EE669: VLSI Technology

Ion implantation

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Ion implantation is used mostly for doping of silicon in VLSI processing. Ion implantation provides a technique by which the dose of implanted dopants can be precisely controlled. In ion implantation, an ion beam is accelerated towards the target with an energy typically greater than 50 eV. The ion beam can be focused and can also be tilted with reference to the wafer surface.

Ion implantation can be selectively applied over regions on the wafer by using an appropriate masking material. In a diffusion process the mask has to withstand high temperatures. However in an ion implantation process the wafer is not intentionally heated. For moderate doses, the temperature of the wafer would not increase substantially above room temperature. So it is possible to use photo resist to mask ion implantation.

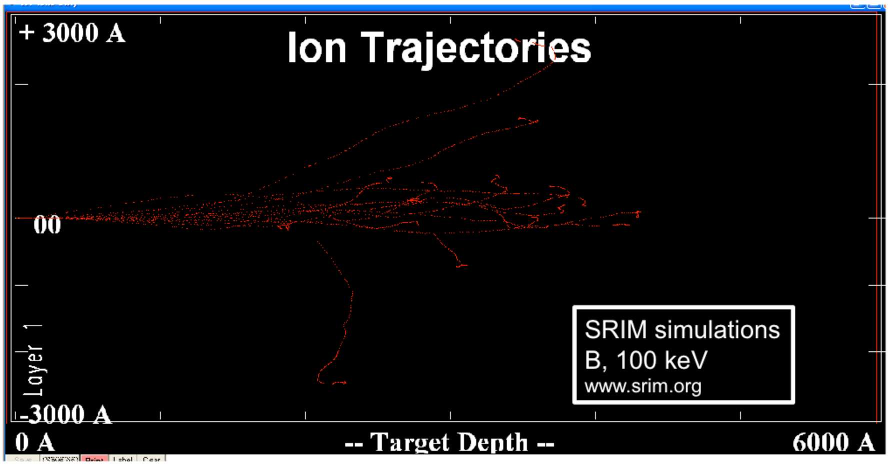
The ion energies can be in the range of a few 100s of eV to MeV. In a crystalline silicon lattice, the energy required to dislodge atoms from their lattice sites and create a stable vacancy – interstitial pair is 15 eV. This means that each implanted ion would cause damage to the crystalline structure. Hence the silicon as implanted would not be very useful. Typically the damage has to be annealed out and the implanted dopants activated by high temperature thermal processing subsequent to implantation.

This also allows us to implant ions below masks to certain extent.

These properties of ion implantation makes the process most favored for doping in VLSI processing. Ion implantation is used for field stop doping, well doping, anti-punch through doping, threshold voltage control, source/drain extension doping, halo doping and deep source/drain doping in VLSI technology.

However the equipment is costly and requires high level of maintenance. Also the throughput is low. These factors make the process not very attractive for Universities and also for solar cell processing.

Visualization of ion implantation



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SRIM is a Monte Carlo simulation program for calculating the trajectory of accelerated ions in an amorphous material.

Each ion entering the target material would go through a series of events which would result in loss of ion energy and the ion would eventually come to rest. These events are random in nature. We would be interested to find where the ions come to rest so that we can know the doping profile in the device we are trying to fabricate.

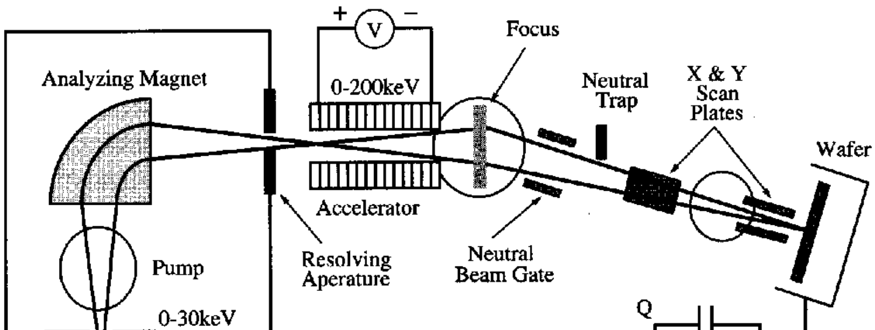
The ion stopping processes are (i) interaction of the incident ion with nuclei of atoms in the target material, leading to nuclear stopping. The ions would be deflected and the nuclei can be displaced. In some cases the ion can be recoiled. (ii) If the material can be seen as a sea of electrons, the entry of the ion would polarize the electron sea with negative charges building up around the positively charged ion. However the ion is implanted with very high energy and the electrons may not move as fast, leading to a drag in the electron movement which pulls the ion back. (iii) Ion can interact with the electrons in the outer shells of atoms in the target leading to scattering.

If the target material is amorphous, the interaction of the ion with atoms from the target would result in random deflections of the ions and also the impacted atoms. This would also result in random placement of ions in the target material. However if large number of ions are implanted, we would be able to talk of an average distribution of the implanted ions.

However for small dimension MOSFETs, the channel depletion region would contain a very small number of dopants. For example, a MOSFET with channel length of 30 nm, channel width of 30nm and channel depletion depth of ~ 20nm, the number of dopants in the depletion layer can be ~ 90. In such cases, the placement of these dopants can be important and we may be able to talk of averages only with large standard deviations. This remains an important challenge for small dimension devices.

The above discussion implies that an accurate mathematical description using closed form mathematical expressions is nearly impossible. However we would first discuss a first order approximation and subsequently consider deviations from the first order theory.

Ion Implanter



$$\frac{mv^2}{R} = q(\vec{v} \times \vec{B})$$

$$Q = \frac{1}{qA}\int Idt$$

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The figure of the slide shows the schematic of an ion implanter. You need a source of ions. Typically the ions are created by a plasma discharge or electrons from a thermionic emitter. The source of the molecules to be ionized would be in gaseous form or evaporated from solid sources. The ions are subsequently accelerated. The output of the ion source would have neutral species as well as ions. The ions can be singly charged or have multiple charges. Typical ions used for implantation are As^+ (for Arsenic), P^+ (for phosphorous) B^+ or BF_2^+ (for Boron) etc. Ge, Si and C implants are also used in VLSI processing.

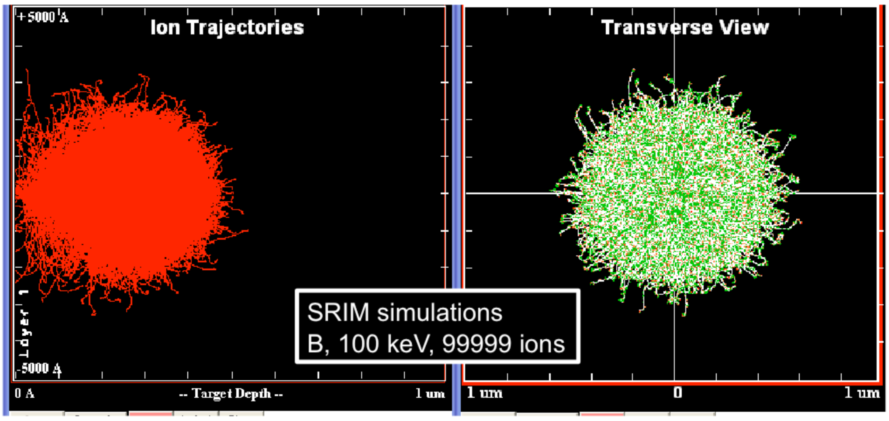
The ion analyzer filters out ions that are not interesting. In fact it is important to use only one kind of ion for implantation. Let us say the ion source provides singly charged and doubly charged ions. They would have different kinetic energies due to the differing charge states. This would lead to different depths of implants for the two ions and this is in general contrary to our requirements.

