Ion Implantation

EE 2520

1 Introduction

1. Ion implantation provides a very precise means to introduce a specific dose or number of dopant atoms into a semiconductor substrate

2. The basic requirement is a source of ions of sufficiently high density. Either a solid source or a gas source are conventionally used to deliver ions to the ion implanter

3. As shown in the schematic in Fig.1 The gas from the feed source is ionized by energetic electrons boiled off a hot filament or by a plasma discharge

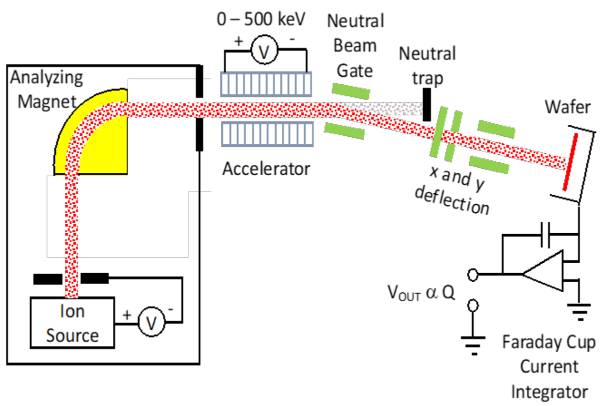


Figure 1: Schematic of Ion Implantation process

4. The ions are extracted by a voltage bias on a grid and mass analyzed to select only one ion species and perhaps even a single isotope of ion species

5. The selected ions are further accelerated in a small linear accelerator to final energy of implantation

6. The ion path typically undergoes an electrostatic deflection which scans the beam onto the wafer

7. The implant dose is measured by locating the sample at the end of a deep faraday cup which collects the current and integrates it over time.

8. Modern ion implanters are designed to produce beam currents as high as 25 mA and to operate with accelerating voltages as high as 500 KeV.

9. Fig.2 shows many of the applications of ion implantation in CMOS processing

10. Ion implantation is a random process because each ion folls a random trajectory, scattering off the lattice silicon atoms before losing its energy and coming to rest at some location

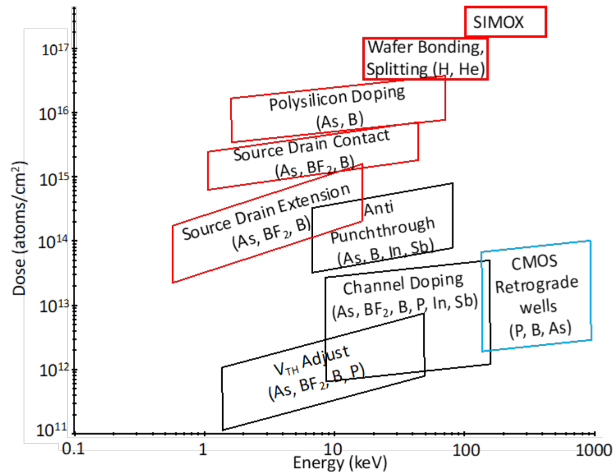


Figure 2: Typical ranges of implant dose and energy in CMOS processing

11. Some Key Points:

- Heavy ions like antimony do not travel as far in the crystal as light ions like boron
- If different ions are implanted with the same energy, the heavy ions stop at a shallower depth
- The projected range R_p depends on the energy that is used for the implant, with higher energies giving a deeper range
- While each implanted ion itself follows a random trajectory with a range R, on average the distribution of a large group of ions will peak at the projected depth R_p below the surface of the wafer
- Because of the random nature of the process, some ions will stop sooner because of more collisions, while some will travel further.
- The distribution thus can be modeled as a Guassian with peak at R_P and a standard deviation of $\pm\Delta R_p$
- The heavy ions with a smaller range have a narrow distribution than the light ions

12. The distribution is given by

$$\boxed{C(x) = \frac{Q}{\sqrt{2\pi}\Delta R_p} exp\left(-\frac{(x - R_p)^2}{2\Delta R_p^2}\right) = C_p exp\left(-\frac{(x - R_p)^2}{2\Delta R_p^2}\right)} \quad (1)$$

