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2. Semiconductor Doping Technology

Without exaggeration almost all of the basic MOSFET parameters are affected by the distribution of dopants in the device. Doping refers to the process of introducing impurity atoms into a semiconductor region in a controllable manner in order to define the electrical properties of this region. The doping with donors and acceptors allows to modify the electron and hole concentration in silicon in a very large range from 10^{13} cm^{-3} up to 10^{21} cm^{-3} . The carrier concentration can also be varied spatially quite accurately which is used to produce pn-junctions and built-in electric fields. All electronic and optical semiconductor devices incorporate dopants as a crucial ingredient of their device structure.

Ion implantation is the primary technology to introduce doping atoms into a semiconductor wafer to form devices and integrated circuits [17,7]. This low-temperature process uses ionized dopants which are accelerated by electric fields to high energies and are shot into the wafer. The main reason in applying this technique is the precision with which the amount and position of the doping can be controlled. Dopant ions can be masked by any material which is thick enough to stop the implant as well as by existing device structures, which is referred to as self-aligned implants. After the implantation process the crystal structure of the semiconductor is damaged by the implanted particles and the dopants are electrically inactive, because in the majority of cases, they are not part of the crystal lattice. A subsequent thermal annealing process is required to activate the dopants and to eliminate the produced crystal damage.

Continuous growth and dominance of CMOS technology has directly resulted in the growth of ion implantation applications [17]. Leading edge CMOS processes which are used to fabricate a modern microprocessor require up to twenty ion implants per wafer. The doping requirements span several orders of magnitudes in both, energy and dose, for a wide range of dopant masses. An important implantation application for CMOS processing is, for instance, to form the source/drain regions in the substrate. Downscaling of MOS transistor dimensions requires the reduction of the source/drain junction depth to compensate the influence of the shorter channel length on the threshold voltage [7]. The subsequent application of an enhanced annealing process step like the flash-assist RTA (rapid thermal annealing) technique leads to a very limited diffusion which barely changes the as-implanted doping profiles and junction depth [26]. The distribution of dopants in the final device is therefore mainly determined by the ion implantation step, whereby channeling of implanted ions, which results from the regular arrangement of atoms in the silicon crystal structure, plays a major role.

2.1 Fundamentals of Semiconductor Doping

The starting material used for the fabrication of semiconductor devices is monocrystalline silicon. Silicon wafers are produced either by the Czochralski crystal pull method or by the floating-zone crystal growth technique [27]. Dopants are added to the silicon during the growth process in order to set the resistivity of the wafer in the range from $1\text{ m}\Omega\text{cm}$ - $30\Omega\text{cm}$ [4]. Defects in the silicon crystal become much more severe for smaller device dimensions. Today, silicon wafers with a (100) surface plane are commonly used in semiconductor manufacturing [28], because the lowest defect density at the Si/SiO₂ interface can be achieved by thermal oxidation of (100) silicon. In this work we consider crystalline substrates of silicon, silicon-germanium, and germanium. At zero temperature the conductivity in a pure semiconductor crystal is zero, because the vacant conduction band is separated by an energy gap E_g from the filled valence band. As the temperature is increased, electrons are thermally excited from the valence band to the conduction band. Both the electrons in the conduction band and the vacant orbitals or holes left behind in the valence band contribute to the electrical conductivity.

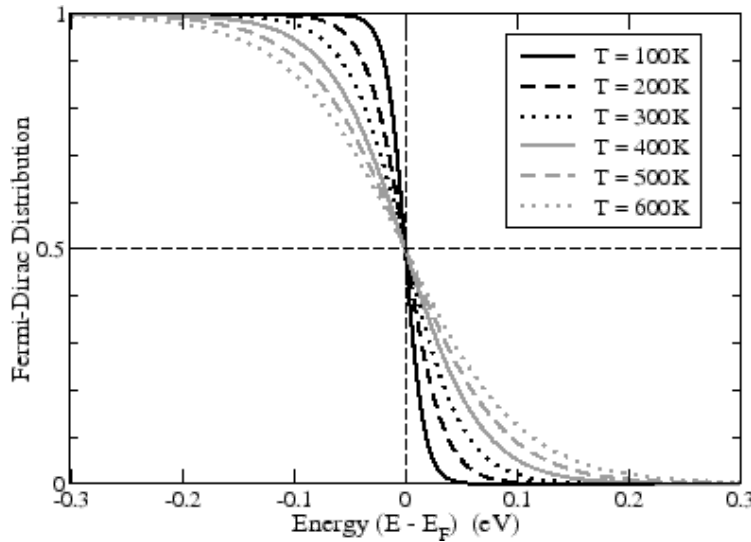


Figure 2.1: Fermi-Dirac distribution function for various temperatures.

2.1.1 Intrinsic Semiconductor

An intrinsic semiconductor is one that contains a negligibly small amount of impurities compared with thermally generated electrons and holes. The energy distribution of electrons in solids is given by the Fermi-Dirac statistics [29]. The probability that an electronic state at energy E is occupied by an electron in thermal equilibrium is given by the Fermi-Dirac distribution

$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)} \quad (2.1)$$

In Fig. 2.1 the Fermi-Dirac distribution function $f(E)$ versus energy $(E - E_F)$ is presented for different temperatures. The Fermi energy E_F is the energy at which the probability of occupation by an electron is exactly one-half. The probability of not finding an electron at energy E , $1 - f(E)$, is the probability of finding a hole there. At absolute zero temperature, $T = 0K$, all the states below the Fermi level are filled, $f(E) = 1$ for $E < E_F$, and all the states above the Fermi level are empty $f(E) = 0$ for $E > E_F$. At finite temperatures, continuous thermal agitation exists, which results in excitation of electrons from the valence band to the conduction band and an equal number of holes are left in the valence band. This process is balanced by recombination of the electrons in the conduction band with holes in the valence band. The width of the transition from one to zero of the probability distribution $f(E)$ increases with the thermal energy $k_B T$. Note that $f(E)$ is symmetrical around the Fermi level E_F . For energies that are $3k_B T$ above or below the Fermi energy, the exponential term in (2.1) becomes larger than 20 or smaller than 0.05, respectively. The Fermi-Dirac distribution can thus be approximated by simpler expressions according to

$$f(E) \doteq \exp\left(-\frac{E - E_F}{k_B T}\right) \quad \text{for } (E - E_F) > 3k_B T, \quad (2.2)$$

$$f(E) \doteq 1 - \exp\left(\frac{E - E_F}{k_B T}\right) \quad \text{for } (E - E_F) < -3k_B T. \quad (2.3)$$

The electron and hole concentrations in an intrinsic semiconductor under thermal equilibrium condition depend on the density of states $N(E)$, that is, the number of allowed energy states per unit energy per unit volume and is given by [29]

$$N(E) = 4\pi \left(\frac{2m_{e,h}}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}}. \quad (2.4)$$

The electron concentration n in the conduction band is given by integrating the product of the density of states $N(E)$ and the probability of occupying an energy level $f(E)$ according to

$$n = \int_{E_C}^{\infty} f(E) N(E) dE, \quad (2.5)$$

where E_C is the energy at the bottom of the conduction band. Substituting (2.2) and (2.4) into (2.5) and solving the integral results in

$$n = N_C \exp \left(-\frac{E_C - E_F}{k_B T} \right), \quad N_C \equiv 2 \left(\frac{2\pi m_e k_B T}{h^2} \right)^{\frac{3}{2}}, \quad (2.6)$$

where N_C is the effective density of states in the conduction band [29]. In a similar way the hole concentration in the valence band can be obtained according to

$$p = \int_{-\infty}^{E_V} [1 - f(E)] N(E) dE, \quad (2.7)$$

where E_V is the energy at the top of the valence band. Substituting (2.3) and (2.4) into (2.7) and solving the integral yields

$$p = N_V \exp \left(-\frac{E_F - E_V}{k_B T} \right), \quad N_V \equiv 2 \left(\frac{2\pi m_h k_B T}{h^2} \right)^{\frac{3}{2}}, \quad (2.8)$$

where N_V is the effective density of states in the valence band [29].

