Chapter 8
Ion Implantation

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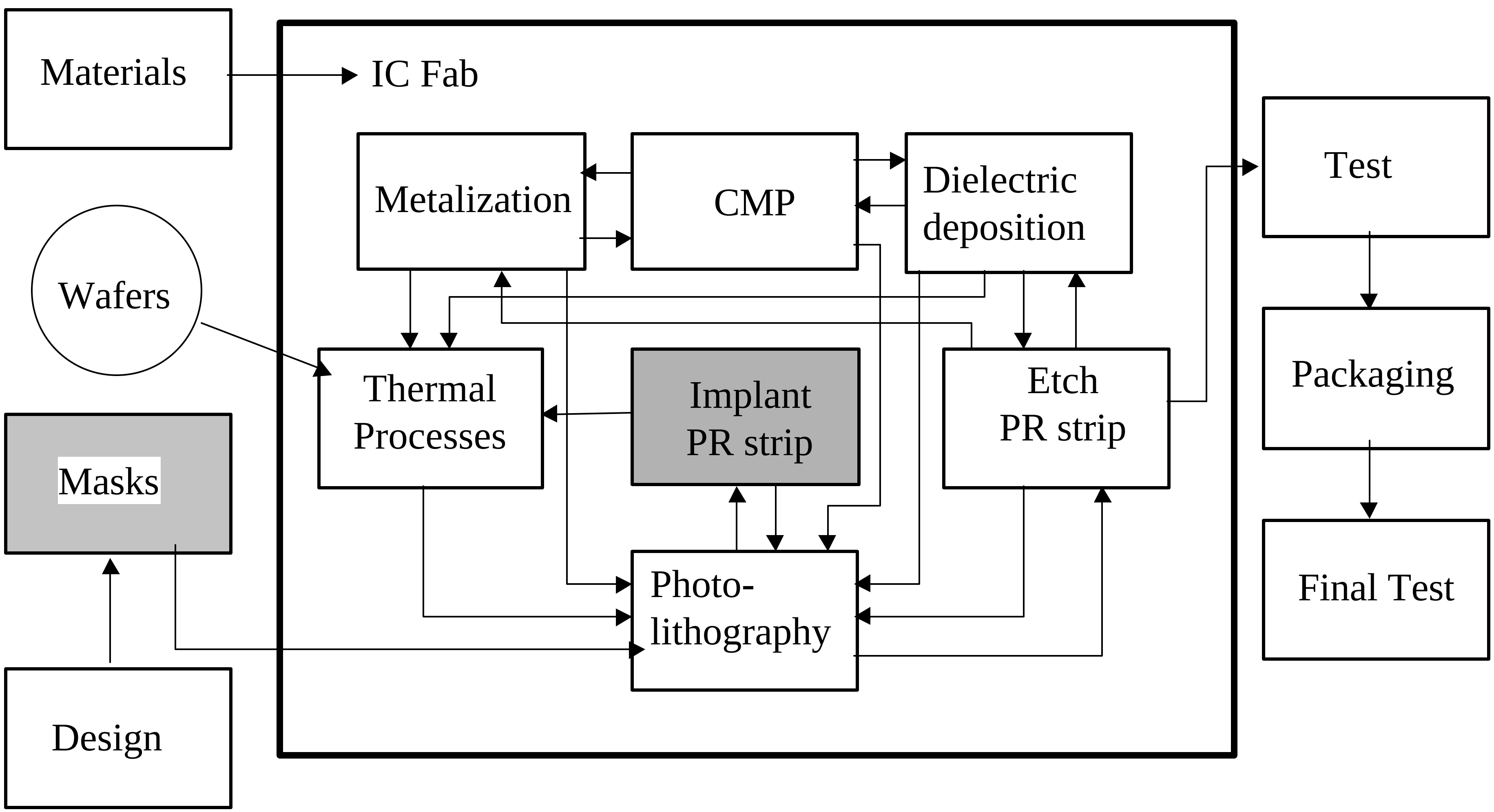
Objectives

- List at least three commonly used dopants
- Identify three doped areas
- Describe the advantages of ion implantation
- Describe major components of an implanter
- Explain the channeling effect
- Relationship of ion range and ion energy
- Explain the post-implantation annealing
- Identify safety hazards

Ion Implantation

- Introduction
- Safety
- Hardware
- Processes
- Summary

Wafer Process Flow



Introduction: Dope Semiconductor

- What is Semiconductor?
- Why semiconductor need to be doped?
- What is n-type dopant?
- What is p-type dopant?

Introduction

- Dope semiconductor
- Two way to dope
  - Diffusion
  - Ion implantation
- Other application of ion implantation

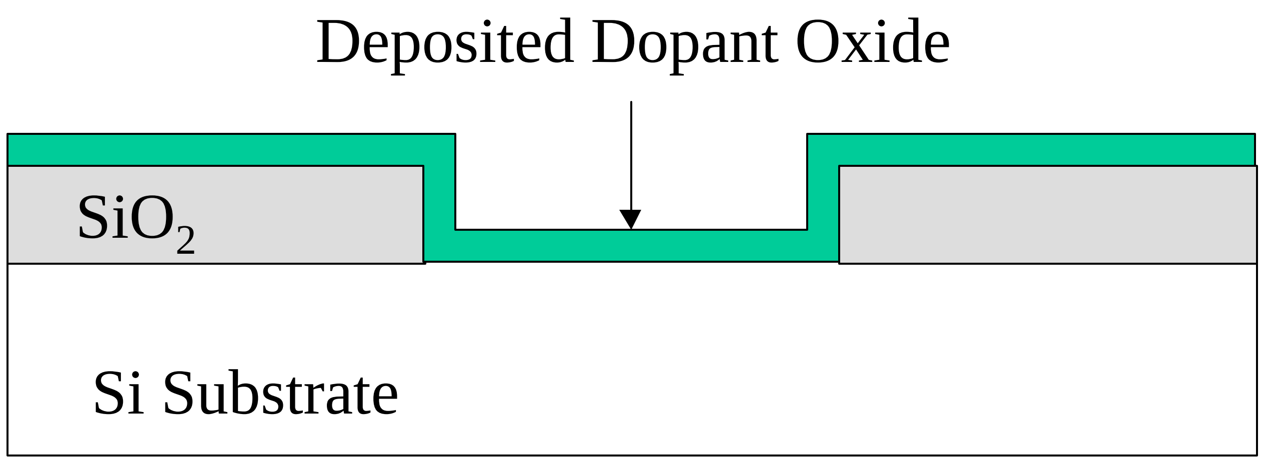
Dope Semiconductor: Diffusion

- Isotropic process
- Can't independently control dopant profile and dopant concentration
- Replaced by ion implantation after its introduction in mid-1970s.

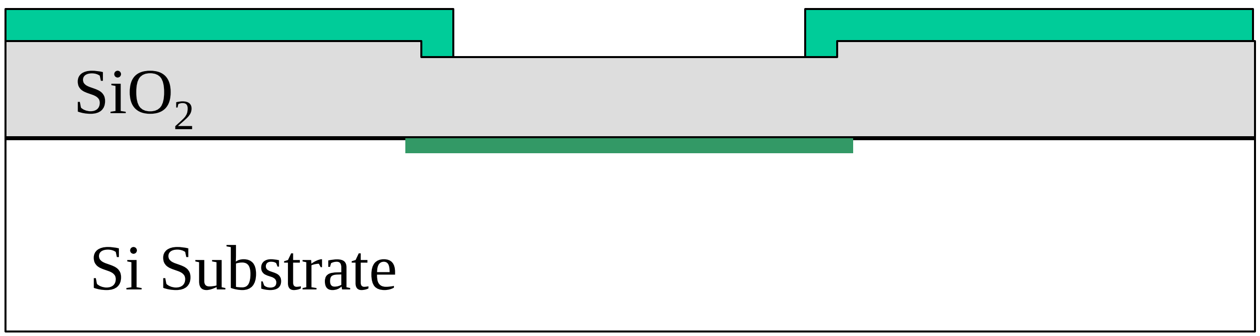
Dope Semiconductor: Diffusion

- First used to dope semiconductor
- Performed in high temperature furnace
- Using silicon dioxide mask
- Still used for dopant drive-in
- R&D on ultra shallow junction formation.

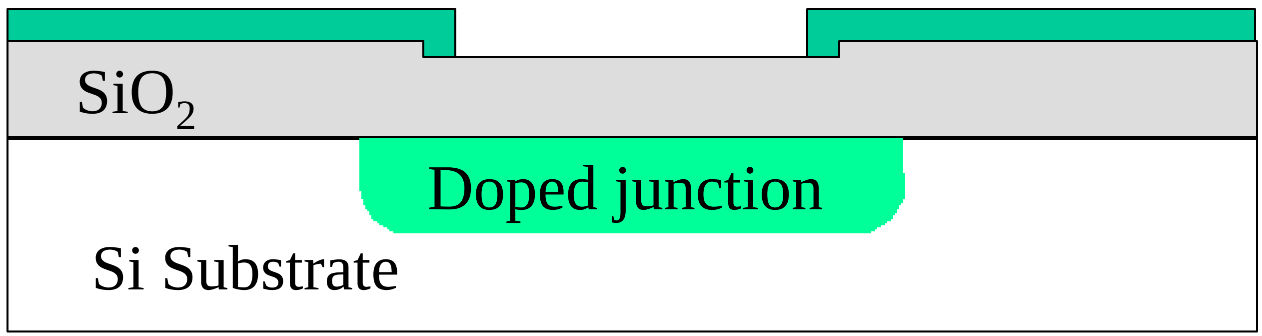
Dopant Oxide Deposition



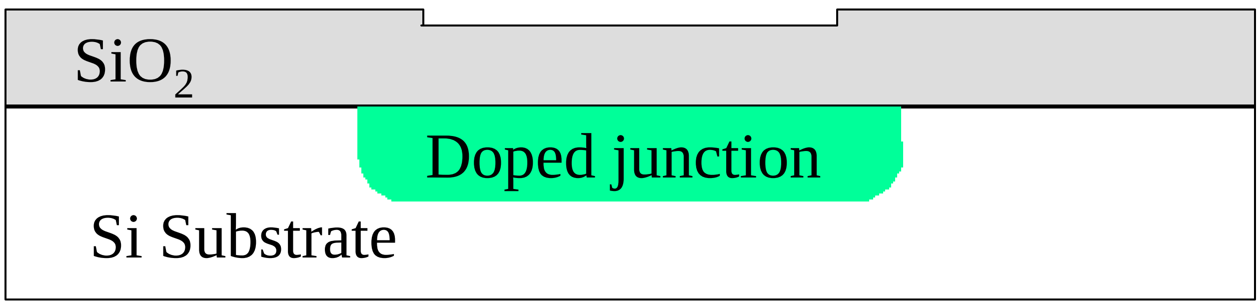
Oxidation



Drive-in



Strip and Clean



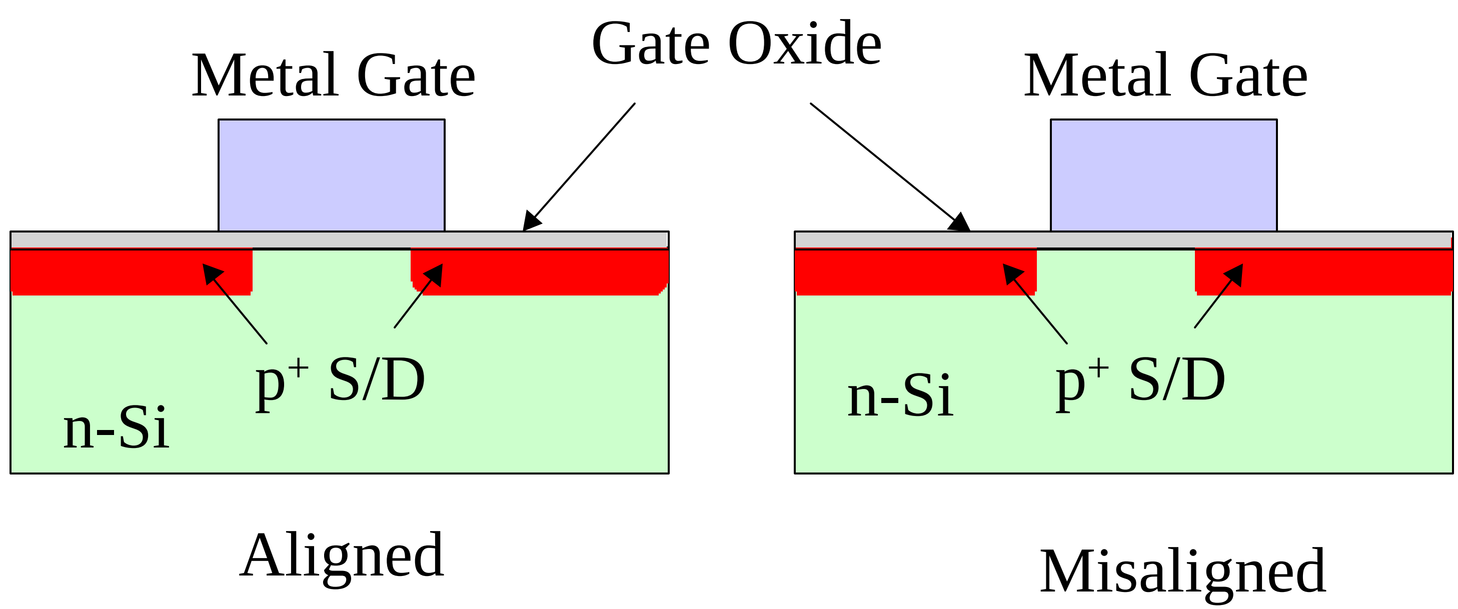
Dope Semiconductor: Ion Implantation

- Used for atomic and nuclear research
- Early idea introduced in 1950’s
- Introduced to semiconductor manufacturing in mid-1970s.

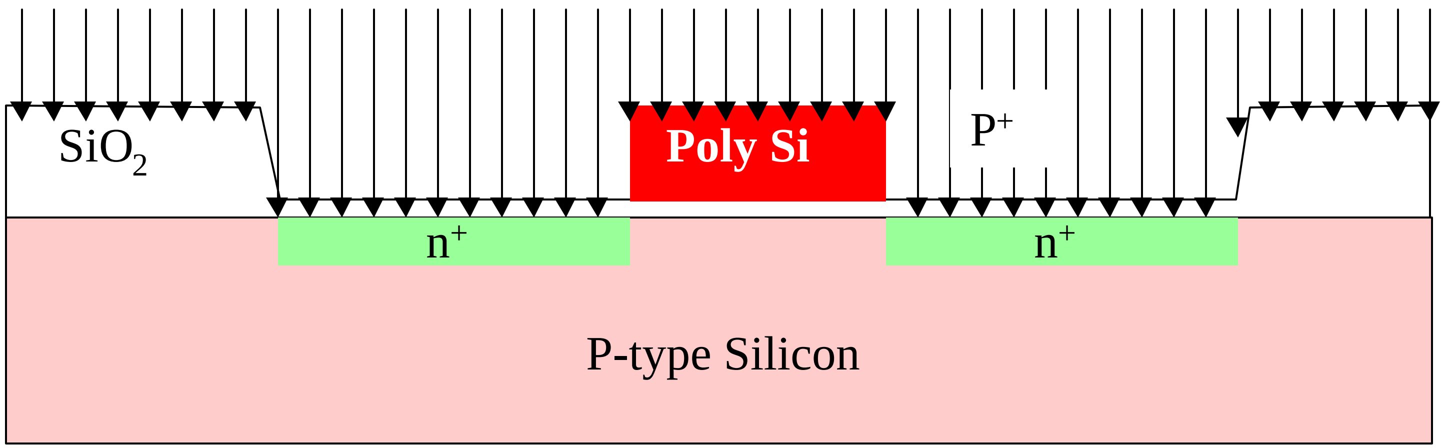
Dope Semiconductor: Ion Implantation

- Independently control dopant profile (ion energy) and dopant concentration (ion current times implantation time)
- Anisotropic dopant profile
- Easy to achieve high concentration dope of heavy dopant atom such as phosphorus and arsenic.

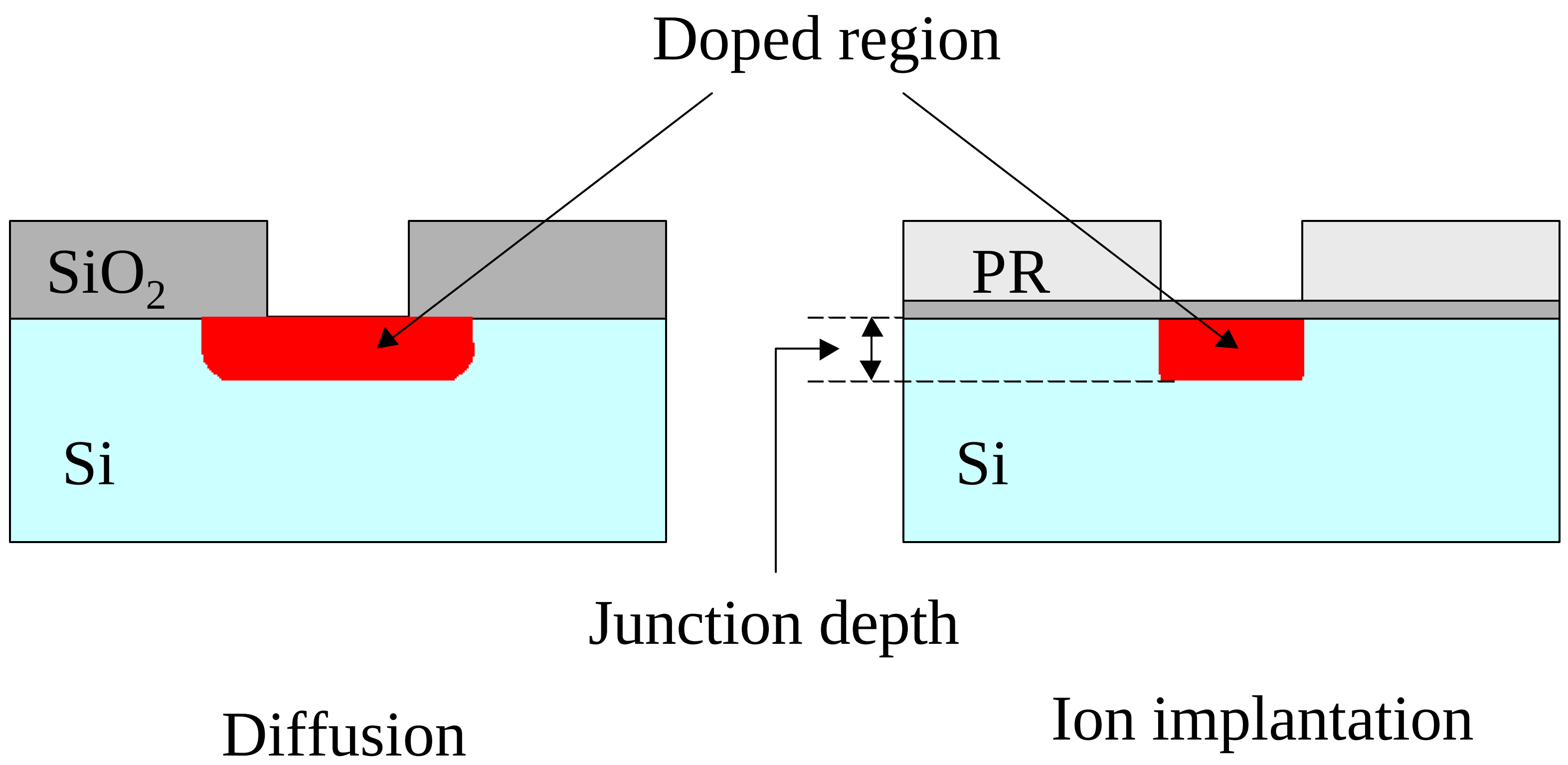
Misalignment of the Gate



Ion Implantation, Phosphorus



Comparison of Implantation and Diffusion



Comparison of Implantation and Diffusion

Diffusion	**Ion Implantation**
High temperature, hard mask	Low temperature, photoresist mask
Isotropic dopant profile	Anisotropic dopant profile
Cannot independently control of the dopant concentration and junction depth	Can independently control of the dopant concentration and junction depth
Batch process	Both Batch and single wafer process

Ion Implantation Control

- Beam current and implantation time control dopant concentration
- Ion energy controls junction depth
- Dopant profile is anisotropic

Applications of Ion Implantation

Applications	Doping	Pre-amorphous	Buried oxide	Poly barrier
Ions	n-type: P, As, Sb p-type: B	Si or Ge	O	N

Other Applications

- Oxygen implantation for silicon-on-insulator (SOI) device
- Pre-amorphous silicon implantation on titanium film for better annealing
- Pre-amorphous germanium implantation on silicon substrate for profile control
- ……..

Some Fact about Phosphorus

Name	Phosphorus
Symbol	P
Atomic number	15
Atomic weight	30.973762
Discoverer	Hennig Brand
Discovered at	Germany
Discovery date	1669
Origin of name	From the Greek word "phosphoros" meaning "bringer of light" (an ancient name for the planet Venus)
Density of solid	1.823 g/cm^3
Molar volume	17.02 cm^3
Velocity of sound	N/A
Electrical resistivity Refractivity	10 $\mu\Omega$ cm 1.001212
Reflectivity	N/A
Melting point	44.3 C
Boiling point	277 C
Thermal conductivity	0.236 $W\ m^{-1}\ K^{-1}$
Coefficient of linear thermal expansion	N/A
Applications	N-type dopant in diffusion, ion implantation, epitaxial grow and polysilicon deposition. Dopant of CVD silicate glass (PSG and BPSG).
Main sources	P (red), PH_3, $POCl_3$

Some Fact about Arsenic

Name	Arsenic
Symbol	As
Atomic number	33
Atomic weight	74.9216
Discoverer	Known since ancient times
Discovered at	not known
Discovery date	not known
Origin of name	From the Greek word "arsenikon" meaning "yellow orpiment"
Density of solid Molar volume	5.727 g/cm^3 12.95 cm^3
Velocity of sound	N/A
Electrical resistivity	30.03 μΩ cm
Refractivity	1.001552
Reflectivity	N/A
Melting point	614 C
Boiling point	817 C
Thermal conductivity	50.2 $W\ m^{-1}\ K^{-1}$
Coefficient of linear thermal expansion	N/A
Applications	N-type dopant in diffusion, ion implantation, epitaxial grow and polysilicon deposition.
Main sources	As, AsH_3

Some Fact about Boron

Name	Boron
Symbol	B
Atomic number	5
Atomic weight	10.811
Discoverer	Sir Humphrey Davy, Joseph-Louis Gay-Lussac,
Discovered at	England, France
Discovery date	1808
Origin of name	From the Arabic word "buraq" and the Persian word "burah"
Density of solid	2.460 g/cm^3
Molar volume	4.39 cm^3
Velocity of sound	16200 m/sec
Electrical resistivity	$> 10^{12}$ $\mu\Omega$ cm
Refractivity	N/A
Reflectivity	N/A
Melting point	2076 C
Boiling point	3927 C
Thermal conductivity	27 W m^{-1} K^{-1}
Coefficient of linear thermal expansion	6 10^{-6} K^{-1}
Applications	P-type dopant in diffusion, ion implantation, epitaxial grow and polysilicon deposition. Dopant of CVD silicate glass (BPSG)
Main sources	B, B_2H_6, BF_3

Stopping Mechanism

- Ions penetrate into substrate
- Collide with lattice atoms
- Gradually lose their energy and stop
- Two stop mechanisms

Two Stopping Mechanism

- Nuclear stopping
  - Collision with nuclei of the lattice atoms
  - Scattered significantly
  - Causes crystal structure damage.
- electronic stopping
  - Collision with electrons of the lattice atoms
  - Incident ion path is almost unchanged
  - Energy transfer is very small
  - Crystal structure damage is negligible

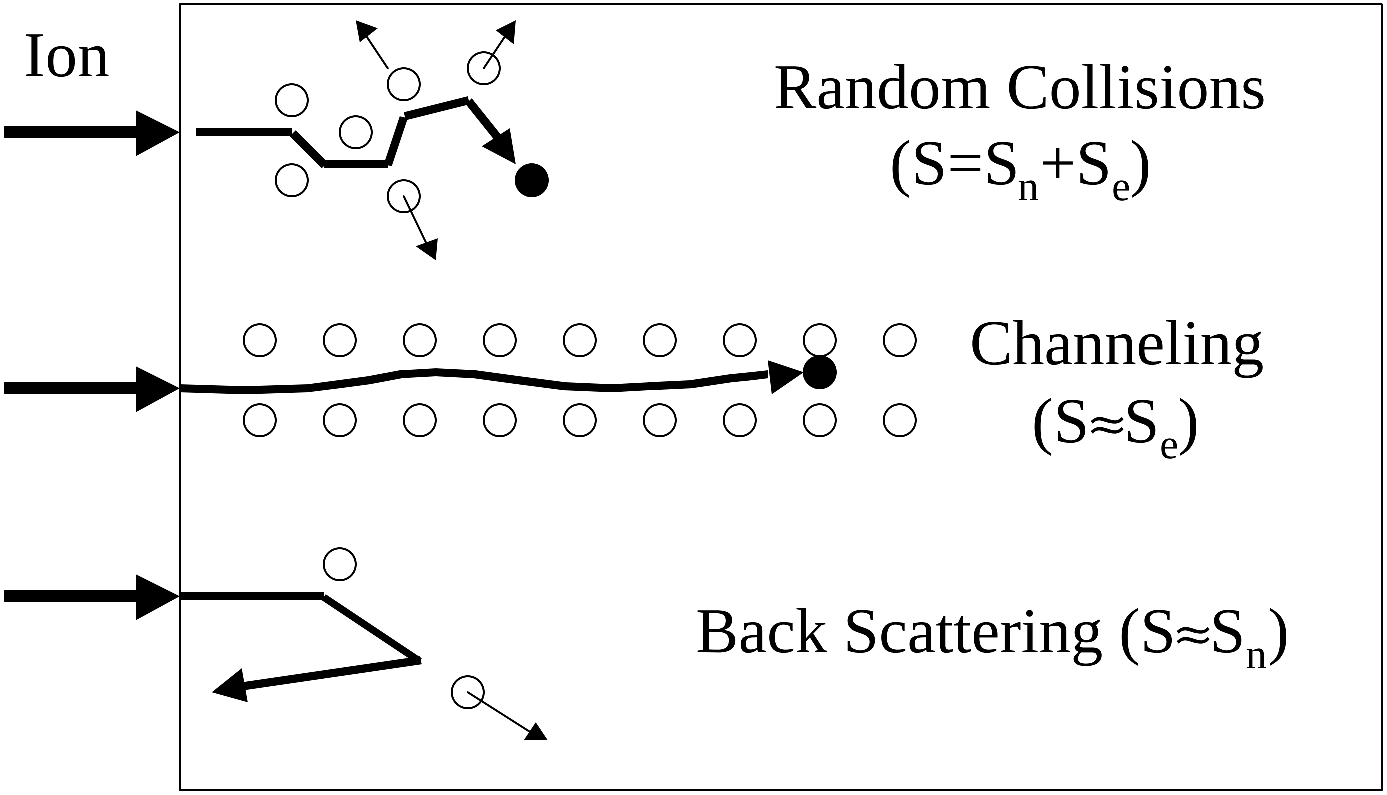
Stopping Mechanism

- The total stopping power

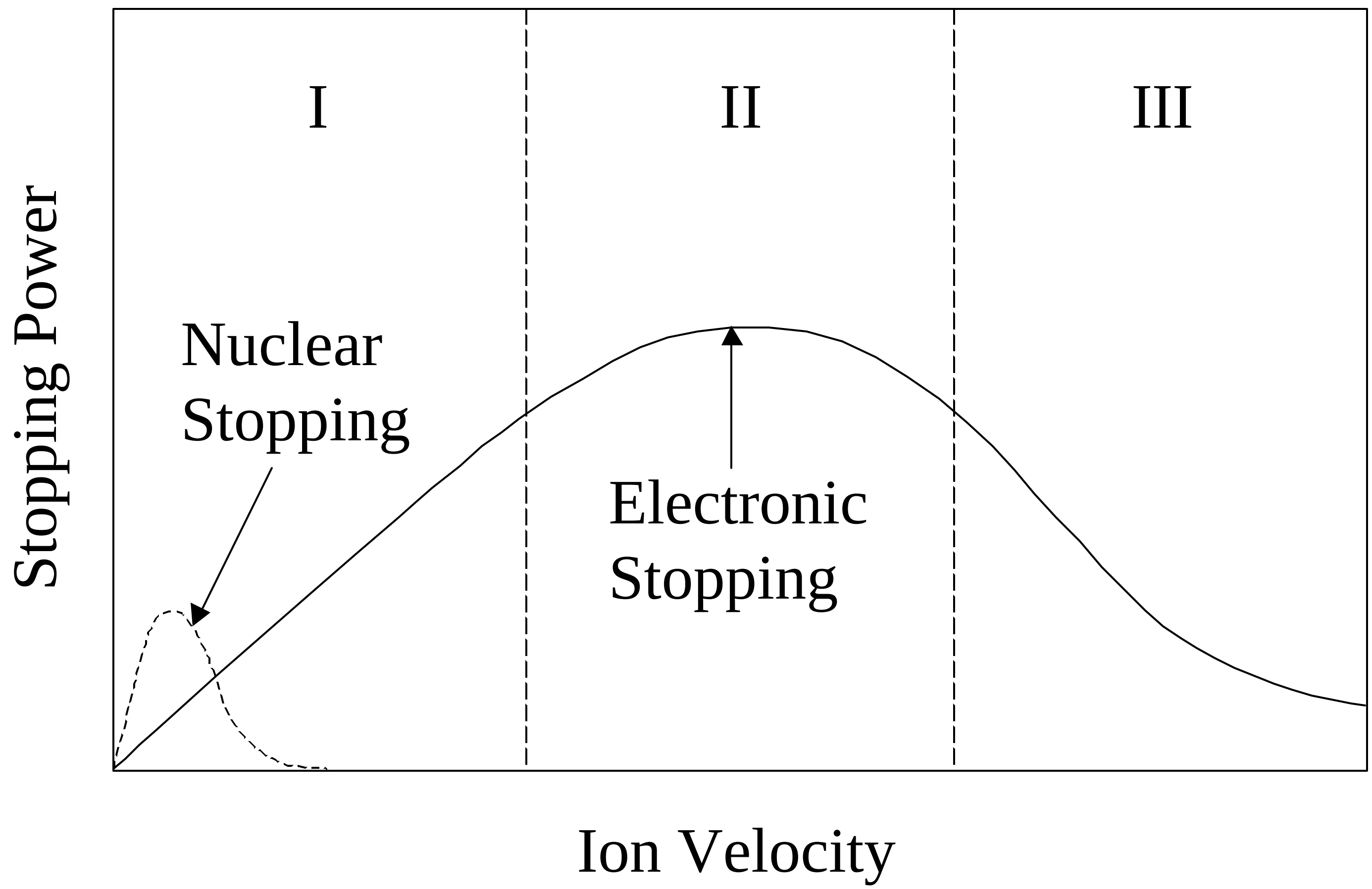
$$S_{total} = S_n + S_e$$

- S_n: nuclear stopping, S_e: electronic stopping
- Low E, high A ion implantation: mainly nuclear stopping
- High E, low A ion implantation, electronic stopping mechanism is more important

