Beam Energy Purity on Axcelis XE High Energy Ion Implanter

Shu Satoh, Jonathan David
Axcelis Technologies
108 Cherry Hill Drive, Beverly Massachusetts, USA 01915
shu.satoh@axcelis.com

***Abstract*— The multi-stage RF acceleration in the Axcelis Purion XE high energy ion implanter has strong velocity filtering which allows only those ions with the correct flight time at the correct phase at each acceleration gap to get properly accelerated. On Purion XE, the energy spectrum exiting the RF linac is further purified with a magnetic momentum analyzer to remove any ions with the wrong energy or charge state before proceeding to electrostatic beam scanning and a magnetic parallelizing lens. A new on-tool EC detection method is introduced, which is based on the Energy Tracking System on Purion XE, to avoid the sole reliance on costly SIMS analysis for routine beam purity confirmations. We demonstrate the effectiveness of the new method and also demonstrate the energy purity of Purion XE.**

Keywords—implantation, RF linac, Energy Contamination, Energy analyzer

I. Introduction

The ability to create a precise dopant depth profile reliably and repeatedly has been the one of the big promoting factors for ion implantation over other doping technologies. Beam energy purity, or lack of energy contamination (EC), is one of the important performance criteria on ion implanters.

Axcelis high energy serial ion implanter Purion XE is based on the RF linear accelerator (RF linac) technology [1]. From its acceleration principle, the RF linac acts as a strong velocity filter, to accelerate only those ions which happen to be at the right place at the right time at all the 24 RF accelerating gaps. When ions reach the wafer, the ions have already gone through three filters, first from AMU magnet (magnetic mass analysis), second from the velocity filtering of the RF linac and third through the magnetic energy filter immediately after the RF linac. All these three filters help to purify the ion beam in energy and mass spectra before reaching the process wafer.

Detection of EC is not straightforward. Sweeping an energy filter, either a magnetic filter, as usually found on high energy implanters, or electrostatic filter found on some medium current implanters, does not reveal the presence of EC. It is because either filters filter the ions by rigidity, magnetic rigidity or electrostatic rigidity, not by pure energy value, and EC pass through the filters by possessing the same rigidity as the desired main beam. Because of this difficulty, detection of EC has been done almost exclusively with the SIMS depth profile analysis. Although SIMS is a very powerful method with the fantastic wide sensitivity dynamic range, its off-line nature makes it quite unpractical, or inconvenient, tool for implanter setup or tuning.

Purion XE has a beam diagnostic tool, called ETS (Energy Tracking System) which measures beam energy, or more precisely electrostatic rigidity of the beam, using the precision beam scanner, independently from the beam energy reading by the magnetic energy filter [2].

In this study, we have used the ETS as an on-tool on-line EC detection tool.

II. Energy Contamination in high energy implanter

Purion XE is based on the RF linear accelerator (RF linac) technology. In RF linac, for ions to be successfully accelerated, they have to be within narrow ranges of phase angles of RF voltages at 26 acceleration gaps in Purion XE. This requirement for meeting the phase angles at the accelerating gaps shows up as a very strong ion velocity filtering property of RF linac. Actually, the velocity filters based on RF acceleration were used as mass spectrometers in the applications where the equipment weight was of great concern, like in upper atmosphere study on rocket [3]. Thanks to the velocity filtering property of the RF linac, the beam energy spectra of the RF linac have interesting features, 1) the desired beam is always at the highest energy, and 2) the desired beam is the strongest. Fig.1 is a Parmela [4] simulation result for a typical RF linac energy spectrum, which shows the features, the desired beam at the top end with low energy broad continuum from the ions who "missed-the-bus". These features are in stark contrast to the typical energy spectra on tandem DC accelerators, of which energy spectra contain multiple peaks from multiple charge states, in which a desired beam is quite often the weakest among them.

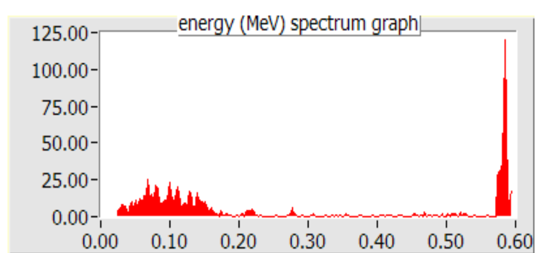

Fig. 1. Typical Output Energy Spectrum from RF Linac

A. *EC through Magnetic Energy Filter*

To understand the nature of EC, we have to understand how EC sneaks through an energy filter, either magnetic or electrostatic, although the energy of EC is, by definition, different from the energy of the main beam. An energy filter filters the ions according to the rigidity, again, magnetic or electrostatic, of ion beam, not to the energy, and EC can sneak through an energy filter by possessing the same rigidity as that of the main beam.

