

# Ultra Shallow Depth Profiling by Secondary Ion Mass Spectrometry Techniques

M. Anderle, M. Barozzi, M. Bersani, D. Giubertoni, P. Lazzeri

*ITC-irst, via Sommarive 18, 38050 Povo, Trento, Italy*

**Abstract.** Ultra shallow dopant profiles are one of the major challenges for ULSI silicon metrology. Following the ITRS 2002, the 90nm technology node will appear in 2004 along with the maximum drain extension in the range of 15-25 nm for both P-MOS and N-MOS devices. In this frame, a very abrupt junction with a decay length of 4 nm/decade is mandatory. A depth resolution better than 0.7 nm in profiling shallow implanted dopants is consequently required. In this review, after a brief summary on necessities and difficulties of (N-MOS) ultra shallow profiling for the 90 nm technology node, we present a comparison between two Secondary Ions Mass Spectrometry (SIMS) approaches using different instruments (Magnetic Sector and Time of Flight Spectrometers) for the characterization of arsenic ultra shallow profiles. A particular relevance is dedicated to the methodological optimization and data processing, mainly in quantification and depth scale determination. Quantitative SIMS results have been compared with complementary techniques like LEXES, MEIS and RBS.

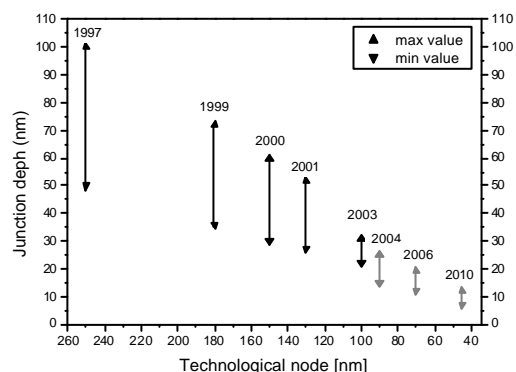
## INTRODUCTION

Ultra shallow profile characterization is nowadays one of the main metrology topics in microelectronics device production [1, 2, 3].

As shown in figure 1, the junction depth in the last 5 years scaled down more than a factor 2, in a technology development that systematically anticipated the road map short term forecasts.

Secondary Ion Mass Spectrometry has been considered as the most suitable tool to obtain dopant depth profiles because of its sensitivity and precision [2, 4, 5]. Nowadays, the new technology requests for ultra shallow profile characterizations have severe analytical requirements, especially in the dynamic range extension, in the quantification accuracy improvement, and in the depth scale calibration. Fast time response in SIMS analyses is also an important issue [1, 6].

The early works on ultra shallow junction (USJ) formation and characterization by SIMS have been focused on boron as a dopant, for technological and metrological reasons [2]. In the last 5 years the metrological studies have also been extended to arsenic ultra shallow profiles. But only since 2001 have we observed a wide and systematic interest on these topics [7, 8, 9]. However results sometimes are not in good agreement.



**FIGURE 1.** Junction depth vs. technology nodes.

The next step in microelectronics production is the 90 nm technology node [10]. This N-MOS generation devices require a junction depth ranging from 15 to 25 nm, with a lateral abruptness of 4.1 nm/dec. Ultra low As implant energies and suitable thermal treatments (Flash RTA) have to be used to obtain 90 nm NMOS junctions with the correct sheet resistance. The required As implant energy is between 1 to 3 keV with dose of the order of  $1 \times 10^{15}$  at/cm<sup>2</sup>.

To completely characterize this NMOS junction, several features of the arsenic profile have to be defined. First of all, the junction depth has to be measured with an accuracy better than 10%. Also the As profile distribution and the total dose have to be estimated. Moreover checking the wafer uniformity in the range of 1% is required.

To obtain this information by SIMS measurements, the following analytical conditions are required: a depth resolution of 0.4-0.8 nm, an altered layer below 1nm; a detection limit below  $1 \times 10^{17}$  at/cm<sup>3</sup>; a quantification accuracy better than 10% and a repeatability of less than 1%.

In the last ten years, great efforts have been done in order to develop adequate instruments which can accomplished the previously reported analytical requirements [1]. The main goal was to introduce mass spectrometers able to produce sub-keV impact energy primary beams in order to reduce the width of the initial transient and to find a suitable depth resolution.

