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Article

Effect of Low-Energy Ion Implantation on Semiconductors

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Abstract: This paper provides a physical definition of the concept of ion implantation and a schematic of an ion implantation setup. It is shown that the key parameters for determining ion implantation modes are the energy of accelerated ions and the irradiation dose. The results demonstrate that ions exhibit significant lateral scattering, which leads to changes in the size of the selective implantation regions, where theory allows for the calculation of ion ranges in solids.

Keywords: ion doping, ion implantation, acceleration energy, irradiation dose, lateral direction, selectivity, surface.

Ion implantation is the process of introducing ions into a solid (target, substrate) with sufficient energy to penetrate the surface layers. The most common application of ion implantation is the ion implantation process in the fabrication of integrated circuits (ICs). The setup diagram is shown in Fig. 1.

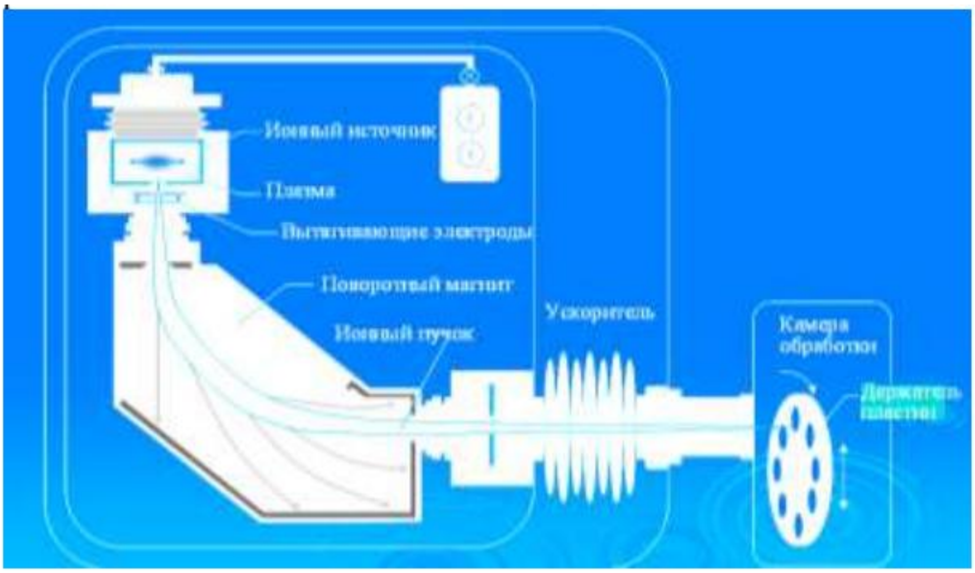

Fig. 1. Schematic diagram of the ion implantation setup

The ion implantation setup consists of: ion source; extractor (extraction electrodes); magnetic mass separator (rotating magnet); accelerating system; scanning system; substrate processing chamber. The ion source serves to ionize impurity molecules and form an ion beam. Ions are extracted from the ion source under the action of an accelerating potential *U*. In the separator, the ions move in a constant magnetic field. The magnetic induction vector is directed perpendicular to the plane of the drawing. The Lorentz force bends the ion trajectories along a radius R :

$$R = \frac{mv}{qB},$$

where m/q is the ratio of the mass of the ion to its charge;
V is the ion velocity ;
B is the magnitude of the magnetic field induction.
In turn, the speed of the ion is determined

$$v = \sqrt{\frac{2qU}{m}}.$$

Thus, only impurity ions of a certain type (m / q) and with constant energy pass along the radius R.

These ions irradiate a target (a silicon substrate). The parameters of the ion implantation setup are: ion energies are 50–300 keV, and irradiation doses Q range from 10^{13} to 10^{17} ion/cm ^{2}.

The classification of installations (implanters) is given in Table 1.

Classification of implanters

Implanter parameter	Description
Average beam current	The beam current is less than 10 mA. The accelerating voltage is less than 180 keV. Typically, the substrate is stationary, and the beam is scanned (this is simpler and cheaper).

The beam current is high	Beam current 10–25 mA. High-dose implantation. Acceleration voltage less than 120 keV. The substrate is scanned, and the beam is stationary, since the electric field does not fully penetrate the beam.
The accelerating voltage is high	Acceleration voltage of 200–3000 keV. Ions can penetrate deep trenches and thick oxide layers. Formation of deep pockets and buried layers is possible .
Oxygen and hydrogen implanters	High current devices used for high dose oxygen or hydrogen implantation

When determining ion implantation modes, the key parameters are the energy of accelerated ions and the radiation dose. An ion with a charge q, under the influence of a potential difference U, acquires an energy

$$E_0 = qU.$$

In general, the charge of an ion is determined by q ne , where n is the ionization multiplicity, which is usually n 1, 2, or 3; e is the electron charge.