The ions coming out of the analyzer through the aperture can be further accelerated to the required energy. The ion beam is subsequently focused on to the wafer. The ion beam is then raster scanned over the wafer for implantation. It can be appreciated that due to the raster scan process, the throughput of ion implanters would be low. This is one more reason not to use the process for solar cell processing.

Some of the ions on the way from the analyzer may get neutralized. The neutral species can not be subjected to deflections using electric or magnetic fields for raster scan. So a neutral trap is used to eliminate from the beam. The neutral trap deflects the beam slightly by using an electric field. Only ions would be deflected and the neutral atoms would be removed from the beam.

The number of ions implanted on the wafer can be measured using a charge measurement system like an electrometer. The ions would be neutralized upon implantation and this would result in a current out of the wafer through the backside. The measured current can be integrated to find the charge implanted on the wafer. This can be used to find the number of ions implanted on the wafer per unit area. The number or ions implanted per unit are is called the implant dose.

Ion implantation profiles



- **The traces of 99999 ions of Boron implanted into Si at 100 keV**

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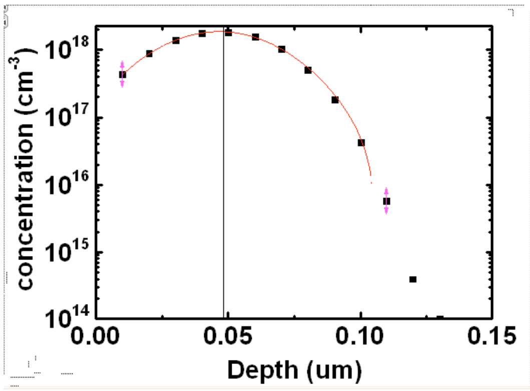
The ions are implanted at the centre of the vertical axis of the left figure. Even though the ion trajectory on the average has a preference in the direction of implant, the individual ions would be scattered in all 3 directions.

The implanted profile can be described to a first order by a Gaussian profile with a mean called the ion range and a standard deviation which is called straggle. The ions are also distributed laterally. Intuitively the lateral profile on any plane parallel to the surface of the surface would also be a Gaussian with the mean being along a line perpendicular to the surface at the point of implant. The standard deviation of the lateral profile is called the lateral straggle.

Lateral straggle is important for masked implants. For example, the source – drain extension implants in a MOSFET fabrication is masked by the gate in a self aligned MOSFET process. The lateral straggle would result in source to channel overlap, which is important for the functioning of the device. However large overlap would lead to higher parasitic capacitance and also to poor short channel control.

Ion implantation profiles (2)



SRIM simulations
B, 10 keV, 99999 ions

$$C(x) = C_P \exp\left(-\frac{(x-R_P)^2}{2\Delta R_P^2}\right)$$

$$Q = \int_{-\infty}^{\infty} C(x)dx = \sqrt{2\pi}\Delta R_P C_P$$

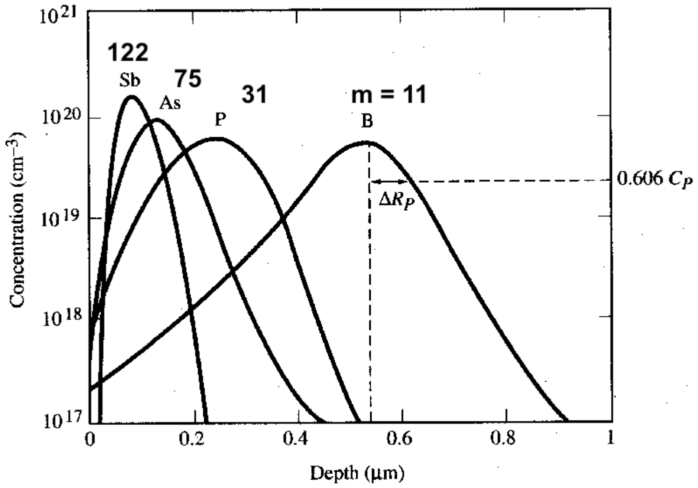
Range = 48 nm
Straggle = 20 nm

The figure shows the implanted profile perpendicular to the wafer surface along a line passing through the point of implant. The equations describe the Gaussian function which approximately represents the implant profile. The total dose implanted can be calculated by integrating the implant profile.

The straggle is the half width of the profile +/- 0.6 C_P about maximum concentration.

The total dose of ions given in ions or dopants per cm^2 is an important specification for the implantation process. The dose can be easily measured using the Faraday cup arrangement we had seen before on slide 3. Since the current can be measured with high precision, the dose can be controlled with high precision.

Ion implantation profiles (3)



Implant energy = 200 keV

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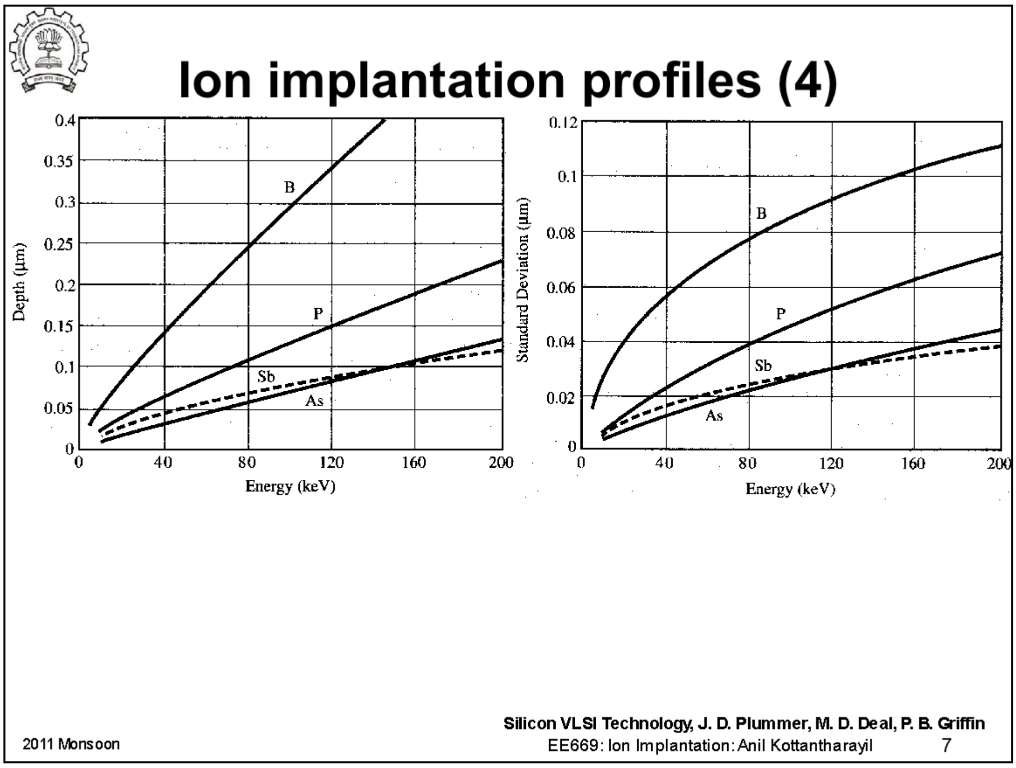
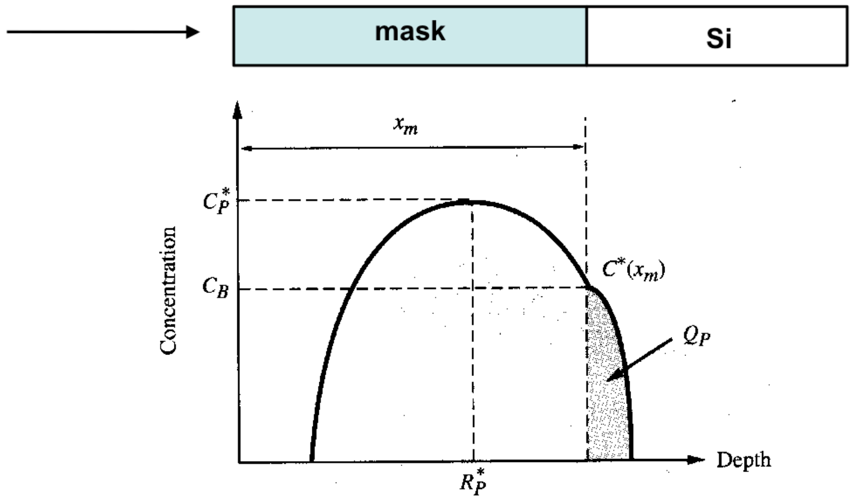
The figure shows the implant profiles for different common dopants. The implanted species in all the cases are the singly charged ions of the dopant atoms. The implant energy is 200keV. It is clear that the lighter the element, deeper it gets implanted.



