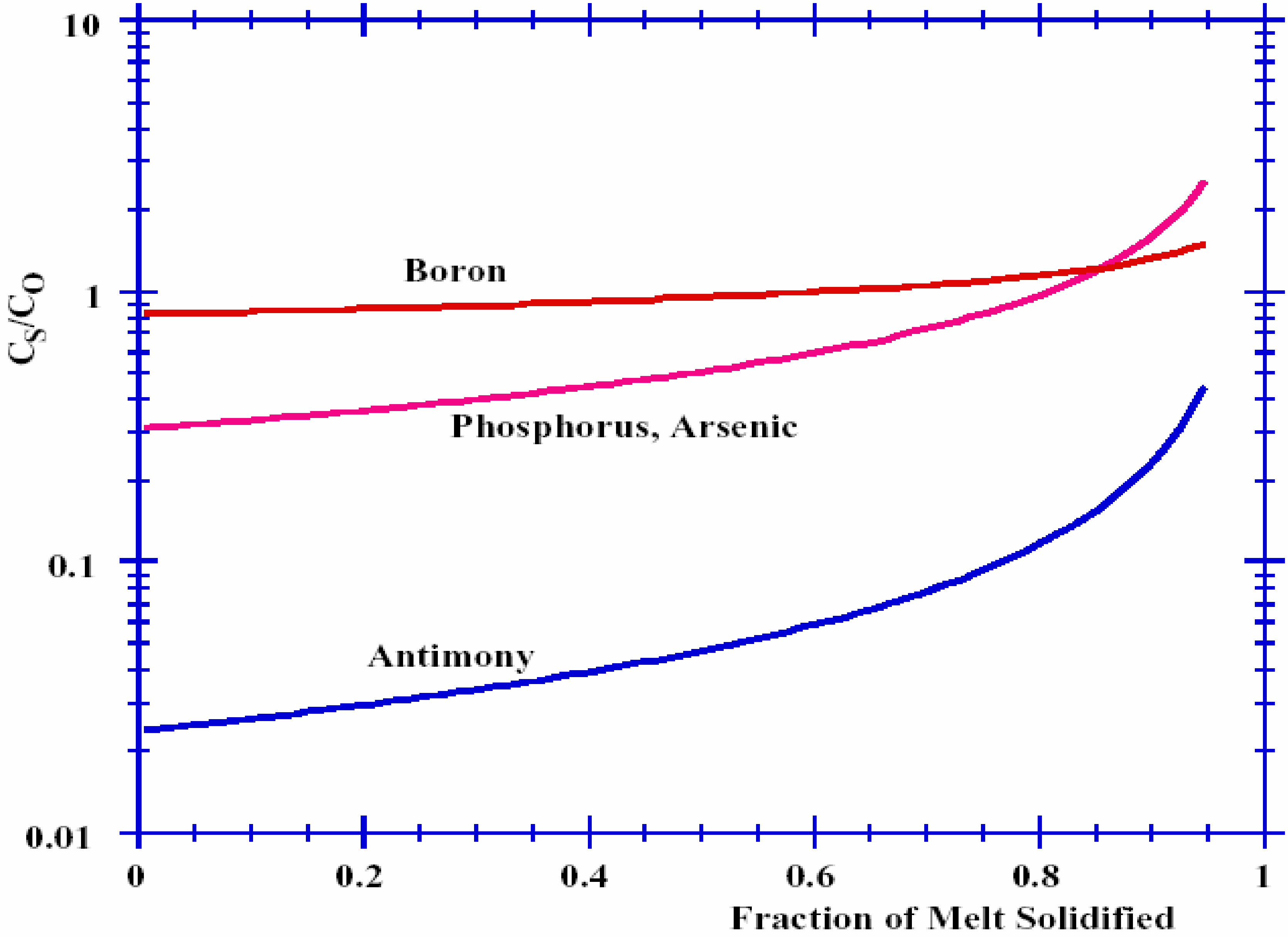
• In the float zone process, dopants and other impurities are rejected by the regrowing silicon crystal. Impurities tend to stay in the liquid and refining can be accomplished, especially with multiple passes.