- R_p: Projected Range normal to the surface
- ΔR_p: Standard deviation or straggle about the range
- Q: Dose
- C_p: Peak concentration

13. The total dose is given by

$$\boxed{Q = \sqrt{2\pi}\Delta R_p C_p} \quad (2)$$

14. Typical doping profiles of various dopants is shown in Fig.3

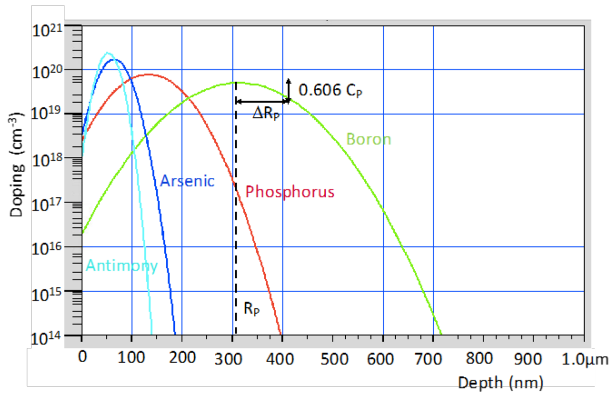
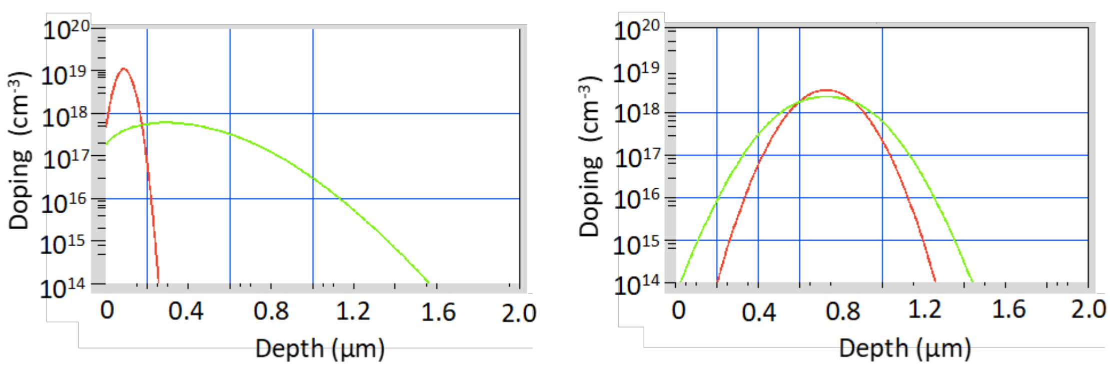


Figure 3: Doping profiles of various dopants

15. After ion implantation, it is common to diffuse the implanted ions to create the desired final profile
16. There are two simple analytical methods for calculating the shape of the final diffused profile
17. The implant is shallow enough and the diffusion is long enough that the implant can be treated as a delta function at the surface. The dopant profile is shown in Fig.4a



(a) One-sided Guassian

(b) Deep Gaussian Profile

Figure 4

18. The near surface profile can typically be approximately treated as a one-sided Guassian. The deviation is due to segregation effects that affect the near surface profile. The concentration can be estimated by the equation

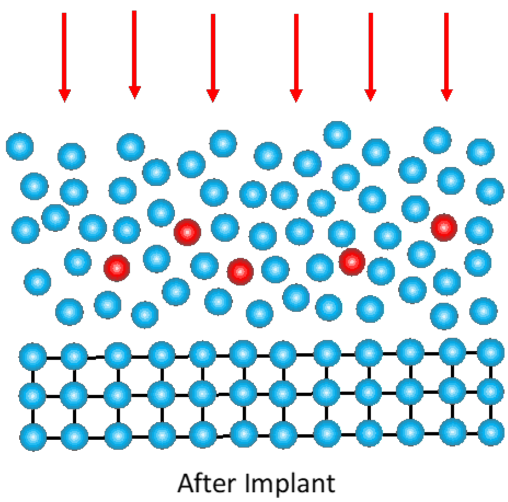
$$\boxed{C(x,t) = \frac{Q}{\sqrt{\pi D t}} exp\left(-\frac{x^2}{4Dt}\right) = C(0,t) exp\left(-\frac{x^2}{4Dt}\right)} \quad (3)$$

