Ion Implantation

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  - **Introduction**
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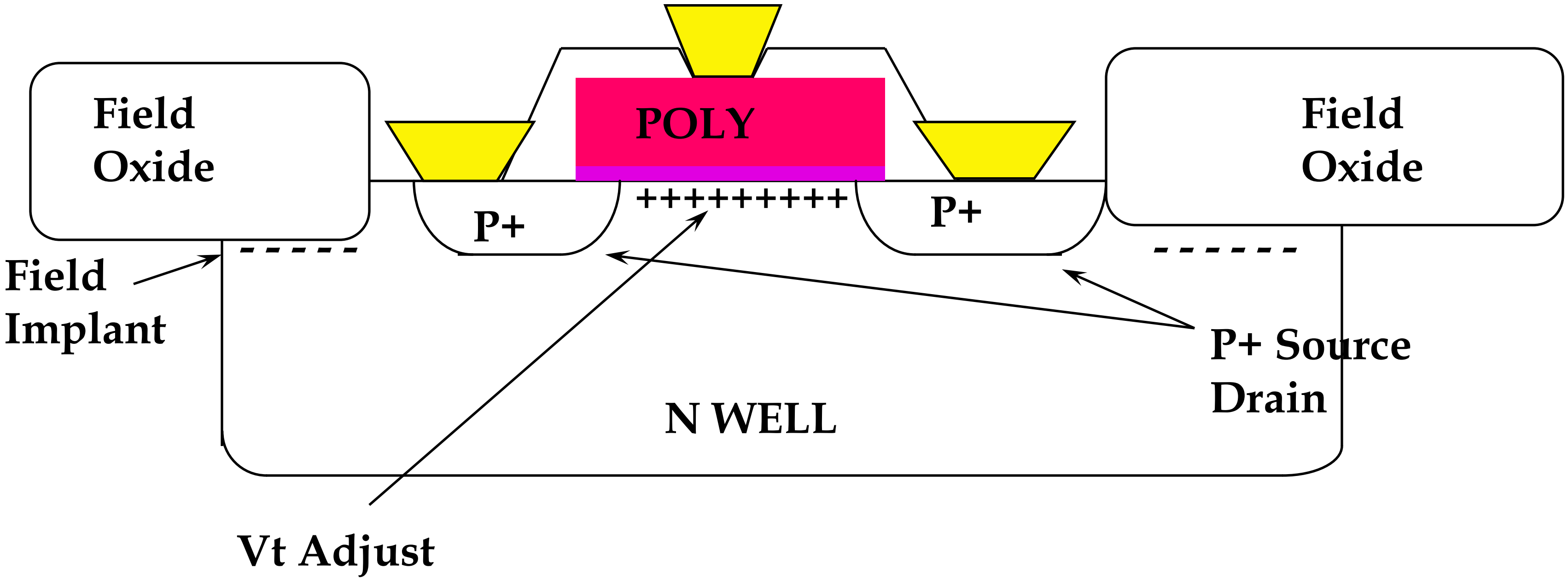
Introduction

- Introducing dopants into the silicon crystal can alter the “type” of the silicon
  - **from n type to p type and vise versa**
- Dopants are usually introduced in a two stage process
- Predeposition and Drive-in
- Implant and Drive-in (anneal)

Doping the Silicon



Doping the Silicon 2

- In older processes the Source /Drain regions were doped using Thermal Diffusion
- With the maturing of implant technology, CMOS processes became possible because of the greater control over the dopant quantities introduced to the silicon
- In CMOS processes up to about the 130nm node all of the doping with the exception of the saturation doping of polysilicon was done by implantation.
- Below the 130nm node this is also now done by implant with the poly doped N-Type over the N-Channel and P-Type over the P-Channel

Process Overview

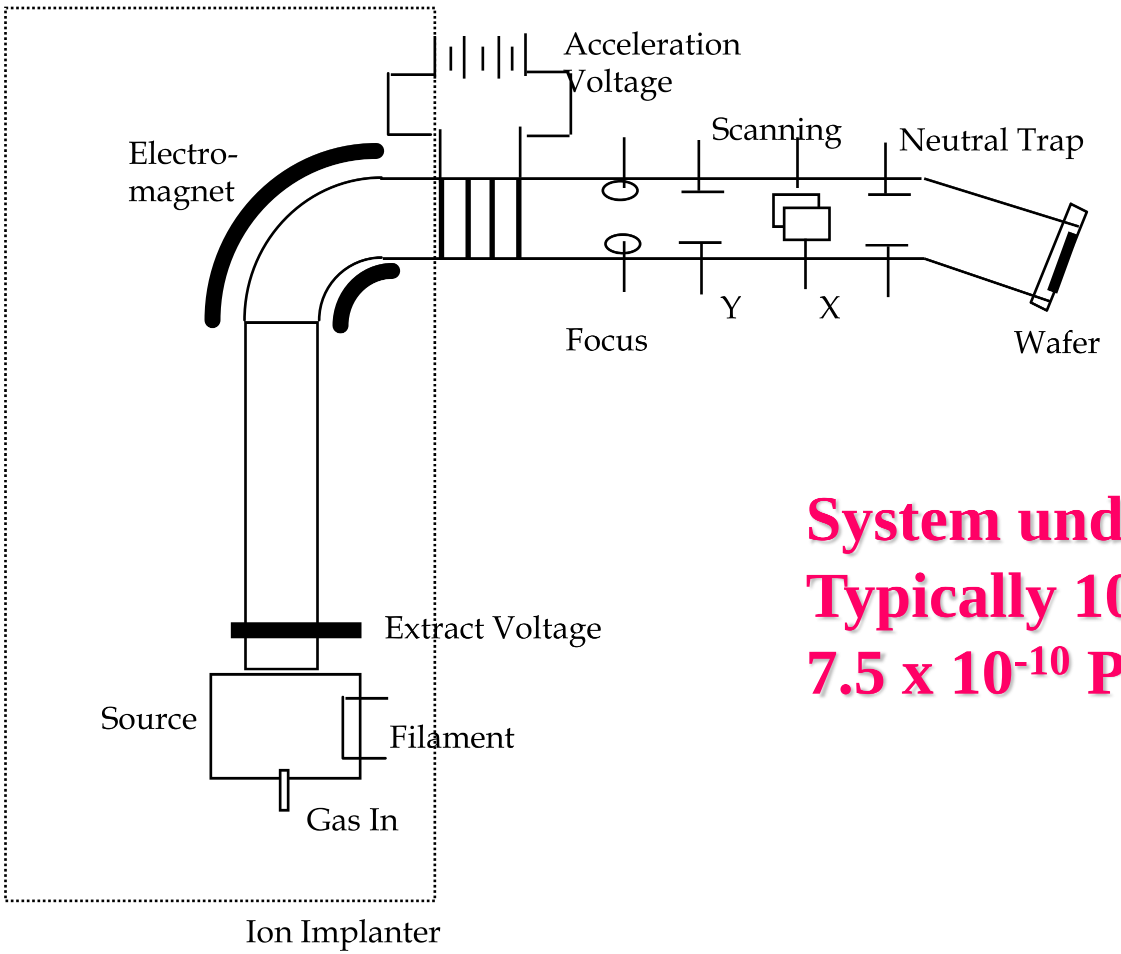
- Ion implantation is an enabling technology
- Single MOS processes were possible prior to the development of implantation
- Furnace doping techniques are too coarse for the fine control needed in the doping of the well regions in CMOS processes
- Furnace doping saturation dopes the surface during the pre-deposition stage, whereas implantation can control the dopant quantity down to the 10^{11} cm^{-2} region