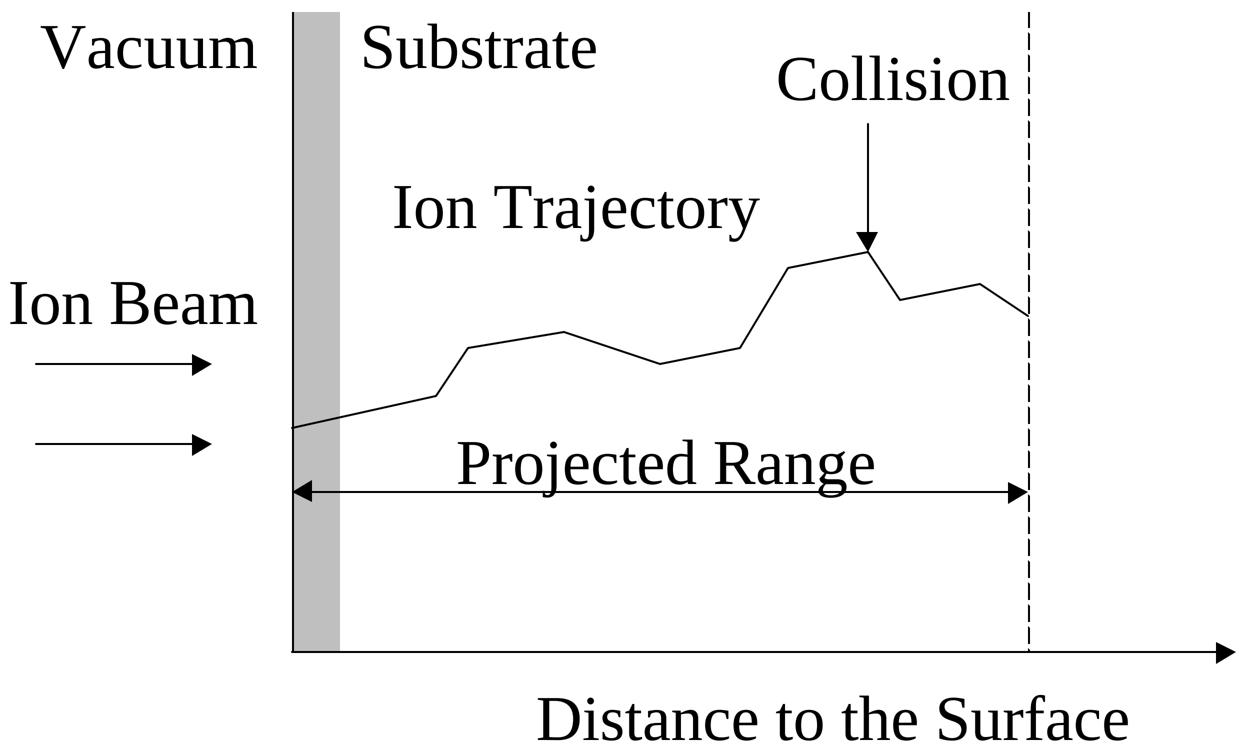
Stopping Mechanisms



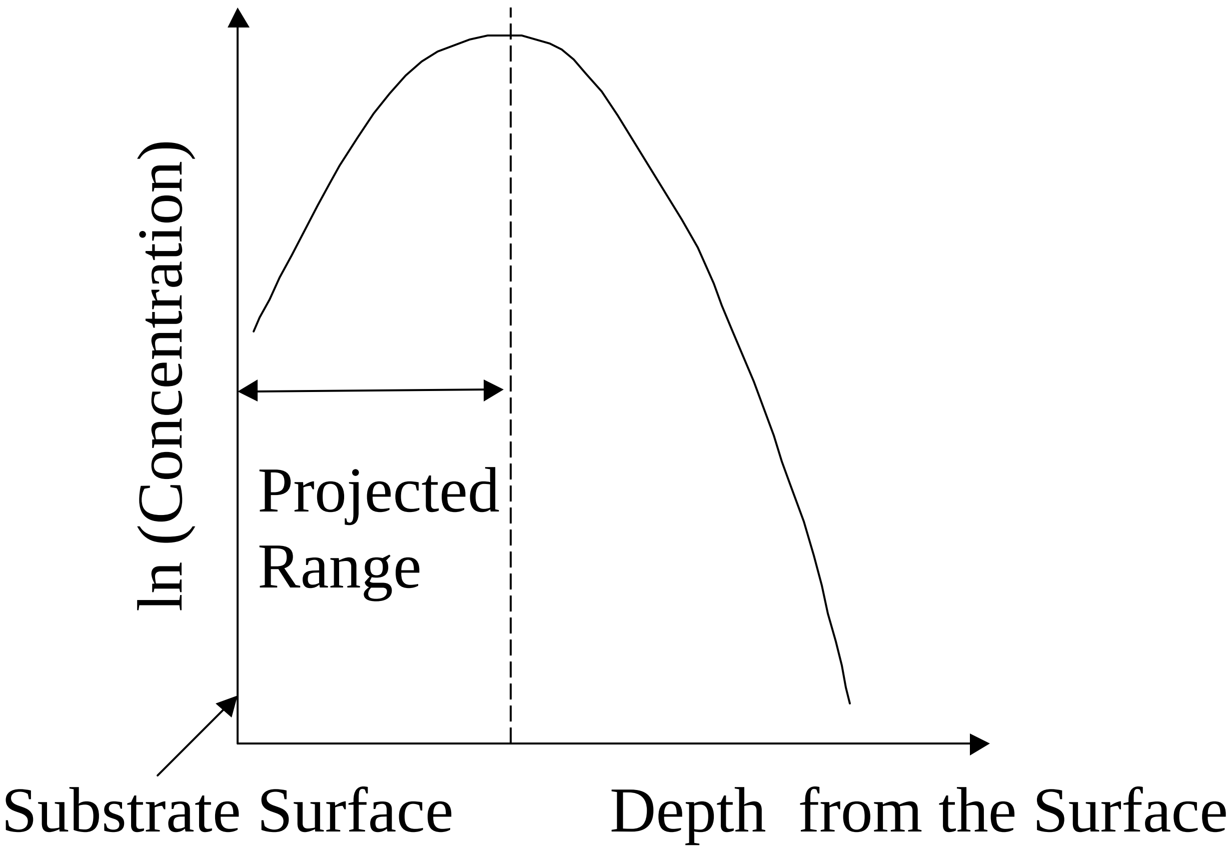
Stopping Power and Ion Velocity



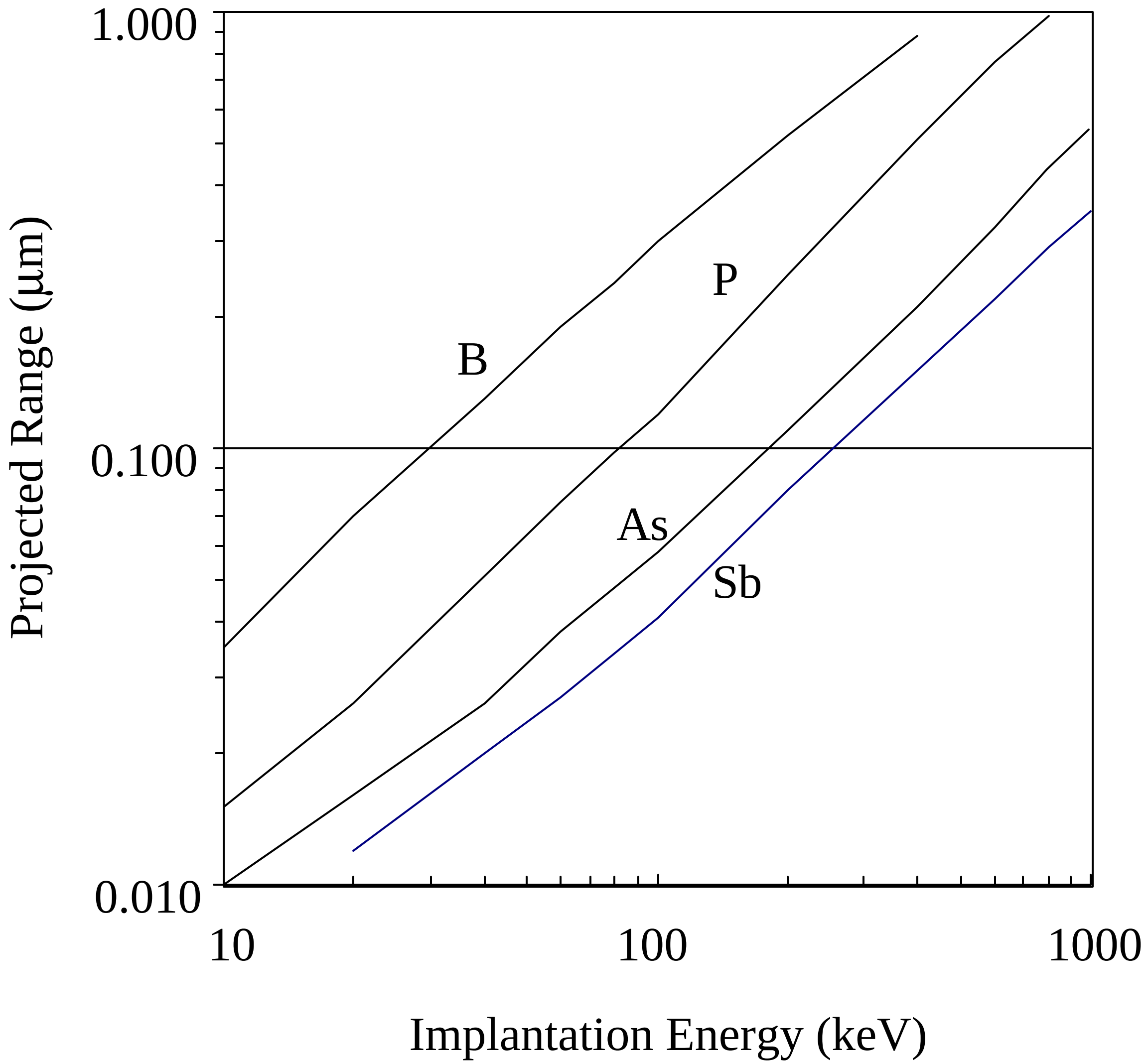
Ion Trajectory and Projected Range



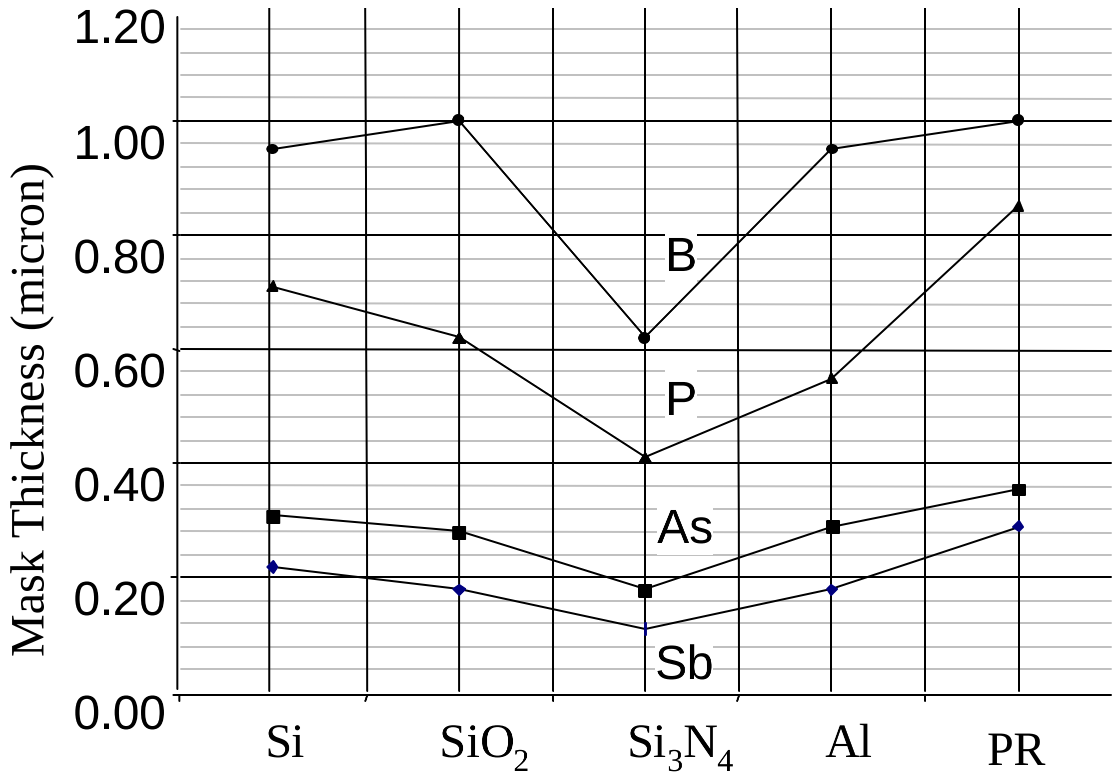
Ion Projection Range



Projected Range in Silicon

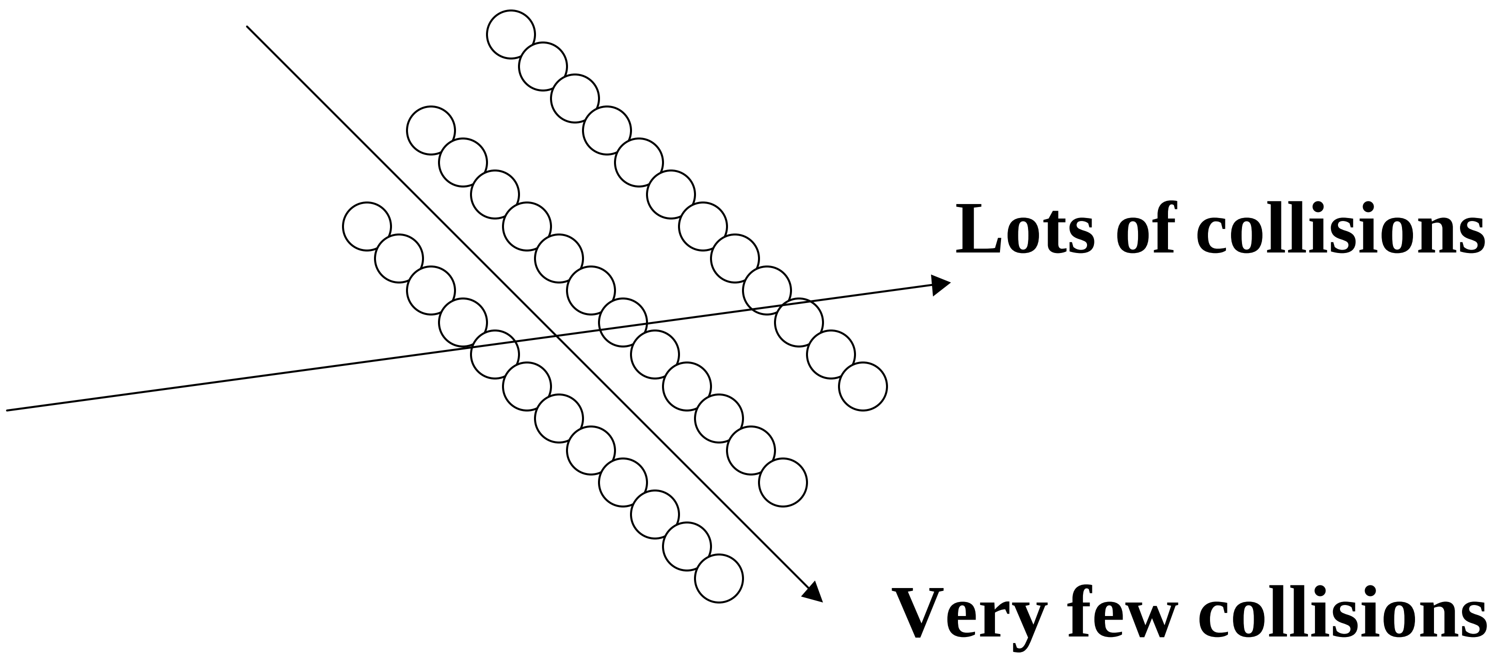


Barrier Thickness to Block 200 keV Ion Beam

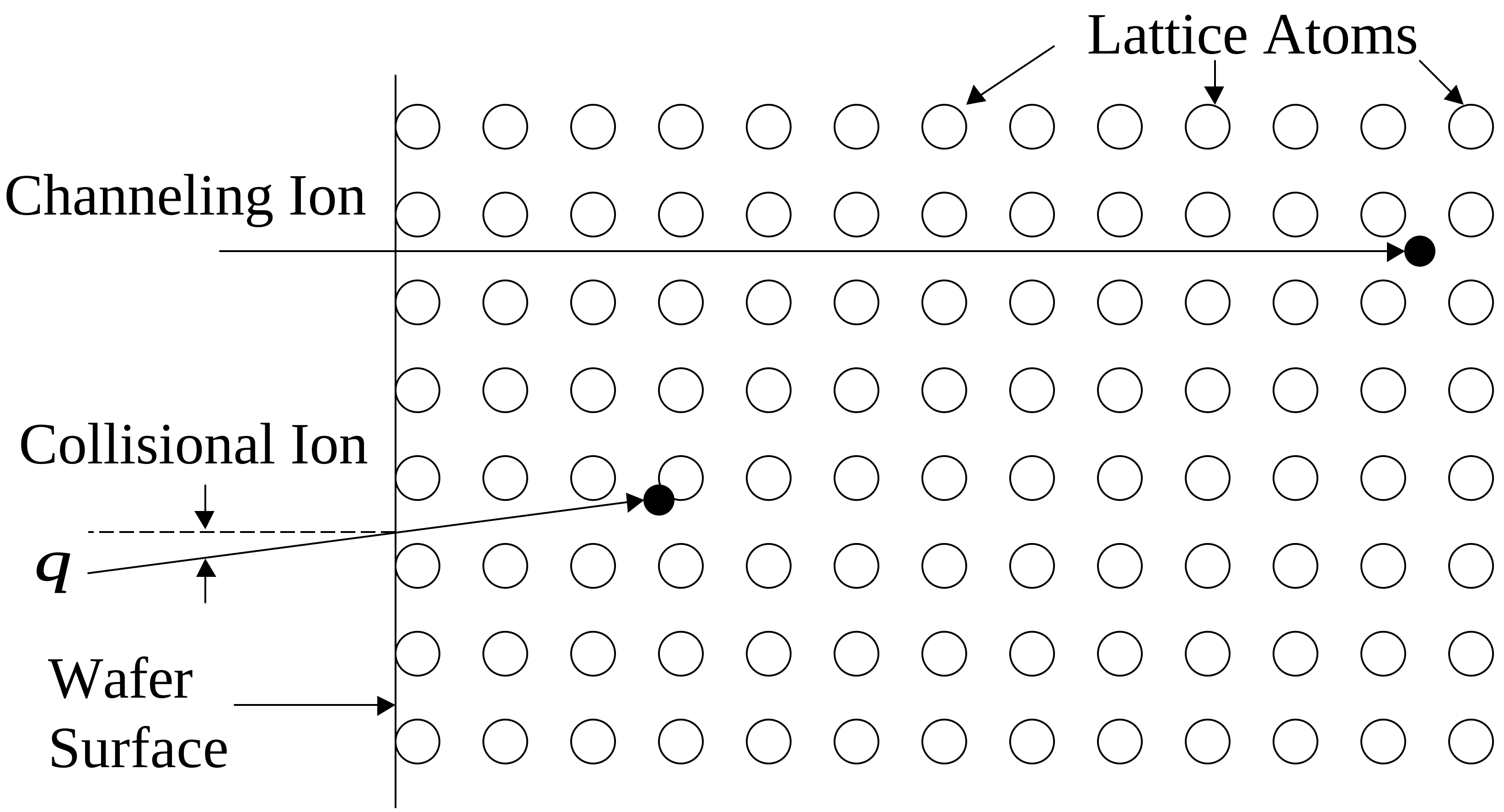


Implantation Processes: Channeling

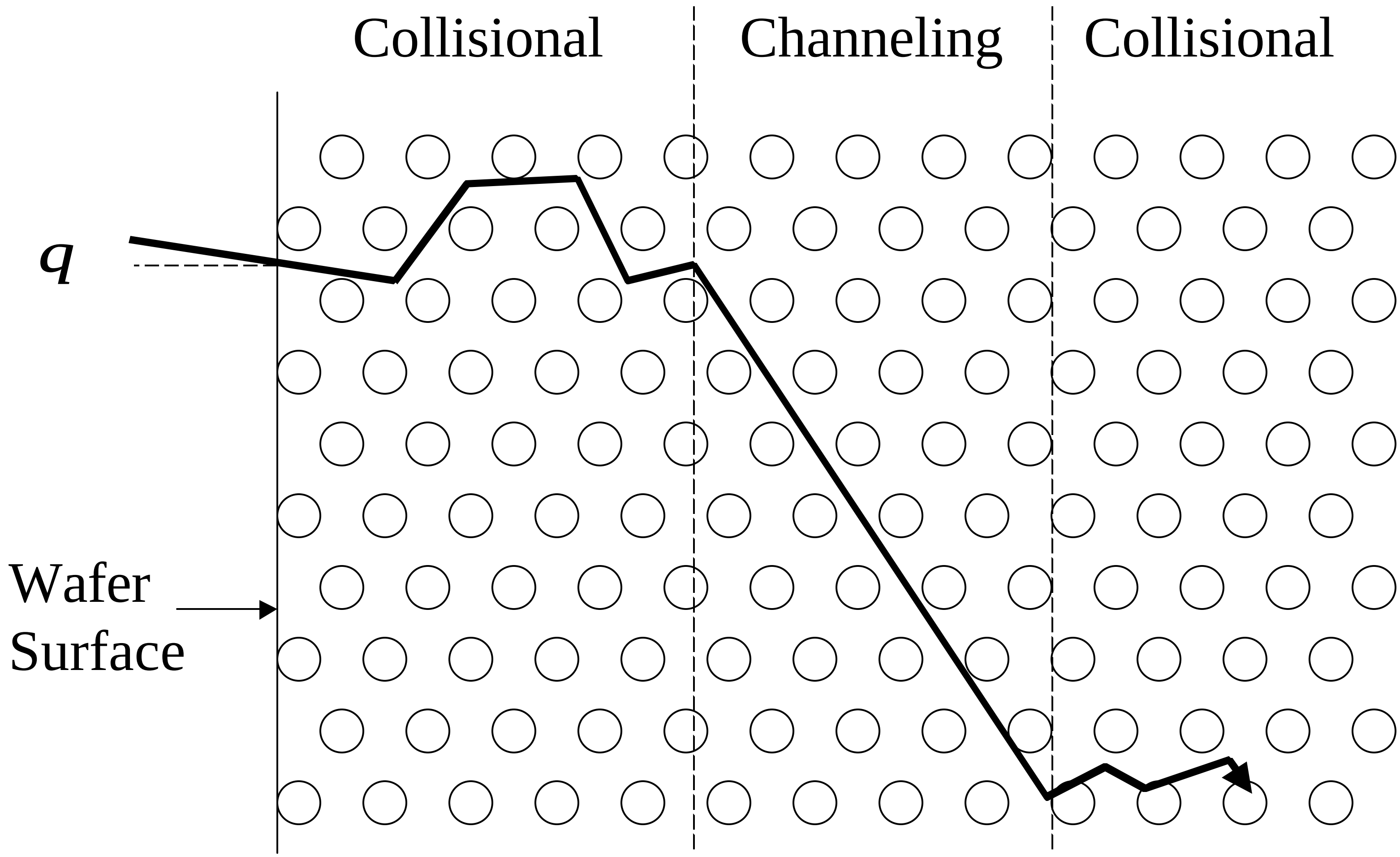
- If the incident angle is right, ion can travel long distance without collision with lattice atoms
- It causes uncontrollable dopant profile



