Process fabrication IIII

E. Giulio Villani

Instrumentation Training Lectures, Oxford 12/05/2023

Overview

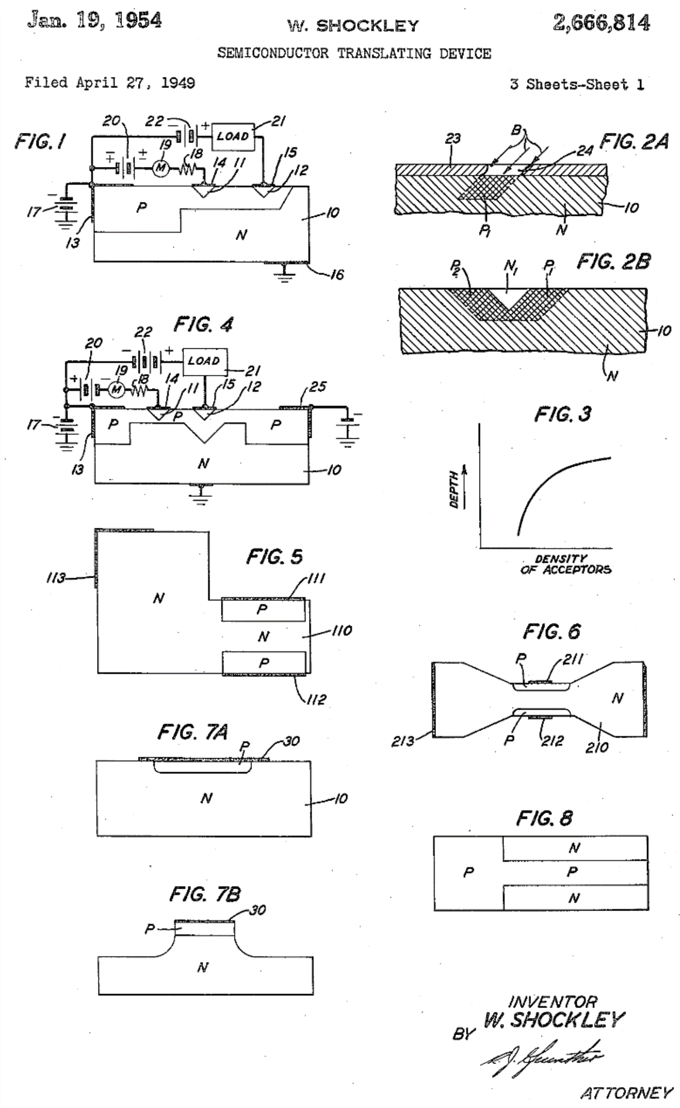
- **Semiconductor fabrication process IIII**
  - **Implantation**
    - *Introduction*
    - *Tools/equipment*
    - *Ions interaction/dopants profiles*
    - *Masking*
    - *Channeling*
    - *Implantation damage and annealing*
    - *Example*
  - Metallization
    - *Introduction*
    - *Tools/equipment*

Ion Implantation Introduction

- Technique to introduce atoms of dopants into a semiconductor material and create regions of different electrical characteristics

- Historically proposed by Shockley in 1949, became common in the 70's

- Ionized gas ions are accelerated by strong electric field and injected into a target wafer (a few nm to a few µm depth). Ion implanters spin-off from particle accelerator technology



Jan. 19, 1954 W. SHOCKLEY 2,666,814

SEMICONDUCTOR TRANSLATING DEVICE

Filed April 27, 1949 3 Sheets-Sheet 1

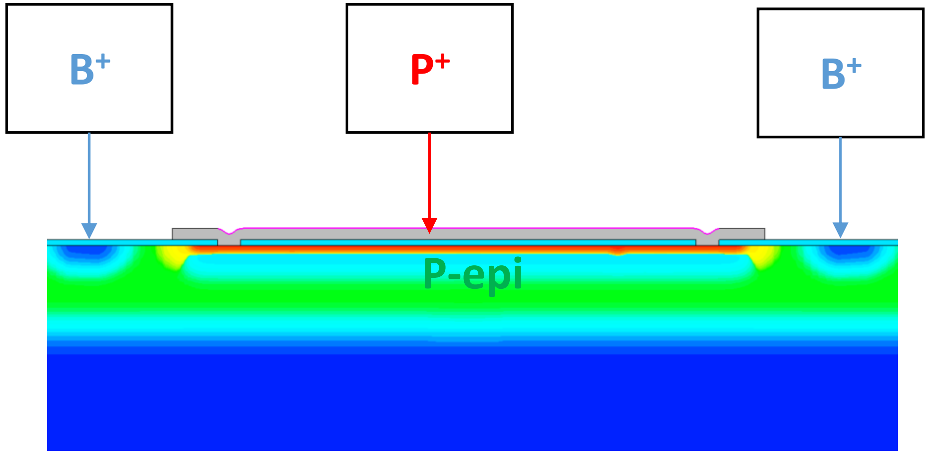
INVENTOR
W. SHOCKLEY
BY
ATTORNEY

...the layer is formed by bombardment of one face of the N-type body with nuclear particles and the N-type zones in the layer are produced by masking the surface areas of the layer from the bombarding particles.

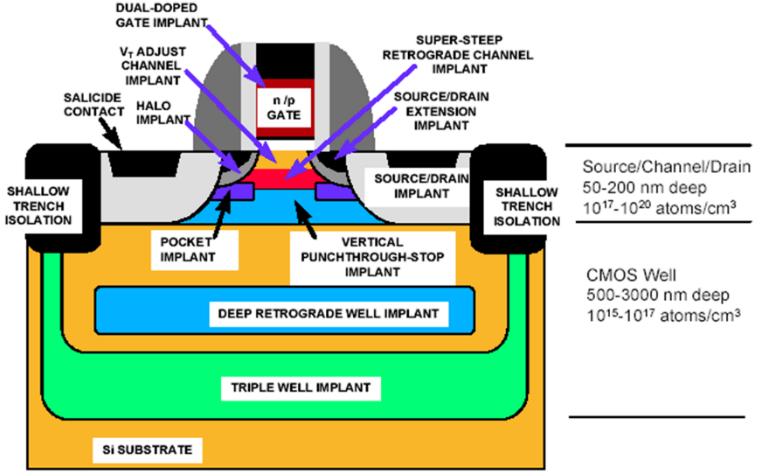
Ion Implantation Introduction

Pros

- Precise control of dose and depth profile, complex profiles
- Room Temperature process (can use photoresist as mask)
- Wide selection of masking materials e.g. photoresist, oxide, poly-Si, metal
- Excellent dose uniformity across wafers
- Little lateral dopant diffusion, important for small devices



4 implantations process, 1 metal layer

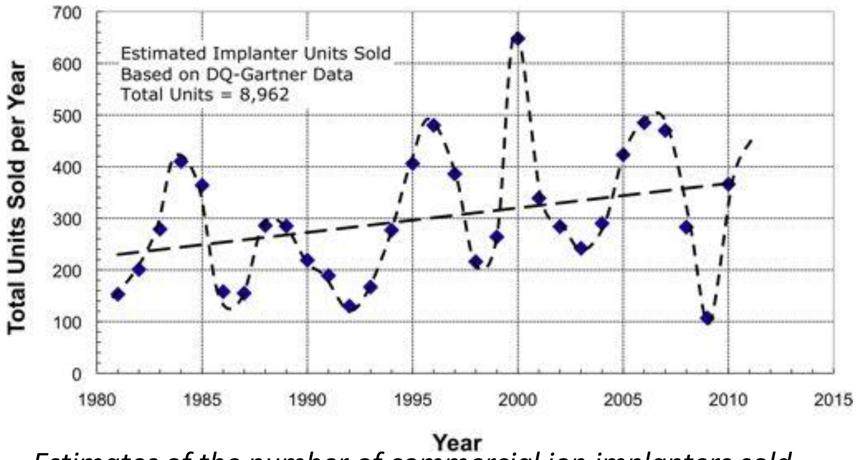


>10 implantations process

Ion Implantation Introduction

Cons

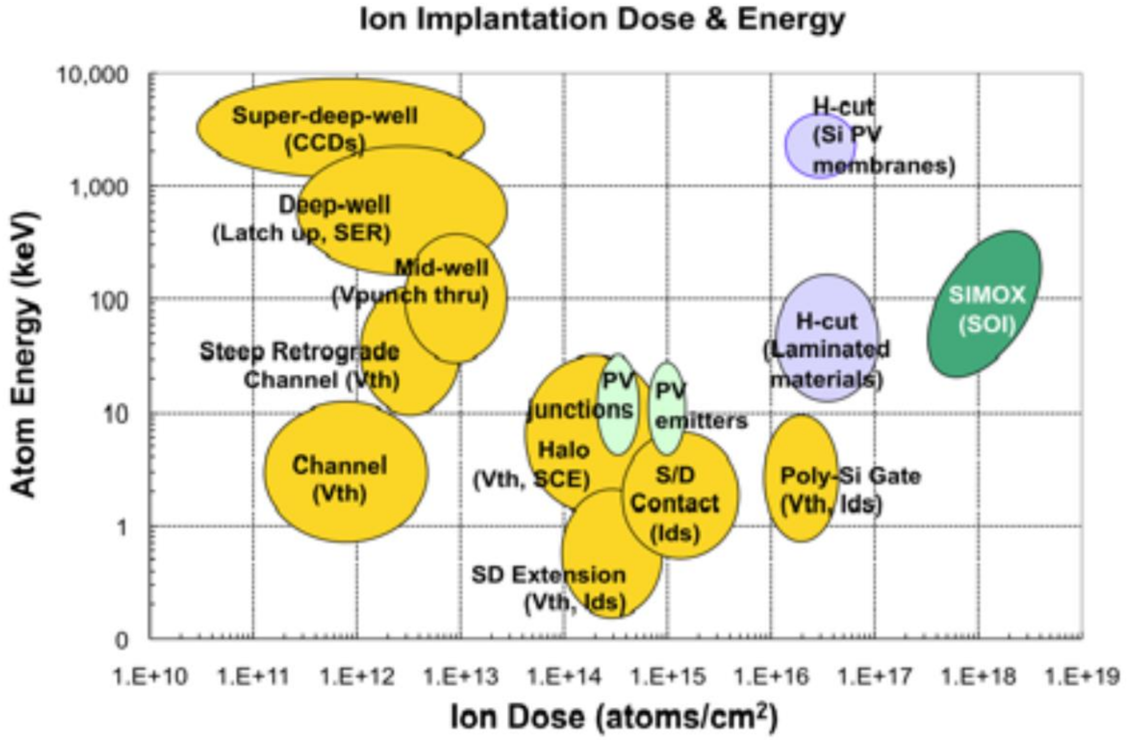
- Equipment very expensive (> 1M$)
- Radiation damage: reticle damage due to implantation not always possible to correct
- Difficult to obtain very shallow and very deep doping
- Masks material can be scattered into the wafer, creating impurities and defects