The range and straggle for implantation of various elements in silicon as a function of implant energy are shown on this slide. The ion range can decide the type of implant you may choose for a particular application in VLSI. For example if you want to do a deep implant of n-type dopants, the preferred dopant may be phosphorous. However Arsenic may be preferred for shallow implants. So in a typical scaled p-channel MOSFET fabrication, the phosphorous may be the preferred species for well implant, Arsenic would be preferred for source and drain implant. In a n-channel process, Arsenic may be preferred for the source and drain extension implant whereas Arsenic or phosphorous may be used for deep source and drain implants.

For p-type dopant, usually there is only one choice that is Boron. The other elements though heavier, have low solid solubility in Silicon and hence not suitable for shallow and high concentration doping applications. For example, for shallow p-type junction implant like the source and drain extension implant in Silicon, the range provided by low energy Boron implant may still be too high. A possible alternative is to use BF_2^+. The mass of BF_2^+ is 49 atomic mass units whereas that for B is 11 atomic mass units. But then you also implant Fluorine into silicon.

Masking of implants



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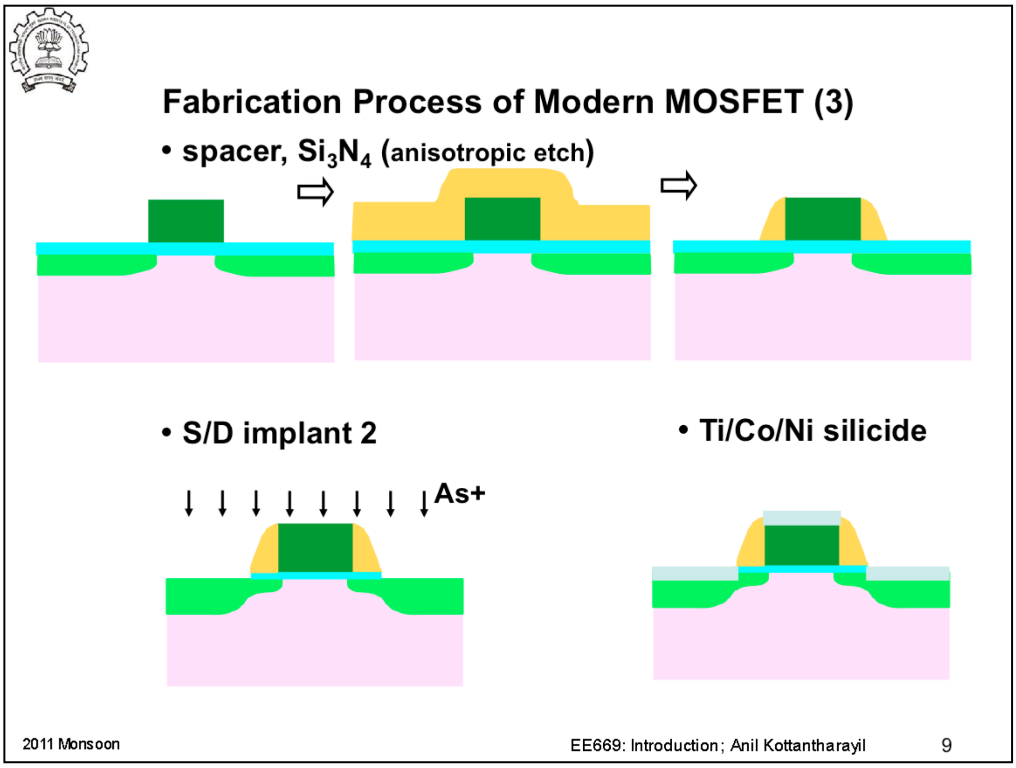
The idea of masking is to implant the dopant only in regions where we want to have them. However the ions would be also implanted in the masking material and a certain fraction of the dose can be expected to be implanted into the silicon as well. The mask thickness should be designed so that the tail of the distribution in silicon should not have a peak exceeding a specified value, C_B.

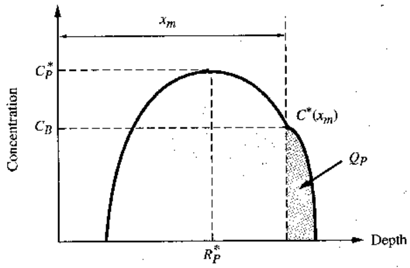
The mask for implants in a typical MOSFET technology can be photo resist, SiO_2, Si_3N_4 and poly-Si.



This is a slide from the first module of this course.

We will focus on the S/D extension implant. The implant is carried out after the etching of the poly-Si gate. We would like to dope the extension regions by an n-type dopant . So Arsenic is implanted. But we should make sure that the Arsenic is not implanted into the channel region through the gate. The channel should be o-type doped. If we implant Arsenic through the gate, then due to compensation effects, the net p-type doping would decrease and this would result in reduction of threshold voltage of the device. The analysis of masking we discuss in the next slide can help us design an appropriate thickness of the poly-Si which is required to block the source/drain implant from the channel.

Masking of implants (2)



$$C^*(x_m) = C_P^* \exp\left(-\frac{(x_m - R_P^*)^2}{2\Delta R_P^{*2}}\right) \le C_B$$

$$x_m \ge R_P^* + \Delta R_P^* \sqrt{2\ln\left(\frac{C_P^*}{C_B}\right)} = R_P^* + m\Delta R_P^*$$

$$Q_P = C_P^* \int_{x_m}^{\infty} \exp\left(-\frac{\left(x - R_P^*\right)^2}{2\Delta R_P^{*2}}\right) dx = \frac{Q}{\sqrt{2\pi}\Delta R_P^*} \int_{x_m}^{\infty} \exp\left(-\frac{\left(x - R_P^*\right)^2}{2\Delta R_P^{*2}}\right) dx$$

$$Q_P = \frac{Q}{2} erfc\left(\frac{x_m - R_P^*}{\sqrt{2}\Delta R_P^*}\right)$$

C^* is the concentration of the dopant in the masking material.

