ION IMPLANTATION FOR SEMICONDUCTOR DEVICES: THE LARGEST USE OF INDUSTRIAL ACCELERATORS

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Abstract

Ion acceleration of dopants and other ions is a critical and nearly universally employed tool for the fabrication of transistors in semiconductor devices and the various forms of electronic, photovoltaic and photonic materials. This paper reviews the major types of accelerators, ion sources, and scanning methods used in contemporary practice for ion implantation for electronic applications.

INTRODUCTION

The use of accelerated ions to dope and modify semiconductor materials, generally called ion implantation, is a core technology for the fabrication of integrated circuits (IC), which form the backbone of the global communications and advanced computation capabilities that have transformed modern life over the last half-century. The use of ion implanters in the IC industry, starting in the 1970s for precision doping of channel structures at doping densities of $\sim 10^{-4}$ monolayers to set the threshold conditions for transistor switching, enabled the practical fabrication of complementary metal-oxide-semiconductor (CMOS) transistors that are now the dominant form of IC devices. Development of accelerator technologies capable of delivering highly stable and collimated ion beam currents, ranging from a few µA to 100 mA, and incident ion energies, ranging from 100 eV to ~10 MeV, have provided a broad and capable technology for fabrication of ICs for logic, memory, and analog operations, as well as an increasingly varied array of optical sensors and imaging devices. Ion implantation is now used for the overwhelming majority of applications for doping of semiconductor materials and in an increasing array of applications for creation and modification of electronic and photonic materials.

The yearly revenues from the sale of industrial ion implantation and materials modification tools are a US$1.5B market (in "normal" economic environments). In addition, there are substantial markets for suppliers of dopant species materials (~US$140M/year) and a diverse array of suppliers of spare and upgrade parts and services. Additional parts of the ion implantation commercial infrastructure include the suppliers of system components, magnets, power supplies, and vacuum pumps, and a varied array of metrology tools focused on process characterization and control applications.

The average number of commercial ion implantation systems sold per year, predominantly for fabrication of Si-based IC devices, has increased from ~250 to ~400 per year since 1980, as seen in Fig. 1. The year-to-year sales show large fluctuations due to the highly cyclic nature of IC fab construction trends, especially when driven by additional factors, such as shifts in dominant wafer sizes, introduction of new implanter machine types and IC devices, expansion into new global regions, and variations driven by general economic cycles. The combination of these technology and market factors has resulted in a rather steady "5-year" cycle in units sold per year over the last 3 decades.

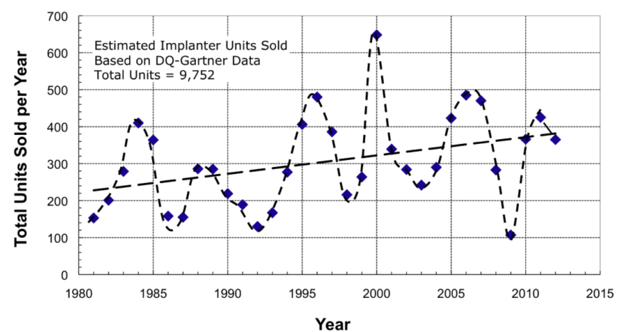

Figure 1: Estimates of the number of commercial ion implanters sold per year, mainly for IC fabrication. The data shown here are an underestimate, particularly for the earlier years.

SEMICONDUCTOR APPLICATIONS OF ION IMPLANTATION

The planar CMOS transistor, illustrated in Fig. 2, has been the workhorse device structure for IC devices for logic and memory applications since the mid-1980s.

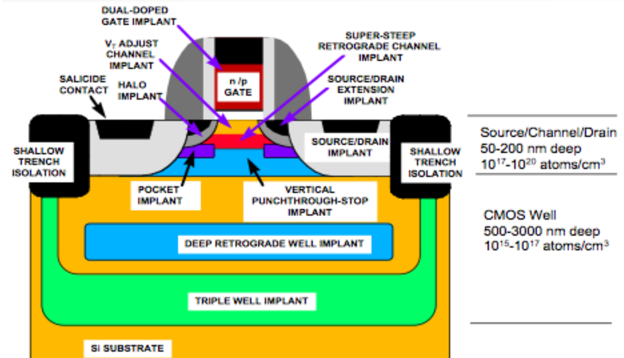

Figure 2: Sketch of major doped regions for a planar CMOS transistor.