Float Zone Crystal Growth



分凝系数

Segregation Fraction for FZ Refining

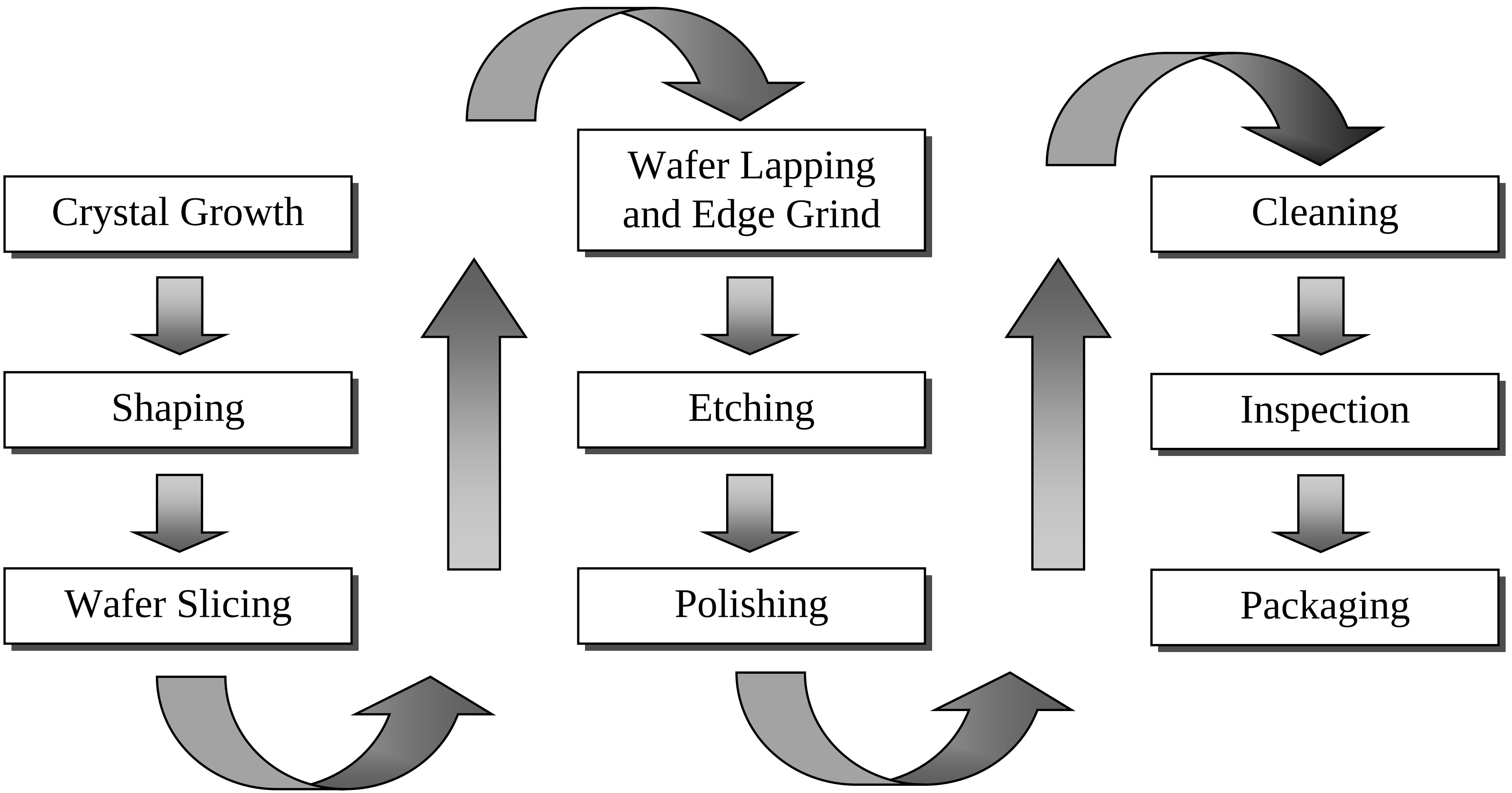


Dopant Concentration Nomenclature

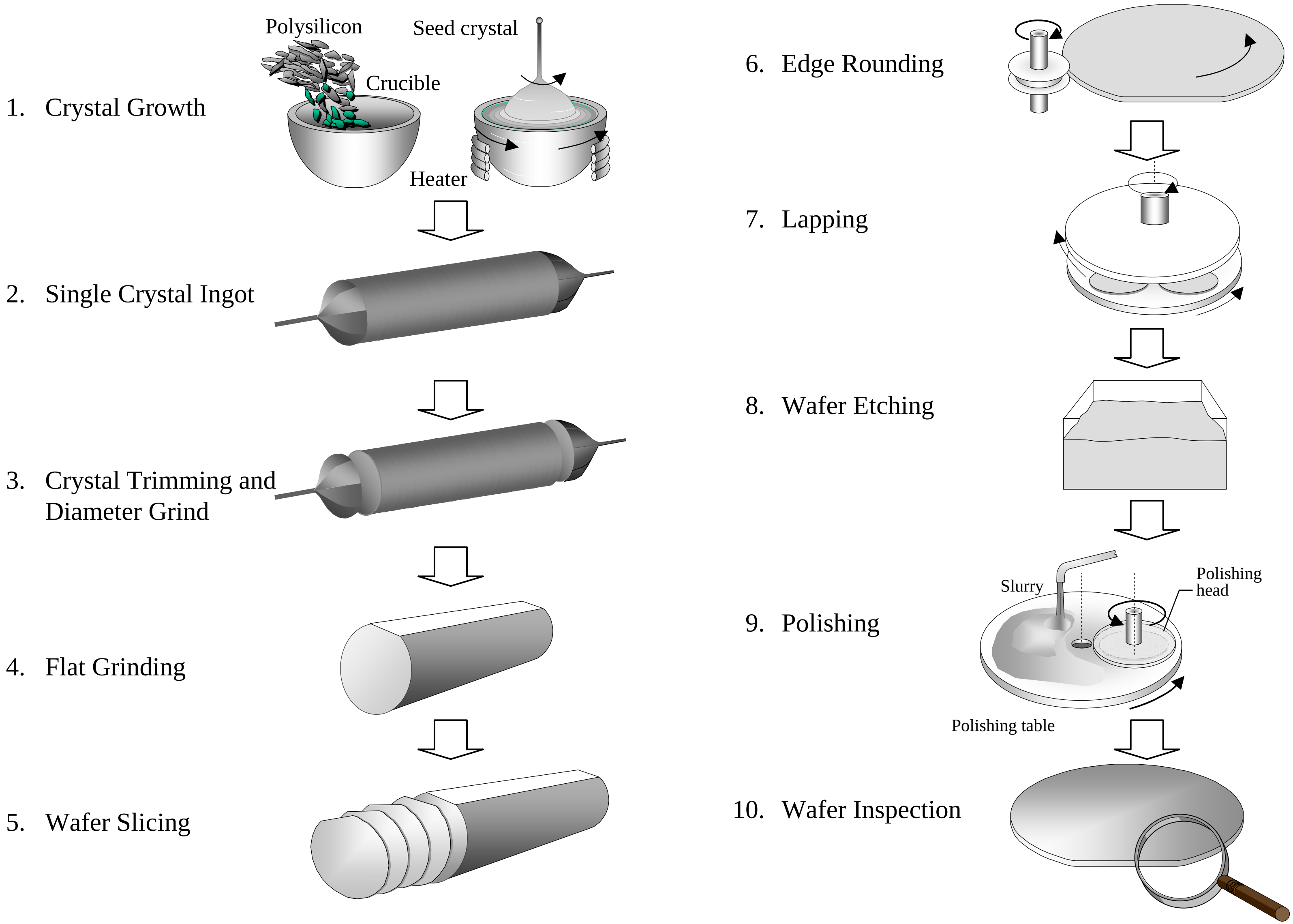
掺杂浓度命名

		Concentration (Atoms/cm^3)			
Dopant	**Material Type**	**$< 10^{14}$** (Very Lightly Doped)	**10^{14} to 10^{16}** (Lightly Doped)	**10^{16} to 10^{19}** (Doped)	**$>10^{19}$** (Heavily Doped)
Pentavalent	**n**	n^{--}	n^{-}	**n**	n^{+}
Trivalent	**p**	p^{--}	p^{-}	**p**	p^{+}

Basic Process Steps for Wafer Preparation

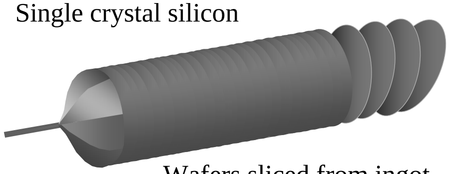


Preparation of Silicon Wafers

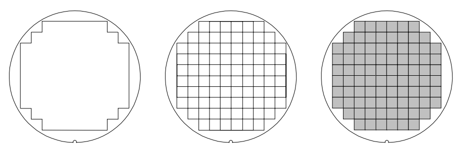


Stages of IC Fabrication

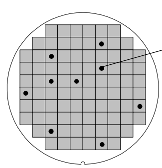
1. Wafer Preparation includes crystal growing, rounding, slicing and polishing.



2. Wafer Fabrication includes cleaning, layering, patterning, etching and doping.

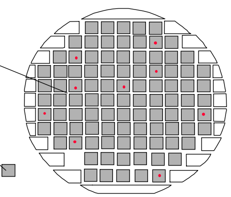


3. Test/Sort includes probing, testing and sorting of each die on the wafer.

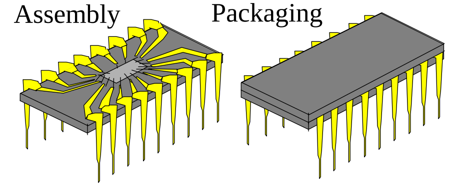


4. Assembly and Packaging:

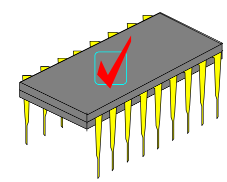
The wafer is cut along scribe lines to separate each die.



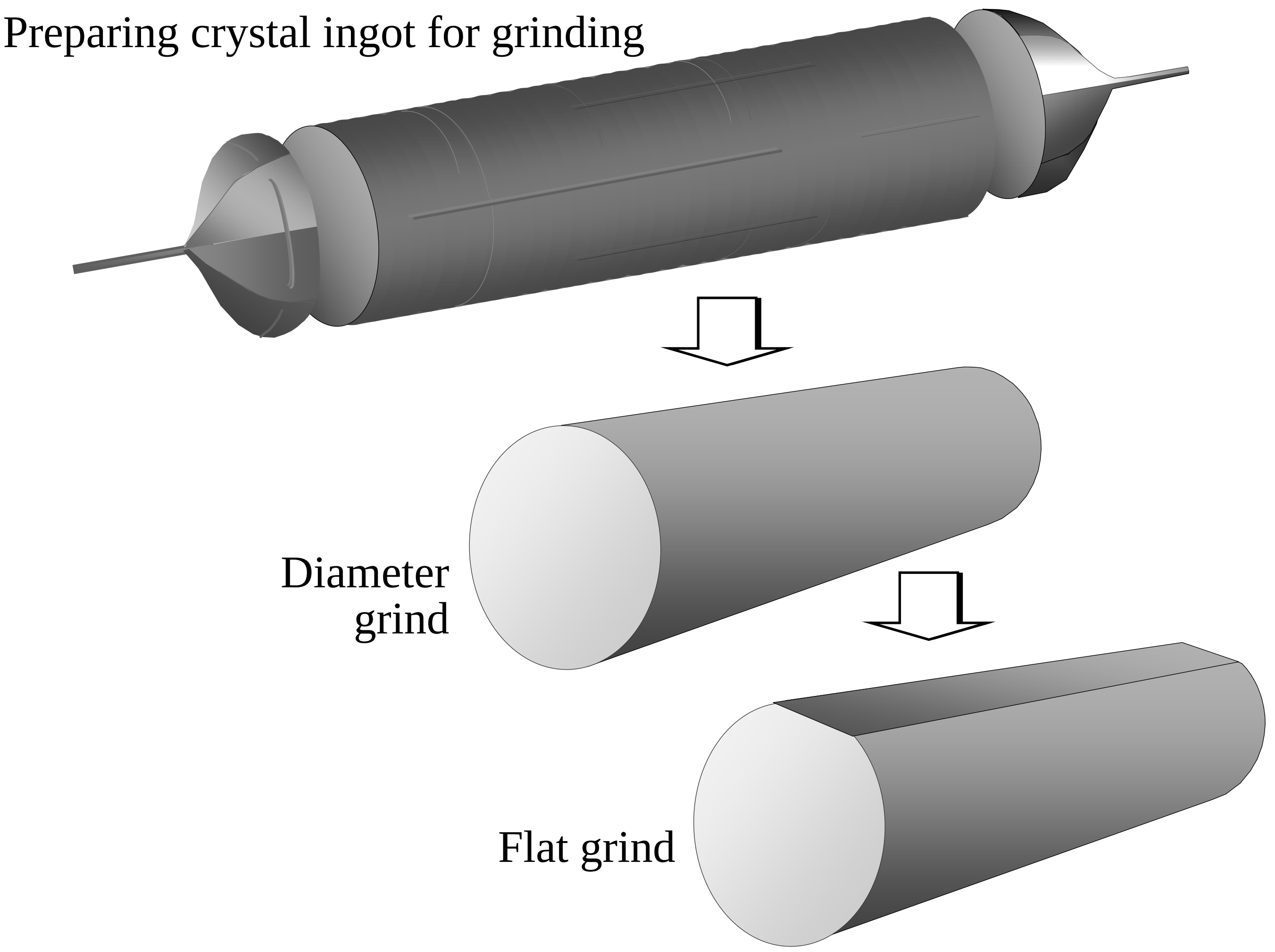
Metal connections are made and the chip is encapsulated.



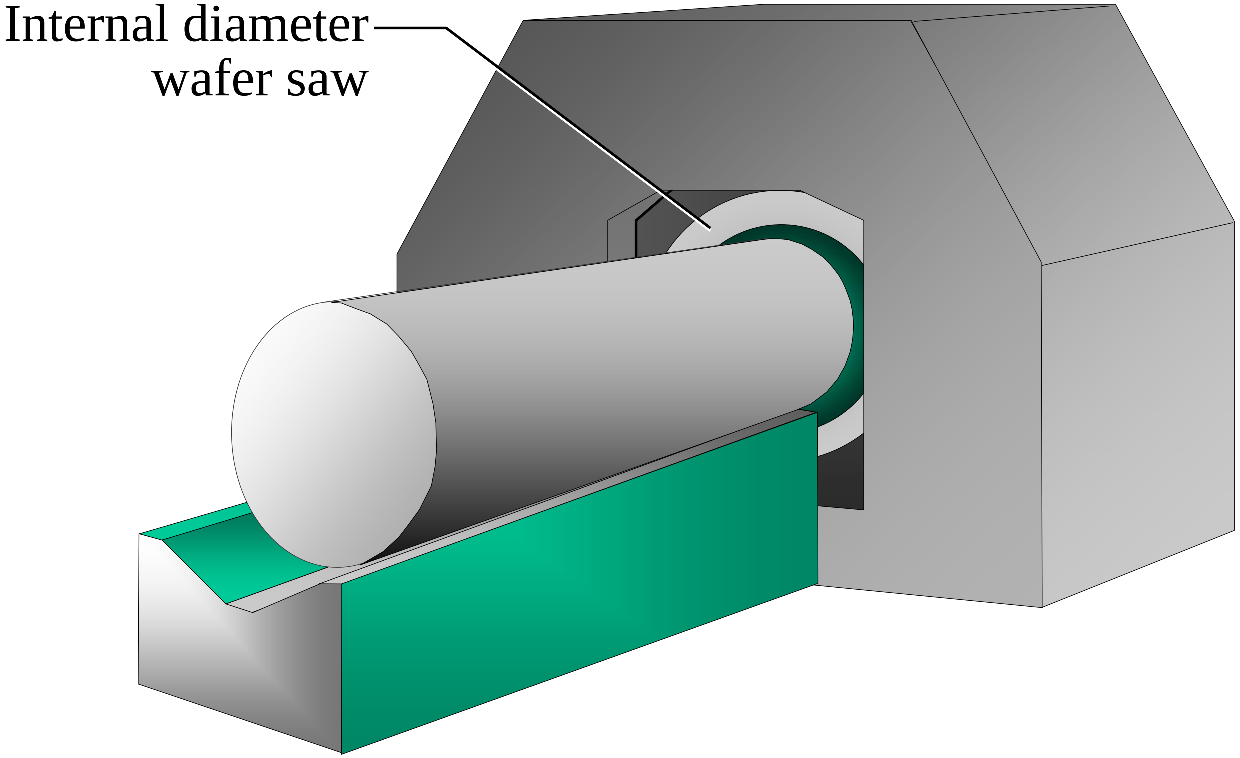
5. Final Test ensures IC passes electrical and environmental testing.