Q_P can be considered as the dose that would have been in the mask beyond x_m if the mask were to be very thick.

Masking of implants (3)

$$E = \int VJdt = V \int Jdt = qVQ$$

- The ions implanted are decelerated in the wafer resulting in dissipation of the kinetic energy of the ions
  - heating of the wafer
  - thermal mass of the wafer + chuck assembly
- The mask should withstand such temperature
- Photo resist used as mask undergoes chemical and physical changes ~ 120 C

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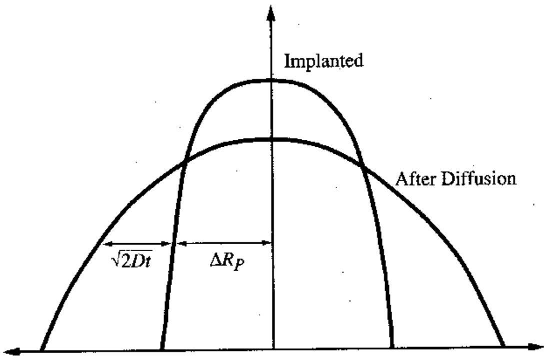
The ions implanted are decelerated in the wafer resulting in dissipation of the kinetic energy of the ions. This can be expected to increase the temperature of the wafer. Since the wafer is placed on a conducting chuck for implantation, the temperature calculation should take into account the thermal mass of the system including the wafer and chuck assembly.

Q is the implant dose in ions or atoms per unit area and q is the electronic charge in Coulomb.

The energy dissipated is per unit area. J is the current density, i.e. the current per unit area. As the dose increases, the energy dissipated in the substrate would also increase. We must appreciate the fact that the mask is expected to capture most of the dose implanted on it. The mask would also get heated. In a VLSI process, in most instances it is important to remove the photo resist after implantation. For example, we should mask the p-channel device regions during the source/drain implant for the n-channel device. This is done using a mask. This mask would be then subjected to a heavy implant. Typically this mask would undergo some changes during such heavy implantation which makes it difficult to remove.

Diffusion of implanted profiles



$$C(x) = \frac{Q}{\sqrt{2\pi}\Delta R_P}\exp\left(-\frac{(x-R_P)^2}{2\Delta R_P^2}\right) \qquad C(x) = C(0)\exp\left(-\frac{x^2}{4Dt}\right)$$

$$C(x) = \frac{Q}{\sqrt{2\pi(\Delta R_P^2 + 2Dt)}}\exp\left(-\frac{(x-R_P)^2}{2(\Delta R_P^2 + 2Dt)}\right)$$

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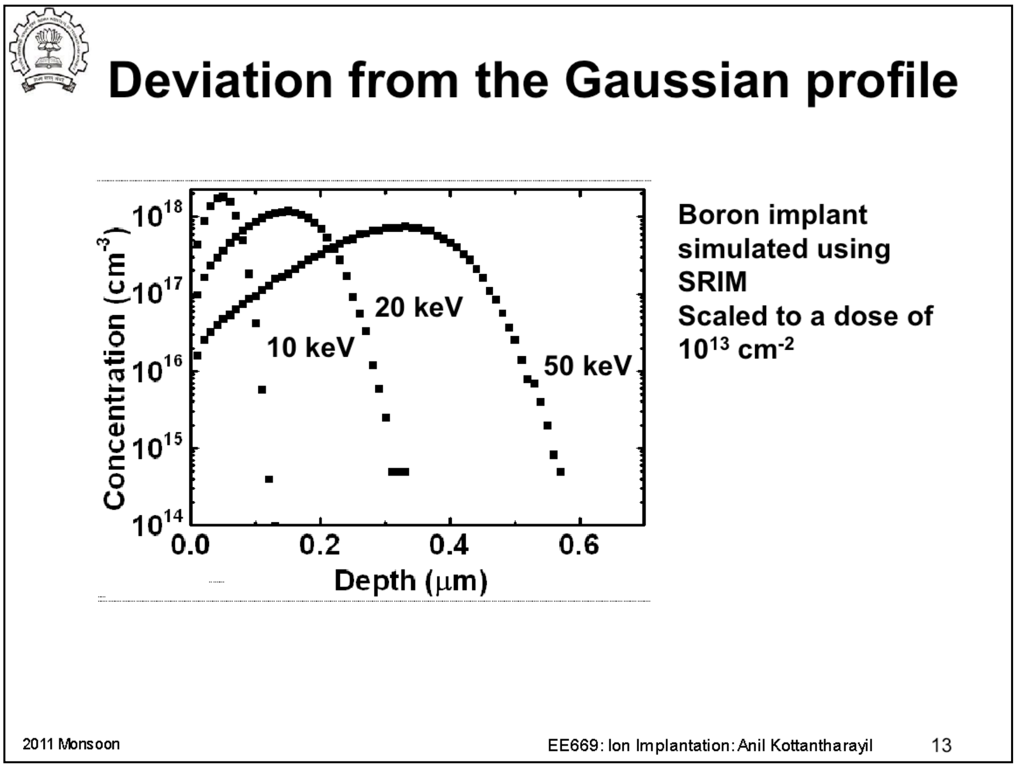
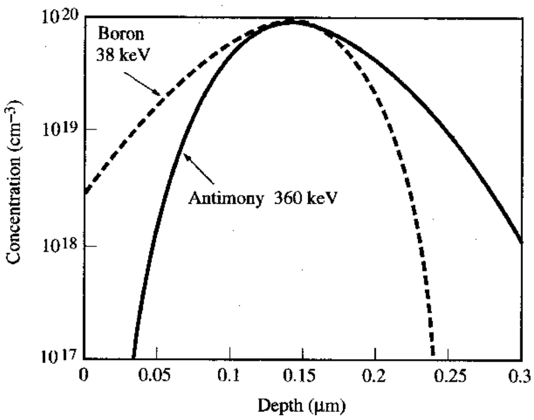
If we assume that the implanted profiles follow a Gaussian function and assume intrinsic diffusion conditions (no field effects and no assistance from point defects), then the diffused profile would also follow a Gaussian function. Noting the similarities between the implanted profile and the diffused profile equations, the original implanted profile may be thought of as a diffused profile with $2Dt = \Delta R_P^2$. Recollecting the theory of subsequent diffusions, the concentration profile after implantation and diffusion be written in the form of the third equation on the slide.



So far we had assumed that the implanted profile can be described using a Gaussian profile. This would allow us to make first order calculations of junction depth and peak concentration for a given energy. The same information can also be used for first order design of mask thickness for masked implants.

However the actual implanted profiles differ from a Gaussian. The slide shows implant profiles for Boron implantation into Silicon at three energies. As the energy increases, the profile is seen to be more skewed towards the surface of the substrate. A Gaussian would be symmetric about the range.

Deviation from the Gaussian profile (2)



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However the skew seems to depend on the ion. This slide compares the the profiles of B and Sb. The Sb implant is seen to be skewed more into the substrate.

Boron being lighter than Si can be deflected off towards the surface more than for the heavier element like Sb. This explains the skew.

