Ion Beam Technologies for the 20nm Technology Node, 450mm Wafer Processes, and Beyond

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Abstract

An innovative ion beam line capable of high ion beam current production, excellent ion mass resolving power, minimal energy contamination for sub-keV ion beams, all while maintaining high degrees of beam intensity and angle uniformity, has been designed and developed to meet ion implantation process and productivity requirements of the 20nm technology node (and beyond) and of 450mm wafers. The testing results have demonstrated that the beam line's performance meets the required specifications in terms of ion beam current, energy purity and beam uniformities. The detailed designs and measured performance results are presented in this paper.

1. Introduction

Ion implanters used in IC device fabrication are charge particle accelerators that accelerate ions from a few hundred eV to several MeV. When ion implantation was first adopted for doping semiconductors it was not known what a large range of capabilities would ultimately be needed. Depending on ranges of implant dose and energy, ion implanters can be classified into high energy (energy up to several MeV), medium current (low dose), and low energy/high current (low energy and high dose). This paper intends to address technology advances specific to high current implanters.

Conducting paths in the transistor such as source and drain (S/D), source drain extension (SDE) and gate doping are realized by ion implantation. As the semiconductor IC world continues the trends of Moore's Law, the device feature size and dimensions become ever smaller, which pushes semiconductor equipment vendors to provide ion implanters with some unique features to address the more stringent process needs, specifically, higher beam current and lower implant energies. These features address the device applications requirements of higher implant doses, as feature sizes scale down, and lower implant energies for shallower junctions. A more dynamic driver of requirements is the need to dope and modify (with non-dopants) vertical and "3-D" devices, including finFETs (precision implant angle control) and Monolithic 3D ICs (ultra high dose implants).

In 1980, the first true high current ion implanter was introduced, which used a Freeman ion source and produced 12mA of arsenic ion current at energies up to 80keV. The rapid change in manufacturing processes has led to new and improved implanters being developed almost on an annual basis. In the modern implanter, the beam currents have been raised to 40mA; tool uptime has been improved to greater than 90%. The wafer size in the first tier semiconductor fabrication plants is now 300mm and has increased seven times since the 50mm wafers of the 1970s. Each wafer size change obsoleted the previous generation of implanters. The changes needed were not only related to wafer handling, but the increase in area meant that to maintain equivalent wafer throughput, the beam current needed to be increased correspondingly.

As semiconductor device dimensions continue to shrink below the 20nm technology node, source-drain junction depths are reduced accordingly. Ultra low energy (sub-keV) ion implantation with high beam current is required for shallow junction formation. Due to space charge limits in low energy ion beam transport, it is necessary to extract an ion beam at higher energy (>1keV) and decelerate them to a target energy, for example 700eV before the beam impacts the wafer. Energy contamination can occur due to energetic neutral particles that result from charge exchanges between beam ions and beam line residual gas atoms/molecules prior to and during deceleration. Thus preventing neutrals from reaching the wafers is a key factor to be considered in beam line designs.

For high current implanter architecture, it is preferred that 300mm wafers are individually processed via a 1D mechanical scan over a uniform linear or ribbon shaped ion beam. As wafer size further increases to 450mm this architecture will be a more viable solution than the alternate scheme of a spot-shaped ion beam with a 2D mechanical wafer scan. However, in order to make this 1D architecture workable for ion implantation on advanced IC devices, the linear or ribbon beams, including ultralow energy (sub-keV) beams, must be uniform in ion beam current intensity and angle over a large dimension (>450mm).

Therefore, the challenges of developing a new high current beam line for the 20nm technology node and 450mm wafer processes are to produce high ion beam currents that scale with the increased wafer size, ultralow energy beams with high beam energy purity for shallow junction implants, and uniform beam intensity and angle along the longer beam dimension. This paper presents a new concept beam line that addresses the above requirements and key performances in terms of beam current, energy purity, and uniformity.

