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ORIGINAL PAPER

Purion XEmax, Axcelis ultra-high energy implanter with Boost™ technology

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Abstract

Axcelis Purion XEmax is an ultra-high energy implanter, producing up to 15 MeV arsenic and 14.5 MeV phosphorus beams. With the patented Boost™ technology, the highest energy beams are generated from a 3 + charge state extracted at the ion source, which delivers higher beam current, longer source life and eliminates energetic metal contamination. Its beam line is optimized for angle control to give the best angle performance in the industry.

Introduction

The competition to improve red and IR sensitivity within the CMOS Image Sensor (CIS) industry is expanding the performance requirements of ion implanters [1]. An energy range well above 10 MeV was once only considered for nuclear physics experiments but is now needed for advanced CIS devices. The sensitivity of CIS devices to metallic contamination calls for even tighter control of ion beam purity [2]. Additionally, the increased use of channeled implants has placed stricter controls on beam angle uniformity and distribution to maintain yield across the wafer. The Purion XEmax -high energy implanter described in this paper was designed to meet the challenges of the evolving CIS market.

Boost technology

Initially conceived as an architecture to increase boron beam current at energies above the B++ maximum energy [3], Boost is the key technology in the Purion XEmax for production of the ultra-high energy ions. Boost can improve beam current, source lifetime and eliminate energetic metal contamination.

The traditional approach to attaining high energies is the extraction of very high charge state (such as 4 + and beyond) ions from the source. For industrial applications like ion implantation, the use of high charge states from the ion source comes with limited available beam currents. The fraction of As^{4+} ions is $<1\%$ in the typical ion source even at an elevated plasma condition [4]. Running an ion source to produce very high charge state ions requires a dense plasma with a high electron temperature, leading to shorter source life.

Instead of starting with high charge states at the ion source, Boost technology uses charge exchange reactions to convert lower charge state ions which are accelerated to several MeV to higher charge state ions, up to 6 +.

Charge exchange reactions occur when high speed ions or neutral atoms go through a layer of gas and some pick up or lose electrons through the interactions with the residual gas atoms, changing their charge state. As the energy of the incoming ion goes up to MeV level, the entire charge state distribution after the passage through gas layer shifts to higher values, i.e., the electron loss reactions become dominant [5]. For example, about 20 to 30% of 6 MeV As^{3+} ions are converted into As^{4+} through the charge exchange reaction, producing As^{4+} at much higher efficiency than at the ion source. The high efficiency in creating higher charge states through charge exchange reactions is one of the strong benefits of the Boost technology, increasing the beam currents for 4 + and above charge states. Also, since the ion source is tuned to produce only up to 3 + ions, much longer source life is guaranteed.

To get the maximum energy of 15 MeV Arsenic, Purion XEmax starts with As^{3+} at the ion source, accelerates it and then converts the accelerated beam into As^{6+} with Boost

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technology for further and more efficient acceleration through LINAC 2 stage to 15 MeV.

Layout of major components

Purion XEmax consists of 7 modules: Injector, RF LINAC 1, Booster with charge selector magnets, RF LINAC 2 with 90° energy analyzer, High Energy Beam line (HEB) with beam scanner, S-bend angle corrector and Process module with the required implant control subsystems. All together, they form a large C shaped arrangement as shown in Fig. 1 in an enclosure of 8.65 × 8.8 m which fits nicely in the two traditional implanter tool bays. The injector, LINAC 1 and Process modules are inherited from Axcelis Purion XE [6]/VXE high energy implanters.

Purion XEmax has two modes of operation, Boost mode and non-Boost mode. In non-Boost mode, the booster module is a simple drift space with 90° bending magnets. In Boost mode, gas is introduced in the charge exchange canal to promote the charge exchange reactions. The 90° bending magnet system acts as a charge state selector to choose the desired charge state among the distribution created after the passage through the gas layer. The charge exchange canal is doubly differentially pumped to keep the reactions within the Booster region. After the 2nd acceleration stage through LINAC 2, the beam goes through a 90° energy filter magnet system, a quadrupole doublet for focusing adjustment and is then electrostatically scanned horizontally into S-bend angle corrector magnet.