SYSTEM OVERVIEW

- ION SOURCE
- MASS ANALYSIS
- ACCELERATION
- SCANNING
- DOSE MEASUREMENT
- VACUUM SYSTEM

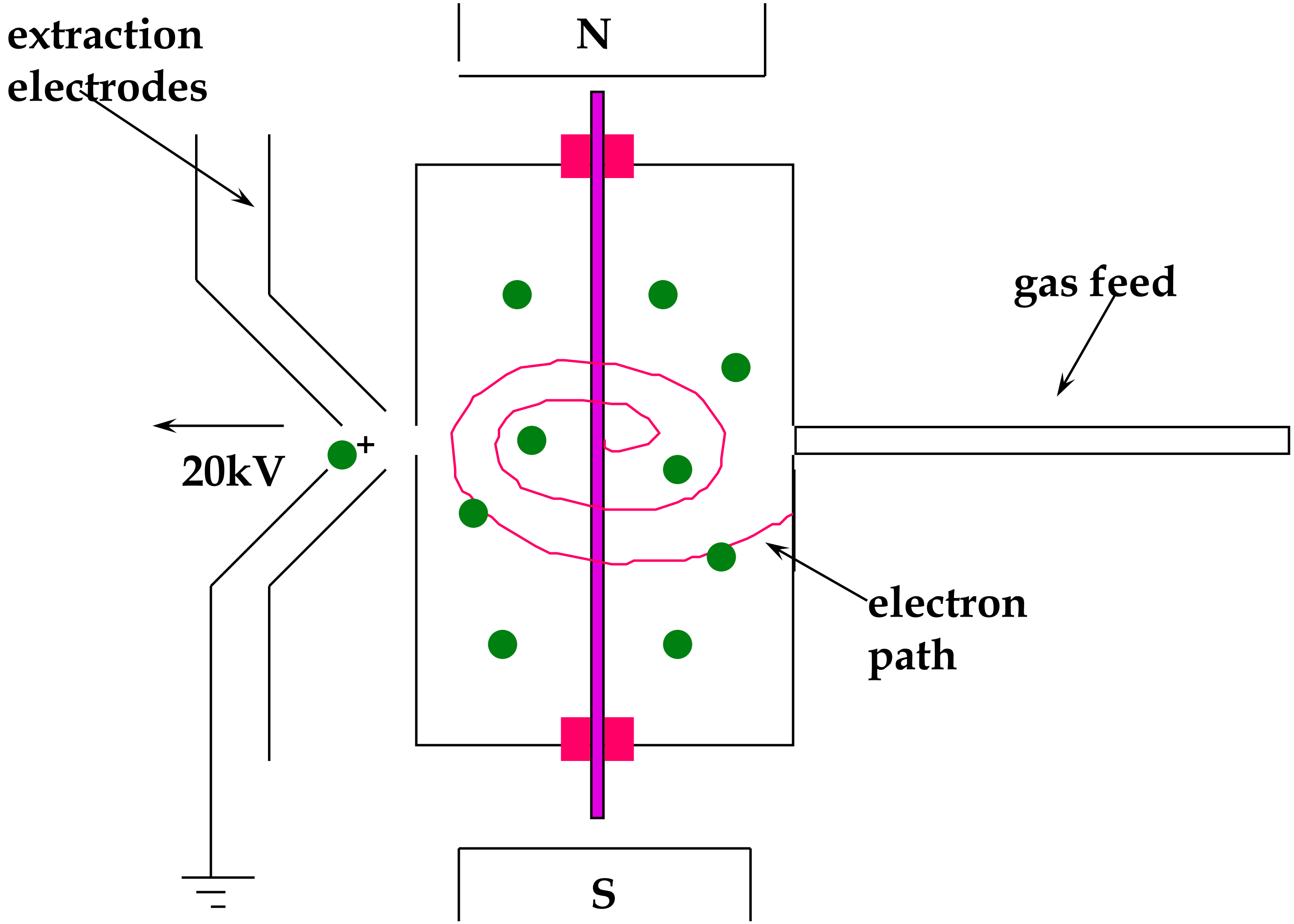
ION IMPLANTER SCHEMATIC

High Voltage Terminal



System under vacuum
Typically 10^{-8} Torr
7.5×10^{-10} Pa

ION SOURCE



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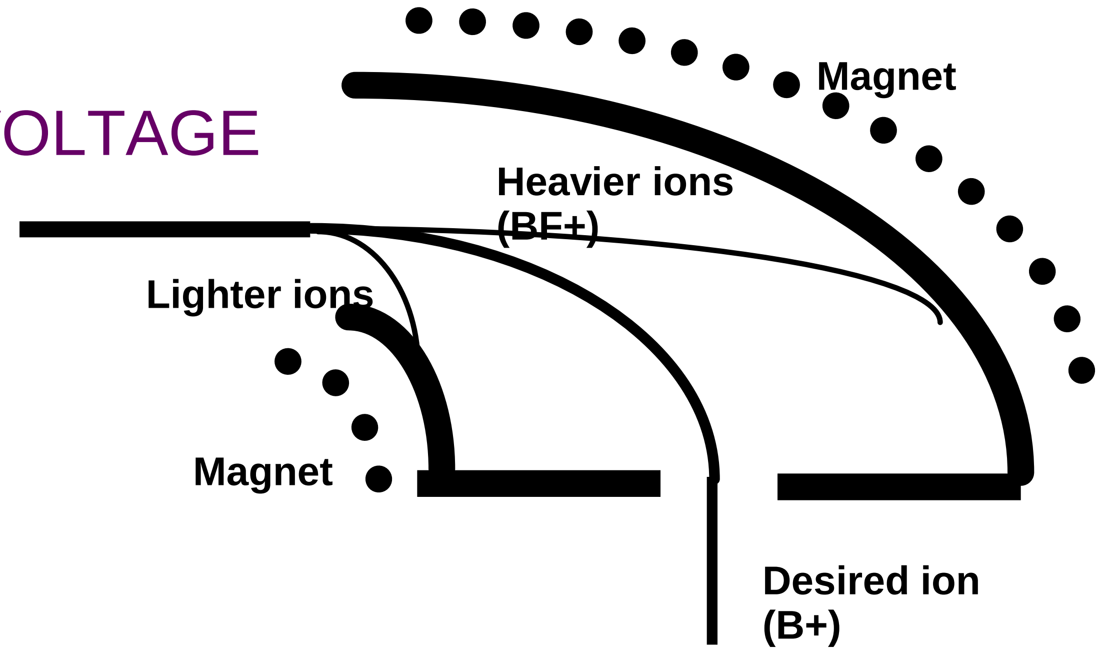
IMPLANT GASES

SPECIES	IMPLANTED SPECIES	SOURCE	DOPANT TYPE
BORON	B^{11}	BF_3	P TYPE
PHOSPHOROUS	P^{31}	PH_3	N TYPE
ARSENIC	As^{74}	AsH_3	NTYPE

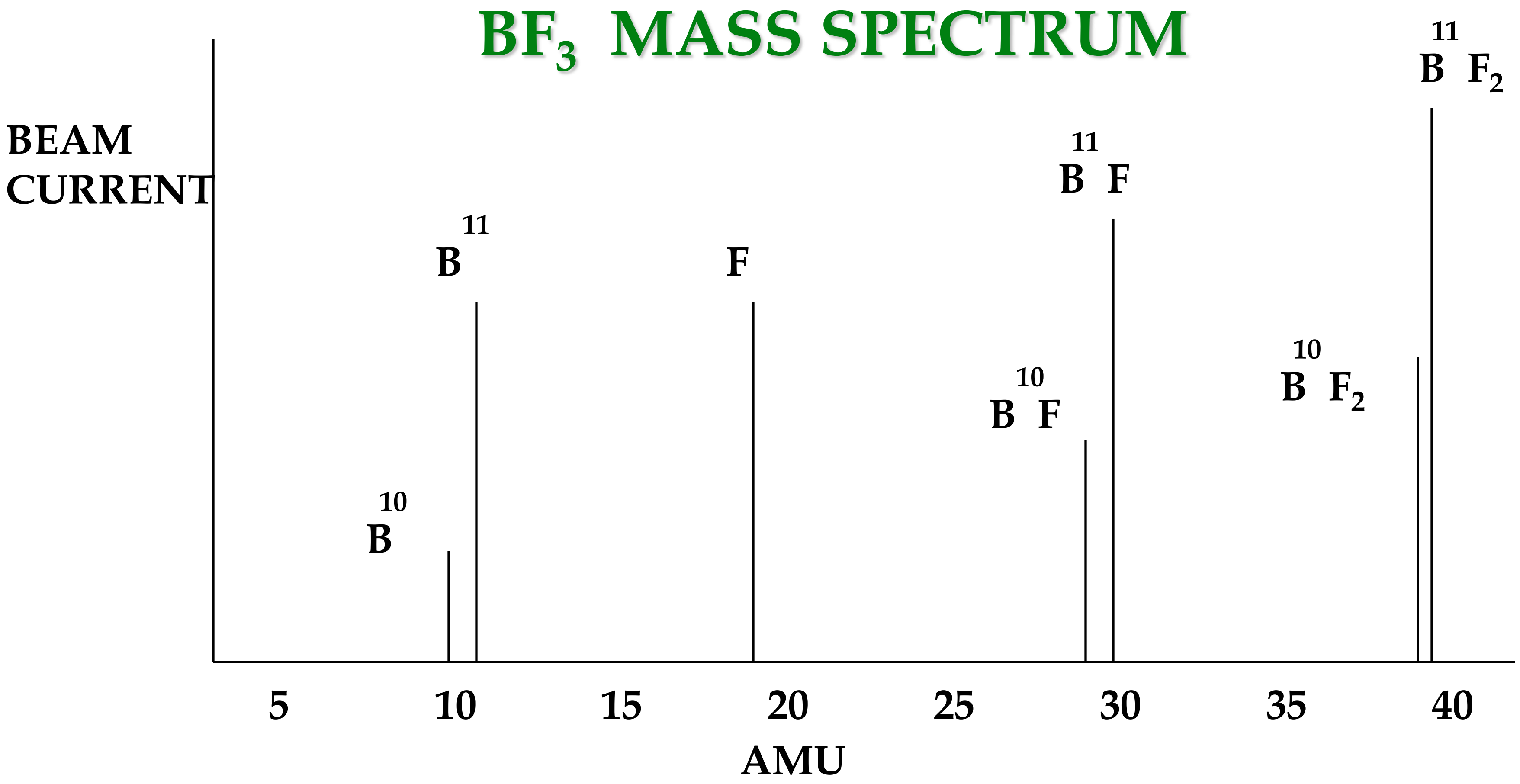
MASS ANALYSER MAGNET

- $B=(2mV/qr^2)^{1/2}$
- B=MAGNETIC FIELD STRENGTH
- m=ION MASS
- V=ACCELERATING VOLTAGE
- q=ION CHARGE
- r=MAGNET RADIUS