2. Beam line design and description

A. Overall beam line design

A high current semiconductor implanter consists of a beam generating module (beam line), a wafer scanning module and an Equipment Front End Module (EFEM). The implantation process capabilities are defined by the beam line. Therefore, beam line development has been the core effort for all commercial implanter manufacturers.

As shown in Fig. 1, ions are generated in an indirectly heated hot cathode ion source. The source ions are extracted by the accelerating electrical fields between the ion source and the extraction electrodes to form vertically convergent ion beams that cross over in the middle of a sector dipole magnet that is part of mass analyzer module. The ion beams are mass analyzed through the analyzing magnet module and leave the module with divergence at decently large expanding angles. When the vertically expanding ion beams reach the desired beam dimension, they are collimated, decelerated (or not decelerated, i.e. drift) and deflected by the collimation and deceleration module so that high energetic neutrals and ions with energies out of the specified range are filtered. Simulation results indicate good quality ion beams with minimum optical aberrations can result on the wafer plane because the beam travels in the linear regions of the optical components and the beam's envelope varies gradually along the beam line.

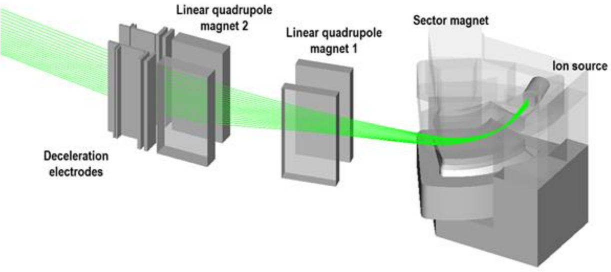

Figure 1. Overview of a beam line where ion source, sector dipole magnet, linear quadrupoles, and deceleration electrodes as well as numerically simulated ion beam trajectories are shown.

This beam line possesses the following features that are required by a high current implanter that is for the 20nm technology node, 450mm wafer processes, and beyond:

1. high intensity or high perveance ion beam formation to produce ultrahigh ion beam currents on implanted wafers;
2. good mass resolving power to minimize ion species cross contamination;
3. large ion beam acceptance optics to transmit the high perveance ion beam efficiently to the lower beam line to be collimated and decelerated;
4. variable beam dimensions can be easily configured, and no additional beam line element is needed to extend an ion beam from 300 mm to 450 mm;
5. energy purity with low energy due to efficient neutral particle filtering by deflected beam collimation and deceleration design;
6. industry bench marked quality sub-keV beams because of the low aberration ion beam optics.

B. Ion source and ion beam formation

The indirectly heated cathode (IHC) ion source was first used in ion implantation by Wilson[2]. It was introduced into commercial high current ion implanters by Ferlazzo at Eaton Corporation in 1993[3]. Referring to Fig. 2, a cathode is heated by 400-600eV electrons that are thermionically emitted from a hot filament and accelerated by an electric field in between the filament and the cathode. The cathode, biased at -60 to 150V, emits electrons which are electrically attracted to the walls of the arc chamber at local ground. But the axial magnetic field, B in Fig. 2, prevents them from reaching the walls with the electrons emitted from the biased cathode reflected at the opposite end at the cathode potential forming a Penning trap. The trapped electrons can only reach the anode by scattering off gas atoms and/or molecules, thereby ionizing them. A plume of plasma forms in an intense cylinder from top to bottom. The detailed descriptions can be seen in ref. [4]

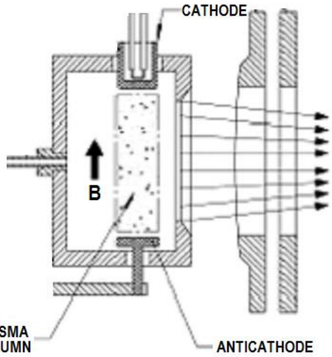

Figure 2. Cross-section view of an indirectly heated cathode ion source

This type of source keeps most the ions off from eroding the cathode, extending its life, and is very efficient in its use of the electrons. The plasma density and the shape of the exit aperture of the ion source in combination with the extraction electrodes are important elements in beam formation since the quality and density of the ion beam entering the mass analyzing magnet module are determined in this region.