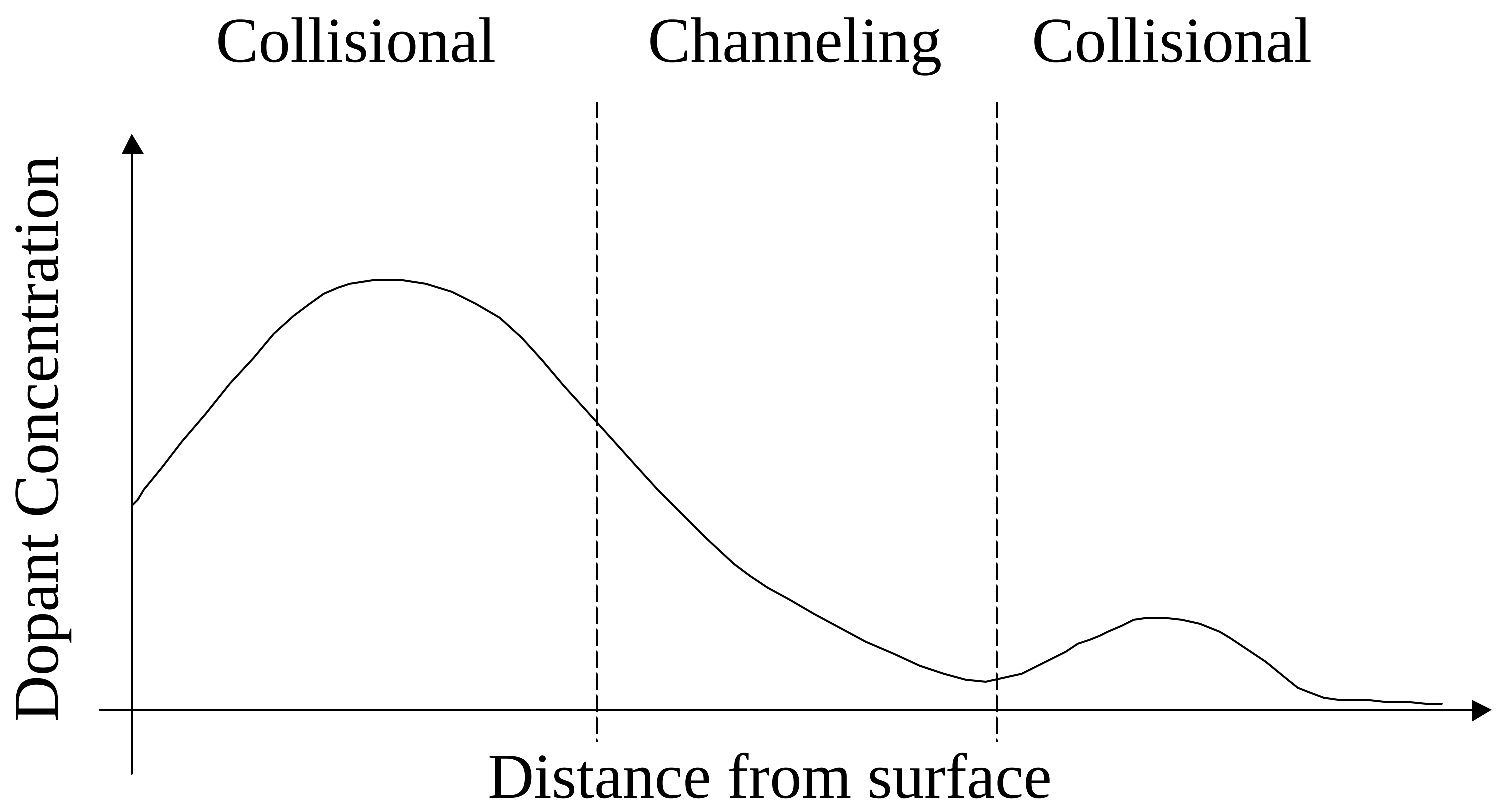
Channeling Effect



Post-collision Channeling



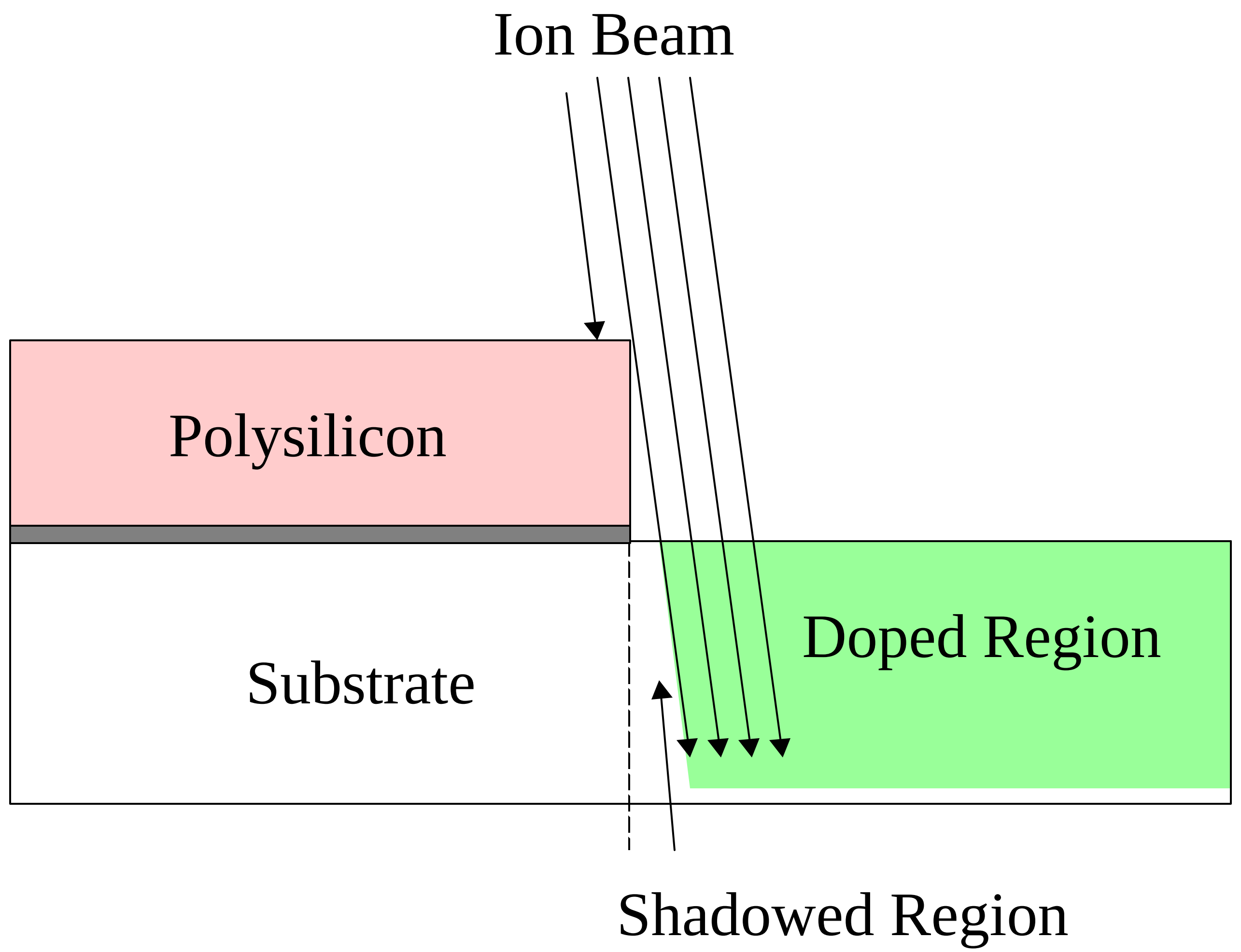
Post-collision Channeling



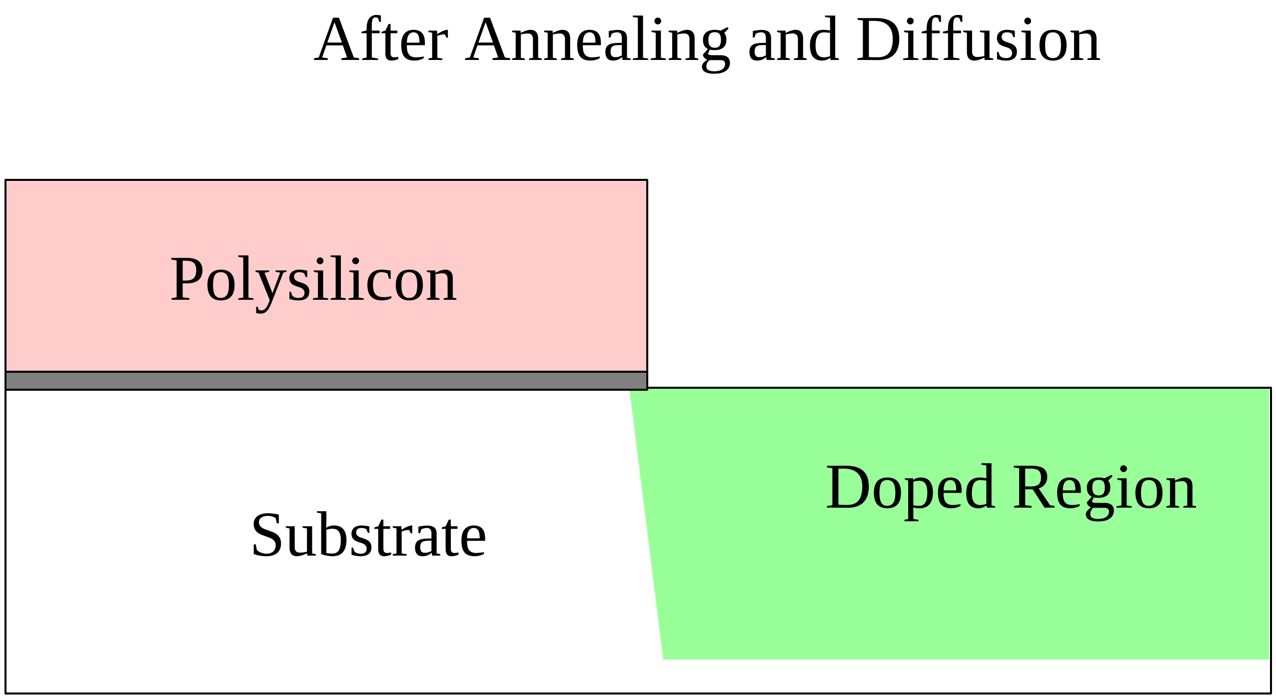
Implantation Processes: Channeling

- Ways to avoid channeling effect
  - Tilt wafer, 7° is most commonly used
  - Screen oxide
  - Pre-amorphous implantation, Germanium
- Shadowing effect
  - Ion blocked by structures
- Rotate wafer and post-implantation diffusion

Shadowing Effect



Shadowing Effect



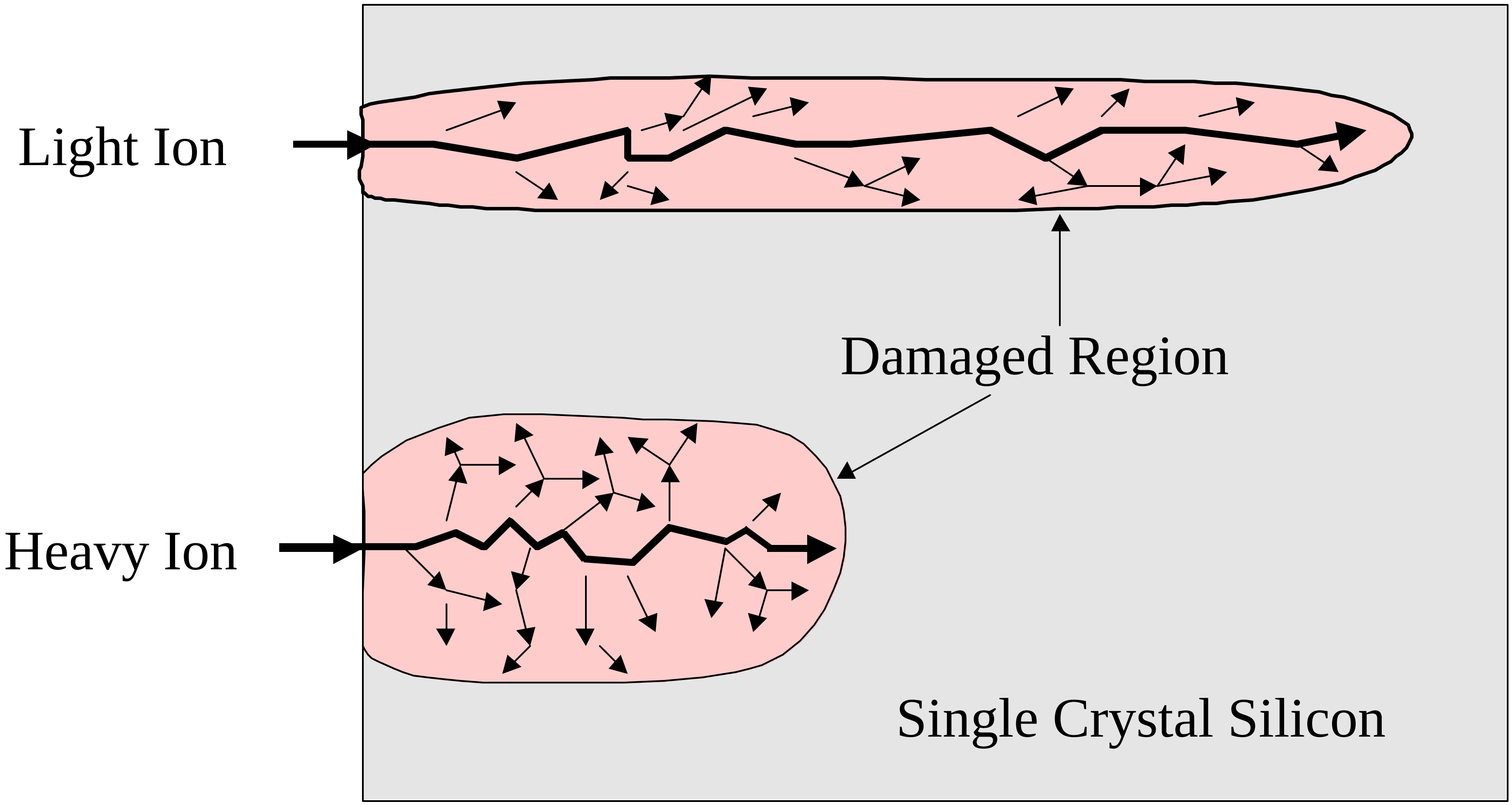
Q & A

- Why don’t people use channeling effect to create deep junction without high ion energy?
- Ion beam is not perfectly parallel. Many ions will start to have a lot of nuclear collisions with lattice atoms after they penetrating into the substrate. Some ions can channel deep into the substrate, while many others are stopped as the normal Gaussian distribution.

Damage Process

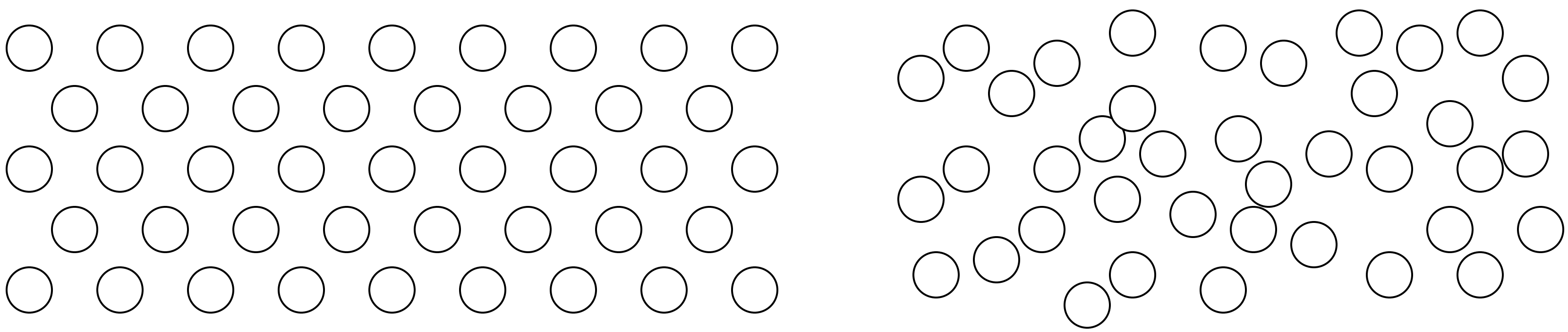
- Implanted ions transfer energy to lattice atoms
  - Atoms to break free
- Freed atoms collide with other lattice atoms
  - Free more lattice atoms
  - Damage continues until all freed atoms stop
- One energetic ion can cause thousands of displacements of lattice atoms

Lattice Damage With One Ion



Implantation Processes: Damage

- Ion collides with lattice atoms and knock them out of lattice grid
- Implant area on substrate becomes amorphous structure



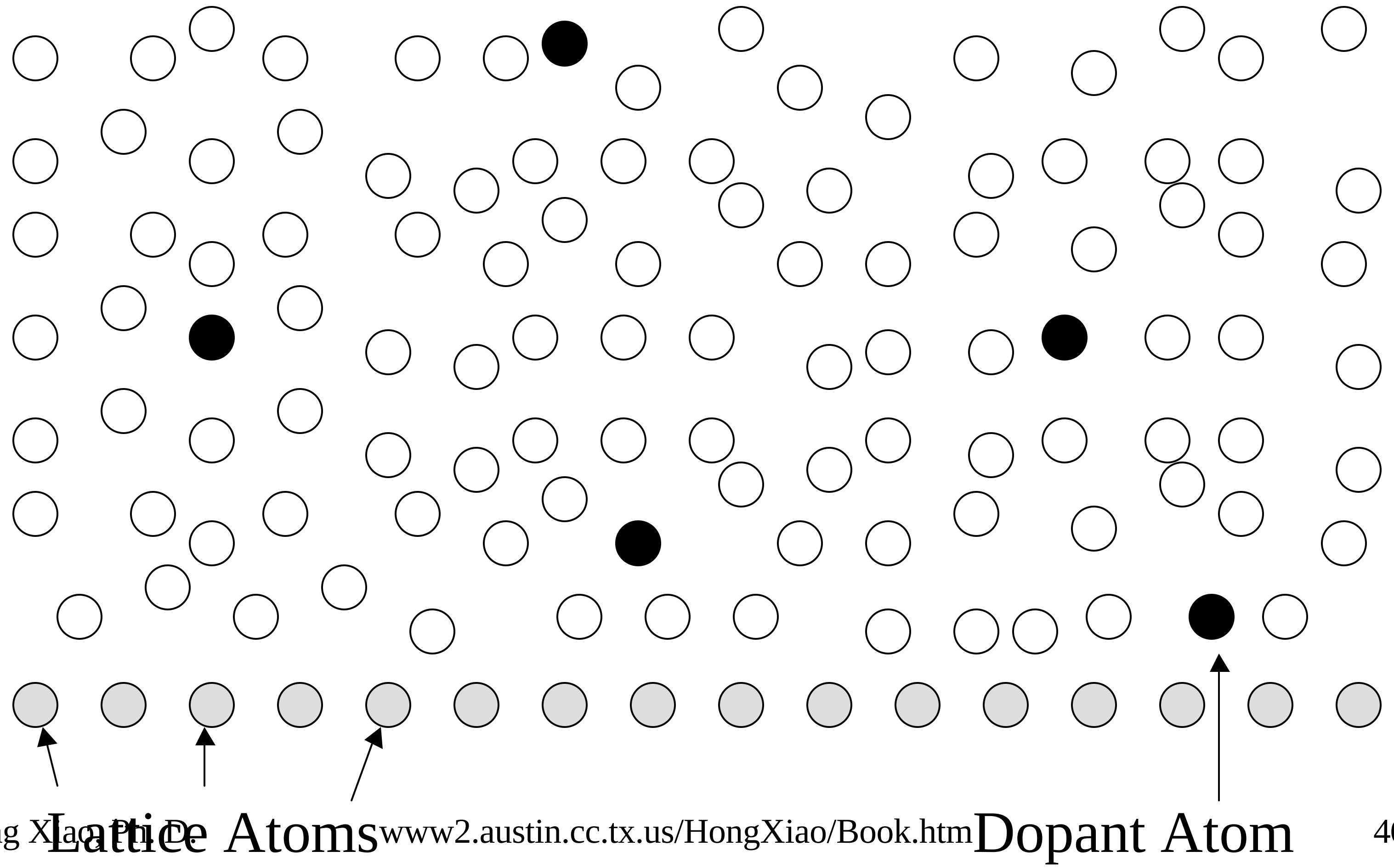
Before Implantation **After Implantation**

Implantation Processes: Anneal

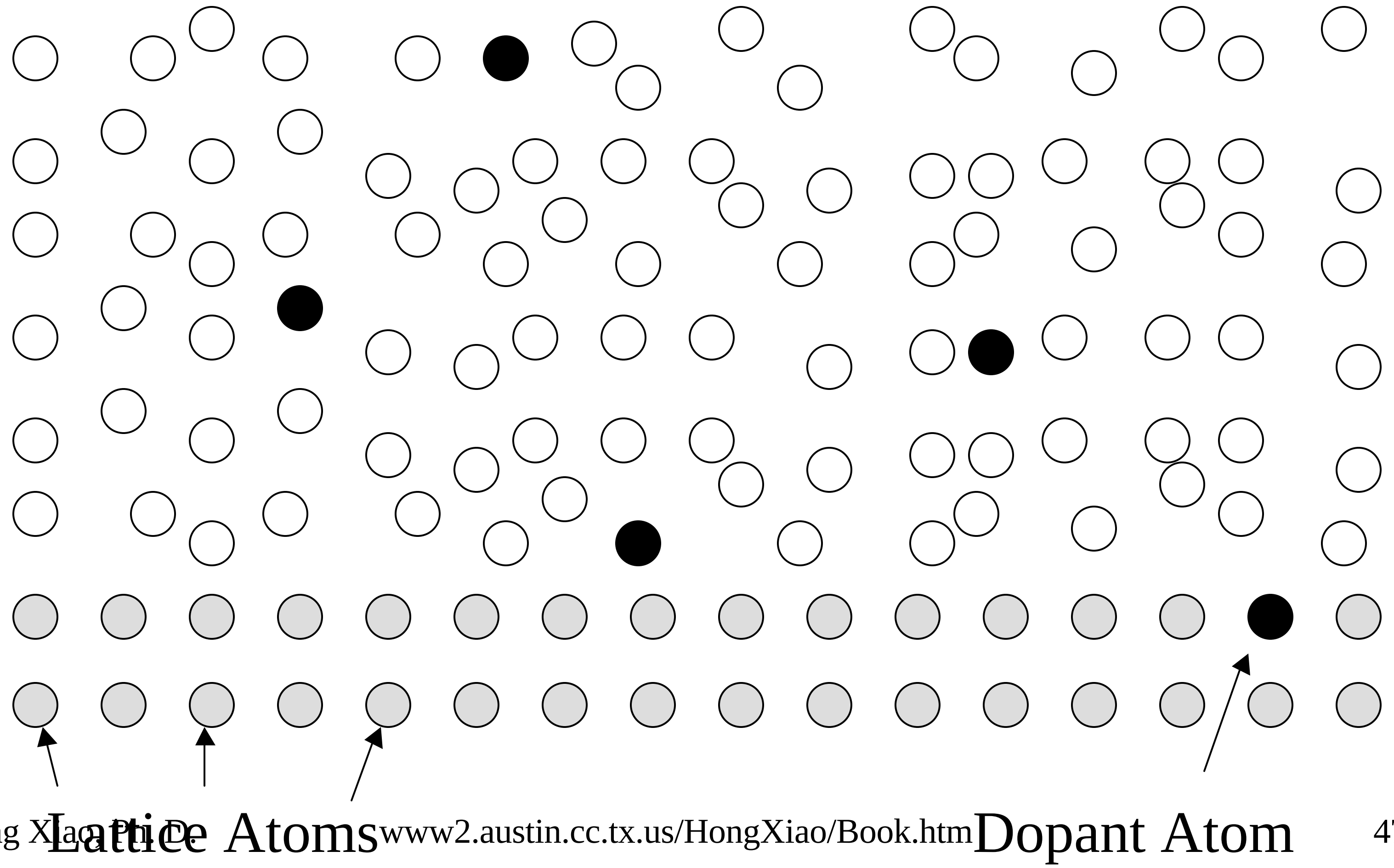
- Dopant atom must in single crystal structure and bond with four silicon atoms to be activated as donor (N-type) or acceptor (P-type)

- Thermal energy from high temperature helps amorphous atoms to recover single crystal structure.