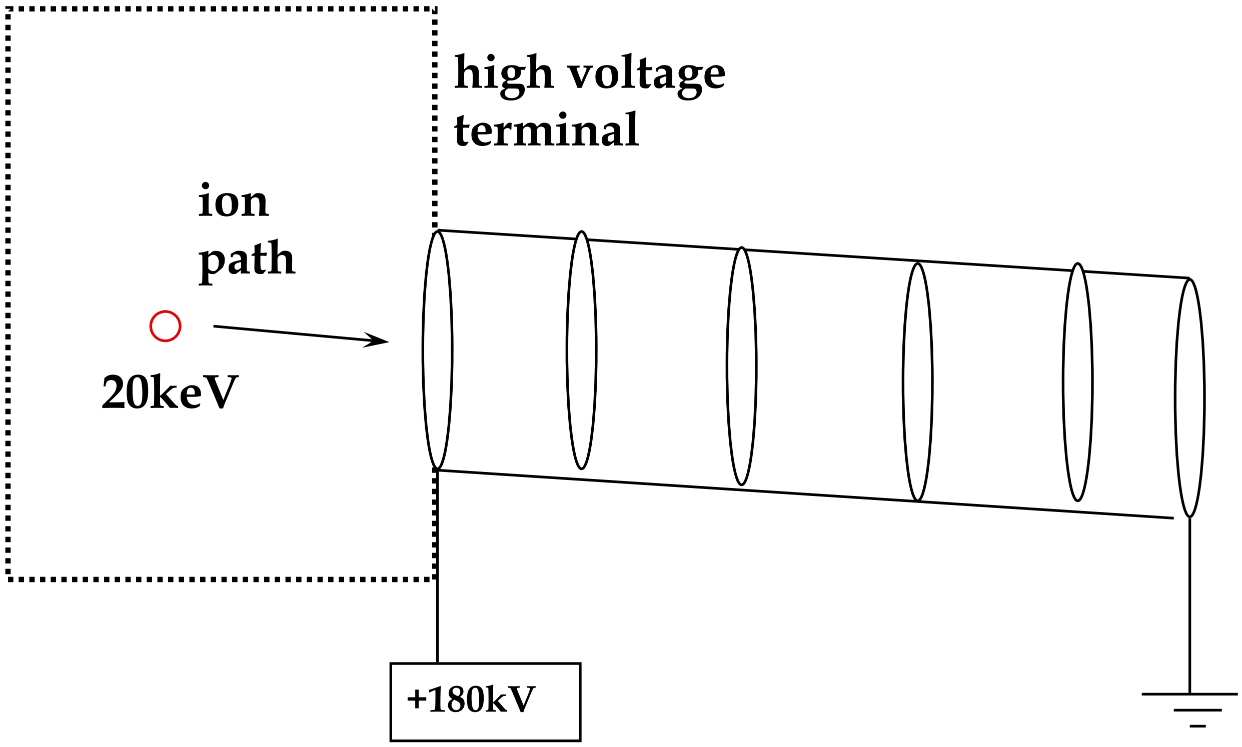


MASS SELECTION MAGNET

MASS ANALYSIS



ACCELERATING COLUMN



ACCELERATION

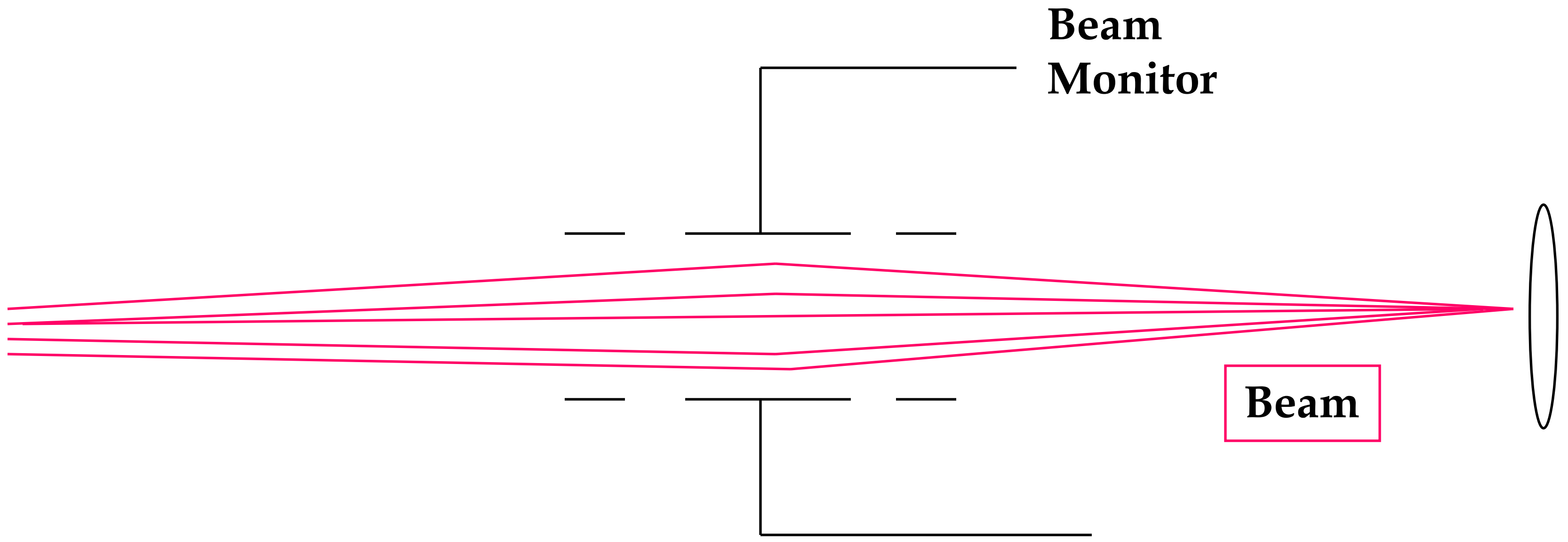
- ION ENERGY

ION ENERGY = CHARGE ON ION X ACCELERATING VOLTAGE

ION CHARGE = 1
ACCELERATING VOLTAGE = 50kV
ION ENERGY = 50keV

ION CHARGE = 2
ACCELERATING VOLTAGE = 50kV
ION ENERGY = 100keV

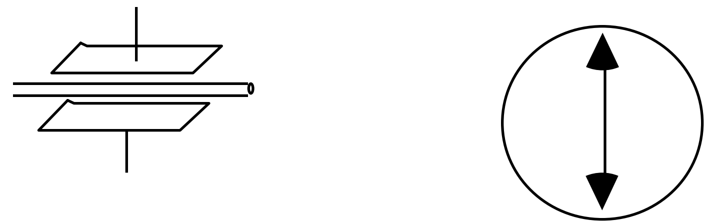
FOCUS



SCANNING

- Electrostatic Scanning
  - **Used on medium current machines**
- Mechanical scanning
  - **used on high current machines**
- Hybrid scanning
  - **used on medium current systems on large wafer sizes (8 inch)**