The traditional magnetic sector instruments have also offered advantages like high transmission and high mass resolution, but at the same time they suffer by the fact that the high extraction field acts as a retarding (in positive secondary ion mode) or as an accelerating potential (in negative secondary ion mode). In the arsenic shallow depth profiling, where the best detection limit is reached by using cesium as primary beam and monitoring secondary negative ions, the only way to overcome this problem was by lowering both source acceleration voltage and secondary extraction field [11]. The consequence is a poor detection limit and the determination of the junction depth is precluded in most of the cases. Problems are also associated with the analysis by oxygen beam. In fact, even though the measurement of dose is more accurate [2], the detection limit hinders the possibility to obtain the junction depth. Moreover the recommended normal incidence analysis [12] is precluded and the oblique incidence angle could heavily influence the depth resolution because of the rapid onset of roughening [13]. The new generation of magnetic sector instruments, such

as Cameca Wf, overcomes these problems by the introduction of a floating primary column together with a screened extraction field [14].

The quadrupole mass spectrometers allow to appreciable reduction of the roughness problems because of the possibility to change the incidence angle keeping fixed the impact energy. The best analytical condition can be determined for both oxygen and cesium primary beams in order to have good depth resolution, avoid roughness formation, and reach good detection limits. The limitation of this class of mass spectrometers is the low mass resolution with consequently poor detection limit for species such as arsenic or phosphorus in silicon.

The use of Time of Flight (TOF) SIMS in shallow depth profiling has been growing rapidly after the introduction of the 'dual beam' mode by Benninghoven et al. [15]. The measurement is accomplished using a sputtering beam, usually a reactive species beam, and a gallium beam for the analysis. This configuration allows independent optimization of sputtering condition and detection features. The sputtering beam in shallow depth profiling is set at low impact energy whereas the analysis beam can be at high impact energy as long as the beam intensity is low. The introduction of the so-called 'three-lens' analysis gun allowed very low detection limits [16].

In this contribution a characterization approach for As USJ profiling using the new Cameca SC Ultra instrument is presented. A particular relevance is dedicated to the methodological optimization and data processing, mainly in quantification and depth scale determination. These experimental data are compared with those obtained by employing TOF SIMS. Quantitative SIMS results have been compared with complementary techniques as LEXES, MEIS and RBS.

## EXPERIMENTAL

Arsenic implants in monocrystalline silicon at different energies and annealed samples have been measured. Table I lists the measured samples with the respectively used analytical techniques.

The dynamic SIMS profiles have been carried out by using the new magnetic sector CAMECA SC-Ultra apparatus. This instrument is equipped with a floating voltage primary column coupled with a new secondary extraction system [14]. The primary

column biased at a floating voltage allows impact energy variations without changes in the ion optical electronics, therefore with unchanged primary beam transmission. Cesium primary beam monitoring secondary negative ions has been used. The monitored species were  $^{28}\text{Si}^{75}\text{As}^-$ ,  $^{28}\text{Si}_2^-$  and  $^{28}\text{Si}^-$ . Different primary impact energies have been tested.

**TABLE I. Samples list and analytical techniques.**

Sample	nominal dose and energy	Ann.	SIMS	RBS	MEIS	TOF	LEXES
As @ 5 keV	1E14@5keV	--	v	v			v
	3E14@5keV	--	v	v			v
	6E14@5keV	--	v	v		v	v
	1E15@5keV	--	v	v			v
	6E14@5keV	Yes	v	v			v
As @ 3keV	6E14@5keV	Yes	v	v			v
	2E15@3keV	--	v	v	v	v	v
	2E15@3keV	Yes	v	v			v
	2E15@3keV	Yes	v	v		v	v
As @ 1keV	2E15@1keV	--	v	v			v

The acquisition area was  $100 \times 100 \mu\text{m}^2$  inside of a  $300 \times 300 \mu\text{m}^2$  sputtered crater. In table II, the main analytical conditions are reported. The Cs primary beam current was around 10 nA, the raster size was fixed at  $250 \times 250 \mu\text{m}^2$  with 30% of electronic gate.

The TOF-SIMS arsenic profiles have been obtained by using TOF SIMS IV (ION-TOF). A Cs beam set at 0.5 keV impact energy and delivering 39 nA of current has been used for sputtering. The analyzing beam was Ga at 15 keV and 4.6 pA, with an impact angle of  $45^\circ$ .

Low Energy X-ray Emission Spectroscopy (LEXES) and Medium Energy Ion Scattering (MEIS) are both nondestructive analytical techniques which provide absolute dose values. These measurements are not significantly affected by the surface transient regions typical of the SIMS depth profiles. The LEXES analyses have been performed at the CAMECA laboratories. This technique (also called “shallow probe”), is particularly suited to determine the dose of shallow implanted dopants, with precision even lower than 0.1% for arsenic implants [17].

