Ion Implantation

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Introduction

- Ion implantation is a controlled doping technique.
- In ion implantation, dopant atoms are vaporised, accelerated and directed at the silicon substrate.
- They enter the crystal lattice, collides with silicon atoms, and gradually lose energy, finally coming at rest at some depth within the lattice.
- The average depth can be controlled by adjusting the acceleration energy.
- The dopant dose can be controlled by monitoring the ion current during implantation.

Introduction

- The principle side effect- disruption of the silicon lattice caused by the ion collision- is removed by subsequent heat treatment known as **Annealing**.
- Implantation energies ranges from 1KeV to 1 MeV, resulting in ion distribution with average depth ranging from 100 A to 10µm.

Range Theory

- It explains
  - The physics of ion collisions
  - Its application to calculating range distributions
  - The effect of a crystal lattice, damage and recoil distributions.

Range Theory-Ion stopping

- As each implanted ion enters the target, it undergoes a series of collision with target atom until it finally comes to rest at some depth.
- The initial ion energy typically 100KeV, is much higher than lattice binding energies, 10 to 20eV, so the ion must come very close to a lattice atom if it is to be significantly deflected.
- This is one reason of scattering due to elastic collision between pair of nuclie, ignoring the relatively weak lattice forces.
- A second component of scattering coming from inelastic collision with electrons in the target.

Range Theory-Ion stopping

- The total stopping power S of the target, defined as the energy (E) loss per unit length of the ions is the sum of these two terms

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

- Once we have integrated S,we can integrate it to sum the energy losses to find how far an ion will travel before all the energy has gone.

Range Theory-Ion stopping

- We can find the rate of energy loss to nuclear collisions per unit path length by summing up the energy loss for each possible impact parameter multiplied by the probability of that collision occurs..If the maximum possible energy transfer in a collision is Tmax and there are N target atoms per unit volume , then

$$S_n = \left(\frac{dE}{dx}\right)_{max} = N\int_0^{T_{max}} T d\sigma$$

Range Theory-Ion stopping

- Where by classical dynamics ,T is given by

$$T(p) = \frac{4M_1M_2}{(M_1+M_2)^2} E sin^2 \left[\frac{\theta(p)}{2}\right]$$

Where M1 and M2 are the atomic mass numbers of ion and target atom resp.

The probability of having an impact between p and p+dp also known as the differential scattering cross section dσ.

Range Theory-Ion stopping

- **Nuclear stopping** is elastic, so energy lost by the incoming ion is transferred to the target atom, which is recoiled away from its lattice site.
- **Electonic stopping** is caused by interaction with the electron of the target.
- Detailed modeling is very complex, but in the low energy regime the stopping is similar to a viscous drag force and is proportional to the ion velocity v. Lindhard and Scharff proposed the following expression , which is commonly used

$$S_e = \left[\frac{2q^2 a_0 Z_1^{7/6} Z_2 N}{\varepsilon_0 \left(Z_1^{2/3} + Z_2^{2/3}\right)^{3.2}}\right]\left(\frac{v}{v_0}\right) = \left[\frac{Z_1^{7/6} Z_2}{\left(Z_1^{2/3} + Z_2^{2/3}\right)^{1/2}}\right] 8\pi a_0 h\mu v$$

Range Theory-Ion stopping

- Where a_0=Bohr's radius, v_0=Bohr's velocity and N =target atom number density.
- Experimental measurements have shown that, although expression predicts the correct general trend, there are oscillations in the stopping power as the ion number increases.
- Electron stopping is inelastic-the energy lost by incident ion is dissipated through the electron cloud into thermal vibration of target.

