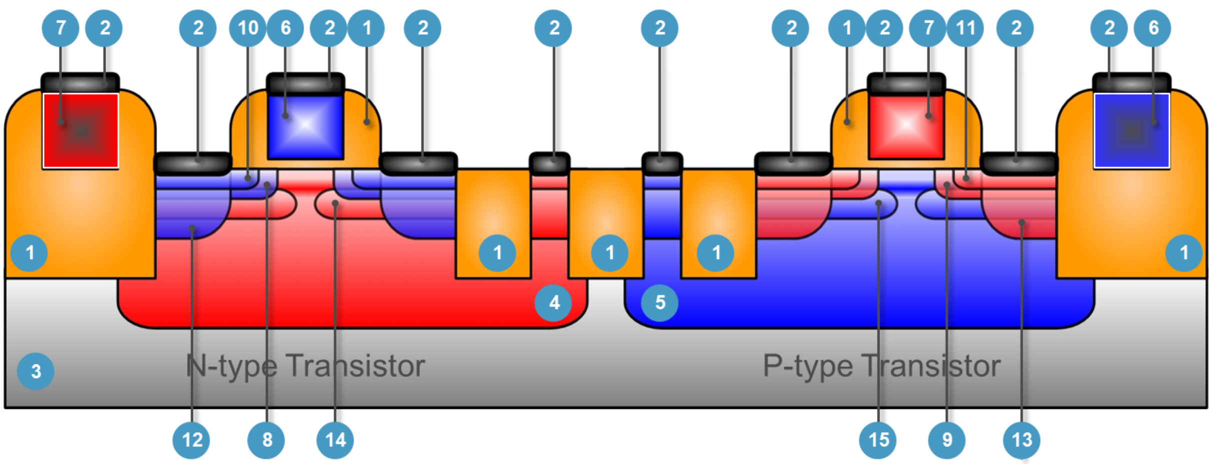
An Introduction to Ion Implantation

Ion implantation (a form of doping) is an integral part of integrated circuit manufacturing. Pioneered in the first half of the 20th century, this technology has become the dominant method of semiconductor doping. As the complexity of chips has grown, so has the number of implant steps. Today, a complementary metal oxide semiconductor (CMOS) integrated circuit with embedded memory may require up to 60 implants (Figure 1)

What is Ion Implantation?

An ion is an atom or molecule in which the number of electrons differs from the number of protons, giving it a negative or positive electrical charge. In ion implantation, a beam of positive ions (e.g., boron, arsenic, phosphorus, carbon, or germanium) is accelerated by means of intense electrical fields to penetrate the surface of a wafer, thus modifying the surface layer to control its electrical properties or modify its behavior during another process (e.g., an etch).



- 1 Trench/Oxide Layer
- 2 Salicide Contact
- 3 Substrate (Silicon)
- 4 P-Well/N-Channel
- 5 N-Well/P-Channel
- 6 N-Gate
- 7 P-Gate
- 8 N-Channel Halo
- 9 P-Channel Halo
- 10 NMOS Source Drain Extension
- 11 PMOS Source Drain Extension
- 12 NMOS Source/Drain
- 13 PMOS Source/Drain
- 14 N-Channel/Pocket
- 15 P-Channel Pocket

Figure 1. Fabricating today's complex chips can involve several dozen implant processes to promote or control current flow.

Two factors dictate the amount of energy required for an ion to penetrate the surface: host material properties and the depth to which the doping must extend to achieve the desired effect. For example, a resin or polymer will be much easier to penetrate than glass or metal. Depending on the application, ion energy can range from less than 1 keV to more than 3,000 keV. Penetration depth is also dependent on the angle of incidence of the incoming ions. The dose (or number of ions implanted in a given area) also varies widely by application and depends on the strength of the ion beam current and the duration of the process. Following implantation, the wafer is typically annealed (heated and cooled under controlled conditions) to activate the dopant atoms and repair physical damage to the crystal lattice of the host material.

Effects of Ion Implantation

Ion implantation commonly modifies the characteristics of the surface layer by introducing either p-type or n-type dopant ions into the host material. The objective of the material modification differs according to the location being doped. The implant can be precisely customized to reach specific areas within the die, using patterned photoresist mask to protect other regions of the die from the implant, thereby enabling local electrical modification to form various circuit device elements. In addition to photoresist, other films (e.g., polysilicon, oxide, nitride) deposited on the wafer can be used as mask layers.

P-type doping creates an abundance of “holes” (i.e., positive charge) by removing weakly bound outer electrons from the host material’s atoms when chemically bonding with them. The holes can enhance conductivity by acting as additional electrical charge carriers. N-type doping results in the release of an abundance of negatively-charged “free” electrons when bonding with the host material, which can also enhance conductivity. In other applications, these two types of doping can be used to minimize the occurrence of unwanted current flow [e.g., resistance to punch-through between source and drain (see Figure 1)].

How does Ion Implantation Work?