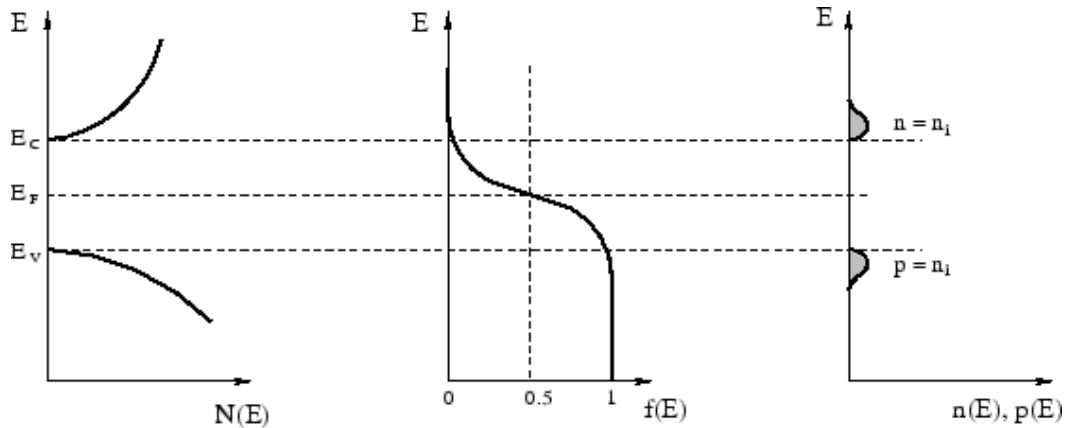


Figure 2.2: Density of states, probability distribution, and resulting electron and hole concentration in an intrinsic semiconductor [29].

For an intrinsic semiconductor the number of electrons in the conduction band is equal to the number of holes in the valence band, that is, $n = p = n_i$ where n_i is the intrinsic carrier concentration. In Fig. 2.2 the intrinsic electron and hole concentrations are obtained graphically from the product of $N(E)$ and $f(E)$. The Fermi level for an intrinsic semiconductor is obtained by equating (2.6) and (2.8) which yields

$$E_F = E_i = \frac{E_C + E_V}{2} + \frac{k_B T}{2} \ln \left(\frac{N_V}{N_C} \right). \quad (2.9)$$

The intrinsic Fermi level E_i lies very close to the middle of the bandgap $E_g \equiv E_C - E_V$, because the second term in (2.9) is much smaller than the bandgap at room temperature.

The intrinsic carrier concentration can be calculated from equations (2.6), (2.8), and (2.9) according to

$$np = n_i^2, \quad (2.10)$$

$$n_i = \sqrt{N_C N_V} \exp\left(-\frac{E_g}{2k_B T}\right). \quad (2.11)$$

Table 2.1: Bandgap and intrinsic carrier concentration at 300K for three common semiconductors [30].

Material	E_g (eV)	n_i (cm ⁻³)
Ge	0.66	$2.4 \cdot 10^{13}$
Si	1.12	$9.65 \cdot 10^9$
GaAs	1.42	$2.25 \cdot 10^6$

The intrinsic carrier concentration is largely controlled by $E_g/k_B T$, the ratio of the band gap and the temperature. When this ratio is large, the conductivity will be low. Table 2.1 summarizes these key values for germanium, silicon, and gallium arsenide at room temperature and Fig. 2.3 shows the temperature dependence of n_i for these semiconductors.

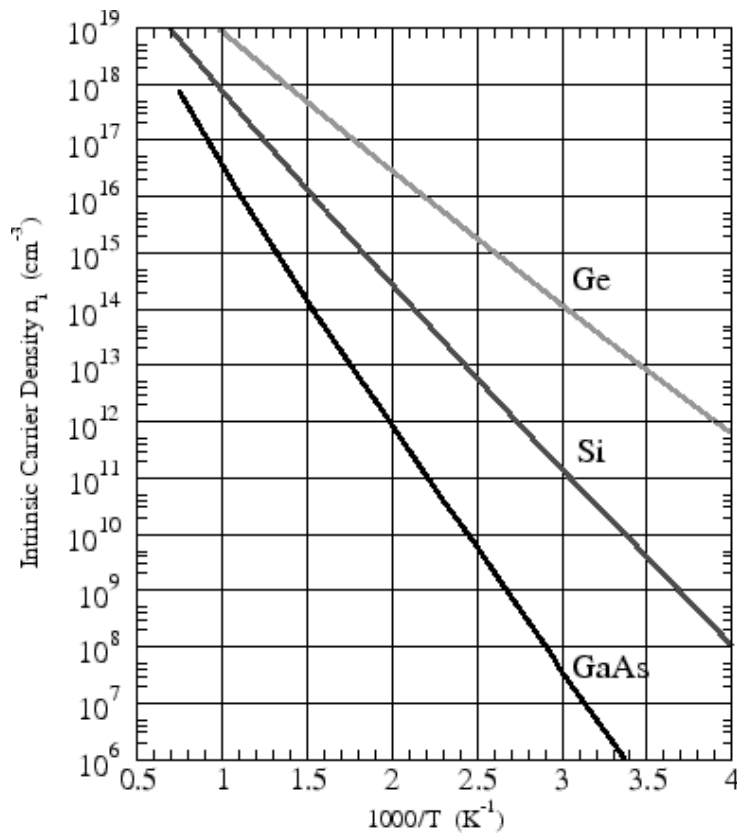


Figure 2.3: Intrinsic carrier densities of Ge, Si, and GaAs as a function of reciprocal temperature [30].

2.1.2 Donors and Acceptors

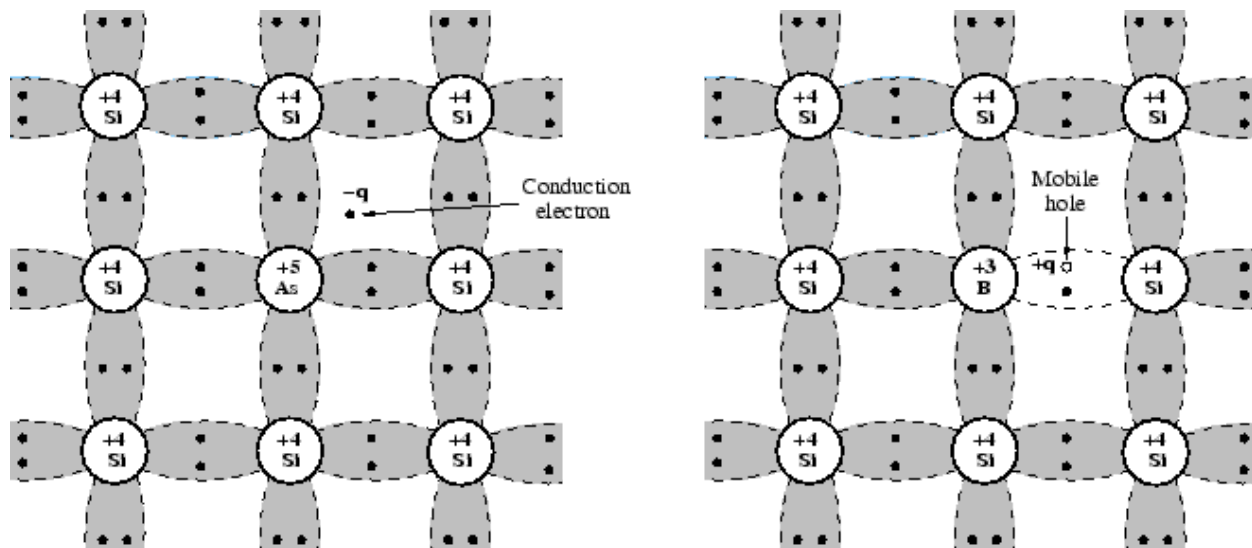


Figure 2.4: Schematic bond representation for n-type silicon doped with arsenic and p-type silicon doped with boron.