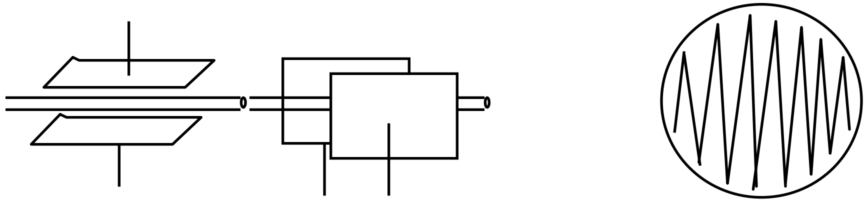
ELECTROSTATIC SCANNING



WAFER

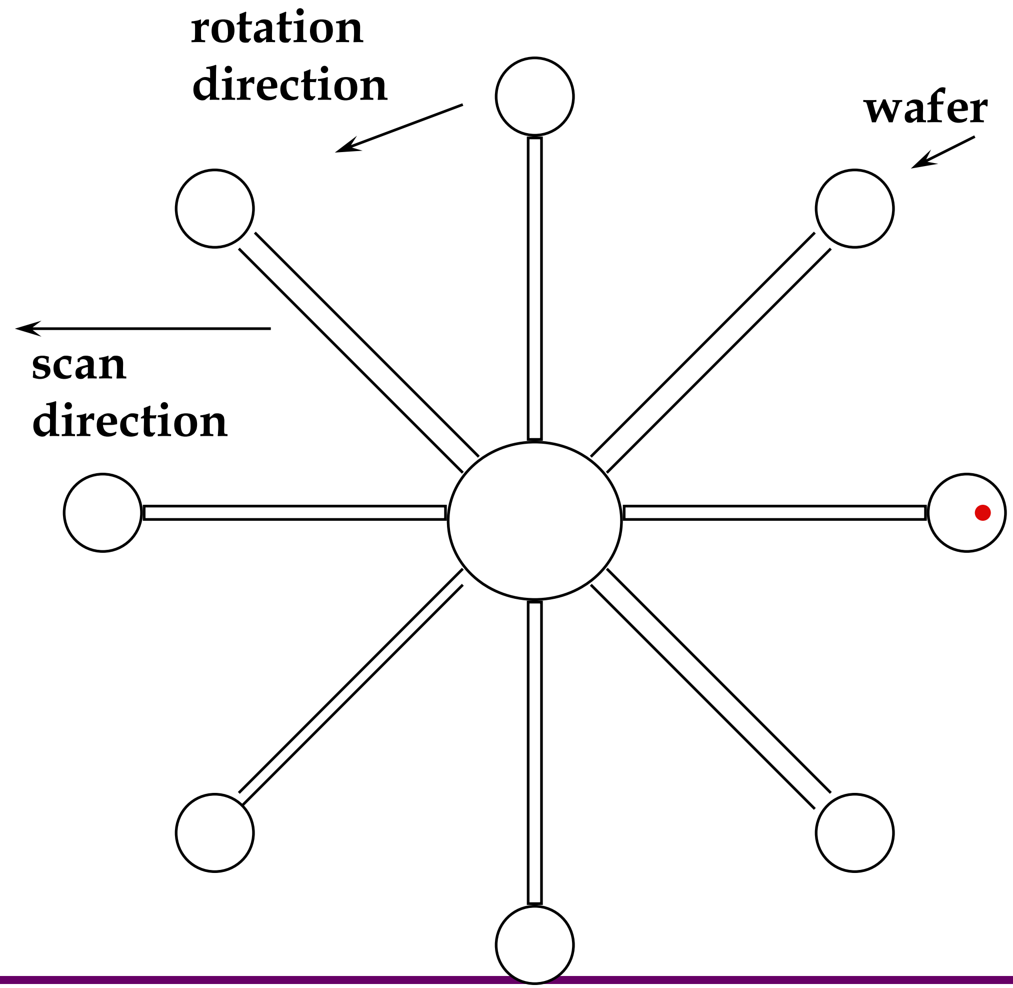
Y Scan

X Scan



X and Y Scan

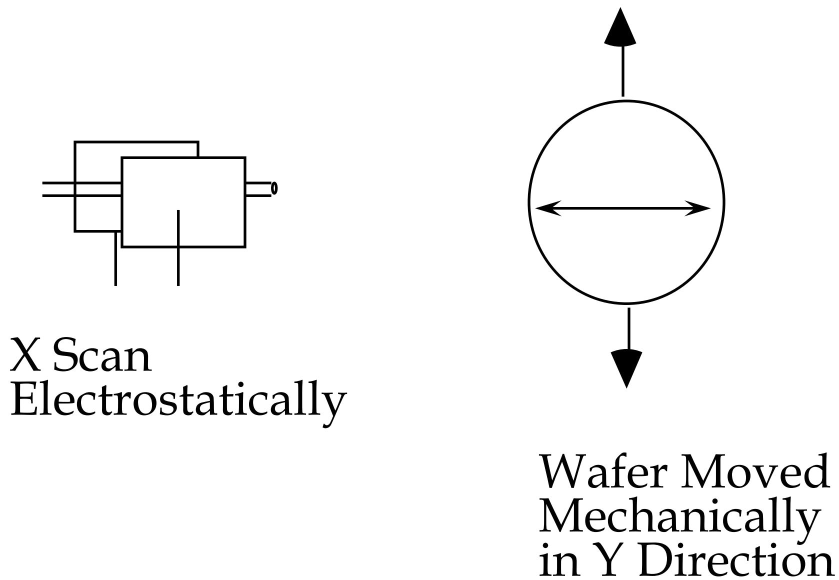
MECHANICAL SCANNING



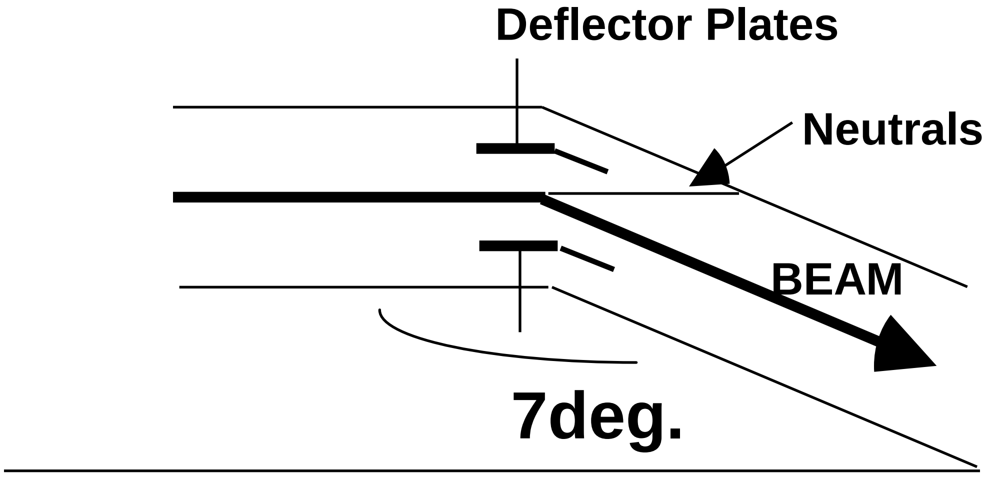
Stationary Beam

Wafer Moved
Mechanically
in X and Y
Direction

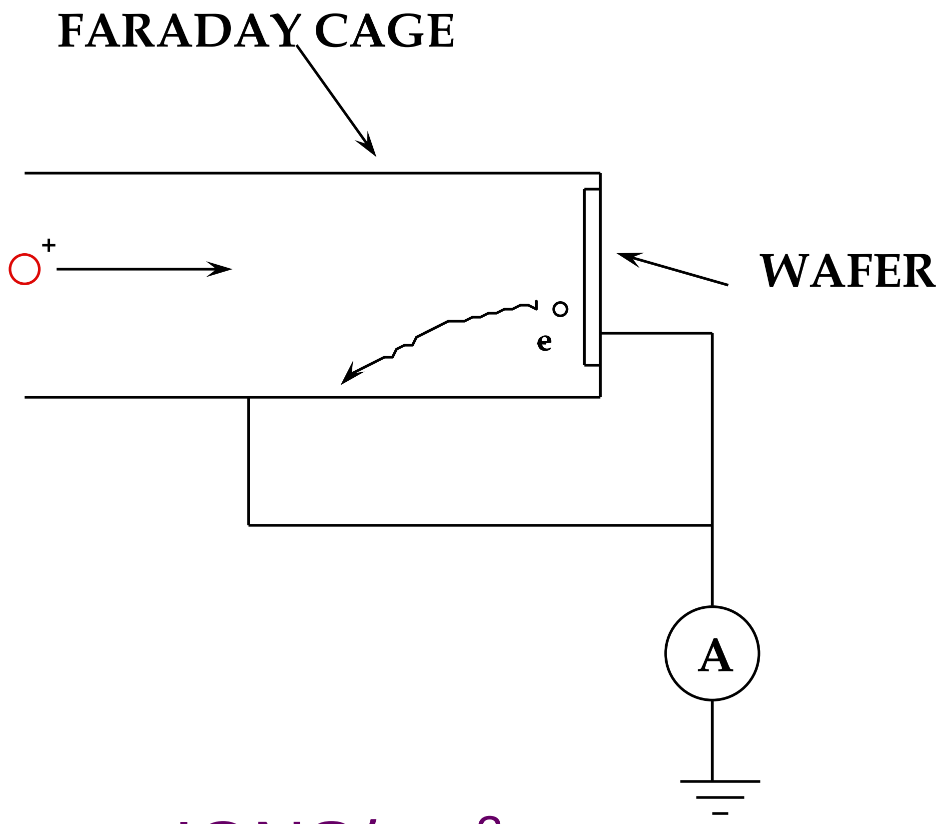
HYBRID SCANNING



NEUTRAL TRAP



DOSE MEASUREMENT



- DOSE : IONS/cm^2

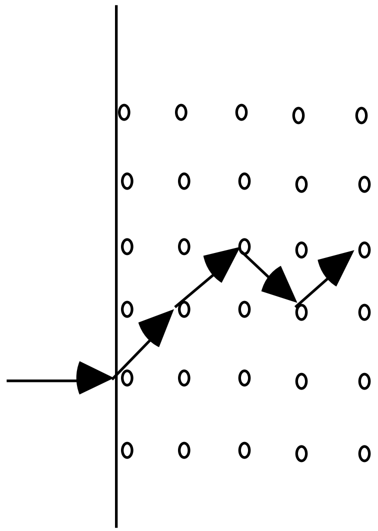
DOSE MEASUREMENT

- Typical dose ranges
- CMOS wells 1e12-1e13 ions/cm^2
- Threshold adjust implants 1e11-1e12 ions/cm^2
- Source drain implants 1e15-1e16 ions/cm^2