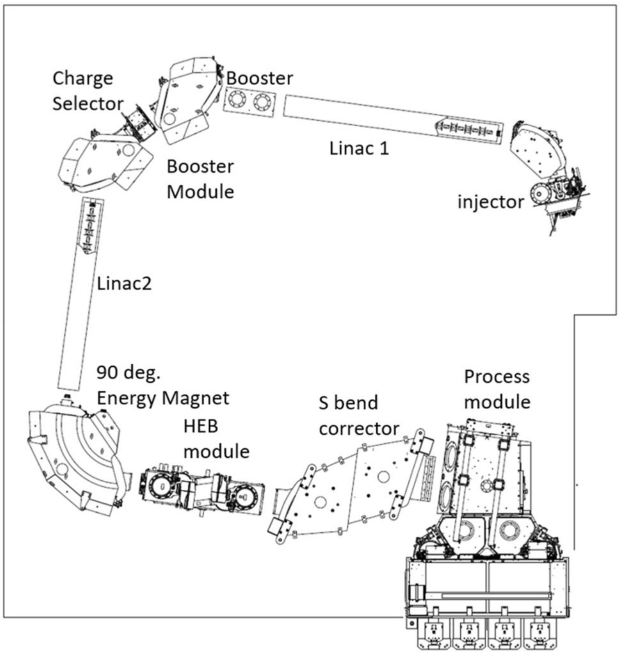

Fig. 1 Layout of XEmax

The S-bend corrector magnet system consists of two opposite polarity 35° dipole magnets and gives several process advantages over a single bend angle corrector magnet or an electrostatic angle corrector lens, so-called p-lens, as described later.

Energy and beam current

Table 1 shows the typical arsenic beam energy and available maximum beam current in pμA (particle μA = 6.25×10^{12} particles/s), as a function of the initial and final charge states. Table 1 reflects data for arsenic with Boost mode on. Boost mode is required for energies above 11 MeV, however Boost mode can be turned on at lower energies as well. An initial 2 + beam can also be used with Boost on mode. Utilizing either 3 + or 2 + beams with Boost on will give benefits such as elimination of energetic metal contamination and longer source life.

Boost technology is very efficient for boron as well. The maximum energy and beam current of boron beams are restricted to prevent the generation of fast neutrons, a radiation issue described in a companion paper by Platow et al. [7].

Energetic metal contamination

Because of its significant effect on device performance, metal contamination is rigorously controlled on implants for CIS devices. Metal contaminants on the surface from wafer handling, particles, and sputtering, are routinely monitored, but energetic metal contamination buried deep in the device are getting scrutiny too.

The plasma in the ion source contains many ions of different species, some come from the structural components of the ion source, including minute impurities in the materials. To prevent those unwanted elements from reaching the wafer, all commercial ion implanters rely on magnetic or

Table 1 Charge states, beam energy and max beam current on Purion XEmax for Arsenic beams

Extracted ion charge	Final ion charge	Final ion energy (MeV)	Max beam current (pμA)
As^{2+}	As^{2+}	4	300
As^{3+}	As^{3+}	11	100
As^{3+}	As^{4+}	13	20
As^{3+}	As^{5+}	14.2	10
As^{3+}	As^{6+}	15	6

electrostatic filtering. If the source plasma contains a contaminant of mass $m2$ and charge state $q2$, besides the desired ions of mass $m1$ and charge state $q1$, which satisfies

$$m2/q2 = m1/q1 \quad (1)$$

the contaminant can go through all the magnetic or electrostatic filtering, even after acquiring higher energy through acceleration and can reach the wafer as an energetic metal contaminant.

The potential for energetic metal contamination exists in all ion implanters. To this point there have not been many contaminants from the source plasma that mattered or met the condition of Eq. (1) with the $m1$ and $q1$ of the popular dopant species, boron, phosphorus, and arsenic up to 3 + charge states. This is no longer the case for CIS devices and with the use of As^{4+} ions for achieving ultra-high energy. The m/q for $^{56}Fe^{3+}$, the most abundant isotope of Fe, is 18.67, which is extremely close to the m/q of 18.75 for As^{4+}. The difference of only 0.2% easily allows the $^{56}Fe^{3+}$, if it exists in the source plasma, to pass through the mass analysis to be accelerated together with As^{4+} to reach the wafer.