Range Theory-Range Distribution

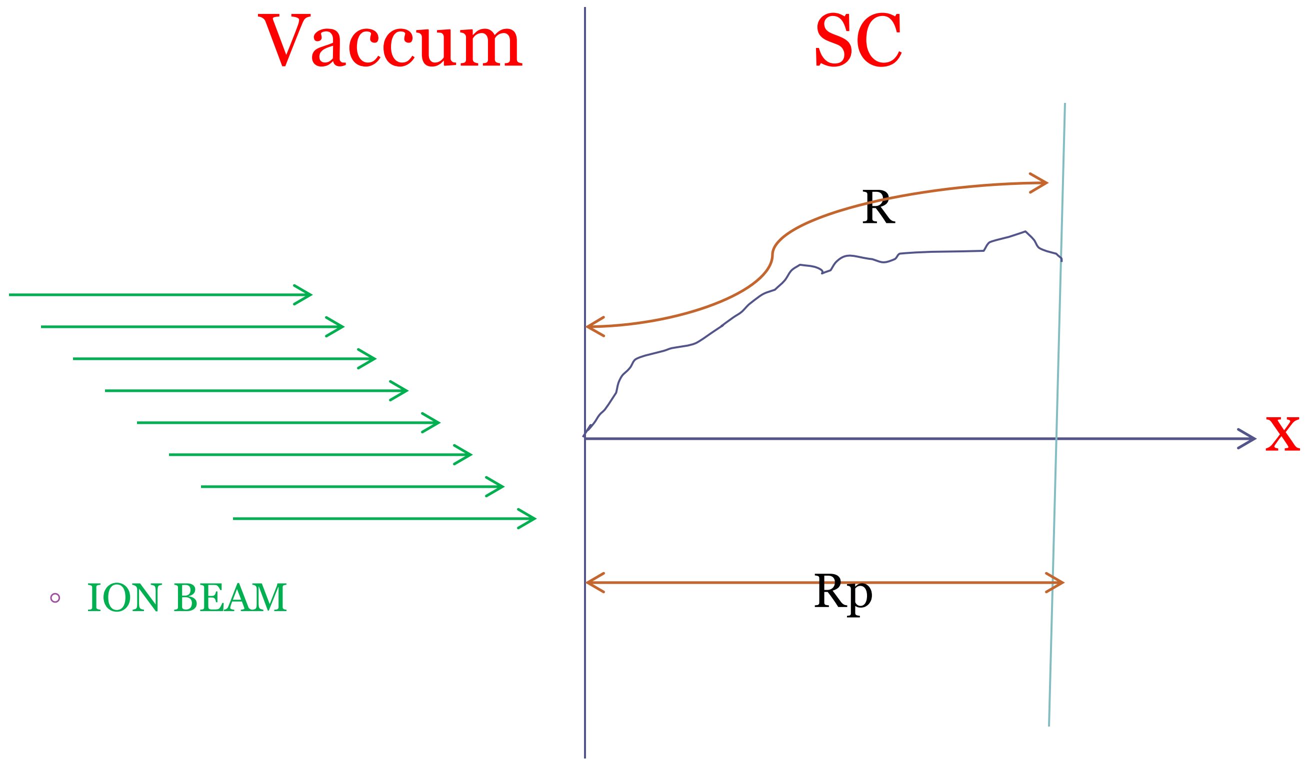
- Each implanted ion has a random path as it moves through the target ,losing energy by nuclear and electronic stopping.
- Since each implantation does contain more than 10^12 ions/cm sq their average behaviour can be well predicted.
- We will consider an ion descending vertically and entering a horizontal silicon surface. The average total path length in silicon is called the range R, and is compared of a mixture of vertical and lateral motion .

Range Theory-Range Distribution

- The average depth of the implanted ion is called the projected range Rp, and the distribution of ion about that depth can be appoximated as Gaussian with standard deviation σp.
- The lateral motion of the ion leads to the lateral gaussian distribution with standard deviation σl.
- The ion range is shown in fig.below .Far from the mask edge, we can neglect the lateral motion and write the concentration n(x) as

$$n(x) = n_0 exp\left[\frac{-(x-R_p)^2}{2\sigma_p^2}\right]$$

Range Theory-Range Distribution



Range Theory-Range Distribution

- If the total dose is Φ, integrating above eqn. gives an expression for the peak concentration

$$n_0 = \frac{\varphi}{\sqrt{2\pi}\sigma_p} \cong \frac{0.4\varphi}{\sigma_p}$$

Range Theory-Damage

- As each ion travels through the target, it undergoes a series of nuclear collision. Every time the ion is scattered, a fraction of its energy is transferred to a target atom, which is displaced from its original position.
- The binding energy of a lattice site is only 10 to 20 eV, so it is easy to transfer enough energy to free an atom from its position and make it travel through the target as a second projectile.
- Now both the ions and the displaced target atom travel and cause further displacements, so the energy is spread over many moving particles. Eventually the energy per particle become too small and the cascade stops.

