

5 / Ion Implantation

Ion implantation offers many advantages over diffusion for the introduction of impurity atoms into the silicon wafer and has become a workhorse technology in modern integrated-circuit fabrication. In this chapter we will first discuss ion implantation technology and mathematical modeling of the impurity distributions obtained with ion implantation. We will subsequently explore deviations from the model caused by nonideal behavior and will discuss annealing techniques used to remove crystal damage caused by the implantation process.

5.1 IMPLANTATION TECHNOLOGY

An ion implanter is a high-voltage particle accelerator producing a high-velocity beam of impurity ions which can penetrate the surface of silicon target wafers. The basic parts of the system, shown schematically in Fig. 5.1, are described in detail below, beginning with the impurity-source end of the system.

1. **Ion Source.** The ion source operates at a high voltage (25 kV) and produces a plasma containing the desired impurity as well as other undesired species. Arsine, phosphine, and diborane, as well as other gases, can be used in the source. Solids can be sputtered in special ion sources, and this technique offers a wide degree of flexibility in the choice of impurity.
2. **Mass Spectrometer.** An analyzer magnet bends the ion beam through a right angle to select the desired impurity ion. The selected ion passes through an aperture slit into the main accelerator column.
3. **High-Voltage Accelerator.** The accelerator column adds energy to the beam (up to 175 keV) and accelerates the ions to their final velocity. Both the accelerator column and the ion source are operated at a high voltage relative to the target. For protection from high voltage and possible X-ray emission, the ion source and accelerator are mounted within a protective shield.

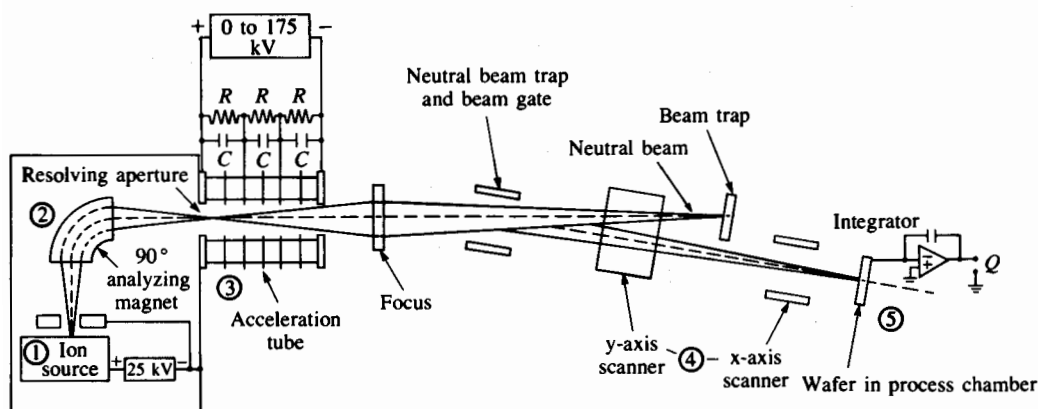


Fig. 5.1 Schematic drawing of a typical ion implanter showing (1) ion source, (2) mass spectrometer, (3) high-voltage accelerator column, (4) x- and y-axis deflection system, and (5) target chamber.

4. **Scanning System.** X- and y-axis deflection plates are used to scan the beam across the wafer to give a uniform implantation and to build up the desired dose. The beam is bent slightly to prevent neutral particles from hitting the target.
5. **Target Chamber.** Silicon wafers serve as targets for the ion beam. For safety, the target area is maintained near ground potential. The complete implanter system is operated under vacuum conditions.

The analyzer magnet is used to select the desired impurity ions from the output of the source. A charged particle moving with velocity \vec{v} through a magnetic field \vec{B} will experience a force \vec{F} , given by

$$\vec{F} = q(\vec{v} \times \vec{B}) \quad (5.1)$$

The force will tend to move the particle in a circle, and the centrifugal force will balance \vec{F} . For the case where \vec{B} is perpendicular to \vec{v} , $q|\vec{v}||\vec{B}| = m|\vec{v}|^2/r$ where $m|\vec{v}|^2/2 = qV$ and V is the accelerator voltage. Thus the magnitude of the magnetic field \vec{B} may be adjusted to select an ion species with a given mass:

$$|\vec{B}| = \sqrt{(2mV/qr^2)} \quad (5.2)$$

The ion source in Fig. 5.1 operates at a constant potential (25 keV) so that the voltage V is known, and an ion species is selected by changing the dc current supplying the analyzer magnet. The selected impurity is then accelerated to its final velocity in the high-voltage column.

The silicon wafer is maintained in good electrical contact with the target holder, so electrons can readily flow to or from the wafer to neutralize the implanted ions. This electron current is integrated over time to measure the total dose Q from the implanter given by

$$Q = \int_0^T I dt / nqA \quad (5.3)$$

where I is the beam current in amperes, A is the wafer area, $n = 1$ for singly ionized ions and 2 for doubly ionized species, and T is the implantation time. The use of a doubly ionized species increases the energy capability of the machine by a factor of 2 since $E = nqV$.

The target wafers can be maintained at relatively low temperatures during the implantation. Low-temperature processing prevents undesired spreading of impurities by diffusion, which is very important in VLSI fabrication. Another advantage of ion implantation is the ability to use a much wider range of impurity species than possible with diffusion. In principle, any element that can be ionized can be introduced into the wafer using implantation.

A production-level ion implanter may cost from \$1 to \$2 million, and cost is its greatest disadvantage. However, the advantages of flexibility and process control have far outweighed the disadvantage of cost, and ion implantation is now used routinely throughout bipolar and MOS integrated-circuit fabrication.