The IHC ion source and beam formation electrodes used in this system were optimized for uniform high perveance beams [5] before the analyzing magnet module. Up to 120 mA beams can be extracted with good qualities in terms of low ion energy spread, low emittance and bright luminosity. The components of ion source and extraction electrodes are designed based on thermal simulations to make the source operation stable and to minimize thermal drift. In order to reduce source and electrode consumable costs, the source and extraction electrodes can be mechanically assembled from inter bolted refractory metal and through the use of graphite parts with good integrity as shown in Fig. 3.

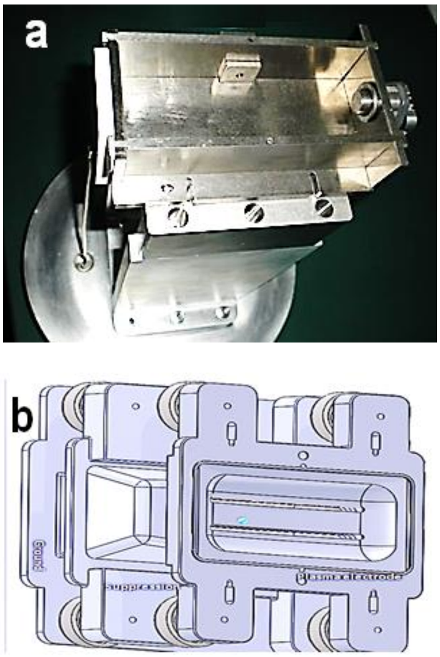

Figure 3. Ion source body (a) and corresponding ion beam extraction electrode assembly (b)

C. Ion mass analyzer module

The mass analyzer is one of the modules that needs very careful and innovative designs in order to achieve the requisite beam line performance. The specific analyzer described in this article consists of a sector dipole magnet and a linear quadrupole magnet. The sector dipole magnet is well studied and its design considerations are discussed in industry literature [6] The linear magnetic quadrupole or bar magnet was first proposed by Prof. Panofsky at Stanford Univ. [7]. This type of magnetic quadrupole is designed to linearly shape ion beams and has been used in commercial ion implanters of VSEA [8] and AIBT [9] to focus/defocus and collimate ion beams.

The combination of the sector magnet and the linear quadrupole offers two degrees of freedom so that the desired beam dimension can be obtained at the horizontal focal point. 3D magnetic simulations of such the system was performed by using Lorenz code [10].

Multi-species ions are generated with BF_3 source feeding gas. The ions of mass 49, one boron 11 and two fluorine atoms and mass 48 together with other ions are extracted from the ion source. The ions then enter the ion mass analyzer that consists of the sector magnet and linear quadrupole. The energetic ions are dispersed in the magnetic fields depending on the momentum of the ions as shown in Fig. 4. The magnetic field strength is tuned to let atomic mass unit (AMU) 49 pass through in the simulations performed in Fig. 4: AMU 49 (black) and 48 (red) ion trajectories travel through the sector magnet and linear quadrupole magnets. These two beamlets are clearly separated by their cross over points. If a narrow slit is properly placed close to the beam cross over point of beamlet 49 as shown in Fig. 4 a high ion mass resolving power can be expected.

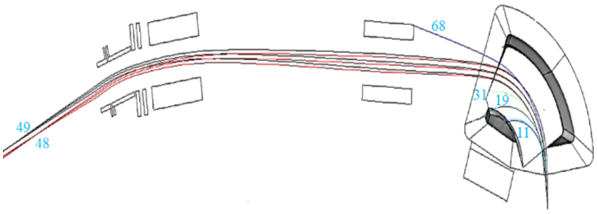

Figure 4. Simulations of different atomic mass (AMU) ion trajectories, AMU numbers are shown next to trajectories.