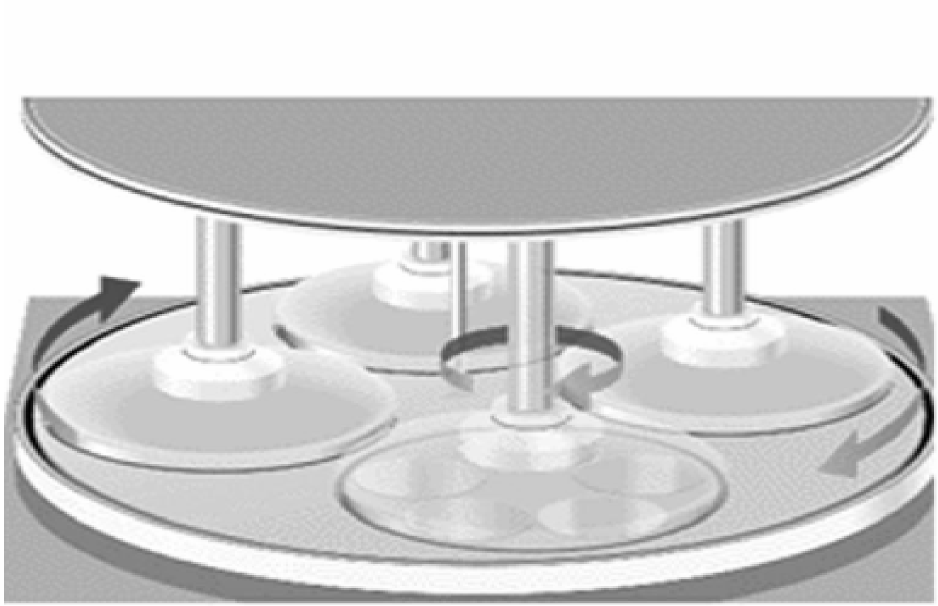
Ingot Diameter Grind

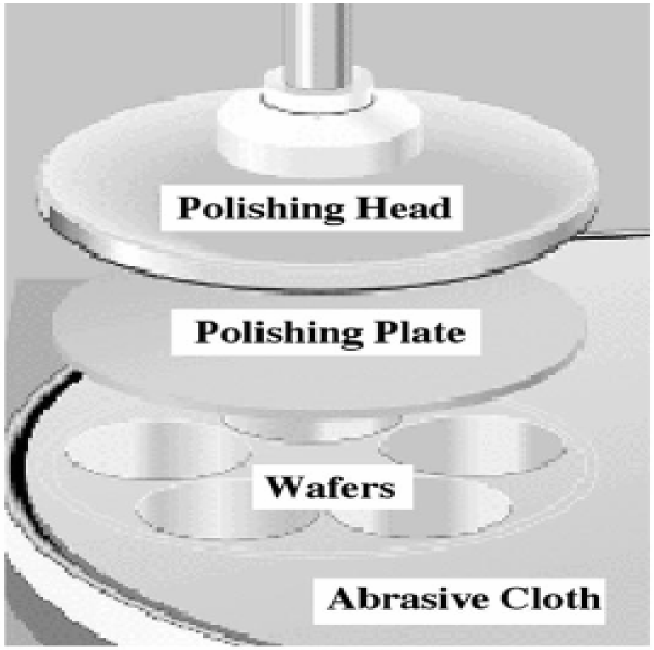


Internal Diameter Saw

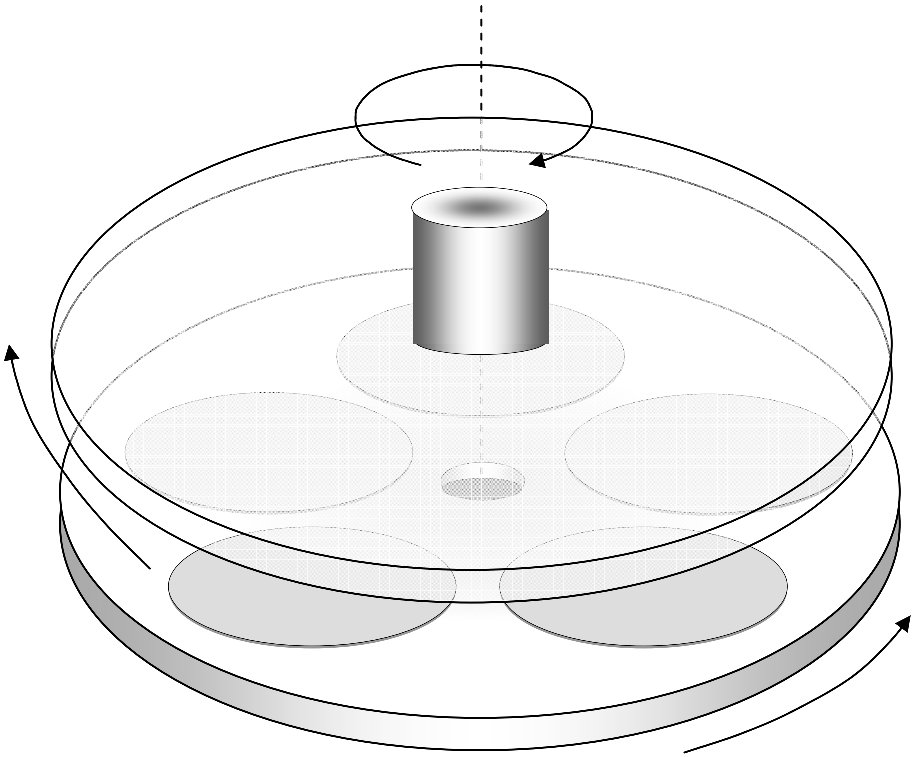


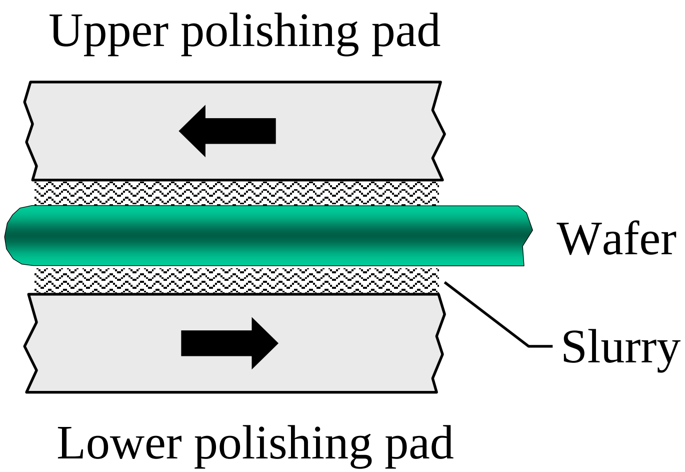
Wafer Polishing



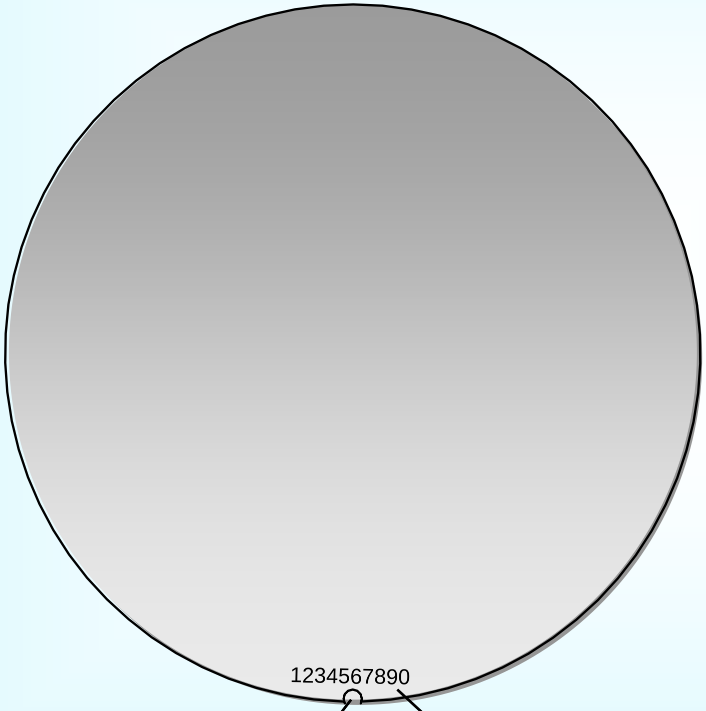


Double-Sided Wafer Polish





Wafer Notch and Laser Scribe

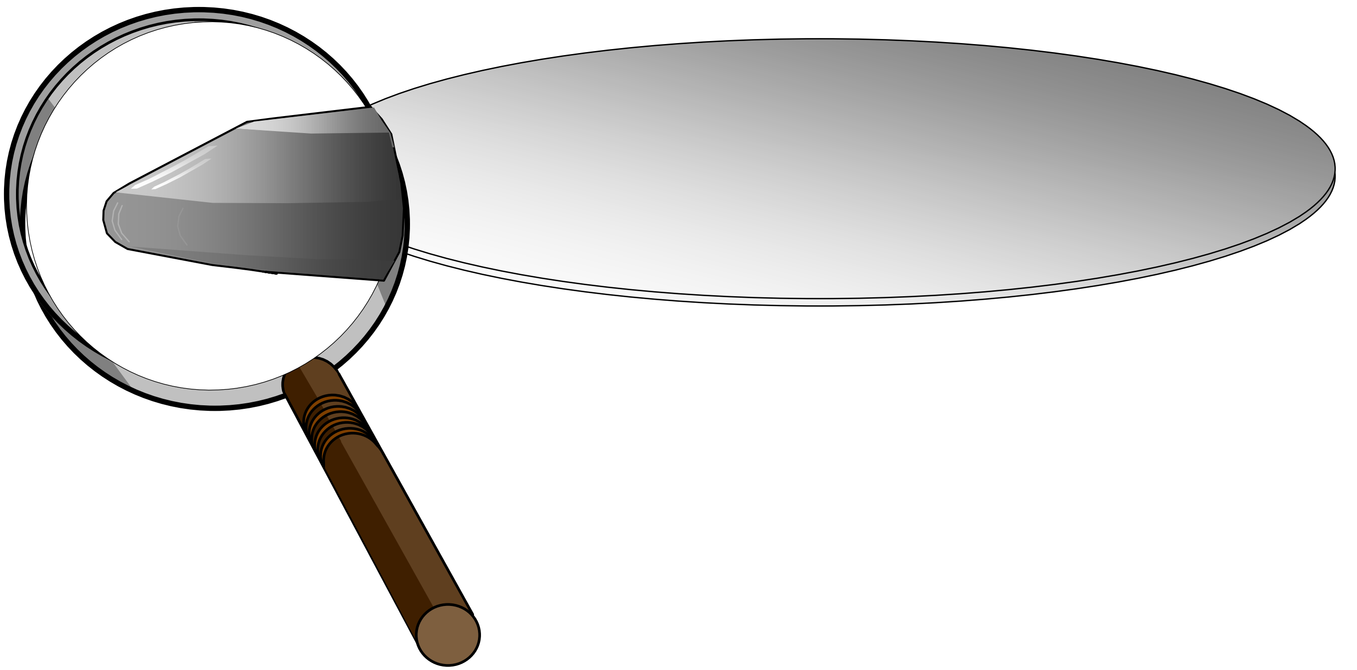


Improving Silicon Wafer Requirements

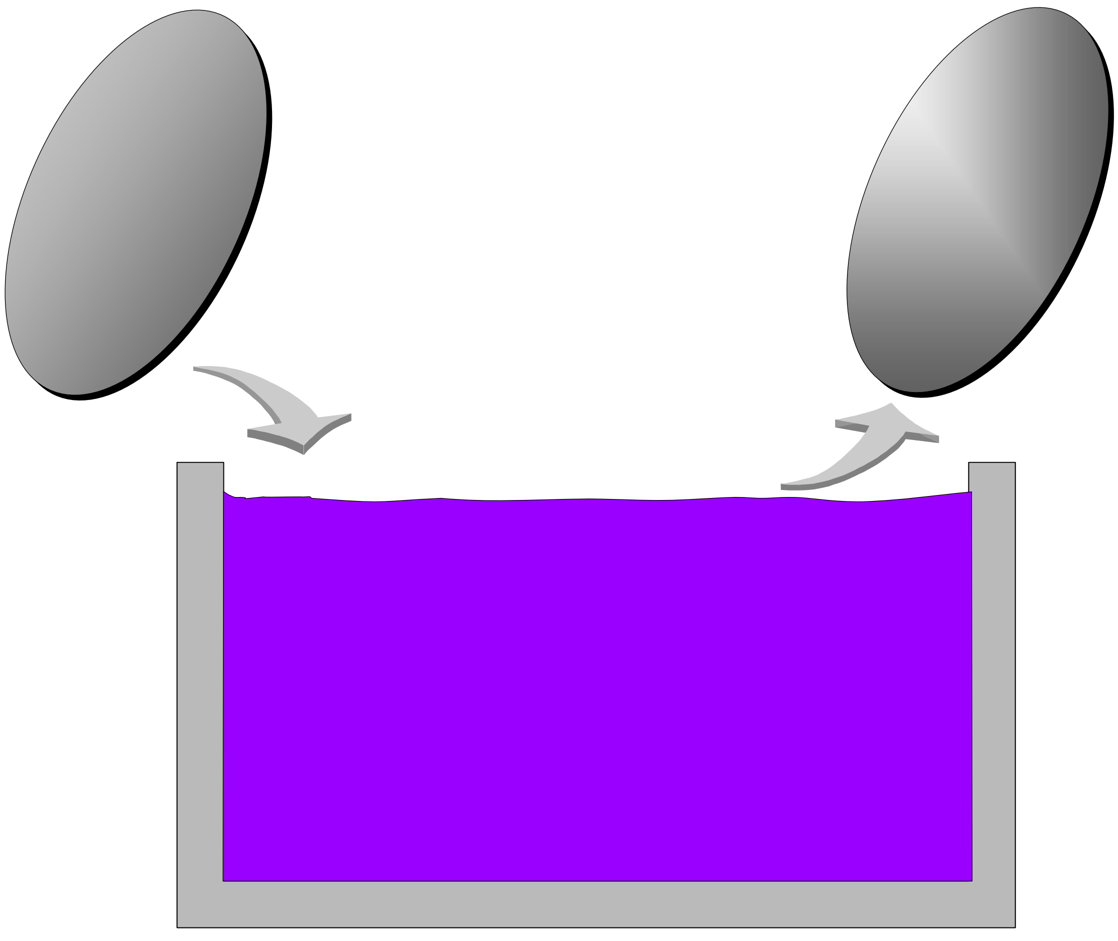
	Year (Critical Dimension)			
	1995 (0.35 μm)	**1998 (0.25 μm)**	**2000 (0.18 μm)**	**2004 (0.13 μm)**
Wafer diameter (mm)	200	200	300	300
Site flatness[A] (μm) Site size (mm x mm)	0.23 (22 x 22)	0.17 (26 x 32)	0.12 26 x 32	0.08 26 x 36
Microroughness[B] of front surface (RMS)[C] (nm)	0.2	0.15	0.1	0.1