5.2 MATHEMATICAL MODEL FOR ION IMPLANTATION

As an ion enters the surface of the wafer, it collides with atoms in the lattice and interacts with electrons in the crystal. Each nuclear or electronic interaction reduces the energy of the ion until it finally comes to rest within the target. Interaction with the crystal is a statistical process, and the implanted impurity profile can be approximated by the Gaussian distribution function illustrated in Fig. 5.2. The distribution is described mathematically by

$$N(x) = N_p \exp[-(x - R_p)^2 / 2 \Delta R_p^2] \quad (5.4)$$

R_p is called the *projected range* and is equal to the average distance an ion travels before it stops. The peak concentration N_p occurs at $x = R_p$. Because of the statistical nature of the process, some ions will be "lucky" and will penetrate beyond the projected range R_p , and some will be "unlucky" and will not make it as far as R_p . The spread of the distribution is characterized by the standard deviation, ΔR_p , called the *straggle*.

The area under the impurity distribution curve is the implanted dose Q , defined by

$$Q = \int_0^\infty N(x) dx \quad (5.5)$$

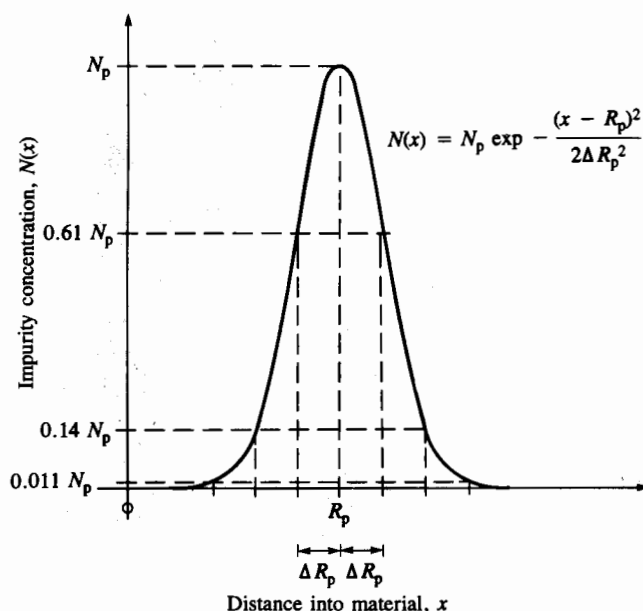


Fig. 5.2 Gaussian distribution resulting from ion implantation. The impurity is shown implanted completely below the wafer surface ($x = 0$).

For an implant completely contained within the silicon, the dose is equal to

$$Q = \sqrt{2\pi} N_p \Delta R_p \quad (5.6)$$

Implanted doses can range from $10^{10}/\text{cm}^2$ to $10^{18}/\text{cm}^2$, and ion implantation is often used to replace the predeposition step in a two-step diffusion process. Doses in the range of 10^{10} to $10^{13}/\text{cm}^2$ are required for threshold adjustment in MOS technologies and are almost impossible to achieve using diffusion. CMOS well formation is another example where the dose control of the ion implanter is a distinct advantage. Doses exceeding $10^{15}/\text{cm}^2$ are quite large and can be quite time-consuming to produce using ion implantation. As a reference for comparison, the silicon lattice atomic sheet density is approximately 7×10^{14} silicon atoms/ cm^2 on the $\langle 100 \rangle$ surface.

The implanted dose can be controlled within a few percent, and this tight control represents another advantage of ion implantation. For example, resistors can be fabricated with absolute tolerances of a few percent in carefully controlled processes using ion implantation, whereas the same resistors would have an absolute tolerance exceeding 20% if they were formed using only diffusion.

The projected range of a given ion is a function of the energy of the ion, and of the mass and atomic number of both the ion and the target material. A theory for range and straggle was developed by Lindhard, Scharff, and Schiott and is called the *LSS theory*.^[1]

This theory assumes that the implantation goes into an amorphous material in which the atoms of the target material are randomly positioned. Figure 5.3 displays the results of LSS calculations for the projected range and straggle for antimony, boron, phosphorus, and arsenic in amorphous silicon and silicon dioxide. For the moment we will assume that these results are also valid for crystalline silicon. Deviations from the LSS theory will be discussed in Section 5.5.

Range and straggle are roughly proportional to ion energy over a wide range, although some nonlinear behavior is clearly evident in Fig. 5.3. For a given energy, the lighter elements strike the silicon wafer with a higher velocity and penetrate more deeply into the wafer. The results indicate that the projected ranges in Si and SiO₂ are essentially the same, and we will assume that the stopping power of silicon dioxide is equal to that of silicon. Figure 5.3 also gives values for the transverse straggle ΔR_{\perp} , which will be discussed in the next section.

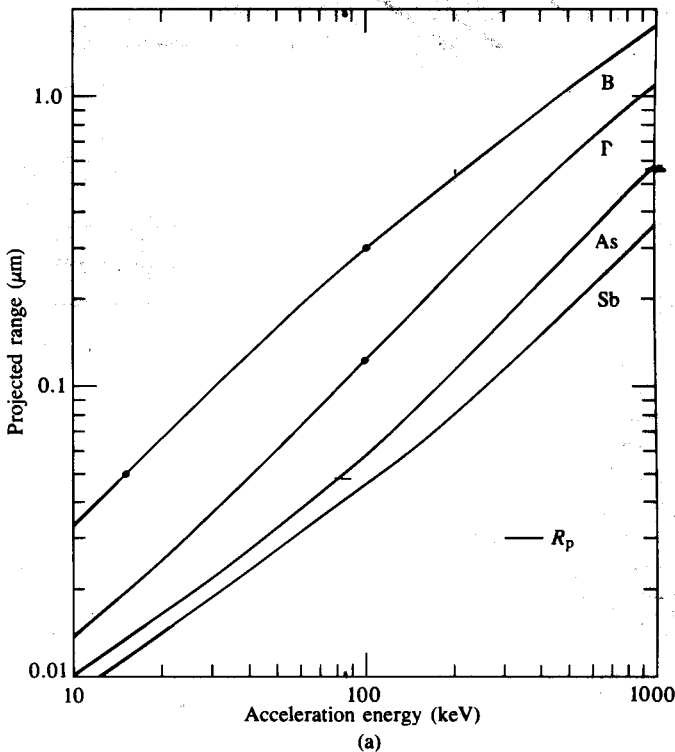


Fig. 5.3 Projected range and straggle calculations based on LSS theory. (a) Projected range R_p for boron, phosphorus, arsenic, and antimony in amorphous silicon. Results for SiO₂ and for silicon are virtually identical. (b) (On page 94) Vertical ΔR_p and transverse ΔR_{\perp} straggle for boron, phosphorus, arsenic, and antimony. Reprinted with permission from ref. [2].