Range Theory-Damage

- The result of one incident ion has been the displacement of many target atoms through nuclear scattering .After many ions have been implanted, an initially crystalline target will be so disrupted that it will have changed to a highly disordered state.
- If the target temperature is high enough, the competing process of self annealing will occur, repairing some or all damaged as it is generated . The result is therefore very temperature dependent.

Range Theory-Damage

- Because only nuclear scattering damage the target, the amount of damage done depends on the nuclear stopping power, which is function of energy.
- Once the target atom is displaced ,several things are possible
- At low temperature, the atom are unable to move far through the lattice, so local relaxation take place to accommodate them.
- Above room temperature, displaced atom can diffuse to empty lattice sites and so repair damage, or can coalesce with other displaced atom to form an extended defect. vacancies that remain behind when an atom is displaced can also diffuse and combine to form extended defects.

Range Theory-Damage

- If the target temperature during implantation is high, perhaps due to heating effect of the ion beam itself, self annealing can be so effective that even heavy ion leave little damage.
- Damage can affect the result of subsequent processing steps:
  - Point defects are known to influence strongly diffussion in silicon.
  - Damaged oxide layers etches faster than undamaged oxide because some of the bonds are already broken,
  - Damage to photoresist used as a mask can break down the organic chains to a carbon rich film, which is much harder to remove, making it unsuitable as a mask for high dose implant.

Range Theory-Damage

- These process rate changes act in addition to the chemical and doping effects caused by the implanted atoms themselves.

Ion Implanter

- An Ion implanter tool consist of following five major subsystem.
  - Ion source
  - Extraction electrode and ion analyzer
  - Accelerator column
  - Scanning system
  - Process Chamber

Ion Source

- The species to be implanted should be present in the beam as charged particle, or ions.
- Because of their electrical charge particles, ions can be controlled and acceleration by magnetic or electric field.
- Ions for implantation are generated in the ion source.
- A positive ion is formed from dopant gas source or by vaporising the solid.
- Typically B+,P+,As+ and Sb+ are produced by ionization of atom or molecules.
- The most common feed material for the source of dopant atom is gas such as B2H6,BF3,PH3 and AsH3 which are diluted with hydrogen and packed in small cylinder of relatively small size(0.4-2.2 liters).

