Chapter 6
Ion Implantation

6.0 Introduction

Ion implantation has been the dominating doping technique for silicon integrated circuit for past 30 years. It is expected to remain as the mean for doping technique for the foreseeable future. Like diffusion process, it is a process where dopant is introduced using ion species such as BF$_3$ and PF$_5$. The ion species are ionized and accelerated to hundreds or thousands of volts of energy by mass separation magnet and impacted into as perfect silicon surface. This will result thousand of silicon atoms being displaced from each ion implant. The implantation energies are between 1.0keV and 1.0MeV. It would result in ion distribution with average depths ranging from 10nm to 10µm. Ion doses vary from $10^{12}$ ions/cm$^2$ for threshold voltage adjustment to $10^{18}$ ions/cm$^2$ for formation of buried insulating layer. The amount of dose can be decreased or increased by varying the implant time and beam current.

The main advantages over the diffusion are low temperature, more precise control and reproducibility of impurity doping, and shallow implant. However, owing to high-energy bombardment causing damaged crystal lattice, Rapid thermal annealing RTA at 400$^0$C to 500$^0$C is required to allow the implanted atom to stay at the right substitutional site, to repair crystal damage, and drive-in the implanted atom.

6.1 Concepts of Ion Implant

Ion implantation provides a very precise way to introduce a specific dose or number of dopant atoms into the silicon lattice. This is because the electrical charge on the ion allows it to be counted by Faraday cup. In spite of the preciseness in which the dose can be controlled.

6.1.1 Ion Implant Stop Mechanism

When ion bombards and penetrates the silicon substrate, it colides with lattice atom. The ion gradually loses its energy and eventually stop inside the crystal lattice. There are two stop mechanisms namely nuclear stopping and electronic stopping. When ion colides with with nuclei of the lattice atom, it can be
scattered significantly and transfer its energy to the atom in lattice. This type of stopping is called *nuclear stopping*. In the hard collision, lattice atom can get enough energy to break free from the lattice binding energy, which causes lattice disorder and damage crystal structure. If the ion colides with electron of the atom. This type of collision, which is a soft collision, will not change the path of the ion and the energy of the ion significantly. It will not cause crystal damage and the range of penetration will be long. This type of collision is called *electronic stopping*.

The type of collision of ion in silicon lattice can be random collision, channel collision, and back scattering. Random collision and back scattering would be the nuclear stopping, while channel collision will have electronic stopping. Figure 6.1 illustrates the type of stopping mechanism. When projected ion hits the nucleus, it constitutes nuclear stopping. When the projected ion enter into substrate, it gets aligned with the gap between the host atoms, and they travel a large distance before finally coming to rest. This phenomenon is called *ion channeling*.

![Figure 6.1: Illustrating different type stopping mechanism](image)

Figure 6.2 shows the relationship between stopping power and velocity of ion for different types of stopping.
The total stopping power $S$ of the target, which is defined the energy loss $E$ per unit path length of the ion $x$, would be consisted of two components namely the nuclear stop and electronic stop. Mathematically, it can be expressed as

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

(6.1)

As mentioned earlier, nuclear stopping is caused by a collision between two atoms and it can be well described by classical kinematics. If the atoms were bare nuclei then at a separation $r$, the coulombic potential $V_c(r)$ between them, which is given by equation (6.2).

$$ V_c(r) = \frac{q^2Z_1Z_2}{4\pi\varepsilon_0r} $$

(6.2)

where $Z_1$ and $Z_2$ are the atomic numbers of the atoms. With the presence of electron spinning around the nucleus, the screening function $f_s(r)$ have to be factor in. The screening function $f_s(r)$ is defined as

$$ f_s(r) = a_1e^{-r/b_1} + a_2e^{-r/b_2} + a_3e^{-r/b_3} + ...... $$

(6.3)

Thus, the coulombic potential $V(r)$ is then equal to
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\[ V_c(r) = \frac{q^2 Z_1 Z_2}{4\pi \varepsilon_0 r} f_c(r) \]  \hspace{1cm} (6.4)

With this interaction potential, the equation of motion of the atom can be integrated to yield the scattering angle for any incident ion trajectory, although it must be done numerically for realistic potentials. With the center of mass frame, it simplifies the derivation of equation involved. Figure 6.3 shows the view of ion scattering showing its relationship between impact parameter and scattering cross section. Based on the center of mass frame CMF a function of the impact parameter \( p \), the energy loss \( T(p) \) by the ion related to scattered angle \( \theta \) is given by equation (6.5).

\[ T(p) = \frac{4M_1M_2}{(M_1 + M_2)^2} E \sin^2 \left[ \frac{\theta(p)}{2} \right] \]  \hspace{1cm} (6.5)

where \( M_1 \) and \( M_2 \) are the atomic mass numbers of ion and target atom respectively. The probability of having an impact parameter between \( p \) and \( p+dp \) is \( 2\pi p dp \), which is also known as the differential scattering cross section \( d\sigma \).