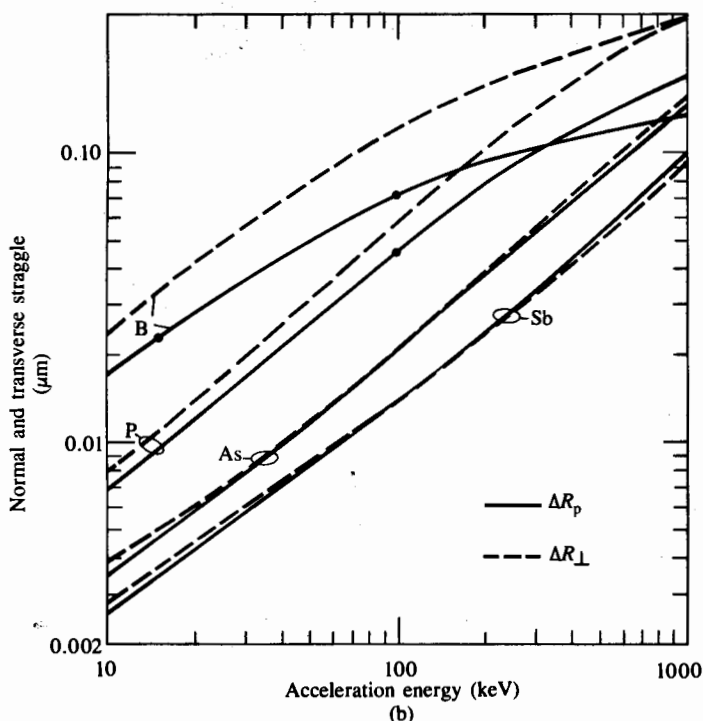


Fig. 5.3 (continued)

Example 5.1: Phosphorus with an energy of 100 keV is implanted into a silicon wafer. (a) What are the range and straggle associated with this implantation? (b) What should the implanted dose be if a peak concentration of $1 \times 10^{17}/\text{cm}^3$ is desired?

Solution: Using Fig. 5.3, the range and straggle are $0.12 \mu\text{m}$ and $0.045 \mu\text{m}$, respectively. The dose and peak concentration are related by eq. (5.6). Note that this is an approximation, since the peak is only a little over $2\Delta R_p$ below the silicon surface.

$$Q = \sqrt{2\pi} N_p \Delta R_p = \sqrt{2\pi} (1 \times 10^{17}/\text{cm}^3) (4.5 \times 10^{-6} \text{ cm}) = 1.13 \times 10^{12}/\text{cm}^2$$

5.3 SELECTIVE IMPLANTATION

In most cases we desire to implant impurities only in selected areas of the wafer. Windows are opened in a barrier material wherever impurity penetration is desired. In the center of the window the impurity distribution is described by eq. (5.4), but near the

edges the distribution decreases and actually extends under the edge of the window, as shown in Fig. 5.4. The overall distribution can be modeled by^[4]

$$N(x, y) = N(x)F(y)$$

$$F(y) = 0.5[\operatorname{erfc}\{(y - a)/\sqrt{2}\Delta R_{\perp}\} - \operatorname{erfc}\{(y + a)/\sqrt{2}\Delta R_{\perp}\}] \quad (5.7)$$

where $N(x)$ is given by eq. (5.4). The parameter ΔR_{\perp} is called the *transverse straggle* and characterizes the behavior of the distribution near the edge of the window. Figure 5.4 shows normalized impurity distributions near the barrier edge calculated with eq. (5.4). Figure 5.3b gives values of both normal straggle ΔR_p and transverse straggle ΔR_{\perp} .

In order to mask the ion implantation, it is necessary to prevent the implanted impurity from changing the doping level in the silicon beneath the barrier layer. Figure 5.5 shows a silicon wafer with a layer of silicon dioxide on the surface. An

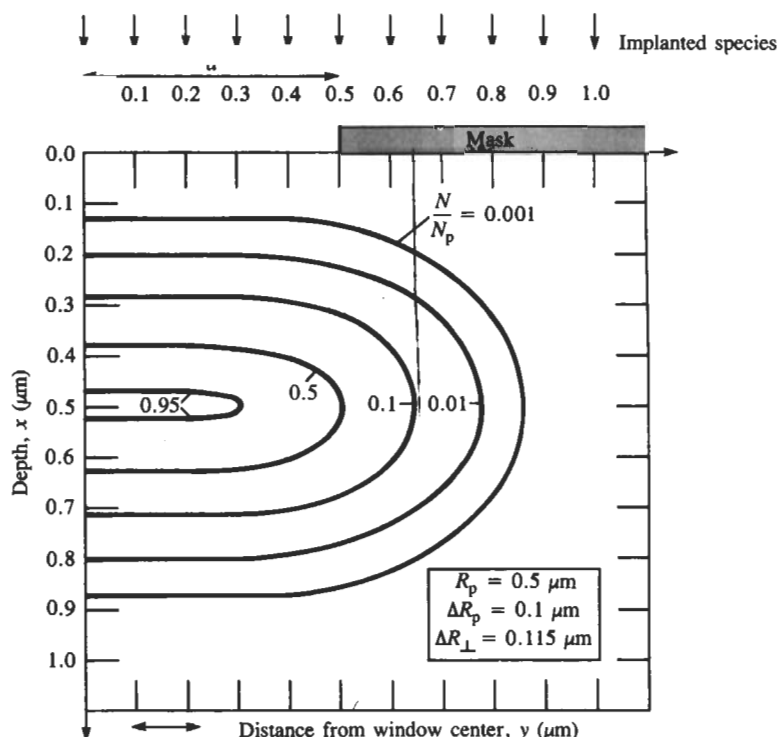


Fig. 5.4 Contours of equal ion concentration for an implantation into silicon through a 1- μm window. The profiles are symmetrical about the x -axis and were calculated using eq. (5.4), which is taken from ref. [4].