Estimates of the number of commercial ion implanters sold per year, mainly for IC fabrication, showing the '5 year cycle'

Ion Implantation Introduction

- Ions used: As, B, P, In, O, Ar
- Energy: 1 - ~1000’s keV
- Flux: $10^{12} – 10^{14}$ cm^{-2} s^{-1}
- Dose: $10^{11} – 10^{18}$ cm^{-2}
- Uniformity: ± 1% across 12’’ wafers
- Absolute dose accuracy: ± 10 -15 %
- Temperature: RT



Dose and atom energy regions for CMOS transistor doping (gold), high dose hydrogen implants for Si layer splitting (lavender), and direct implantation of oxygen to form Silicon-on-Insulator (SOI) wafers (green).

Ion Implantation tools

Typical ion implanter for semiconductor process consists of several elements

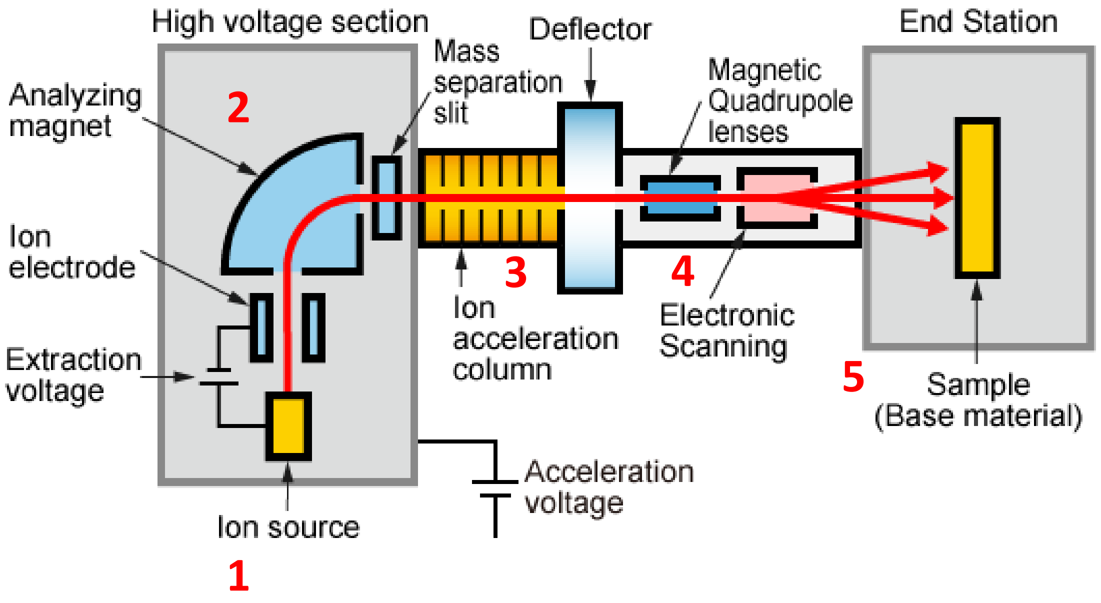
1: Ion source

2: Analyzing Magnetic

3: Ion Accelerator

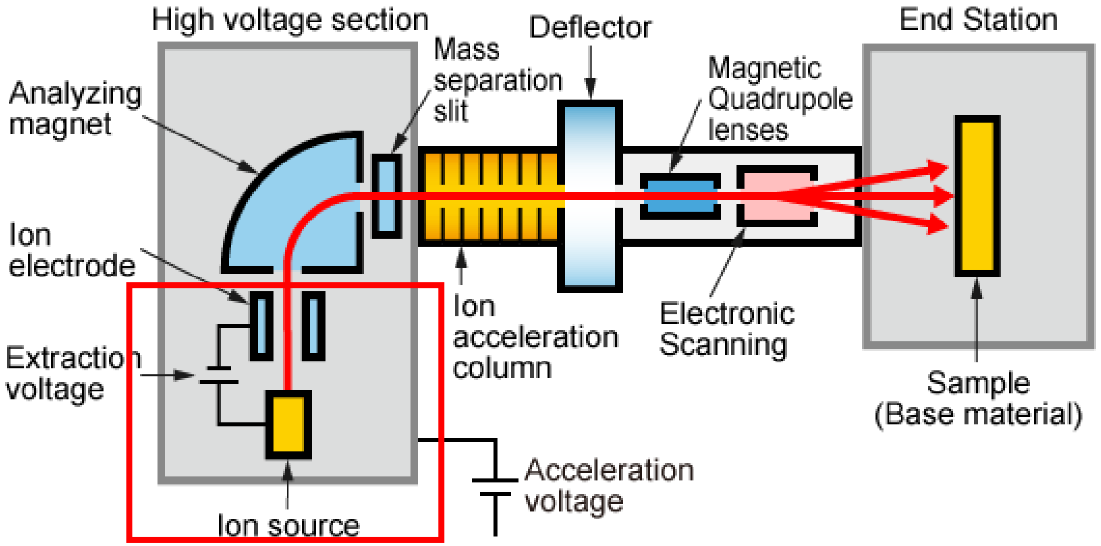
4: Beam manipulating system

5: End station



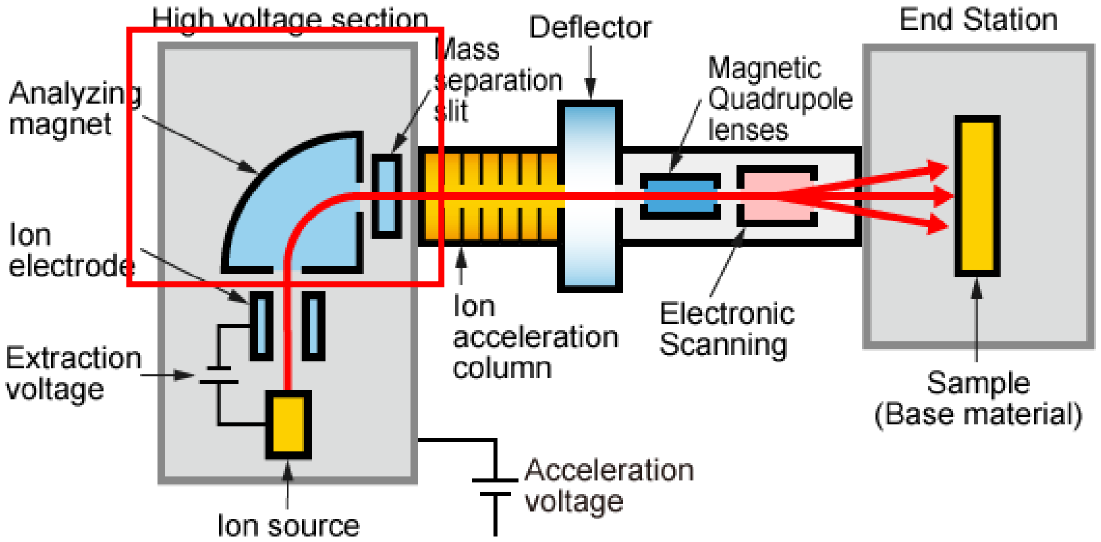
Ion Implantation tools

- **Ion source**:
  - Filament emits thermionic electrons, accelerated to gain enough energy (20 – 30 kV)
  - The electrons collide with the molecules or atoms (AsH_3, PH_3, BCl_3) and ionize them
  - A negative bias to the end side of the chamber extracts the positive ions towards the magnetic analyzer