**TABLE II. Analytical conditions at different impact energies.**

Impact Energy	Floating Voltage	Sample Bias	Impact Angle
1 keV	-5 kV	-3 kV	$45^\circ$
0.5 keV	-5.5 kV	-3 kV	$44^\circ$
0.3 keV	-4.7 kV	-3 kV	$35^\circ$

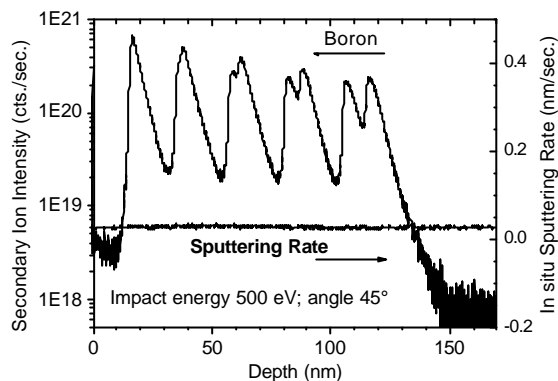
MEIS is based on the same physical principles as RBS, but the lower energy allows a great improvement in the depth resolution [18]. This refined technique gives a simultaneous measurement of atomic mass (with higher sensitivity for heavy masses), depth (with atomic layer depth resolution in favorable cases) and atomic structure (with selectivity between crystals and defects). The experiments have been carried out at the University of Salford MEIS facility using 100keV  $\text{He}^+$  ions incident along the  $[-1-11]$  channeling direction and the  $[111]$  and  $[332]$  blocking directions.

## RESULTS AND DISCUSSION

The main analytical issue when profiling As shallow implants is the necessity to obtain an adequately reduced impact energy for the primary beam, in order to enhance the depth resolution. The instrumental parameters used for the SC-ultra measurements have been calibrated using reference

samples. The first one was boron delta-doped Si multilayers grown by Reduced Pressure Chemical Vapor Deposition (RP-CVD) at a temperature of  $725^\circ\text{C}$ , provided by CEA LETI, Grenoble [19]. It consists of 5 pairs of B deltas, each pair being separated from the other by 15 nm of Si. In every pair the B peak distances are 1, 2, 3, 5 and 8 nm moving from the surface toward the bulk of the sample. The second sample was a Ge monolayer deposited on monocrystalline silicon by MBE.

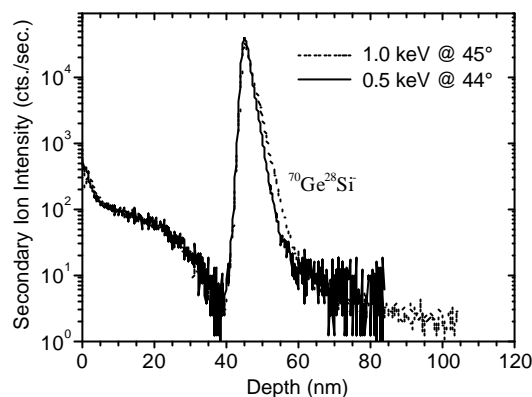
The analysis on the first sample allows evaluation of roughness and sputtering rate variation induced by the primary beam. As shown in Figure 2, at 500 eV of impact energy, the 3 nm spaced pair is resolved and the decay lengths for all the pairs are constant with the depth. Therefore no evidence of roughness formation has been detected. This is in a good agreement with previous works where, at the same energy, roughness occurred at an angle larger than  $55^\circ$  [9, 20].



**FIGURE 2.** Boron delta layers profiled by Cameca SC-Ultra using Cs primary beam. For the quantification we used  $1.32 \times 10^{19}$  at/cm<sup>3</sup> B uniformly doped sample.

Moreover, the in situ sputtering rate measurement by laser interferometer (reported in figure 2) revealed a constant sputtering rate during the entire profile. In this profile the decay length ( $1/e$ ) is enhanced by knock on effects because of the light mass of boron. Figure 3 reports the delta Ge profiles performed at two impact energies. In this case it is possible to evaluate the correct decay length for the two analytical conditions. The upslope decay length ( $\lambda_u$ ) is the same for both of the impact energies used with a value of 0.5 nm. The downslope decay lengths ( $\lambda_d$ ) gives 1.8 and 1.4 nm for 1 keV and 0.5 keV analyses respectively.