![Figure 6.3: Scattering showing its relationship with impact parameter and scattering cross section](image)

Note that based on center of mass frame, the velocity \( v_{imp} \) before impact is equal to the sum of the velocity after impact and the impacted atom, which \( v_{imp} = v_1 + v_2 \), whereby \( v_1 \) and \( v_2 \) are respectively equal to the after impact velocity of implant ion and velocity of atom receiving the impact. According to the center of mass, the after impact momentum of the implant ion is equal to the momentum of atom that receiving the impact.
The rate of energy loss to nuclear collision per unit path length is equal to summing the energy loss for each possible impact parameter multiplied by the probability of that collision occurring. If the maximum possible energy transfer in a collision is $T_{\text{max}}$ and there is $N$ target atoms per unit volume then the nuclear stopping energy is

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

(6.6)

Nuclear stopping is normally elastic. Thus, energy lost by incoming ion is transferred to the target atom, which is recoiled away from its lattice site.

### 6.1.2 Range and Straggle of Ion Implant

Ion implantation is a random process due to each ion follows its own random trajectory, scattering off the lattice silicon atom before its energy and coming to rest at some location as illustrated in Fig. 6.4. The reason ion implantation can be used successfully is because large numbers of ions are implanted so an average depth for the implanted dopants can be calculated.

![Figure 6.4](image)

**Figure 6.4**: The range of an ion implant incident normal to the surface of silicon

The distributions of ion implanted in silicon for various types of dopant are shown in Fig. 6.5. Heavy ion such as antimony Sb does not travel as far as the lighter ion like boron B. The distribution of heavy ion is narrower than the distribution of lighter ion. The peak of the concentration of the ion is not near
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the surface of silicon. It is situated at an average distance away from the surface of silicon, which called the average projected range $R_p$.

Ion travels with random trajectory. Most of them will have the range center around the peak concentration $C_p$. Some ion stop sooner due to more collision in lattice of silicon and some will stop further. This gives rise to a distribution of ions where most of the ions are within a standard deviation $\pm \Delta R_p$ of the project range $R_p$. Notice that the distribution is skewed toward left due to back scattering.

Figure 6.5: Distribution of ion implanted for various types dopant in silicon lattice at an energy of 200keV

Since the number of ions implanted is usually greater than $10^{12}$cm$^{-2}$, the distribution can be described statistically and is often modeled to first order by symmetrical Gaussian distribution given by equation (6.7).

$$C(x) = C_p \exp\left(-\frac{(x-R_p)^2}{2\Delta R_p^2}\right)$$  \hspace{1cm} (6.7)

$R_p$ is the average projected range normal to the surface of silicon, $\Delta R_p$ is the standard deviation or straggle about that range, and $C_p$ is the peak concentration where Gaussian is centered. Fig. 6.6 shows the plot and standard deviation for common dopants in silicon. The results show that the implant depth and
standard deviation are linear for high energy implant. It is obvious that heavy ion such as antimony and arsenic have let penetrating power shown by the depth of implant.

Figure 6.6: (a) Plot of average range $R_p$ and (b) standard deviation $\Delta R_p$ of common dopants in silicon
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The total number of ion implanted is defined as dose and it simply by equation (6.8).

\[
Q_T = \int C(x) \, dx = \int C_p \exp \left( -\frac{(x - R_p)^2}{2\Delta R_p^2} \right) \, dx
\]  

(6.8)

The solution of the integration is equal to

\[
Q_T = \sqrt{2\pi\Delta R_p} C_p
\]

(6.9)

