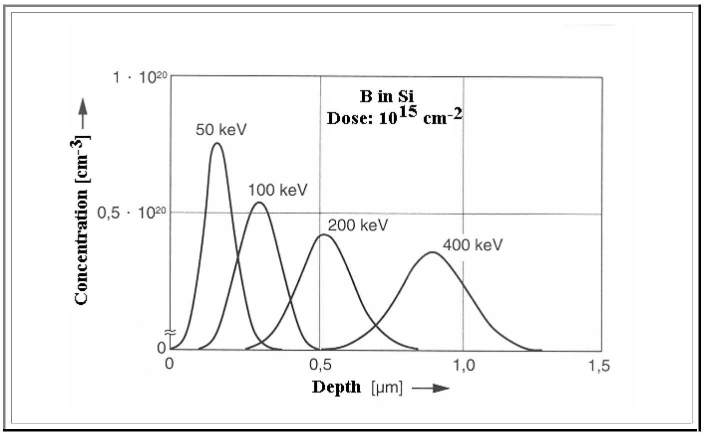
6.3.2 Ion Implantation

Ion Implantation Basics

- What is **ion implantation**, often abbreviated I^2 ? The name tells it succinctly: *Ions* of some material - almost always the dopants **As**, **B**, **P** - are *implanted*, i.e. shot into the substrate.
- Ion implantation may be counted among layer deposition processes because you definitely produce a layer of something different from the substrate even so you do not deposit something in the strict meaning of the term.
- How is it done? Obviously you need an ion beam, characterized by three basic parameters:
  - **1.** The *kind of the ions*. Almost everything from the periodic table could be implanted, but in practice you will find that only **Sb** (as dopant) and occasionally **Ge** and **O** are being used besides the common dopants **As**, **B**, and **P**.
  - **2**. The *energy of the ions* in **eV**. This is directly given by the accelerating voltage employed and is somewhere in the range of **(2 - 200) kV**, always allowing for extremes in both directions for special applications. The energy of the ion together with its mass determine how far it will be shot into a **Si** substrate. The following graph gives an idea of the distribution of **B** atoms after implantation with various energies. The curves for **As** or **P** would be similar, but with peaks at smaller depth owing to the larger mass of these atoms.



  - There are several interesting points to this graph: Obviously everything happens at dimensions ≤ **1 µm**, and a **dose** ***D*** of **10^{15} cm^{-2}** gives a pretty high doping density in the peak value. Moreover, by changing the implantation energy, all kinds of concentration profiles could be produced (within limits). That is completely impossible by just diffusing the dopant into the **Si** from the outside.
  - **3.** The *flux* (number of ions per **cm^2** and second), i.e. the current (in **µA** or **mA**) carried by the ion beam. In order to obtain some rough idea about the current range, we assume a certain beam cross section ***A*** and a constant current density ***j*** in this cross section. A total current ***I*** then corresponds to a current density ***j* = *I*/*A*** and the implanted dose is

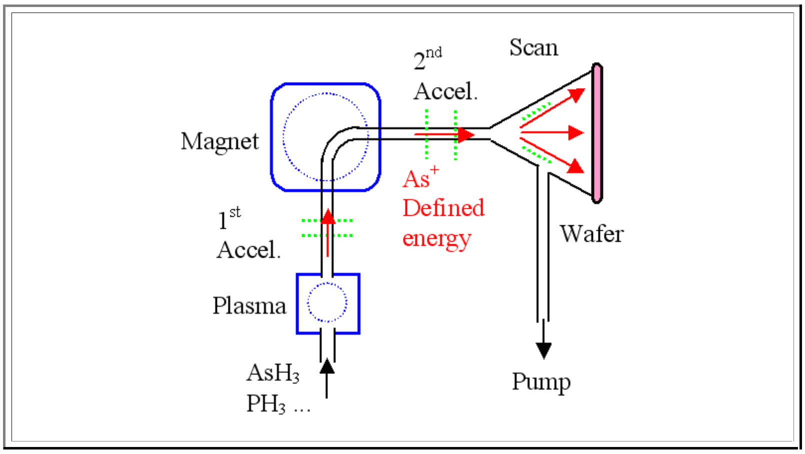
$$\boxed{D = \frac{j \cdot t}{e} = \frac{I \cdot t}{e \cdot A}}$$

