

Dose Quantification for Ultra Low Energy (ULE) Shallow Implants by SARIS™ Laser Ablation ICP Mass Spectrometry

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This article describes an alternative dose analysis methodology for ultra low energy (ULE) ion implantation. Although typically the domain of SIMS, the coupling of laser ablation (LA) for sampling and detection via inductively coupled plasma (ICP) mass spectrometry as SARIS™ permits advantages and functionality not previously available. Spatial and temporal separation of sampling and ionization by utilizing two powerful plasma sources results in much more efficient ionization and more quantitative measurements with less matrix effects. In addition, measurement of dopant doses by SARIS™ LA ICP-MS is not based on depth profiling, thus its data reliability is no longer dependent upon depth resolution. The ion yield variations associated with the near-surface transient region and the effects from co-implanted species such as fluorine that SIMS encounters are completely avoided in SARIS™ measurements. Advantages also include extremely fast sample analysis and the simultaneous availability of all metallic contamination concentrations without ion source modification.

The Challenge

As seen from the International Technology Roadmap for Semiconductor (ITRS) [1], the source/drain junction depth is being reduced each year in order to continue MOS transistor scaling. This year leading-edge foundries and integrated device manufacturers (IDMs) are scheduled to move 65 nm processes into pre-production, while simultaneously developing 45 nm processes in R&D. In designing and manufacturing such VLSI devices, the junction depth needs to be kept below 50 nm and doping concentrations in the channel must be high and accurate. To obtain an ultra shallow junction, the most fundamental trend in the ion implantation world today is to move implant energies lower so that possible surface damage and channeling can be minimized [2]. This trend makes the determination of ultra shallow junction depths and implant doses increasingly difficult.

Determination of implant dose is critical for foundries and IDMs to examine dose retention during implantation and annealing processes, and to calibrate and correlate ion implanters used in different processes within different fabs. Commonly, secondary ion mass spectrometry (SIMS) is used to determine implant doses, where accuracy is strongly dependent upon its depth profiling capability, depth resolution, consistency of ion yield and sputtering rate, and compatibility of the reference standards. As implantation energy decreases and the critical depth for analysis becomes tenths of nm or shallower, depth resolution provided by SIMS is gradually becoming marginal relative to the analysis depth, and exact matrix-matched standards are difficult to find. Additionally, many effects that are insignificant to the dose measurement by SIMS when profiling deeper implants have now become profound. For example, near surface equilibrium phenomenon in the transient region (within the first few nm from surface at least) and ion yield variations associated with native oxide present on wafer surfaces can now all affect the accuracy of the dose measurements by SIMS. Although it remains one of the best depth profilers for junction depth determination, SIMS is apparently approaching its fundamental and physical limitations as a dose measurement tool.

SARIS™ LA ICP-MS

SARIS™ LA ICP-MS (see Figure 1) has been applied diversely in the semiconductor, electronics and disk drive industries [3-4]. When it is used for total implant dose confirmation, its measurement approach is not based on depth profiling, thus its dose data reliability is no longer dependent upon depth resolution. The reduction in implantation energy and junction depth has little and no negative effect on its dose measurement capability. In fact, ULE implants make the SARIS™ analysis even less challenging because laser sampling does not have to penetrate very deep and ICP-MS signal for the same implant at a given dose is actually more intense because of less signal dilution by silicon. LA involves the conversion of solid materials into a plume of neutral atoms, ions, and micro particles by focusing a high-powered and pulsed laser beam onto a wafer surface. The laser in this arrangement is solely used for sampling and the ions directly produced by the laser are not detected. The plume of materials quantitatively generated by LA is transported in an argon carrier gas to the steady-state ICP plasma (~10,000 K) for efficient atomization/ionization (Figure 1). With such an energetic ionization source,

there are few molecular ions and doubly charged ions formed and the mass interferences that SIMS usually encounters [5] are no longer an issue. The ions formed in the ICP are essentially atomic and dominated by singly charged positive ions, which are directly proportional to dopant doses implanted in silicon. These atomic ions are subsequently analyzed by a mass spectrometer, either quadrupole based or via a high-resolution magnetic-sector based.