So far, one has considered whole surface silicon is implanted with ions. It is interesting to think about the implant profile that the beam centered on a particular spot said x, y, z = 0, 0, 0. The UT-Marlow simulation of the distribution of 1,000 ions implanted at a random position unit cell is centered at (0, 0, 0) is shown in Fig. 6.7. The side view shows that the depth distribution of the ion can be approximated by equation (6.7) with a projected range of 50nm and straggle of 20nm. The beam direction view shows that the ion scatter laterally around the impact point centered at y, z = 0, 0. The lateral distribution around the peak can be described statistically by Gaussian distribution with a lateral straggle \( \Delta R_{\perp} \) replacing the vertical straggle.
Most of the time, engineer is not concern with implant at a spot on the wafer. Engineer is interested to know the implant in a window around the area masked from implant. The two dimensional projection near the window edge is of interest because it indicates how many ions scatter under the window due to lateral straggle. Owing to the difficulty to experimentally measure the lateral dopant profile, a two-dimensional distribution is often assumed to be composed of the product of the vertical and lateral distribution such that

\[
C(x, y) = C_{\text{vert}}(x) \exp \left( -\frac{y^2}{2\Delta R_{\perp}^2} \right)
\]  

(6.10)

### 6.1.3 Thickness of Masking

Let’s know determine the thickness of a mask necessary to block the penetration of ion into the silicon. For example, photoresist is often used because impurity is performed at room temperature. Near the edge of the mask, the profile is dominated by the lateral straggle and given by a sum of point response function with the Gaussian equation (6.10). This shall mean the ion profile under the mask edge like the gate of MOSFET can be determined by the lateral straggle of the implant and by how far it moves during annealing. With decrease in device thickness, the straggle under the mask is the most interested region for study.

How thick should a mask be in order it can effectively block the transmission of ion through it? The thickness of the mask should be large enough such that the tail of the implant profile in the silicon is at some specified background concentration as shown in Fig. 6.8.
The superscript * is used to identify the ranges and standard deviation in the masking material since they are in general different from those values in the silicon. The criterion for an efficient and effective masking has to follow equation (6.5).

\[
C^*(x_m) = C^*_P \exp\left(-\frac{(x_m - R^*_P)^2}{2\Delta R^*_P}\right) = \frac{Q_t}{\sqrt{2\pi\Delta R^*_P}} \exp\left(-\frac{(x_m - R^*_P)^2}{2\Delta R^*_P}\right) \leq C_B
\]  
(6.11)

where \( C_P^* = \frac{Q_t}{\sqrt{2\pi\Delta R^*_P}} \). \( C^*(x_m) \) is the concentration at the far side of a mask of thickness \( x_m \) and \( C_B \) is the background concentration in the substrate. Setting \( C^*(x_m) = C_B \) and solving for the mask thickness yields equation (6.12).

\[
x_m = R^*_P + \Delta R^*_P \sqrt{2\ln\left(\frac{C^*_P}{C_B}\right)} = R^*_P + m\Delta R^*_P
\]  
(6.12)

\( m \) is a parameter indicating that the thickness of the mask should be equal to the range plus multiple \( m \) times of the standard deviation in the masking material. Value \( m \) for different levels of masking efficiency can be easily calculated from equation (6.12).
If \( Q_p \) is the amount of dose that penetrates the mask then \( Q_p \) can be calculated using equation (6.13).

\[
Q_p = \frac{Q_T}{\sqrt{2\pi\Delta R_p}} \int_{x_m}^{\infty} \exp\left(-\frac{(x - R_p^* - \Delta)^2}{2\Delta R_p^*}\right) dx
\]  

(6.13)

This equation can be described as error function \( \text{erf} \) which is shown in equation (6.14).

\[
Q_p = \frac{Q_T}{2} \text{erfc}\left(\frac{x_m - R_p^*}{\sqrt{2\Delta R_p^*}}\right) = \frac{Q_T}{2} \left[1 - \text{erf}\left(\frac{x_m - R_p^*}{\sqrt{2\Delta R_p^*}}\right)\right]
\]  

(6.14)

### 6.1.4 Doping Profile of Ion Implant

In general, the mask edge is not vertical or an angled implant is performed. Thus, the numerical method must be used to calculate and show the 2D doping profile. There may be reason to use a high angle implant to introduce dopant underneath the MOS gate. In order to minimize short channel effect in small device, doping may be introduced below the tip extension region under the gate. This “halo” of doping is formed by high tilt implant under the edge of the gate. Tilted implant can cause shadowing effect due to the topography already on wafer. A TSUPREM V numerical simulation of the tilted implant near mask edge is shown in Fig. 6.9.