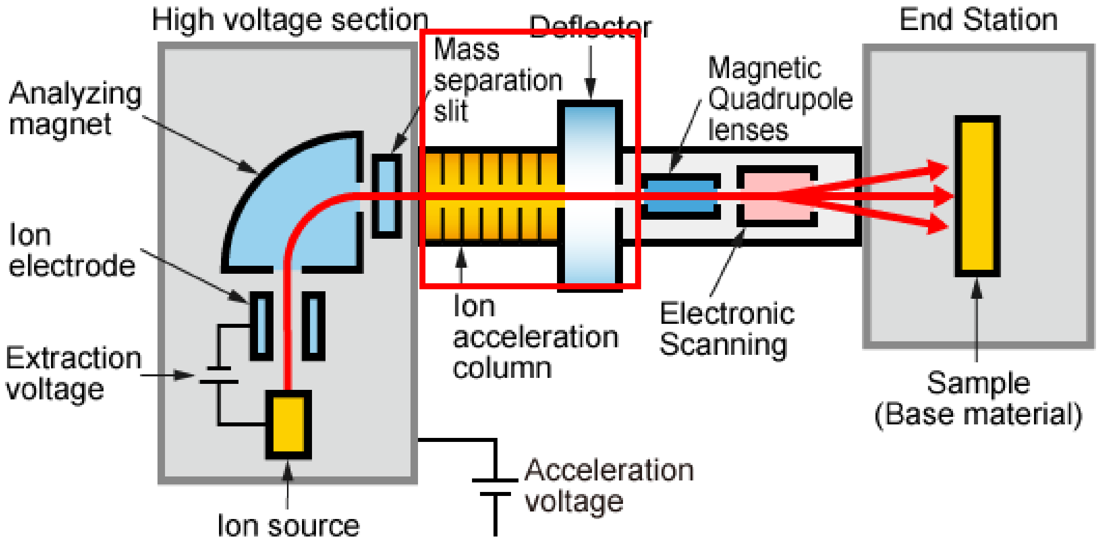
Ion Implantation tools

- **Magnetic analyzer**
    - Plasma provides positive ions, $(B^{11})^+$, BF_2^+, $(P^{31})^+$, $(P^{31})^{++}$
    - The correct ions need to be separated to choose what to implant (e.g. acceptors B^{11}, or donors P^{31})
    - A **magnetic mass analyzer** selects the desired species via a magnet (< 1 T) which bends the ion beam: only one mass will have the correct radius of curvature to exit through the slit (~ mm's) and hit the wafer



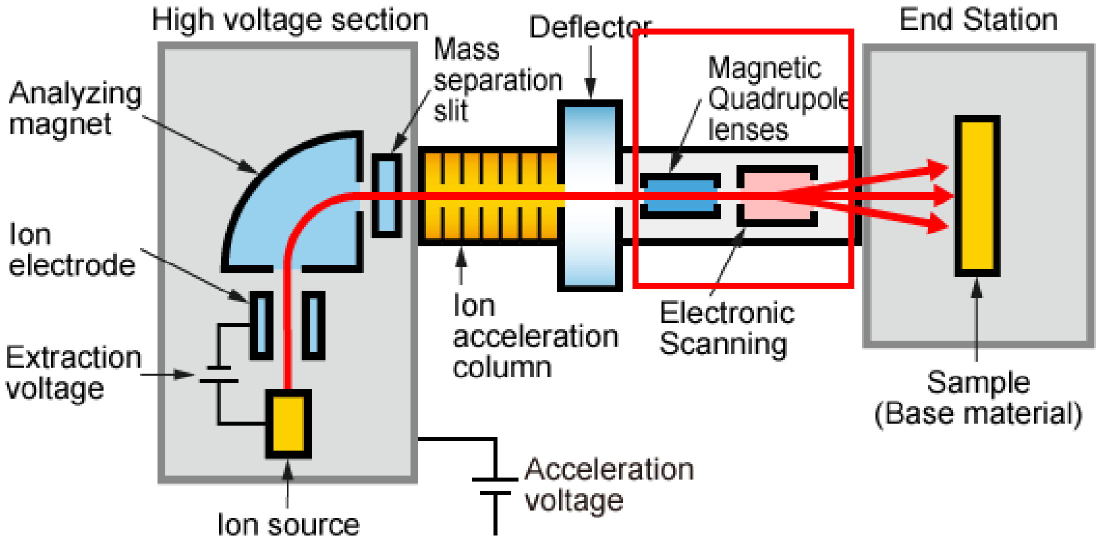
Ion Implantation tools

- **Accelerator**
  - N-sections LINAC, giving a total x n acceleration at relatively low voltage: E ~ 1000’s keV, I ~ mA
  - Single charge ion ⇒ E = e * HV
  - n⁺ charge ion ⇒ E = n* e * HV



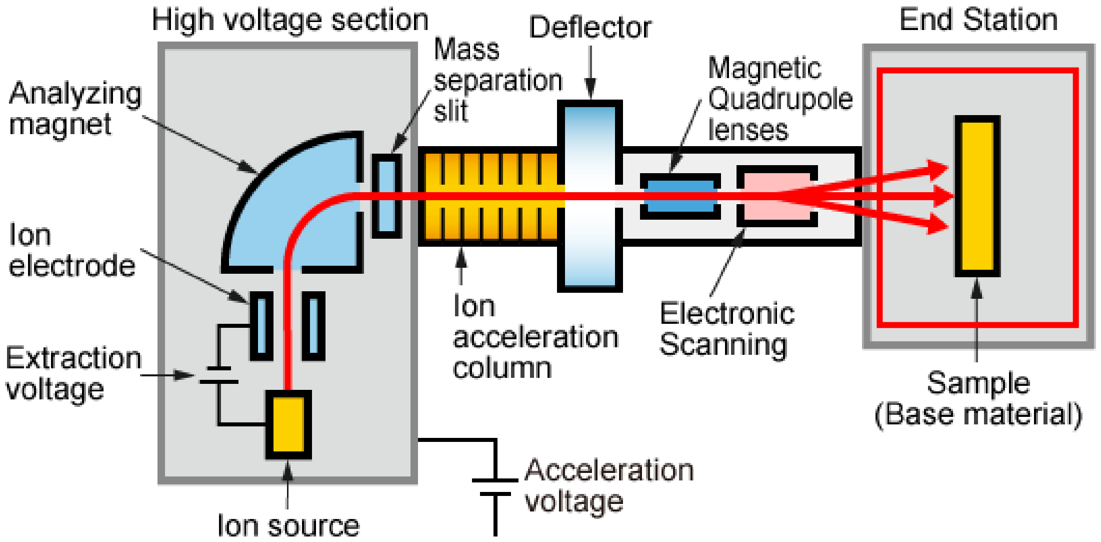
Ion Implantation tools

- **Beam manipulating system**
  - After acceleration the ion beam is focused (~ few cm^2)
  - A small deflection via electrostatic means is applied to discard neutral components to a beam stop
  - The ion beam passes through an electrostatic deflection system and scanned over the wafer (~ Ø 20 cm)



Ion Implantation tools

- **End station**
  - Wafers mounted on rotating disc (15-25 wafers/disc)> 50 wafers/hr
  - Dose measurement performed by integrating the ion current via a Faraday cup
  - Complex design of the Faraday cup is needed for high current implanters



Ion interactions/doping profile

- The many-body problem of **Ion-solid interaction** where one ion (M_1, $n_1 \neq Z_1$) interacts with all target atoms M_2 nuclei and electrons in a solid is practically intractable: some simplifying assumptions are introduced:

- **Classical mechanics** used to describe the motion of ion and nuclei

- **Binary collision approximation** (BCA) to calculate the ion trajectories

- **Adiabatic approximation** : nuclear and electronic systems are treated separately

$$H\Psi(\mathbf{R}_1, \mathbf{R}_{2,k}, \mathbf{r}_{1,i}, \mathbf{r}_{2,k,j}, t) = i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{R}_1, \mathbf{R}_{2,k}, \mathbf{r}_{1,i}, \mathbf{r}_{2,k,j}, t)$$

$$M_1,\ Z_1,\ \mathbf{R}_1,\ \mathbf{r}_{1,i}\ \ (i = 1, n_1\ n_1 \neq Z_1)$$
$$M_2,\ Z_2,\ \mathbf{R}_{2,k},\ \mathbf{r}_{2,k,j}\ \ (j = 1, Z_2\ \ k = 1, N)$$

Ion interactions/doping profile

- **Classical mechanics** : ions move as *classical point-like* particles: e.g. for lightest ion B^{11} @ E =10 keV
- Usually in implantation processes ion energy is not large enough to penetrate the coulomb barrier of the target nuclei, i.e. no nuclear reactions.

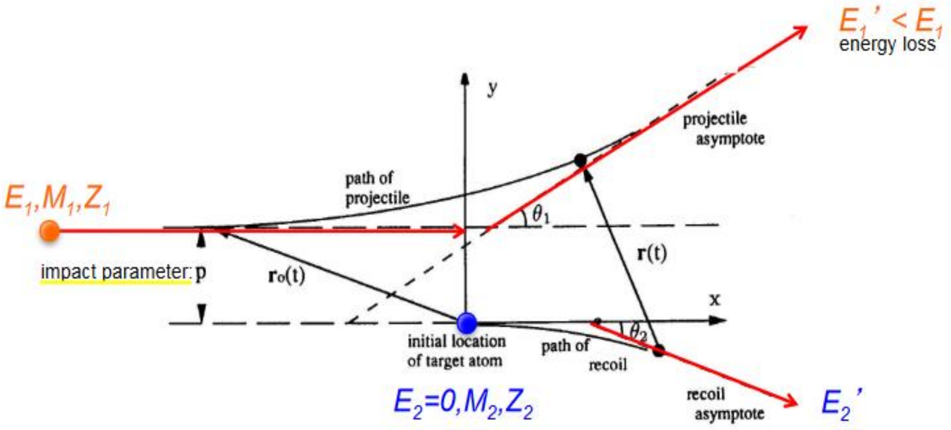
$$\lambda_{ion}[nm] = \frac{h}{M_1 v} = \frac{2.87 \times 10^{-2}}{\sqrt{M[amu]E[eV]}}$$