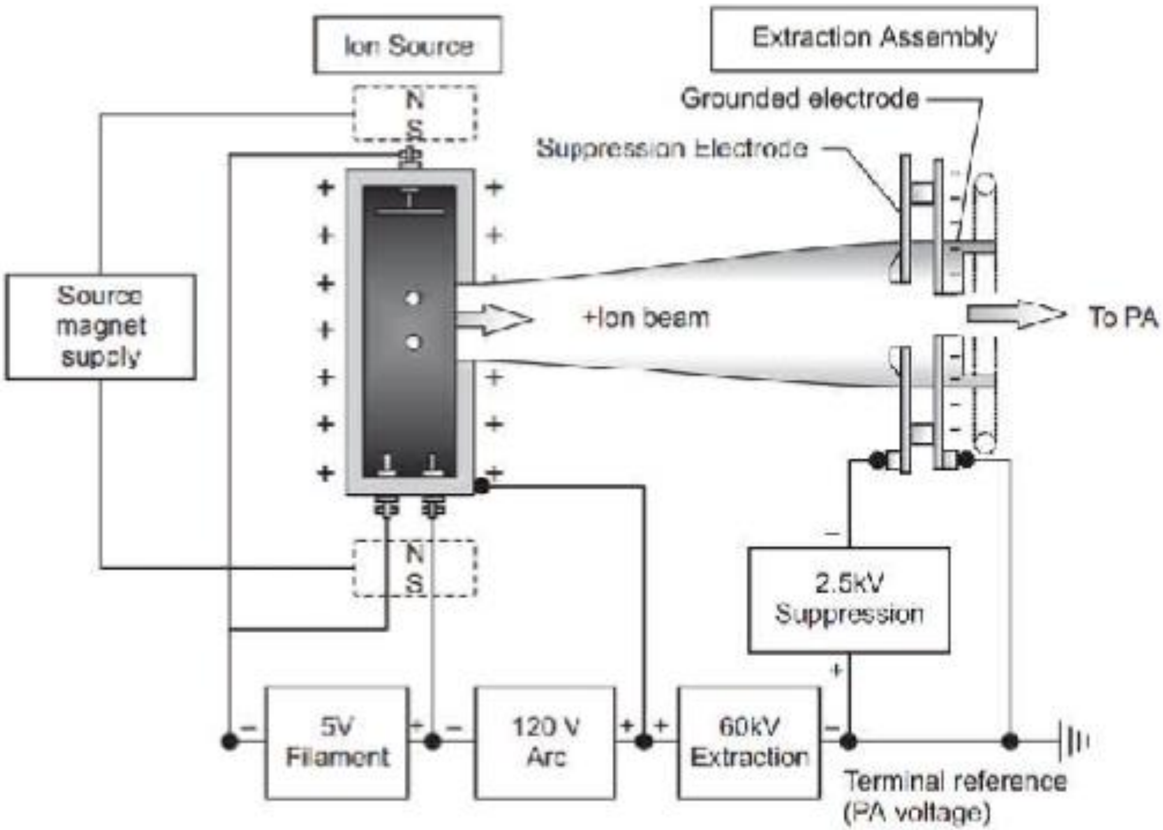
Ion Source

- Another method of suppling feed material is the vapourization of solid dopant source which are normally present in the form of pillet especially in case of arsenic and phosphorus.
- In this they are vapourised at 900 degree C and volatile dopant atoms are transferred to the ion source chamber.
- The disadvantage in this method is the long setup time (40-180 minutes) and advantage is that there is no use hydrogen for dilution.
- Most of this is required to heat and stabalize the vapourizer.

Extraction Electrode and Ion Analyzer

- The traditional implanter extraction system collects the positive ions created inside the ion source and forms them into beam.
- The ions are extracted through a slit in the source .
- They are repelled by the positive bias of chamber (anode) and attracted to the negative bias (cathode)of the extraction assembly.

Extraction Electrode and Ion Analyzer



Extraction Electrode and Ion Analyzer

- This positive ions are attracted by negative electric field, stronger the electric field , then faster the ion will move due to which there will be gain in kinetic energy which make it to penetrate through wafer.
- The negative bias of the extraction electrode also repels stray electron in the source plasma.
- A negatively biased **suppression electrode** is used to focus the ion beam into a parallel beam.

Mass Analyzer magnet

- The ion extracted from the source contain many different ion species with different in atomic mass units and travel at a relatively high speed due to acceleration provided by the extraction voltage.
- In an ion implanter, a magnetic ion analyzer seperates the desired dopant ions from the main body of ion species.
- The analyzer magnet is shaped in a 90 degree angle and its magnetic field causes theion species to be deflected into arc.