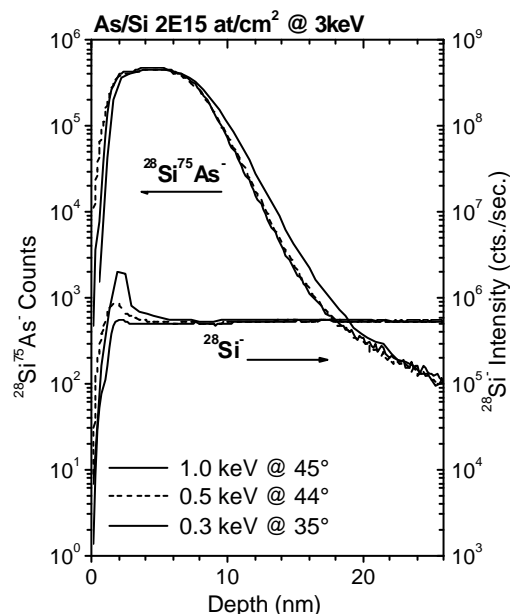
To optimize the analytical condition for ultra shallow As profiling different impact energy conditions have been tested on implanted samples at 3 and 1 keV. In figures 4 and 5 As SIMS profiles in counts/sec performed at different energies are reported. The depth calibration was obtained measuring the sputtering rate by laser interferometry. As shown in figure 4, the profiles performed at 1 keV or lower impact energies present tiny differences. The same measurements carried out on As 1 KeV implanted silicon sample (Figure 5) show the profile at 1 keV of primary impact energy quite different from the 0.3 and 0.5 keV profiles. In this case the use of lower impact energy is consequently mandatory to obtain reliable profiles. The variation of the Si signal is due to the different sputtering rate in the first part of the profile. Therefore the optimized SIMS analytical conditions for as implanted and annealed samples have been determined.



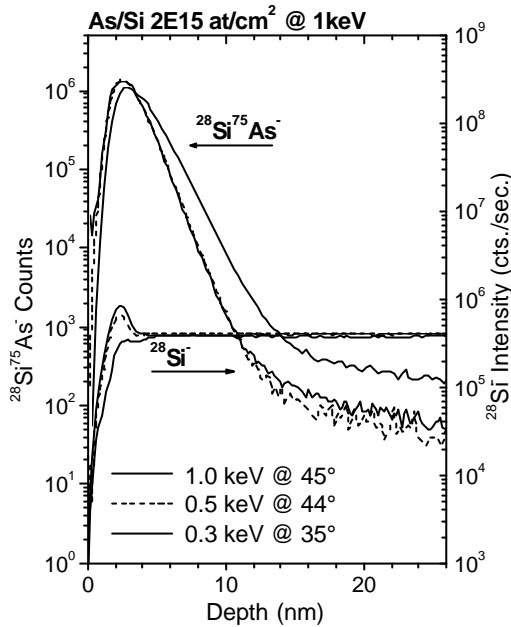
**FIGURE 3.** Ge delta layer profiles.

## Quantification

In a typical SIMS profile until the steady state is reached, we have a transient region in which the concentration of the primary beam ions, cesium in our case, increases. This region is known as the altered layer and it mainly depends on the primary ion beam energy and incident angle. The quantification of arsenic ultra shallow junctions is consequently not an easy step. In fact the distribution of dopant is usually very close to the sample surface and the initial transient width can include a relevant part of the total As amount. Besides the transient effects,



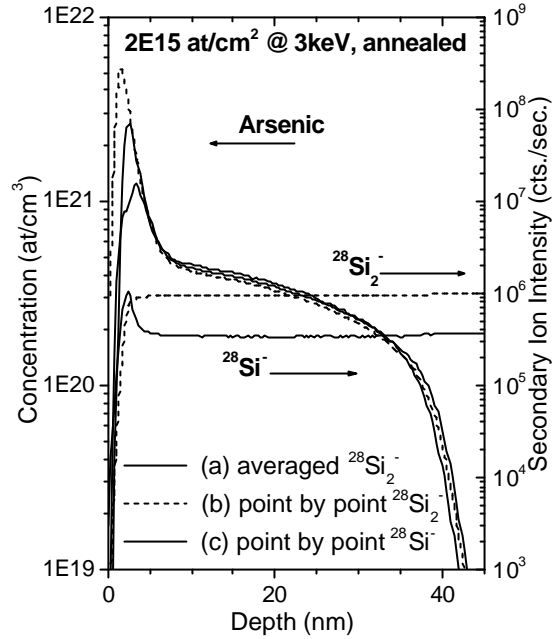
**FIGURE 4.** SIMS profiles at different primary ion energies of 3 keV As implanted silicon sample.



**FIGURE 5.** SIMS profiles at different primary ion energies of 1 keV As implanted silicon sample.

the silicon surface is often covered with a native or thicker oxide and the processing of data faces matrix effects. If we use a sub-keV primary beam in samples where a thicker oxide has been grown, e.g. after an annealing step in a partially oxidizing atmosphere, we can even suppose an initial transient region, an oxide region, an oxide/silicon interface and finally the silicon steady state. In each of these regions the ion yield and the sputtering rate can notably vary so to affect the quantification. In the attempt of overcoming these problems as a first step we corrected the profiles using three different normalization methods [5]: (a) normalization with the average intensity of  $^{28}\text{Si}_2^-$ , (b)  $^{28}\text{Si}^{75}\text{As}^-/^{28}\text{Si}_2^-$  'point-by-point' normalization, (c)  $^{28}\text{Si}^{75}\text{As}^-/^{28}\text{Si}^-$  'point-by-point' normalization.