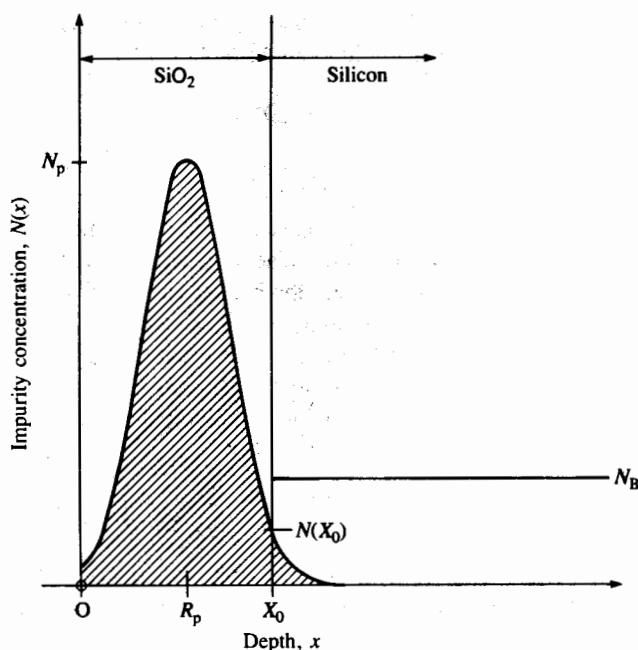


Fig. 5.5 Implanted impurity profile with implant peak in the oxide. The barrier material must be thick enough to ensure that the concentration in the tail of the distribution is much less than N_B .

impurity has been implanted into the wafer with the peak of the distribution in the silicon dioxide. To prevent significantly altering the doping in the silicon, we require that the implanted concentration be less than 1/10 the background concentration at the interface between the silicon and silicon dioxide:

$$N(X_0) < N_B/10$$

or

$$N_p \exp[-(X_0 - R_p)^2 / 2 \Delta R_p^2] < N_B/10 \quad (5.8)$$

Solving eq. (5.8) for X_0 yields a minimum oxide thickness of

$$X_0 = R_p + \Delta R_p \sqrt{2 \ln(10N_p/N_B)} = R_p + m \Delta R_p \quad (5.9)$$

The oxide thickness must be at least equal to the projected range plus some multiple m times the straggle. Table 5.1 gives values of m for various ratios of peak concentration to background concentration. An oxide thickness equal to the projected range plus six times the straggle should mask most ion implantations.

Table 5.1 Values of m for Various Values of N_p/N_B .

N_p/N_B	m
10^1	3.0
10^2	3.7
10^3	4.3
10^4	4.8
10^5	5.3
10^6	5.7

Silicon dioxide and silicon nitride are routinely used as barrier materials during implantation. Since implantation is a low-temperature process, additional materials such as photoresist and aluminum, which cannot withstand high-temperature diffusion, may be used as barrier materials during the implantation.

Silicon nitride is more effective than silicon dioxide in stopping ions, and a silicon nitride barrier layer need only be 85% of the thickness of an SiO_2 barrier layer. On the other hand, photoresist is less effective in stopping ions, and a photoresist barrier layer should be 1.8 times the thickness of an SiO_2 layer under the same implantation conditions. Metals are of such a high density that even a very thin layer will mask most implantations.

Example 5.2: A boron implantation is to be performed through a 50-nm gate oxide so that the peak of the distribution is at the Si-SiO₂ interface. The dose of the implant in silicon is to be $1 \times 10^{13}/\text{cm}^2$. (a) What are the energy of the implant and the peak concentration at the interface? (b) How thick should the SiO₂ layer be in areas which are not to be implanted, if the background concentration is $1 \times 10^{16}/\text{cm}^3$? (c) Suppose the oxide is 50 nm thick everywhere. How much photoresist is required on top of the oxide to completely mask the ion implantation?

Solution: The projected range needs to be $0.05 \mu\text{m}$ in order to place the peak of the distribution at the Si-SiO₂ interface. Using Fig. 5-3a, the R_p of $0.05 \mu\text{m}$ requires an energy of 15 keV. Since the peak of the implant is at the interface, the total dose will be twice the dose needed in silicon. The peak concentration is

$$N_p = Q/\Delta R_p \sqrt{2\pi} = 2 \times 10^{13}/(2.3 \times 10^{-6} \sqrt{2\pi}) = 3.5 \times 10^{18}/\text{cm}^3$$

where the straggle was found using Fig. 5-3b. In order to completely mask the implantation, the tail of the distribution must be less than the background concentration at the interface. The minimum oxide thickness is found using eq. (5.9):

$$X_0 = 0.05 + 0.023 \sqrt{2 \ln(10 \times 3.5 \times 10^{18}/10^{16})} \mu\text{m} = 0.14 \mu\text{m}$$

Since the oxide is $0.05 \mu\text{m}$ thick, the photoresist must provide a thickness equivalent to $0.09 \mu\text{m}$. The resist thickness must be 1.8 times the needed thickness of SiO₂ to provide

an equivalent barrier layer, so the photoresist should be at least $0.16\text{ }\mu\text{m}$ thick. This thickness requirement is easily met with most photoresist layers.

5.4 JUNCTION DEPTH AND SHEET RESISTANCE

Ion implantation is often used to form shallow pn junctions for various device applications. The implanted profile approximates a Gaussian distribution, and the junction depth may be found by equating the implanted distribution to the background concentration, as in Chapter 4.

$$N_p \exp[-(x_j - R_p)^2 / 2 \Delta R_p^2] = N_B$$

$$x_j = R_p \pm \Delta R_p \sqrt{2 \ln(N_p/N_B)} \quad (5.10)$$

Both roots may be meaningful, as indicated in Fig. 5.6, in which a deep subsurface implant has junctions occurring at two different depths, x_{j1} and x_{j2} .