For doping of near-surface (<100 nm) layers on Si with the common dopants B, As, and P, the beam energy

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requirement for atomic species is a fraction of a keV to a few tens of keV. Increasingly, the ion species of choice for low energy (sub-keV) implants is some form of molecular ion containing up to 18 dopant atoms (for $B_{18}H_{22}$), allowing for beamline operation at proportionally higher energies and significantly higher total beam flux for higher production throughputs. For deeper profiles to form CMOS wells for transistors and optical imagers, ion energies range up to several MeV.

The initial applications for ion implantation were for low dose (10^{11} to 10^{12} ions/cm^2) doping of CMOS channels to set the transistor switching, or "threshold", conditions. These implants required relatively modest beam currents, with 100 to 500 µA being common for "medium-current" implanters. By 1980, higher current sources and beamlines were developed for "high-current" machines, to produce beams of 1 to 30 mA of dopant ions. These machines were capable of efficient implants with doses of ~5×10^{15} ions/cm^2 used for CMOS source/drain junctions, as well as emitter, buried layer, and collector implants for bipolar devices.

By the late 1980s, implantation machines capable of ion energies of ~1-2 MeV were being used for doping deep "retrograde" wells in CMOS devices, to suppress latch-up instabilities between neighboring well structures and to reduce radiation-generated "soft failures" in Dynamic Random-Access Memory (DRAM) arrays. With the evolution of complex doping schemes to suppress lateral punch-through between source and drain junctions in short channel (<100 nm) transistors, ion implanters were developed with capabilities for mid-10^{14} ions/cm^2 doping at beam incidence angles up to 45°, to provide additional well doping in a "halo" surrounding shallow source-drain extension (SDE) junctions.

The CMOS transistors of the current decade are three-dimensional structures, called FinFETs or tri-gate transistors. The majority of implants for these devices continue to be the same, with over 40 implant steps per device for doping and materials modification applications. However, some of these implants, such as the source/drain extensions, need to be "conformal" in order to uniformly dope the sidewalls and top surface of the fins.

ACCELERATOR DESIGNS

Given the broad range of energies and doses in use for CMOS transistor doping and other materials processing, a variety of accelerators with quite different designs and beam scanning methods are used for each of the specific application segments shown in Fig. 3. The typical classifications for these general machine types are:

- Medium current — ion beam currents between 10 µA and ~2 mA
- High current — ion beam currents up to ~30 mA; ~100 mA for SIMOX (Separation by Implantation of Oxygen) beams
- High energy — ion energies above 200 keV and up to 10 MeV
- Very high dose — efficient implant of doses greater than 10^{16} ions/cm^2.

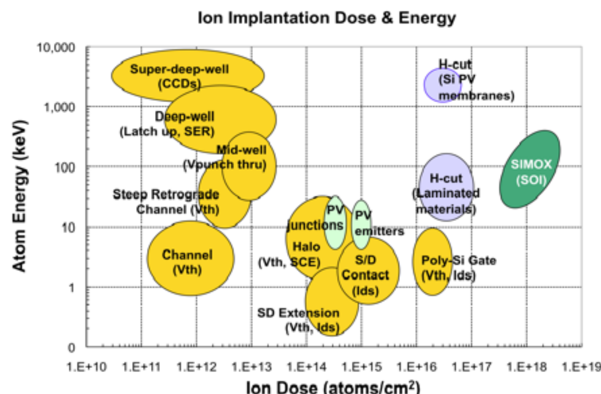

Figure 3: Dose and atom energy regions for CMOS transistor doping (gold), high dose hydrogen implants for Si layer splitting (lavender), and direct implantation of oxygen to form Silicon-on-Insulator (SOI) wafers (green).