Oxygen content (ppm)[D]	≤ 24 ± 2	≤ 23 ± 2	≤ 23 ± 1.5	≤ 22 ± 1.5
Bulk microdefects[E] (defects/cm^2)	≤ 5000	≤ 1000	≤ 500	≤ 100
Particles per unit area (#/cm^2)	0.17	0.13	0.075	0.055
Epilayer[F] thickness (± % uniformity) (μm)	3.0 (± 5%)	2.0 (± 3%)	1.4 (± 2%)	1.0 (± 2%)

Adapted from K. M. Kim, "Bigger and Better CZ Silicon Crystals," *Solid State Technology* (November 1996), p. 71.

Polished Wafer Edge



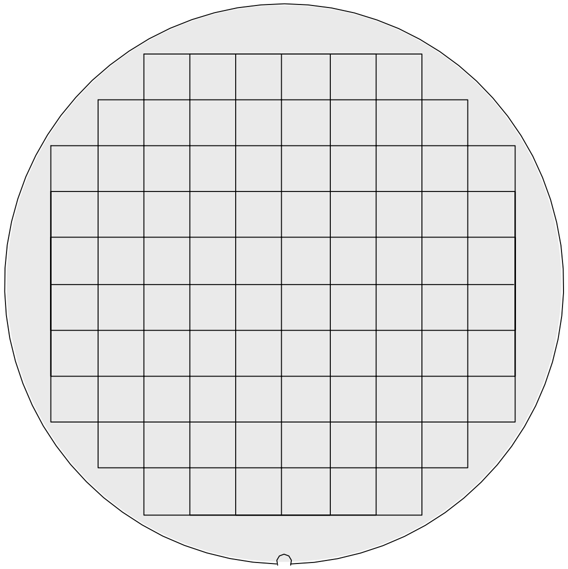
Chemical Etch of Wafer Surface to Remove Sawing Damage



Wafer Dimensions & Attributes

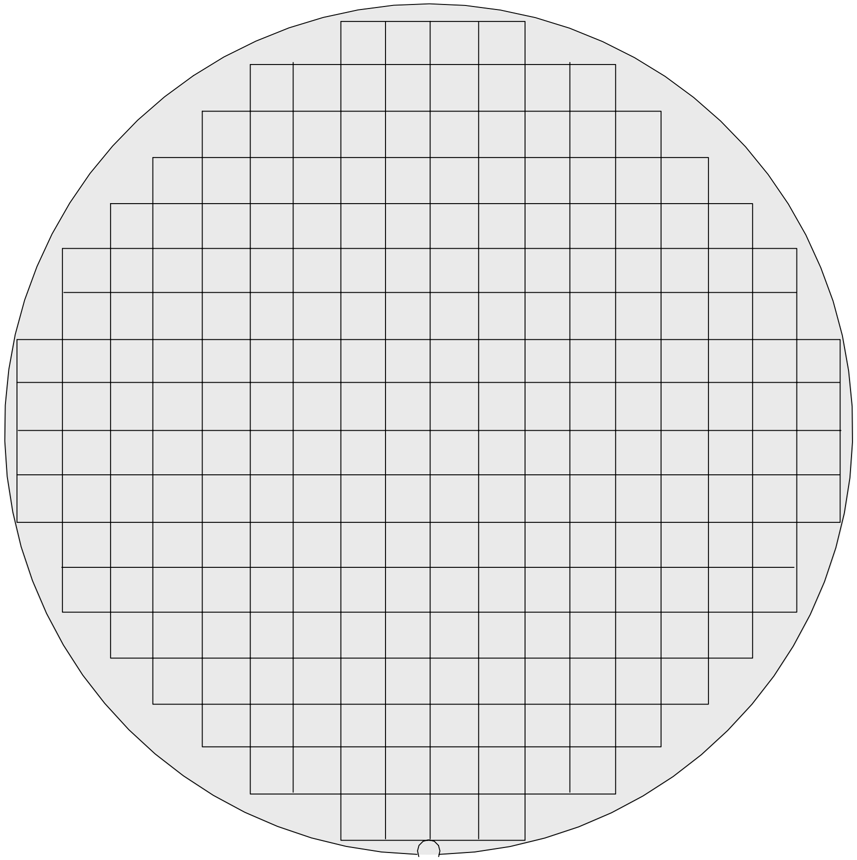
Diameter (mm)	Thickness (μm)	Area (cm^2)	Weight (grams/lbs)	Weight/25 Wafers (lbs)
150	675 ± 20	176.71	28 / 0.06	**1.5**
200	725 ± 20	314.16	53.08 / 0.12	**3**
300	775 ± 20	706.86	127.64 / 0.28	**7**
400	825 ± 20	1256.64	241.56 / 0.53	**13**