19. If the implant is deep, it can be described by two-sided Gaussian after the implant. The profile

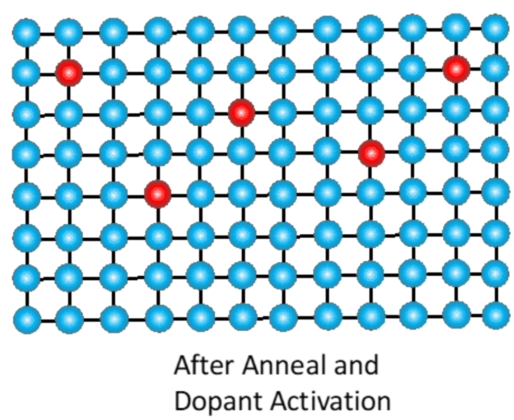
broadens due to two sided Guassian after diffusion. The concentration can be estimated from

$$\boxed{C(x) \;=\; \frac{Q}{\sqrt{2\pi}(\Delta R_p^2 \;+\; Dt)} exp\left(-\frac{(x \;-\; R_p)^2}{2(\Delta R_p^2 \;+\; 2Dt)}\right)} \tag{4}$$

20. Implantation is a collision process and it displaces the lattice atoms from their surface and can completely amorphize the substrate if the damage is severe
21. Annealing the damage repair step can not only repair the damage but also activate the dopants.
22. The fact that this repair and activation process works well has been critical to the widespread adoption of ion implantation
23. Fig.5 shows the arrangments of atoms after implanation and after anneal



(a)



(b)

Figure 5: Lattice arrangement (a) after implantation (b) post annealing

24. The experimental implant profiles are often asymmetric
25. Light ions tend to have profiles skewed towards the surface and heavy ions to have profiles skewed towards the deeper part of the profile
26. An arbitrary probability distribution can be described by a series of moments
27. The projected range is given by

$$\boxed{R_p \;=\; \frac{1}{Q}\int_{-\infty}^{\infty} xC(x)\; dx} \tag{5}$$

28. The straggle or the standard deviation is given by

$$\boxed{\Delta R_p \;=\; \sqrt{\frac{1}{Q}\int_{-\infty}^{\infty}(x \;-\; R_P)^2 C(x)\; dx}} \tag{6}$$

29. The skewness is given by

$$\boxed{\gamma \ = \ \frac{\int_{-\infty}^{\infty}(x \ - \ R_P)^3 C(x) \ dx}{Q\Delta R_p^3}} \tag{7}$$

30. γ is measure of the symmetry of the distribution around the mean value

31. Kurtosis, a measure of how much of the distribution is contained in the tail regions of the distribution is given by

$$\boxed{\beta \ = \ \frac{\int_{-\infty}^{\infty}(x \ - \ R_P)^4 C(x) \ dx}{Q\Delta R_p^4}} \tag{8}$$

32. The integral representations are not convenient. In practsise, equivalent values are described by a functional form known as Pearson's equation, which in turn is put in a look up table

33. Fig.6 shows the ideal and asymmetric profiles represented by Gaussian and Pearson model

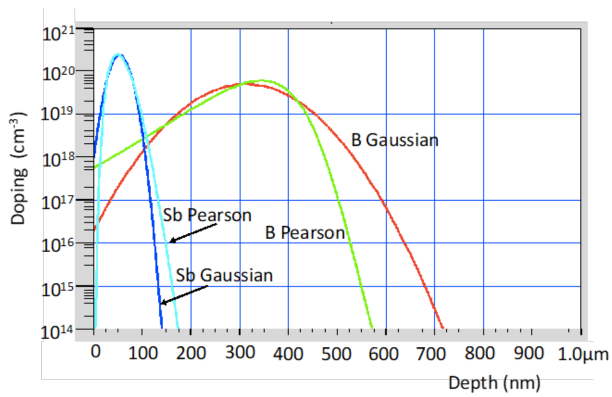


Figure 6: Guassian and Pearson Profiles

34. In the case of light ions such as boron, the Pearson model is clearly skewed towards the surface. The light ions could "bounce" off the heavier lattice atoms in the substrate and therefore more heavily populate the shallow portion of the profile.