D. Beam deceleration and deflecting module

Electrical deflection is the common way to remove neutrals and ions whose energies are out of desired ranges [11]. In order to realize production worthy low energy ion implants Applied Materials introduced the post mass analyzer deceleration in its high current implanter, xR-80. Extremely careful vacuum managements are required to control energy contamination in implants with decelerated ion beams [12]. Combining electrostatic deflection and decelerating ion beams in a high current ion implanter was originated by Advanced Ion Beam Technology, Inc. [13]. An electrostatically S-bend deceleration scheme was developed by AIBT [9]. This scheme accommodated S-bend beams and non-bending beams into one implanter system. However, the S-bend deceleration scheme required much longer beam paths inside the electric field, which makes low energy ion beams uniformity over 300 mm length very challenging. Spot-shaped ion beams coupled with 2 dimensional mechanical wafer scanning have to be utilized to ensure implant dose and angle uniformities. Additional deflection can be imposed into this module with bending in the collimator magnet in order to strengthen filtering capabilities of the neutrals.

In this paper we present an ion beam deflection and deceleration module that ensures not only energy pure ultralow energy ion beams but also high degree beam uniformities with beam dimensions exceeding 450mm. Thus, the single bend deceleration with moderate beam deflecting angle is used in this beam line. The carefully designed electrodes maintain good beam transmission and minimum aberrations as shown in Fig. 5. The deflected and decelerated ion beams have uniform beamlets across the interested range of ±200mm. Such tall beams are fairly straight and banana-shaped beams are not observed. The physical deceleration electrode assembly is shown in Fir. 6. This assembly is fairly compact and modularized for service or re-configuration.

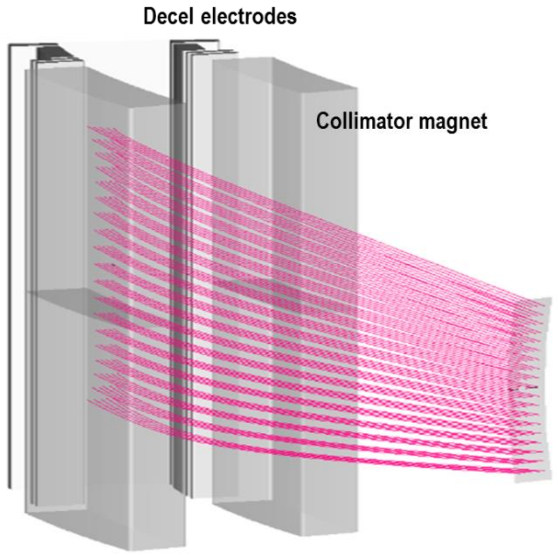

Figure 5. Bend collimation and deflected deceleration to realize high degrees of energy pure ion beams

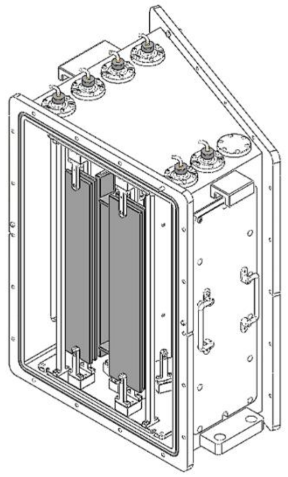

Figure 6. Mechanical assembly of deflecting and decelerating ion beams. The dark parts are made of graphite materials.

3. Beam line performance

A. Ion source operation and beam formation

The performance of ion source and beam formation can be examined by total ion extracted currents from the ion source. Table 1 lists the extraction beam currents of BF_3 and PH_3 as source feeding gases as well as the source parameters.

Table 1. Extraction currents

Source gas	Extracted beam (mA)	Beam energy (keV)	Plasma arc voltage (V)	Plasma arc current (A)
BF_3	120	30	110	6
PH_3	130	30	75	6

The first electrode that faces the source plasma is called the arc slit. Its aperture defines initial ion beam shape and propagating directions. The dimension of the arc slit's aperture is 3.5x60mm. Therefore, the plasma densities in the IHC ion source are ~5x10^{12} cm^3. This plasma density indicates an extremely well performed ion source has been developed.