Ion implantation systems comprise four major components (Figure 2). These are an ion source; an electromagnet to shape, steer, and focus the ion beam; electromagnetic lenses that accelerate or decelerate the ions while further steering the beam; and metrology devices to measure the number of ions reaching the surface of the host material and their angles of incidence.

Within the source chamber, the dopant gas is subjected to an electrical current that causes “shedding” of electrons by the dopant atoms to produce positive ions. These positive ions are mixed with various other ionized species in the chamber and must, therefore, be filtered out for delivery to the wafer surface. This is readily done by means of magnetic and electrostatic fields.

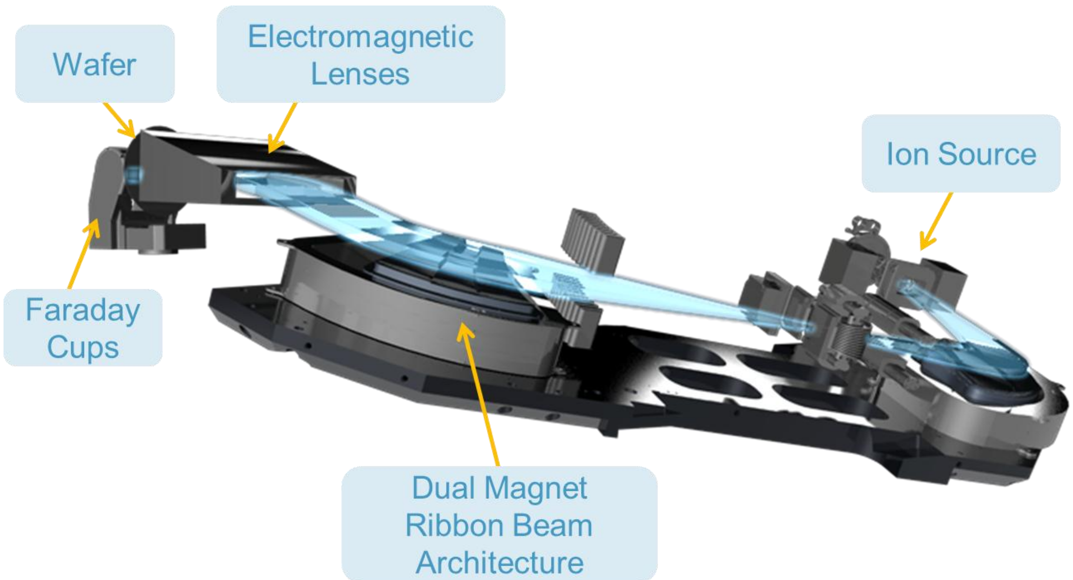


Figure 2. Ion implant systems use electromagnets and electrostatic lenses to filter out and steer the dopant ions from the source to the wafer surface, measuring ion density and angle of incidence using Faraday cups.

Depending on the ion weight or mass and charge, an “analyzer magnet” with a resolving aperture can be used to precisely select the correct ion from all the others generated in the source (Figure 3). The desired ion species at a specific mass, charge, and energy travel through the aperture unobstructed. The paths of species with a lighter mass, higher charge, or less energy are bent more and are removed. Species with a heavier mass, lower charge, or more energy are bent less and are also removed.

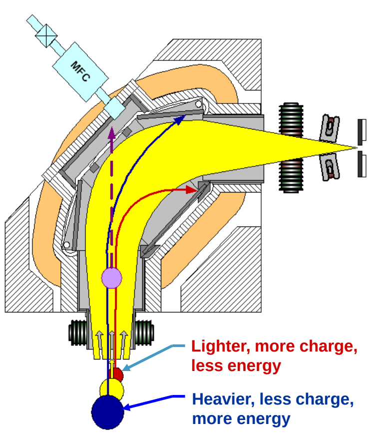


Figure 3. Magnet current is set to allow ions of a specific mass, charge, and energy to pass through the resolving aperture, while others are deflected.

As the beam leaves the analyzer magnet, electrostatic lenses or a second magnet manipulate the beam to spread it uniformly across the wafer and eliminate angular variation (between the ion beam path and the wafer surface), which would compromise performance of the semiconductor device. Besides ensuring exact parallelism of the incident beam, these components can also be used to accelerate or decelerate the incoming ions.

In most applications, doping must be as uniform as possible across the wafer, with wafer-to-wafer and lot-to-lot repeatability of equal importance. To monitor ion dose in real time, Faraday cups situated behind the wafer collect the incoming ion beam for very brief periods, giving the dose control system ongoing "snapshots" of the beam current as the beam scans across the wafer. Monitoring the beam current through a Faraday array as it rocks through various angular positions ensures the incident angle control required for accurate and repeatable implant angle (±0.1°) from recipe to recipe, system to system, and day to day.