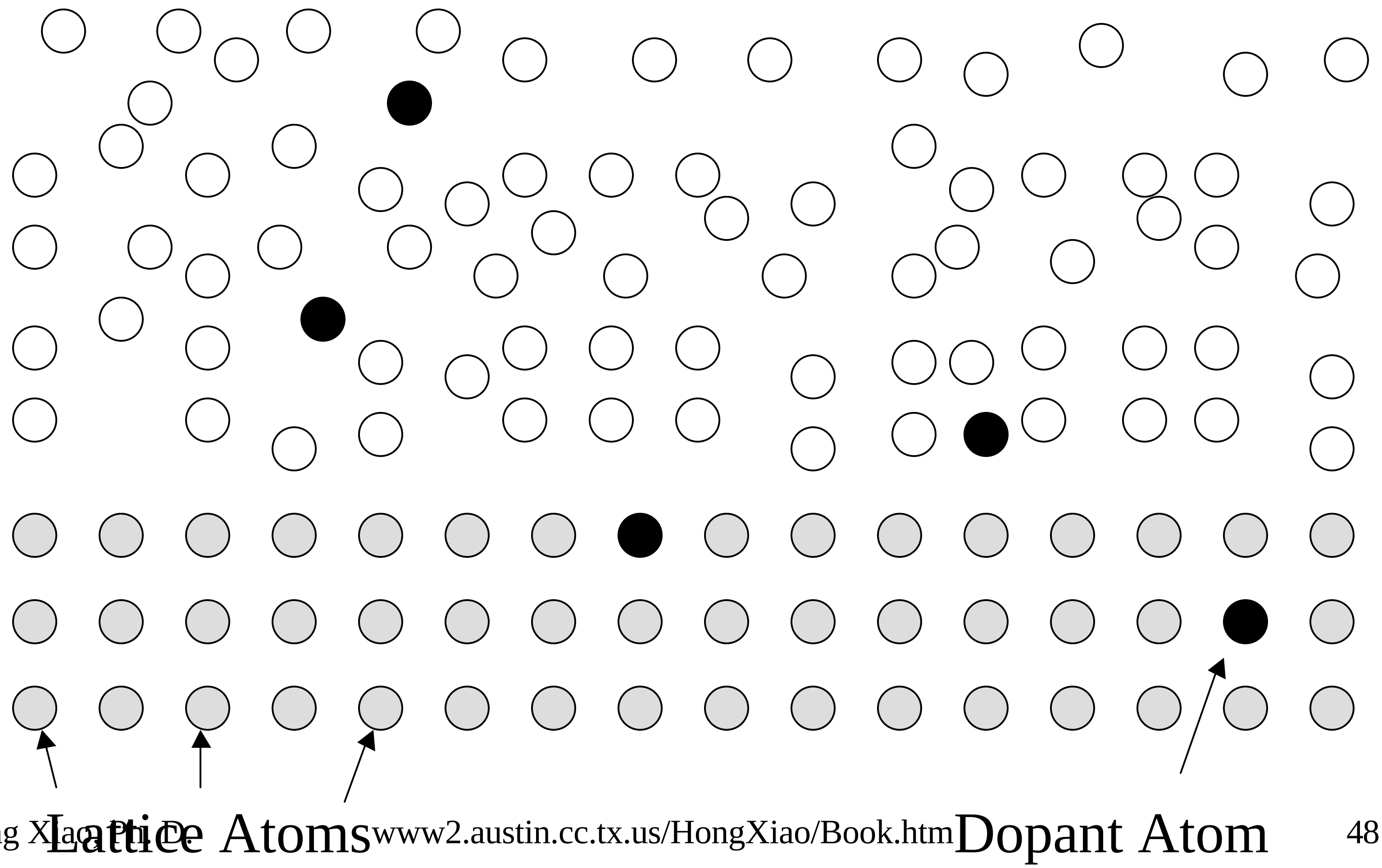
Thermal Annealing



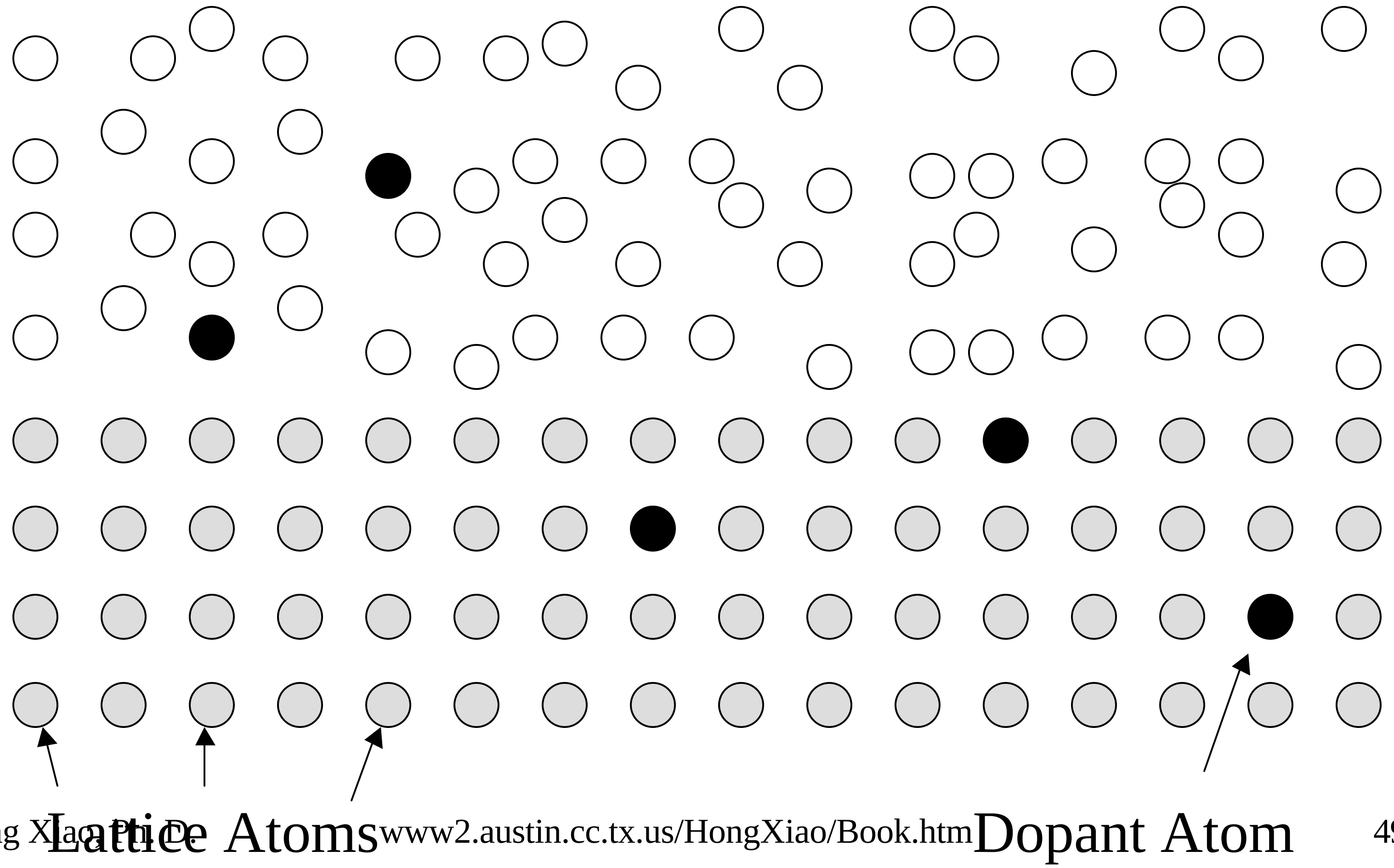
Thermal Annealing



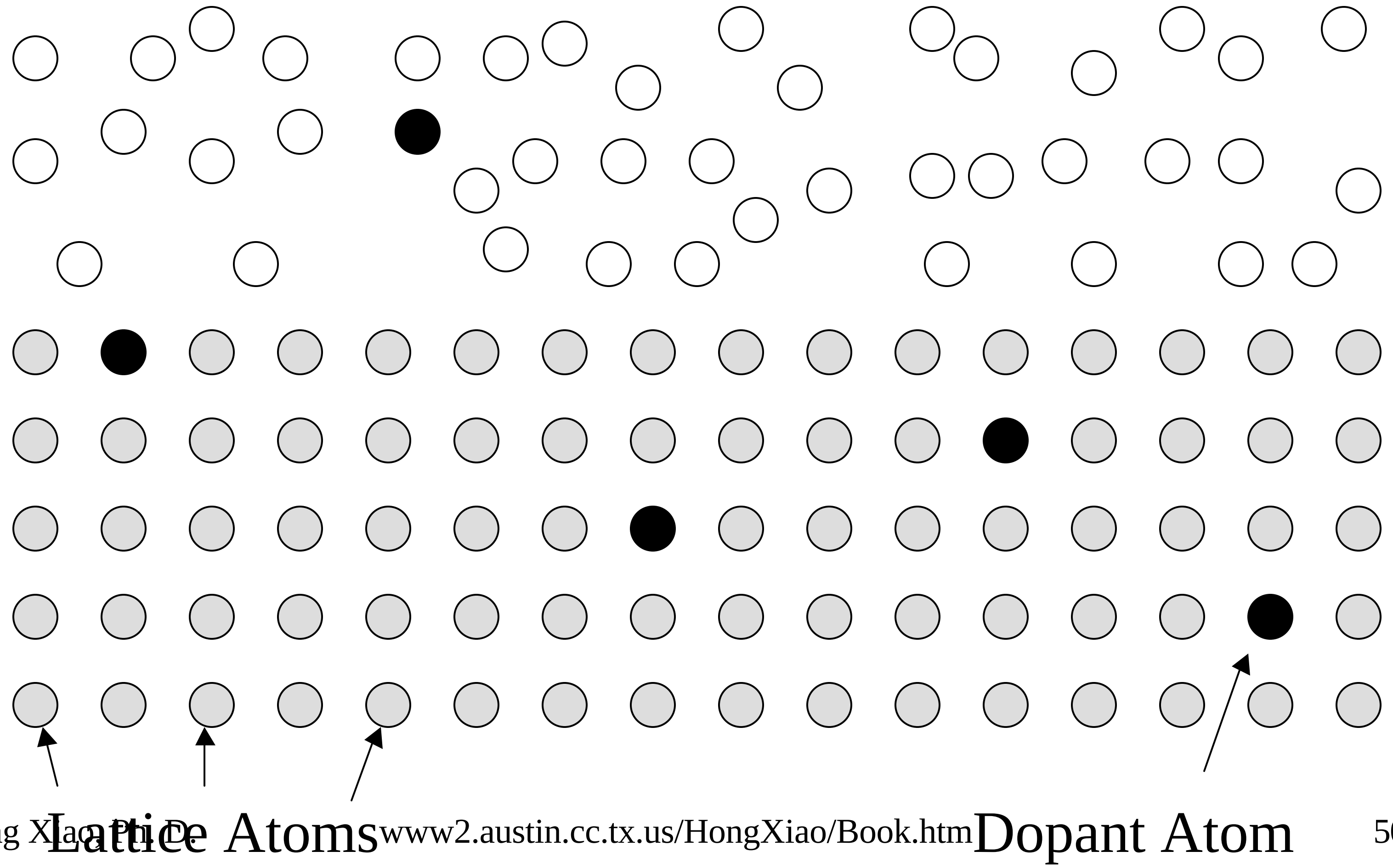
Thermal Annealing



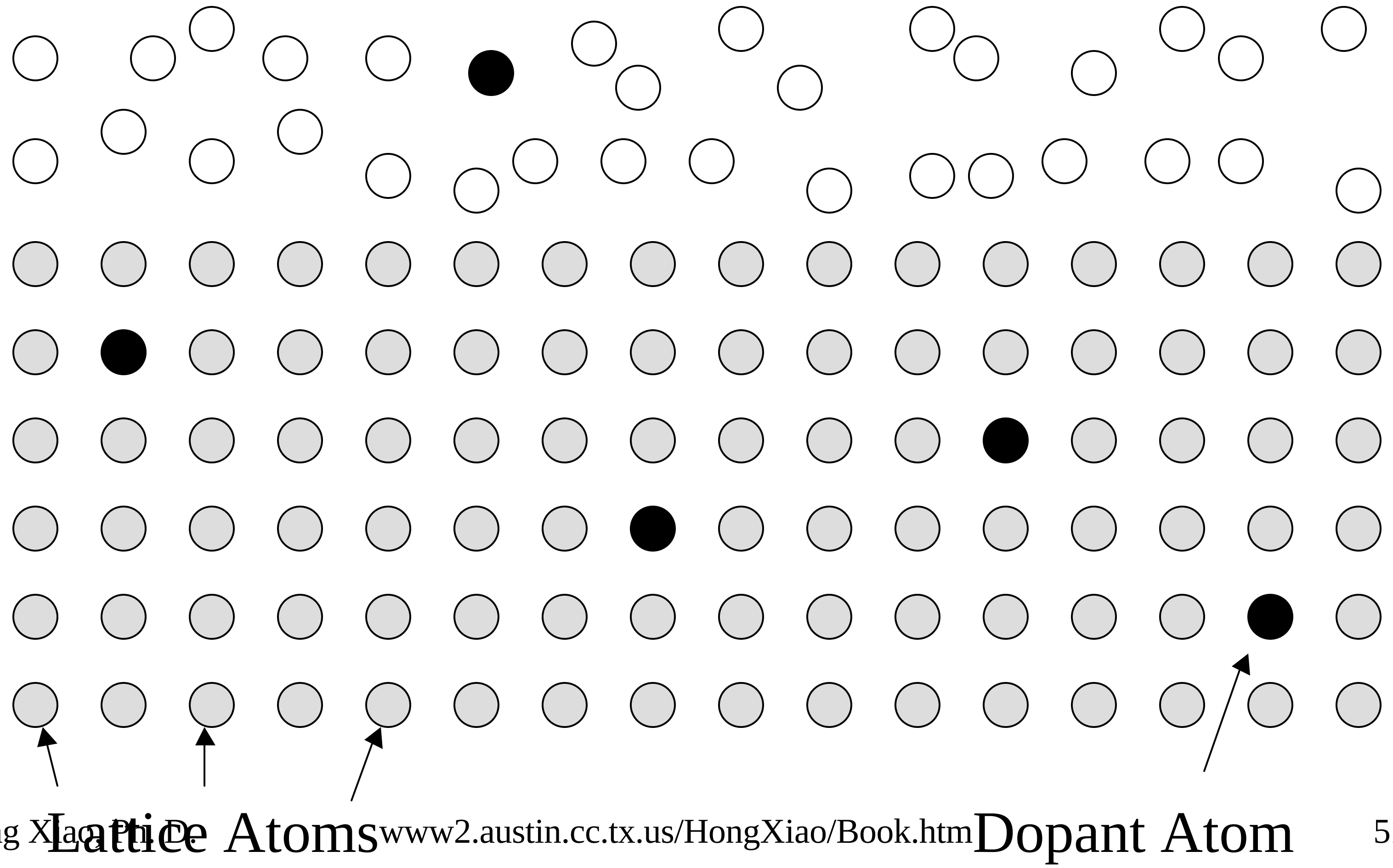
Thermal Annealing



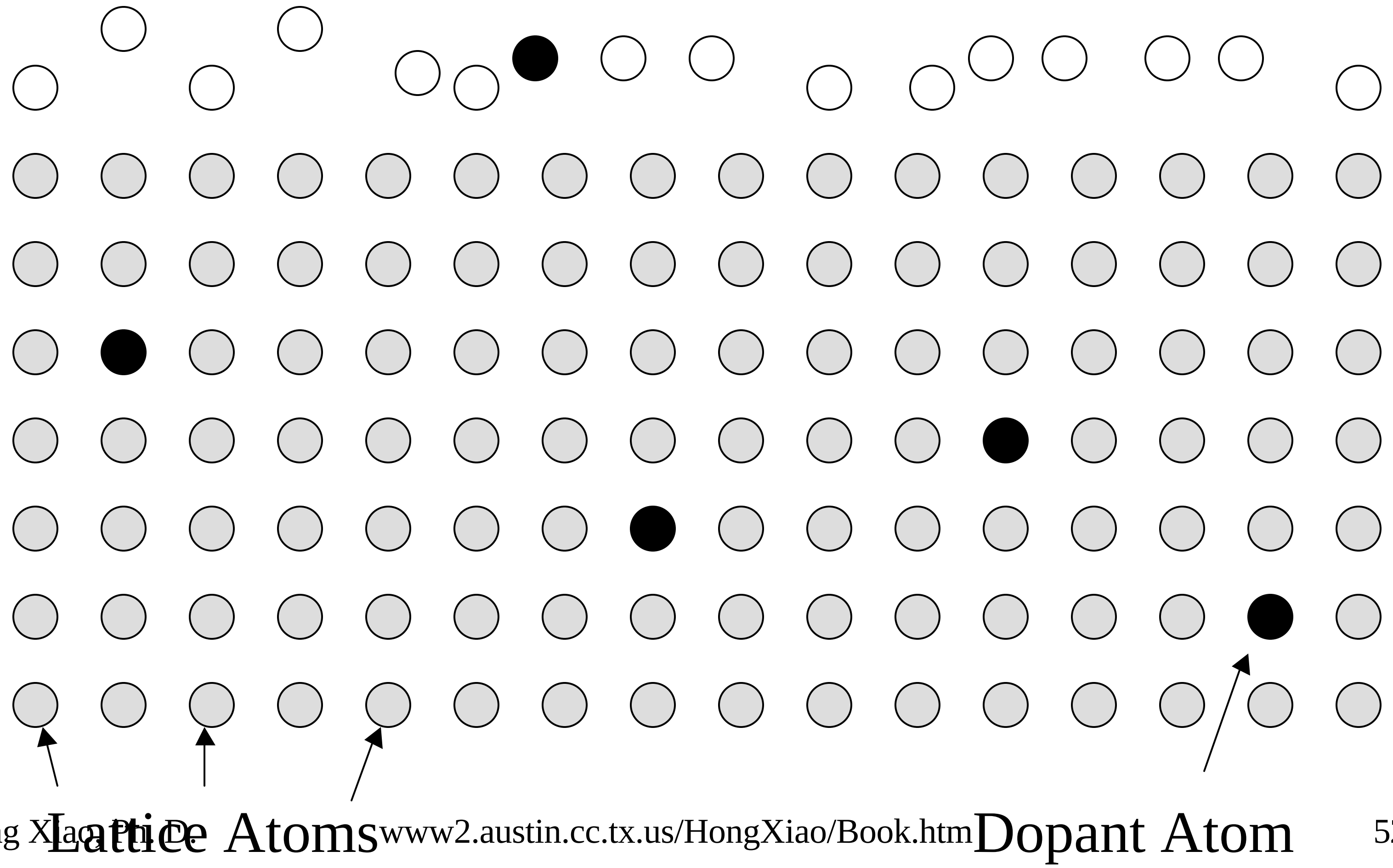
Thermal Annealing



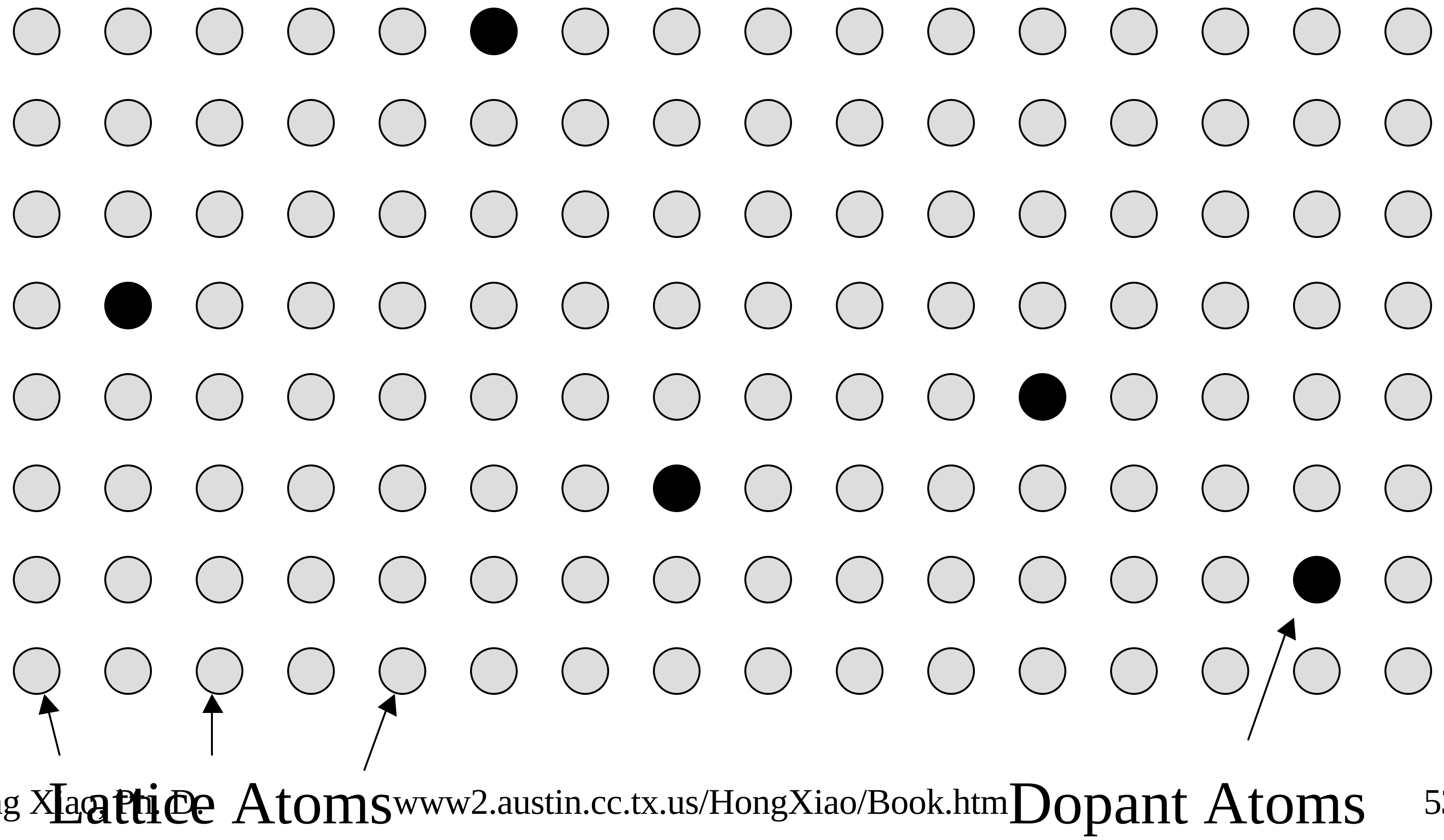
Thermal Annealing



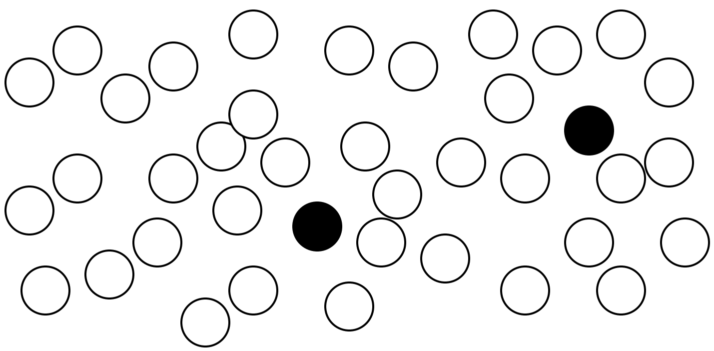
Thermal Annealing



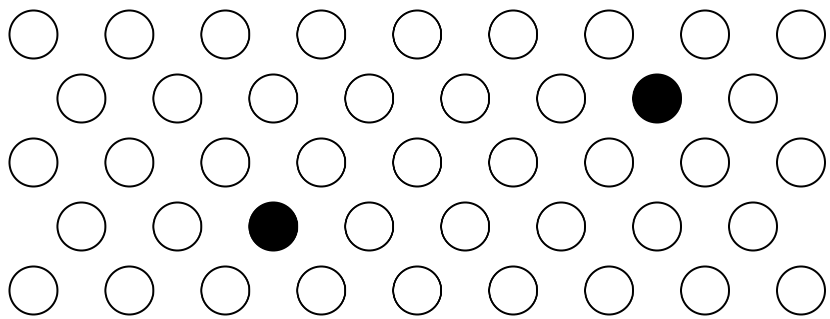
Thermal Annealing



Implantation Processes: Annealing



Before Annealing

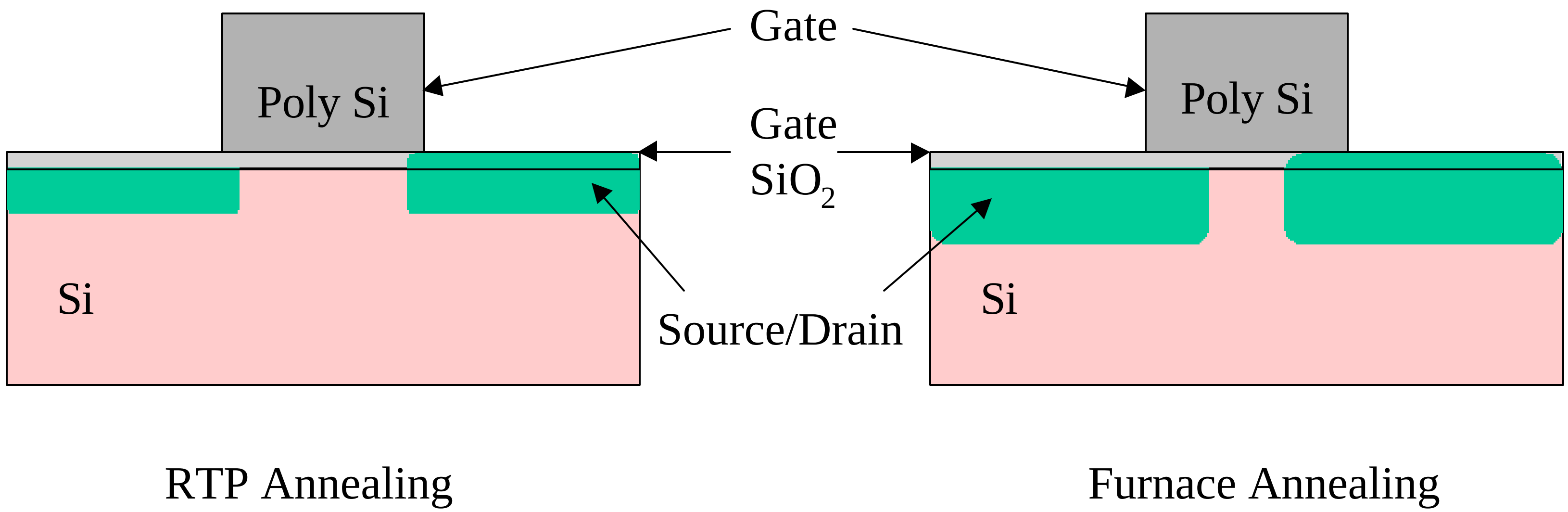


After Annealing

Rapid Thermal Annealing (RTA)

- At high temperature, annealing out pace diffusion
- Rapid thermal process (RTP) is widely used for post-implantation anneal
- RTA is fast (less than a minute), better WTW uniformity, better thermal budget control, and minimized the dopant diffusion

RTP and Furnace Annealing



Question and Answer

- Why can’t the furnace temperature be ramped-up and cooled-down as quickly as RTP system ?

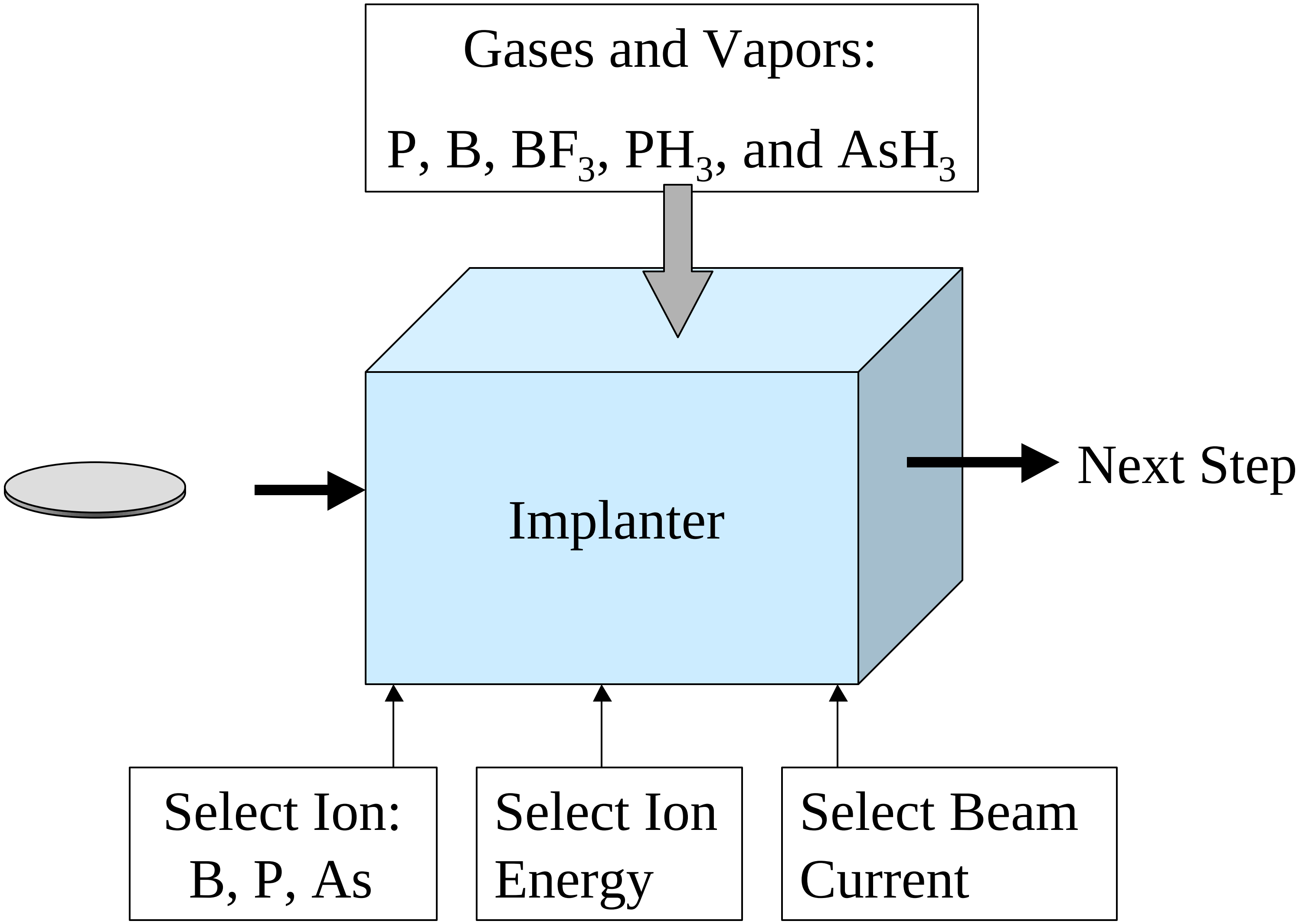
- A furnace has very large thermal capacity, it needs very high heating power to ramp-up temperature rapidly. It is very difficult to ramp up temperature very fast without large temperature oscillation due to the temperature overshoot and undershoot .