B. Ion beam analyzing

The specially designed mass analyzer module described in section2-C delivers very satisfactory results. Mass resolving power is large enough to separate two atomic mass peaks of AMU=48 and 49 sufficiently as shown in Fig. 7. The mass spectrum was taken at moderate beam currents with careful beam tunes to optimize BF_2 beams. Practically, the mass resolving power M/ΔM ≈ 40 at HWHM (Half Width Half Maximum). By adjusting the source magnetic field, we can tune the source to optimal boron ion production with an ion beam ratio of B_{11} to BF_2 greater than 3 to 1.

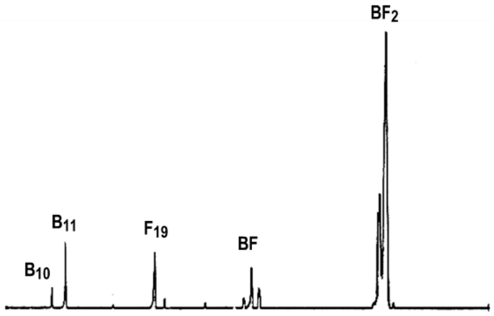

Figure 7. Ion mass spectrum of BF3 as ion source gas

Another key analyzer module performance item is its beam acceptance that can be qualified by beams exiting from the analyzer module. The analyzer beam transmission can be quantified by specie specified ion beam currents versus extracted beam currents. As one can see from Table 2, 65mA of P_{31}^+ and 35mA B_{11}^+ beams at energy of 30keV are transmitted respectively through the analyzer module. These beam current numbers show the module designs and constructions are well done since all these ions are extracted from a small source exit slit with dimension of 3.5x60 mm.

Table 2. Beam currents through mass analyzer

Ion specie	Beam current (mA)	Extracted beam (mA)	Beam energy (keV)
P_{31}	65	100	30
B_{11}	34	98	30

D. Decelerated ion beams

There are three key performance items assessing the deceleration module: energy contamination, beam currents and beam intensity and angle uniformities after the ion beam deceleration.

The most effective and direct way to characterize decelerated ion beam energy purity is to examine low energy boron implanted dopant depth profiles with Secondary Ion Mass Spectrometry (SIMS). Figure 8 shows the SIMS profiles of three B^+ implants of 700eV drift (green line), two deflected and decelerated beams. Both beams were decelerated from 4.2keV thus decelerating ratio is 6:1. There is not any observable difference between the drift beam and the decelerated and deflected beam implants, which leads to a conclusion of very low level energy contamination in the ion beams after being decelerated. By calculating dopant dose differences of dopant concentrations below 1E19 we found the energy contamination is about 0.03%.

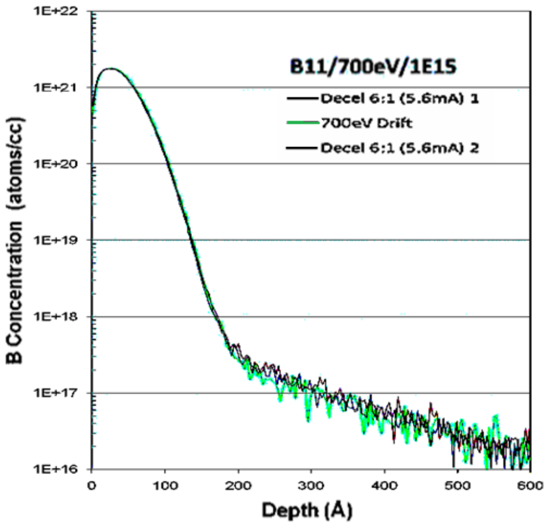

Figure 8. Boron implanted SIMS profiles at 700eV and 1E15 atoms/cm^3 dose, drift beam (green) vs. decelerated beam (black) implants