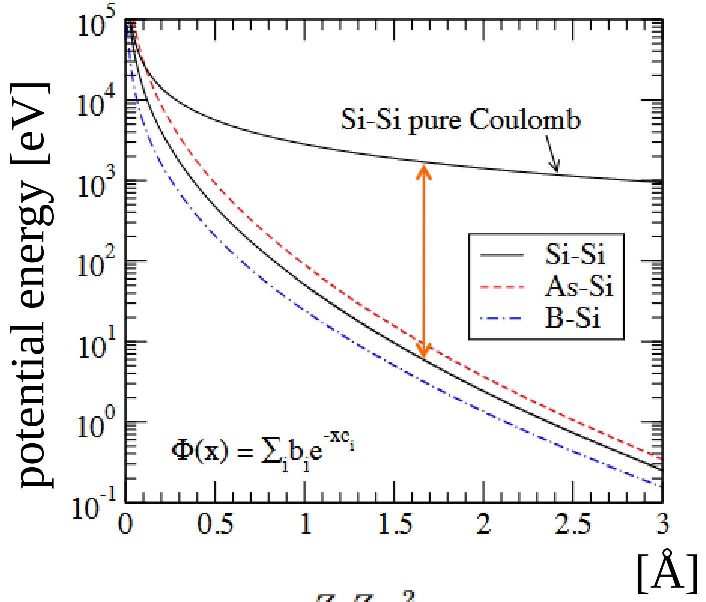
$\lambda = 8.6 \cdot 10^{-5}\ [nm] \ll 0.54\ [nm]$, Si lattice parameter

B^{11} @ $1MeV\ \beta = 0.01$

Ion interactions/doping profile

- **Binary collision approximation** : ion movement is described as a series of successive elastic two-body Coulombic interactions, using a screened potential (i.e. negative charge of ion and target reduces the Coulomb potential strength)





$$V(r) = \frac{Z_1 Z_2 e^2}{r} \Phi(r, Z_1, Z_2)$$

Ion interactions/doping profile

- **Adiabatic approximation** : Scattering of ions with target described using two separate processes:

- *collisions with nuclei* (energy loss and geometry of trajectory)

- *collisions with electrons* (energy loss only).

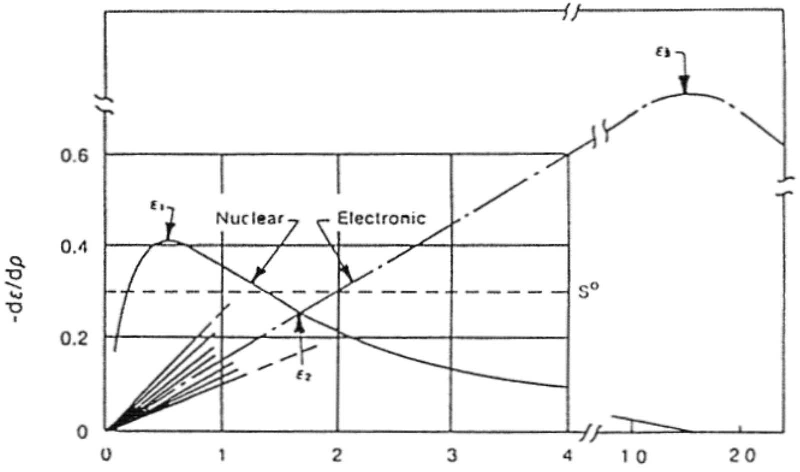
$$S = \left(-\frac{dE}{dx}\right)_{nuclear} + \left(-\frac{dE}{dx}\right)_{electronic} = S_n + S_e$$

S_n *screened potential classical two-body scattering*

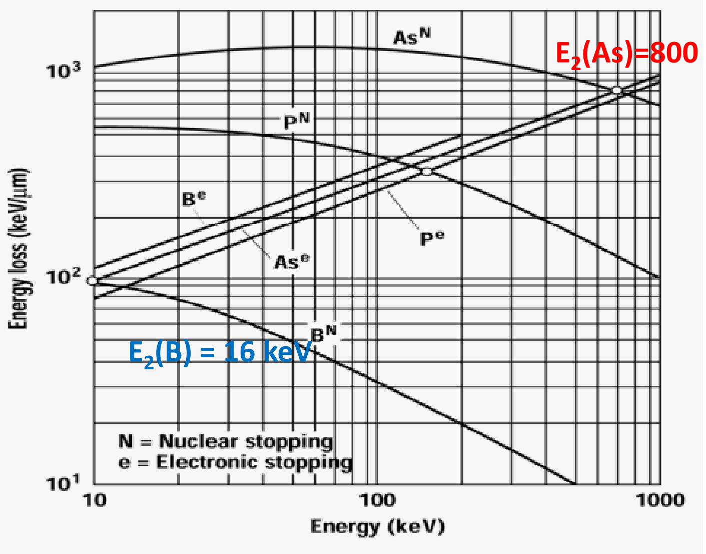
S_e *interactions of ion with target electrons (Lindhard's Bethe-Bloch)*

Ion interactions/doping profile

- At **low energy,** nuclear collisions dominate: as at the end of its range the ion has low energy, S_n dominates leading to more crystalline damage
- At **high energy**, electronic collisions dominate, from scattering of electrons ~ Ohm's law



Nuclear and electronic stopping powers versus energy in reduced units



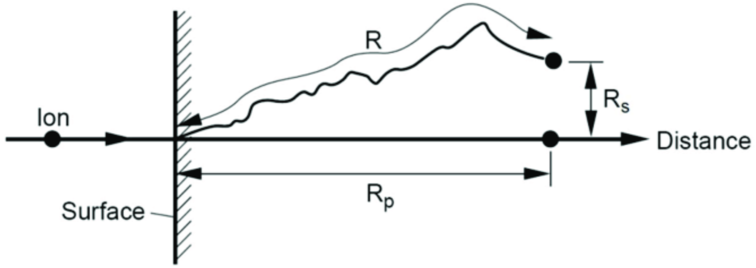
Ion interactions/doping profile

- From $\frac{dE}{dx}$,the total energy stopping power, one can estimate the average ion range

R: range

R_p: projected range along axes of incident ion, with straggle ΔR_p

R_s perpendicular distance

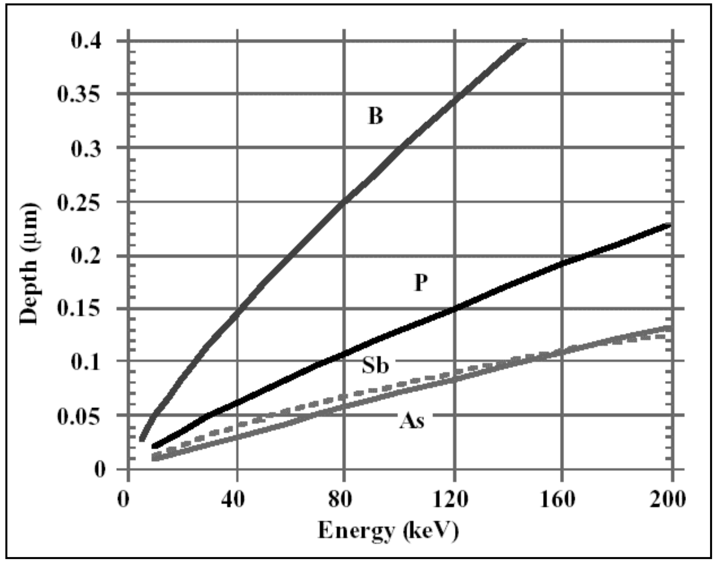


$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_n + \left(\frac{dE}{dx}\right)_e$$

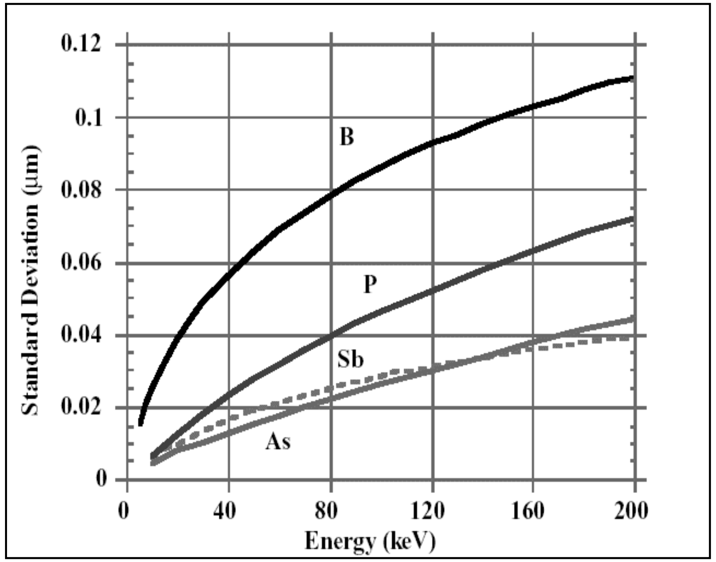
$$R = \int_0^E \frac{dE}{-\frac{dE}{dx}}$$

Ion interactions/doping profile

- Projected range Rp and Straggle ΔRp for common dopants
- Transverse spread increases with R_p ($R = (1 + M_2/3M_1)Rp$
- limiting factor on lower limit of mask opening, which affects maximum device density