Ion Implantation: Hardware

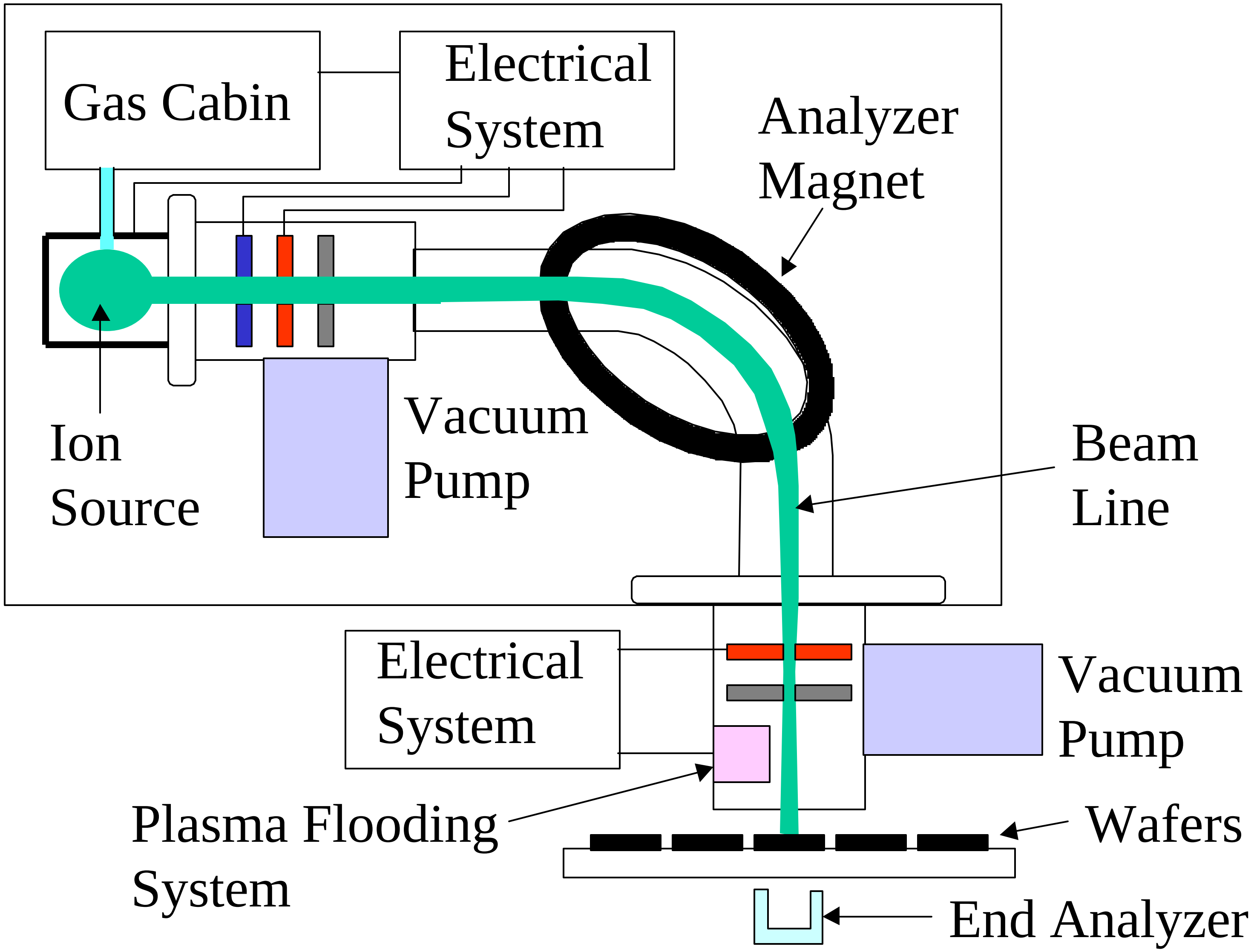
- Gas system
- Electrical system
- Vacuum system
- Ion beamline

Ion Implanter

Implantation Process



Ion Implanter



Ion Implantation: Gas System

- Special gas deliver system to handle hazardous gases
- Special training needed to change gases bottles
- Argon is used for purge and beam calibration

Ion Implantation: Electrical System

- High voltage system
  - Determine ion energy that controls junction depth
- High voltage system
  - Determine ion energy that controls junction depth
- RF system
  - Some ion sources use RF to generate ions

Ion Implantation: Vacuum System

- Need high vacuum to accelerate ions and reduce collision
- MFP >> beamline length
- 10^{-5} to 10^{-7} Torr
- Turbo pump and Cryo pump

- Exhaust system

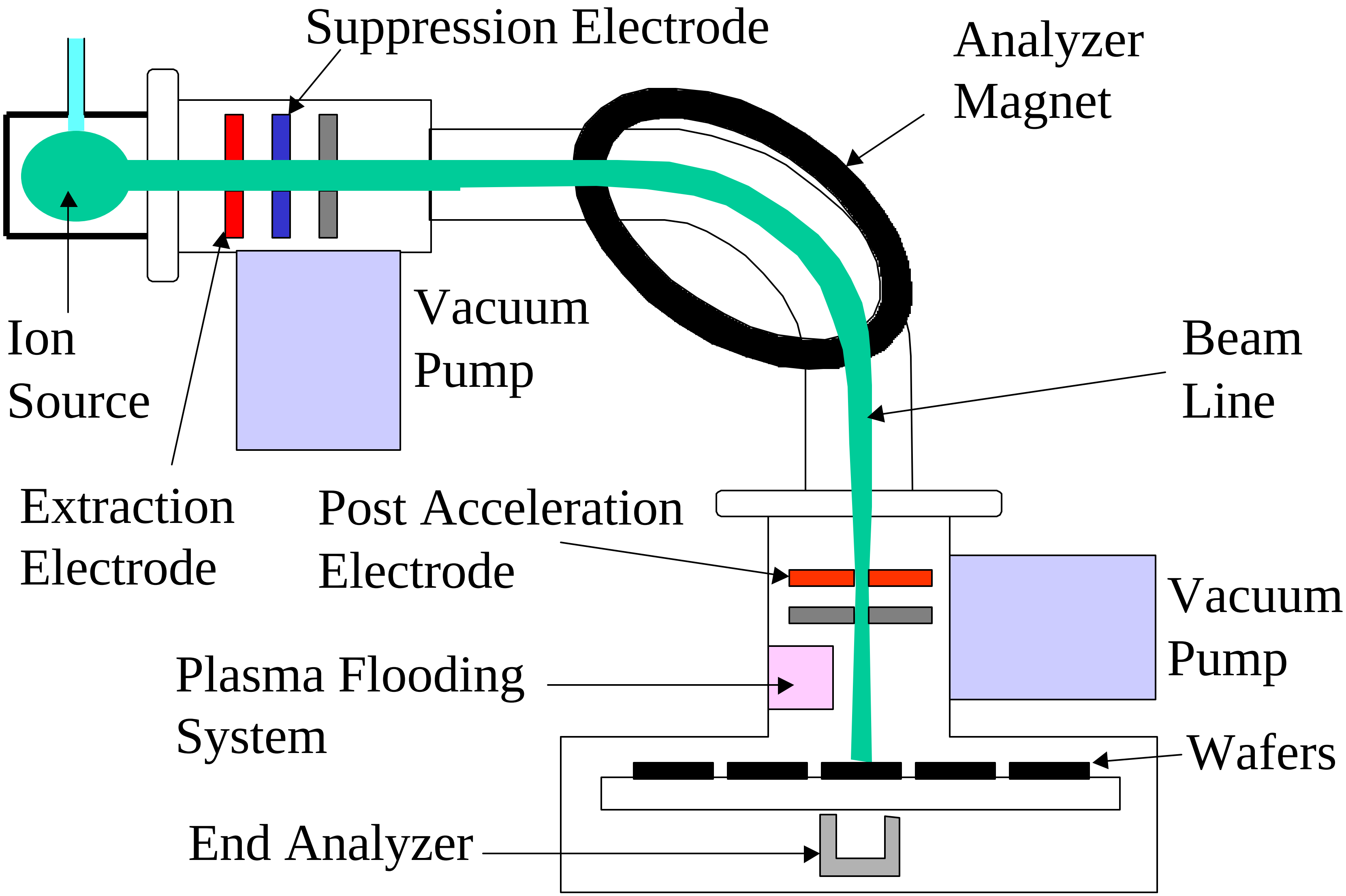
Ion Implantation: Control System

- Ion energy, beam current, and ion species.
- Mechanical parts for loading and unloading
- Wafer movement to get uniform beam scan
- CPU board control boards
  - Control boards collect data from the systems, send it to CPU board to process,
  - CPU sends instructions back to the systems through the control board.

Ion Implantation: Beamline

- Ion source
- Extraction electrode
- Analyzer magnet
- Post acceleration
- Plasma flooding system
- End analyzer

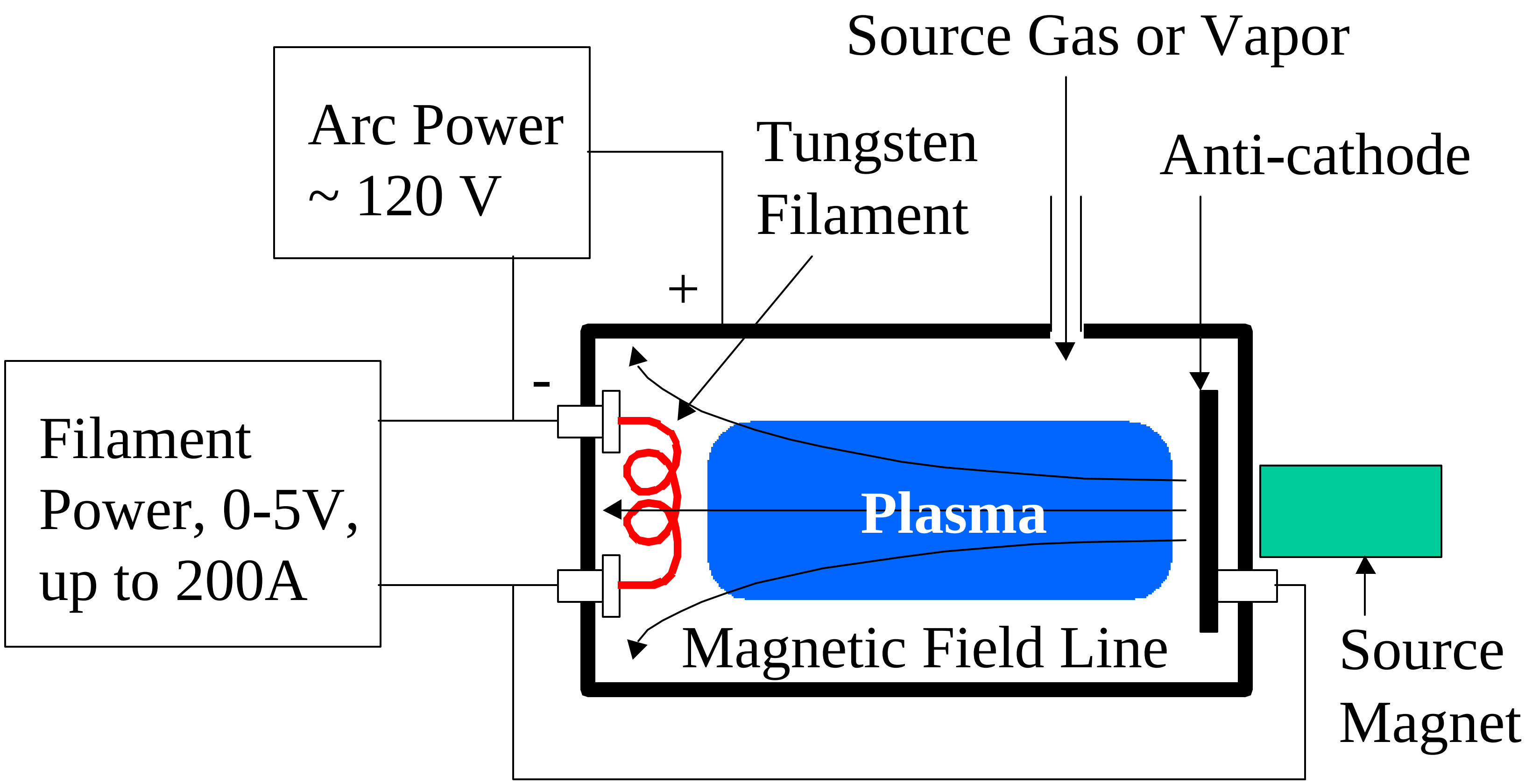
Ion Beam Line



Ion implanter: Ion Source

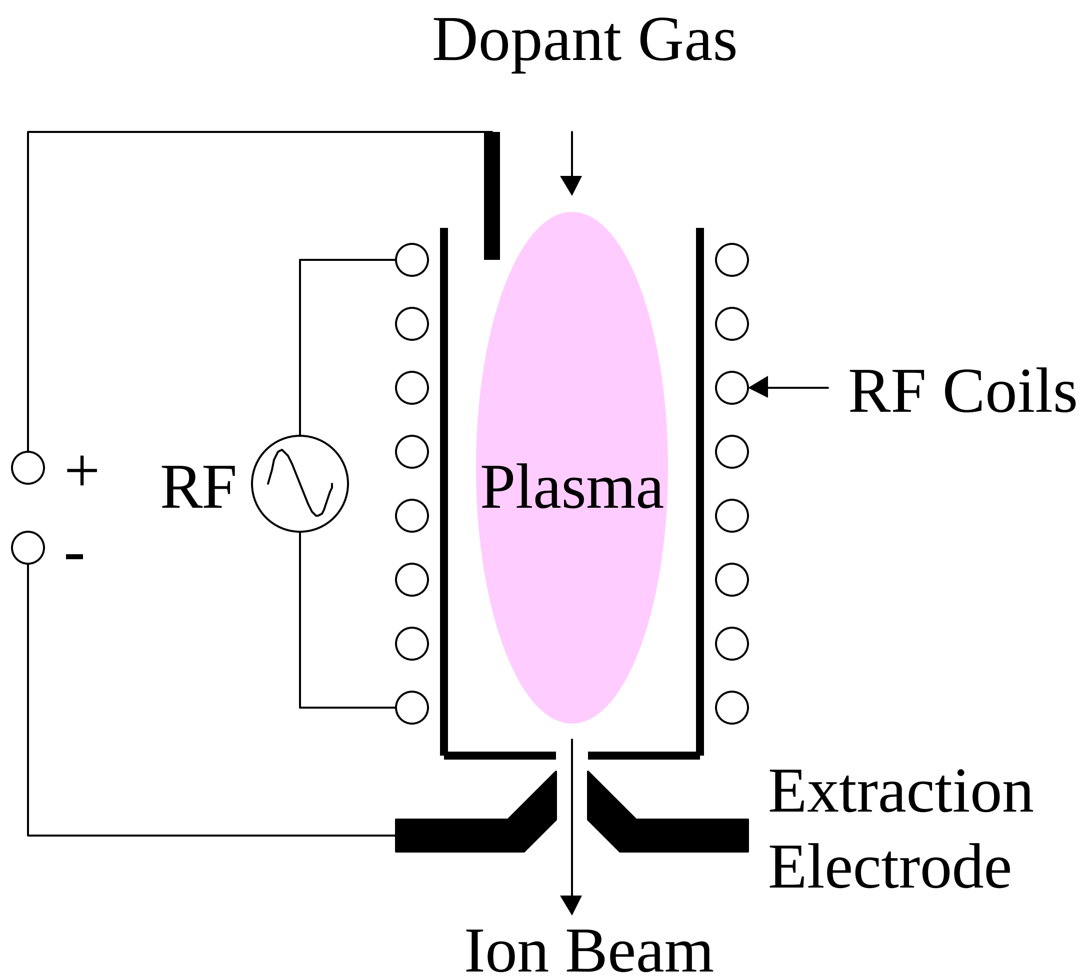
- Hot tungsten filament emits thermal electron
- Electrons collide with source gas molecules to dissociate and ionize
- Ions are extracted out of source chamber and accelerated to the beamline
- RF and microwave power can also be used to ionize source gas

Ion Source

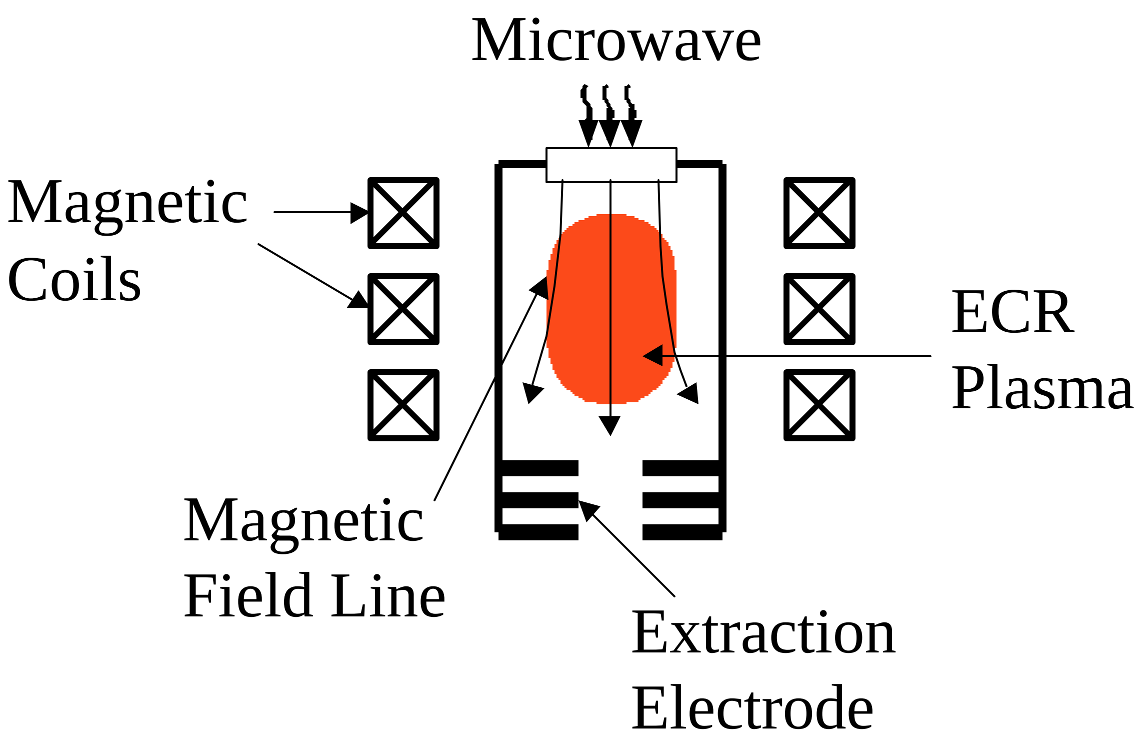


Source Gas or Vapor
Arc Power
~ 120 V
Tungsten
Filament
Anti-cathode
+
-
Filament
Power, 0-5V,
up to 200A
Plasma
Magnetic Field Line
Source
Magnet

RF Ion Source



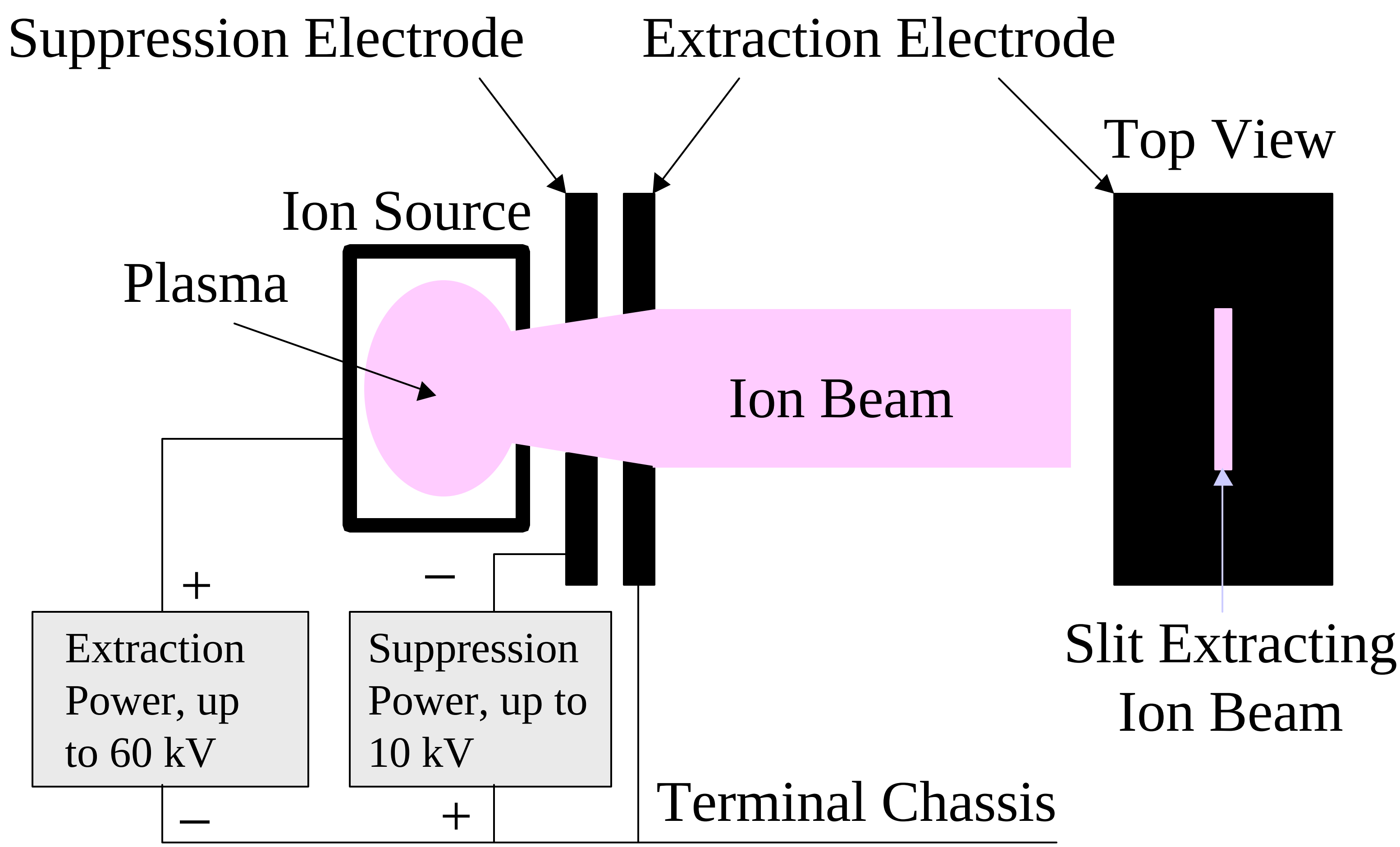
Microwave Ion Source



Ion Implantation: Extraction

- Extraction electrode accelerates ions up to 50 keV
- High energy is required for analyzer magnet to select right ion species.

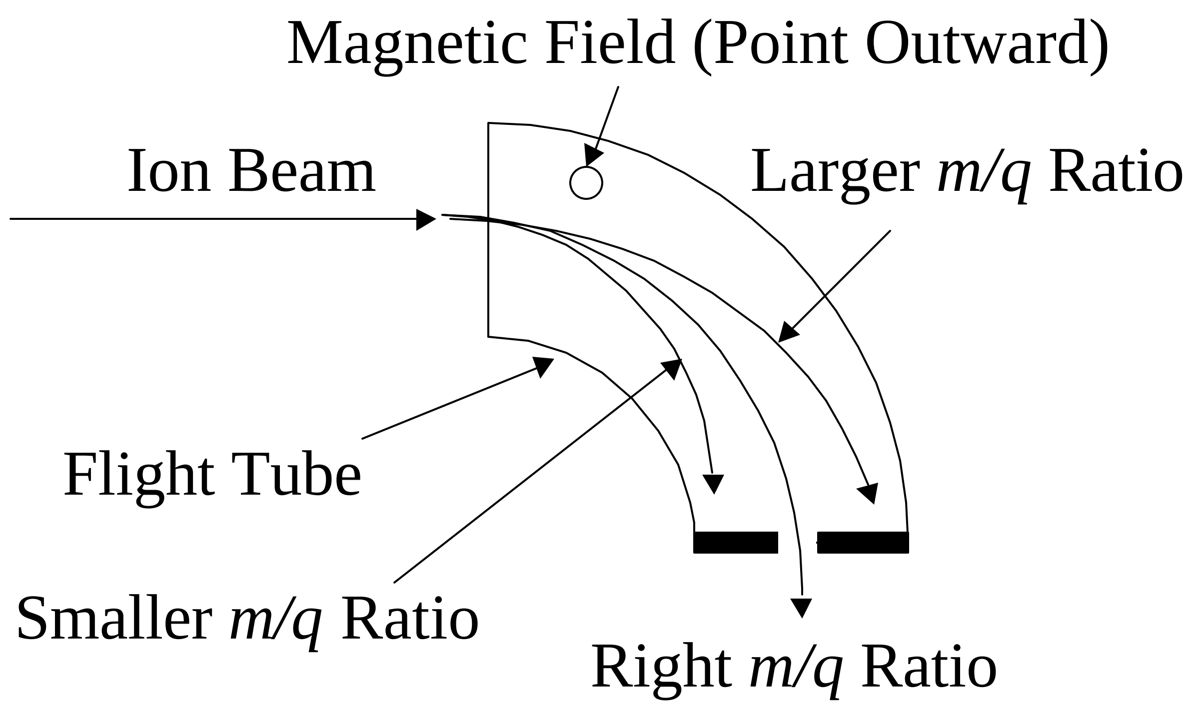
Extraction Assembly



Ion Implantation: Analyzer Magnet

- Gyro radius of charge particle in magnetic field relate with B-field and mass/charge ratio
- Used for isotope separation to get enriched U_{235}
- Only ions with right mass/charge ratio can go through the slit
- Purified the implanting ion beam

Analyzer


Magnetic Field (Point Outward)
Ion Beam
Larger *m/q* Ratio
Flight Tube
Smaller *m/q* Ratio
Right *m/q* Ratio

Ions in BF_3 Plasma

Ions	**Atomic or molecule weight**
^{10}B	10
^{11}B	11
^{10}BF	29
^{11}BF	30
F_2	38
$^{10}BF_2$	48
$^{11}BF_2$	49

Question and Answer

$^{10}B^+$ is lighter and can penetrate deeper than $^{11}B^+$, why don't use $^{10}B^+$ in deep junction implantation?