ION IMPLANTATION

BEAM WAFER INTERACTION

MATHEMATICAL MODEL



The total distance

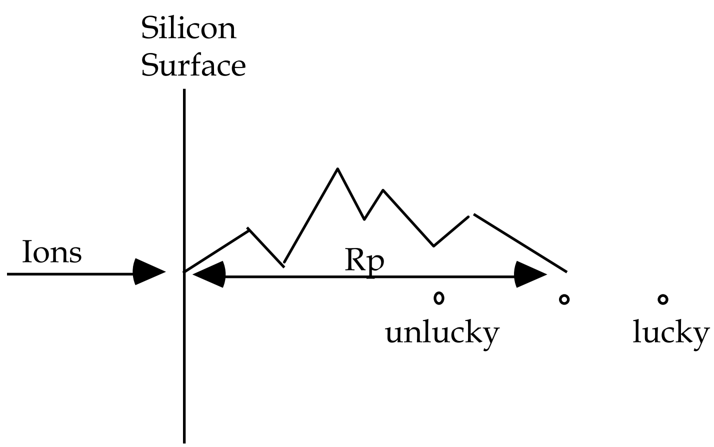
travelled in the Silicon

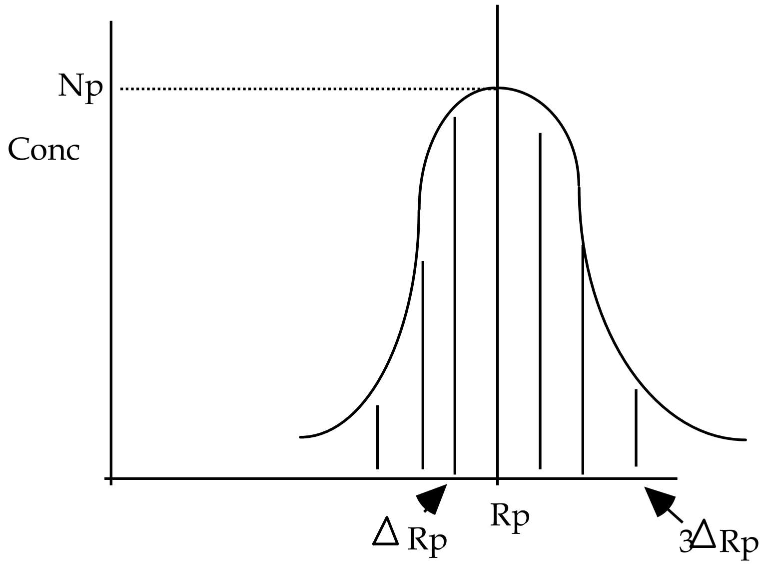
is called the Range⇒ R

- Ions lose energy in collisions with atoms in the silicon lattice (Target Atoms)
- Two types of collision
  - **Nuclear collisions**
    - **Transfer of energy to the target nuclei**
  - **Electronic collisions**
    - **Interaction of the charged ion with the electron cloud of the target atom**

IMPLANT MODELLING

- Rp Average range of ions in the wafer
- Distribution around the range
- Computer models are used to simulate range of ions in the lattice





Gaussian Expression

- The expression which describes this distribution is

$$C_x = C_p \exp\left[-(x - R_p)^2 \Big/ 2\Delta R_p^2 \right]$$

- The area under the Gaussian curve is the implanted dose and is equal to

$$Q = \int_{-\infty}^{\infty} C_x \, dx$$

- For an implant completely contained within the silicon the dose is equal to

$$Q = \sqrt{2\pi}\, C_p \Delta R_p$$

Similarity to The Diffusion Equation

- Note how similar the implant concentration expression is to the diffusion equation

$$C_x = C_p \exp\left[-\left(x - R_p\right)^2 \Big/ 2\Delta R_p^2 \right]$$

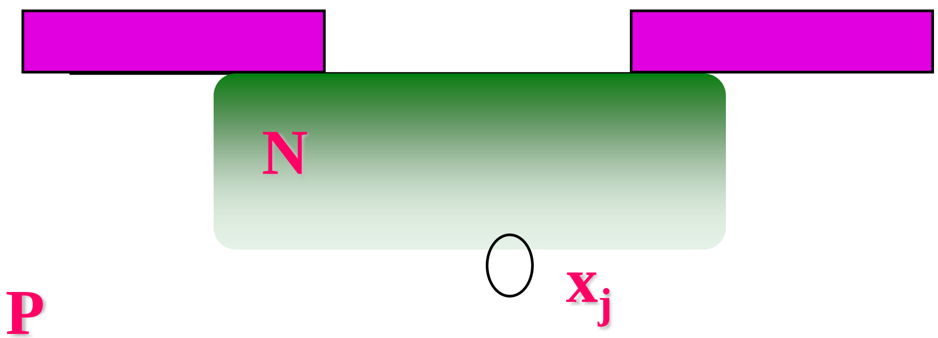
$$C_{(x,t)} = \frac{S}{\sqrt{\pi D t}} \exp\left[-x^2 \Big/ 4Dt \right]$$

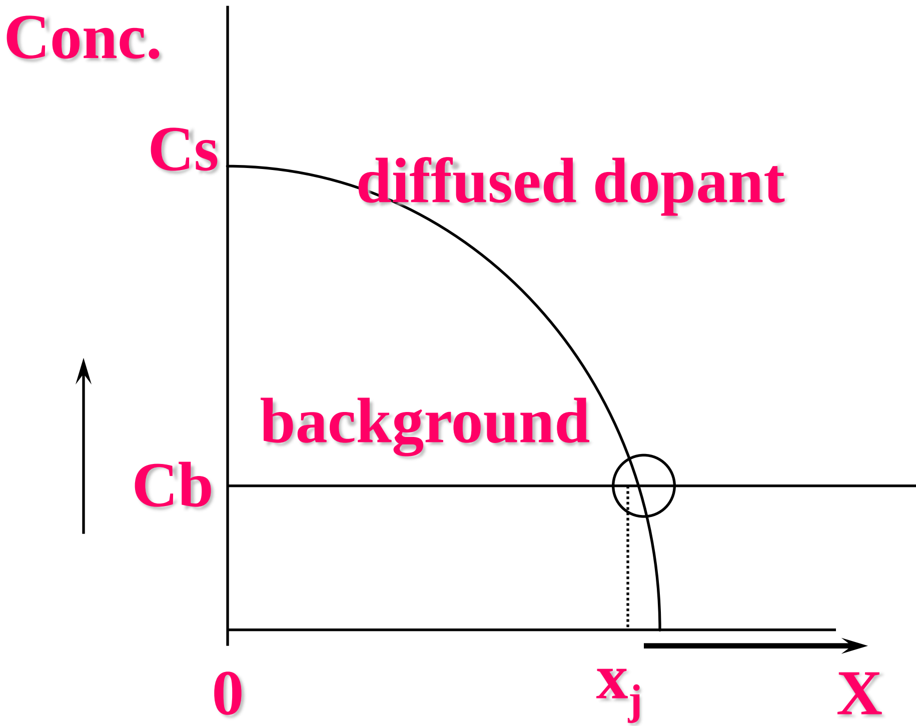
4Dt is represented by $2\Delta Rp^2$

- Similar but the distribution is shifted along the x axis by a distance R_p

Junction Formation

- The junction between the P/N region occurs where the concentration of the introduced dopant is equal to the background dopant concentration