![TSUPREM V simulation of a 50keV phosphorus implant at 30° tilt angle showing asymmetrical implant and shadow caused by gate polysilicon](image)

**Figure 6.9:** TSUPREM V simulation of a 50keV phosphorus implant at 30° tilt angle showing asymmetrical implant and shadow caused by gate polysilicon
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To achieve symmetrical distribution for all devices, the wafer is often rotated during implant or is implanted in four separate rotations. To completely avoid shadowing effect requires that the implant to be done at zero tilt angle.

To understand how the implant profile evolves in the time during subsequent annealing, one can compare the Gaussian formulation from the implant distribution with that from a delta function distribution that has diffused. The solutions for both Gaussian distribution in semi medium are shown in equation (6.15).

\[
\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}
\]

\[
C(x) = C_p \exp \left( -\frac{x - R_p^2}{\sqrt{2} \Delta R_p} \right) \iff C(x) = C(0) \exp \left( -\frac{x^2}{4Dt} \right)
\]

(6.15)

By comparing these solutions, one can see that the implanted Gaussian profile with standard deviation \( \Delta R_p \) has the same form as an initial delta function distribution that has diffused for an effective time temperature cycle of \( \Delta R_p = \sqrt{2Dt} \). Thus, the effect of additional time temperature cycle of annealing on the implanted Gaussian distribution is expressed by equation (6.16).

\[
C(x, t) = \frac{Q_T}{\sqrt{2\pi(\Delta R_p^2 + 2Dt)}} \exp \left( -\frac{(x - R_p)^2}{2(\Delta R_p^2 + 2Dt)} \right)
\]

(6.16)

From equation (6.16), it is clearly shown that a Gaussian distribution remains as a Gaussian distribution and it preserves its shape upon annealing in an infinite medium although its standard deviation or straggle about the peak concentration increase with the diffusion distance as shown in Fig. 6.10.

![Figure 6.10: Profiles of ion implantation before and after annealing](image-url)
6.2 Annealing

After ion implantation, it is necessary to perform annealing so that it can repair the crystal lattice damage and drive-in the implanted ions. Figure 6.11 illustrates the effect of crystal structure before and after annealing.

![Figure 6.11: Illustration the effect of rapid thermal annealing](image)

(i) Before annealing                    (ii) During annealing                   (iii) Post annealing

For VLSI integrated circuit, the challenge is to repair the crystal lattice damage and activate the ion with minimized diffusion so that the shallow implant remains shallow. In order to achieve this requirement, it is necessary to perform annealing in the matter of second. Figure 6.12 illustrates the effect of annealing time. In the section, we shall discuss the conventional furnace annealing method and rapid thermal annealing RTA method.

![Figure 6.12: Illustration the effect of annealing time](image)

(a). Short annealing time                                                 (b). Long annealing time

6.2.1 Furnace Annealing

Annealing characteristics depend on the dopant type and dose involved. There is a clear distinction between cases where silicon has been made in amorphous nature and where it has been only partially disordered. For amorphous silicon, re-growth is done by solid phase epitaxy SPE. The amorphous/crystalline interface moves towards the surface at a fixed velocity that depends on temperature, doping, and crystal orientation. The solid phase epitaxial growth rate of amorphous silicon as a function of temperature for various crystal orientations is shown in Fig. 6.13.
The activation energy for solid phase epitaxy is 2.3eV for silicon of any orientation indicating that the process involves bond breaking at the interface. The presence of impurities such as oxygen, carbon, and nitrogen, or argon would slow down or disorganize the re-grow process because the impurities are binded to broken silicon bonds. Impurities such as boron, phosphorus, or arsenic would increase the growth rate by a factor of 10 for concentration of $10^{20}\text{cm}^{-3}$. This is assumed that substitutional impurities weaken the bonds and increase the likelihood of broken bonds.

The re-growth rate $\nu$ is given by equation (6.17)

$$\nu = A \exp\left(-\frac{2.3\text{eV}}{kT}\right)$$

(6.17)

where $A$ is an experimentally determined parameter. The re-growth rate can be enhanced by a factor of 10 for doping level characteristic of source and drain in MOS device. The re-growth at low temperature quickly eliminates all primary damage of the crystal in the amorphous region so that no anomalous dopant diffusion occurs. Most of the dopant atoms in the amorphous region are incorporated onto substitutional lattice sites during re-growth so that high levels of activation are possible even at low temperature.