  - ***t*** is the implantation time, **e** the elementary charge **= 1,6 · 10^{-19}C**.
- For an implantation time of **1 s** for an area ***A* = 1 cm^2** and a dose ***D* = 10^{15} cm^{-2}**, we obtain for the beam current

$$\boxed{I = \frac{D \cdot e \cdot A}{t} = 10^{15} \cdot 1{,}6 \cdot 10^{-19}\ \mathrm{C \cdot s^{-1}} = 1{,}6^{-4}\ \mathrm{A}}$$

  - Total implantation time for *one* **200 mm** wafer than would be about **300 s**, far too long. In other words, we need implanters capable to deliver beam currents of **10 mA** and more for high doses, and just a few precisely controlled **µA** for low doses.
  - Think a minute to consider what that means: **10 mA** in **1 cm^{-2}** at **200 kV** gives a deposited power of **2 kW** on **1 cm^{-2}**. That is three orders of magnitude larger than what your electric range at home has to offer - how do you keep the **Si** cool during implantation? If you do nothing, it will melt practically instantaneously.

- Since the beam diameter is usually much smaller than the **Si** wafer, the ion beam must be scanned over the wafer surface by some means. For simplicities sake we will dismiss the scanning procedure, even so it is quite difficult and expensive to achieve with the required homogeneity. The same is true for all the other components **-** ion beam formation, accelaration, beamshaping, and so on.
  - If we take everything together, we start to see why ion implanters are very large, very complicated, and very expensive (several million **$)** machines. Their technology, while ingenious and fascinating, shall not concern us here, however, besides giving an extremely simplifed schematic diagram.



- Why do we employ costly and complex ion implantation?
  - Because there simply is no other way to dope selected areas of a **Si** substrate with a precisely determined amount of some dopant atoms and a controlled concentration profile.
  - In our simple drawing of a **CMOS** structure we already have three doped regions (in reality there are much more). Just ask yourself: How do you get the dopants to their places?
- With ion implantation it is "easy":
  - Mask with some layer (usually **SiO_2** or photo resist) that absorbs the ions, and shoot whatever you need into the open areas.
- The only alternative (used in the stone age of **IC** semiconductor technology) is to use **diffusion** from some outside source.
  - Again, mask every area where you do not want the dopants with some layer that is impenetrable for the atoms supposed to diffuse, and expose the substrate to some gas containing the desired atoms at high temperature. After some time, some atoms will have diffused into the **Si** **-** you have your doping.
  - But there are so many problems that direct diffusion is not used anymore for complex **ICs**: Accuracy is not very good, profiles are limited, the necessary high temperatures change the profiles already established before, and so on. Simply forget it. Ion implantation is what you do.
- But like everything (and everybody), implantation has it limits.
  - For example: How do you dope around the trench shown before in the context of integrated capacitors? Obviously, you can't just shoot ions into the side wall. Or can you? Think about how you would do it and then turn to the advanced module.

Defects and Annealing

- After implanting the ions of your choice with the proper dose and depth distribution, you are not yet done.
  - Implantation is a violent process. The high energy ion transfers its energy bit by bit to lattice atoms and thus produces a large number of defects, e.g. vacancies and interstitials. Often the lattice is simply killed and the implanted layer is **amorphous**. This is shown in an illustration module.
  - You must restore order again. Not only are **Si** crystal lattice defects generally not so good for your device, but only dopant atoms, which have become neatly incorporated as substitutional impurities, will be electrically active.
- Implantation, in short, must always be followed by an annealing process which hopefully will restore a perfect crystal lattice and "activate" the implanted atoms.
  - How long you have to anneal at what temperature is a function of what and how you implanted. It is a necessary evil, because during the annealing the dopants will always diffuse and your neat implanted profiles are changing.
  - Much research has been directed to optimal annealing procedures. It might even be advantageous to anneal for very short times (about **1 s**) at very high temperatures, say **(1100 - 1200) °C**. Obviously this cannot be done in a regular furnace like the one illustrated for oxidation, and a whole new industry has developed around "**rapid thermal processing**" (***RTP***) equipment.

Some of the more interesting issues around ion implantation and annealing can be found in future advanced module.