Accelerator systems for ion implantation are provided commercially by a number of vendors, with the business being dominated by a few long-standing companies: Applied Materials/Varian Semiconductor Equipment (Gloucester, MA), the market leader; Nissin Ion Equipment (Kyoto, Japan), with a strong Asian market position; Advanced Ion Beam Technology (Hsinchu, Taiwan), a new high-current vendor; Axcelis Technologies (Danvers, MA), leading the high-energy market; and SEN Corporation (Shikoku, Japan), former Axcelis partner also with a strong Asian market presence. Other smaller vendors include Ion Beam Services (Rousset, France), a new Plasma Immersion Ion Implantation (PIII) and SiC implanter company; Ulvac Technologies (Japan), long-time vendor for research and development (R&D) tools; High Voltage Engineering (Netherlands) and National Electrostatics Corporation (Madison, WI), both supplying specialty R&D tools; and several radio frequency (RF) linac vendors known to be supplying R&D units for MeV proton beams for Si wafer cleaving for photovoltaic (PV) applications.

Beam current requirements for each machine type have increased as the wafer sizes and implanted areas increased from the early days of 75 mm diameter wafers to the present standard of 300 mm, with the contemplated increase to 450 mm after 2015. In addition, the increased requirements for dose accuracy (1% or better) and control of ion incidence angle (<0.5° for critical implants) place tight constraints on ion beam stability, scan uniformity, and beam collimation in the area near the wafer surface.

Beamline System Types

Each of the wide variety of ion implantation beamline designs contains certain general groups of functional components (see Fig. 4). The first major segment of an ion beamline includes a device known as an ion source to

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generate the ion species. The source is closely coupled to biased electrodes for extraction of the ions into the beamline and most often to some means of selecting a particular ion species for transport into the main accelerator section. The ion source usually is an arc-discharge plasma type, fed by a vapor of the atoms to be ionized, accelerated, and implanted. The "mass" selection is often accomplished by passage of the extracted ion beam through a magnetic field region with an exit path restricted by blocking apertures, or "slits", that allow only ions with a specific value of the product of mass and velocity/charge to continue down the beamline.

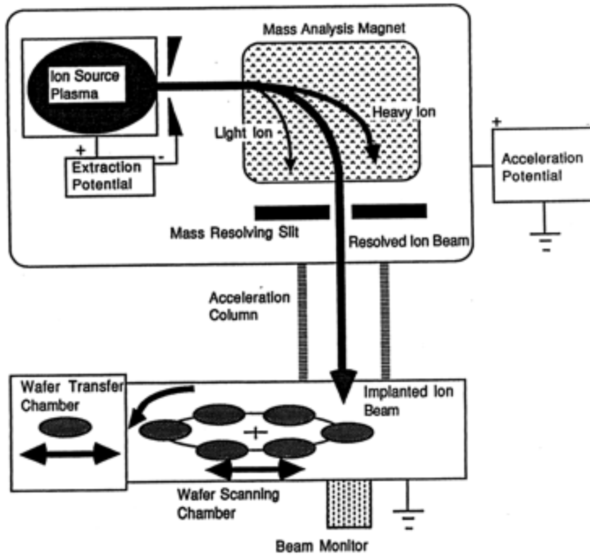

Figure 4: Major ion implantation beamline components.

If, as is often the case, the desired ion energy is different than the potential used to extract ions from the plasma source, the "selected" ion beam is accelerated (or decelerated) by additional sets of electrodes or RF fields. If the target surface is larger than the ion beam diameter and a uniform distribution of implanted dose is desired over the target surface, then some combination of beam scanning and wafer motion is used.

Finally, the implanted surface is coupled with some method for collecting the accumulated charge of the implanted ions, so that the delivered dose can be measured in a continuous fashion and the implant process can be stopped at the desired dose level. Sometimes the wafer is encased within a Faraday cup assembly, with appropriate methods of exclusion of extraneous charges from electrons and other ions within the beam plasma and charge losses due to secondary electrons and sputtered ions.