In processing of modern semiconductor devices, doping refers to the process of introducing impurity atoms into a semiconductor wafer by ion implantation. The purpose of semiconductor doping is to define the number and the type of free charges in a crystal region that can be moved by applying an external voltage. The electrical properties of a doped semiconductor can either be described by using the "bond" model or the "band" model. When a semiconductor is doped with impurities, the semiconductor becomes extrinsic and impurity energy

levels are introduced. In Fig. 2.4 the bond model is used to show that a tetravalent silicon atom (group IV element) can be replaced either by a pentavalent arsenic atom (group V) or a trivalent boron atom (group III). When arsenic is added to silicon, an arsenic atom with its five valence electrons forms covalent bonds with its four neighboring silicon atoms. The fifth valence electron has a relatively small binding energy to its arsenic host atom and can become a conduction electron at moderate temperature. The arsenic atom is called a donor and a donor-doped material is referred to as an n-type semiconductor. Such a semiconductor has a defined surplus of electrons in the conduction band which are the majority carriers, while the holes in the valence band, being few in number, are the minority carriers. In a similar way, Fig. 2.4 demonstrates the behavior, if a boron atom with its three valence electrons replaces a silicon atom, an additional electron is "accepted" to form four covalent bonds around the boron, and a hole carrier is thus created in the valence band. Boron is referred to as an acceptor impurity and doping with boron forms a p-type semiconductor. The dopant impurities used in controlling the conductivity type of a semiconductor usually have very small ionization energies, and hence, these impurities are often referred to as shallow impurities. The energy required to remove an electron from a shallow donor impurity such as arsenic, phosphorus, and antimony can be estimated based on the Bohr model of the hydrogen atom [30,31]. The ionization energy of hydrogen is given by

$$E_H = \frac{m_0 q^4}{8 \epsilon_0^2 h^2} , \quad (2.12)$$

where m_0 is the free electron mass, q is the elementary charge, ϵ_0 is the dielectric constant, and h is the Planck constant. The evaluation of (2.12) results in 13.6 eV for the ionization energy E_H of the free hydrogen atom. The hydrogen atom model may be modified to take into account the dielectric constant of the semiconductor and the effective mass of an electron in the periodic potential of the crystal. Thus, the donor ionization energy is obtained by replacing q^2 with q^2/ϵ and m_0 by the effective mass m_e according to

$$E_D = \frac{m_e q^4}{8 \epsilon^2 \epsilon_0^2 h^2} \equiv \frac{m_e}{m_0 \epsilon^2} E_H . \quad (2.13)$$

The Bohr radius of the donor can also be derived from the hydrogen atom model according to

$$a_D = \frac{\epsilon \epsilon_0 h^2}{m_e q^2 \pi} . \quad (2.14)$$

The applicability to silicon and germanium is complicated due to the anisotropic effective mass of the conduction electrons. To obtain a first order approximation of the impurity levels we use $m_e \approx 0.2 m_0$ for electrons in silicon and $m_e \approx 0.1 m_0$ in germanium. Then the ionization energy for donors E_D , measured from the conduction band edge, can be calculated from (2.13), and is 20 meV for silicon and 5 meV for germanium. Calculations using the correct anisotropic mass tensor predict 29.8 meV for silicon and 9.05 meV for germanium. According to (2.14), the Bohr radius a_D for donors is 30 Å in silicon and 80 Å in germanium, which is much larger than the Bohr radius of 0.53 Å for the hydrogen atom. Therefore, the average distance a_D between the electron and the positive charged donor ion is also much larger than the inter-atomic

spacing of the semiconductor crystal. These large radii of the donor orbits overlap at relatively low donor concentrations in the crystal and an "impurity band" is formed from the donor states, which enables electron hopping from donor to donor.

Shallow acceptor impurities in silicon and germanium are boron, aluminium, gallium, and indium. An acceptor is ionized by thermal energy and a mobile hole is generated. On the energy band diagram, an electron rises when it gains energy, whereas a hole sinks in gaining energy. The calculation of the ionization energy for acceptors is similar to that for donors, it can be thought that a hole is located in the central force field of a negative charged acceptor. The calculated ionization energy for acceptors, measured from the valence band edge, is **50 meV** in silicon and **15 meV** in germanium. The used approach for the calculation of the ionization energy is based on a hydrogen-like model and the effective mass theory. This approach does not consider all influences on the ionization energy, in particular it cannot predict the ionization energy for deep impurities. However, the calculated values do predict the correct order of magnitude of the true ionization energies for shallow impurities. The ionization energy for shallow impurities can also be calculated by means of the density functional theory (DFT). In [32] both approaches are compared to experimental data. The results obtained by the DFT calculation are only for some impurities slightly more accurate than the simple approach. Table 2.2 presents the measured ionization energies for various donor and acceptor impurities in silicon and germanium.

Table 2.2: Ionization energies of shallow impurities in silicon and germanium, in meV.

Material	As	P	Sb	B	Al	Ga	In
Si	49.0	45.0	39.0	45.0	57.0	65.0	157.0
Ge	12.7	12.0	9.6	10.4	10.2	10.8	11.2

For shallow donors, it can be assumed that all donor impurities are ionized at room temperature. A donor atom which has released an electron becomes a positive fixed charge. The electron concentration under complete ionization is given by

$$n = N_D , \quad (2.15)$$

where N_D is the donor concentration. From (2.6) and (2.15), we obtain the distance of the Fermi level from the conduction band edge according to

$$E_C - E_F = k_B T \ln \left(\frac{N_C}{N_D} \right) . \quad (2.16)$$

Under complete ionization, the hole concentration is equal to the acceptor concentration N_A ,

$$p = N_A . \quad (2.17)$$

In a similar way we obtain the distance of the Fermi level from the top of the valence band,

$$E_F - E_V = k_B T \ln \left(\frac{N_V}{N_A} \right) . \quad (2.18)$$

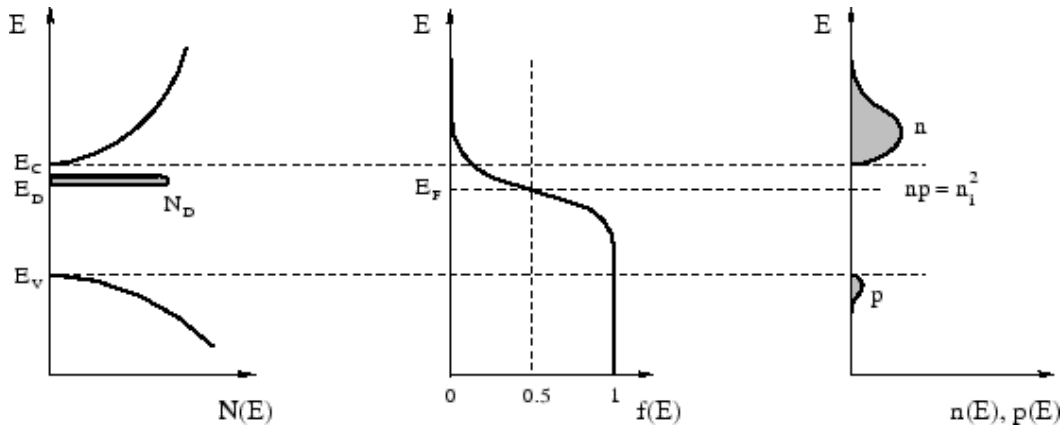


Figure 2.5: Density of states, probability distribution, and carrier concentration in an n-type semiconductor.

Equation (2.16) states that the higher the donor concentration, the smaller the energy difference $(E_C - E_F)$, which means that the Fermi level will move up closer to the conduction band edge. On the other hand side, for a higher acceptor concentration, the Fermi level will move closer to the top of the valence band according to (2.18). According to the implanted impurity type, either n- or p-type carriers will dominate, but the product of n and p is equal to n_i^2 . Note that this result is equal to the intrinsic case, Equation (2.10), which is called the mass action law. Fig. 2.5 shows the graphic procedure for obtaining the carrier concentrations in an n-type semiconductor under thermal equilibrium.