Magnetic energy filters are used in all the currently commercially available high energy implanters, including Purion XE. It is the preferred (or, possibly the only practical) filtering method, mostly because of the difficulties in high voltage reliability required to deflect MeV ion beam on electrostatic filter.

On Purion XE, the magnetic energy filter removes the low intensity low energy ions which somehow survive the velocity filter by RF linac. On a tandem accelerator based high energy implanter, the energy filter is often called as charge filter and plays more active role in choosing a desired beam out of multiplicity of peaks.

A magnetic energy filter filters ions according to ion's magnetic rigidity which is defined here as; $Rm=\sqrt{mE}/q$, where m is the mass, E is the energy and q is the charge state of the ion. The magnetic rigidity Rm defines an energy once the mass and the charge state of the ions are defined. If the output of an accelerator "happens" to contain a beam of the equal magnetic rigidity as the desired beam, but of a different energy, the beam can go through the filter to become EC.

Assuming E_0, and q_0 are the energy and the charge state of a desired main beam, E_1 and q_1 of an EC beam, from the equal magnetic rigidities of both ions, the energy of the EC beam is given as;

$$E_1=(q_1/q_0)^2 * E_0 \qquad (1)$$

From the equation, several important features of EC become clear.

- Charge state of the EC has to be different from the main beam, that is, the EC beam has to go through a charge exchange reaction somewhere to become EC. Since a charge exchange reaction is most likely to be with the residual gas molecules, amount of EC is vacuum dependent, somewhere in the machine.
- Since q_1 and q_0 are integers, the energy of EC can take only a small number of discreet values.
- There will be no neutral EC beam since it requires $E_1=0$.
- The energy of EC will be substantially lower (or higher) than the main beam because of the square of the charge ratio. For example, for 2+ main beam, the energy of 1+ EC beam will be ¼. For 3+ main beam, the energy of 1+ EC beam will be only 1/9 and 4/9 for 2+Ec beam.
- q_0 is 1, 2 or 3 on most of ion beams used on high energy implantations.

TABLE 1. ENERGY AND ELECTROSTATIC RIGIDITY OF EC.

q_0,main beam	q_1,EC beam	E_1,EC beam	Re, EC beam
2	1	¼* E_0	½*Re_0
3	1	1/9* E_0	1/3*Re_0
3	2	4/9* E_0	2/3*Re_0

- On high energy implantation, only EC with a lower energy than the main beam has been of practical concern. The reason may be simply that there is no very high energy EC which can satisfy the equation (1) for $q_1 > q_0$. However, this is a point for future investigation.

Table 1 lists the relationship expressed in the Eq. (1) for the cases of 2+ and 3+ main beam. Only EC with $q_1 < q_0$ are listed. The last column of the table lists the electrostatic rigidity of the EC beam relative to that of the main beam, the quantity we will deal with on the detection system.

III. ENERGY TRACKING SYSTEM AS ENERGY PURITY ANALYZER

Purion XE has the Energy Tracking System (ETS) which measures beam energy using the electrostatic beam scanner as electrostatic energy analyzer [2]. The deflection by an electrostatic beam scanner is proportional to ion's electrostatic rigidity, Re= E/q. Since the electrostatic rigidities of EC beams are different from the main beam (last column in Table 1), EC beam are deflected in different angles from the main beam and can be separated after going through an electrostatic deflector, even if the magnetic energy filter failed to separate them.

On a basic electrostatic deflector, the bend angle is proportional to (E/q) of the beam and deflector voltage as shown in Fig.2. By having a faraday cup off the axis and measuring the scan voltage on detecting the beam on the cup, we should be able to deduce the E/q of the beam.

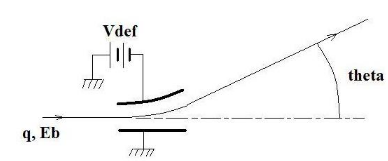

Fig. 2. Basic electrostatic deflector

On the actual implementation of the ETS, two side cups were symmetrically arranged to cancel the beam offset, Fig. 3.