4 moment distribution

1st moment ➔ Range: $R_P = \frac{1}{Q}\int_{-\infty}^{\infty} xC(x)dx$

2nd moment ➔ Straggle: $\Delta R_P = \sqrt{\frac{1}{Q}\int_{-\infty}^{\infty}\left(x - R_P\right)^2 C(x)dx}$

3rd moment ➔ Skew: $\gamma = \frac{\int_{-\infty}^{\infty}\left(x - R_P\right)^3 C(x)dx}{Q\Delta R_P^3}$

4th moment ➔ Kurtosis: $\beta = \frac{\int_{-\infty}^{\infty}\left(x - R_P\right)^4 C(x)dx}{Q\Delta R_P^4}$

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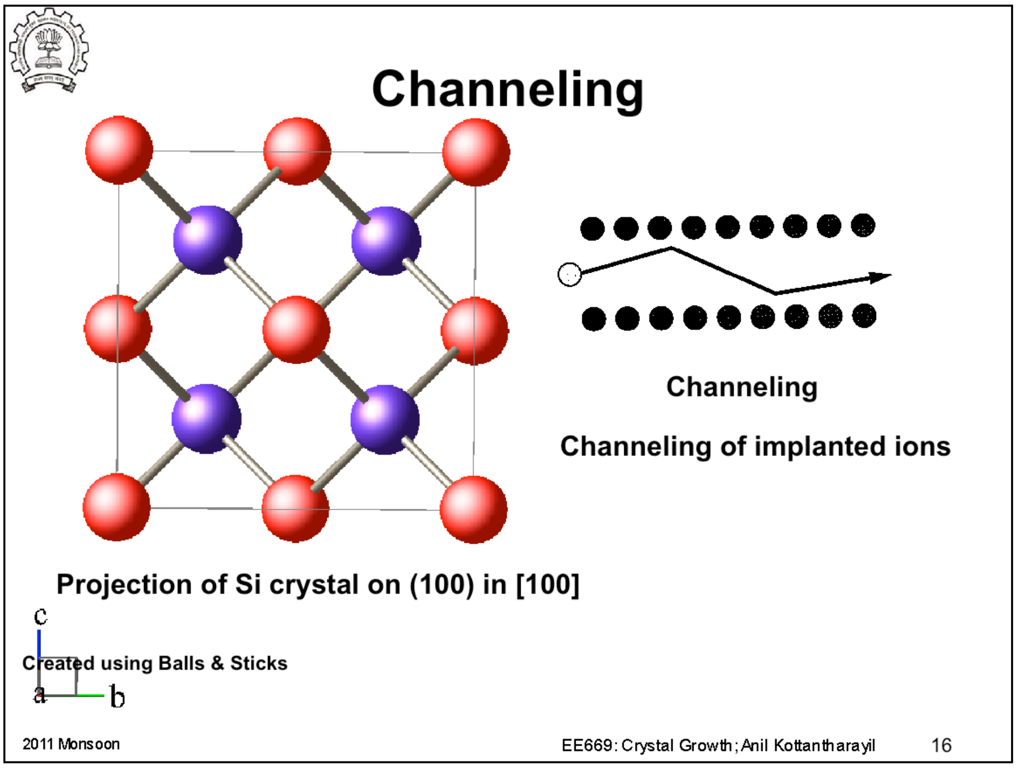
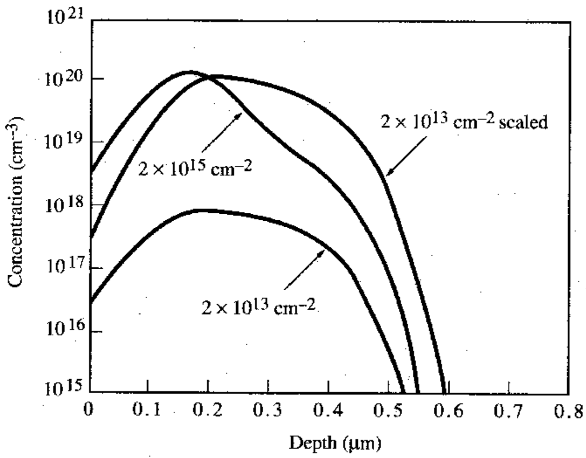
You may wonder how to model the implant profiles. This is a difficult task as the implant process is best described a statistical collision events between the implanted ion and atoms of the target material. So the best way to model is to model these interactions and then build a statistical experiment with sufficient sample size. This is what is done by SRIM. Such simulations can also be carried out using the Monte Carlo models in commercial process simulators. However Monte Carlo simulations are time consuming, as you have to calculate the trajectories of several ions to build a statistical distribution.

A faster simulation method is to represent the implant profile using statistical distributions with have more than two moments. The Gaussian profile has two moments, namely the range and the straggle. An arbitrary distribution can be represented by a series of moments. A distribution with 4 moments are found to be sufficient to describe most of the implant profiles of interest in silicon. Typically a Pearson distribution with 4 moments is used for the description. We would not look at the math of the Pearson distribution as this is beyond the scope of the course.



So far we had assumed no directional dependence for ion implantation. In general the properties of crystalline solids are not isotropic. For the specific case of ion implantation a Si crystal when looked along the [100] direction seems to have spaces between the regular array of atoms. This can be thought of a channel. An ion which shot right into the middle of the channel may go through the channel experiencing only low angle deflections. Such ions would be implanted deeper into the material than an ion shot right on top of an atom or close to an atom.

Channeling (2)



Boron
20 keV
(100) Si

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The slide shows the distribution of boron implants of different doses into (100) Si. If we consider either of the two doses, the resultant distributions can be thought of as composed of two distributions. In simulation software like Sentaurus, the distribution would be described using a dual Pearson distribution with 8 moments.

One thing that may noted here is that the distribution changes as the dose increases. This is because as the dose increases the damage to the crystal increases and the material surface into which the implant is done is no more perfectly crystalline.

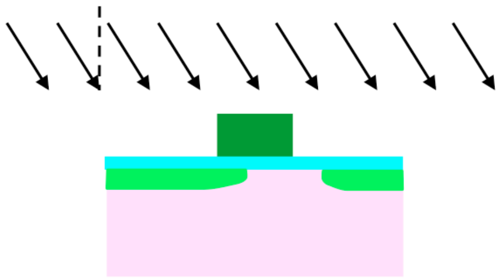
SRIM models only ion implantation into amorphous materials. So channeling effects can be simulated using SRIM.

Channeling would result in deeper junctions than if the Si was amorphous. So one of the obvious thing to do for shallow junction implants is to preamorphize the surface of the silicon prior to the implant. This is probably used for source/drain extension implants in scaled p-channel devices. Preamorphization can be achieved by implanting Si or Ge. In the case of n-channel devices, Arsenic is implanted for source/drain extension doping. Arsenic being heavier than Si, is self amorphizing for the doses of interest for this application, which is ~ 10^{15} cm^{-2}.

Another way to avoid channeling is to deposit SiO_2 on top of silicon. Since SiO_2 is amorphous, the implanted ions are likely to be randomized before they enter Si.

An implant can be also carried out with the wafer slightly tilted with respect to the beam direction. Typically a tilt of 7 degrees is used.