If donor and acceptor impurities are introduced together, the impurity present in a higher concentration determines the type of conductivity in the semiconductor. The Fermi level must adjust itself to preserve charge neutrality. Overall charge neutrality requires that the negative charges (electrons and ionized acceptors) must be equal to the total positive charges (holes and ionized donors):

$$n + N_A = p + N_D . \quad (2.19)$$

Combining (2.10) and (2.19) results in the equilibrium electron and hole concentrations in an n-type semiconductor:

$$n_n = \frac{1}{2} \left[N_D - N_A + \sqrt{(N_D - N_A)^2 + 4n_i^2} \right] , \quad (2.20)$$

$$p_n = \frac{n_i^2}{n_n} . \quad (2.21)$$

The index n refers to the n-type semiconductor. In a similar way the holes and electrons can be calculated in a p-type semiconductor:

$$p_p = \frac{1}{2} \left[N_A - N_D + \sqrt{(N_D - N_A)^2 + 4n_i^2} \right], \quad (2.22)$$

$$n_p = \frac{n_i^2}{p_p}. \quad (2.23)$$

The index p indicates the majority carrier type being holes.

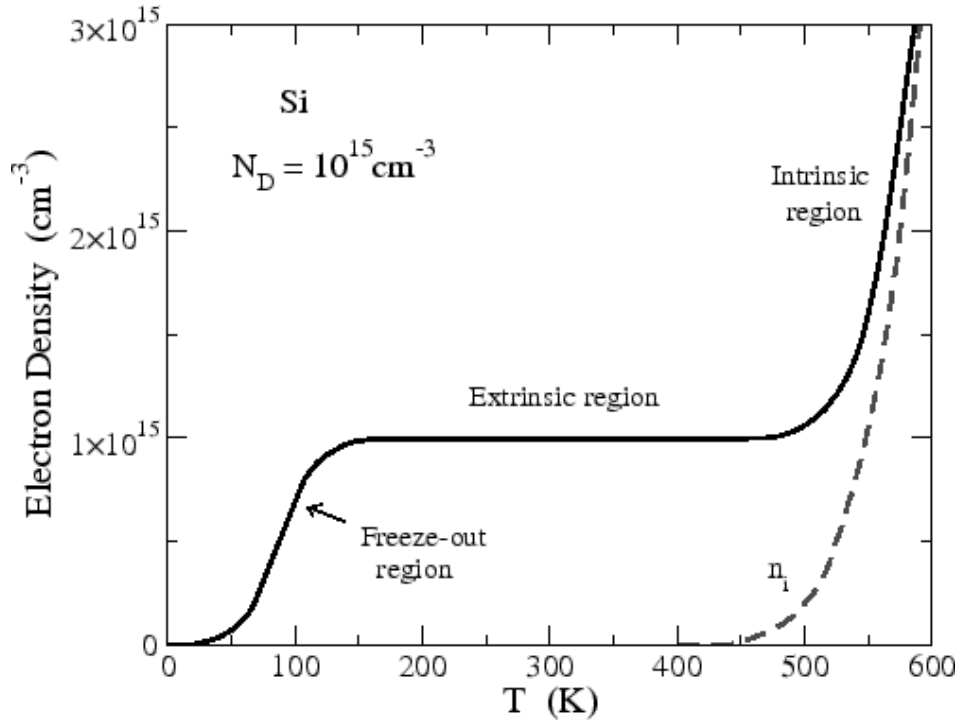


Figure 2.6: Electron density as a function of temperature for a Si sample with a donor concentration of 10^{15} cm^{-3} .

Generally, the magnitude of the net impurity concentration $|N_D - N_A|$ is larger than the intrinsic carrier concentration n_i and the relationships for n_n and p_p can be simplified to

$$n_n \approx N_D - N_A \quad \text{if} \quad N_D > N_A, \quad (2.24)$$

$$p_p \approx N_A - N_D \quad \text{if} \quad N_A > N_D. \quad (2.25)$$

Fig. 2.6 shows the electron concentration in doped silicon with $N_D = 10^{15} \text{ cm}^{-3}$ as a function of the temperature [29]. At low temperatures the thermal energy in the crystal is not sufficient to ionize all available impurities. Some electrons are "frozen" at the donor level and the electron concentration is less than the donor

concentration. As the temperature is increased, the condition of complete ionization is reached, $n_n = N_D$. As the temperature is further increased, the electron concentration remains essentially the same over a wide temperature range. This region is called extrinsic. As the temperature is increased further, we reach a point where the intrinsic carrier concentration becomes comparable to the donor concentration. Beyond this point the semiconductor becomes intrinsic. The temperature at which the semiconductor becomes intrinsic depends on the impurity concentration and the bandgap value. It can be obtained from Fig. 2.3 by setting the impurity concentration equal to n_i .

2.2 Ion Implantation Technology

Ion implantation is a process whereby a focused beam of ions is directed towards a target wafer. Ionized particles are used in this process, because they can be accelerated by electric fields and separated by magnetic fields in an easy way in order to obtain an ion beam of high purity and well-defined energy. The ions have enough kinetic energy that they can penetrate into the wafer upon impact. The basic features of an ion implanter for doping semiconductors and the need to anneal the implant were patented by Shockley in 1957 [33]. The accelerators developed for nuclear physics research and isotope separation provided the technology from which ion implanters have been developed and the specific requirements of the semiconductor industry defined the evolution of the architecture of these small accelerators [34]. The next section describes some key elements of a modern ion implanter like the ion source and the beam transport system as well as a technique to achieve uniform doping over large wafers. The wafers are processed one at a time or in batches and are moved in and out of the vacuum by automated handling systems. The productivity of an ion implanter is of economic importance and there is continuing need to increase the usable beam current especially at low energies.

2.2.1 Ion Implantation Equipment

Commercial ion implanters are linear accelerators (linacs) that accelerate ions up to an energy of several MeV. Early machines of the 1970s typically used cold cathode ion sources, which were able to produce ion currents of up to $200\mu\text{A}$. In 1978, the first true high current ion implanter was introduced, which used a Freeman ion source and produced 10mA of ion current at energies up to 80keV [7]. The rapid change in manufacturing process has led to new and improved implanters being developed almost on a yearly basis. The wafer size is now 300mm and has increased seven times since 50mm wafers in 1970. Each size change obsoleted the previous generation of implanters. The changes needed were not only related to wafer handling, but the increase in area of 36 times meant that to maintain equivalent wafer throughput, the beam current needed to be increased correspondingly and as a result effects such as wafer heating, wafer charging, space charge and contamination became quite significant problems [34].

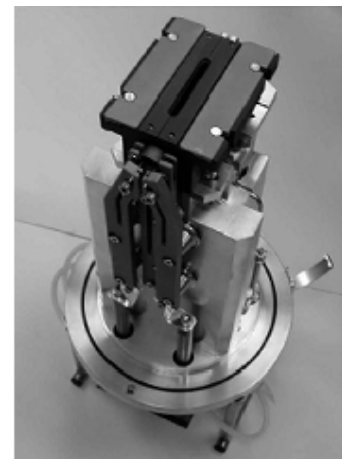
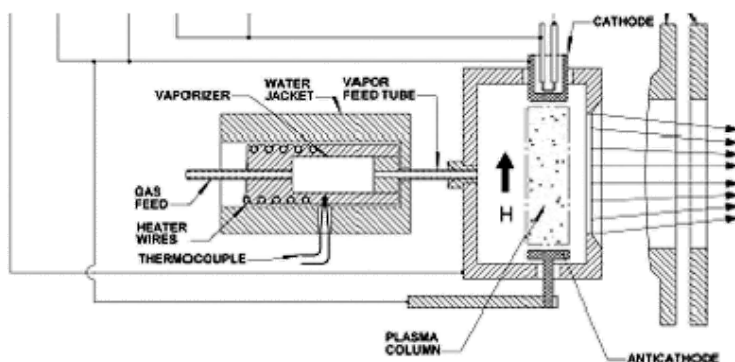


Figure 2.7: Cross-sectional schematic of a Bernas ion source with indirectly heated cathode and vaporizer (left) and corresponding photo (right) [34].