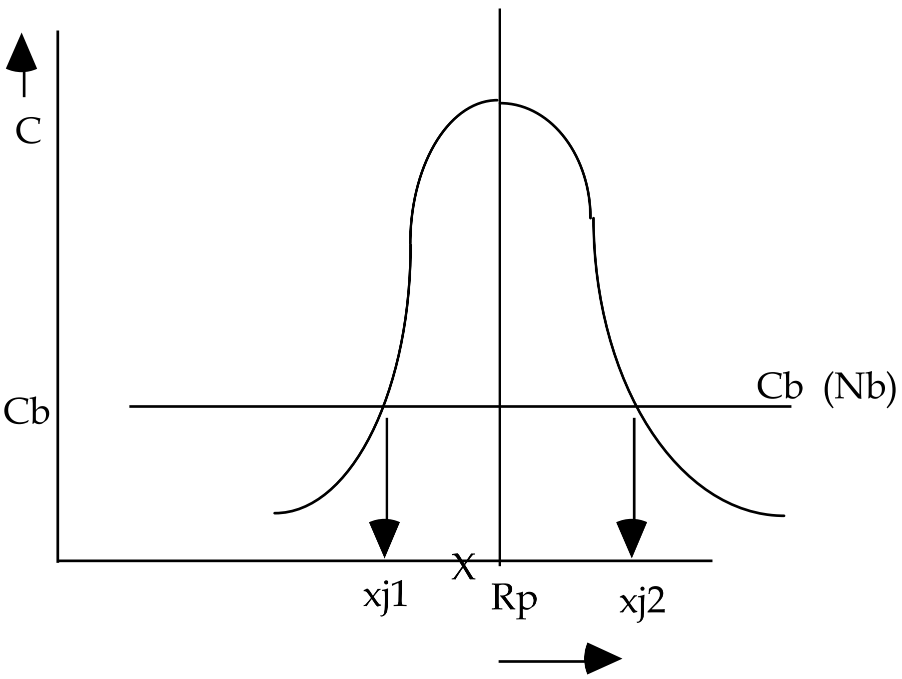




Implant

JUNCTION FORMATION

- High energy implant
- Two junctions can be formed during implant



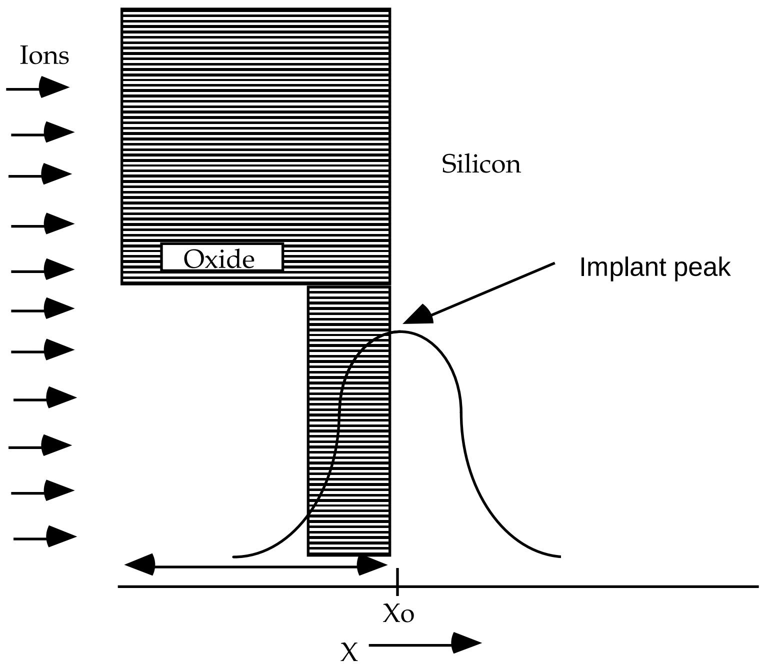
$$C_x = C_p \exp\left[-(x - R_p)^2 \Big/ 2\Delta R_p^2 \right]$$

Junction occurs where the implanted concentration is equal to the background concentration.

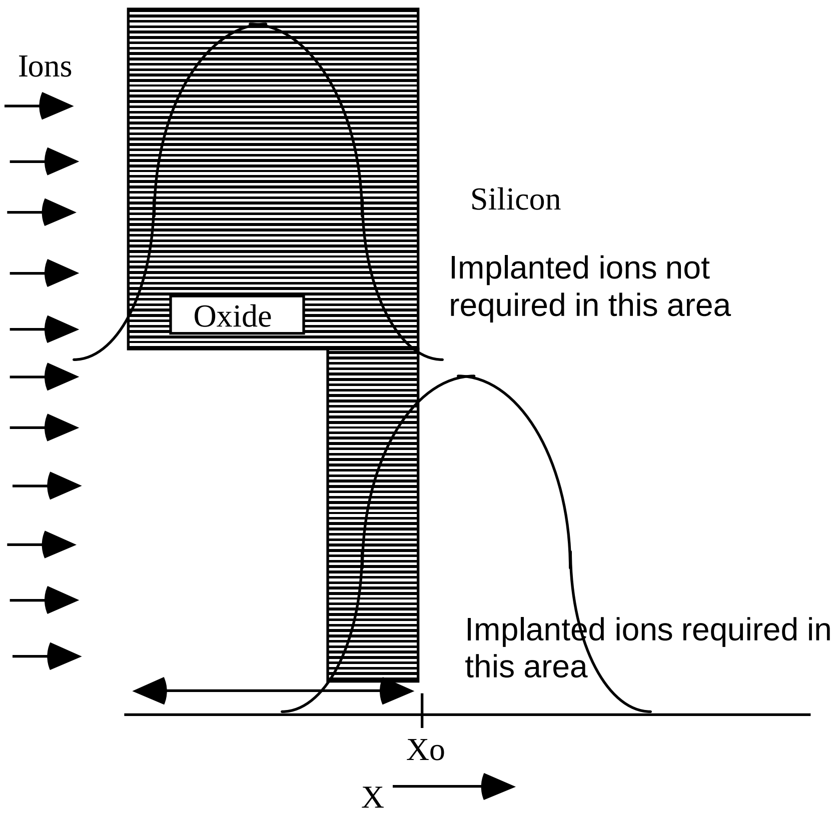
$$x_j = R_p \pm \Delta R_p \sqrt{2 \ln C_p \big/ C_b}$$

JUNCTION FORMATION

- Peak concentration normally at surface of the silicon, the oxide/silicon interface



IMPLANT MASKING



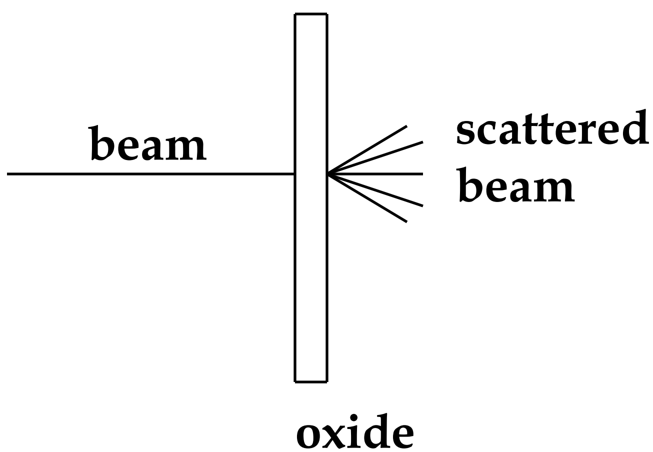
- Normally the implant energy is chosen to put the peak of the implant just at the oxide/silicon interface
- This mimics the type of junction profile formed with thermal doping

Channeling

- Channelling is where incident ions fly between the target atoms in the silicon lattice
- The ions do not have collisions as early as “expected”
- This means that ions travel further than the models would normally predict

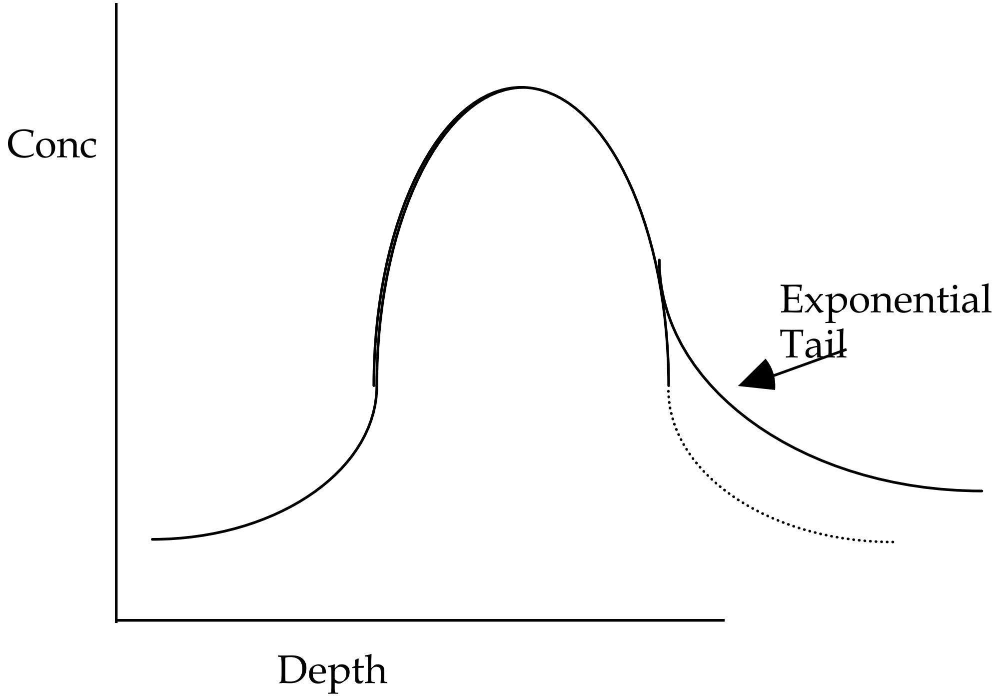
Prevention of Channeling

- Wafer normally tilted to avoid channeling
- Implant oxide also helps to reduce channeling by scattering ion beam