The only conventional way to avoid energetic contamination in an As^{4+} beam is the complete elimination of Fe impurity in the ion source components. Considering the frequent part replacements in the ion source, especially running As^{4+}, the complete elimination may not be economically feasible.

The elimination of energetic Fe on As^{4+} implants is a compelling example how Boost technology helps address the needs of the CIS device performance. With Boost technology, Purion XEmax does not have to run As^{4+} even for the top energy of 15 MeV, which eliminates the chance of meeting Eq. (1) on $^{56}Fe^{3+}$. Figure 2 shows the two SIMS depth profiles of Fe in an Arsenic 5E14 12 MeV implants, As^{4+} with Boost off (green) and the other with Boost on (blue) starting with As^{3+} boosted to As^{4+}. The Fe peak at around 3 µm was eliminated completely with the use of Boost technology.

Examinations of other possible energetic metal contamination revealed two cases for arsenic implant. ^{50}Ti, with 5.34% abundance, has the exact same m/q as $^{75}As^{3+}$ for the Ti^{2+} charge state. Although conventional filtering methods cannot remove the Ti if it is in the source plasma in a As^{3+} beam, Boost technology gives a solution by changing the charge state of As^{3+} into As^{4+} at the Booster. Once As^{3+} is converted into As^{4+}, the magnetic rigidities of Ti^{2+} differs from that of As^{4+} beam and the Charge selector magnets can easily remove Ti^{2+} or Ti^{3+} out of the main beam.

Another possible case is ^{37}Cl, 24.47% abundance, which has a very close m/q with As^{2+} for the Cl^{+} charge state. It can be an energetic contaminant if the mass resolving power of the injector is not high enough to remove it from an As beam. Again, turning on Boost mode, even at low energy to convert As^{2+} into As^{3+} will break the close m/q relationship to enable complete removal of the Cl ions.

Angle controls

The use of channeling is rapidly becoming very prevalent to gain extra depth in higher energy implantations. The $E^{-1/2}$ dependency of the channeling critical angle [8] narrows the channels for high energy implants, which in turn requires very tight overall angle control on high energy implantations.

On a hybrid scan implanter, as with all the single wafer implanter products from Axcelis, the ion beam is scanned

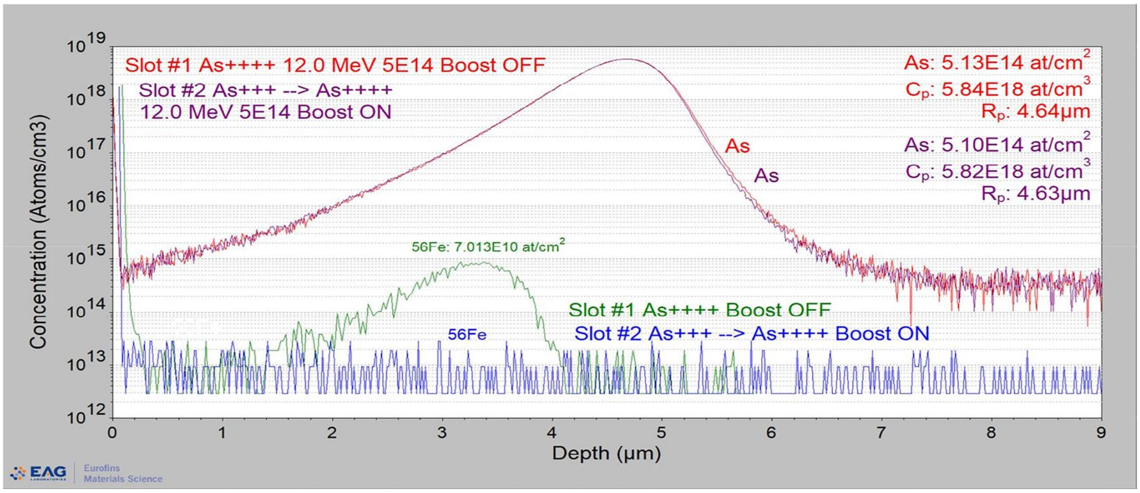

Fig. 2 SIMS profiles of energetic Fe on As++++ implant and with Boost mode on

only in the horizontal direction and is stationary in the vertical direction. On all Axcelis Purion series high energy implanters, including XEmax, vertical angle control is done by adjusting wafer tilt after finding the mean vertical angle with a devise called VBA [9]. Despite its simplicity, the VBA is an efficient and precise tool for finding the mean vertical beam angle.