Example 5.3: Boron is implanted into an n -type silicon wafer to a depth of $0.3\text{ }\mu\text{m}$. Find the location of the junction if the peak concentration is $1 \times 10^{18}/\text{cm}^3$ and the doping of the wafer is $3 \times 10^{16}/\text{cm}^3$.

Solution: From Fig. 5.3a, the implant energy is 100 keV. From Fig. 5.3b, the straggle is $0.07\text{ }\mu\text{m}$. Equating the Gaussian distribution to the background concentration yields

$$3 \times 10^{16} = 10^{18} \exp -(x_j - R_p)^2 / 2 \Delta R_p^2$$

or

$$x_j = R_p \pm 2.65 \Delta R_p$$

This yields junction depths of $0.12\text{ }\mu\text{m}$ and $0.49\text{ }\mu\text{m}$.

The peak of an implantation is often positioned at the silicon surface. For this special case, we may use Irvin's curves for Gaussian distributions to find the sheet resistance of the implanted layer, as discussed in Chapter 4. These curves may also be used to find the sheet resistance of a layer which is completely below the surface (see Problem 5.4). Note that an implanted Gaussian impurity distribution will remain Gaussian through any subsequent high-temperature processing steps.

Diffused profiles generally have the maximum impurity concentration at the silicon surface. Ion-implantation techniques can be used to produce profiles with subsurface peaks or "retrograde" profiles which decrease toward the wafer surface. Multiple implant steps at different energies can also be used to build up more complicated impurity profiles.

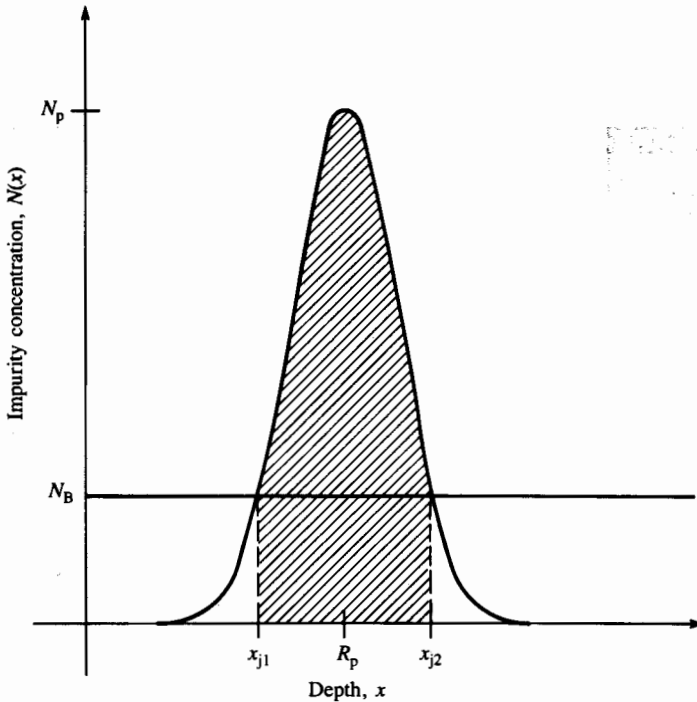


Fig. 5.6 Junction formation by impurity implantation in silicon. Two pn junctions are formed at x_{j1} and x_{j2} .

5.5 CHANNELING, LATTICE DAMAGE, AND ANNEALING

5.5.1 Channeling

The LSS results of Section 5.2 are based on the assumption that the target material is amorphous, having a completely random order. This assumption is true of thermal SiO_2 , deposited Si_3N_4 and SiO_2 , and many thin metal films, but it is not valid for a crystalline substrate. The regular arrangement of atoms in the crystal lattice leaves a large amount of open space in the crystal. Figure 5.7 shows a view through the silicon lattice in the $\langle 110 \rangle$ direction. If the incoming ion flux is improperly oriented with respect to the crystal planes, the ions will tend to miss the silicon atoms in the lattice and will “channel” much more deeply into the material than the LSS theory predicts. However, electronic interactions will eventually stop the ions.

The effects of channeling are demonstrated in Fig. 5.8. Phosphorus has been implanted at an energy of 40 keV into a silicon target with several orientations of the ion beam relative to the $\langle 100 \rangle$ silicon surface. The appearance of a random target can be achieved by tilting $\langle 100 \rangle$ silicon approximately 7° relative to the incoming beam. The results are represented by the x 's in Fig. 5.8. The range for this case compares well with

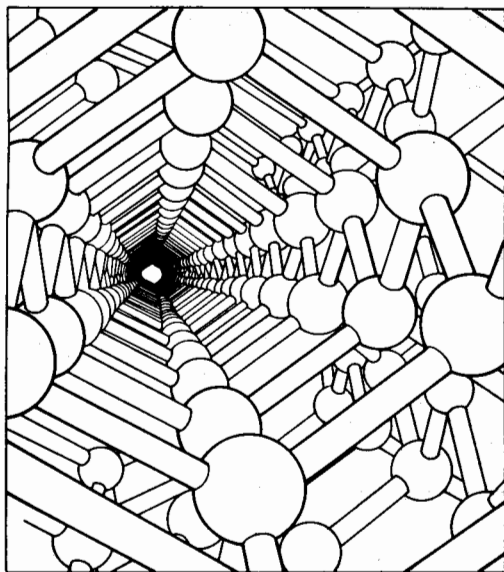


Fig. 5.7 The silicon lattice viewed along the $\langle 110 \rangle$ axis. From *THE ARCHITECTURE OF MOLECULES* by Linus Pauling and Roger Hayward. Copyright © 1964 W. H. Freeman and Company. Reprinted with permission from refs. [3a] and [3b].