Increase in Number of Chips on Larger Wafer Diameters (Assume large 1.5 x 1.5 cm microprocessors)



88 die

200-mm wafer



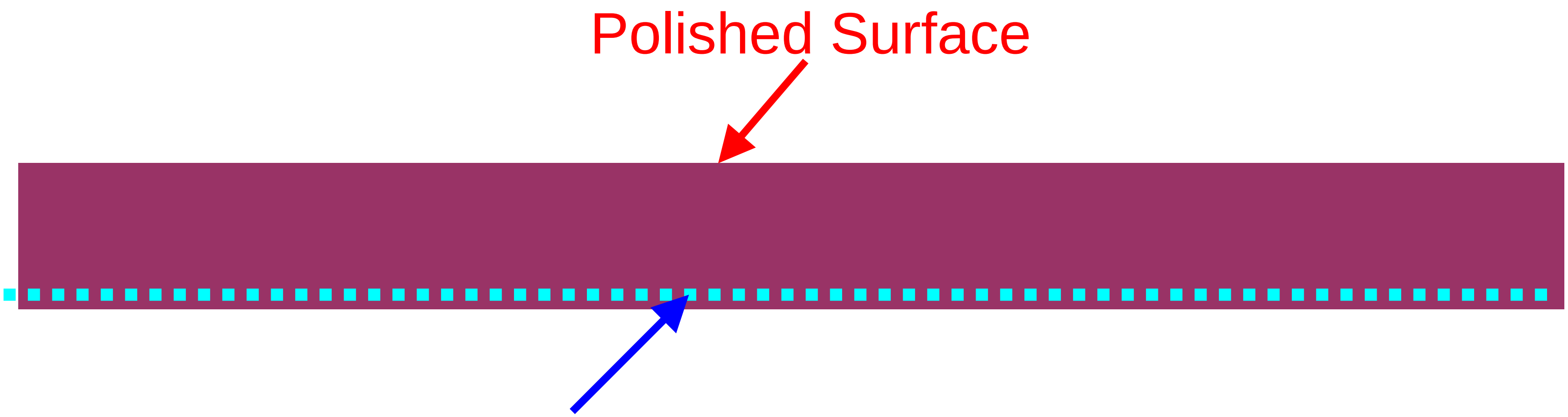
232 die

300-mm wafer

Quality Measures

- Physical dimensions
- Flatness
- Microroughness
- Oxygen content
- Crystal defects
- Particles
- Bulk resistivity

“Backside Gettering” to Purify Silicon



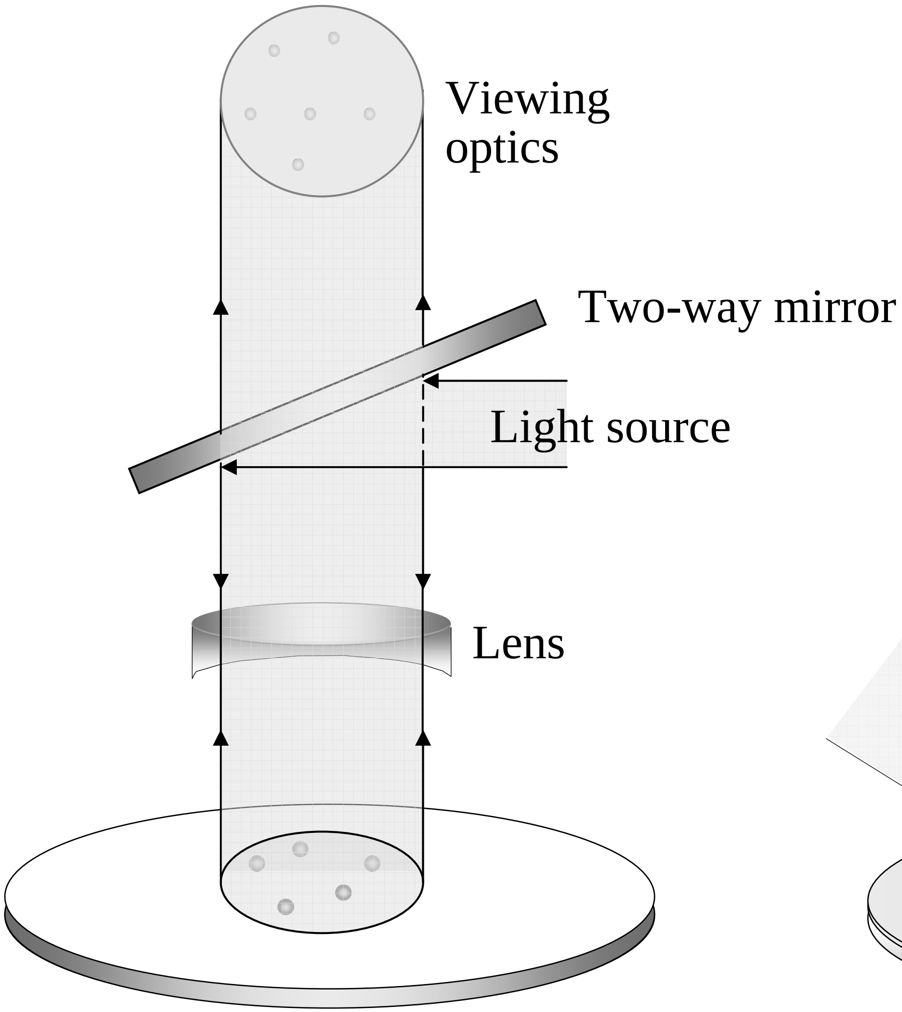
Backside Implant: Ar (50 keV, $10^{15}/cm^2$)

The argon amorphizes the back side of the silicon. The wafer is heated to 550°C, which regrows the silicon. However, the argon can not be absorbed by the silicon crystal so it precipitates into micro-bubbles and prevents some damage from annealing. The wafer is held at 550°C for several hours, and all mobile metal contaminants are attracted to and then captured by the argon stabilized damage. Once captured, they never leave these sites.