Projected range R_p



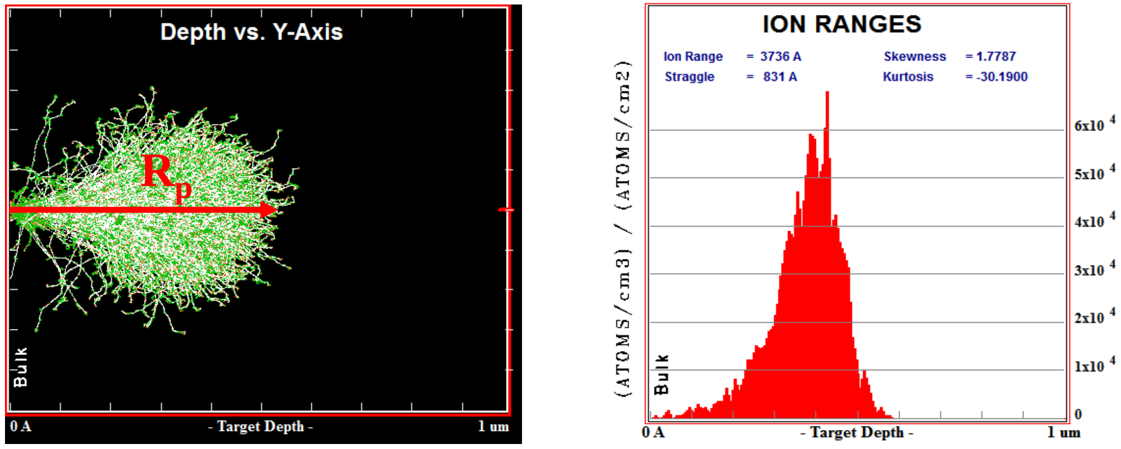
Straggle ΔR_p

Ion interactions/doping profile

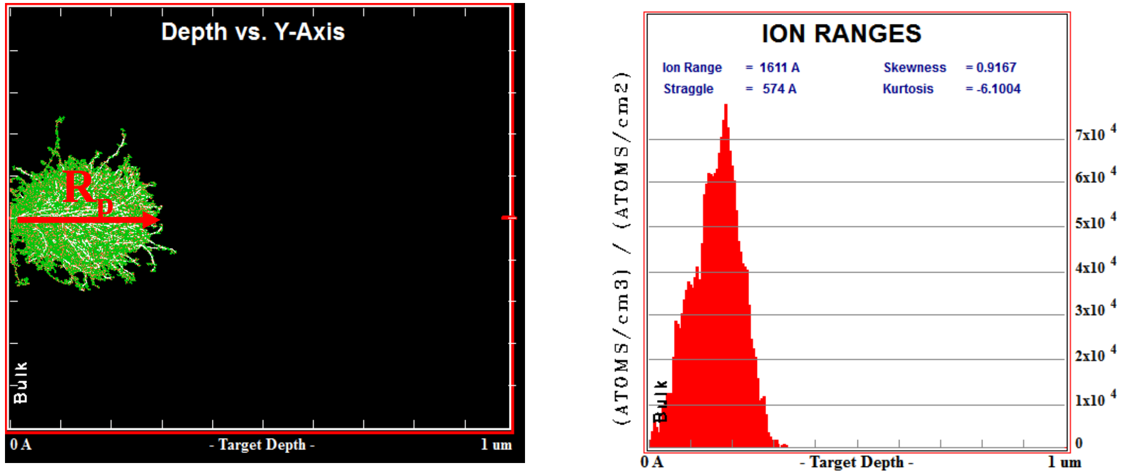
- Example of MC (>5000 runs) ion range simulations (SRIM) of B^{11} and P^{31} implanted in amorphous Si

- No annealing, i.e. no dopants activation, no thermal diffusion

B^{11}(120keV) in Si

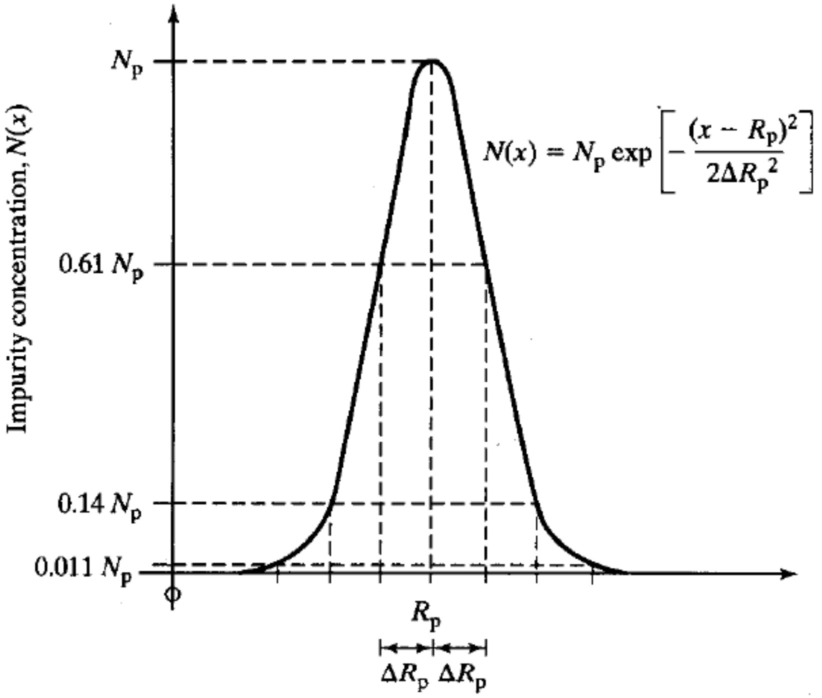


P^{31}(120keV) in Si



Ion interactions/doping profile

- The range distribution of implanted impurities is described, as a first approximation, by a **symmetrical Gaussian distribution** (2 moments: R_p : projected range, ΔR_p : straggle)



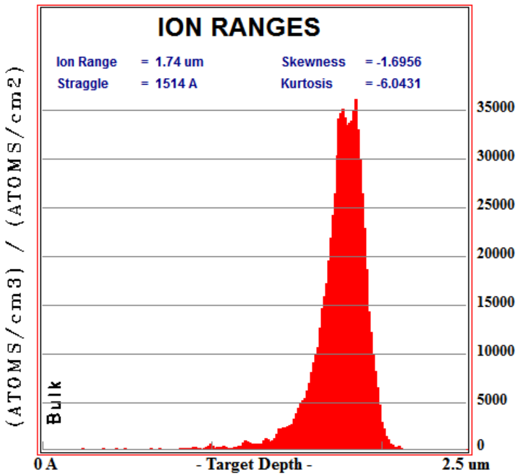
$$N(x) = N_{pk} e^{-\frac{(x-R_p)^2}{2(\Delta R_p)^2}} = \frac{Q}{\sqrt{2\pi}\Delta R_p} e^{-\frac{(x-R_p)^2}{2(\Delta R_p)^2}}$$

$$Dose = \int_0^L N\,(x) = Q = \sqrt{2\pi}\Delta R_p N_{pk} [atoms \cdot cm^{-2}]$$

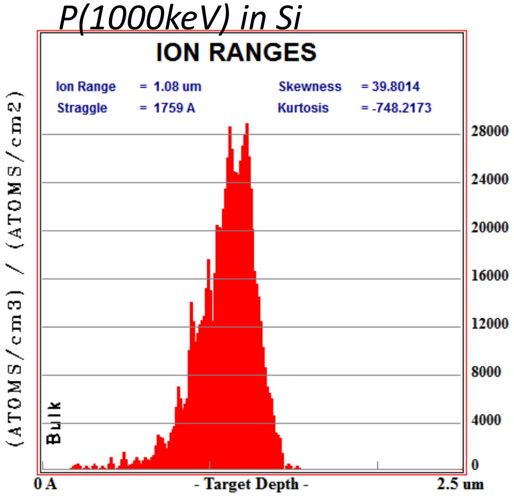
Ion interactions/doping profile

- Higher moments are needed to describe realistic profiles:
  - **skewness** (γ), describing asymmetry of distribution
  - **kurtosis** (β), describing peak sharpness of the profile

B(1000keV) in Si



P(1000keV) in Si



$$Q = m_0 = \int_{-\infty}^{+\infty} N(x)dx$$

$$R_p = m_1 = \int_{-\infty}^{+\infty} xN(x)dx$$

$$\Delta R_p = m_2 = \int_{-\infty}^{+\infty} (x - R_p)^2 N(x)dx$$

$$\gamma = m_3 = \frac{1}{\Delta R_p{}^3} \int_{-\infty}^{+\infty} (x - R_p)^3 N(x)dx$$

$$\beta = m_4 = \frac{1}{\Delta R_p{}^4} \int_{-\infty}^{+\infty} (x - R_p)^4 N(x)dx$$

Ion interactions/doping profile

- Analytical description of doping profiles can be obtained from Pearson distribution
- Coefficients of Pearson's equation are related to the four moments
- Explicit formula for the implanted profile can be obtained

$$\frac{df}{dx} = \frac{(x-a)f}{b_0 + b_1 x + b_2 x^2}$$

Pearson distribution function defined as solution to this DE

$$a = b_1 = -\frac{\gamma \Delta R_P^2 (\beta + 3)}{10\beta - 12\gamma^2 - 18}$$

$$b_0 = -\frac{\Delta R_P^4 (3\gamma^2 - 4\beta)}{10\beta - 12\gamma^2 - 18}$$

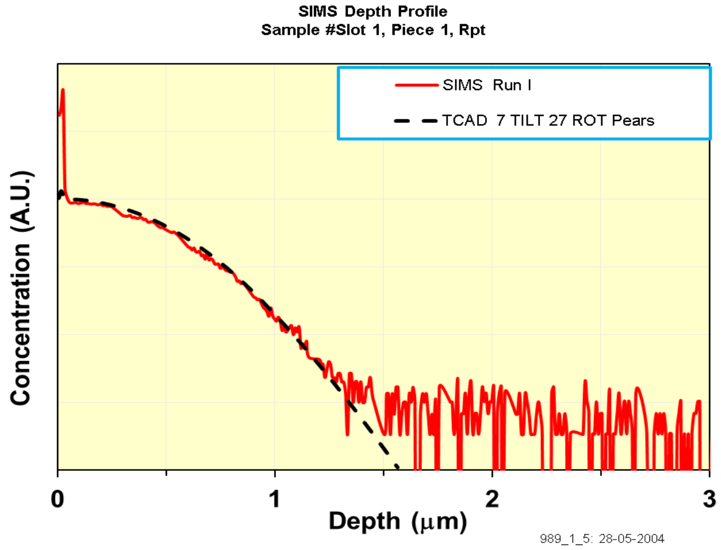
$$b_2 = -\frac{6 + 3\gamma^2 - 2\beta}{10\beta - 12\gamma^2 - 18}$$

$$C(x) = C_o \exp\left\{\frac{1}{2b_2}\ln(b_2 x^2 + b_1 x + b_0) - \frac{2b_2 a + b_1}{b_2\sqrt{4b_2 b_0 - b_1^2}} \arctan\left(\frac{2b_2 x + b_1}{\sqrt{4b_2 b_0 - b_1^2}}\right)\right\}$$