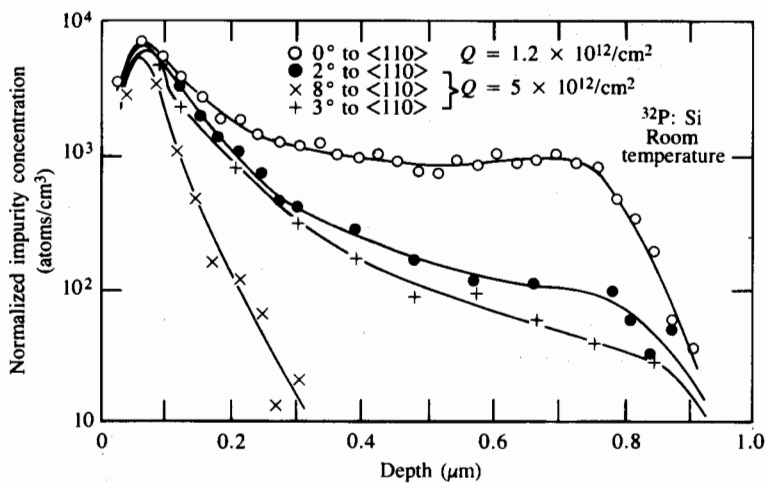


Fig. 5.8 Phosphorus impurity profiles for 40-keV implantations at various angles from the $\langle 110 \rangle$ axis. Copyright 1968 by National Research Council of Canada. Reprinted with permission from ref. [5].

the LSS calculations presented in Fig. 5.3. The open circles represent the boron profile implanted perpendicular to the $\langle 100 \rangle$ surface. Note that the range for the "channeled" case is almost twice that predicted by the LSS theory. Results for two other angles of incidence are given in Fig. 5.8, showing progressively less channeling as the angle is increased.

5.5.2 Lattice Damage and Annealing

During the implantation process, ion impact can knock atoms out of the silicon lattice, damaging the implanted region of the crystal. If the dose is high enough, the implanted layer will become amorphous. Figure 5.9 gives the dose required to produce an amorphous silicon layer for various impurities as a function of substrate temperature. The heavier the impurity, the lower the dose required to create an amorphous layer. At sufficiently high temperatures, an amorphous layer can no longer be formed.

Implantation damage can be removed by an "annealing" step. Following implantation, the wafer is heated to a temperature between 800 and 1000 °C for approximately 30 min. At this temperature, silicon atoms can move back into lattice sites, and impurity atoms can enter substitutional sites in the lattice. After the annealing cycle,

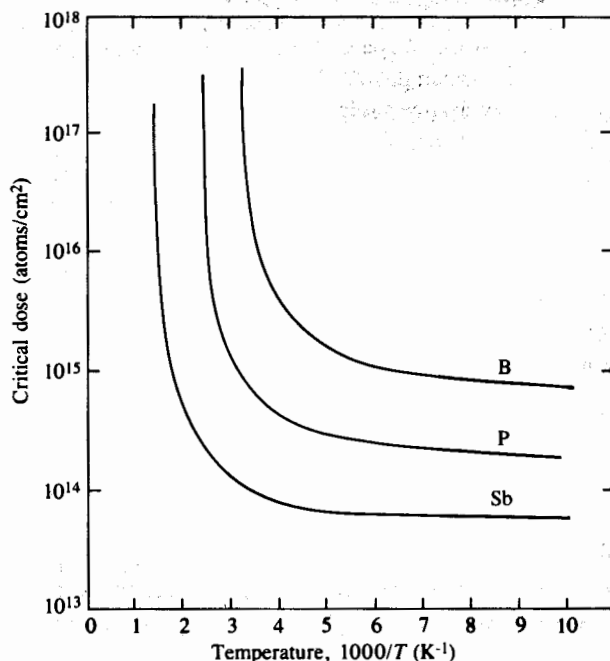


Fig. 5.9 A plot of the dose required to form an amorphous layer on silicon versus reciprocal target temperature. Arsenic falls between phosphorus and antimony. Copyright 1970 by Plenum Publishing Corporation. Reprinted with permission from ref. [6].

nearly all of the implanted dose becomes electrically active, except for impurity concentrations exceeding $10^{19}/\text{cm}^3$.

Annealing cycles for 30 min at temperatures approaching 1000°C can cause considerable spreading of the implant by diffusion. It has been found that truly amorphous layers can actually be annealed at lower temperatures through the process of solid-phase epitaxy. The crystalline substrate seeds recrystallization of the amorphous layer, and epitaxial growth can proceed as rapidly as $500 \text{ \AA}/\text{min}$ at 600°C . During solid-phase epitaxy, impurity atoms are incorporated into substitutional sites, and full activation is achieved at low temperatures.

Low-energy arsenic implantations produce shallow amorphous layers that can be annealed using solid-phase epitaxy to yield shallow, abrupt junctions that are ideal for VLSI structures. Boron, however, is so light that it does not produce an amorphous layer even at relatively high doses, unless the substrate is deliberately cooled (see Fig. 5.9). Today, boron is often implanted using ions of the heavier BF_2 molecule. The lower-velocity implant results in shallow layers that can be annealed under solid-phase-epitaxy conditions.

5.5.3 Deviations from the Gaussian Theory

If we take a detailed look at the shape of the implanted impurity distribution, we find deviations from the ideal Gaussian profile. When light ions, such as boron, impact atoms of the silicon target, they experience a relatively large amount of backward scattering and fill in the distribution on the surface side of the peak, as in Fig. 5.10. Heavy atoms, such as arsenic, experience a larger amount of forward scattering and tend to fill in the profile on the substrate side of the peak. A number of methods have been proposed for mathematical modeling of this behavior, such as the use of Pearson Type-IV distributions.^[8] However, for common implant energies below 200 keV, the Gaussian theory provides a useful model of the impurity distribution. This is particularly true since the forward and backward scattering tend to alter the tails of the distribution where the concentration is well below the peak value.

5.6 SUMMARY

Ion implantation uses a high-voltage accelerator to introduce impurity atoms into the surface of the silicon wafer, and it offers many advantages over deposition by high-temperature diffusion. Ion implantation is a low-temperature process minimizing impurity movement by diffusion, which has become very important to VLSI fabrication. Low-temperature processing also permits the use of a wide variety of materials as barrier layers to mask the implantation. Photoresist, oxide, nitride, aluminum, and other metal films can all be used, adding important increased flexibility to process design.