The ion source in an implanter must be capable of producing stable beams of the common dopants such as boron, phosphorus, arsenic, antimony, and indium. A beam current of up to 30mA and a lifetime of more than 100h before failure are required for cost effective productivity [34]. Among several different sources that have been developed the Bernas source with an indirectly heated cathode has become the source of choice for almost all implanters built today, and each manufacturer has developed a specialized design for their equipment [35]. Fig. 2.7 shows a typical example of this ion source. The ionizing electrons oscillate between the indirectly heated cathode and an anticathode and are confined by the magnetic field of a small electromagnet. The plasma density and the shape of the exit aperture of the ion source in combination with the extraction electrodes are important elements in the beam line since the quality and density of the ion beam entering the analyzing magnet system are determined in this region. A detailed discussion of extraction geometries can be found in a review by Hollinger [36], and of the beam transport system by Rose and Ryding [34].

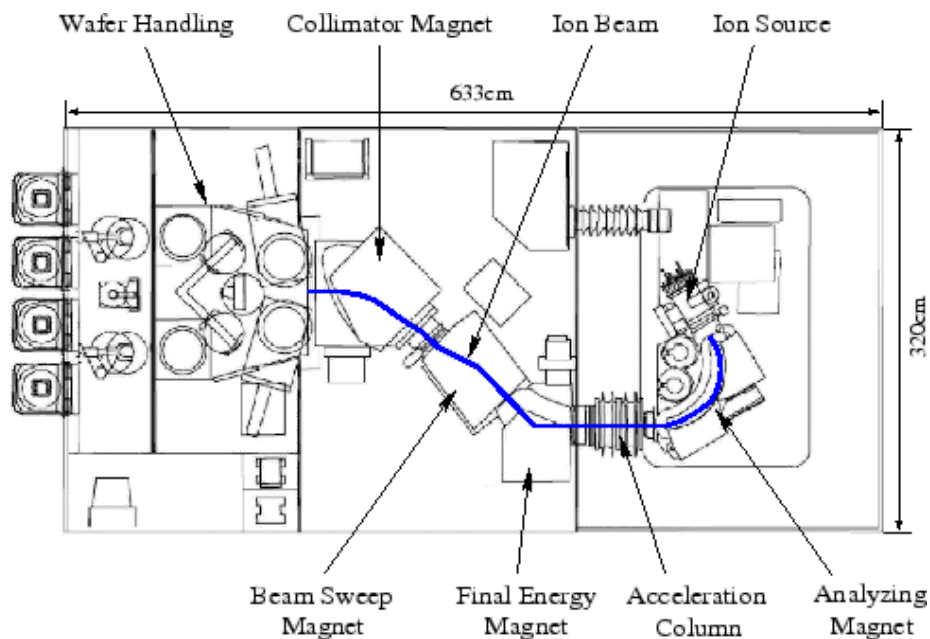


Figure 2.8: Schematics of the medium-current implanter EXCEED3000AH [37].

When ion implantation was first adopted for doping semiconductors it was not realized what a large range of capabilities would ultimately be needed. Today, different machine types are used to cover the entire range of both energies and beam currents required for semiconductor fabrication. The machines can be grouped in medium current, high current, high energy implanters, and specialized implanters, for example, the oxygen implanter for SIMOX (separation by implantation of oxygen) technology [38].

Almost all the medium-current implanters which deliver beam currents in the range of a few mA incorporate the concept of hybrid scanning by combining a beam scan and a one-axis mechanical wafer scan. Fig. 2.8 shows an example of a modern medium-current implanter from Nissin Corp. for 300mm wafers which can be employed for the 45nm technology and beyond [37]. The ion beam is generated in the ion source, mass analyzed at the analyzing magnet, accelerated or decelerated at the acceleration column, energy filtered at the final energy magnet, swept by the beam sweep magnet, and then collimated through the collimator magnet. This implanter uses a one-dimensional hybrid scan, where the ion beam is scanned and collimated by magnetic fields in horizontal direction and the wafer is then mechanically scanned in vertical direction. The typical energy range covered is between about 3keV and 250keV for singly charged ions. Using double or triple charged ions extends the energy range to approximately 750keV. Several manufacturers produce machines of this type and they are widely employed, because they satisfy many of the lower doping requirements for devices, they have a wide energy range and wafer throughputs as high as 450 wafers/h can be achieved [37].

When source/drain implants requiring doses of 10^{16} ions/cm² became important, high-current implanters capable of beam currents larger than 10mA were developed to allow fast processing of wafers. The decreasing junction depth is creating a challenge for high-current implanters because below a few keV it is difficult to obtain reasonably high beam currents [34].

2.2.2 Crystallographic Considerations

Channeling of implanted ions results from the regular arrangement of silicon atoms in rows and planes in crystalline silicon. The silicon crystal has a diamond structure, where each silicon atom is covalently bonded to four other silicon atoms in a tetrahedral arrangement. This configuration belongs to the face-centered cubic (FCC) crystal system with silicon atoms in all corners of a cube, in the center of each cube face, and at four interstitial positions within the cube, as shown in Fig. 2.9. The unit cell of the silicon crystal with its lattice constant a of 5.4307 Å at 25°C defines the channels in silicon, where complex channeling behavior can arise from this relatively simple arrangement of atoms.

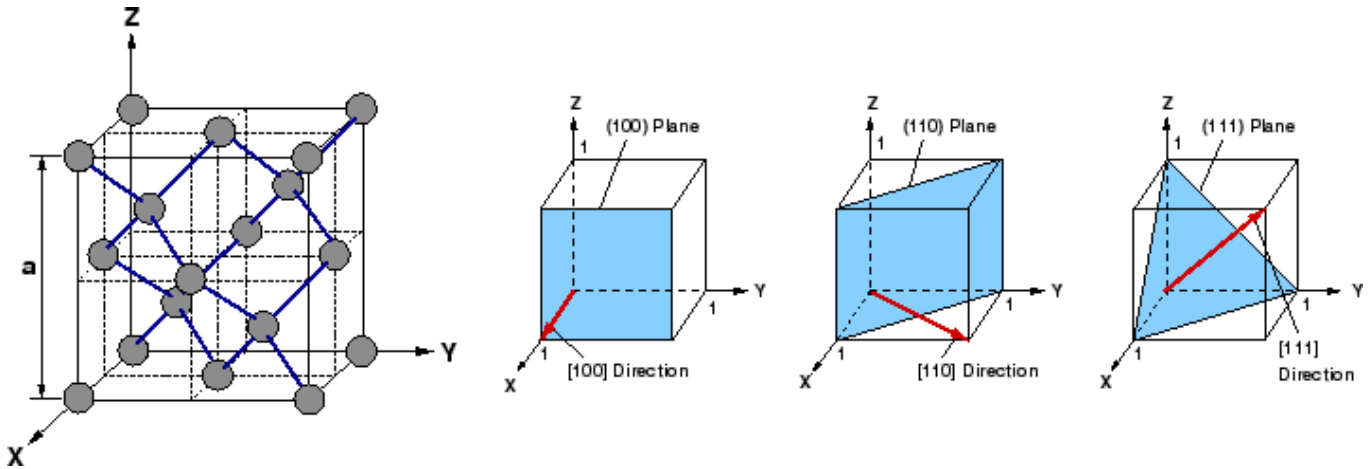


Figure 2.9: Illustration of the silicon crystal structure and Miller index notation.