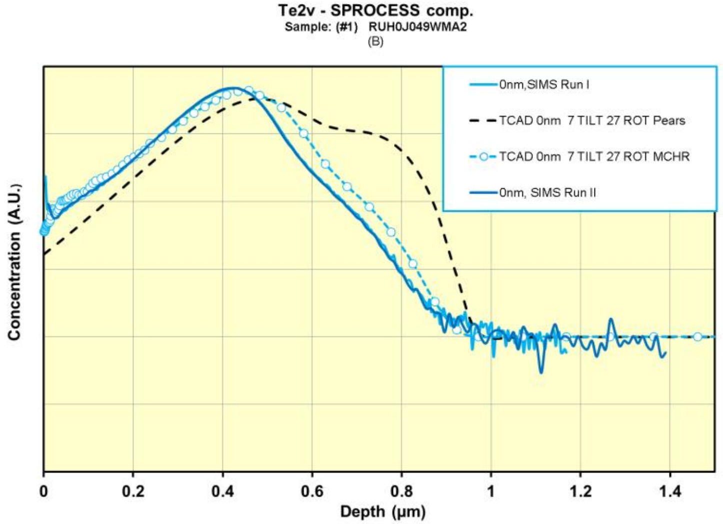
Generic profile formula from Pearson distribution

Ion interactions/doping profile

- Analytical doping profiles description reasonably accurate for heavy ions
- Lighter ions more accurately described using MC (crystal orientation depending)



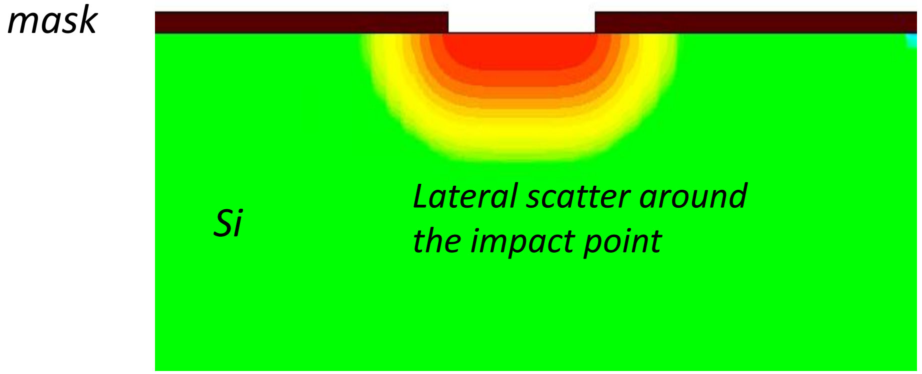
SIMS and Pearson IV distribution – 31P



SIMS, Pearson IV distribution and MC run – 11B

Masking

- Purpose of the mask is to Implant only in certain parts of the wafer, using a suitably thick mask (i.e. that its R_p lies within the mask material)
- The thickness of the mask should be large enough that the tail of the implant profile in the silicon should not significantly alter the doping concentration (C_B)



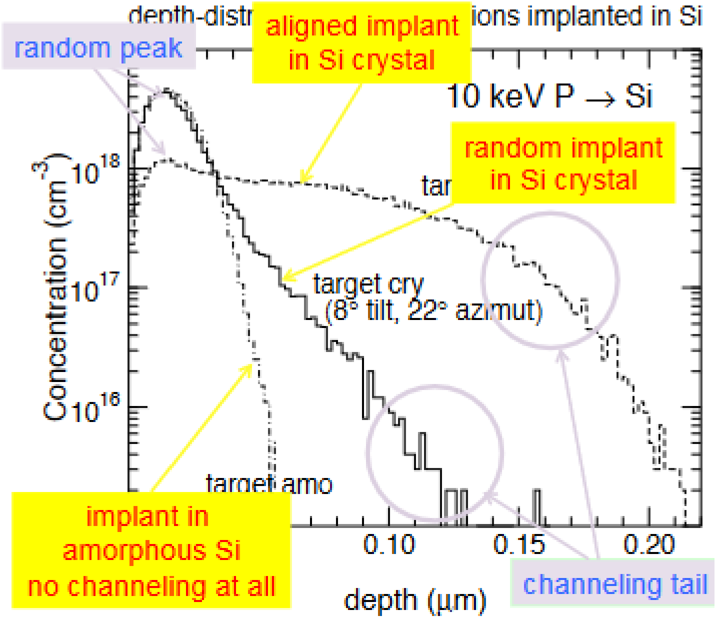
MATERIAL THICKNESS NEEDED TO MASK

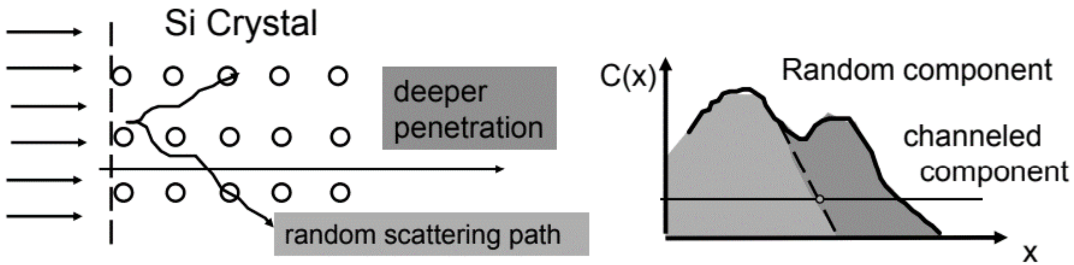
At 200 KeV	Poly	SiO2	Si3N4	Al	Resist
Boron	0.9µm	1.0µm	0.61µm	0.9µm	1.0µm
Phosphorous	0.7µm	0.6µm	0.42µm	0.55µm	0.8µm
Arsenic	0.3µm	0.3µm	0.18µm	0.28µm	0.35µm
Antimony	0.2µm	0.2µm	0.16µm	0.18µm	0.25µm
At 100 KeV	Poly	SiO2	Si3N4	Al	Resist
Boron	0.65µm	0.7µm	0.42µm	0.7µm	0.7µm
Phosphorous	0.4µm	0.36µm	0.25µm	0.3µm	0.45µm
Arsenic	0.18µm	0.16µm	0.1µm	0.16µm	0.20µm
Antimony	0.12µm	0.11µm	0.07µm	0.10µm	0.14µm

FOR 0.0001% TRANSMISSION

Channeling

- During ions implantation in a periodic structure, directional effects due to nuclear scattering might confine the ions into regions minimizing interactions along the path.
- Channelling: Average penetration depth is larger, affecting the final doping profile

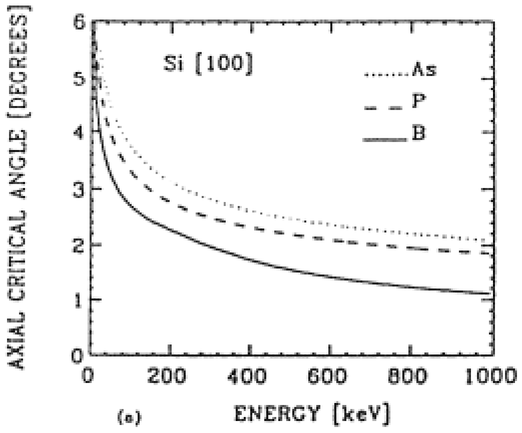


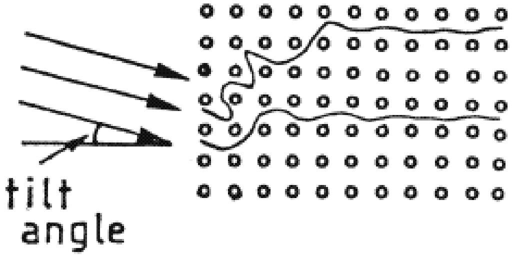


Channeling

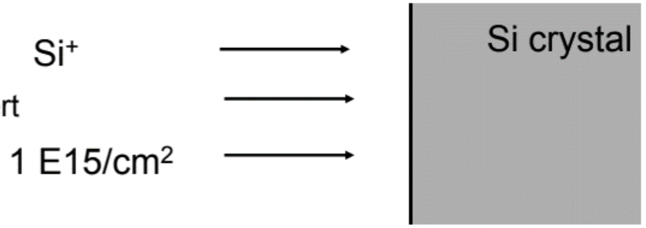
To minimize channelling:

- **pre-amorphization** of the wafer via implantation
- the wafer is **tilted** by some degrees with respect to ion beam: the value of the critical angle below which there is channelling depends on crystal orientation and energy of the ion. In practice a tilting angle of 7 degrees is used

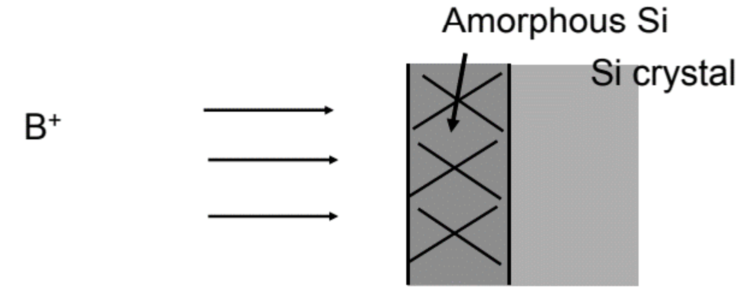




Step 1
High dose Si+ implantation to covert surface layer into amorphous Si

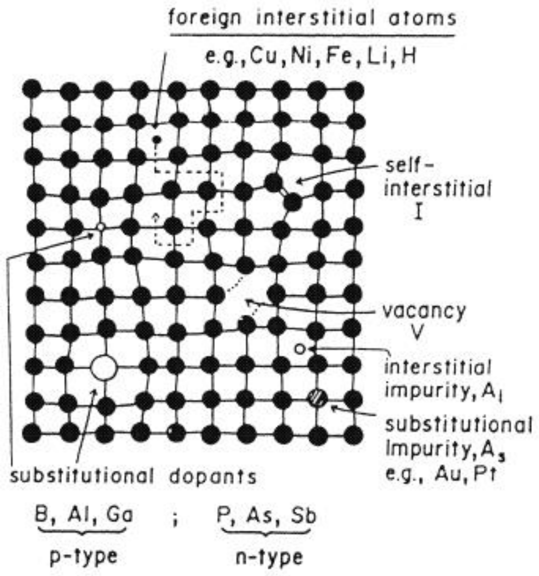


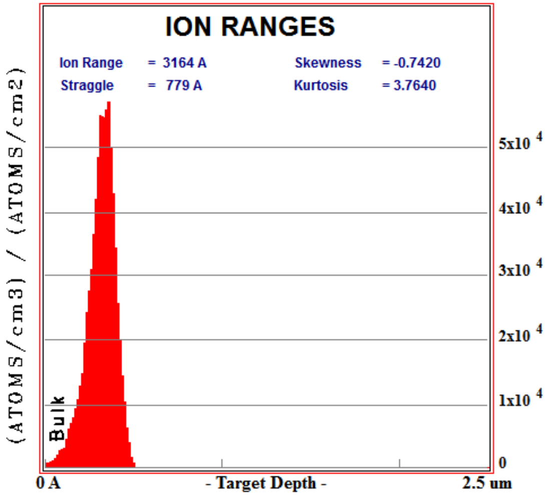
Step 2
Implantation of desired dopant into amorphous surface layer

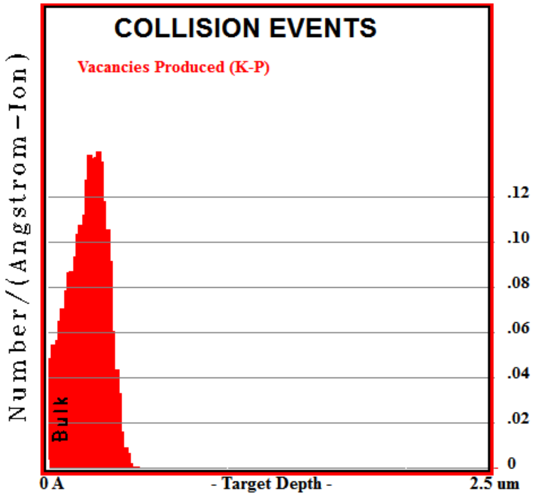


Implantation damage and annealing

- Ion implantation creates defects in the target crystal, by displacing atoms from their regular lattice sites (see radiation damage lectures)
- The elementary radiation defect consists of Frenkel defect, i.e. displaced atom (interstitial) plus the related vacancy.
- More complex defects form as a result of accumulation and clustering of interstitials and vacancies (divacancies V-V, vacancy impurities, like V-O, As-I…)



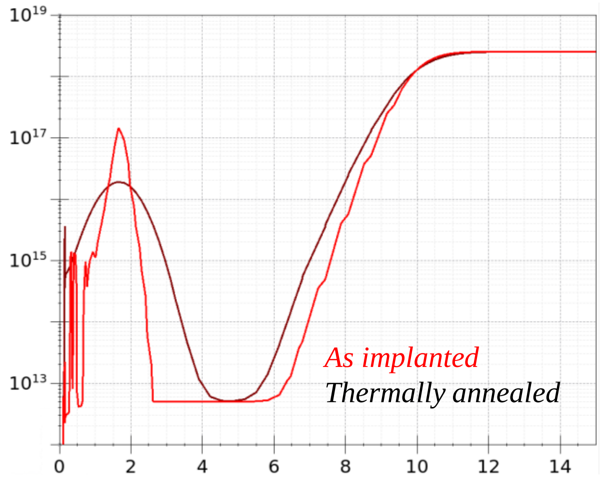




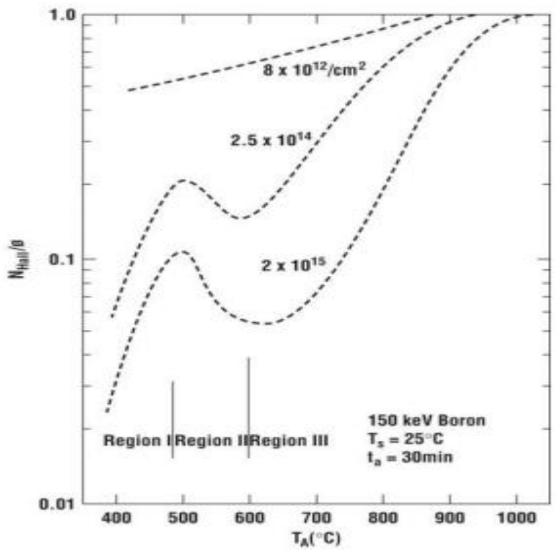
Implantation damage and annealing

- After implantation process a thermal treatment is required to activate electrically the dopant (i.e. to have them moved to substitutional positions) and to restore the crystalline order of the semiconductor.

- Annealing at high temperature (~1000°C) could result in perfect crystal, but leads to dopant diffusion. Particularly serious issue in modern technologies, where very shallow junctions are used



Doping profiles from ^{11}B implantation in <100> Si, as implanted and after thermal annealing

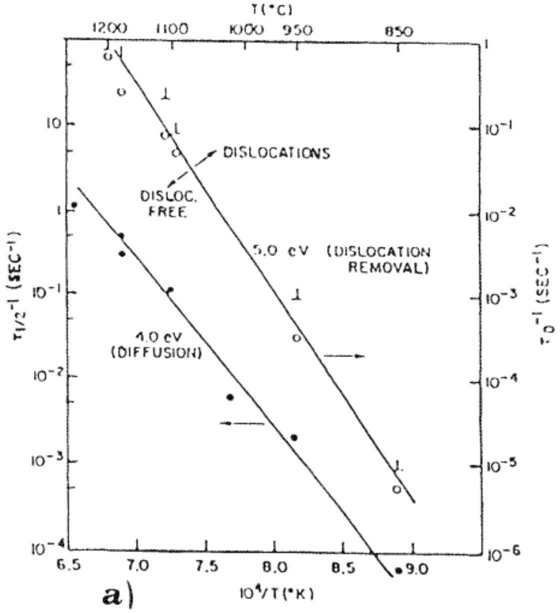


Isochronal annealing of boron. The ratio of the free-carrier to dose (fraction of boron atoms located in substitutional lattice points) is plotted versus the anneal temperature for three doses of boron.

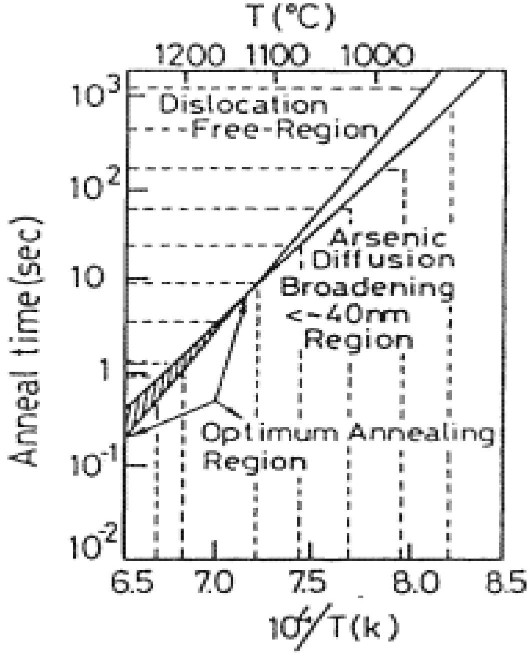
Implantation damage and annealing

- Activation energy for removal of point defects (V and I) usually higher than that of impurity diffusion.