Ion implantation also permits the use of a much wider range of impurity species than diffusion. In principle, any element that can be ionized can be introduced into the wafer using implantation. Implantation offers much tighter control of the dose introduced into

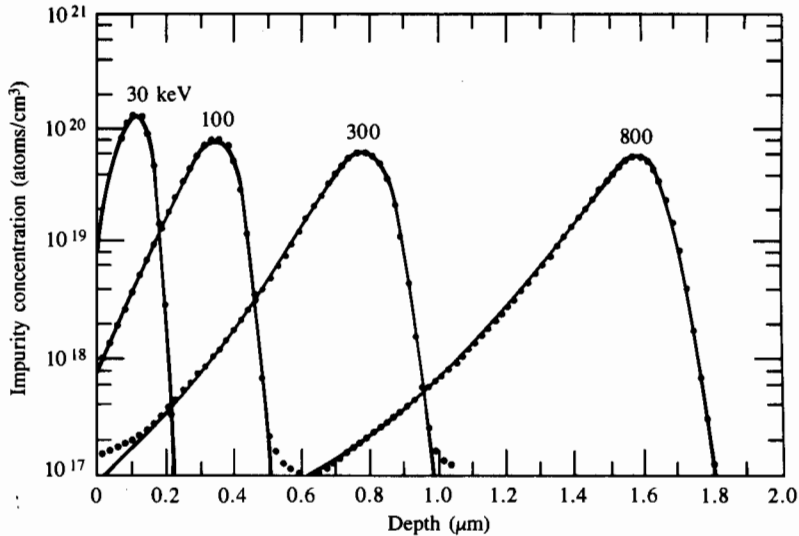


Fig. 5.10 Measured boron impurity distributions compared with four-moment (Pearson IV) distribution functions. The boron was implanted into amorphous silicon without annealing. Reprinted with permission from Philips Journal of Research.^[8]

the wafer, and a much wider range of doses can be reproducibly achieved than possible with diffusion.

Diffused profiles almost always have the maximum impurity concentration at the surface. Ion-implantation techniques can be used to produce new profiles with subsurface peaks or retrograde profiles which decrease toward the wafer surface. Implantation can introduce impurities into very shallow layers near the surface, again a significant advantage for VLSI structures.

The main disadvantage of ion implantation is the cost of the equipment, which may exceed \$2 million for a production machine. Also, the ion implanter has trouble achieving high doses ($>10^{16}/\text{cm}^3$) in a time reasonable for high-volume production. New high-current machines are being developed to overcome this latter problem. Overall, the flexibility and process control achievable with ion implantation have far outweighed the disadvantage of cost, and ion implantation is used routinely for state-of-the-art bipolar and MOS integrated-circuit fabrication.

Ion implantation results in profiles which can be modeled by a Gaussian distribution. The depth and width of the distribution depend on both the ion species and the energy of the implantation. In order to prevent channeling, implantation is normally performed at an angle of approximately 7° off the normal to the surface.

The implantation process damages the surface, and an annealing step is required to remove the effects of the damage. Low doses may result in the need for annealing at 800 to 1000 $^\circ\text{C}$ for 30 min. However, if the surface layer has become amorphous, annealing can be achieved through solid-phase epitaxy at temperatures of only 600 $^\circ\text{C}$.

REFERENCES

- [1] J. Lindhard, M. Scharff, and H. Schiott, "Range Concepts in Heavy Ion Ranges," *Mat.-Fys. Med. Dan. Vid. Selsk.*, 33, No. 14, 1963.
- [2] J. F. Gibbons, W. S. Johnson, and S. W. Mylroie, *Projected Range in Semiconductors*, Second Edition, Dowden, Hutchinson, and Ross, New York, 1975.
- [3] (a) L. Pauling and R. Hayward, *The Architecture of Molecules*, W. H. Freeman, San Francisco, 1964. (b) S. M. Sze, Ed., *Semiconductor Devices Physics and Technology*, McGraw-Hill, New York, 1985.
- [4] S. Furukawa, H. Matsumura, and H. Ishiura, "Lateral Distribution Theory of Implanted Ions," in S. Namba, Ed., *Ion Implantation in Semiconductors*, Japanese Society for the Promotion of Science, Kyoto, p. 73 (1972).
- [5] G. Dearnaley, J. H. Freeman, G. A. Card, and M. A. Wilkins, "Implantation Profiles of ^{32}P Channeled into Silicon Crystals," *Canadian Journal of Physics*, 46, 587-595 (March 15, 1968).
- [6] F. F. Morehead and B. L. Crowder, "A Model for the Formation of Amorphous Si by Ion Implantation," p. 25-30, in Eisen and Chadderton (see Source Listing 4).
- [7] B. L. Crowder and F. F. Morehead, Jr., "Annealing Characteristics of n -type Dopants in Ion-Implanted Silicon," *Applied Physics Letters*, 14, 313-315 (May 15, 1969).
- [8] W. K. Hofker, "Implantation of Boron in Silicon," *Philips Research Reports Supplements*, No. 8, 1975.
- [9] J. F. Gibbons, "Ion-Implantation in Semiconductors—Part I: Range Distribution Theory and Experiment," *Proceedings of the IEEE*, 56, 295-319 (March, 1968).
- [10] J. F. Gibbons, "Ion Implantation in Semiconductors—Part II: Damage Production and Annealing," *Proceedings of the IEEE*, 60, 1062-1096 (September, 1972).
- [11] T. Hirao, G. Fuse, K. Inoue, S. Takayanagi, Y. Yaegashi, S. Ichikawa, and T. Izumi, "Electrical Properties of Si Implanted with As Through SiO_2 Films," *Journal of Applied Physics*, 51, 262-268 (January, 1980).