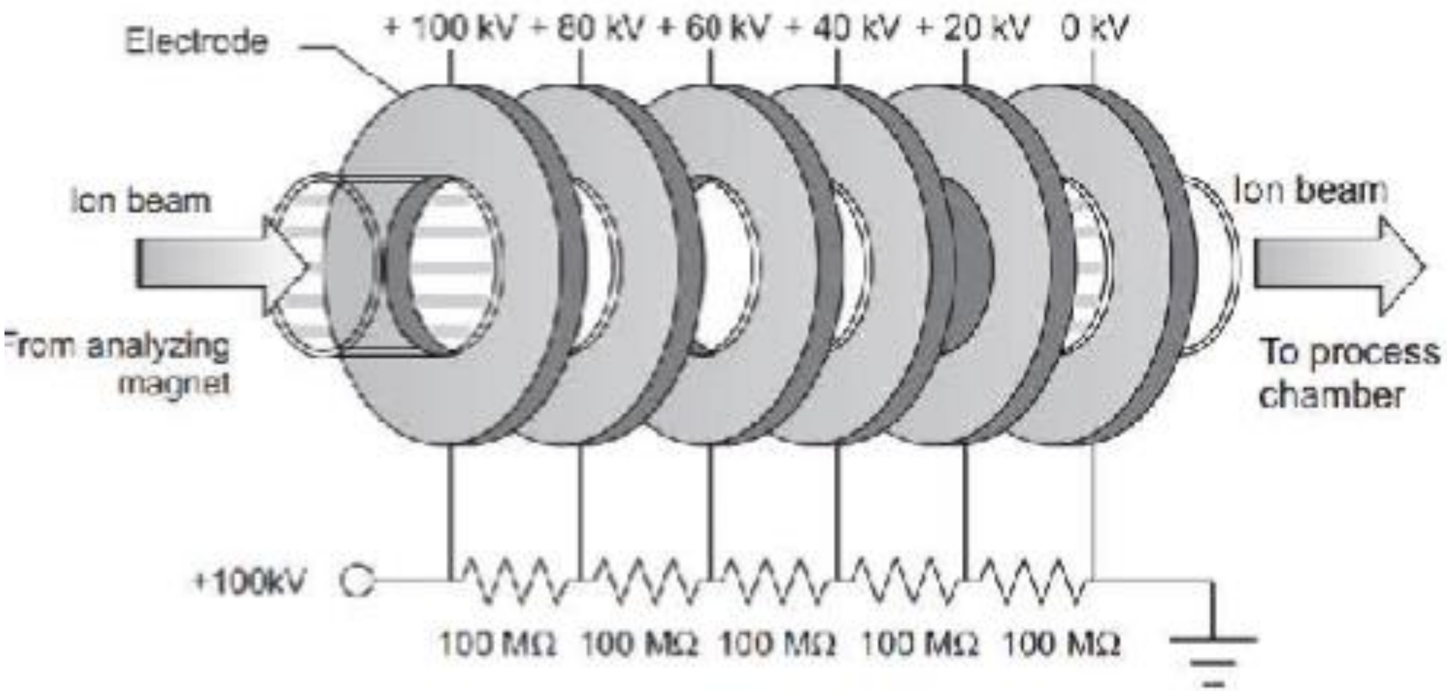
Mass Analyzer magnet

- For a given field strength, ion with heavier masses are not able to bent at appropriate angle while the lighter ions bend too easily. There is one ion species , however, that bends just enough at the appropriate field strength to alow it to pass through the center of the magnet analyzer.
- This is the dopant species that eventually get implanted into the wafer.

Acceleration Column

- To achieve additional ion acceleration beyond the analyzer magnet , positive ions are accelerated in an electric field in side an acceleration column.
- The acceleration column is alinear design made of series of electrode separated by insulators each with the increasing negative charges.
- This give higher beam energy which causes deeper ion implantation