Shadowing effects in implantation



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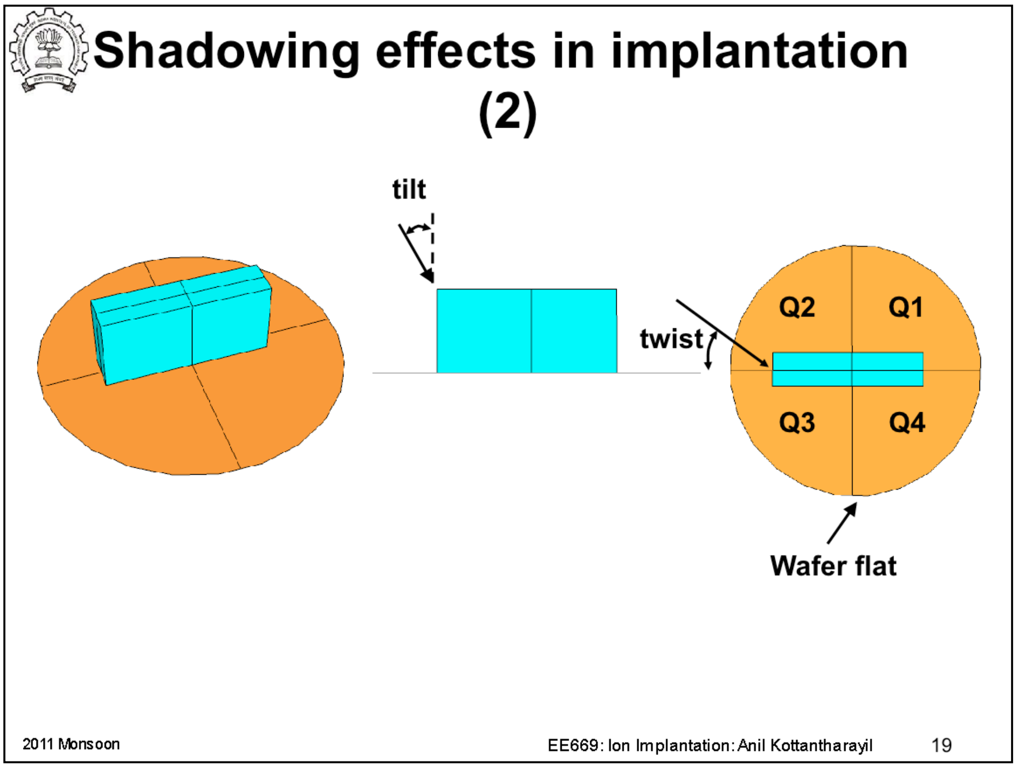
Tilt is represented in this image by showing the beam as being tilted. Typically the wafer is tilted with respect to the beam.

When we do a tilted implant on a wafer surface which has a topography, we may end up with shadows as shown. If the right hand side junction is used as the source junction, the transistor would not work. If it is used as the drain junction, it may work if the gate edge to junction off set is not too high. But you can expect very high series resistance.

Some times a shadow can be usedful. For example see Hemant V. Deshpande , B. Cheng, Jason C.S. Woo "Improvement of Flicker Noise in Lateral Asymmetric Channel N-MOSFET for Sub-Micron Analog Application," Proceedings of the 30th European Solid-State Device Research Conference, Ireland, 2000 p.496-p.499.

One way to avoid shadowing is to rotate the wafer during implantation.



In 3D device architectures like FinFETs the situation can be more complicated. The fin itself presents a topography. The source and drain extensions are on the sides of the fin. If the fin is oriented parallel to the wafer flat, providing a tilt in an arbitrary way would not help. We may also want to apply a twist. Then it would not make sense to continuously rotate the wafer during the implant. The implantation is done in quadrants of the wafer as shown. The implant may be done in two quadrants, or four quadrants. The dose implanted in one quadrant would be the total dose divided by the number of quadrants you want to implant to.

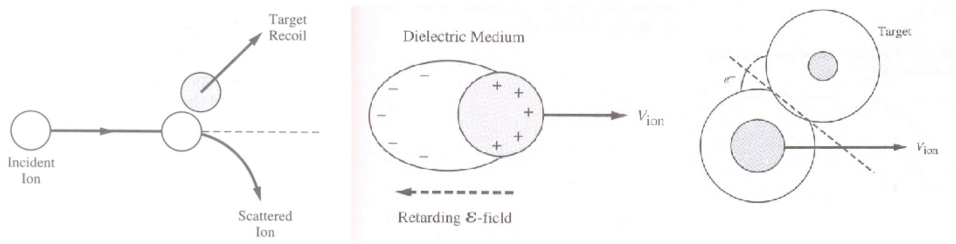
Specifying implant processes

- Implant species: As, P, B, BF_2, Sb, In, O, H, …
- Energy: range, straggle, skew and kurtosis
- Dose: Concentration
- Tilt: Channeling
- Tilt and twist: Shadowing effects
- Number of quadrants: Shadowing effects

Typical: As, 25 keV, 10^{15} cm^{-2}, 7° tilt, 0 twist, 4Q

How do we specify an implant process?
The process parameters for ion implantation are shown on this slide.

Ion stopping processes



Nuclear stopping | **Non local electronic stopping** | **Local electronic stopping**

Electronic stopping

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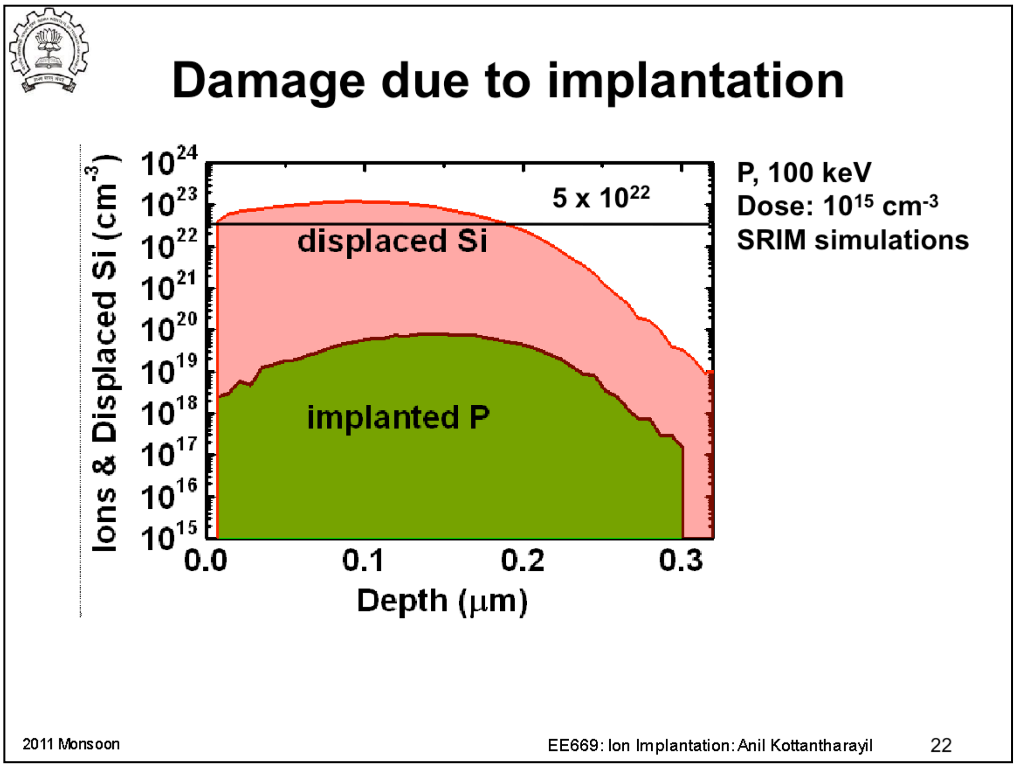
The 3 types of ion stopping are possible:

1. Nuclear stopping: the fast moving ion can interact with the nuclei of atoms of the target material. Depending on the angle of the collision and the interaction time, the ion can be scattered and the target atom can recoil or be displaced. This would lead to destruction of the crystalline structure of the material (of course if it was crystalline to begin with). The energy loss in this process would be high. Typically in Si, the creation of a stable pair of interstitial and vacancy by ion collision requires 15 eV. The recoiled ions target atoms can create further damage.
2. Non local electronic stopping: Since the ion is positively charged, it can polarize the material. The electronic charge that builds up around the ion would exert force on the ion. This can drag the fast moving ion.
3. Local electronic stopping: This results from interaction of the electrons in the ion with the electrons of the target atom. In the nonlocal case, these electrons can be from several neighboring atoms and hence it is called non local.