SOURCE LISTING

- (1) J. W. Mayer, L. Eriksson, and J. A. Davies, *Ion-Implantation in Semiconductors*, Academic Press, New York, 1970.
- (2) G. Dearnaley, J. H. Freeman, R. S. Nelson, and J. Stephen, *Ion-Implantation*, North-Holland, New York, 1973.
- (3) G. Carter and W. A. Grant, *Ion-Implantation of Semiconductors*, John Wiley & Sons, New York, 1976.
- (4) F. Eisen and L. Chadderton, Eds., *Ion Implantation in Semiconductors*, First International Conference (Thousand Oaks, CA), Gordon and Breach, New York, 1970.
- (5) I. Ruge and J. Graul, Eds., *Ion Implantation in Semiconductors*, Second International Conference (Garmisch-Partenkirchen, West Germany), Springer-Verlag, Berlin, 1972.
- (6) B. L. Crowder, Ed., *Ion Implantation in Semiconductors*, Third International Conference (Yorktown Heights, NY), Plenum, New York, 1973.
- (7) S. Namba, Ed., *Ion Implantation in Semiconductors*, Fourth International Conference (Osaka, Japan), Plenum, New York, 1975.
- (8) F. Chernow, J. Borders, and D. Bruce, Eds., *Ion Implantation in Semiconductors*, Fifth International Conference (Boulder, CO), Plenum, New York, 1976.

PROBLEMS

5.1 Boron is implanted with an energy of 60 keV through a 0.25- μm layer of silicon dioxide. The implanted dose is $1 \times 10^{14}/\text{cm}^2$.

- Find the boron concentration at the silicon-silicon dioxide interface.
- Find the dose in silicon.
- Determine the junction depth if the background concentration is $3 \times 10^{15}/\text{cm}^3$.

5.2 An arsenic dose of $1 \times 10^{12}/\text{cm}^2$ is implanted through a 50-nm layer of silicon dioxide with the peak of the distribution at the Si-SiO₂ interface. A silicon nitride film on top of the silicon dioxide is to be used as a barrier material in the regions where arsenic is not desired. How thick should the nitride layer be if the background concentration is $1 \times 10^{15}/\text{cm}^3$?

5.3 An implantation will be used for the predeposition step for a boron base diffusion. The final layer is to be 5 μm deep with a sheet resistance of 125 ohms per square ($N_B = 10^{16}/\text{cm}^3$).

(a) What is the dose required from the ion implanter if the boron will be implanted through a thin silicon dioxide layer so that the peak of the implanted distribution is at the silicon-silicon dioxide interface?

(b) What drive-in time is required to produce the final base layer at a temperature of 1100 °C?

5.4 (a) Use Irvin's curves to find the sheet resistance of a boron layer implanted completely below the surface in n -type silicon ($N_B = 10^{15}/\text{cm}^3$). Assume the layer has a peak concentration of $1 \times 10^{19}/\text{cm}^3$, and the range and straggle are 1.0 μm and 0.11 μm , respectively. (Hint: Think about conductors in parallel.)

(b) What is the dose of this implantation?

(c) What was the energy used for this ion implantation?

(d) At what depths are pn junctions located?

5.5 The source and drain regions of a self-aligned n -channel polysilicon-gate MOS transistor are to be formed using arsenic implantation. The dimensions of a cross section of the device are given in Fig. P5.5. Calculate the channel shrinkage caused by lateral straggle if the peak concentration of the implantation is $10^{20}/\text{cm}^3$ and the substrate doping is $10^{16}/\text{cm}^3$. Assume that the channel region is in the silicon immediately below the oxide. Use $R_p = 0.1 \mu\text{m}$, $\Delta R_p = 0.04 \mu\text{m}$, and $\Delta R_{\perp} = 0.022 \mu\text{m}$.

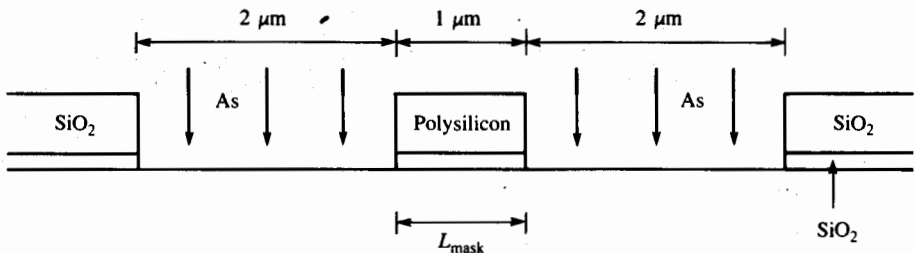


Fig. P5.5

5.6 An implanted profile is formed by two boron implantations. The first uses an energy of 100 keV and the second an energy of 200 keV. The peak concentration of each distribution is $5 \times 10^{18}/\text{cm}^3$. Draw a graph of the composite profile and find the junction depth(s) if the phosphorus background concentration is $10^{16}/\text{cm}^3$. What are the doses of the two implant steps.

5.7 A high energy (5 MeV) is used to implant oxygen deep below the silicon surface in order to form a buried SiO_2 layer. Assume that the desired SiO_2 layer is to be $0.2 \mu\text{m}$ wide.

(a) What is the oxygen dose required to be implanted in silicon?

(b) What beam current is required if a 125-mm-diameter wafer is to be implanted in 15 min?

(c) How much power is being supplied to the ion beam? Discuss what effects this implantation may have on the wafer.

5.8 The threshold voltage of a NMOS transistor may be increased by ion implantation of boron into the channel region. For shallow implantations, the voltage shift is given approximately by $\Delta V_T = qQ/C_{\text{ox}}$ where Q is the boron dose and $C_{\text{ox}} = \epsilon_0/X_0$. X_0 is the oxide thickness and ϵ_0 is the permittivity of silicon dioxide: $3.9 \times (8.854 \times 10^{-14} \text{ F/cm})$. What boron dose is required to shift the threshold by 0.75 V if the oxide thickness is 40 nm?

5.9 An ion implanter has a beam current of $10 \mu\text{A}$. How long does it take to implant a boron dose of $10^{15}/\text{cm}^2$ into a wafer with a diameter of 125 mm?

5.10 Write a computer program to calculate the sheet resistance of an arbitrary Gaussian layer in silicon.