The Miller indices are commonly used to define planes of atoms and directions in the crystal. The Miller indices (hkl) of a particular plane are a set of three integers which are derived arithmetically from the intercepts x_1 , y_1 , z_1 of that plane with the coordinate axes X , Y , Z . The length of the intercepts is a related quantity which is specified in multiples of the lattice constant a . The Miller indices (hkl) are defined as

$$h = \frac{s_1}{x_1}, \quad k = \frac{s_1}{y_1}, \quad l = \frac{s_1}{z_1}, \quad (2.26)$$

where the factor s_1 is the lowest common multiple (LCM) of the three intercepts x_1 , y_1 , z_1 . This is illustrated in Fig. 2.9, which shows the Miller indices for three of the major planes in the silicon lattice. If a plane has a negative intercept value, this is indicated with a bar over the corresponding Miller index. For example, a plane with the intercepts 1, -1, 2 is designated as $(\bar{2}\bar{2}1)$ plane.

There are some additional important points concerning the Miller index notation. In the FCC crystal structure, a direction that has the same h , k , l values in its Miller indices as a plane is perpendicular to that plane. Thus,

$[100]$, $[110]$, and $[111]$ directions are perpendicular to (100) , (110) , and (111) planes, as demonstrated in Fig. 2.9. There are directions and planes that are identical with respect to physical properties like channeling. For example, the directions $[100]$, $[010]$, $[001]$, $\bar{[100]}$, etc. are all equivalent and referred to as $\langle 100 \rangle$ directions, while the corresponding group of equivalent planes is designated as $\{100\}$ planes.

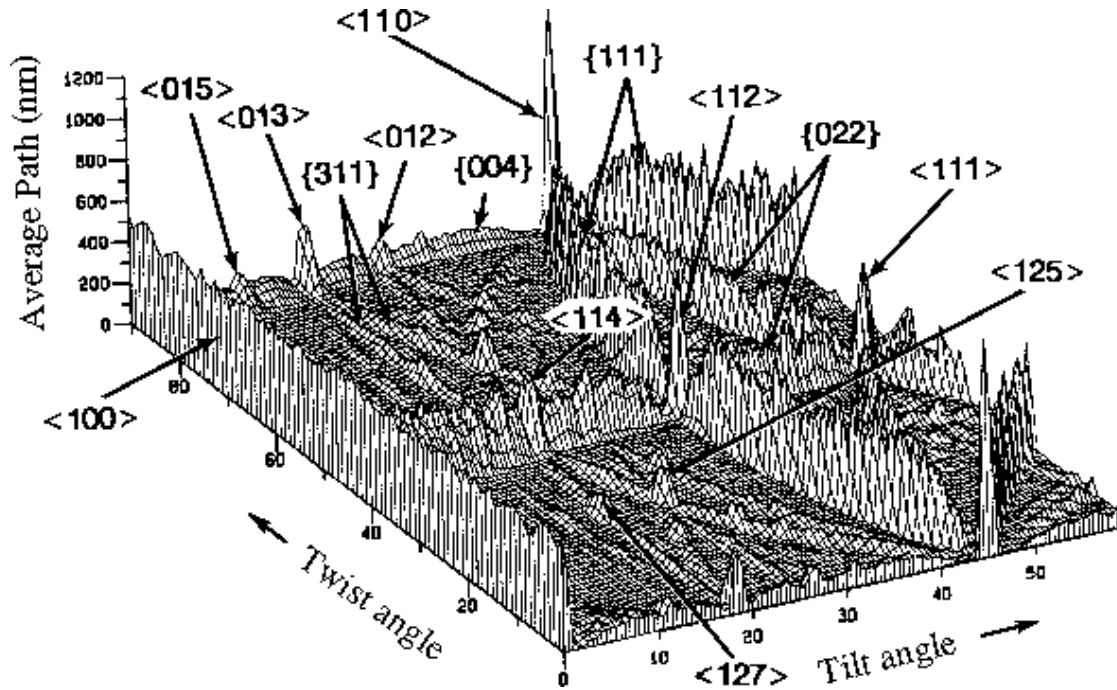


Figure 2.10: Simulated average path lengths of boron ions which are implanted with an energy of 100keV (Lever and Brannon [40]).

Channels exhibit a lower stopping power for the incoming ions since the atomic and electronic densities in the channels are considerably lower than elsewhere in the crystal. This means that ions which are moving along a channel have longer ranges than ions which are traveling in non-channeling directions. Channeling arises not only by the lower stopping power in the center of the channel but also by a focusing effect due to the atoms at the edges of the channel [41]. Lever and Brannon have performed comprehensive investigations of boron channeling in silicon in the region 0° - 60° tilt from the $\langle 100 \rangle$ axis in order to identify the major axial and planar channels [40]. The strongest channeling occurs due to the $\langle 110 \rangle$ axial channel which produces the two peaks at 45° tilt, 0° twist and at 45° tilt, 90° twist in Fig. 2.10. Other major channels appear in the $\langle 111 \rangle$ direction (planar channel), and in $\langle 100 \rangle$ direction (axial channel). It can also be observed that the effect of tilt angle is much stronger than that of the twist angle. For instance, a tilt of 7° and a twist of 22° can be used to minimize the channeling of ions.

Channeling is a significant phenomenon for implantation energies from 1keV up to several MeV. In the lower energy regime a larger deflection of an ion occurs even when the ion is traveling near the center of the channel [40]. This behavior is a direct consequence of the fact that the effective radius of silicon atoms along the channel increases as the ion energy is reduced. At a low enough energy the effective radii of the silicon atoms defining the channel become large enough to block that channel. Channeling can be reduced by a screening layer or by pre-amorphization. An amorphous layer, preferable silicon dioxide, can be deposited on the crystalline substrate to scatter the implanted ions. The pre-amorphization implant is performed before the desired implant in

order to destroy the crystal structure of the substrate. Preferred ion species are silicon, germanium, or xenon. Both methods were investigated by simulation studies in [42].

2.2.3 Process Parameters for Ion Implantation

The ion implantation process is mainly determined by the following five process parameters:

- dopant species,
- ion beam energy,
- implantation dose,
- and tilt and twist angles.

The simplest semiconductor device is the pn-junction diode which can be easily formed by ion implantation. Fig. 2.11 illustrates a typical n^+/p -doping profile which is formed by a p-well implant followed by the n^+ -implant with its maximum concentration near the surface.

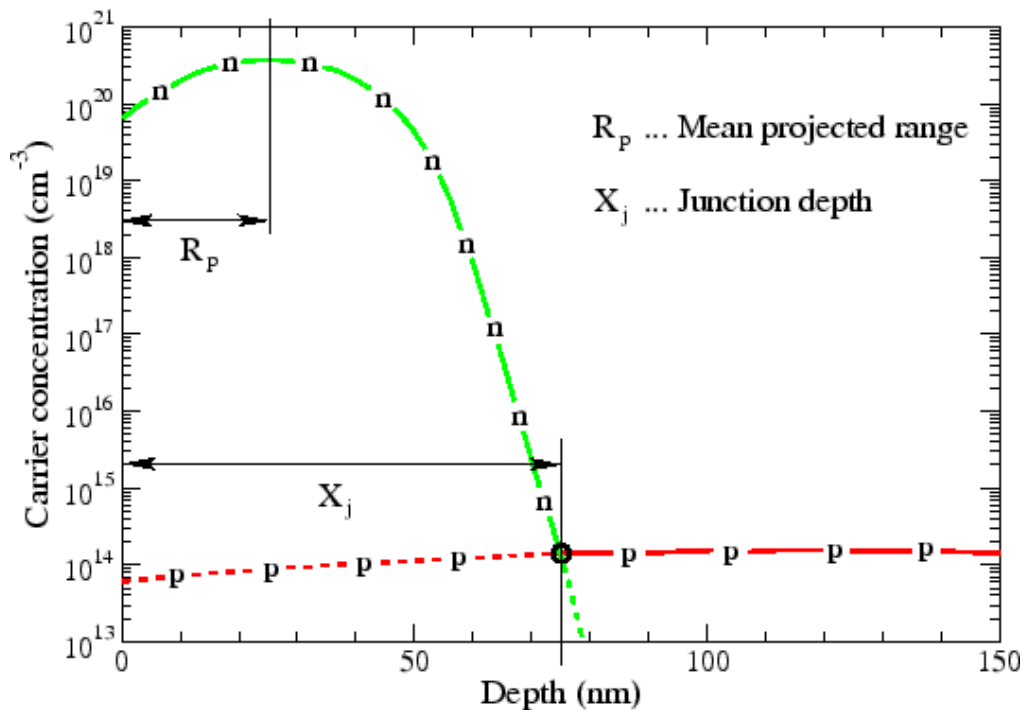


Figure 2.11: Typical implant doping profiles for pn-junction formation.