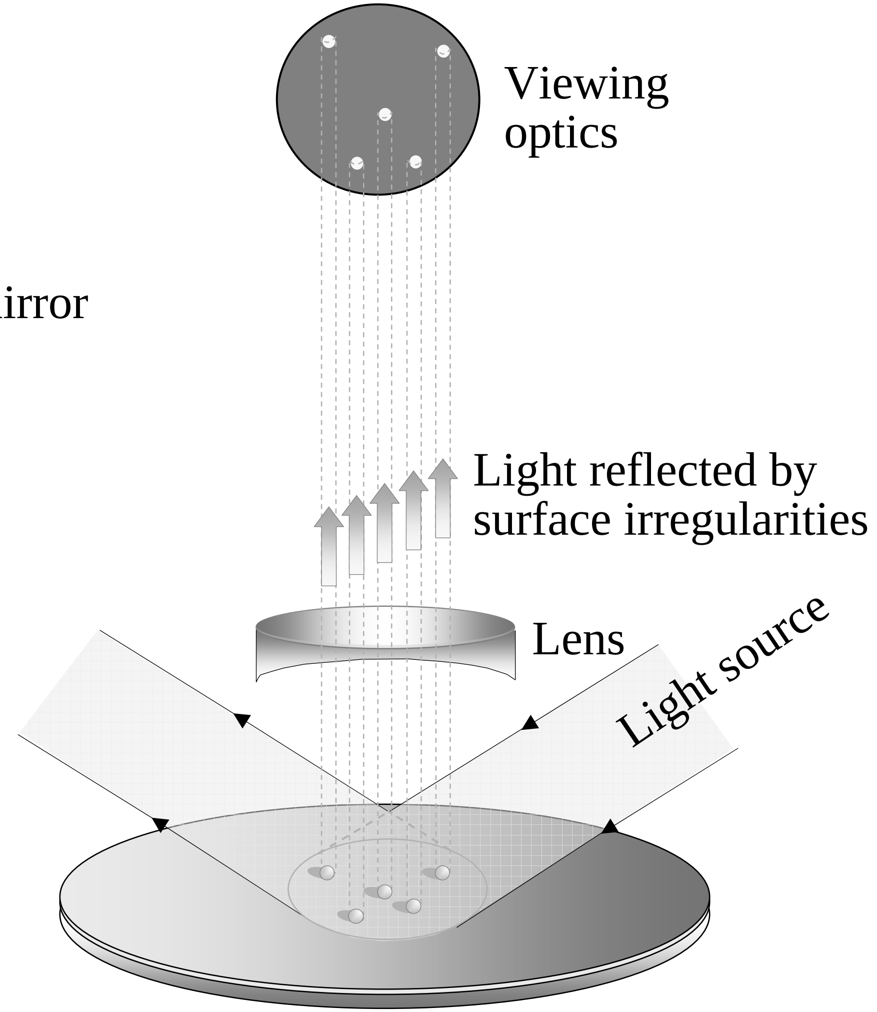
Measurement of Wafer Characteristics

Darkfield and Brightfield Detection

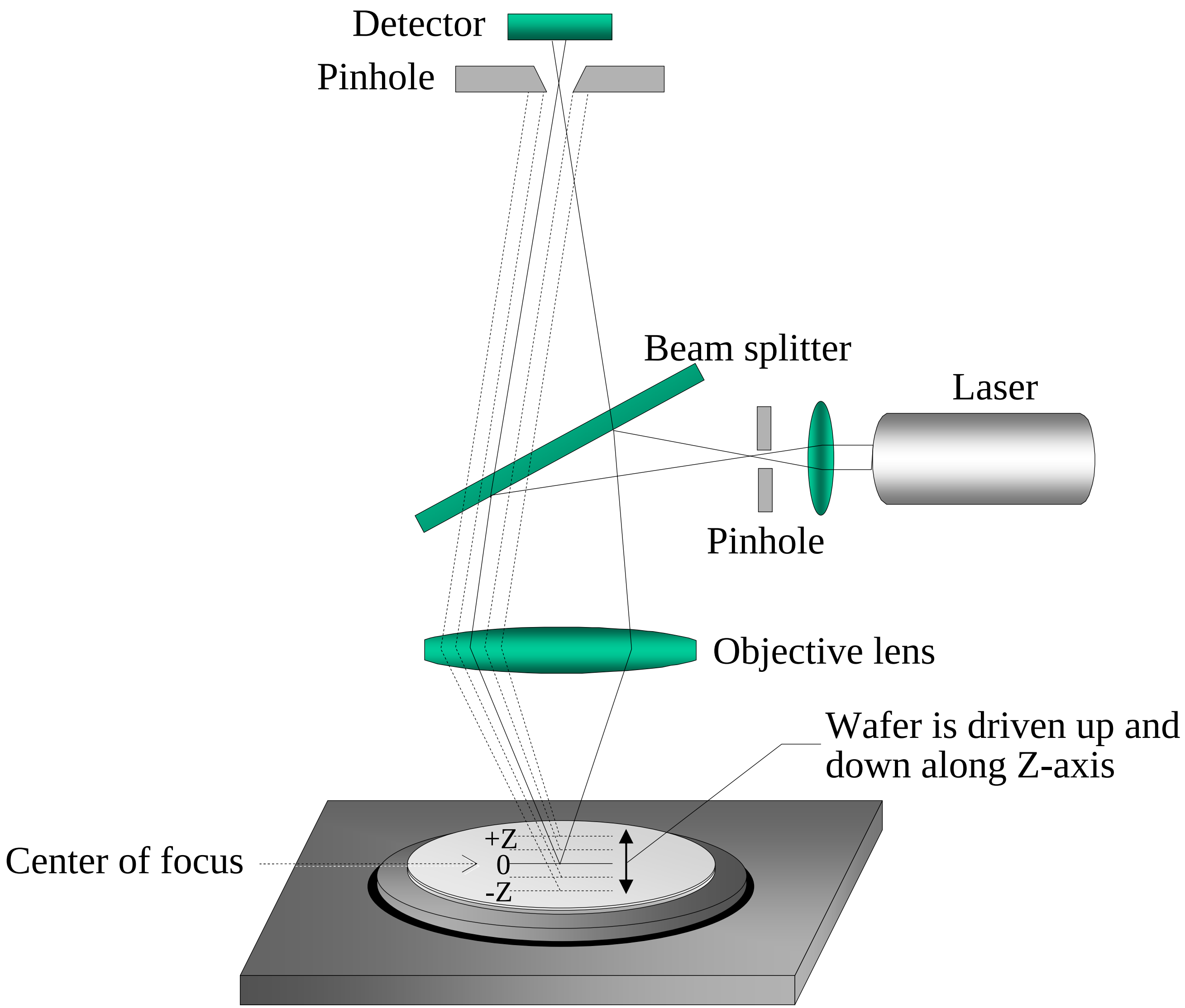
Brightfield imaging



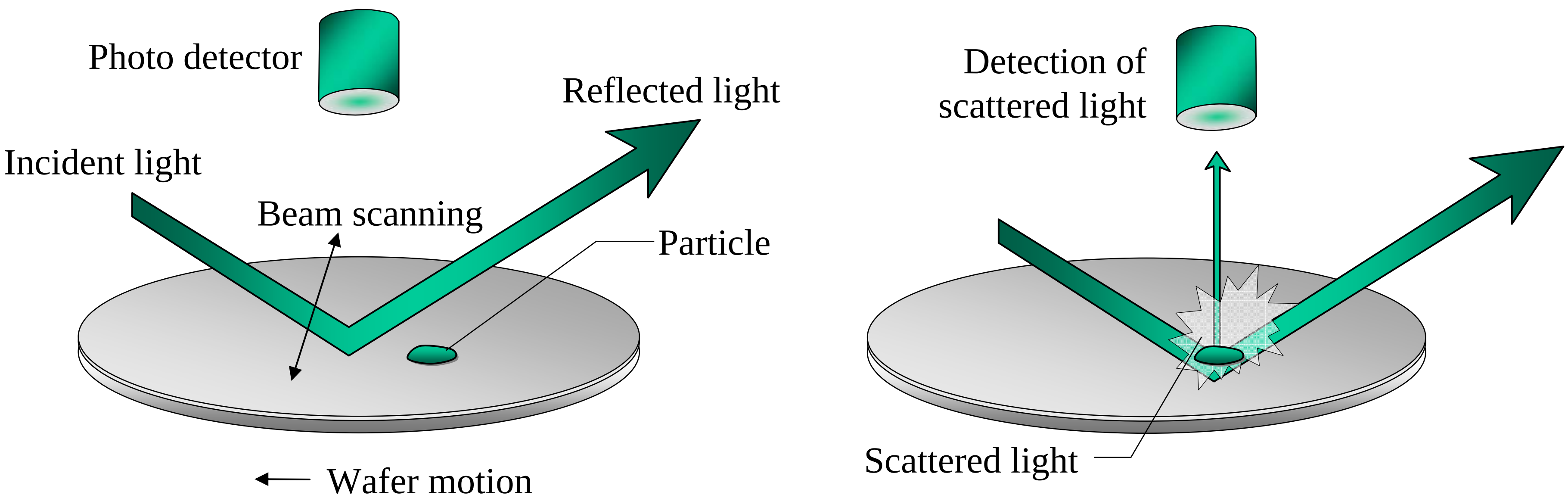
Darkfield imaging



Principle of Confocal Microscopy

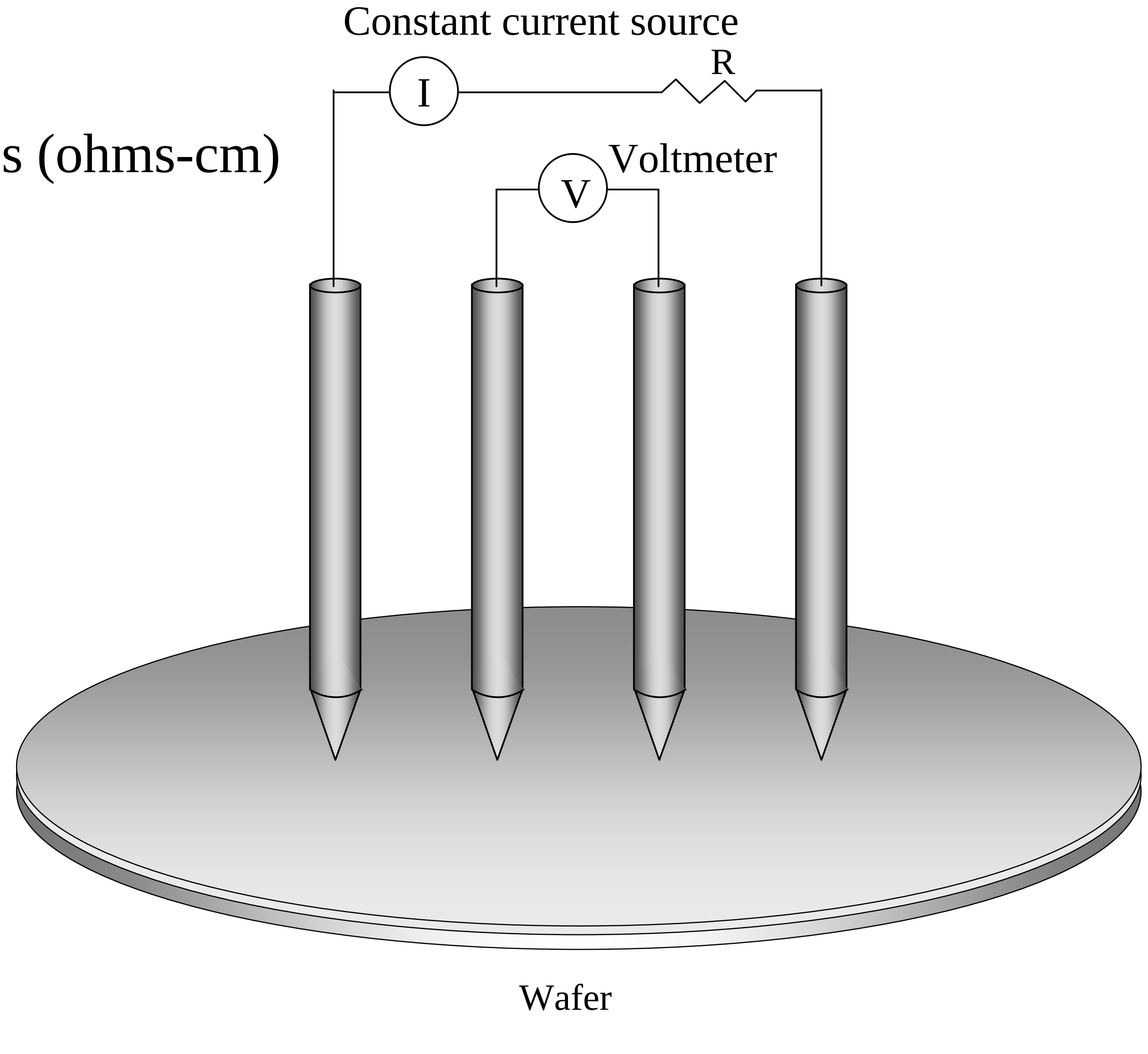


Particle Detection by Light Scattering

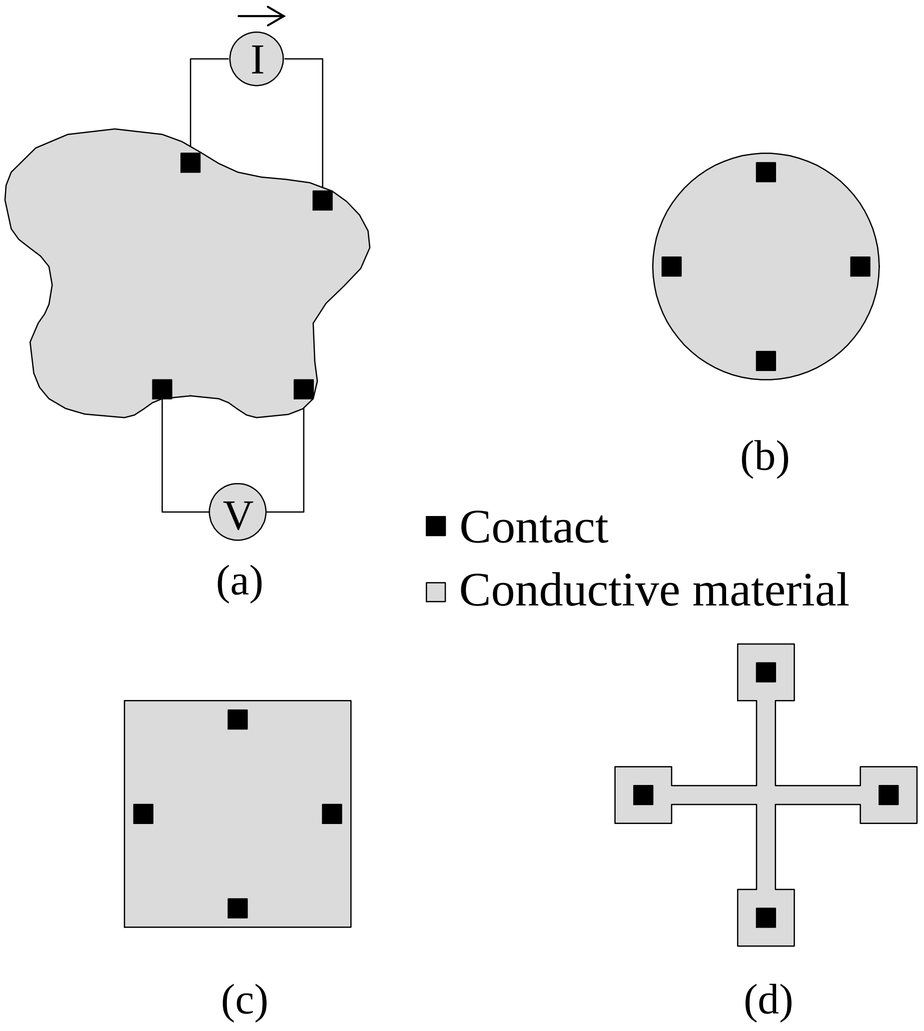