The deflector voltage is a triangle waveform and instead of measuring a DC scan voltage on seeing the beam on the cups, a time delay between the pulses from the two cups is used as an indication of the deflection voltage, Fig.4. The pulse timing can be views as two symmetrical (E/q) spectra with E/q=0 origin in the middle. If the beam has no EC, the time spectra will show only two prominent peaks. If the beam contains EC with less E/q than the main beam, another pair of peaks appear between the

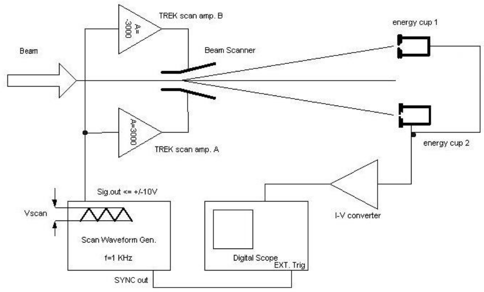

Fig. 3. ETS block diagram.

two main peaks, i.e., at smaller E/q locations. Table 1 lists the E/q of the EC relative to the main beam. If the time spectra is rescaled so that the two main peaks corresponds to +/- 1, relative E/q of EC could be read straight from the graph to verify the agreement with the numbers in the Table 1. By checking the time spectra for a pair of extra peaks and their peak heights relative to the main peaks, we can use the ETS as an Energy Purity Analyzer.

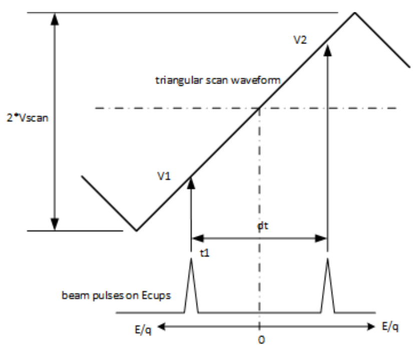

Fig. 4. Pulse timing spectrum from ETS

IV. Test of Energy Purity Analyzer

A. Test with forced EC creation

Since EC is rarely seen in Purion XE, testing the Energy Purity Analyzer poses a problem. A special arrangement in the RF linac, a gas cell at one resonator location, gave a great opportunity for the tests of the analyzer. In the arrangement, a tube of about 20cm long was inserted into the RF linac and N2 gas was introduced into the middle of the tube to enhance charge exchange reactions. The SIMS depth profile, Fig.5, taken on the arrangement on B+++ beam clearly showed an EC, corresponding to 2+ EC at 4/9*E energy, or 1270KeV.

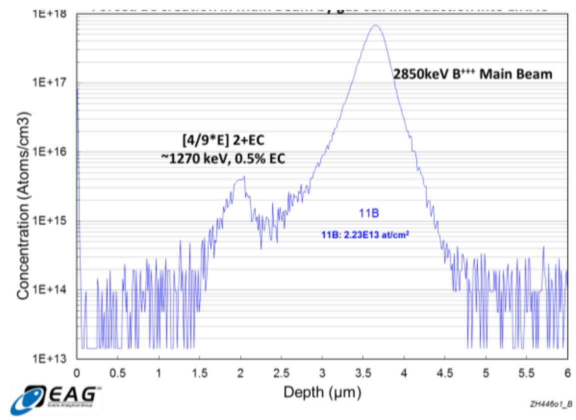

Fig. 5. SIMS depth profile on Forced EC creation. B+++2850KeV

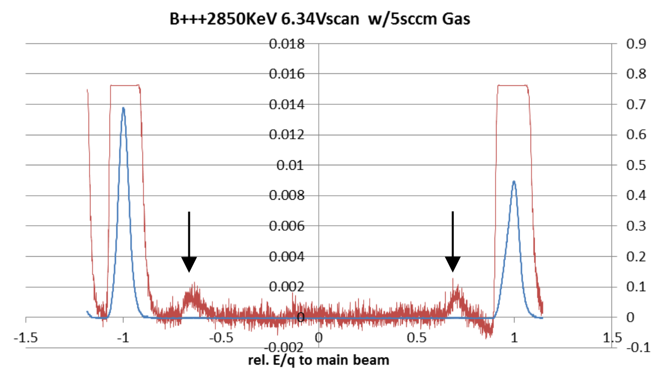

Fig. 6. Time Spectrum from Beam Purity Analyzer on the Forced EC creation.