- Only 20% of boron atoms are ^{10}B
- $^{10}B^+$ ion concentration is only 1/4 of $^{11}B^+$
- $^{10}B^+$ beam current is 1/4 of $^{11}B^+$ beam current
- Quadruple implantation time, lower throughput

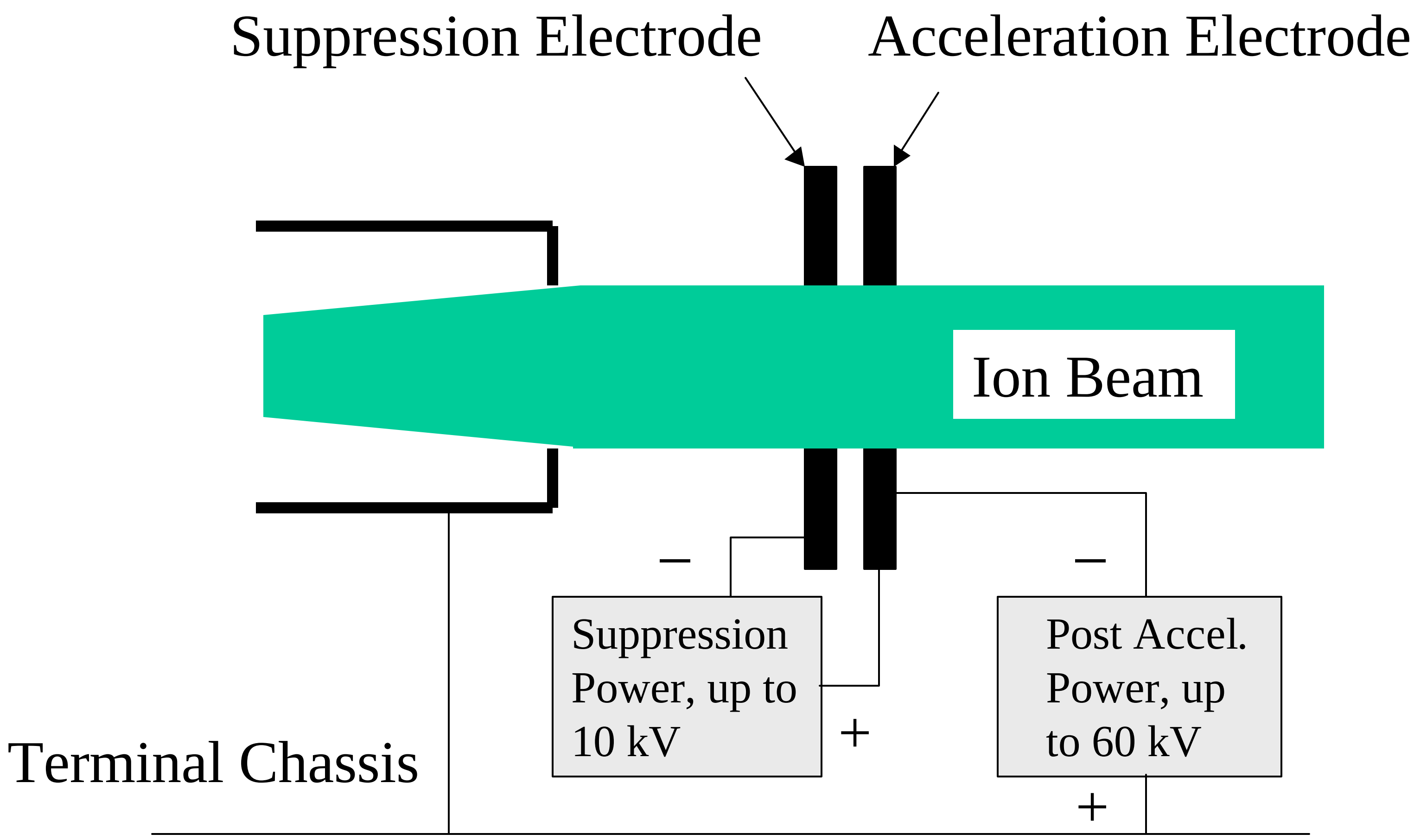
Ion Implantation: Post Acceleration

- Increasing (sometimes decreasing) ion energy for ion to reach the required junction depth determined by the device
- Electrodes with high DC voltage
- Adjustable vertical vanes control beam current

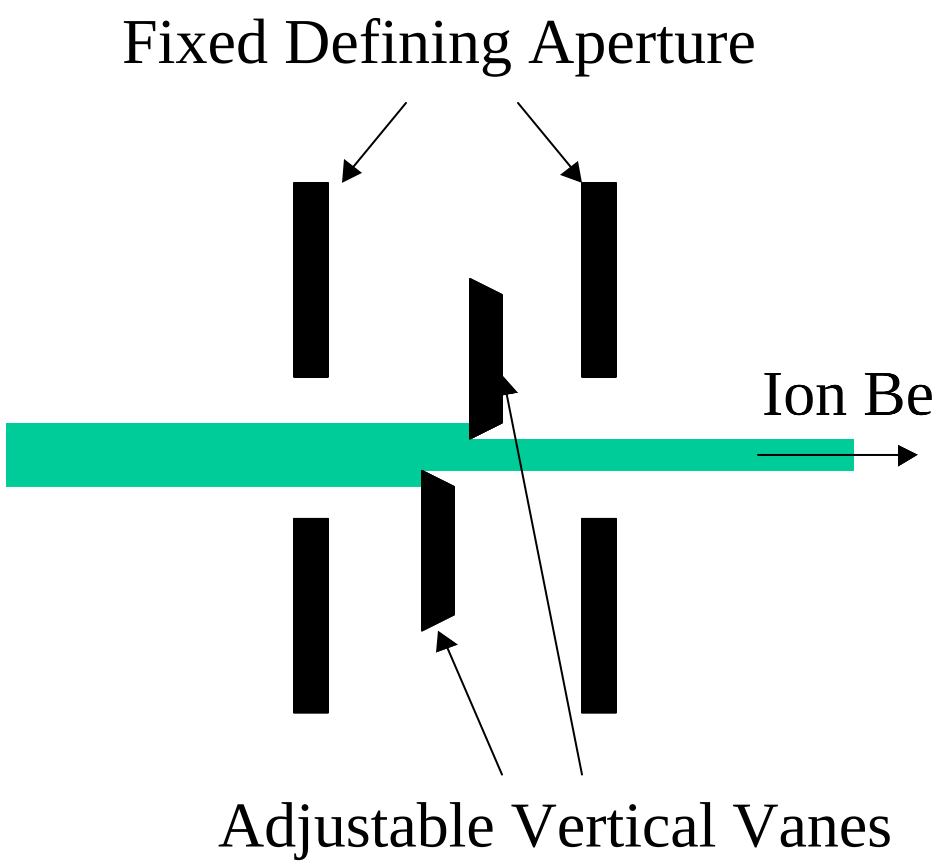
Ion Implantation: Plasma Flooding System

- Ions cause wafer charging
- Wafer charging can cause non-uniform doping and arcing defects
- Elections are “flooding” into ion beam and neutralized the charge on the wafer
- Argon plasma generated by thermal electrons emit from hot tungsten filament

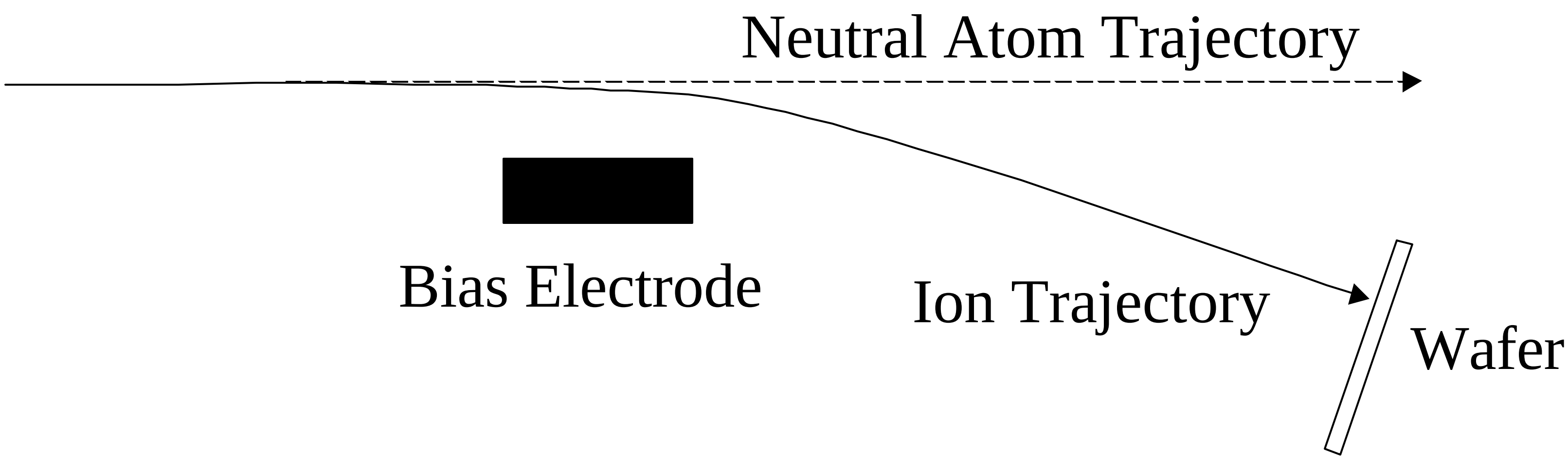
Post Acceleration



Ion Beam Current Control



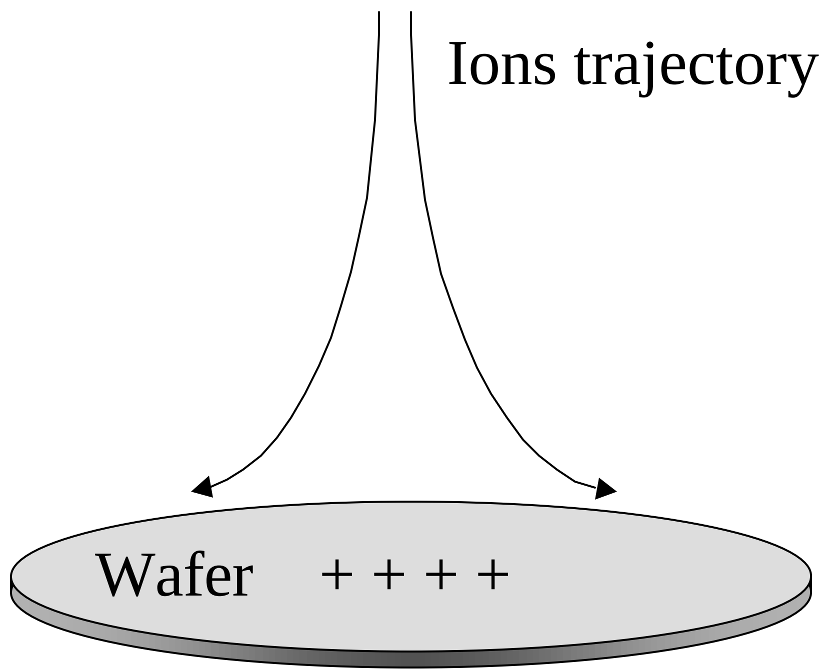
Bending Ion Trajectory



Charge Neutralization System

- Implanted ions charge wafer positively
- Cause wafer charging effect
- Expel positive ion, cause beam blowup and result non-uniform dopant distribution
- Discharge arcing create defects on wafer
- Breakdown gate oxide, low yield
- Need eliminate or minimize charging effect

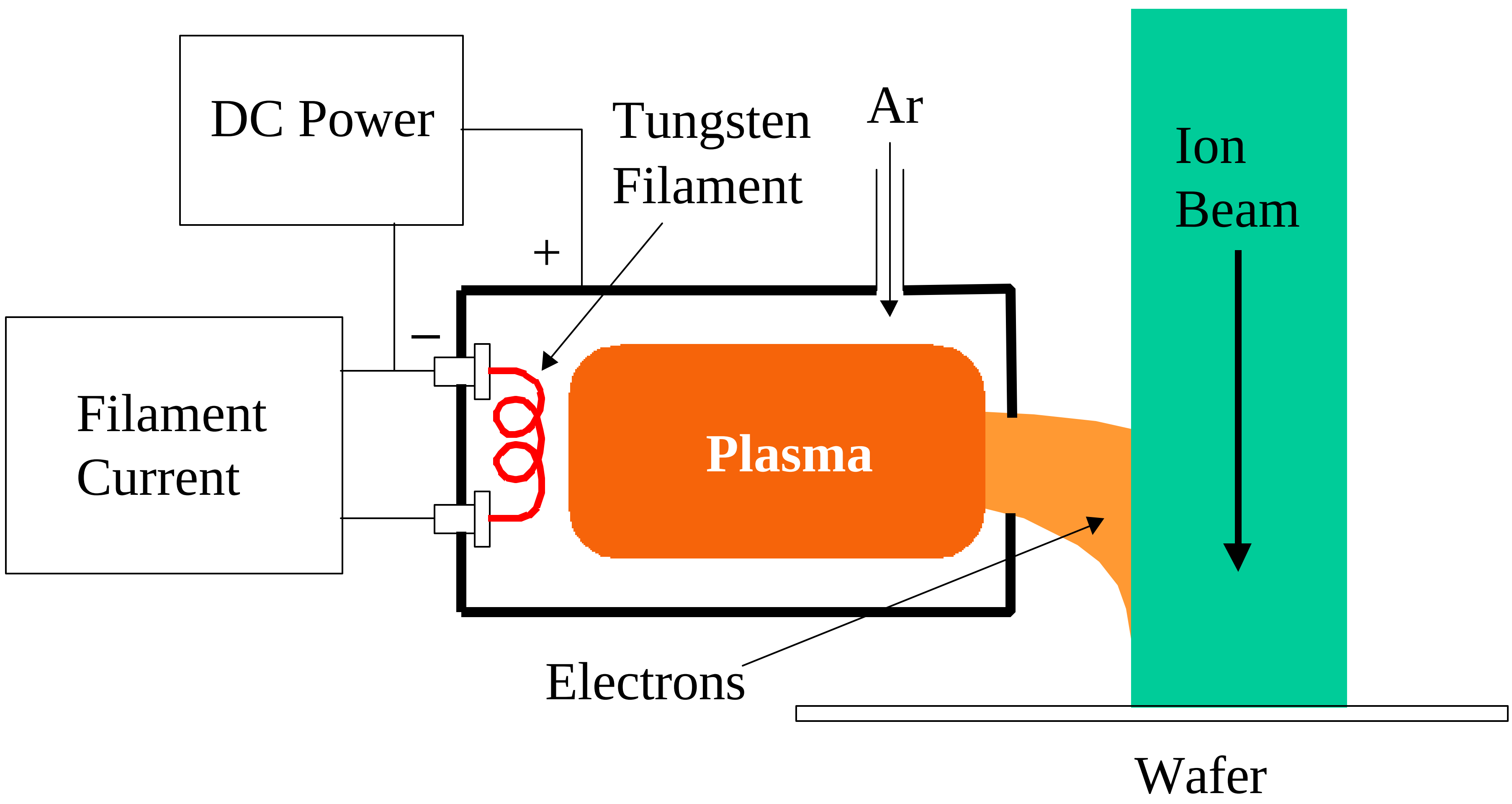
Charging Effect



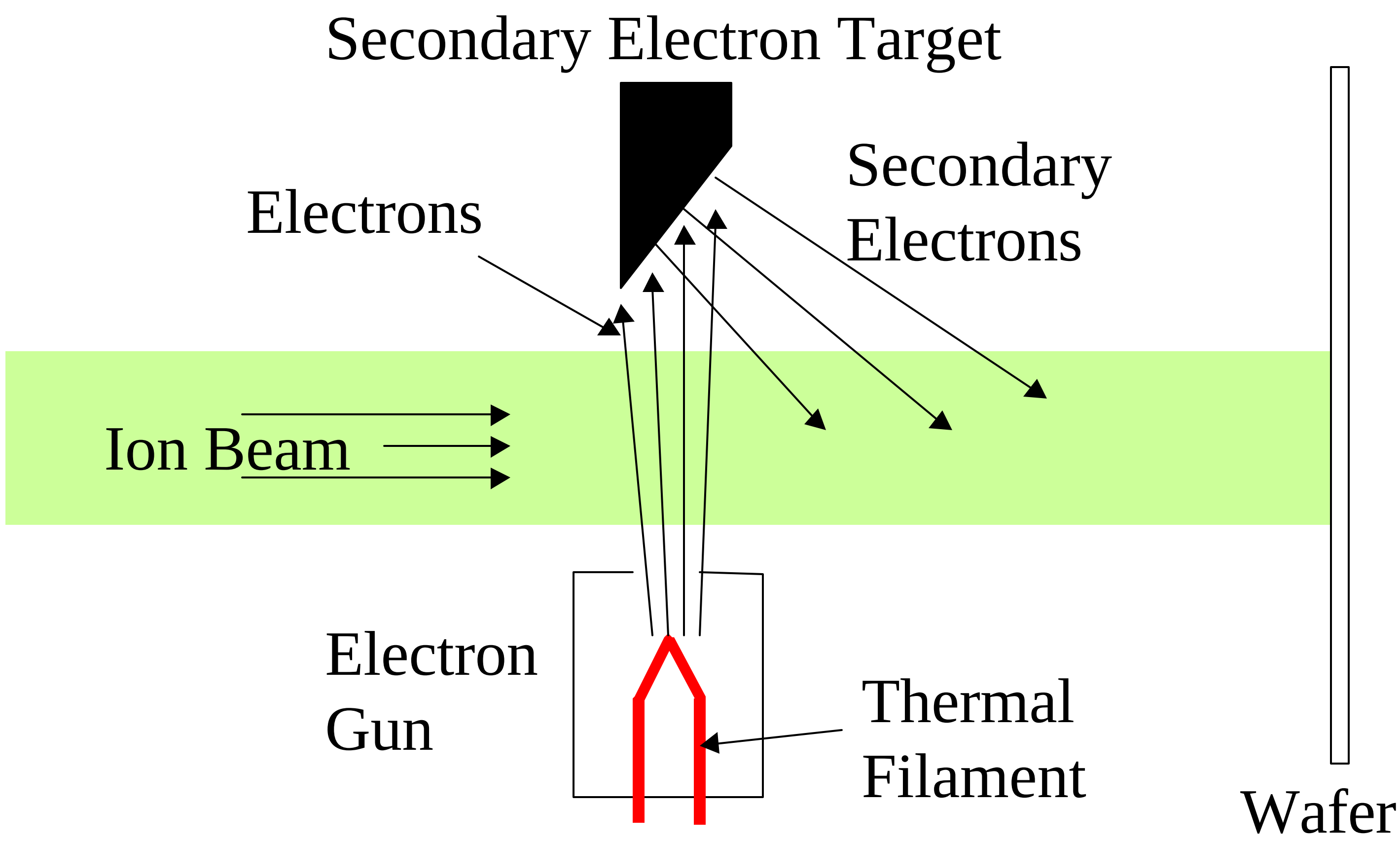
Charge Neutralization System

- Need to provide electrons to neutralize ions
- Plasma flooding system
- Electron gun
- Electron shower are used to

Plasma Flooding System



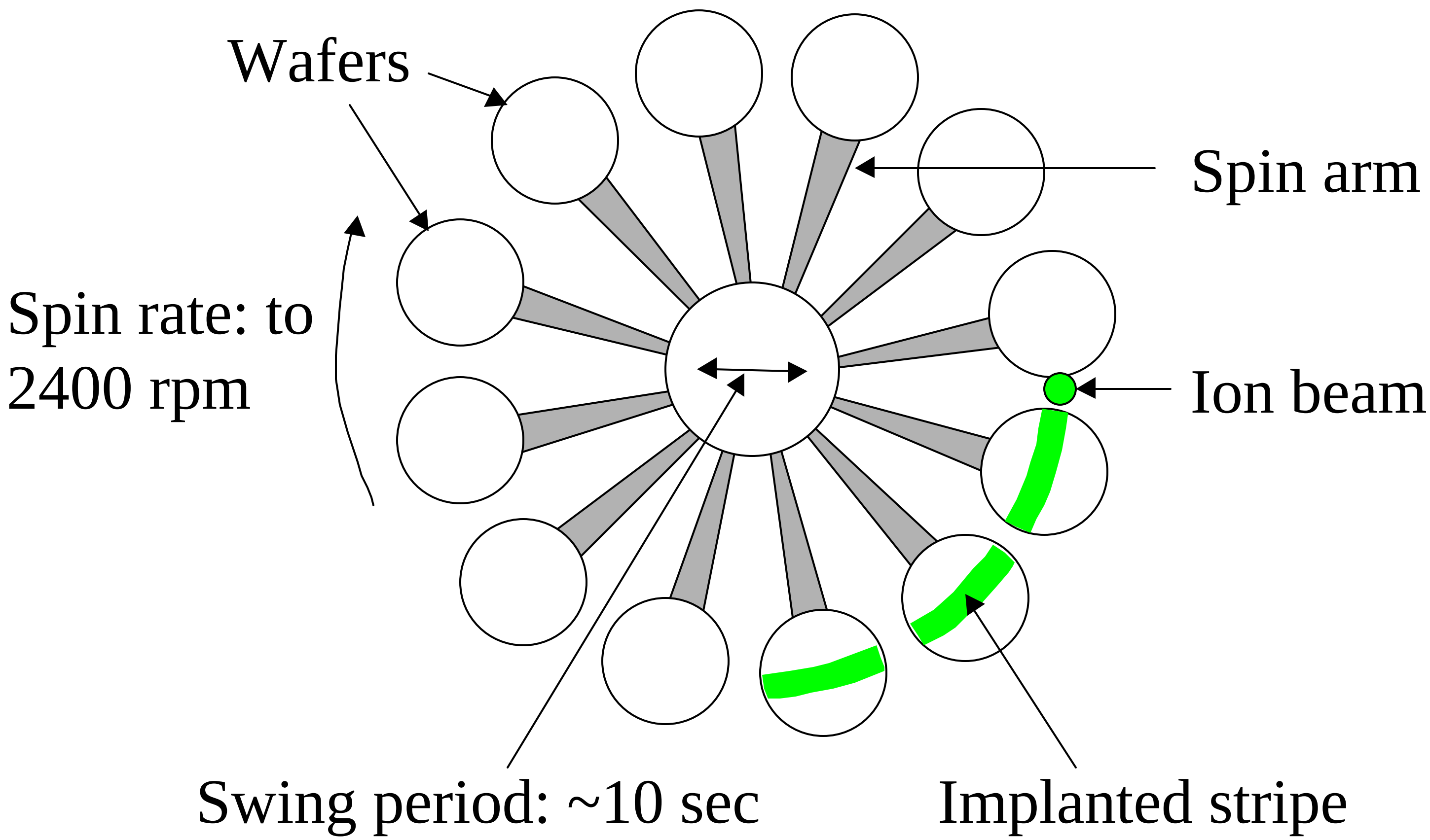
Electron Gun



Wafer Handling

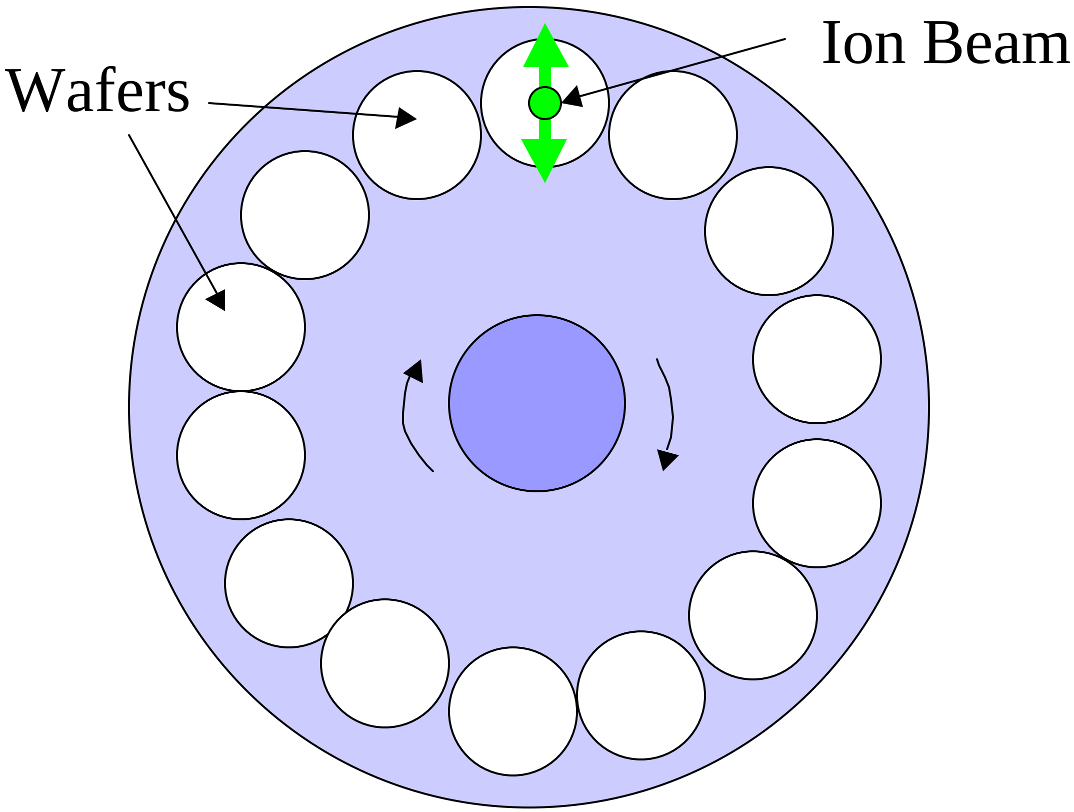
- Ion beam diameter: ~25 mm (~1”),
- Wafer diameter: 200 mm (8”) or larger
- Needs to move beam or wafer, or both, to scan ion beam across the whole wafer
  - Spin wheel
  - Spin disk
  - Single wafer scan

Spin Wheel

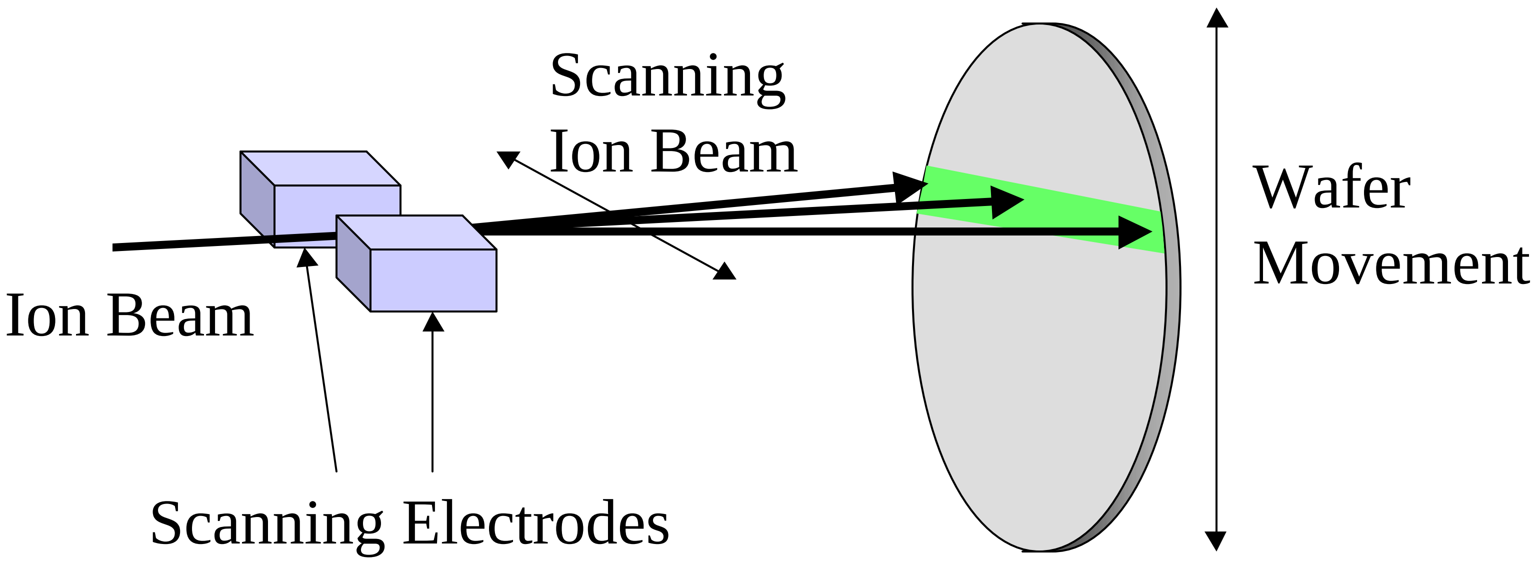


Wafers
Spin arm
Spin rate: to 2400 rpm
Ion beam
Swing period: ~10 sec
Implanted stripe

Spin Disk



Single Wafer Scanning System



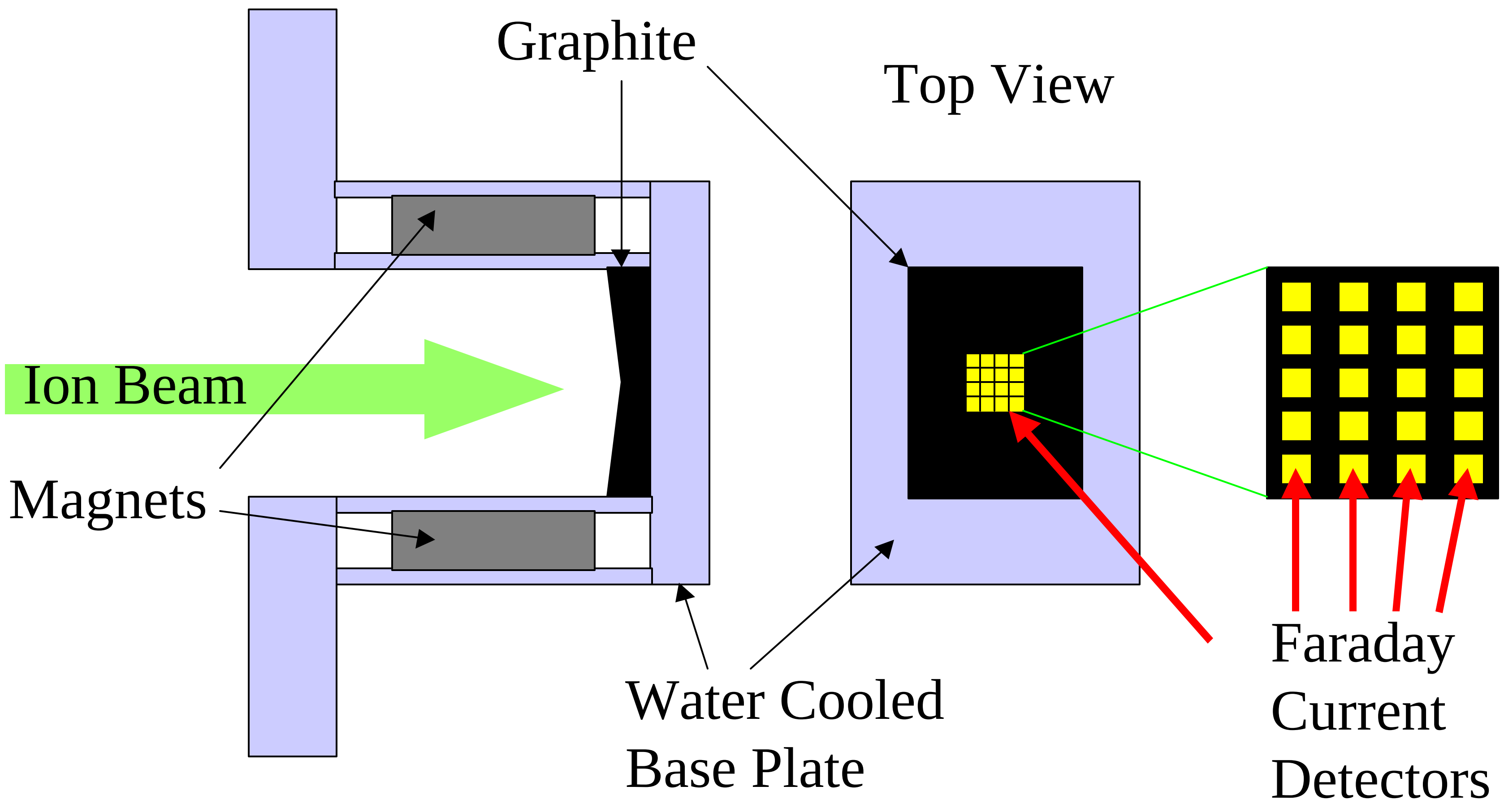
Ion Implantation: Beam Stop

- absorb the ion beam energy,
- ion beam detector
  - beam current, beam energy, and beam shape measurement
- Water cooled metal plate carries away the heat and blocks the X-ray radiation