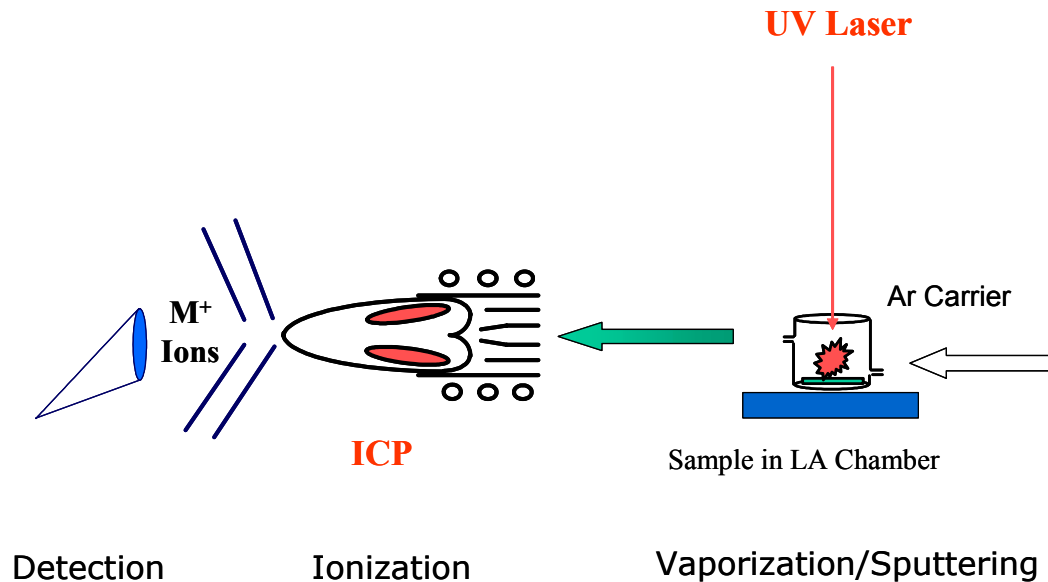


Figure 1. Conceptual diagram of laser ablation ICP mass spectrometry (LA ICP-MS).

Figure 2 shows a schematic diagram of laser sampling process on a wafer and a representative ICP-MS signal profile obtained with a ULE boron shallow implant. The laser sampling depth chosen for the dose measurement is typically a little bit deeper than implant depth to ensure that nearly 100% of the dopant in silicon is ablated within the selected sampling area. As shown in the figure, the $^{11}\text{B}^+$ signal begins rising immediately after the pulsed laser beam is directed onto the wafer surface, reaching the maximum and then leveling off to form a plateau while the laser continuously rasters across the wafer surface. After the laser is switched off, the signal quickly decays to baseline without showing much tailing.