The design of an ion implantation beamline often needs additional components to satisfy the target requirements. These include components to make the scanned beam parallel at the surface of the target wafer and sources of electrons and ions to be injected into the ion beam plasma in the region close to the final target surface. These electrons and ions are needed to improve the space-charge balance in the ion beam, thus stabilizing the beam collimation and controlling the local potentials and current flows on the target surface.

The Varian VIISta 900XP [1], shown in Fig. 5, is an example of a medium-current beamline implanter with many of the components shown in Fig. 4. This beamline is capable of overall acceleration of single-charged ions to 300 kV (and P^{+3} ions to 900 keV) and contains a number of additional components, including a small deflection magnet and slit assembly placed directly after the source/extraction region and an electrode array for either accelerating or decelerating the selected ion beam prior to emerging from the main mass-selection (analyzer) magnet. The main function of the source filter magnet and slit is to prevent the P_2^+ and P_3^+ multimer ions (which can lead to energy and dose errors in P^{+2} and P^{+3} beams) from entering the main selection magnet and slit assembly and traveling to the target wafer.

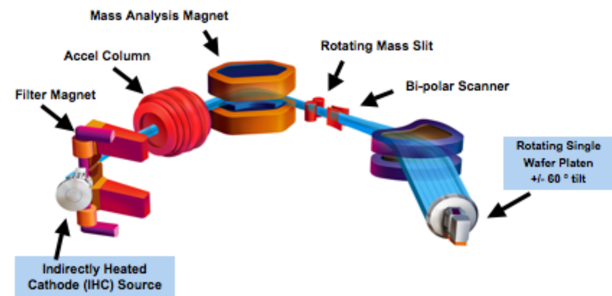

Figure 5: Beamline components of a Varian VIISta 900XP medium-current ion implanter.

Accel-Decel Beamlines

High-current beamlines, which are designed to maximize the ion flux delivered to the target wafer surface and often operate at low energies (1 keV or less), are usually shorter and contain fewer beamline components than medium-current designs. The short beamline path (often <2 m from source to wafer) and open geometries in the magnet analysis section result in improved ion transmission in "drift" mode with the only acceleration stage at the source extraction. To further increase the available ion flux for low energy (<1 keV) implants, an electrostatic deceleration lens is added just after the mass resolving slits. With the decel lens powered up, boron ion beams at energies as low as 0.2 keV can be delivered to the wafer surface with beam currents comparable to drift mode currents at 10x higher energies.

A limitation of this "accel-decel" mode of beam transport is that if dopant atom neutrals are formed by collisions with background gas molecules in the region following the mass analysis magnet and before the decel lens, neutral dopant atoms would be implanted at the extraction voltage energy along with the decelerated ions. This type of "energy contamination" is minimized by the operation of a turbopump in the region around the mass resolving slits (to reduce the ion neutralization rate from

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collisions with background gases) and by restricting the difference between the drift and decelerated ion energies.

Modulation of the ion energy along the beamline path is also a useful strategy to maximize beam transmission and facilitate beam shaping and focus. In the example of the AMAT/VSE VIISta Trident HC high-current implanter beamline shown in Fig. 6, a ribbon-shaped beam is formed by the extraction electrodes and focused at a mass resolving slit ("ion selection aperture") located downstream from the 90° mass analysis magnet [2]. The beam is then directed and shaped by another downstream magnet, prior to being implanted into a wafer scanned up and down in the ribbon beam. The ion beam can be decelerated at two stages along the way: directly after the mass resolving slits and after the final beam-shaping magnet.

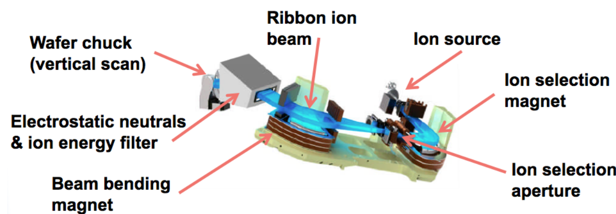

Figure 6: Example of advanced beamline architecture (AMAT/VSE VIISta Trident HC), which includes an inclined beamline, a neutrals and final ion energy filter just before the wafer, and a horizontally uniform ribbon beam for implanting a vertically scanned 300mm wafer that can be cryogenically cooled.