- Different slopes in Arrhenius plots allow to use high temperature to enhance annealing and depress diffusivity: Rapid Thermal Annealing (**RTA**)



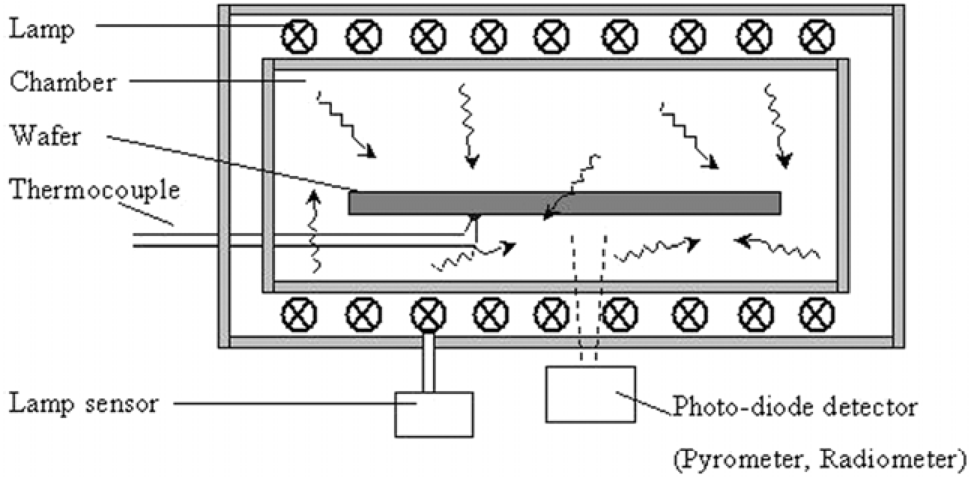
Dislocation removal rate in As implanted Si and As diffusivity vs. 1/T

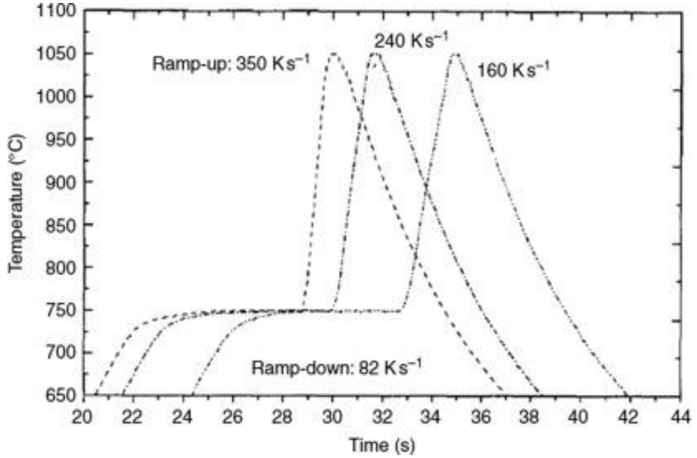


Implantation damage and annealing

- Rapid thermal annealing of wafers (**RTA**) optimizes the defects suppression, whilst minimizing dopants diffusion

- Wafers are rapidly heated by lamps (10's kW) to 1000 C for 1 – 20 secs max





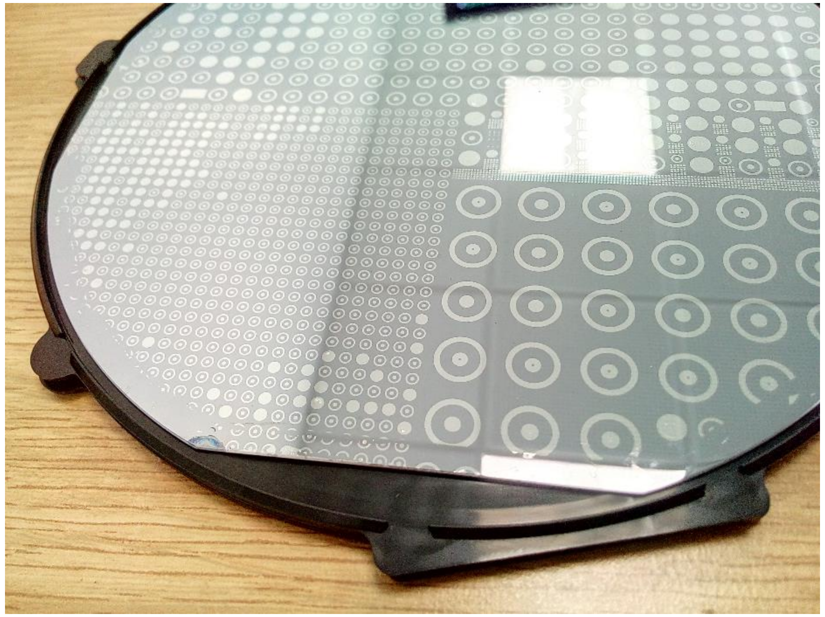
Overview

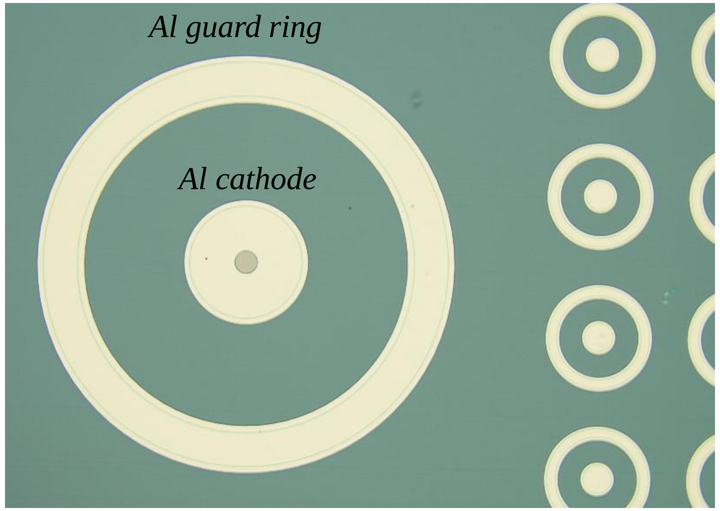
- Semiconductor fabrication process II
    - Implantation
        - *Introduction*
        - *Tools/equipment*
        - *Ions interaction/dopants profiles*
        - *Masking*
        - *Channeling*
        - *Implantation damage and annealing*
    - **Metallization**
        - *Introduction*
        - *Tools/equipment*

Metallization

- Once devices have been fabricated in the wafer (Front End of Line), metal layers are deposited to form conductive connections
- Modern technologies moved from Al to Cu to reduce resistivity in interconnect in Back End of Line (BEOL). This is a more complex process (Dual Damascene process) than sputtering

Schottky diode on P-type Si wafer

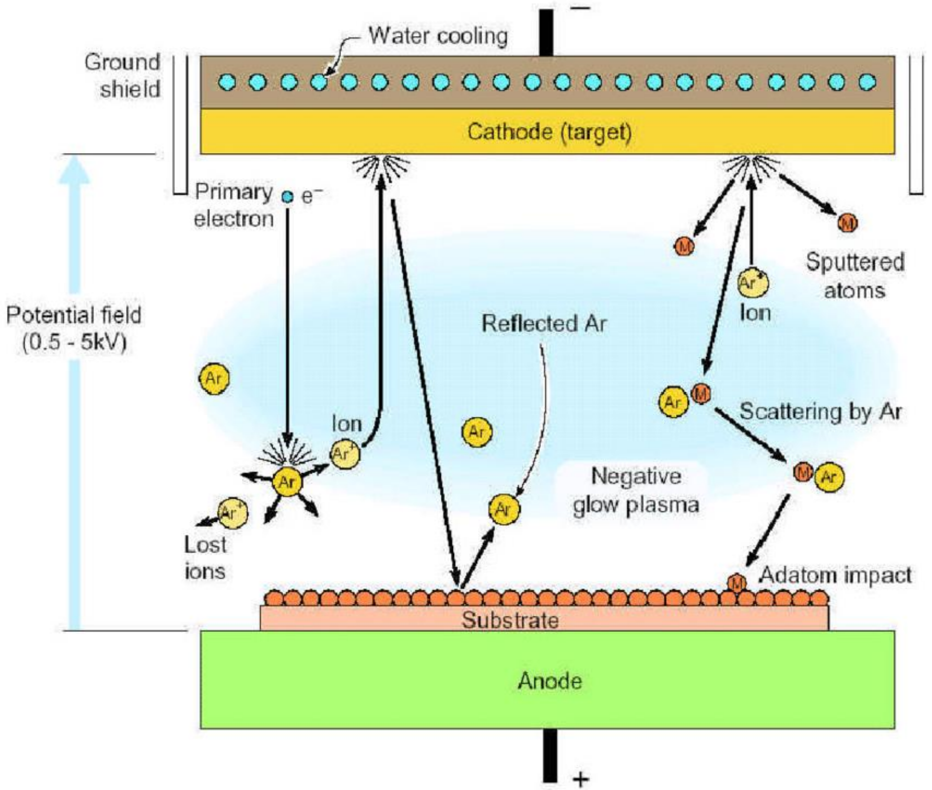




Metallization

- Sputtering (**PVD**, Physical Vapor Deposition) is one of the most common method to deposit thin film of metal

- Good step coverage obtained by reducing the mean free path of sputtered atoms (increasing Ar ions, magnetron sputtering) Sputtering also used to clean wafer before deposition, by Ar^+ etching



Cathode (target -) is the material to deposit, generally cooled

An inert gas (Ar) is ionized, accelerated and collides with the target. Ejected atoms have energies ~ 10’s eV

Some atoms sputters off and, after scattered paths, land and deposit onto the wafer (+)

Process fabrication II Summary

Thank you

giulio.villani@stfc.ac.uk

- Introduction to Ion Implantation
  - Characteristics, tools and equipment
  - Ion interactions, masking and channeling, doping profiles
  - Implantation damage and annealing required

- Metallization
- Purpose, Tools/equipment