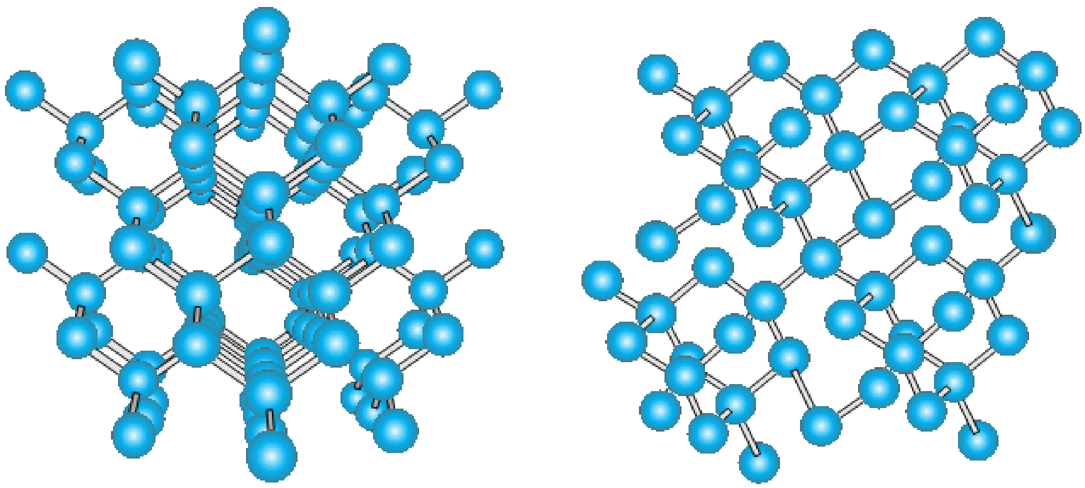
35. The heavier ions like Antimony show the opposite behavior with the Pearson distribution skewed towards the deeper part of the profile. Heavy ions scatter forwards as they slow down in the target material

36. Semiconductor substrates are crystalline with a regular array of atoms. This leads to the existence of planar and axial channels that can have dramatic effects on the implant profile

37. Fig.7 shows Silicon Crystal in two different angle. In one case the crystal is aligned to 110 axial channel and in other cases the crystal is tilted and atoms are randomly oriented.

38. **Channeling:** Once a dopant ion enters in a channel, the small angle scattering events from the atoms that line the walls of the channel steer the ion for quite a long distance along the channel before the ion comes to rest from the electronic drag forces. Alternatively the ion may exit the channel because of sharp collision.

39. The effect of channeling on the implant profile is to cause a tail that continues much further than expected



(a) (b)

Figure 7: Silicon Structure (a) 110 axial channels (b) tilted

2 Nuclear and Electronic Stopping

1. In crystalline materials, the trajectory of ions bombarded is completely determined by the structure of the lattice after the ion is set in motion

2. The ion scatters deterministically from target atoms determined from classical two-body collision theory, slowing down by an additional drag force from electronic interactions.