In a sophisticated combination of beam optics and system design, the AIBT high-current implanter, shown in Fig. 7, uses a number of electrodes to decelerate and deflect low-energy ions in a vertical ribbon beam along a "chicane" path (similar to turns in motorcycle racing tracks), before they emerge in front of the wafer scanning position [3]. Neutral dopant atoms that enter the decel stage continue undeflected into a beam trap. When higher energy ions are desired, the ribbon beam is switched back to a straight beam bath, thus bypassing the chicane decel electrode assembly.

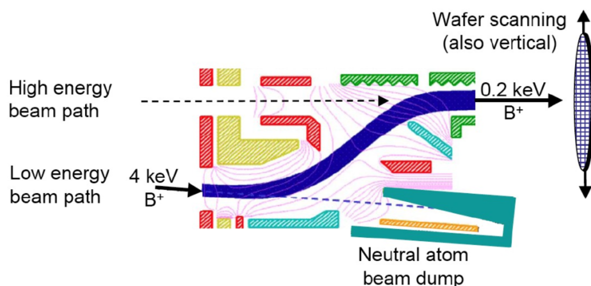

Figure 7: Schematic top view of the "chicane" beam path for deceleration of a vertical ribbon beam in the AIBT iPulsar high current implanter with a beam dump for neutral atom contaminants.

MeV Beamlines

When high-energy ions (>200 keV to several MeV) are needed, variations on either tandem or linear accelerators, developed in the 1930s for nuclear physics research, are used. In the tandem approach, multiple changes in the ion charge state along the beam path are induced to obtain a multiplication of the acceleration by a DC high-voltage potential, as seen in Fig. 8. First, positive ions are extracted from a plasma source and passed though a metallic vapor stream in order to form a beam of negative ions via collisional electron pickup. After undergoing mass selection in a magnet and slit assembly, the desired negative ions are accelerated toward a positive potential region, usually encased within a pressurized SF_6 atmosphere to allow for isolation of high potentials (up to several MV) in a compact chamber. At the center of this tandem beamline, the fast negative ions pass through a high level of Ar gas atoms, resulting in collisional charge exchange that transforms the negative ion beam to positive charged ions with various charge states. As the positive ions leave this shielded charge exchange region, they are accelerated away from the high positive potential in the center of the tandem. Single-charged positive ions leave the tandem beamline with a kinetic energy equal to twice the center positive potential. Double-charged positive ions have a final energy of three times the center potential. Useful, although low level, dopant beam currents with charge states up to +4 (with energy equal to 5 times the center potential) can be obtained for some ions with commercial tandem implanters. A magnetic selector segment placed at the exit of the tandem accelerator section allows only the ions with a desired charge state (and energy) to be passed to the target wafer.

In the Varian 3000XP tandem high-energy implanter shown in Fig. 8, positive ions are filtered by a magnetic field after the high-voltage acceleration stage to reject unwanted ions with undesirable energies and charge states [4]. The selected ions are then scanned along a horizontal beam path and directed through a magnetic beam-shaping element to produce a series of parallel beam paths at the wafer, which is moved up and down to produce vertical wafer scanning similar to the design shown in Fig. 5.

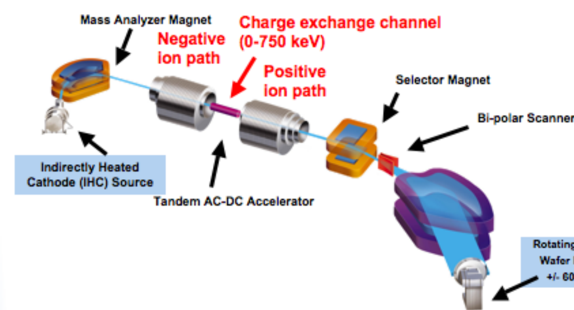

Figure 8: Schematic of the high-energy tandem accelerator beamline for the Varian 3000XP implanter with an operational range from 5 keV to 3 MeV.