The decelerated beam current intensities are measured with a slot Faraday. The slot Faraday scans across the major beam dimension and 1D profiles of beam currents along the major beam dimension can thus be measured. The 1D profile of a decelerated B11-700eV beam is shown in Fig. 9. Great attention have been paid on this ultralow beam as 700eV boron implants are commonly used in source/drain (S/D) extension doping in the most advanced CMOS device fabrication. The 1D profile in Fig. 9 shows the beam line produces a high quality decelerated ion beam because this 1D profile was taken 250 mm downstream of the deceleration electrodes without any beam shaping or beam intensity tuning. We have developed a method to view low energy boron beam cross section by letting a beam strike on a thin sheet of aluminum foil that is electrically grounded. The boron atoms are implanted into a few nm below the foil surface leaving a dark mark as shown Fig. 9 (right). This mark truly represents the beam's 2D shape because the foil is conductive and grounded. The beam mark shows that the 700eV boron beam is thin and tall to cover 380 mm vertical range. The narrow beam width and well defined beam envelope indicate this ultralow energy beam has minimal aberrations (very small imperfections) which is very critical for low energy S/D extension implants. The 1D beam profile and beam cross section mark show this advanced beam line delivers good quality ion beams since the data were taken without any beam fine tunes of intensity and angle. The beam intensity peaks in the bottom and top ends can be clipped by physical blockers so that the usable range as shown by the shaded area in Fig. 9 can be 350mm. The total beam current is about 8mA by integration over the interested range (350mm). The taller beams needed to cover the 450mm wafer size can be handled by increasing the distance between the two linear quadrupoles to let the beams expand more. The high quality low energy beams can be realized in the same principles discussed earlier in this section.

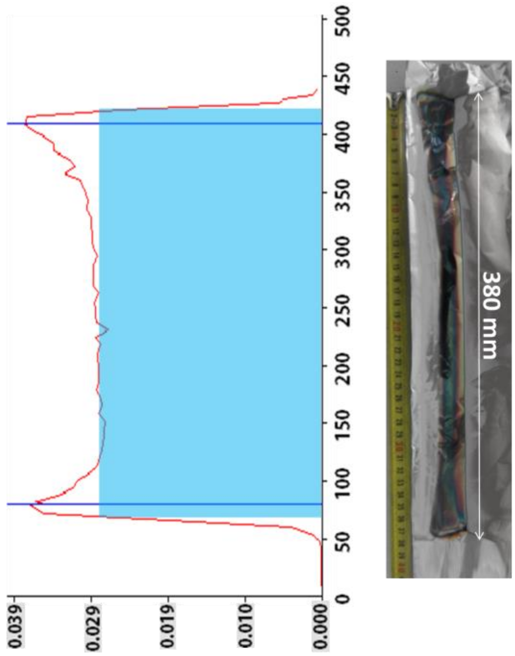

Figure 9 1D-profile (left) and beam cross section burn (right) of a decelerated boron 700eV beam

4. Summary and conclusion

The conceptual designs of an advanced ion beam line are presented and discussed. The numerical simulations of the modules in the beam line are carried out. The simulated results confirm the feasibility of the beam line to meet the key requirements of generating high ion beam currents, low energy contamination in decelerated ion beams, and uniform and small aberration beams. Meeting these requirements is essential for the successful extension of ion implantation processes to the 20nm technology node and to the move to

450mm wafers. The completed beam line was constructed based on the numerical simulations. The beam line has demonstrated the following performance. 1) extraction of up to 130mA ion beam current, 2) obtainment of 65mA phosphorus and 34mA boron beams after the mass analyzing module; 3) separation of atomic mass numbers 49 and 48 beamlets; 4) confirmation of energy contamination below 0.03% using decelerated ultralow energy during a 700eV boron implant; 5) uniformity of the decelerated beam's linear intensity and angle over a range of 350mm and achieved beam current of almost 10mA of 700eV boron beam. These results demonstrate that the presented beam line technology is one of the best options for high current ion implanters to meet the needs of the 20nm technology node, 450mm wafer processes, and beyond.

Acknowledgments

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Note

Items described in this paper include multiple pending patent applications in the U.S. and China.

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