Table 2.3: Physical properties of common impurities in silicon.

Species	Type	Atomic number	Mass (amu)	Comment
Antimony	n	51	120.904	Small diffusion coefficient
Arsenic	n	33	74.922	Box-like profiles
Boron	p	5	11.009	Strong channeling effect
Germanium	-	32	71.922	Bandgap engineering
Phosphorus	n	15	30.974	Well formation

Silicon	-	14	27.977	Pre-amorphization
Xenon	-	54	131.3	Pre-amorphization

Ion implantation is a random process, because each ion follows an individual trajectory which is determined by the interactions with the atoms and electrons of the target material. The final position of an implanted ion is reached where it has lost its kinetic energy. The average depth of the dopant distribution is referred to as the mean projected range R_p . The junction depth X_j is the point where the donor and acceptor concentrations are equal, as shown in Fig. 2.11.

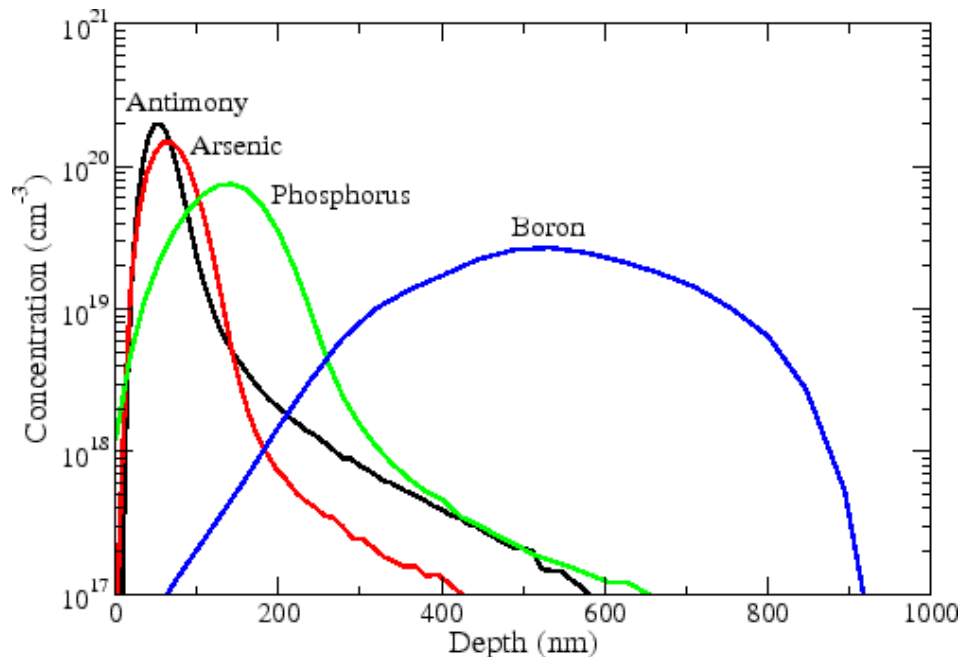


Figure 2.12: Simulated distribution of dopant ions implanted in crystalline silicon with an energy of 100keV and a dose of 10^{15} cm^{-2} .

Dopant Species

Several dopant species are used for ion implantation applications. Table 2.3 summarizes some properties of the most important dopants for CMOS technology. Arsenic, phosphorus, and sometimes antimony are used for n-type doping, while the common p-type dopant is boron. The distribution of these dopants are compared in Fig. 2.12, using equal implantation dose and energy. The profiles were simulated with the ion implantation simulator. If different ions are implanted with the same energy, heavy ions like antimony stop at a shallower depth than the light ions. The very light boron atom has the largest projected range R_p and the broadest

distribution, since a deeper penetration gives rise for more random collision events. Sometimes electrically inactive species like silicon or germanium are implanted before the boron implant to form an amorphous layer beneath the surface which suppresses the channeling effect for boron. Amorphizing pre-implants by germanium facilitate the forming of ultra-shallow junctions for the p-MOSFET, not only by controlling channeling, since germanium also reduces significantly the boron diffusion during the subsequent RTA annealing step. Shallower boron profiles can also be obtained by implanting molecular ion species like BF_2 or $\text{B}_{10}\text{H}_{14}$. The

disadvantage of the molecular ion implantation is that additional impurities are introduced.

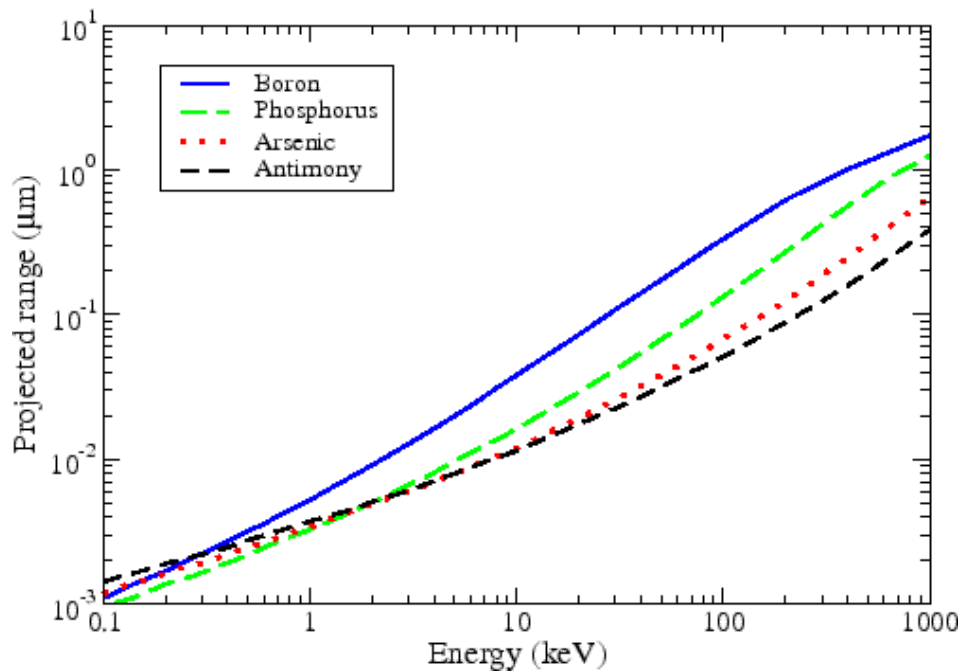


Figure 2.13: Projected range R_p for dopant atoms in amorphous silicon versus energy.