If the implantation conditions are not sufficient to create an amorphous layer then the crystal lattice repair occurs by the generation and diffusion of point defects. The repair process has activation energy of about 5.0eV and it requires temperature at least 900°C in order to remove all defects. Therefore, it is easier to repair fully amorphized layer than a partially damage layer.

Annealing at high temperature causes competition between solid phase epitaxy SPE and local diffusive rearrangement that can lead to polysilicon formation. Thus, it is best to precede the high temperature step by low temperature re-growth. High temperature defect diffusion can then repair extended defects remaining after solid phase epitaxy SPE. Annealing a partially damaged layer at low temperature can actually impair the process of lattice reconstruction because the stable extended defects such as dislocation loop can be formed, which requires temperature of 1,000°C to remove them.
Figure 6.13: Solid phase epitaxial growth rate of amorphous silicon as function of temperature for different crystal orientation

6.2.2 Rapid Thermal Annealing

Annealing has the objective to repair the damage with minimizing diffusion. Repairing crystal damage is a process with activation energy of 5.0eV, while diffusion has activity energy ranges from 3.0eV to 4.0eV. Owing to different in activation energy, at sufficiently high temperature repair crystal lattice is faster than diffusion.

Furnace annealing is capable of supply high temperature but the practical steps require to load and to remove wafer without stressing them lead to minimum anneal time of 15 minutes. This time is much longer than the required
time to repair crystal lattice at high temperature. Thus, diffusion is unavoidable. Rapid thermal annealing RTA is a method that covers various techniques of heating wafers for periods range from nanoseconds to 100s, allowing repair of crystal lattice with minimum diffusion.

Rapid thermal annealing can be divided into three classes, which are adiabatic, thermal flux, and isothermal annealing. In adiabatic annealing, the heating time is short, which is less than 0.1\(\mu\)s. This type of annealing only affects a thin surface film. A high energy laser pulse can be used to melt the surface to a depth of less than 1.0\(\mu\)m and surface crystallizes by liquid phase epitaxy with no defect left. Dopant diffusion in liquid state is very fast so that the final profile is roughly rectangular extending from the surface to the melt depth. By adjusting the pulse time and energy, a shallow junction can be obtained. But this method is not possible to preserve either doping profile or surface film. Thus, it is not generally used in VLSI circuit.

Thermal flux annealing method has annealing time ranges from \(10^{-7}\)s to 1.0s. It is done by heating from one side of the wafer with a laser, electron beam, or flash lamp that provides a temperature gradient across the thickness of wafer. Generally, the surface is not melted but the surface damage can be repaired by solid phase epitaxy SPE before any diffusion occurs. Figure 6.14 shows an arsenic profile annealed with scanned laser beam. Almost complete electrical activation is obtained without diffusion. Unfortunately, the rapid quenching from high temperature leaves many point defects which may condense to form dislocation, degrading the lifetime of minority carrier.

The process time for isothermal annealing involved heating process, is longer than 1.0s. Isothermal annealing uses tungsten-halogen lamp or graphite resistive strip to heat the wafer from one or both sides of the wafer as shown in Fig. 6.15.
Figure 6.14: Profile of arsenic using furnace and scanned laser thermal rapid annealing

Figure 6.15: Schematic showing an isothermal annealing system
This technique provides advantages for VLSI processing because good activation can be obtained with less diffusion than with furnace annealing technique. The process is clean because the walls of the chamber remain cold during the process. Figure 6.16 shows the annealing of very high concentration of boron under various annealing conditions.

Furnace annealing process for 30 minutes at temperature of 1,000°C leaves some dopants trapped by defects near the peak of the profile. A similar state occurs with rapid thermal annealing for 10s at temperature of 1,100°C but it has much reduced diffusion. Increasing the RTA time to 30s removes the damage.
trapping but it gives a final profile not deeper than the furnace annealing process, which does not repair the damage crystal lattice as shown Fig. 6.14.

6.3 Ion Implanter

Common ion implanter has much the same as the linear accelerator. Indeed the early history of ion implanter made much progress when research in nuclear physics shifted to high energy that laboratory machine was no longer useful and was instead used to investigate the relatively low energy of ion-solid interaction that is useful for ion implantation. A schematic of an ion implanter is shown in Fig. 6.17. Basically, the ion implant system consists of several systems, which are gas system, electrical system, vacuum system, control system, and beam line system. These systems will be discussed in details in the following sub-sections.