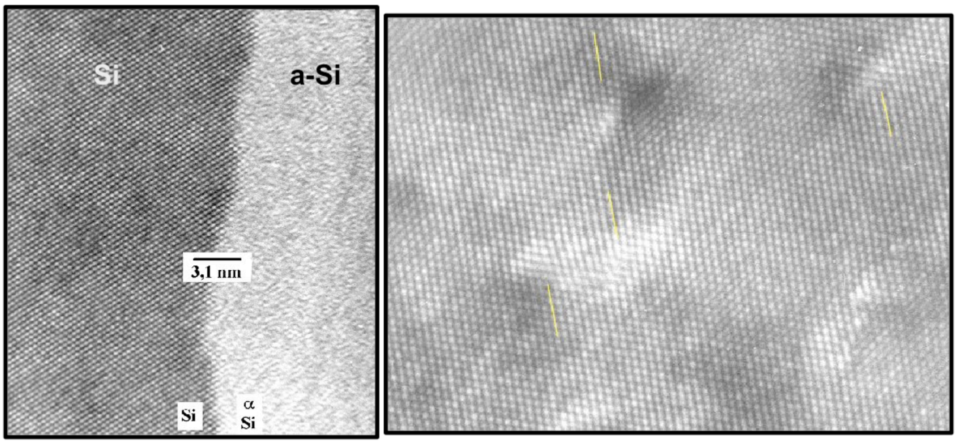
How much damage can be created by an ion? Typically an energy of 15 eV is required for creating a stable vacancy – interstitial pair. So we can assume that about 1000 such pairs are generated per ion implanted at 15 keV. The figure shows the density of displaced silicon by a phosphorous ion implant into silicon. The displaced or recoiled Si density is high near the surface and decreases as we go deeper into Si.

We may note that the density of atoms in Si is 5 x 10^{22} cm^{-3}. So in the region where the displaced Si density is higher, all the Si atoms are displaced from their original position. So the material may become amorphous in those regions. We may also note in this case that the implanted ion density peaks somewhat deeper than the peak of the damage profile.

It is possible that the displaced atom to end up in a vacancy, and this would not create a defect. So the point defect density is less than the number of displacement events.

For a material to be considered amorphous, not all atoms have to be displaced form their lattice sites. 10% crystal damage may be sufficient to say that the material is amorphized. .

Damage due to implantation (2)



http://www.tf.uni-kiel.de/matwis/amat/elmat_en/kap_6/illustr/i6_4_1.html

The HRTEM images on this slide shows the amorphized region in an implanted Si wafer. Defects are also seen deeper in Si. Of course ions have been implanted into those regions but those regions are not amorphized.

Implant anneal

$Si_S \rightarrow I + V$ — Primary defects

$A \rightarrow$???

$I + V \rightarrow Si_S$

$A + V \rightarrow A_S$

} ~ 400 C

+1 defect — Secondary defects

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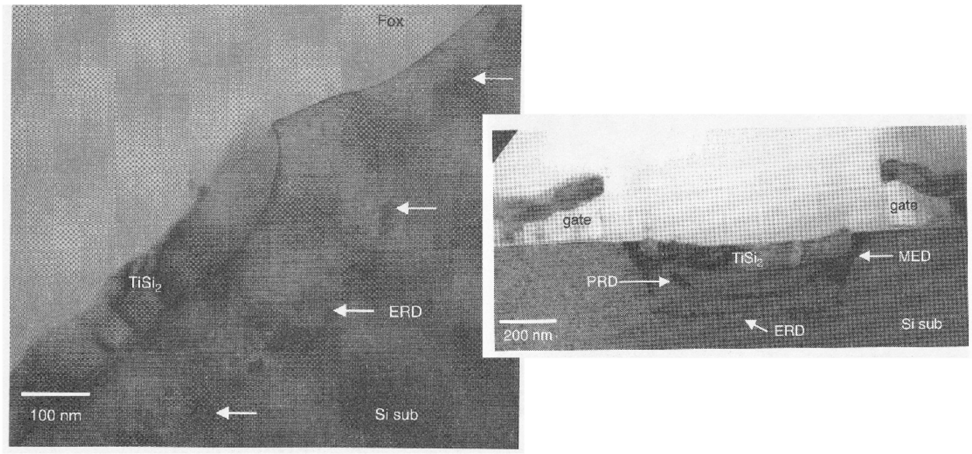
Let us say we implant ion A into Si. A Si atom may be displaced from their lattice sites giving rise to a vacancy and interstitial. Now we want to anneal the damage and activate the implanted dopant. The interstitial can recombine with the vacancy annealing two defects. In this case the dopant would be left in the interstitial position. The other possibility is that the dopant would occupy a vacancy site. In this case the interstitial would remain. In both cases, an interstitial or a dopant atom in an interstitial site are in excess. This is called a +1 defect.

The point defects generated due to implantation can be easily rearranged by short thermal annealing at low temperatures like 400 C. However the +1 defect annealing is more complicated as the interstitials have to accommodated somewhere. It is likely that these form interstitial clusters. The +1 defect can be either Si interstitial or dopant interstitial. In the later case, the dopant is not activated. So reasonable dopant activation requires a higher temperature anneal.

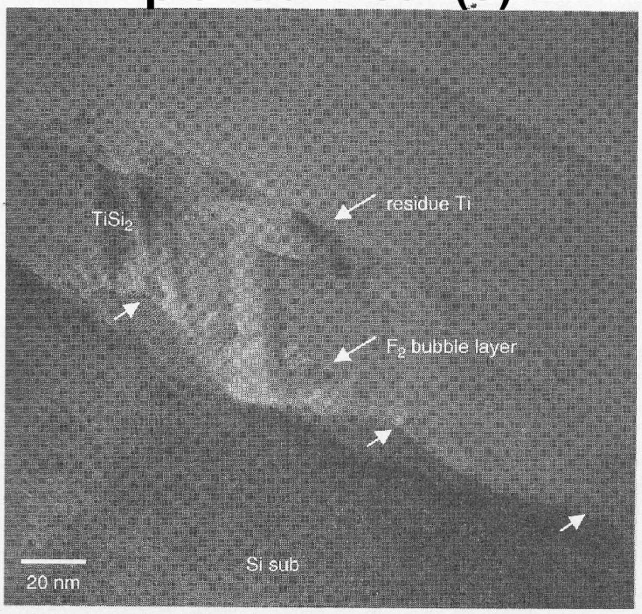
Implant anneal (2)



C.-H. Tung, G. T. T. Sheng and C.-Y. Lu, ULSI Semiconductor Technology Atlas, Wiley Interscience, 2003

+1 defects when annealed may lead to clusters of interstitials in the {311} planes – experimentally observed. Three kinds of such defects are shown in these figures, namely End of Range (EOR) – at the edge of the amporphised region, Projected Range Defects (PRD) and Mask Edge Defects (MED).