Ion Implantation: End Analyzer

- Faraday charge detector
- Used to calibrate beam current, energy and profile

Beam Stop


Graphite
Top View
Ion Beam
Magnets
Water Cooled
Base Plate
Faraday
Current
Detectors

Ion Implantation: The Process

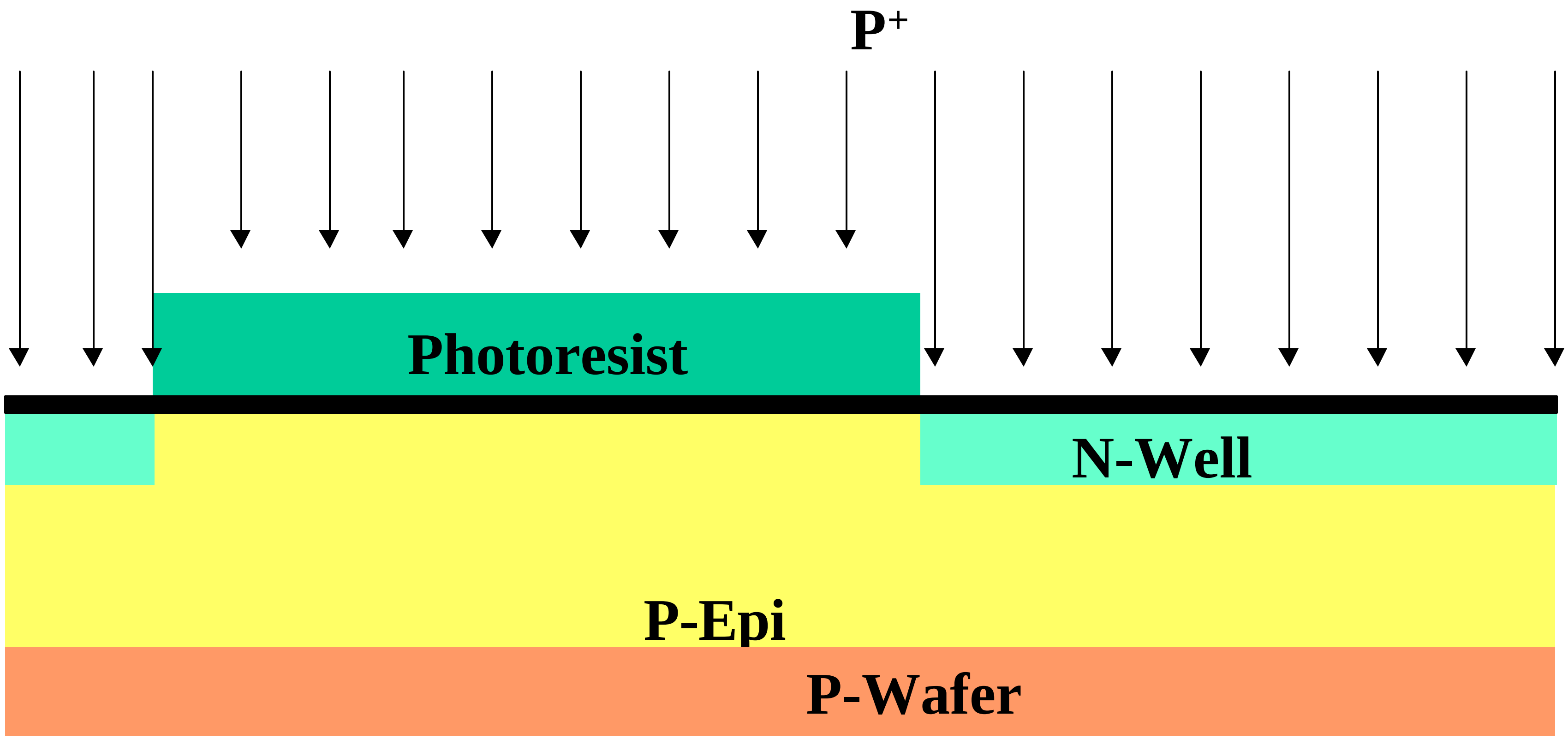
- CMOS applications
- CMOS ion implantation requirements
- Implantation process evaluations

CMOS Implantation Requirements

Implant Step	0.35 mm, 64 Mb	0.25 mm, 256 Mb	0.18 mm, 1 Gb
N-well			
Well	P/600/2×10^{13}	P/400/2×10^{13}	P/300/1×10^{13}
Anti-punch through	P/100/5×10^{13}	As/100/5×10^{12}	As/50/2×10^{12}
Threshold	B/10/7×10^{12}	B/5/3×10^{12}	B/2/4×10^{12}
Poly dope	P/30/2×10^{15}	B/20/2×10^{15}	B/20/3×10^{15}
Poly diffusion block	-	-	N_2/20/3×10^{15}
Lightly doped drain (LDD)	B/7/5×10^{13}	B/5/1×10^{14}	B/2/8×10^{13}
Halo (45° implant)	-	-	As/30/5×10^{13}
Source/drain contact	B/10/2×10^{15}	B/7/2×10^{15}	B/6/2×10^{15}
P-well			
Well	B/225/3×10^{13}	B/200/1×10^{13}	B/175/1×10^{13}
Anti-punch through	B/30/2×10^{13}	B/50/5×10^{12}	B/45/5×10^{12}
Threshold	B/10/7×10^{12}	B/5/3×10^{12}	B/2/4×10^{12}
Poly dope	P/30/5×10^{15}	P/20/2×10^{15}	As/40/3×10^{15}
Poly diffusion block	-	-	N_2/20/3×10^{15}
Lightly doped drain (LDD)	P/20/5×10^{13}	P/12/5×10^{13}	P/5/3×10^{13}
Halo (45° implant)	B/30/3×10^{12}	B/20/3×10^{12}	B/7/2×10^{13}
Source/drain contact	As/30/3×10^{15}	As/20/3×10^{15}	As/15/3×10^{15}

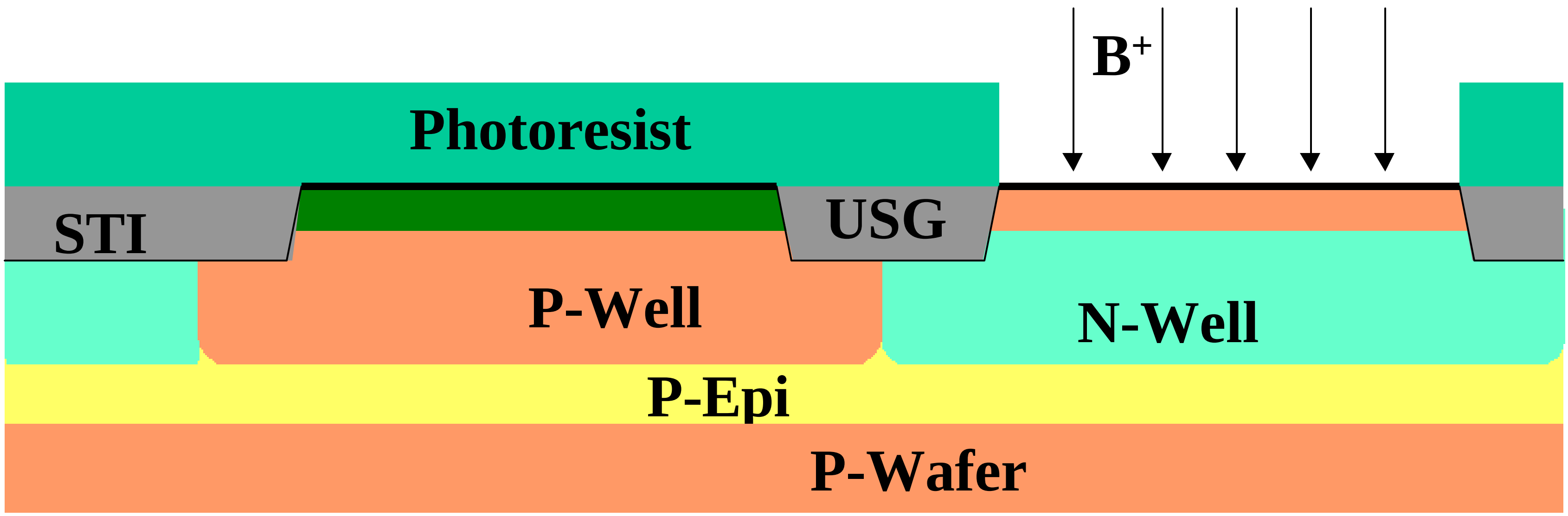
Implantation Process: Well Implantation

- High energy (to MeV), low current ($10^{13}/cm^2$)



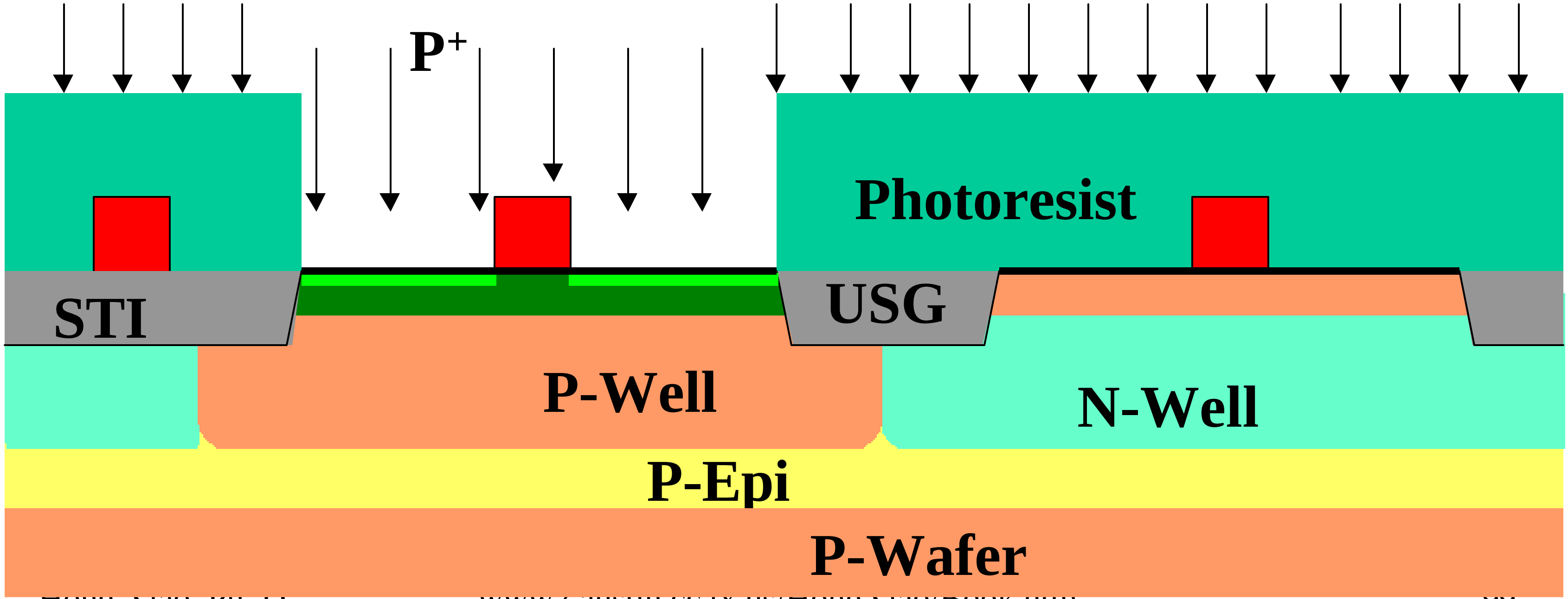
Implantation Process: V_T Adjust Implantation

Low Energy , Low Current



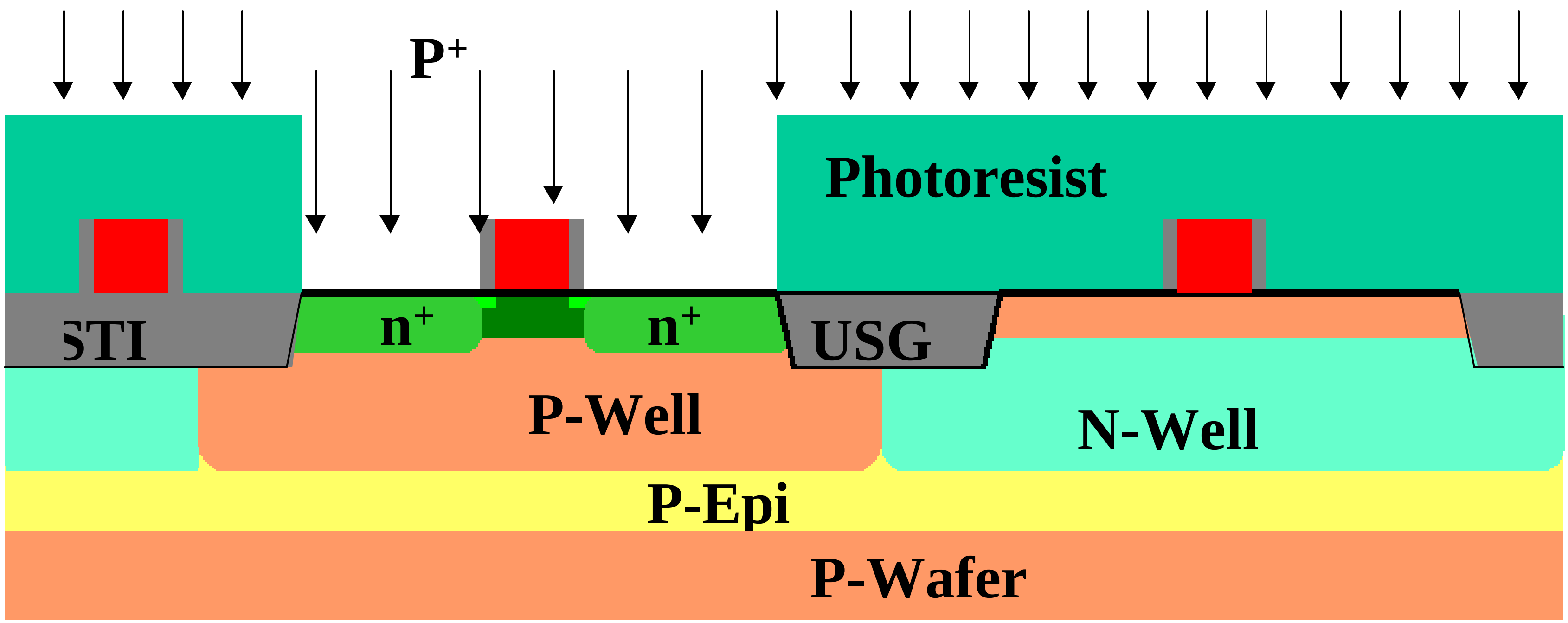
Lightly Doped Drain (LDD) Implantation

- Low energy (10 keV), low current ($10^{13}/cm^2$)



Implantation Process: S/D Implantation

- Low energy (20 keV), high current (>10^{15}/cm^2)



Ion Implantation Processes

Ion Implantation	Energy	Current
Well	High energy	low current
Source/Drain	Low energy	high current
V_T Adjust	Low energy	low current
LDD	Low energy	low current

Process Issues

- Wafer charging
- Particle contamination
- Elemental contamination
- Process evaluation

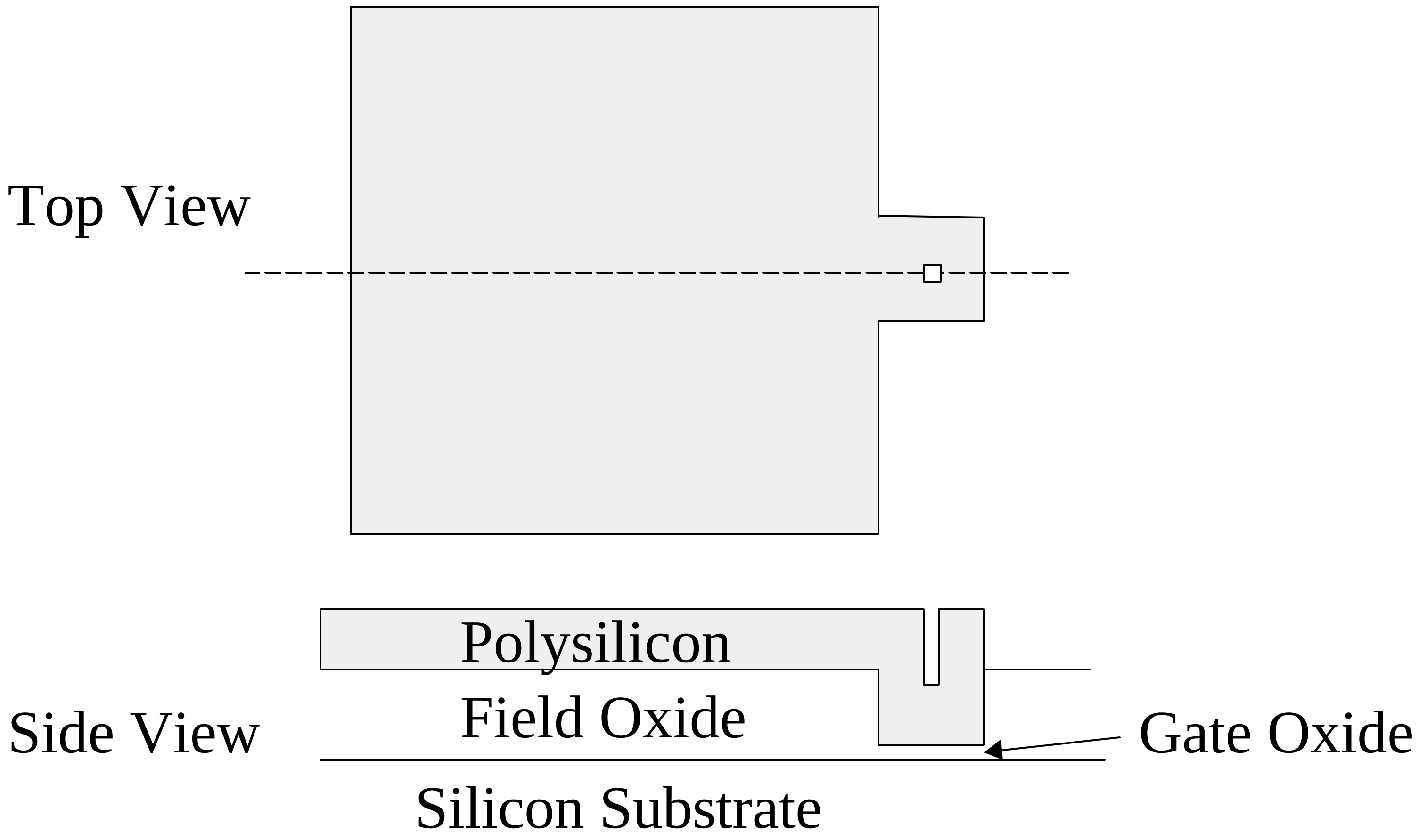
Wafer Charging

- Break down gate oxide
- Dielectric strength of SiO_2: ~10 MV/cm
- 100 Å oxide breakdown voltage is 10 V
- Gate oxide: 30 to 35 Å for 0.18 μm device
- Require better charge neutralization

Wafer Charging Monitoring

- Antenna capacitor changing test structure
- The ratio of polysilicon pad area and thin oxide area is called antenna ratio
- Can be as high as 100,000:1
- The larger antenna ratio, the easier to breakdown the thin gate oxide

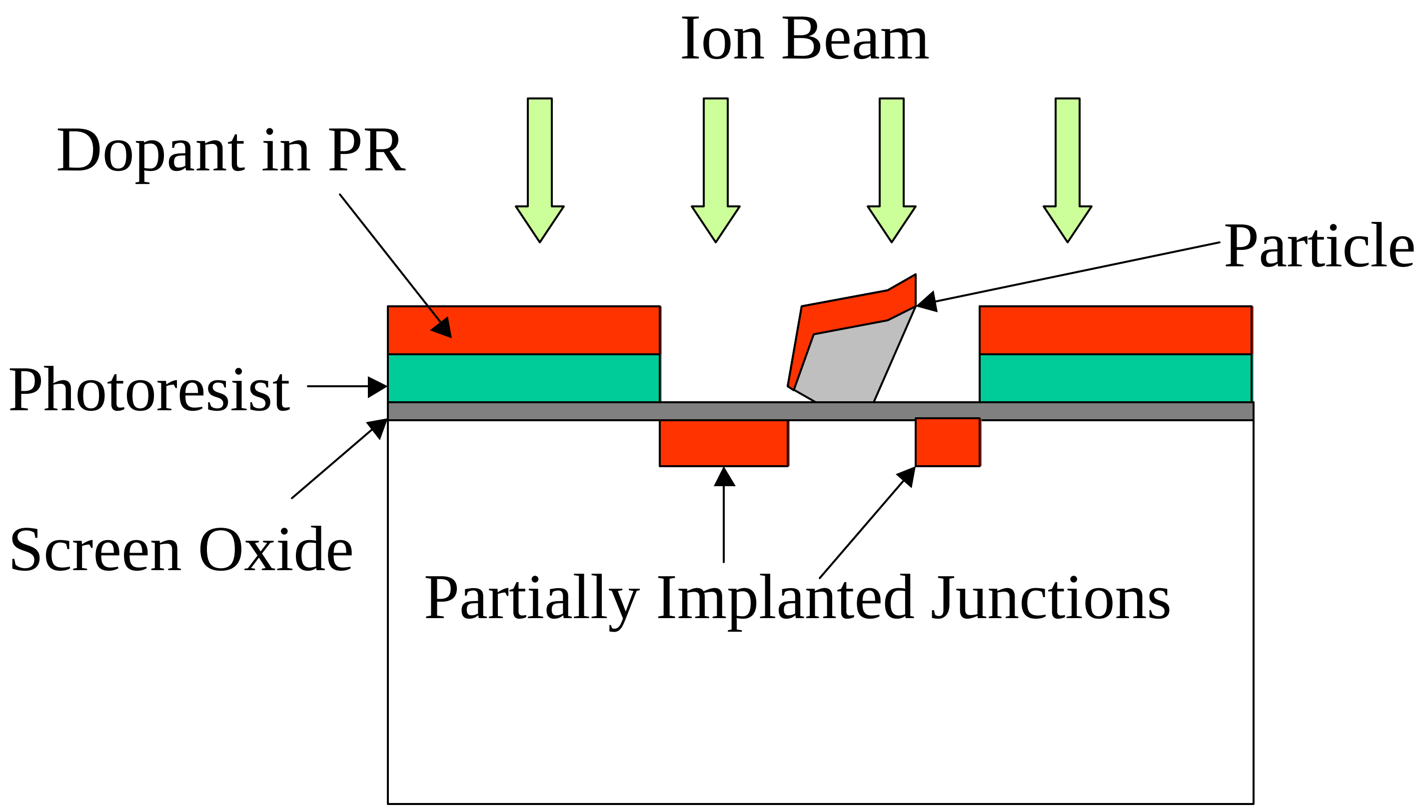
Antenna Ratio



Particle Contamination

- Large particles can block the ion beam especially for the low energy processes,
- V_T adjust, LDD and S/D implantations,
- Cause incomplete dopant junction.
- Harmful to yield

Effect of Particle Contamination



Elemental Contamination

- Co-implantation other elements with intended dopant
- $^{94}Mo^{++}$ and $^{11}BF_2^{+}$, same mass/charge ratio (A/e = 49)
- Mass analyzer can't separate these two
- $^{94}Mo^{++}$ causes heavy metal contamination
- Ion source can't use standard stainless steel
- Other materials such as graphite and tantalum are normally used

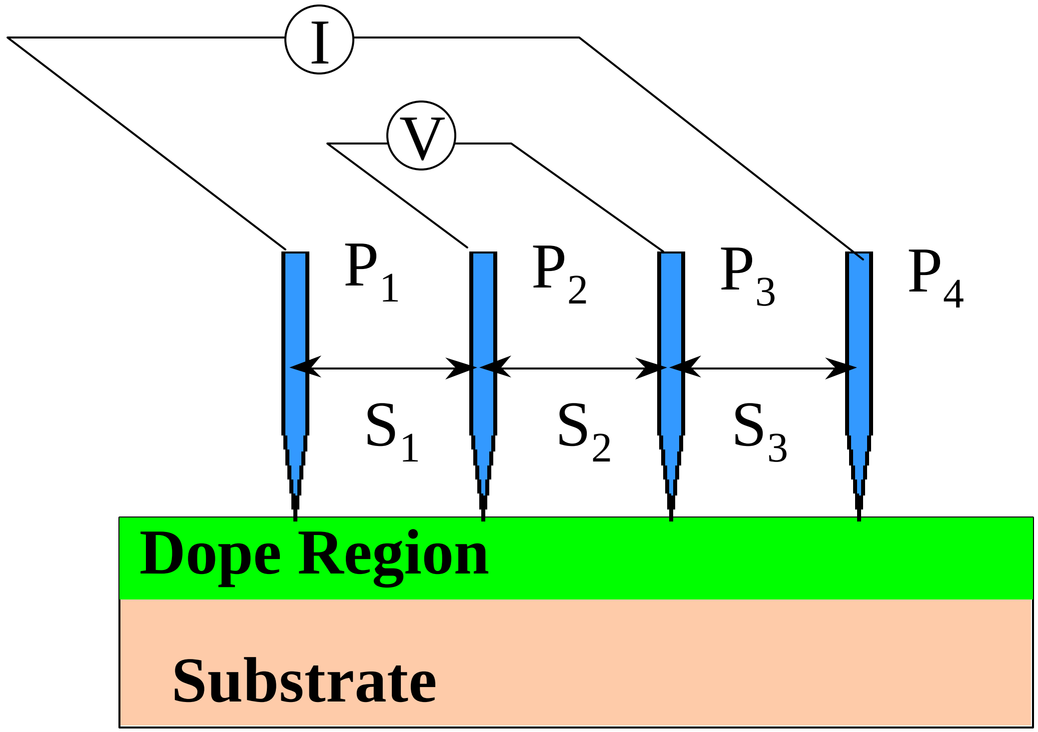
Process Evaluation

- Four-point probe
- Thermal wave
- Optical measurement system (OMS)

Four-Point Probe

- Perform after anneal
- Measure sheet resistance
- Sheet resistant is a function of dopant concentration and junction depth
- Commonly used to monitor doping process