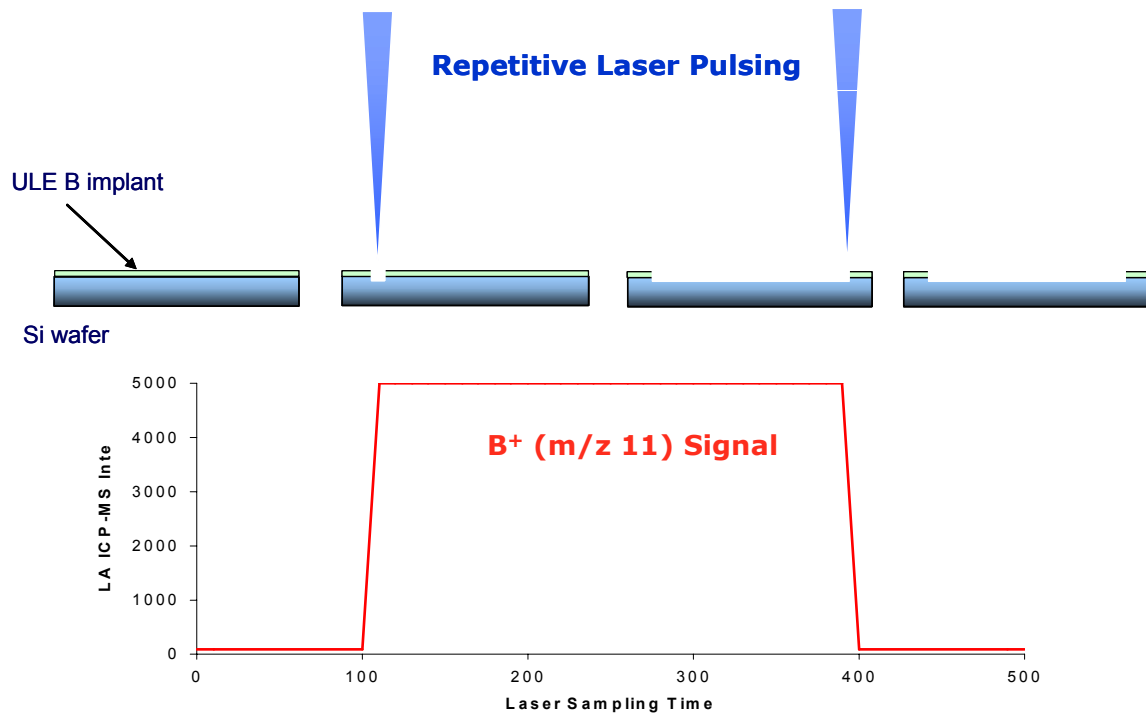


Figure 2. Schematic diagram of laser ablation wafer sampling process and representative ICP-MS signal profile obtained with a ULE shallow boron implant.

Calibration and Standardization

With the availability of NIST traceable solid standards developed in our laboratory, SARIS™ LA-ICP-MS has been found to be suitable for quantifying ULE implant doses. Usually a minimum of three wafer standards are ablated prior to any implant dose measurements to establish a relationship between the signal intensities and implant doses. The signal intensities (either averaged plateau or integrated area under the signal profile) and implant doses were found to be linearly related and their relationship may be expressed as simple and straightforward as

$$Y = aX + b$$

where Y is the SARIS™ signal intensity and X is total implant dose with a and b the slope and intercept of the linear calibration curve. For the dose calibration and measurements, neither complicated calculations nor corrections are necessary. Calibration curves constructed for $^{11}\text{B}^+$, $^{31}\text{P}^+$, $^{75}\text{As}^+$, and $^{121}\text{Sb}^+$ implants have correlation coefficients

typically better than 0.995, and their linear dynamic ranges are many orders of magnitude.

Accuracy and Precision Assessments

Sample wafers are analyzed under exactly the same condition as calibration standards. The accuracy and analytical precision of SARIS™ have been assessed using low energy and ultra low energy $^{11}\text{B}^+$ and $^{75}\text{As}^+$ implants. The representative results with $^{11}\text{B}^+$ implanted at 0.5 keV and $^{75}\text{As}^+$ implanted at 20 keV are presented in Table 1. As shown, the SARIS™ results are in excellent agreement with the nominal doses calculated based on ion implanter beam currents and the length of time for implant. The load to load repeatability or precision is around 2-3%.

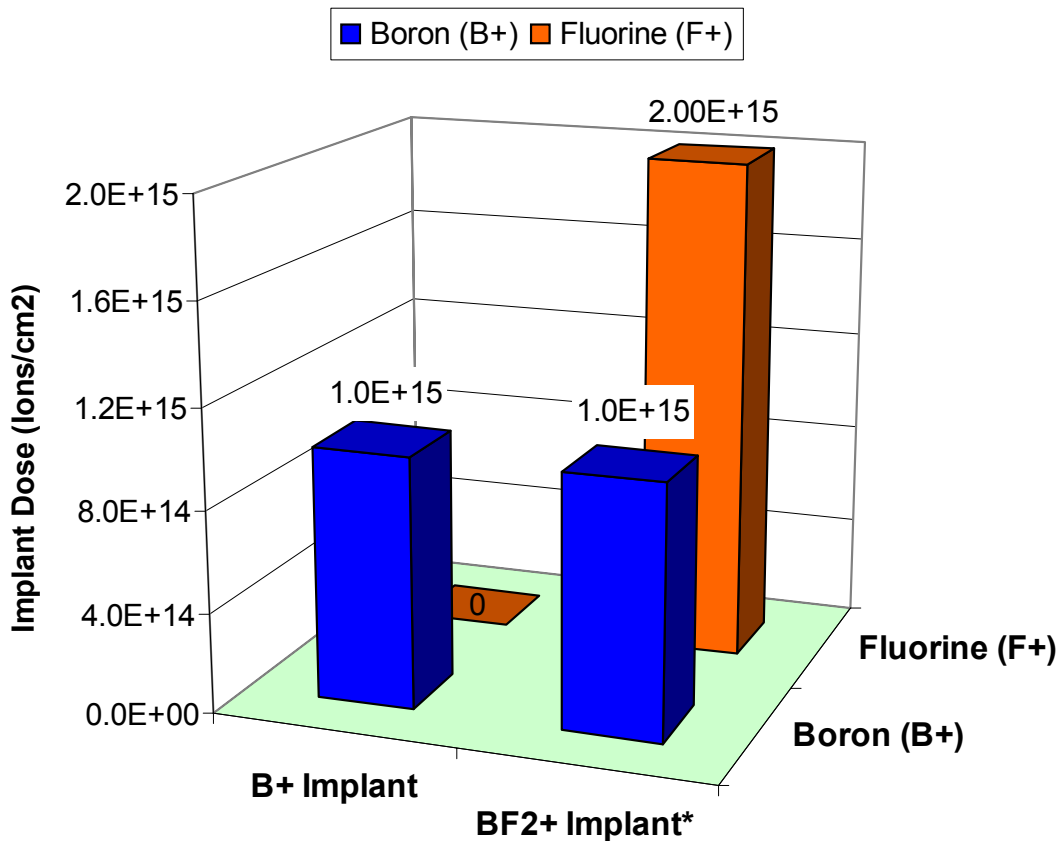
Table 1. Total dose results obtained using SARIS™ laser ablation ICP-MS