Acceleration Column



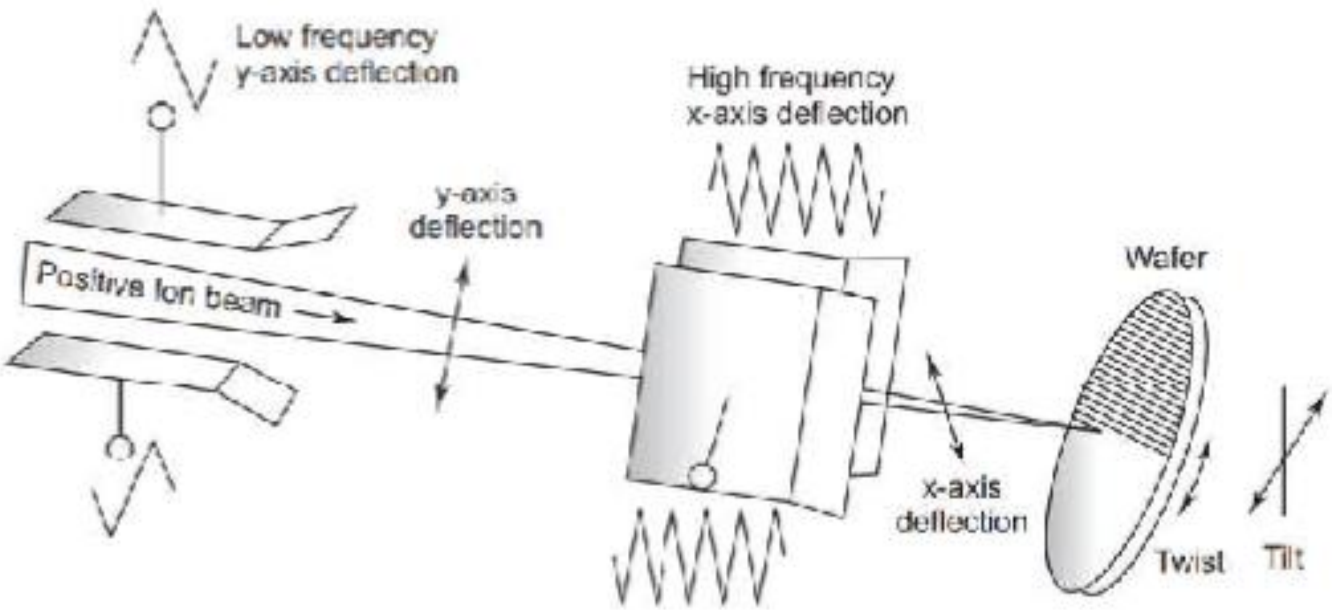
Scanning system

- Wafer scanning is done either by moving the beam over a stationary wafer or moving the wafer through a stationary beam.
- Low to medium current implanter keeps the wafer stationary, while high current ion implanter keeps the ion beam stationary.
- The different type of scanning used in implanter are
  - Electrostatic scanning
  - Mechanical scanning
  - Hybrid Scanning

Scanning system

- **Electrostatic Scanning**
- In this scanning the ion beam are deflected across the wafer by applying specific controlling voltage to set of X-Y electrodes.
- An electrostatic scan move beam across the wfer (x-axis) 15,000 times per second while it scan up and down (Y-axis) 1200 times per second.
- Special care is taken to ensure the scan is uniform at the outer edge of the wafer where the scan has to stop and reverse direction.
- In electrostatic characteristics the wafer can be twisted and tilted relative the ion beam to active desired junction characteristics, and to reduce channelling effects.