Fig.6 shows the time spectrum from the Beam Purity Analyzer. The horizontal scale is normalized so that the peaks from the main beam are located at +/- 1 and the same trace is shown in a expanded scale for details. The small peaks were clearly observed at around +/-0.66, which are in good agreement with the predicted +/- 2/3 for 2+ EC in E/q. The peak height is about 0.3% in electrical current, which converts into about 0.45% in concentration, again in good agreement with the EC concentration from the SIMS depth profile.

B. Test on standard Purion XE

A comparison was made between the SIMS depth profile and the Beam Purity Analyzer time spectrum on B++ 2000KeV beam. This particular implant was oriented for channeling and the main peak gets broader in deeper side. Fig.7 shows the SIMS depth profile on the beam, showing well channeled main peak and no trace of EC on the shallow side.

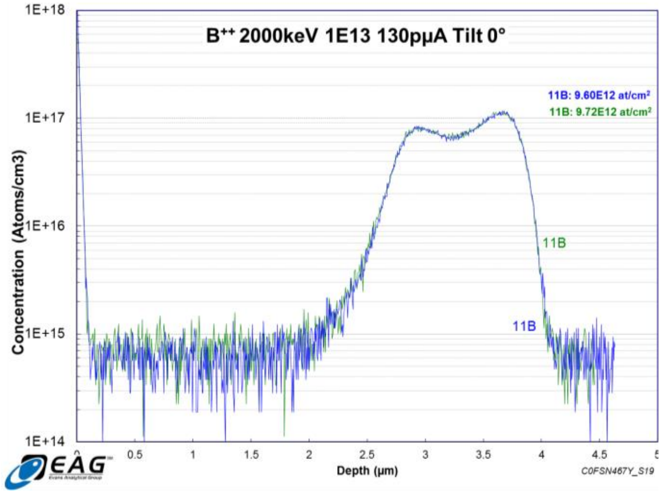

Fig. 7. SIMS depth profile, B++2000KeV, channeling condition

Fig.8 shows the Purity Analyzer time spectrum on the recipe. Again, the trace is also shown in expanded scale for detailed examination. Since the main beam is 2+, a possble EC would be 1+ with ¼*E energy and ½*Re(main). It would appear at +/- 0.5 in the relative (E/q) scale in the time spectrum.

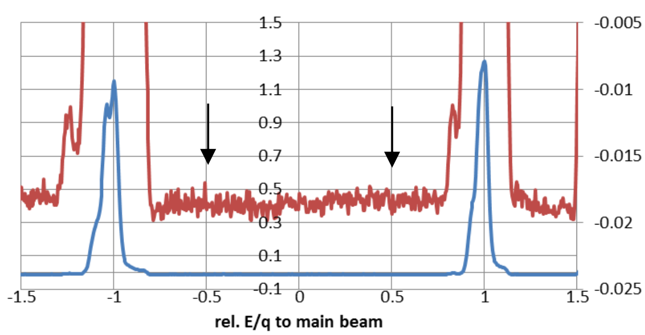

Fig. 8. Time Spectrum of Purity Analyzer on B++2000KeV

As we can see from the time spectrum, there is no traces of peaks at aroudn E/q= +/- 0.5, proving the absence of the ¼*E 1+ EC with the agreement with the SIMS depth profile.

V. Conclusion

An Energy Purity Analyzer based on the Purion XE Energy Tracking System was tested and good agreements with SIMS analysis were obtained.

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References

[1] Shu Satoh, Joseph Ferrara, Edward Bell, Shital Patel and Manny Sieradzki, "Optima XE Single Wafer High Energy Ion Implanter", Proceedings of the 17th Int. Conf. in Ion Implantation Technology, p. 273-276 (2008)

[2] Jonathan David, Shu Satoh, Kevin Wu, Cindy Geary and James Deluca, "Beam Energy Tracking System on Optima XEx High Energy Ion Implanter", Proceedings of the 19th Int. Conf. in Ion Implantation Technology, p. 364-367 (2012)

[3] R. Jayaram, Mass Spectrometry, Theory and Applications, Plenum Press, New York, 1966.

[4] L. M. Young, Parmela, LA-UR-96-1835, Los Alamos National Laboratory, 2002