To indicate the ionization multiplicity, the "+" sign is used: $^{31}p^{+}$, $^{31}p^{++}$, $^{31}p^{+++}$.

The number 31 denotes the atomic mass of the phosphorus ion. Sometimes, molecular ions, rather than monoatomic ones, are used for implantation, for example: $^{14}N_2^{+}$– a singly ionized nitrogen molecule with an atomic mass of 14 and a molecular weight of 28, or BF_2^{+}– an ionized triatomic boron fluoride molecule.

Molecular ions, when introduced into a crystal, usually immediately disintegrate into individual atoms. To calculate the energy of each atom with mass M_1, which is part of an accelerated ion with molecular mass M_m, the following relationship is used:

$$E_1 = E_0 \frac{M_1}{M_\text{м}}.$$

The irradiation dose (D) is determined by the ion current density j and the irradiation duration t : D jt [C/m2]. The value of D does not explicitly reflect the number of impurity ions, so it is customary to express the dose as the number of particles introduced per unit surface area:

$$Q = D/q = jt/en \quad [\text{ион/м}^2].$$

Interaction of ions with a solid: When ions move through a solid (target), they lose energy and change direction as a result of interaction with the crystal lattice. There are two types of interactions with the lattice: elastic and inelastic collisions.

Elastic (nuclear) collisions are those in which the ion's energy is transferred to the target atoms. They are discrete in nature and are accompanied by significant ion scattering.

Inelastic (electronic) collisions are those in which the ion's energy is transferred to the electrons. The energy transferred is relatively small, and ion deceleration can be considered a quasi-continuous process. Furthermore, due to the significant difference in mass between the ion and electron, inelastic losses are not accompanied by significant scattering of the primary ions. For the same reason, elastic energy losses of "heavy" ions (the ion mass is greater than the target atom mass) result in comparatively small scattering angles, and their trajectory is more linear than that of light ions (the ion mass is less than the target atom mass).

Losing their energy in atomic and electron collisions, the ions slow down and finally come to rest inside the target, creating implanted ions. Because the number of collisions and the energy transferred during collisions are variable quantities characterizing a random process, the ion penetration depth will not be uniform.

Ions with the same energy E_0, mass M_1 and atomic number Z_1 fall on the substrate surface and move along individual trajectories, which are shown for three ions in Fig. 2.

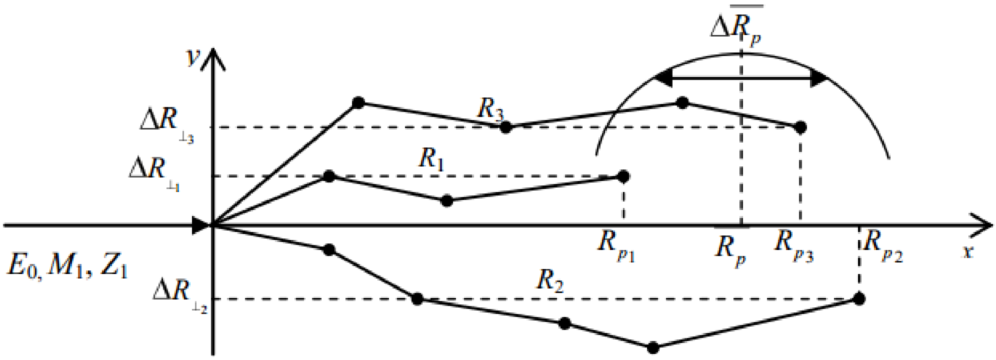

Fig. 2. Ion ranges in a solid

The path that the ions travel is called the total range – *R*. After deceleration, the ions stop at points whose positions are characterized by the projected ranges Rp^1, Rp^2, Rp^3.

Due to the random nature of collisions, the ranges of ions in semiconductors are distributed according to a certain statistical law (Gauss's law), which is characterized by the average projected range R_p and the standard deviation ΔR_p.

In practice, another very important parameter is ΔR – this is the projection of the runs onto the *y- axis* (lateral scattering).

The results of Monte Carlo calculations of 128 trajectories of boron ions B^+ (50 keV) implanted into silicon are shown in Fig. 3.

Fig. 3. Trajectory of boron ions in silicon

It is evident that the ions exhibit significant lateral scattering. This leads to a change in the size of the selective implantation regions.

A theory that allows the calculation of ion ranges in solids was developed by Lindhard , Scharf, and Schiott (LSS).

The theory is based on the following assumptions:

1) solids with which ions interact are homogeneous, isotropic, with a disordered arrangement of atoms (amorphous target approximation);
2) elastic and inelastic interactions occur independently of each other (additivity principle);

In atomic collisions, ions lose energy much less than the initial energy of the ion , which allows us to apply a statistical approach to calculating the range of ions.

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