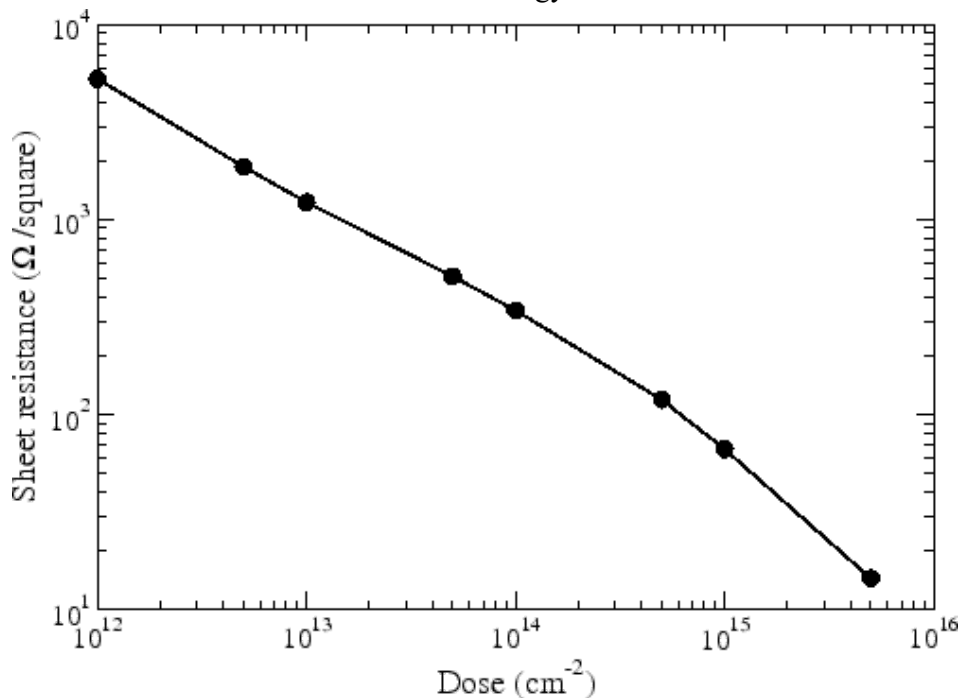


Figure 2.14: The sheet resistance was measured by Cypress Semiconductor for RTA annealed wafers using the Prometrix four-point probe.

Ion Energy and Dose

The ion energy controls mainly the penetration depth of ions, and the amount of implanted ions is given by the dose, expressed in ions/cm². In modern semiconductor technology, the energy ranges from 100eV to 3MeV, and the dose from 10¹¹ to 10¹⁶ ions/cm². Energies below a few keV at a high dose are used for the formation of ultra-shallow junctions. Energies in the medium range are applied for poly doping or for channel engineering like threshold voltage adjust or halo implant. Higher energies are required for some low dose applications like

retrograde wells. Within the energy range for each doping application, lower mass species are typical implanted at lower energies than heavier species. The dose of the application depends on device design requirements and is independent of the dopant species. The process parameters energy and dose can be controlled very accurately by electrical measurements. A modern implanter guarantees a deviation in energy below 1%. The beam current is a measure of the flow of charged particles, whereby $1\mu\text{A}$ beam current corresponds to $6.25 \cdot 10^{12}$ ions/s. The ion beam is turned off by the dose integrator when it has counted the desired number of ions.

Fig. 2.13 shows the experimentally determined mean projected range R_p of the most important dopant species as a function of the implantation energy [43,44,16,45]. The R_p values are extracted from profiles measured by secondary ion mass spectrometry (SIMS). Note that the R_p data are averaged since SIMS data exhibit a wide variation in results and only amorphous target materials are commonly used to identify the R_p versus energy dependence. In Fig. 2.13 it can be observed that the projected range of an ion is larger for lower mass species. Therefore, boron has the largest projected range of all investigated dopants, while antimony has the shortest projected range. An exception of this rule can be observed for arsenic and antimony at lower energies. This effect arises because the stopping power is dominated by nuclear stopping in the low energy regime, while it is dominated by electronic stopping in the high energy regime (as described in Section 3.1.3). Antimony has the maximum position of the nuclear stopping power at a slightly higher energy than arsenic which results in a lower stopping power below 5keV (inverse region) and a larger R_p , respectively.

The total dose Q can be calculated by numerical integration of the dopant concentration profile $C(z)$ from the wafer surface to at least the junction depth X_j ,

$$Q = \int_0^{\infty} C(z) dz \approx \int_0^{X_j} C(z) dz . \quad (2.27)$$

Fig. 2.14 shows the sheet resistance R_s versus dose ($R_s \propto \frac{1}{Q}$). The concept of sheet resistance is often used to characterize doped layers. The resistance R of a rectangular block of uniformly doped material with resistivity ρ , length L , width W , and thickness T_{Si} can be written as

$$R = R_s \cdot \frac{L}{W} , \quad \text{with} \quad R_s = \frac{\rho}{T_{Si}} . \quad (2.28)$$

However, to avoid confusion between R and R_s , the sheet resistance is specified in the unit of "Ohm per square" ($\Omega/\square$). The L/W ratio, defined by the unmasked implantation area, can be thought of as the number of unit squares of material in the ion implanted resistor. The maximum reasonable dose around 10^{16} cm^{-2} for the formation of highly conductive regions is determined by the solid solubility of the dopant species in the semiconductor material. At dopant concentrations higher than the solid solubility a part of the dopants cannot be activated, because they precipitate and form immobile clusters during the subsequent RTA annealing process.

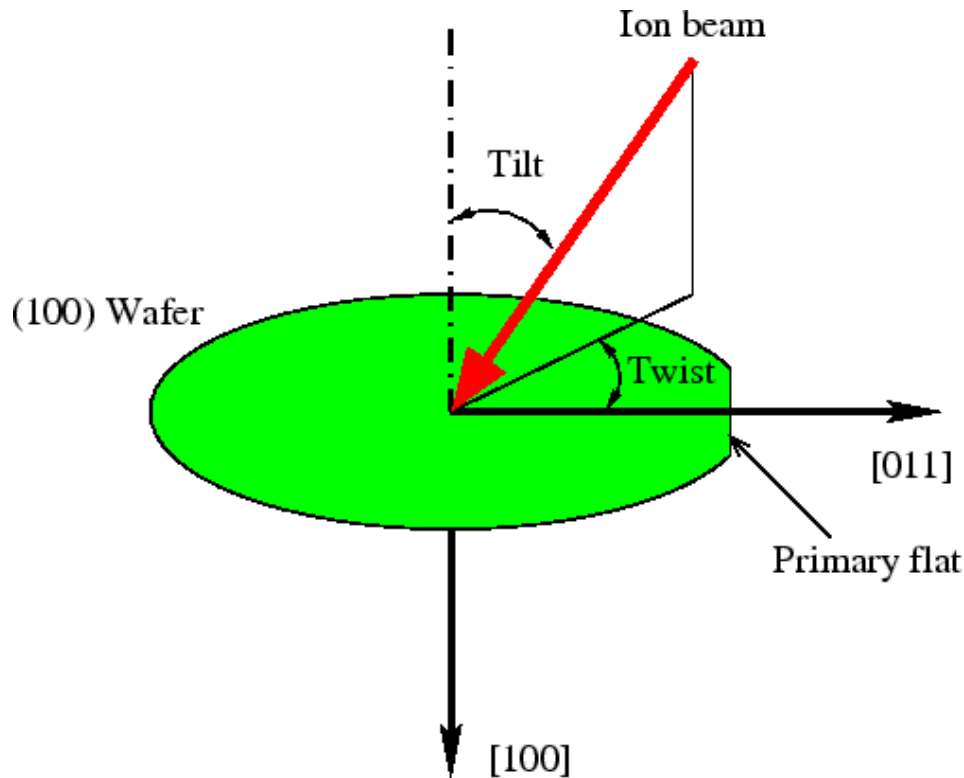


Figure 2.15: Definition of tilt and twist angle for the ion beam [17].

Tilt and Twist Angle

The direction of incidence of the ion beam with respect to the wafer crystal orientation is defined by the tilt and twist angle, as shown in Fig. 2.15. The tilt is the angle between the ion beam and the normal to the wafer surface. Wafer rotation or twist is defined as the angle between the plane containing the beam and the wafer normal, and the plane perpendicular to the primary flat of the wafer containing the wafer normal. The primary flat defines the orientation of the silicon crystal, which is aligned to a $[011]$ direction in a (100) oriented wafer.

The Miller index notation for describing directions and planes in the crystal lattice system is explained in Section 2.2.2. An appropriate tilt and twist can be used to minimize the channeling effect. Large tilt angles are required in some implantation applications, for instance, in halo implants.

There are two silicon crystal orientations that are used in IC manufacturing, (100) and (111) silicon [28], which means that the crystal terminates at the wafer surface on $\{100\}$ or $\{111\}$ planes, respectively. Primarily because of the superior electrical properties of the (100) Si/SiO₂ interface, (100) wafers are dominant in manufacturing today.

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