3. The rate at which an ion loses energy depends on both the nuclear and electronic stopping power of the target

$$\boxed{\frac{dE}{dx} \;=\; -\,N[S_n(E) \;+\; S_e(E)]} \tag{9}$$

4. N is the target atomic density ($5 \times 10^{22}\ cm^{-3}$ for silicon)

5. $S_n(E)$ and $S_e(E)$ are the nuclear and electronic stopping powers ($eV\ cm^2$)

6. If $S_n(E)$ and $S_e(E)$ are known, then the range of the ion can be calculated using

$$\boxed{R \;=\; \int_o^R dx \;=\; \frac{1}{N}\int_o^{E_o} \frac{dE}{[S_n(E) \;+\; S_e(E)]}} \tag{10}$$

7. The projecteed range R_p is related to R by

$$\boxed{R_p \;=\; \frac{R}{[1 \;+\; m_2/3m_1]}} \tag{11}$$

8. m_1 is the mass of the implanted ion and m_2 is the substrate atomic mass
9. When an ion with mass m_1, atomic number Z_1 and kinetic energy E_o collides with a stationary target atom of mass m_2 and atomic number Z_2, it loses eneryg by interacting with the electric field of the nucleus of the target.
10. Not all collisions are head on collisions, so the nuclear energy loss depends on the distance of closest approach known as impact parameter b
11. As the ion interacts with the electric field of the nucleus, it exchanges its kinetic energy for potential energy, reaching a maximum transfer at the distance of closest approach
12. This potential energy is partitioned between the ion and target atom in accordance with their masses and the ion continues on a deflected path while the lattice atoms recoils
13. The velocities and trajectories can be found from the conservation of momentum and energy in a classical treatment of colliding particles
14. The nuclear energy loss is elastic, in that the energy lost by the ions is transferred to the lattice atom.
15. These nuclear interactions give rise to scattering and deflected trajectories, with the deflection angle depending on the impact parameter b
16. The energy lost by the ion in a scattering event is given by

$$\boxed{\Delta E \;=\; E_1 \frac{4m_1 m_2}{(m_1 \;+\; m_2)^2} cos^2\phi} \tag{12}$$

17. The angles depend on the parameter b, the masses of the atoms and the interaction potential between the ion and the lattice atoms
18. The previous equation ignores the electrostatics. due to charged nature of ions, they also experience coloumb's force. This lead to the screening potential

$$\boxed{V(r) \;=\; \frac{q^2 Z_1 Z_2}{r} exp(-r/a)} \tag{13}$$

19. where Z_1 and Z_2 are atomic number of atoms with mass m_1 amd m_2 . The parameter a is called screening parameter given by

$$\boxed{a \;=\; \frac{0.885a_o}{[Z_1^{2/3} \;+\; Z_2^{2/3}]^{1/2}}} \tag{14}$$

20. a_o is the Bohr's radius. The screening potential $V(r)$ is integrated along the path of ions to get scattering angle
21. To predict the scattering angle, the interaction of the ion with the screened coloumb potential is integrated over the path length where the nuclear force is important.
22. The scattering is deterministic. Hence the angles are precalculated for each impact parameters and are used in simulations

23. The nuclear stopping power $S_n(E)$ depends on the ion energy.

24. The nuclear energy loss is small at very high energies because fast particles have less interaction time with the scattering nucleus

25. The nuclear energy loss tends to dominate towards the end of the range where the ion has lost much of its energy and where the nuclear collision produce most of the damage

26. $S_N(E)$ can sometimes be usefully approximated as a constant value at energies below electronic stopping

$$\boxed{S_n(E) \;=\; S_n^o \;=\; \frac{2.8 \times 10^{-15} Z_1 Z_2}{[Z_1^{2/3} \;+\; Z_2^{2/3}]^{1/2}} \frac{m_1}{m_1 + m_2}} \tag{15}$$

27. This are multiple energy loss mechanism in electronic stopping

    - Target electrons can be excited to higher energy levels in the atoms that they surround
    - Target atoms can be ionized by conduction exciting conduction band electrons to high enough energies to free them from atoms to which they are bound
    - Treating the target material as a dielectric leads to a drag force on the ion becayse of polarization fields set up in the substrate. This is typically modelled as drag force

28. The simplest model of electronic energy loss is

$$\boxed{S_e(E) \;=\; kE^{1/2}} \tag{16}$$

29. $k \;=\; 0.2 \times 10^{-15} eV^{1/2} cm^2$ for silicon

30. Electronic stopping is inelastic, with the transferred energy generally being converted to heat in the substrate