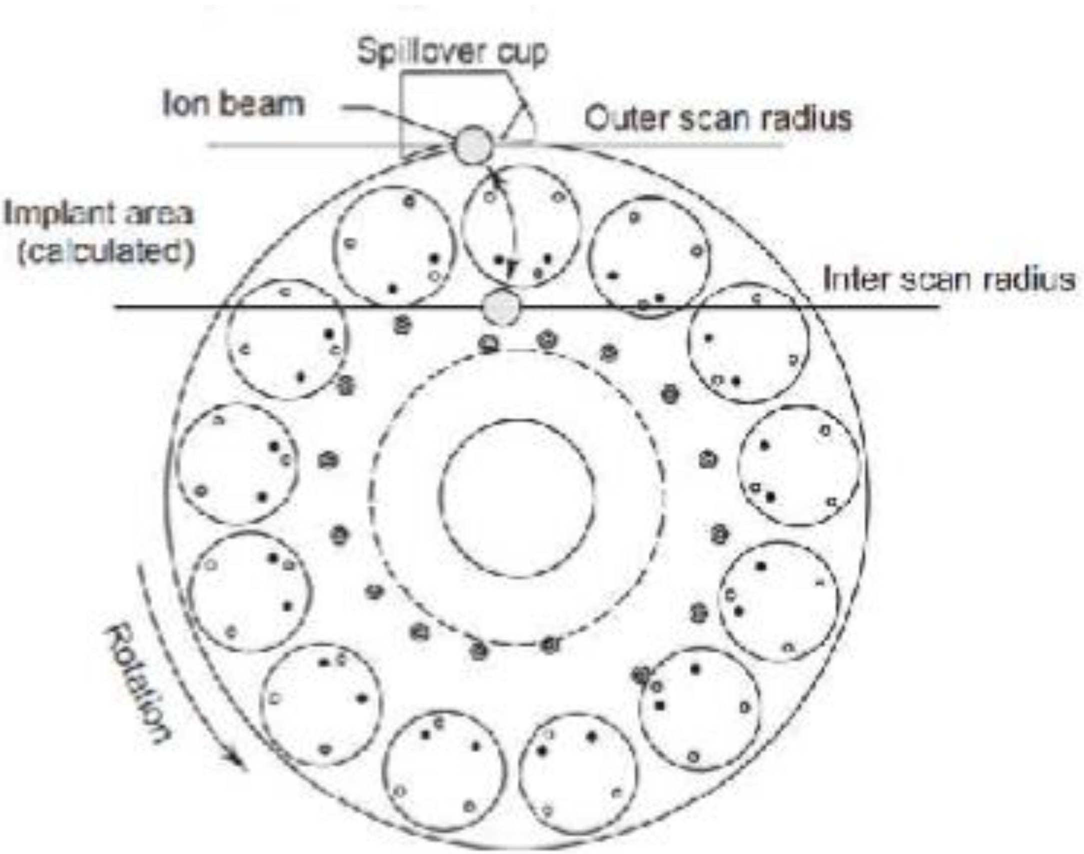
Scanning system



Scanning system

- **Mechanical scanning**
- With mechanical scanning, the ion beam is fixed and the wafer are mechanically moved through the beam.
- This method is generally used for high current implanter because electrostatic beam deflection is difficult at high currents and energies.
- Mechanical scanning is done by rotating multiple wafers (upto 25,000mm wafers) fixed on the outer circumference of a large wheel assembly disk that is simultaneously moving up and down while rotating at 1000 to 1500 rpm.

Scanning system



Scanning system

- Mechanical scanning is a batch process.
- Reduce wafer heating due ion beam energy.