Channeling Affect

- Exponential tail due to channeling in wafer



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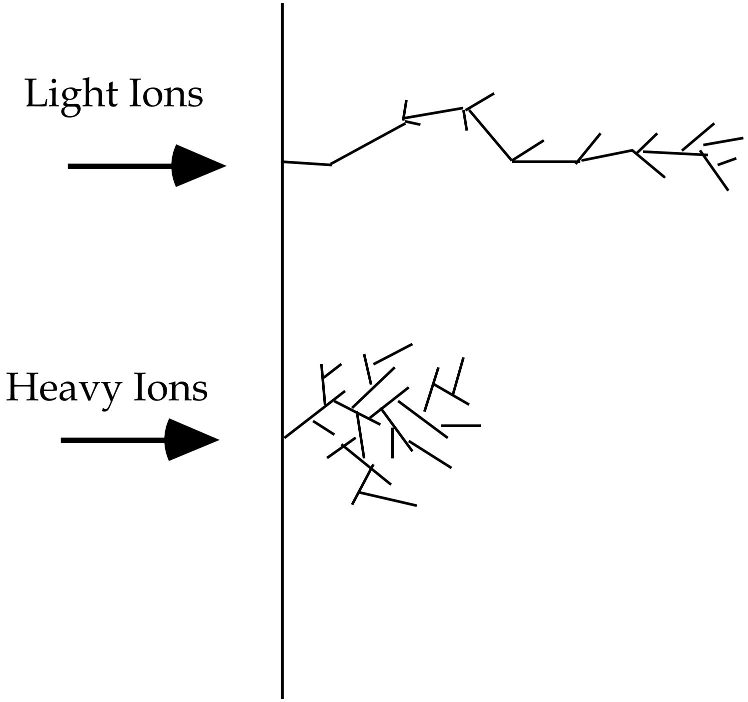
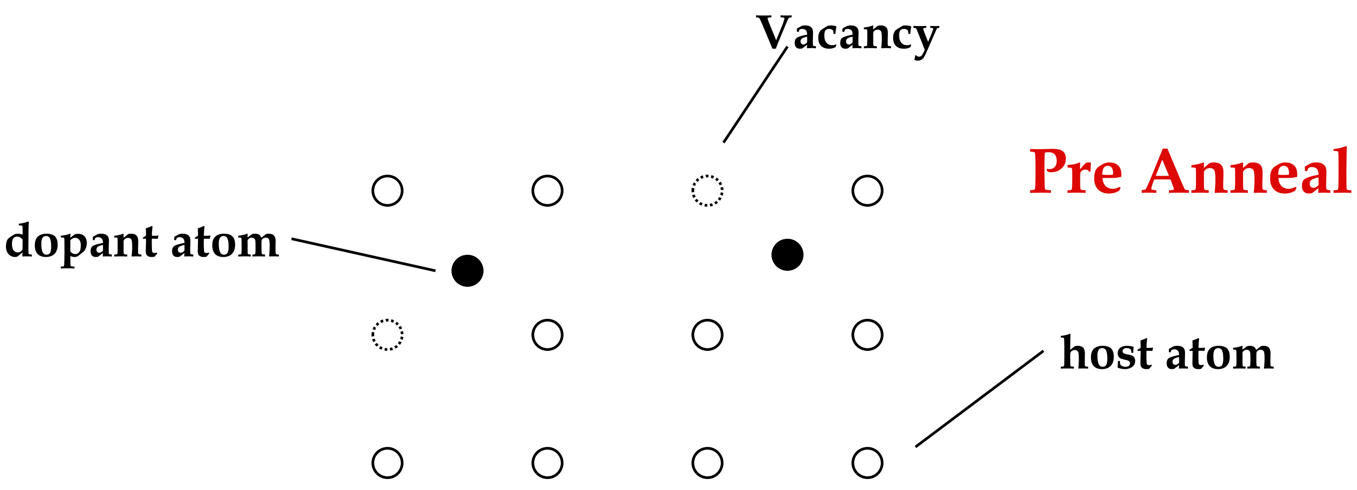
DAMAGE

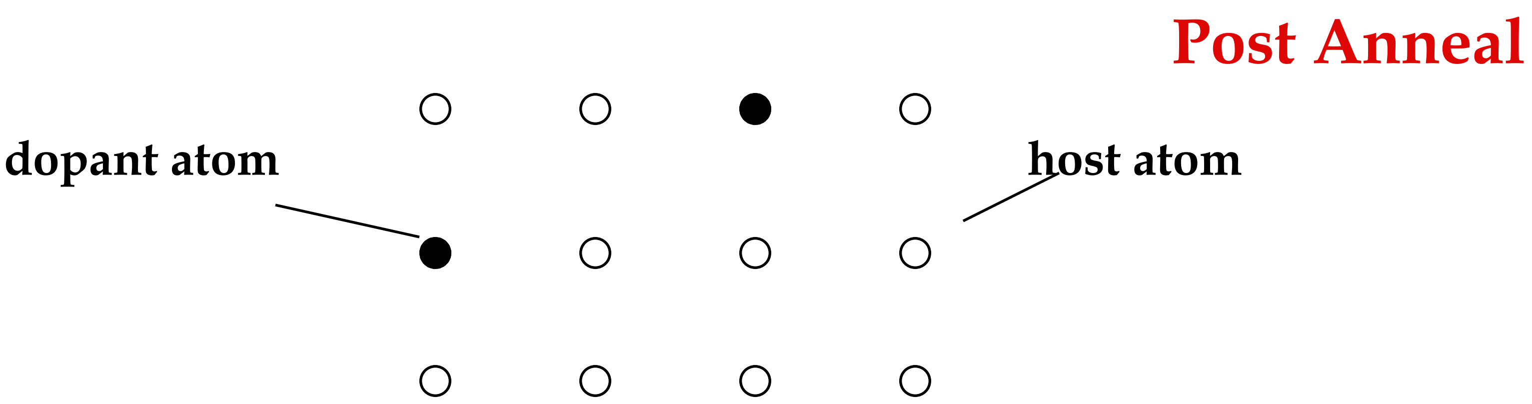
- Electronic collisions
  - **ions lose energy due to excitation of electrons in silicon wafer**
- Nuclear collisions
  - **collisions between ions and atoms in the wafer**
- For the same energy heavy ions create more damage close to the surface
  - **Even light ions lose the last of their energy through nuclear collisions**



ANNEALING



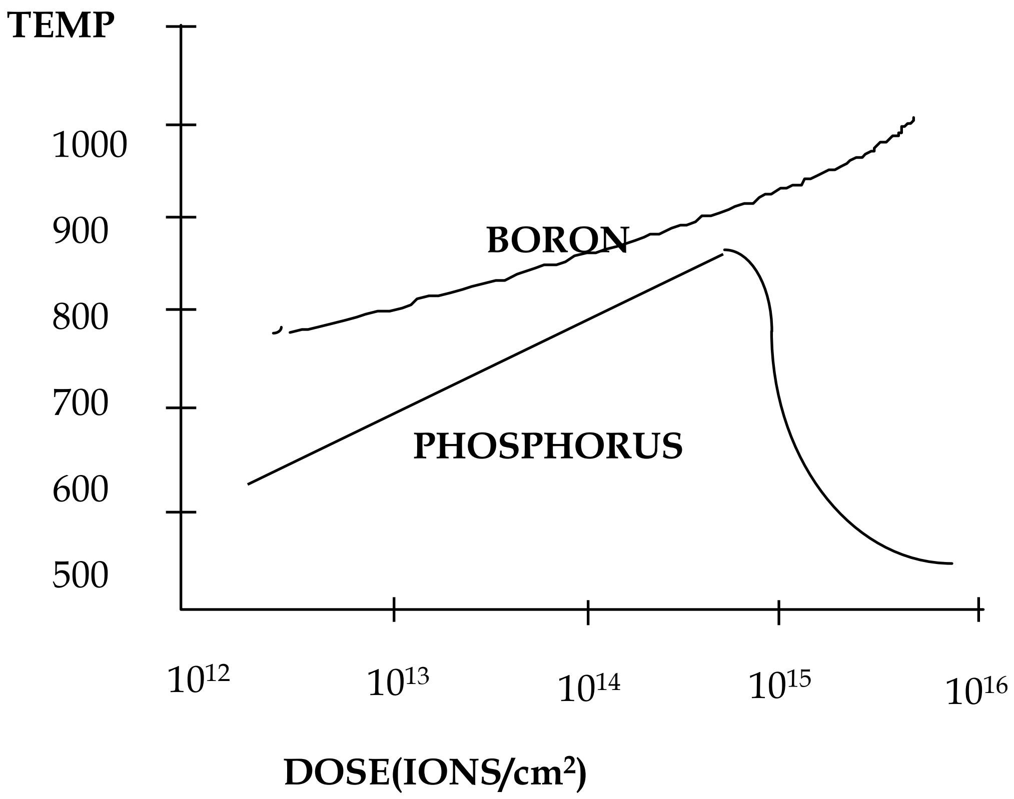
Vacancy
Pre Anneal
dopant atom
host atom