Another quantification issue is related to the high arsenic concentration region. In fact to ensure low electrical resistivity the shallow implants are usually performed at very high fluence. In "non-shallow regime" (100 keV  $^{75}\text{As}$  implanted silicon, analysis with a 3 keV Cs beam) Tomita et al. [5] report that monitoring  $^{28}\text{Si}^{75}\text{As}^-$  and normalizing "point-by-point" to  $^{28}\text{Si}_2^-$  ensures a Relative Sensitivity Factor (RSF) in silicon constant against arsenic concentration ranging from  $5.8 \times 10^9$  to  $5.8 \times 10^{21}$  at/cm<sup>3</sup>. This means that the ion yield remains constant. They obtained similar results monitoring  $^{75}\text{As}^-$  and normalizing "point-by-point" to  $^{28}\text{Si}^-$ . Nevertheless the  $^{75}\text{As}^-$  ion shows less ion yield than



**FIGURE 6.** Arsenic annealed sample profiled by using 1 keV impact energy. The quantification uses three different normalization methodologies.

$\text{SiAs}^-$  giving a non adequate detection limit for determining the junction depth. Moreover the  $^{75}\text{As}^-$  exhibits a spike near the surface that masks the true distribution [14]. For these reasons, to characterize As shallow profiles we monitored  $\text{SiAs}^-$  species.

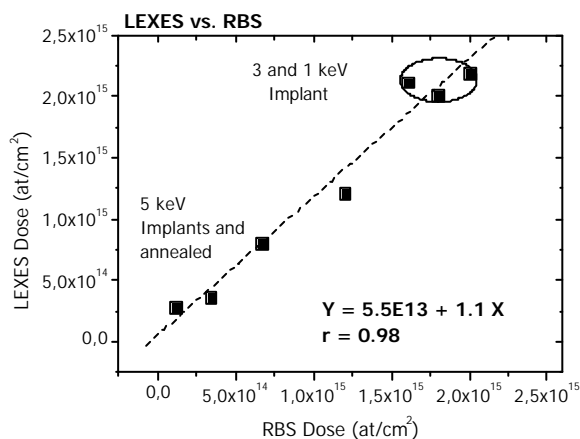
Figure 6 shows arsenic profiles obtained at 1 keV of primary beam impact energy on an annealed 3 keV implant (nominal dose  $2 \times 10^{15}$  at/cm<sup>2</sup>). The RSF was determined by analyzing a 5 keV implant in silicon. In such a sample the arsenic distribution is far from the surface and the quantification turns out less affected by the surface effects. It is evident from the figure how the chosen normalization method affects the measured arsenic distribution close to the surface and consequently the dose measurement. The As peak measured by method (b) is five times greater than the one measured by (c).

## LEXES

An indication of the appropriate method of normalization can be given only by comparing the SIMS quantification with the results obtained by alternative techniques. LEXES (low energy x-ray emission spectroscopy) can be a suitable comparison test for this class of samples. We measured the samples reported in Table I by SIMS with two analytical conditions (1 keV at 45° of incidence and

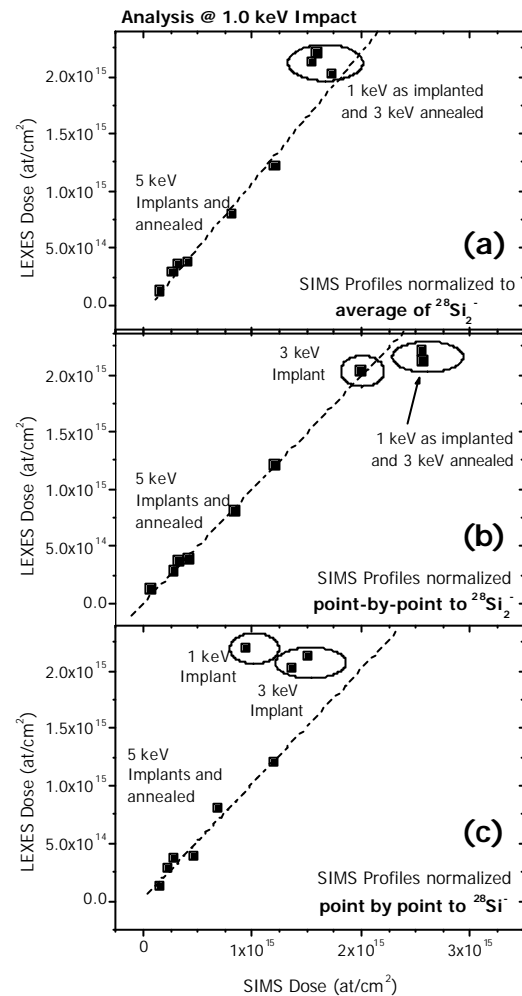
at 0.5 keV at 44°) monitoring  $^{28}\text{Si}^{75}\text{As}^-$ ,  $^{28}\text{Si}_2^-$  and  $^{28}\text{Si}^-$ . Then we quantified the profiles obtained using the three methods previously defined. The results have been compared with the dose values measured by LEXES. Before this we checked the accuracy of the LEXES quantification by comparing the measured doses with the values measured by RBS. Figure 7 reports arsenic dose measured by LEXES against the values obtained by RBS. The good linearity obtained (correlation coefficient  $R = 0.98$ ) is indicative of the accuracy of LEXES.