Four-Point Probe Measurement

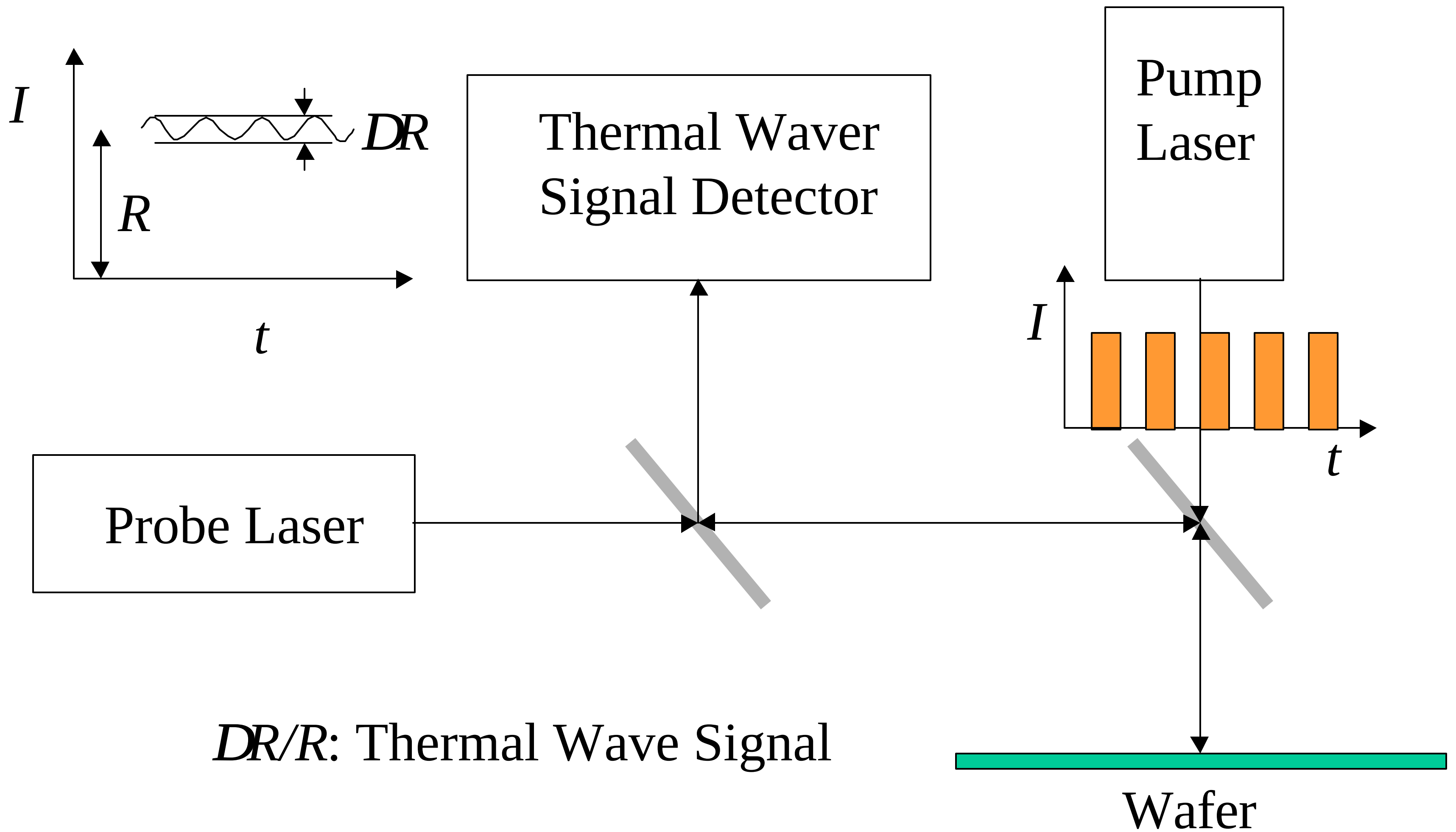


For a typical four-point probe, $S_1 = S_2 = S_3 = 1\text{mm}$,
If current is applied between P_1 and P_4, $R_s = 4.53\ V/I$
If current is applied between P_1 and P_3, $R_s = 5.75\ V/I$

Thermal Wave System

- Argon "pump" laser generates thermal pulses on wafer surface
- He-Ne probe laser measures DC reflectivity (*R*) and reflectivity modulation induced by the pump laser (*DR*) at the same spot
- Ratio *DR*/*R* is called thermal wave (TW) signal,
  - TW signal *DR*/*R* related to the crystal damage
  - crystal damage is a function of the implant dose

Thermal Wave System



DR/R: Thermal Wave Signal

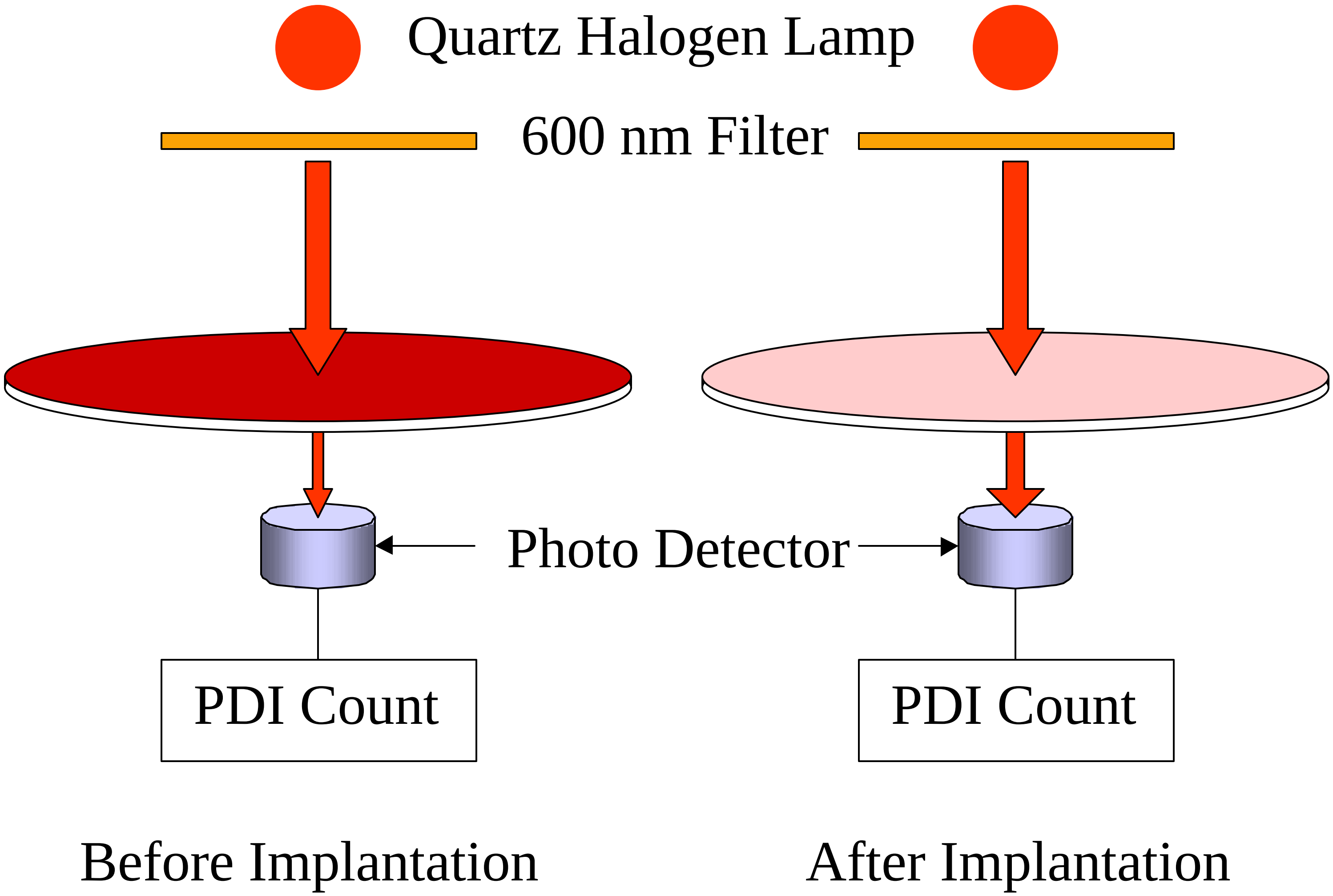
Thermal Wave System

- Performed immediately after the implant process
  - Four-point probe needs anneal first
- Non-destructive, can measure production wafers
  - Four-point probe is only good for test wafers
- Low sensitivity at low dosage
- Drift of the TW signal over time
  - needs to be taken as soon as the implantation finished
- Don’t have very high measurement accuracy
  - Laser heating relax crystal damage

Optical Measurement System (OMS)

- transparent wafer coated a with a thin layer of copolymer, which contains energy sensitive dye
- During ion implantation, energetic ions collide with dye molecules and break them down
- Makes the copolymer becomes more transparent
- The higher the dosage, the higher the transparency
- Photon count change before and after implantation
- Determine dosage of certain ion at certain energy

Optical Measurement System (OME)



Ion Implantation: Safety

- One of most hazardous process tools in semiconductor industry
- Chemical
- Electro-magnetic
- Mechanical

Ion Implantation: Chemical Safety

- Most dopant materials are highly toxic, flammable and explosive.
- Poisonous and explosive: AsH_3, PH_3, B_2H_6
- Corrosive: BF_3
- Toxic: P, B, As, Sb

- Common sense: get out first, let the trained people to do the investigation.

Ion Implantation: Electro-magnetic Safety

- High voltage: from facility 208 V to acceleration electrode up to 50 kV.
- Ground strip, Work with buddy!
- Lock & tag

- Magnetic field: pacemaker, etc.

Ion Implantation: Radiation Safety

- High energy ions cause strong X-ray radiation
- Normally well shield

Ion Implantation: Corrosive by-products

- BF_3 as dopant gas
- Fluorine will react with hydrogen to from HF
- Anything in the beamline could have HF
- Double glove needed while wet clean those parts

Ion Implantation: Mechanical Safety

- Moving parts, doors, valves and robots
- Spin wheel
- Hot surface
- ……

Technology Trends

- Ultra shallow junction (USJ)
- Silicon on insulator (SOI)
- Plasma immersion ion implantation (PIII)

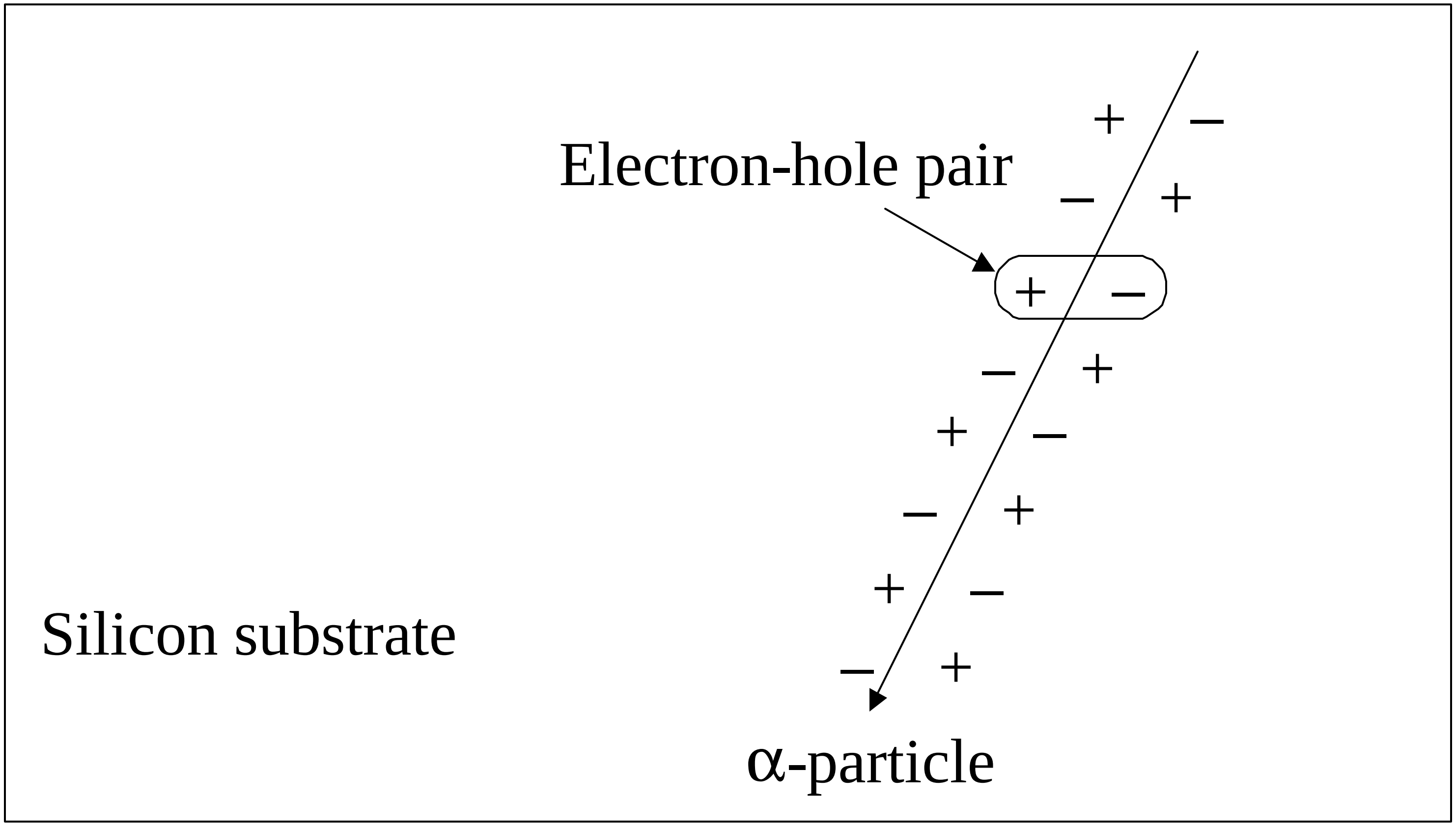
Ultra Shallow Junction (USJ)

- USJ ($x_j \leq 0.05$ μm) for sub-0.1 μm devices
  - p-type junction, boron ion beam at extremely low energy, as low as 0.2 keV
- The requirements for the USJ
  - Shallow
  - Low sheet resistance
  - Low contact resistance
  - Minimal impact on channel profile
  - Compatible with polysilicon gate

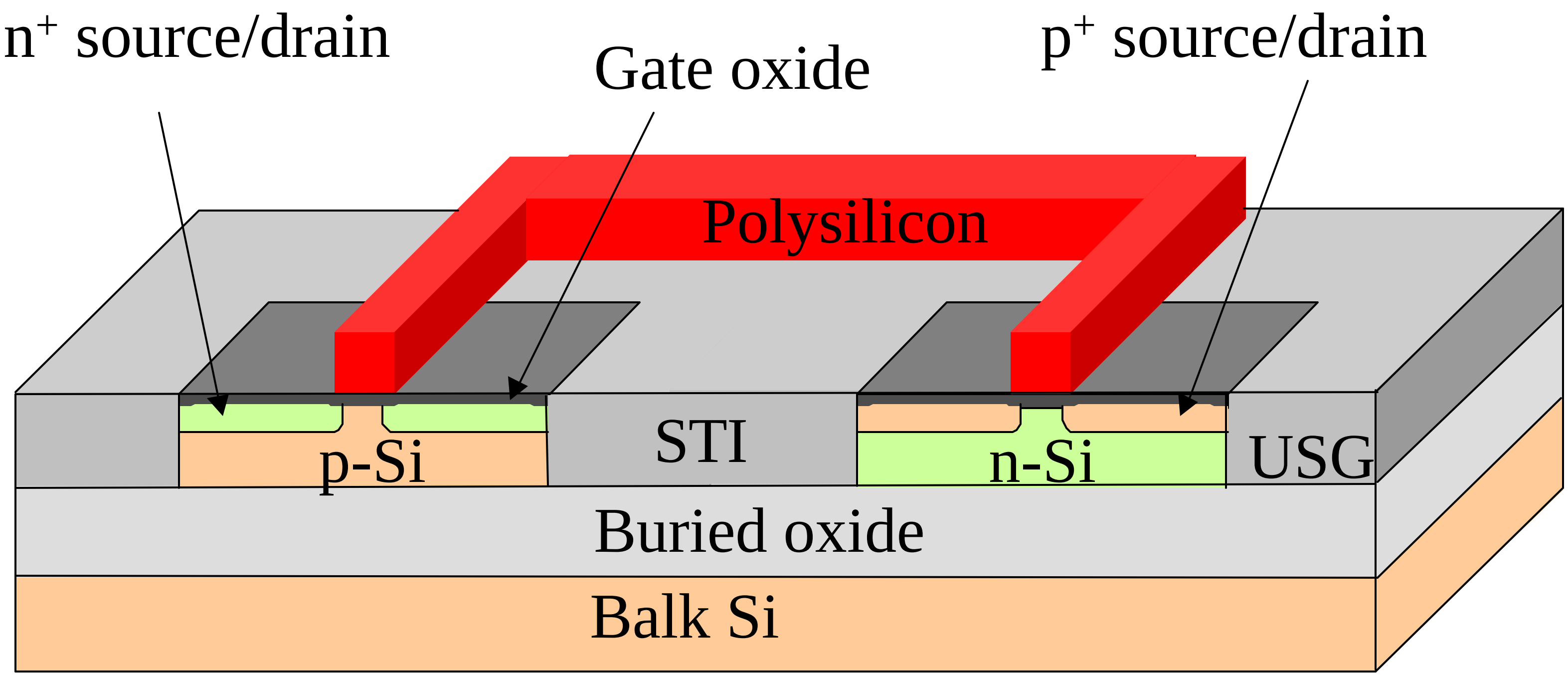
Soft Error

- Electron-hole pairs generated by α-decay
- Electrons from substrate overwrite the messages in memory capacitors
  - Storage capacitors need large capacitance
  - Limit further shrinking device feature size
- Silicon-on-insulator (SOI) complete isolate device from bulk substrate

α-particle Induced Electron-hole Pairs



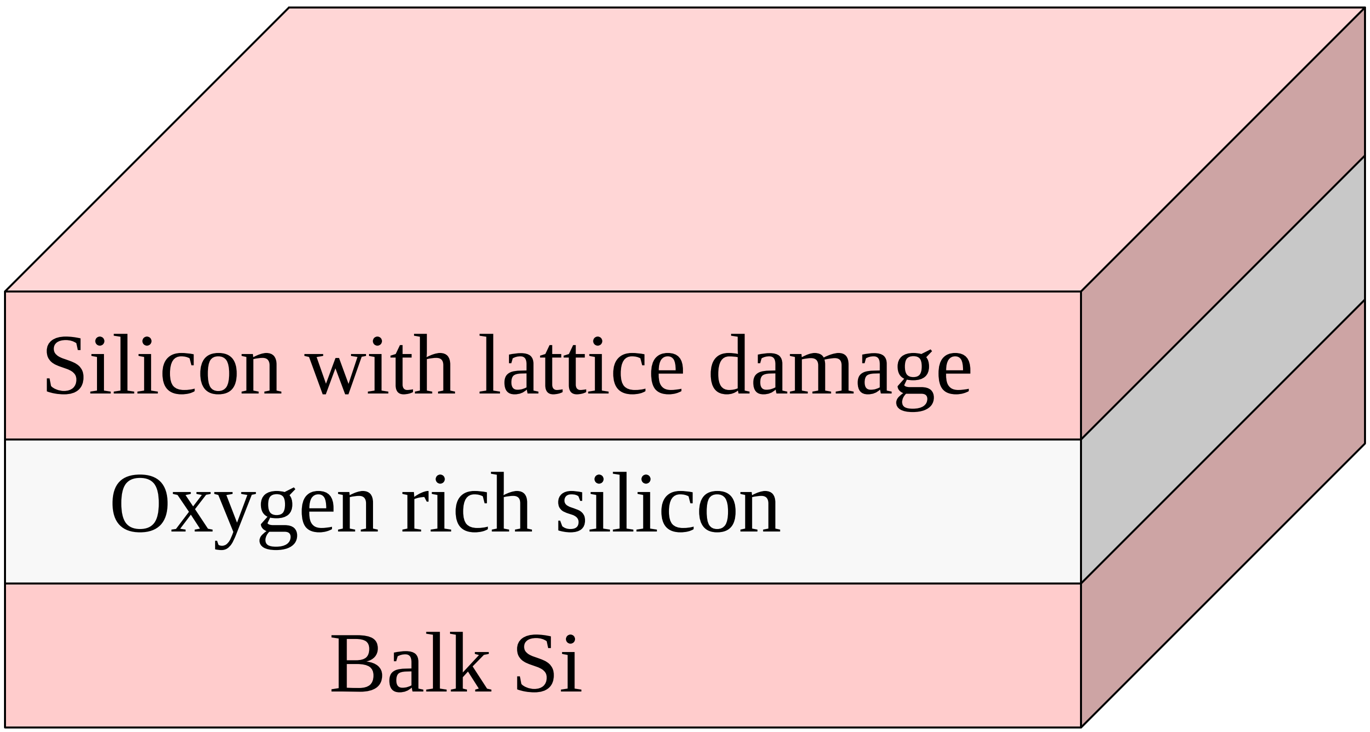
CMOS on SOI Substrate



SOI Formation

- Implanted wafers
  - Heavy oxygen ion implantation
  - High temperature annealing
- Bonded wafers
  - Two wafers
  - Grow oxide on one wafer
  - High temperature bond wafer bonding
  - Polish one wafer until thousand Å away from SiO_2

Oxygen Ion Implantation

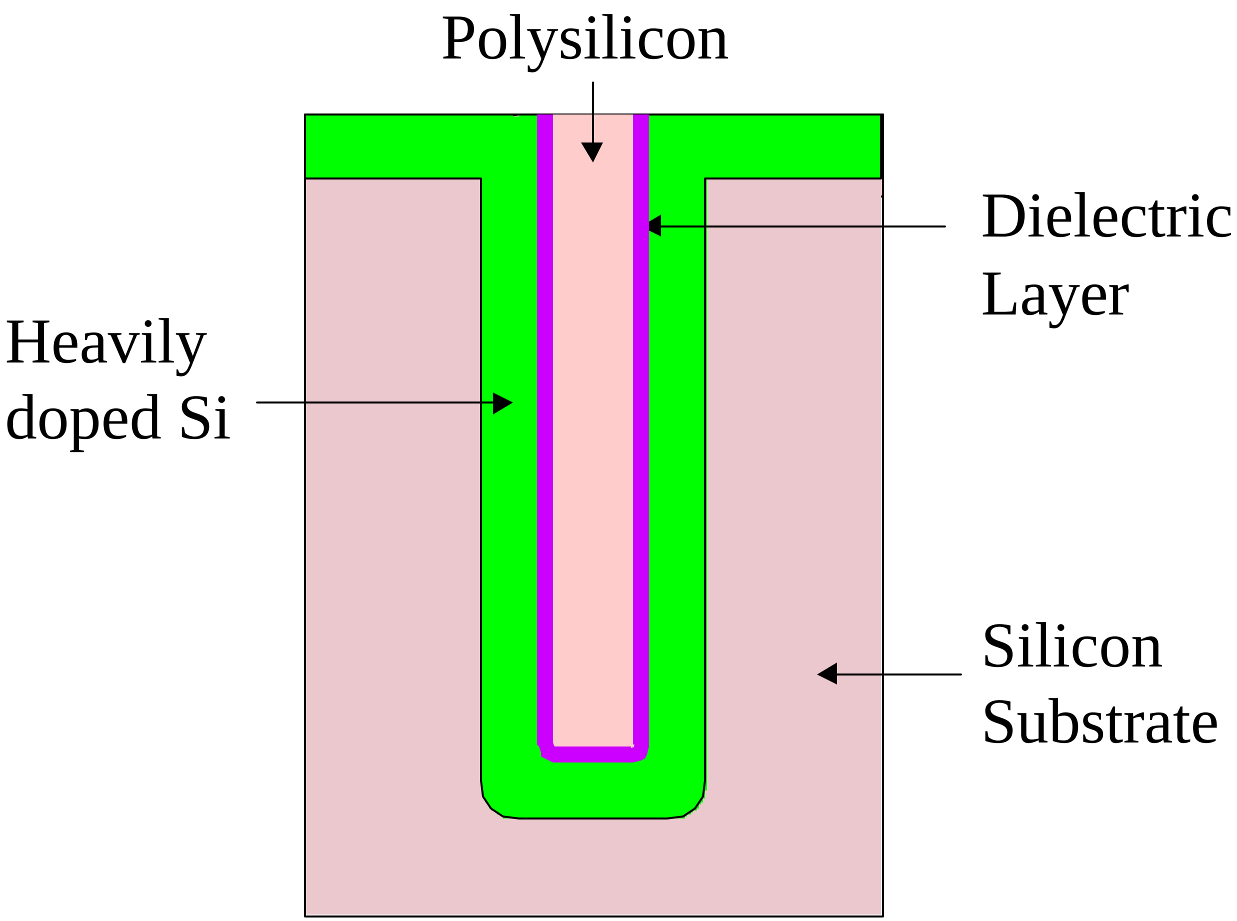


High Temperature Annealing

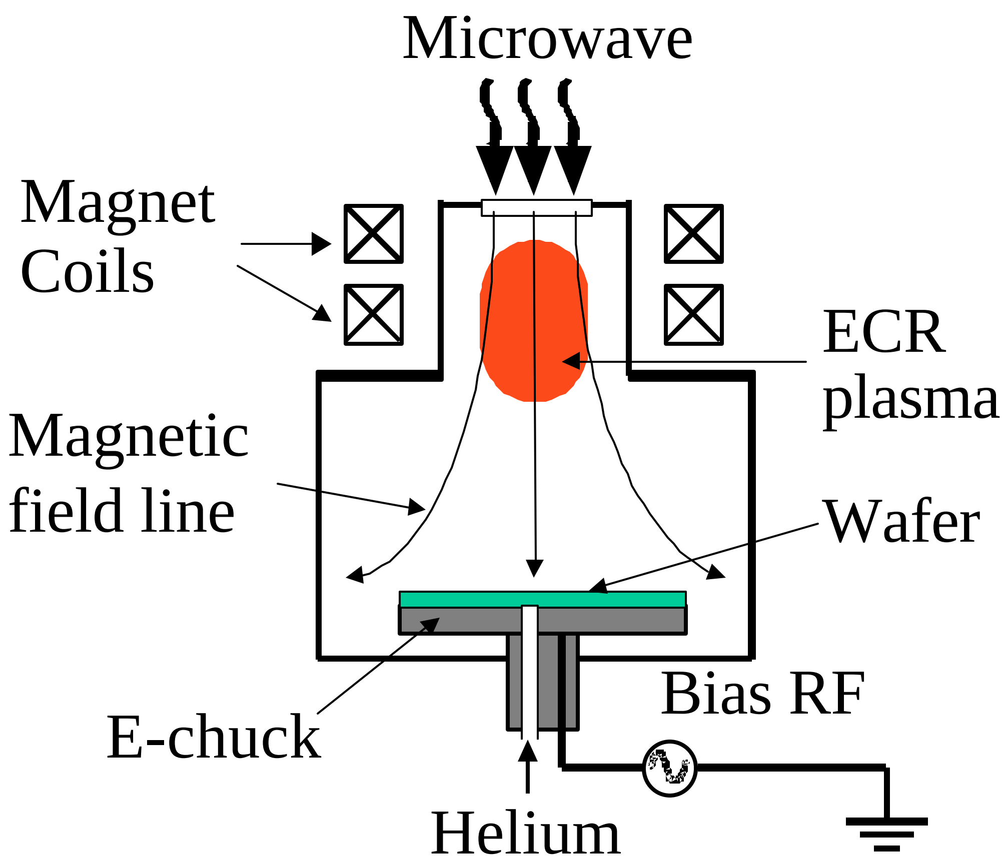
Plasma Immersion Ion Implantation

- Deep trench capacitor for DRAM
- Deeper and narrower
- Very difficult to heavily dope both sidewall and bottom by ion implantation
- Plasma immersion ion implantation (PIII)
- An ion implantation process without precise ion species and ion energy selection

Deep Trench Capacitor



ECR Plasma Immersion System



Summary of Ion Implantation

- Dope semiconductor
- Better doping method than diffusion
- Easy to control junction depth (by ion energy) and dopant concentration (by ion current and implantation time).
- Anisotropic dopant profile.

Summary of Ion Implantation

- Ion source
- Extraction
- Analyzer magnets
- Post acceleration
- Charge neutralization system
- Beam stop

Summary of Ion Implantation

• Well	High energy, low current
• Source/Drain	Low energy, high current
• Vt Adjust	Low energy, low current
• LDD	Low energy, low current