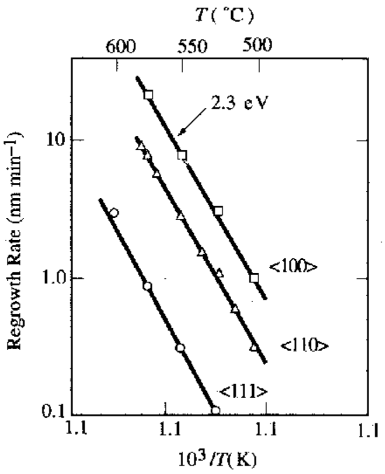
Implant anneal (3)



C.-H. Tung, G. T. T. Sheng and C.-Y. Lu, ULSI Semiconductor Technology Atlas, Wiley Interscience, 2003

When BF_2 is used for ion implantation, fluorine bubbles may show up for high doses.

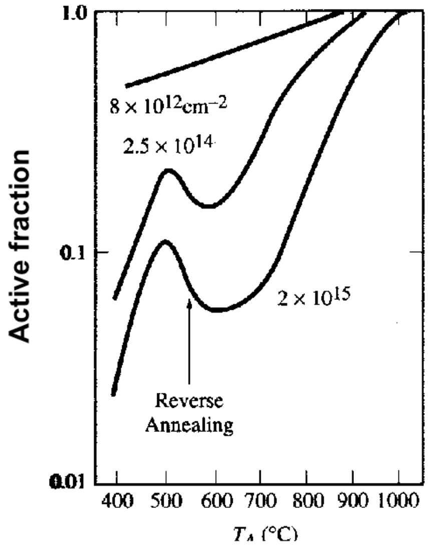
Solid phase epitaxy



$$v = A\exp\left(-\frac{2.3}{kT}\right)$$

Solid phase epitaxial regrowth of the amorphous Si can be start from the amorphous-crystalline interface. This is a layer by layer regrowth of the crystalline structure from the undamaged template. The process can happen at temperature as low as 500C and has an activation energy of 2.3 eV. During the regrowth significant amount of dopant activation can also occur in the regrown region.

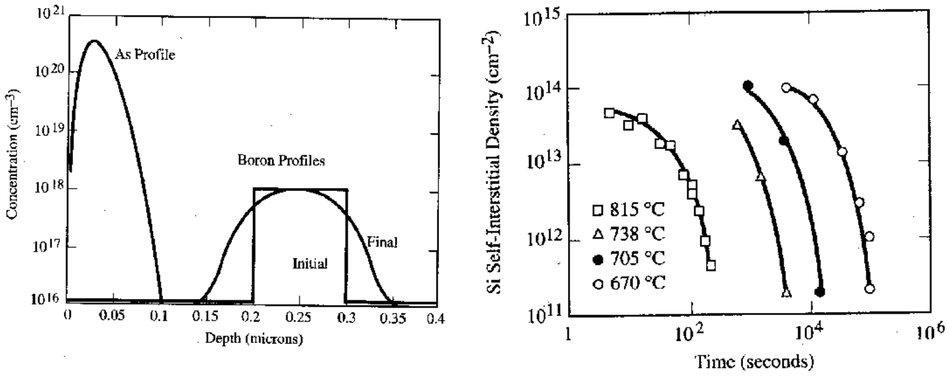
Dopant activation



B doping
30 min anneal

Dopant activation from implant damaged regions is a complex process. It is seen that the activation process is highly depend on the damage created and hence the dose. For low dose implantation, significant fraction of the dopants can be activated by a low temperature anneal process. However as the dose increases, more damage is created. Although the annealing seems to be ok for low temperature, there is a reverse annealing seen in the 450C to 600C temperature range. The annealed fraction decreases as the temperature is increased in this temperature range. There is a competition for the vacancies by the dopants and Si interstitials or boron – Si complexes are formed during this phase. However the activation picks up again for higher temperatures.

Transient enhanced diffusion



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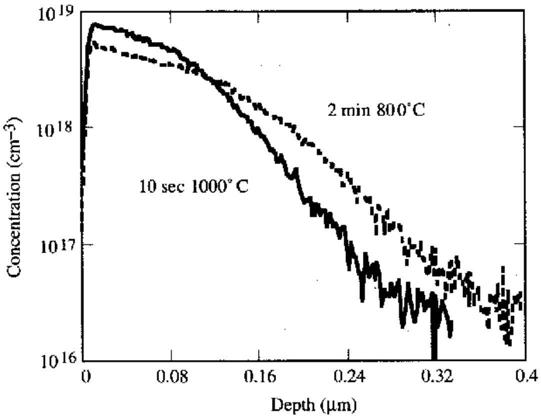
TED is a phenomenon in which during the implant activation a fast diffusion (~ 1000 X faster than normal) diffusion is seen during the initial phase of the anneal. The example on the left illustrate the point clearly. A boron retrograde profile is created in the Si by epitaxial processes. As is subsequently implanted into Si surface. The As implant creates significant concentration of defects in the surface layer.

During the anneal of these defects, secondary defects, {311} clusters, would be created. These clusters dissolve creating a large flux of insteristials in Si. Boron diffusion is assisted by interstitials and hence the diffusion is enhanced.

This is a typical scenario in n-channel MOSFETs. The channel would contain a boron profile that was implanted for threshold voltage control. The source/drain implant is typically As with dose in the range of 10^{15} cm^{-2}. So the boron diffusion would be enhanced during the activation anneal.

Transient enhanced diffusion (2)

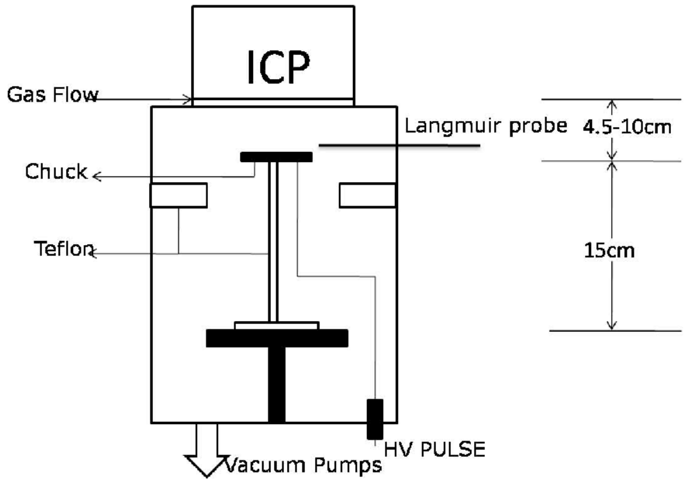


On reason to call this transient enhanced is that the defect annealing at high temperature can happen quite fast. So once all the defects are annealed, the diffusion would slow down.

The above figure shows more diffusion for lower temperature for identical boron implant conditions.

Another reason to call this transient may be could be that in modern VLSI fabrication, implant activation is usually carried using RTP systems. The temperature in such cases would be ramped up from some low value to anneal temperature like 1050 C. There can be significant boron diffusion during the temperature transient due to the high diffusion at temperature lower than the highest process temperature.

Plasma immersion ion implantation (PIII)



For shallow junction formation, people are looking at various possibilities. One of them is PIII.

Plasma immersion ion implantation (PIII)