Figures 8 and 9 show the LEXES measured doses against the SIMS values determined by methods a), b) and c) with impact energy of 1 and 0.5 keV respectively. The linear fits reported have been calculated without including the 1 keV and the 3 keV samples. At 1 keV of primary beam energy all the methods give a good correspondence of determined doses for the 5 keV implants, but only methods a) and b) measure the right dose for the 3 keV as implanted sample. All the methods fail the quantification for the 1 keV as implanted and the 3 keV annealed samples, i.e. the samples with the higher arsenic concentration close to the surface or the surface oxide. Method b),  $^{28}\text{Si}^{75}\text{As}^-/^{28}\text{Si}_2^-$  ‘point-by-point’ normalization, overestimates the total amount of dopant, whereas method c),  $^{28}\text{Si}^{75}\text{As}^-/^{28}\text{Si}^-$  ‘point-by-point’, underestimates it. Both the methods look unable to manage the first nanometers quantification and surprisingly the best agreement is obtained by normalizing to a constant as the average intensity of  $^{28}\text{Si}_2^-$  (method a)).



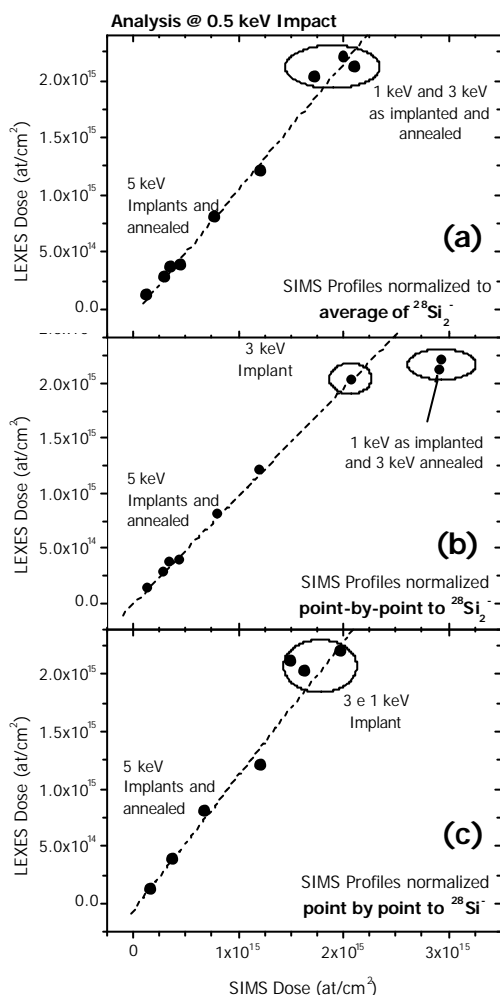
**FIGURE 7.** LEXES vs RBS measured dose comparison.

At 500 eV of impact energy (reduced transient width) the accuracy of method a) looks even better than at 1 keV; method c) turns out more effective whereas the dose measured by method b) is definitely too high for the critical samples. Therefore the high arsenic spike revealed in Figure 6 for method b) is probably due to an artifact.



**FIGURE 8.** LEXES measured doses vs. SIMS values obtained using an impact energy of 1 keV and three different normalization methods.

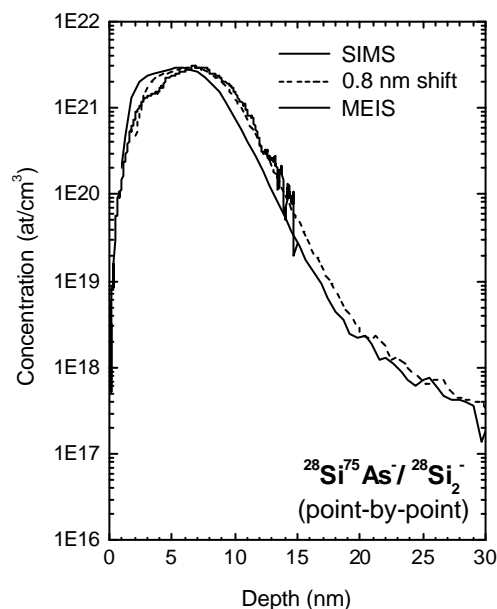
## MEIS



**FIGURE 9.** LEXES measured doses vs. SIMS values obtained using an impact energy of 0.5 keV and three different normalization methods.