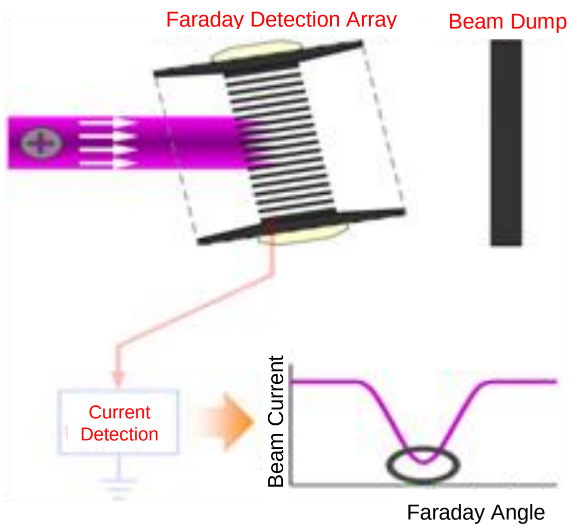


Figure 4. Controlling incident beam angle is essential for accurate and repeatable implant.

Types of Ion Implantation Systems

Four types of implant systems are used today to address the broad application space shown in Figure 5. Application ranges overlap, with cost and productivity considerations typically determining system choice.

High-current systems are used for low-energy and/or high-dose applications. High beam density and low-energy transport are important characteristics of high-current systems, which typically operate from 200eV to 60 or 80keV. Medium-current systems are used for lower dose applications and have the widest energy range (2keV up to 900keV) and highest mechanical throughput (up to 500wph). High-energy systems are characterized by their very deep implant capabilities, employing energy in the MeV range at relatively low doses.

Plasma-based implantation systems are used for applications requiring exceptionally high doses or for conformal doping of regions that cannot be reached with the line-of-sight beam line systems described above. Plasma implantation applications include sidewall doping in advanced devices, such as three-dimensional fin field effect transistors.

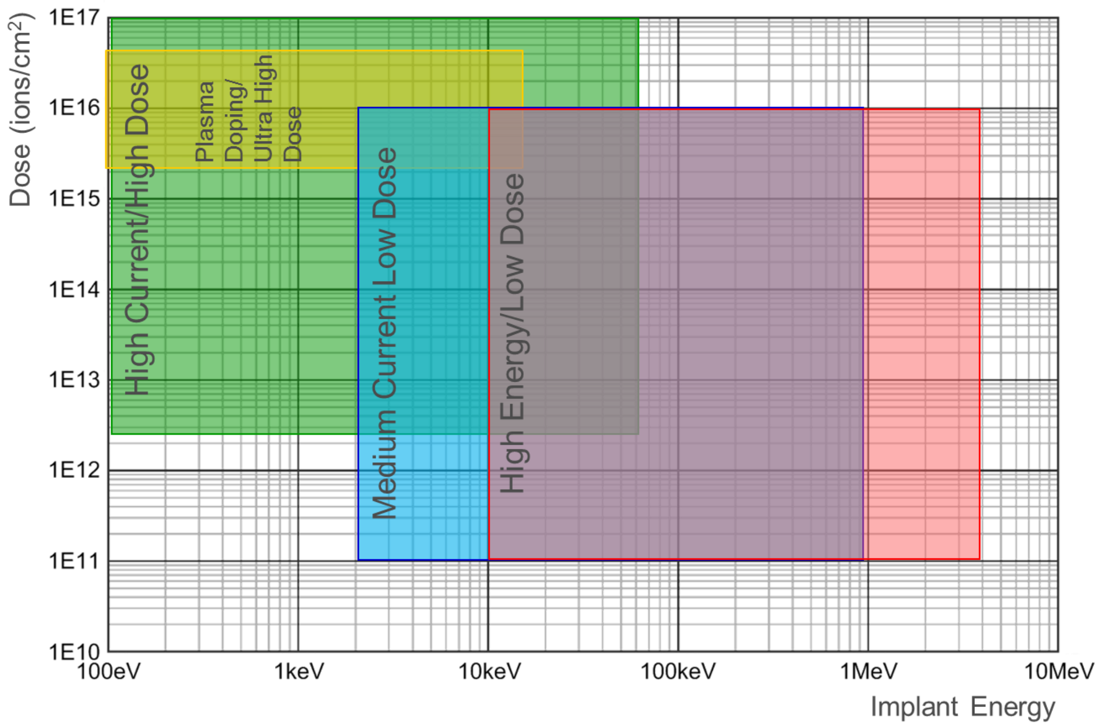


Figure 5. The wide range of dose and energy requirements for implant applications exceeds the Capability of one ion beam system; doping three-dimensional devices requires plasma-based technology.

Bibliography

Doering, R. and Nishi, Y, Ed., Handbook of Semiconductor Manufacturing Technology, Second Edition, CRC Press, Taylor and Francis Group LLC, Boca Raton, 2008, 1720 pp.

Ziegler, J. F., Ed. Ion Implantation: Science and Technology, Ion Implant Technology Co.: Edgewater, MD, 2000, 687 pp.

Ryssel, H. and Ruge, I. Ion Implantation, John Wiley and Sons: New York, 1986, 350 pp.