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Commercial tandem accelerators are in operation with 2 MV potentials providing 8 MeV B^{+3} ions for doping profiles extending ~10 μm into Si. At these boron ion energies, control of gamma and neutron radiation calls for careful shielding and selection of beamline component materials, active radiation monitors, and limits to operating beam currents.

Phase-synchronized linear accelerators have also been used for high-energy ion implanters for over 20 years. In the Axcelis Purion XE high-energy implanter shown in Fig. 9, twelve RF cavities resonating at 13.57 MHz with maximum potentials up to 80 kV each combine to provide a beamline with mA-level beam currents for single-charged dopant ions at energies of ~1.5 MeV [5]. Double-charged P^{+2} ions can be accelerated to 2.9 MeV with 0.7 particle-mA beam currents for deep n-well applications. The positive ion beam from a plasma ion source enters the linac section after passing through a 70° mass-selection magnet (on the left in Fig. 9). After the beam is bunched and accelerated through the linac assembly, it is filtered with a 58.5° magnet (on the right in Fig. 9), that is tuned to select ions with the desired energy for transmission to the beam and wafer scanning stages.

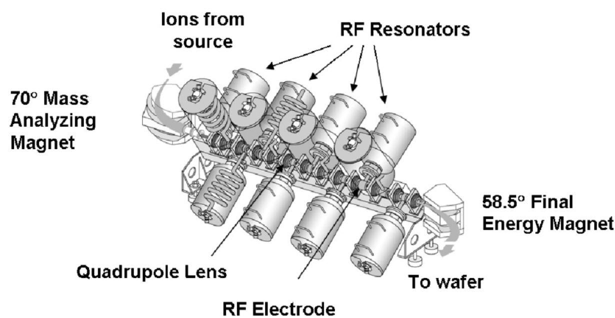

Figure 9: RF linac section of the Axcelis Purion XE high-energy implanter with an operation range from 5 keV to 1.5 MeV for B^+ (1.2 MeV for P^+ and 2.9 MeV for P^{+2}).

Plasma Immersion Ion Implanters

The systems used for very high dose (>10^{16} ions/cm^2) and low-energy (a few keV and less) implantation employ a radically simplified design. In PIII tools, the usual beamline components are eliminated, leaving only a means for generating a plasma containing dopant ions and a wafer mounted on a platen that can be biased. The ions in the plasma formed near the wafer are accelerated into the wafer surface by short (a few μs) negative potential pulses applied to the wafer platen at energies up to the maximum desired value.

PIII systems are remarkably compact in comparison to beamline accelerators, resembling the look of CVD and plasma etch systems. An example is shown in Fig. 10. The applications for these types of implanters include:

- High dose (~5x10^{16} B/cm^2) boron implants at energies of a few keV to counter-dope n^+ poly-Si to form p^+-doped gate electrodes in DRAM devices
- High dose doping of three-dimensional CMOS device structures, such as source-drain regions of finFETs
- High dose implantation of non-dopant ions for local enhancement or reduction of plasma etch rates and other materials modification applications.

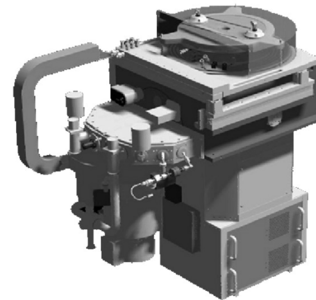

Figure 10: The Varian VIISta PLAD is an RF plasma doping tool, where a pulsed bias voltage is applied to the target wafer to implant ions from the plasma. The wafer bias voltages range from 0.1 to 10 kV [6].

SUMMARY

Ion implantation technology has been built on >40 years of experience, and accelerators are a key component of these tools. Even though commercial systems provide ion energies that span a range of 10^4 and implant doses that span a range of 10^8, the basic hardware designs are similar [7]. Implanter systems have evolved historically over time and will continue to evolve, as new device applications and CMOS device scaling brings more demanding requirements.

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