From all these data it is difficult to define the appropriate quantification method in order to have a correct dosimetry by SIMS. The normalization with the average intensity of  $^{28}\text{Si}_2^-$  measures dose values in agreement with LEXES but it looks like a lucky compromise without considering the variations of the ion yield and sputtering rate at the surface. Further studies will be necessary in order to investigate the role of the oxide at the surface. It is worth noting that information different from the dose measurement, e.g. the junction depth, could be determined anyway. In fact the normalization method affects the first nm's of the curves but the 'steady state' part of the profiles will be the same if the RSF has been determined from a suitable standard, i.e. an arsenic distribution not too close to the surface.

In order to evaluate the accuracy of the methodology we compared the SIMS profiles obtained at 1 keV of impact energy on 3 keV As implanted silicon samples with the MEIS profile. The result is shown in Figure 10. The thin continuous curve is the SIMS profile obtained by normalizing the curve "point by point" to the  $^{28}\text{Si}_2^-$  signal and determining an RSF from the analysis of a 5 keV implanted sample. Two facts are evident: both SIMS and MEIS measure the same value of peak concentration but the SIMS curve looks shifted towards the surface. The dashed curve is obtained adding 0.8 nm to the depth of the SIMS profiles. The agreement of the peak concentration and of the descending part of the profiles is very good. It looks like in the initial part of SIMS analysis there was a shrink of the real profile due to an underestimation of sputtering rate. Nevertheless, apart from the initial part of the profile, the agreement between SIMS and MEIS profiles is very encouraging. Therefore technologically important information like the junction depth can be determined by SIMS but care must be paid by considering this 0.8 nm shift. Anyway the good reproducibility of SIMS analysis ensures that this depth shift will affect all the SIMS profiles and therefore the relative comparison of the measured junction depth of several samples will be self consistent.

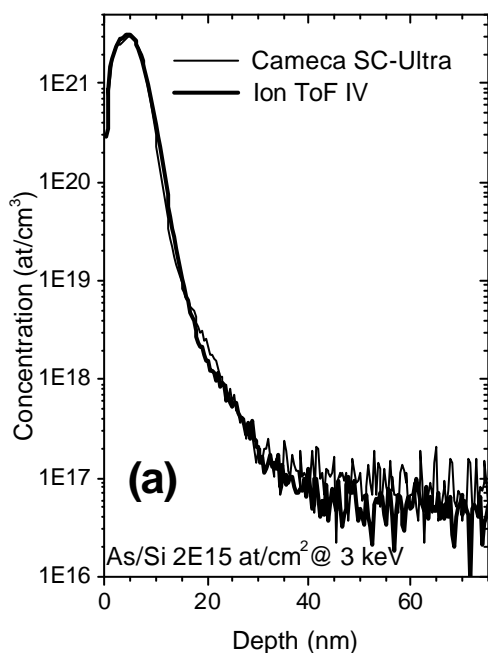


**FIGURE 10.** Comparison between MEIS and SIMS profiles of 3 keV As implanted silicon sample. The Cs impact energy in SIMS analysis was 1 keV.

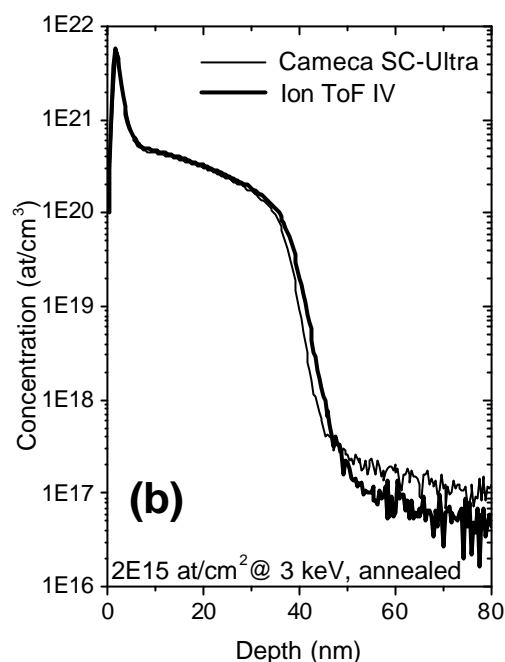
Measurements on arsenic shallow depth profiles done by using a quadrupole SIMS with oxygen primary ions at normal incidence [21] do not show this shift but in that case the sensitivity limit is around  $2 \times 10^{18}$  at/cm<sup>3</sup> and the SIMS profile decay length is worse than that obtained by MEIS analysis.