Post Anneal
dopant atom
host atom

ANNEALING

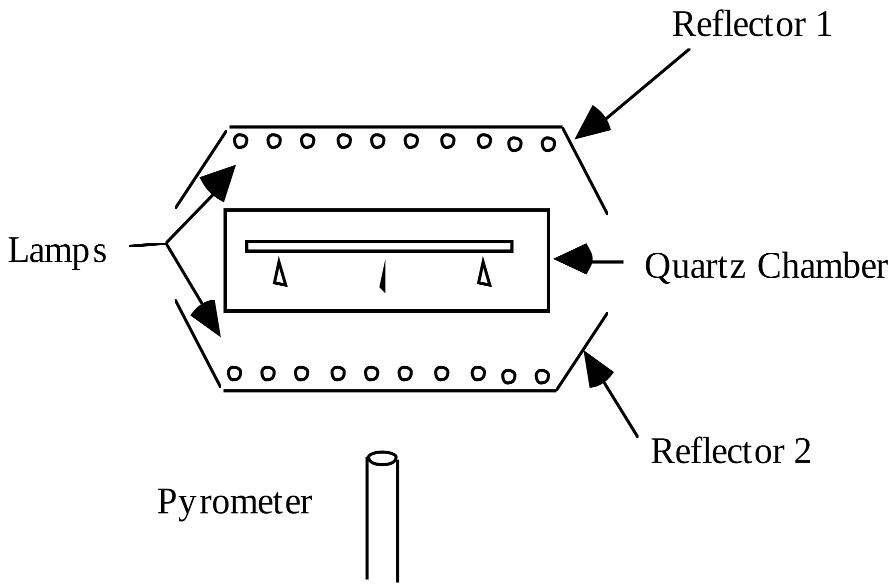
- Heavier ions create an amorphous layer at the surface
- A lower annealing temp. required at high doses due to formation of this amorphous layer
- The effect is know as "Solid Phase Epitaxial Growth"
- The underlying still crystalline silicon acts as a seed for the recrystallization



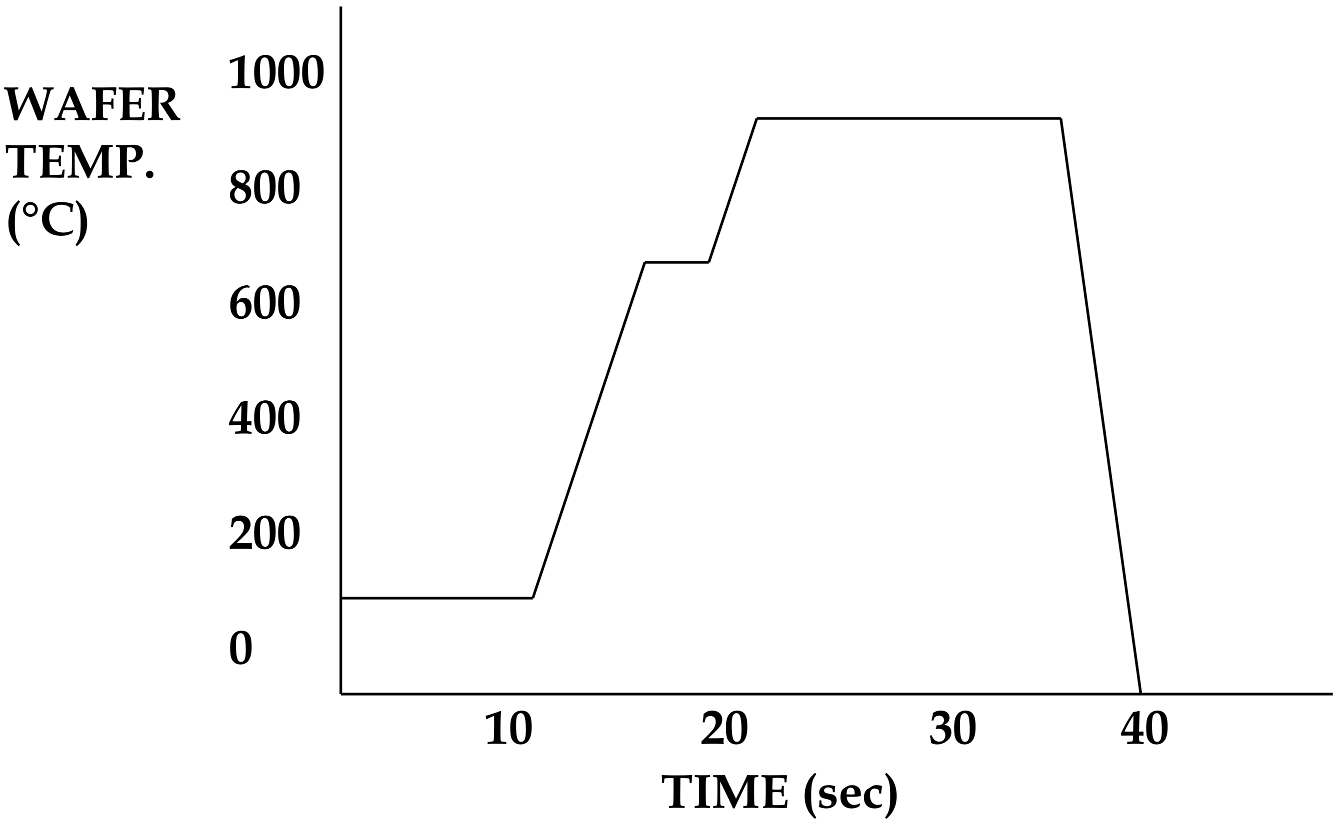
ION IMPLANTATION

RAPID THERMAL PROCESSOR

RAPID THERMAL PROCESSER



RTP



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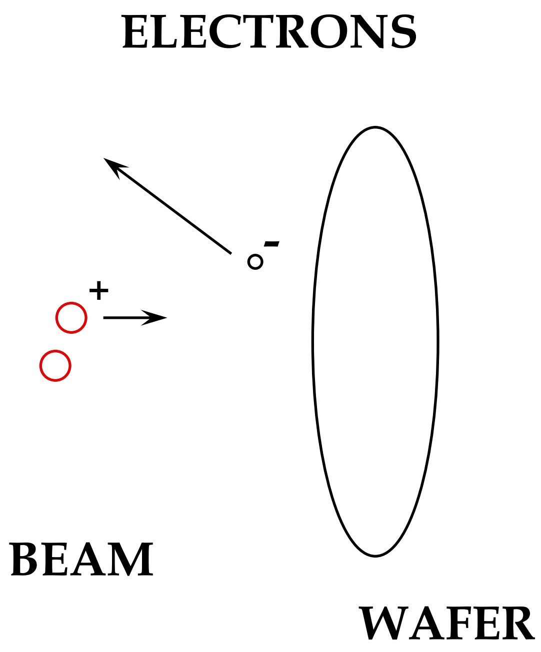
ION IMPLANTATION

WAFER CHARGING

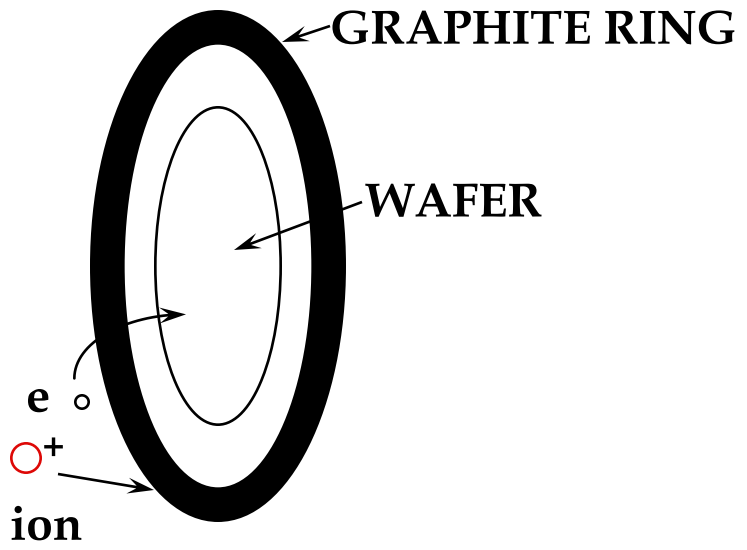
WAFER CHARGING

- Positive ions arrive at wafer
- Negative electrons removed from wafer
- Charge builds up on wafer surface
- Use source of electrons to neutralize the wafer charge



CHARGE NEUTRALISATION

- Beam is scanned outside wafer
- Ions hit graphite ring and knock out electrons
- Electrons are carried to wafer surface
- Electrons are used to prevent positive charge build up



Summary Implantation

- Enabling technology
- Modern processes all doping introduction by implantation
- Implanted species must have a heat treatment after the implant
  - **To repair crystal damage**
  - **To activate the implanted ions**