Beam angle control in the scanned or horizontal direction is much harder since the beam fanning out of the scanner is converted into a parallel shifting beam over a > 300 mm distance and the variation in angle is strongly affected by the architecture and quality of the angle corrector system.

The situation is very similar to the aberration in a large aperture low F optical lens. On an ion beam, however, the bundle of rays is not only finite in size, but also contains many ions of slightly different angles. Traditionally, only the “mean” angle within the ray was considered, but on Purion XEmax, we have paid great attention to minimizing the angle distribution within the ray.

On controlling the “mean” horizontal beam angle, the two coil currents on the S-bend angle corrector are adjusted to minimize the average over the measured mean angles at 7 locations within the 300 mm width. The balance between the two coil currents is adjusted to minimize the 1st order coefficient in the relationship between the 7 angles and the horizontal locations, normally called “beam parallelism”. The angle correction by the S-bend corrector achieves excellent parallelism of the scanned beam with mean beam angle measurements across the 300 mm scan width within a range of ± 0.03°.

In addition to minimizing the variation of the horizontal beam angles, we paid attention to minimizing the angle spread within the “ray” of the beam. The narrow energy resolving aperture called HD-ERS helps tune the LINAC for minimum energy spread and minimizing the beam size at the slit.

The S-bend angle corrector is equivalent to an achromatic optical lens with two opposite polarity elements, where its energy-to-angle dispersion, or chromatic aberration in optical field, is far smaller than that of the conventional single bend angle corrector or the electrostatic angle corrector, called p-lens. The small energy-to-angle dispersion of S-bend corrector also helps reduce the final horizontal beam angle spread on the presence of small energy spread in the ion beam accelerated by RF LINAC.

Purion XEmax has an insertable aperture called VDS which helps beam tuning to minimize the vertical beam angle spread on the implant location. Some preliminary measurements of the vertical beam angle spread showed the spread to be much less than that of a typical horizontal beam angle spread.

Figure 3 shows the SIMS profiles of 8 MeV arsenic channeling implants with 0.05° tilt angle increments. Clear differences in the SIMS profiles between the tilt angle increments proves the vertical beam angle spread is substantially smaller than 0.05°. A companion paper by Kondratenko et al. [10] gives the details. The combination of the superior beam angle control and the accuracy of the Purion platform wafer tilt were able to provide a highly channeled MeV beam that is paramount for CIS photodiode design.

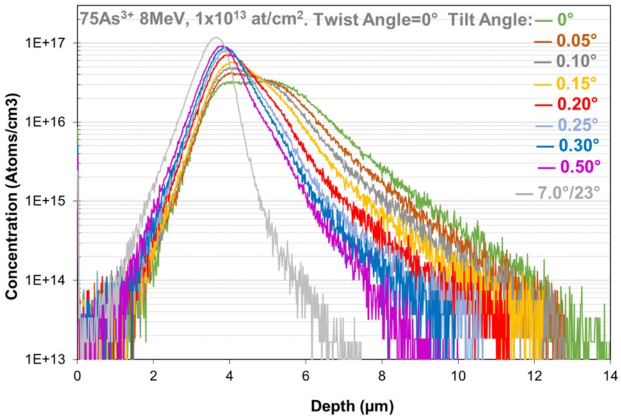

Fig. 3 As distribution profiles at zero and low tilt angles from zero to 0.3° with 0.05° increment, $E = 8$ MeV, Dose = 1E13 at/cm^2

Summary

Axcelis’ ultra-high energy implanter, Purion XEmax was designed to meet the stringent requirements for CIS device manufacturing. Boost technology not only helps in producing arsenic ions up to 15 MeV of energy using only 3 + beam at the ion source, but also provides powerful methods to eliminate the energetic metal contaminations which are quite difficult to remove in other ways. The rigorous attention in the design of the beam line for precise angle control produced unparalleled channeling performances.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest No funds, grants, or other support was received.

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