## TOF SIMS

Finally we compared the profiles obtained by magnetic sector SIMS with the ones obtained by ToF SIMS. Both the instruments utilized are at the present state of art of SIMS technology. Figures 11 a) and b) show the results obtained on 3 keV,  $2 \times 10^{15}$  at/cm<sup>2</sup>, As implanted and annealed silicon samples respectively. The magnetic sector analyses have been performed with a Cesium primary beam at 500 eV of impact energy and 44° of incidence angle. The TOF SIMS analytical conditions were previously described in the experimental section. All the profiles were quantified by determining an RSF from a 5 keV arsenic implanted silicon sample. The magnetic sector data were normalized 'point-by-point' to  $^{28}\text{Si}_2^-$  whereas for the ToF data normalization was "point-by-point" to  $^{30}\text{Si}$ .



**FIGURE 11A.** Comparison between ToF and Magnetic Sector SIMS profiles of 3 keV As implanted silicon sample.

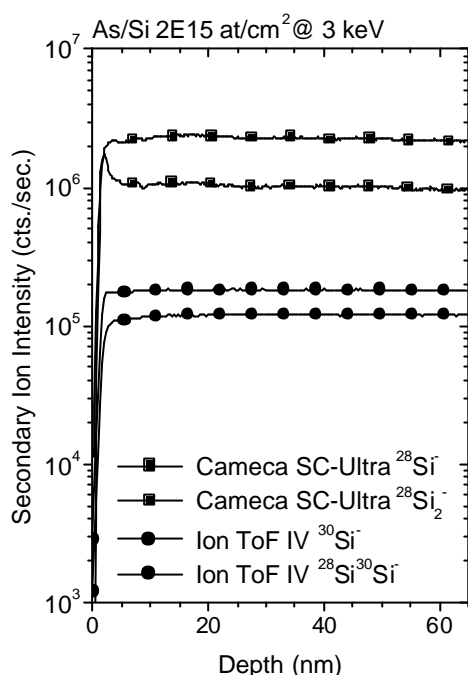


**FIGURE 11B.** Comparison between ToF and Magnetic Sector SIMS profiles of 3 keV As implanted and annealed silicon sample.

Despite the different normalization methods adopted, the profiles obtained by the two instruments are nearly identical. The detection limit is comparable and the shape of As distribution is the same. Even the surface spike in the annealed sample is the same. From the LEXES comparison we saw that the height of this spike is related to the normalization method. Here two different normalizations surprisingly give the same high surface concentration.

Figure 12 reports the matrix signals measured by the two mass spectrometers. There is no evidence of a surface spike in the ion signals recorded by TOF-SIMS. On the contrary the matrix signal detected by magnetic sector dynamic SIMS shows strong variation at the surface especially for monoatomic ions. The reason for this different behavior could be related to the different mechanism of secondary ion emission. In fact in TOF-SIMS analysis possible variations of sputtering rate due to Cs bombardment are not related to the monitored secondary ions, their amount being determined only by the Ga analysis beam. Anyway the agreement in the profiles by the two instruments is an evident confirmation of the results obtained.





**FIGURE 12.** Matrix signals recorded by magnetic sector and ToF SIMS at the same impact energy (500eV).

## CONCLUSIONS

The 90 nm technology node requires accurate and highly reproducible dopant profile characterization. In particular the junction depth is the most important parameter to determine. SIMS is still the analytical technique of choice to obtain ultra shallow dopant profiles. 1 keV and sub keV cesium oblique primary beams with an impact angle between  $55^\circ$  and  $45^\circ$  are the suitable analytical conditions to measure arsenic profiles. No sputtering rate variation or induced roughness has been detected using this approach. The detection limit of routine analyses with a magnetic sector instrument, around  $1 \times 10^{17}$  at/cm<sup>3</sup>, allows proper determine the junction depth. 1 keV impact energy is adequate to measure 5 and 3 keV arsenic implanted and annealed silicon samples. For shallower profiles sub keV conditions are required. Dose evaluation is obtainable by SIMS if only a small fraction of dopant lies in the altered layer. Sub keV analyses and any normalization do not permit an accurate determination of the total dose on 1 keV arsenic implanted and annealed silicon samples. In this case the use of complementary analytical techniques is required. Magnetic sector SIMS and TOF SIMS analyses on arsenic shallow implants are in good agreement.

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