![Schematic of an ion implanter](image)

**Figure 6.17:** Schematic of an ion implanter

6.3.1 Gas System

The basic requirement of an ion implanter is the source of ion of sufficiently high energy. Either a solid source is vaporized or gas source is conventionally used to delivery material for the ion implanter. Arsine, phosphine, diborane, and boron trifluoride gas sources. The common gas sources are extremely toxic and have been used in dilute mixture 15% in hydrogen gas in high pressure more than 400psi cylinder. Owing to safety concern, solid sources of elemental boron, arsenic or phosphorus are at time preferred. The main advantage of solid is that it can be vaporized and implanted. New gas such as zeolite matrix which acts as
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A molecular sieve to absorb and store gas in cylinder below atmospheric pressure reduces the risk of release and explosion.

6.3.2 Electrical System

High voltage and current electrical system is required for ion implanter. High voltage dc power is needed to accelerate ion. Up to 200kV dc power supply system is equipped in an implanter. The ion in the ion source is generated either a hot filament or RF plasma system. The hot filament requires large current and a few thousand volt bias power supply, whereas the RF ion source system needs a thousand watt of RF power. The analyzer magnet needs a high current to generate the magnetic field strong enough to deflect ion trajectory and helps to select right ions and create ultra pure ion beam.

6.3.3 Vacuum System

The beam line must be in high vacuum condition to minimize collision between energetic ions with neutral gas molecules along the ion trajectory. Collision can cause ion scattering and loss and creation of unwanted ion species for ion implantation. The vacuum requirement is $10^{-7}$ torr for beam line system. The high vacuum requirement can be achieved by combining the cryo pump, turbo pump, and dry pump.

The dangerous gases are used in ion implantation. Thus, the exhaust of the vacuum system of ion implanter must be separated from the exhaust of other systems. The exhaust gas needs to go through a burn box and a scrubber before it can be released into the atmosphere. In the burn box, the flammable and explosive gases are neutralized with oxygen in high temperature flame. In the scrubber, flushing water dissolves corrosive gases and burn dust passing it.

6.3.4 Control System

The ion implanter needs to precisely control the ion beam energy, current, and ion species. The implanter needs to control the mechanical parts such the robot for wafer loading and unloading, and control wafer movement in order to achieve uniform implantation across the wafer. The throttle valves are controlled according to the pressure setting point to maintain system pressure.
6.3.5 Beam Line System

The ion beam line system is the most important part of an ion implanter. It consists of an ion source, extraction electrodes, mass analyzer, post acceleration, plasma flooding system, and end analyzer. We shall discuss these components in details.

6.3.5.1 Ion Source

Dopant ion is generated from ion source through ionization discharge of the atom or molecule of dopant vapor or gaseous dopant chemical compound. The hot filament ion source is one of the most commonly used ion source. The thermal electron hot filament is accelerated by the arc power supply to attain energy high enough to dissociate and ionize dopant gas molecule or dopant atom. Magnetic field in the ion source forces the electron into gyro-motion, which helps electron to travel longer distance and increase the probability of its collision with dopant molecule to generate more dopant ions. Other types of ion source are RF ion source and microwave ion source. The RF ion source uses inductive coupling of the RF power to ionize the dopant ions. The microwave ion source uses electron cyclotron resonance to generate plasma and ionized dopant ions.

6.3.5.2 Extraction

An extraction electrode with negative bias draws the positive ion out from the plasma in the ion source and accelerates it to sufficiently high 50keV energy. It is a requirement for ion to attain high energy before the analyzer magnetic field can select the right type of ion species. When the dopant ions accelerate toward the extraction electrode, some of the ions pass through the slit and continue to travel along the beam line. Dome hit the extraction electrode surface, which generates X-ray and excites some secondary electrons. A suppression electrode with sufficiently lower electrical potential up to 10kV than the extraction electrode is used to prevent these electrons being accelerated back to the ion source that would cause damage. All electrodes are shaped with a narrow slit through which ions are extracted as a collimated ion flux forming an ion beam.