Four Point Probe

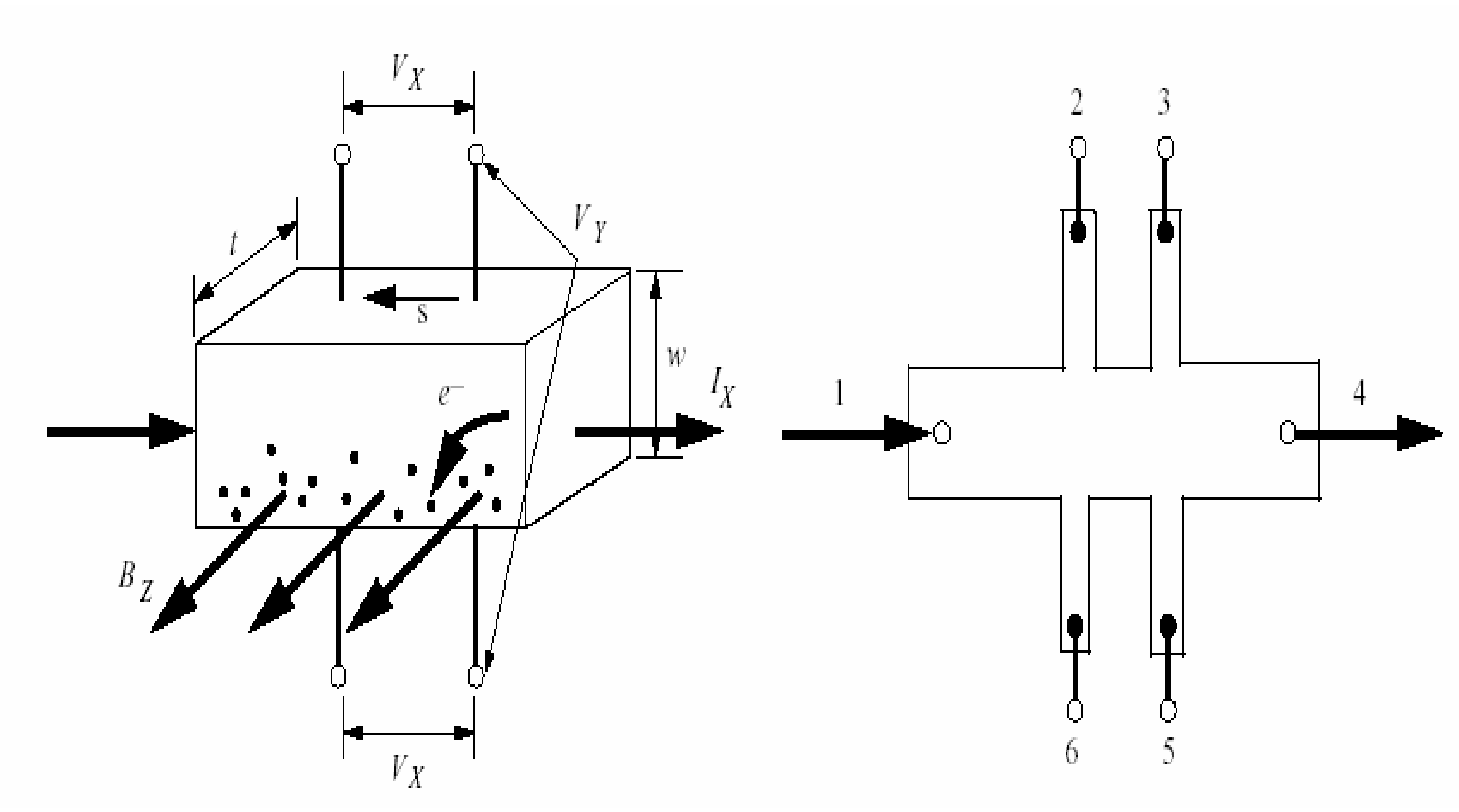
$$\rho_s = \frac{V}{I} \times 2\pi s \text{ (ohms-cm)}$$



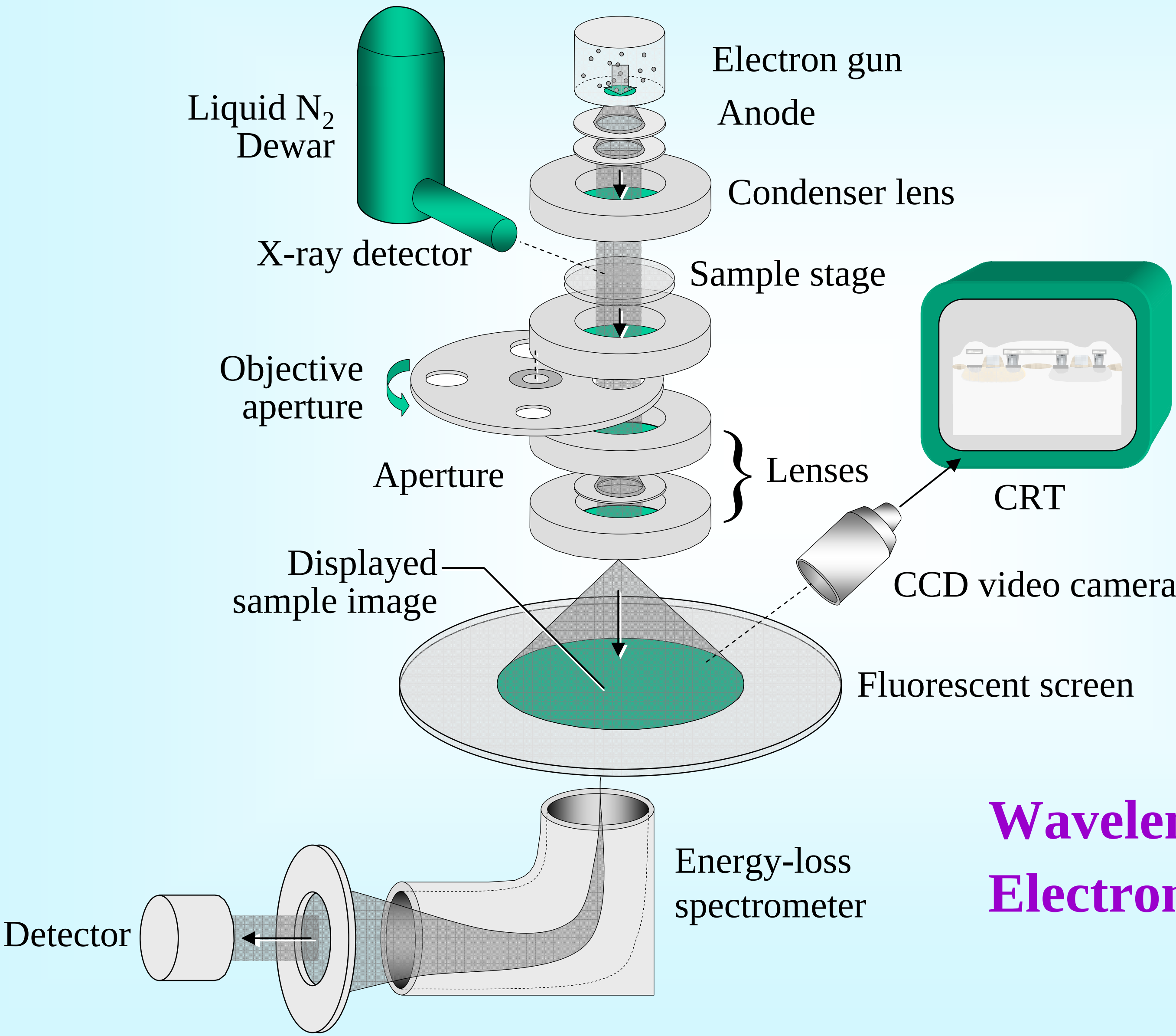
"Van der Pauw" Sheet Resistivity
(similar to 4-point probe, but uses shapes on wafer)



Conceptual representation of Hall effect measurement. The right sketch is a top view of a more practical implementation.