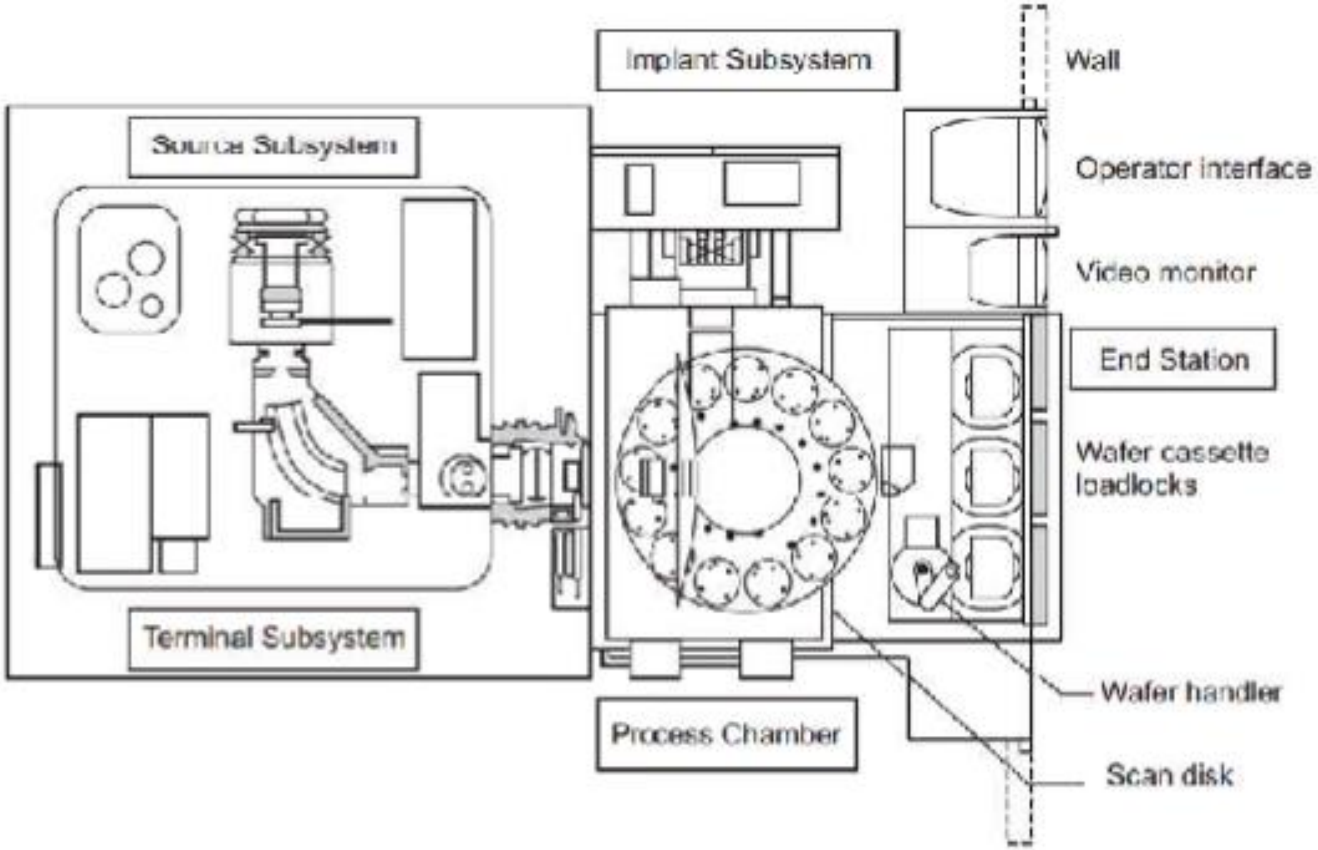
Hybrid Scanning

Combination of both above type of scanning.

Process Chamber

- The implantation of the ion beam int the wafer take place in the process chamber.
- The process chamber is a major sub-assembly that includes
  - Scanning system
  - End station with vaccum load lock for loading and unloading wafers
  - The wafer handler system
  - Computer control System
  - There are also methods for dose monitoring and channelling control.

Process Chamber



Process Chamber

- End station can be large if used for mechanical scanning.
- It is pumped down to the vaccum required for implantation with multiple roughing, turbo pumps and cryo pumps to reach base pressure (typically 10-8 torr).
- Load/unload systems in the end station use robotic handling to move wafers between an inputs station and the scanning disk in the target chamber.

Process Chamber

- Cassette are loaded into the input rack and the load locks are used to initially seal the input chamber.
- A roughing pump lowers the pressure around the cassettes. When pressure is low enough, a turbo pump continues the pump down until reaching high vaccum.
- At this point, an isolation valve opens and a robotic mechanism moves the cassette into the main target chamber.
- When the cassette is in the process chamber, a robotic wafer handler system moves the wafer from the cassette and place them on the scanning disk.

Annealing

- Ion implantation damages the silicon lattice by knocking atoms out of the lattice structure.
- With high dose, the implanted layer actually becomes amorphous.
- Furthermore , the implanted ions rarely enters the lattice structure site of the silicon, instead stopping in interstitial sites outside the lattice.
- These interstitial dopants are electrically inactive until activated by a high temperature annealing step.
- Annealing heats the implanted silicon substrate to repair crystalline damage and electrically activate dopants by moving the atoms into crystal lattice.

Annealing

- There are two basic methods for heating implanted wafers to anneal.
  - Furnance Anneal
  - Rapid thermal Anneal.(use rapid thermal processor)