6.3.5.3 Mass Analyzer

In magnetic field, the charge ion starts to rotate from the magnetic force, which always perpendicular to the direction of the charged ion. For the fixed magnetic field strength and ion energy, the gyro radius is related only to the mass to
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charge ratio or m/q of the charge ion. This property had been used for isotope separation to get enriched uranium 235 for making nuclear bomb. In most of the ion implanter, mass analyzer is used to select precisely the right of ion for implantation and weed out unwanted ion species. Species with less m/q value will deflect more and will not pass through slit of the mass analyzer. Likewise, species with large m/q ratio will be stop too. A mass analyzer of an ion implanter is shown in Fig. 6.18.

Boron trifluoride BF$_3$ is one of the commonly used materials for $p$-type implant. In the plasma, there are combinations of dissociative, ionized radicals, and recombined molecules. Boron has two isotopes, which are boron 10$^{10}$B (19.9%) and boron 11$^{11}$B (80.1%). Thus, in the plasma state are a number of ion types, which are $^{10}$B (10g), $^{11}$B (11g), $^{10}$BF (29g), $^{11}$BF (30g), F$_2$ (38g), $^{10}$BF$_2$ (48g), and $^{11}$BF$_2$ (49g). The figure in the parenthesis indicates the atom weight or molecular weight. For $p$-well implantation, the lighter weight $^{11}$B$^+$ is preferred because it can penetrate deeper into silicon substrate. For shallow junction implant, $^{11}$BF$_2^+$ is preferred because of its large size and heavy weight. At the lowest energy level, an ion implanter can provide $^{11}$BF$_2^+$ ion for shallowest $p$-type junction implant.

6.3.5.4 Post Acceleration

After the analyzer selects the correct ion species, the ion goes through the post acceleration section, where the beam current and final ion energy are controlled. The ion beam current is controlled by a pair of adjustable vanes, and the ion energy by post acceleration electrode potential. Ion beam focus and beam sharp are controlled in this part by defining apertures and electrodes.
For the high energy ion implants, which are mainly in the well and buried layer, it requires several high voltage acceleration electrodes connected in series along the beam line in order to accelerate the ions to several mega electron volts. For ultra shallow ion implant like the $p$-type boron implant, the electrode of post acceleration is connected in reversed way so that ion beam is decelerated instead accelerated when passing the electrode. It can generate a pure ion beam with energy as low as 500eV.

To avoid asymmetrical distribution of implant for all devices, the wafer is often rotates during implant or is implanted in four separate rotations. To completely avoid shadowing effect requires that the implant to be done at zero tilt angle. Alternatively, the x-y scan plates can direct the beam to scan the surface of wafer for ion implantation.

**Exercises**

6.1. A 100keV boron atom makes a head-on collision with a silicon atom. Use an unscreened coulomb potential to estimate the closest distance the atom come to each other during the collision. Calculate the amount of energy loss by boron atom during the collision.

6.2. State the advantages of ion implantation over diffusion methods for adding impurity dopant into silicon.

6.3. A process engineer wants to dope the polysilicon and at the same time doing arsenic drain and drain diffusion for an $n$-channel MOSFET. The source and drain implant dose is $2.0 \times 10^{15} \text{cm}^{-2}$ at an energy of 50keV.

   (i). For the stated implant condition, what is the minimum polysilicon thickness that can be used if the implant is not affecting the channel doping concentration of $1.0 \times 10^{16} \text{cm}^{-3}$ near surface? You may ignore the thickness of the oxide that may block some ion implants.

   (ii). Assuming this polysilicon thickness is actually used, how much of the implant dose will penetrate the polysilicon mask if the process engineer decides to change the implant to 80keV.

6.4. Given the projected straggle for 80keV phosphorus implant on a 200mm silicon wafer at a dosage of $5 \times 10^{14} \text{ions cm}^{-2}$ is 0.06µm. Calculate the value of peak concentration.
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6.5. In ion implantation process, an effective and efficient masking is important to prevent ion implant reaching the substrate. State the condition in terms of ion concentration at the end-edge of the mask and the substrate concentration in order to prevent changing the doping concentration of substrate.

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

6.7. State the reason why the peak concentration of ion implant decreased as annealing process at temperature.

6.8. State the reason why the peak concentration of ion implant decreased as annealing process at temperature.

6.9. State the purpose of mass analyzer.

6.10. In plasma, phosphorus vapor can be ionized and form different ion such as P⁺ and P²⁺. Can a mass analyzer separate these two atoms? Which ion has deeper penetration?

Bibliography