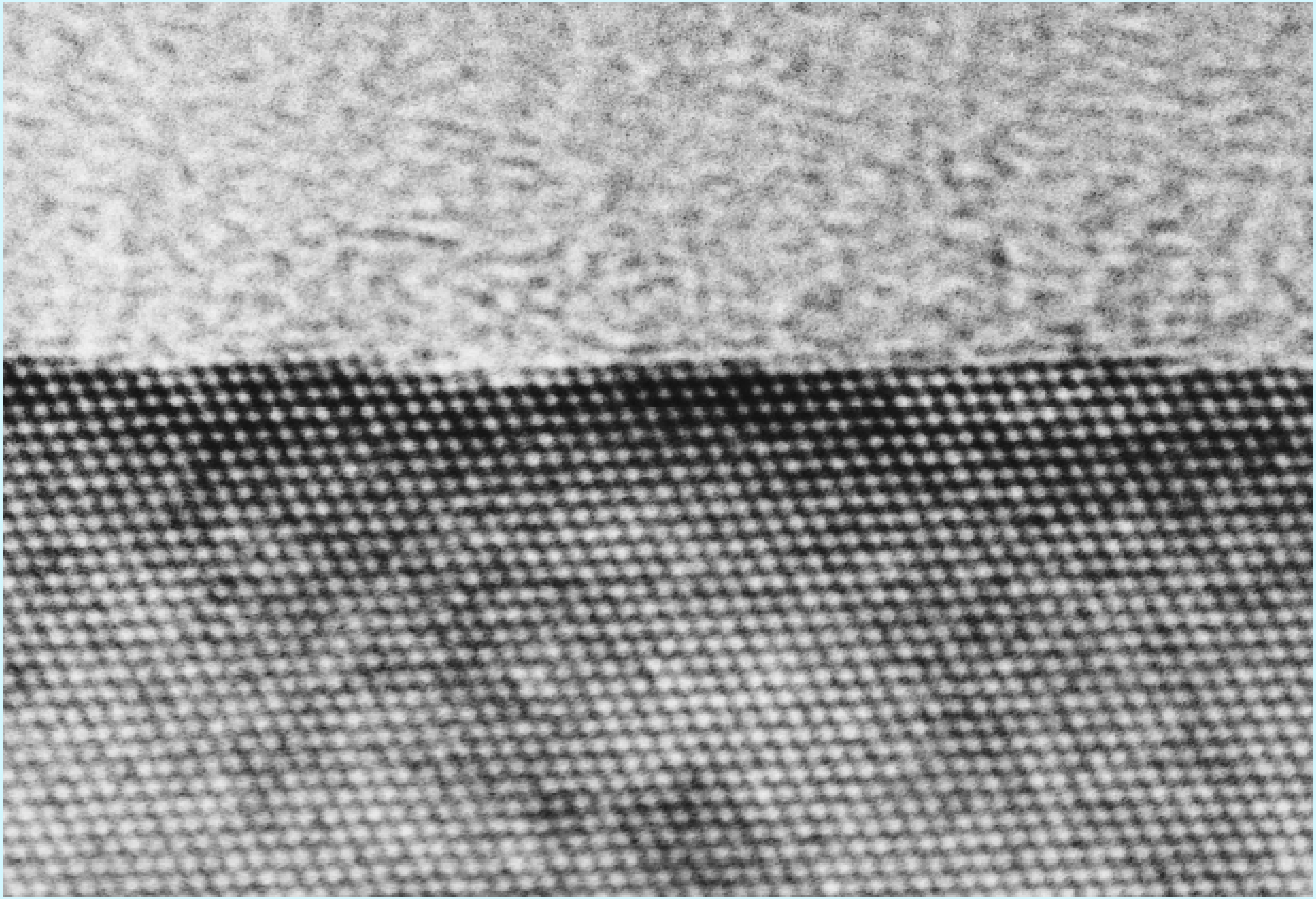


Schematic of "TEM"
Transmission Electron Microscope



Wavelength of 1 MeV Electron ~ 1Angstrom

Electron Microscopy (TEM) of SiO_2 on Si



Oxygen Contamination in Silicon

Oxygen is the most important impurity found in silicon. It is incorporated in silicon during the CZ growth process as a result of dissolution of the quartz crucible in which the molten silicon is contained. The oxygen is typically at a level of about 10^{18} /cm^3. It has recently become possible to use a magnetic field during CZ growth to control thermal convection currents in the melt. This slows down the transport of oxygen from the crucible walls to the growing silicon interface and reduces the oxygen concentration in the resulting crystal.

Oxygen in silicon is always present at concentrations of ~10-20 ppm ($5x10^{17}$- 10^{18}/cm^3) in CZ silicon. The oxygen can affect processes used in wafer fabrication such as impurity diffusion.

Oxygen has three principal effects in the silicon crystal.

(1) In an as-grown crystal, the oxygen is believed to be incorporated primarily as dispersed single atoms designated O_I occupying interstitial positions in the silicon lattice, but covalently bonded to two silicon atoms. The oxygen atoms thus replace one of the normal Si-Si covalent bonds with a Si-O-Si structure. **The oxygen atom is neutral in this configuration** and can be detected with the FTIR method. Such interstitial oxygen atoms improve the yield strength of silicon by as much as 25%, making silicon wafers more robust in a manufacturing facility.

(2) The **formation of oxygen donors**. A small amount of the oxygen in the crystal forms SiO_4 complexes which act as donors. They can be detected by changes in the silicon resistivity corresponding to the free electrons donated by the oxygen complexes. As many as 10^{16}/cm^3 donors can be formed, which is sufficient to significantly increase the resistivity of lightly doped P-type wafers. During the CZ growth process, the crystal cools slowly through ~500^{o}C temperature and oxygen donors form. The SiO_4 complexes are unstable at temperatures above 500°C and so usually wafer manufacturers anneal the grown crystal or the wafers themselves after sawing and polishing, to remove the oxygen complexes. These donors can reform, however, during normal IC manufacturing, if a thermal step around 400-500°C is used. Such steps are not uncommon, particularly at the end of a process flow.

(3) The tendency of the oxygen to precipitate under normal device processing conditions, forming **SiO_2 regions** inside the wafer. The precipitation arises because the oxygen was incorporated at the melt temperature and is therefore supersaturated in the silicon at process temperatures.

Carbon Contamination in Silicon

Carbon is normally present in CZ grown silicon crystals at concentrations on the order of $10^{16}/cm^3$.The carbon comes from the graphite components in the crystal pulling machine. The melt contains silicon and modest concentrations of oxygen. This results in the formation of SiO that evaporates from the melt surface. Generally, the ambient in the crystal puller is Ar flowing at reduced pressure, and the SiO can be transported in the gas phase to the graphite crucible and other support fixtures. SiO reacts with graphite (carbon) to produce CO that again transports through the gas phase back to the melt. From the melt, the carbon is incorporated into the growing crystal.

Four Effects of Carbon on Silicon

(1) Carbon is mostly substitutional in the silicon lattice. Since it is a column IV element, it does not act as a donor or acceptor in silicon. Carbon is known to affect the precipitation kinetics of oxygen in silicon. This is likely because there is a volume expansion when oxygen precipitates and a volume contraction when carbon precipitates because of the relative sizes of O and C. There is thus a tendency for precipitates that are complexes of C and O to form at minimum stresses in the crystal. Since precipitated SiO_2 is crucial in intrinsic gettering, this can have an effect on gettering efficiency.

(2) Carbon is also known to interact with point defects in silicon. Silicon interstitials tend to displace carbon atoms from lattice sites, presumably because this can help to compensate the volume contraction present when there is carbon in the crystal.

(3) Thermal donors (Oxygen Effects) normally form around 450°C. There is also evidence that if C is present at ~1 ppm, these donors may also form at higher temperatures (650-1000°C).

(4) Higher concentrations of C to Si (levels of a few percent) can change the bandgap of the silicon and may allow the fabrication of new types of semiconductor devices in the future.

Chapter Review (Wafer Fabrication)

- **Raw materials (SiO_2) are refined to produce electronic grade silicon with a purity unmatched by any other available material on earth.**
- **CZ crystal growth produces structurally perfect Si single crystals which are cut into wafers and polished.**
- **Starting wafers contain only dopants, and trace amounts of contaminants O and C in measurable quantities.**
- **Dopants can be incorporated during crystal growth**
- **Point, line, and volume (1D, 2D, and 3D) defects can be present in crystals, particularly after high temperature processing.**
- **Point defects are "fundamental" and their concentration depends on temperature (exponentially), on doping level and on other processes like ion implantation which can create non-equilibrium transient concentrations of these defects.**