Ultra Low Energy B ⁺ Implants (0.5 keV)				Low Energy As ⁺ Implants (20 keV)		
Wafer No.	Expected (Ions/cm ²)	Found (Ions/cm ²)	Difference %	Expected (Ions/cm ²)	Found (Ions/cm ²)	Difference %
1	8.0 E14	8.25 E14	3.1 %	1.0 E15	1.1 E15	10%
2	2.0 E15	2.10 E15	5.0 %	2.0 E15	2.0 E15	0%
3-1	1.5 E15	1.58 E15	5.1 %	6.5 E14	6.6 E14	1.5%
3-2	1.5 E15	1.51 E15	0.7 %	6.5 E14	6.4 E14	1.5%
3-3	1.5 E15	1.55 E15	3.6 %	6.5 E14	6.3 E14	3.0%
3-4	1.5 E15	1.51 E15	0.7 %	6.5 E14	6.5 E14	0.0%
3-5	1.5 E15	1.51 E15	0.7 %	6.5 E14	6.8 E14	4.6%
	Average	1.53 E15	2.2 %	Average	6.5 E14	0.0%
	S.D.	0.03 E15		S.D.	1.9 E13	
	R.S.D.	1.99 %		R.S.D.	2.9 %	

Co-implant Matrix and Annealing Effect Studies

It is important to note that the solid sampling and ionization in direct wafer analysis are two fundamentally different processes requiring very different optimization conditions [3]. Unlike SIMS analysis which typically utilizes a single ion beam, SARIS™ employs

two powerful plasma sources (a laser and an ICP), spatially and temporally separating its ionization from the sampling process (see Figure 1). By doing so, sampling and ionization can be independently optimized resulting in much more efficient ionization and more quantitative measurements with less matrix effects. The advantages of SARIS™ can be seen when analyzing high dose BF₂ implants, which usually present a special challenge with the SIMS technique [5]. Because the highly electronegative fluorine in silicon can enhance yields of positive secondary ions during conventional SIMS analysis, a special compensation technique called “O₂-leak” or “Oxygen flood” has to be used by SIMS analysts to reduce this enhancement effect [5]. Figure 3 shows the results obtained by SARIS™ with low energy B⁺ and BF₂⁺ implanted at 1.0 E15 atoms/cm². Because no fluorine matrix effect is observed, identical dose results were obtained for both implants.



* F+ doses were provided by ion implantation company

Figure 3. Results obtained for low energy B⁺ and BF₂⁺ implanted at identical dose. There is no fluorine effect with SARIS™.

The effect of thermal annealing was also studied using SARIS™. Figure 4 shows SARIS™ results with low energy As⁺ implanted at 2.0 E15 atoms/cm² before and after a thermal annealing process. The identical dose concentrations (2.1 E15 atoms/cm²) indicate that SARIS™ results are not affected by thermal annealing. It should be pointed out that ⁷⁵As⁺ ions in As⁺ implants are directly and reliably measured by SARIS™ LA ICP-MS. Because the ICP ionization source produces essentially singly charged atomic ions, the ²⁹Si³⁰Si¹⁶O⁺ molecular interference at m/z 75 that SIMS encounters [5] was not observed in SARIS™ LA ICP-MS. Use of ¹⁰³AsSi⁻ ion for implant dose measurements by SIMS, especially for ULE implants, can also be problematic due to the presence of native oxides on wafer surfaces. In wafer cleaning and surface preparation, it is well known that control of native oxide growth on wafers is a very challenging issue [6]. The variation in native oxide on wafers can alter the ion yield of ¹⁰³AsSi⁻. In fact, both enhancement and suppression in ¹⁰³AsSi⁻ ion yield have been reported.

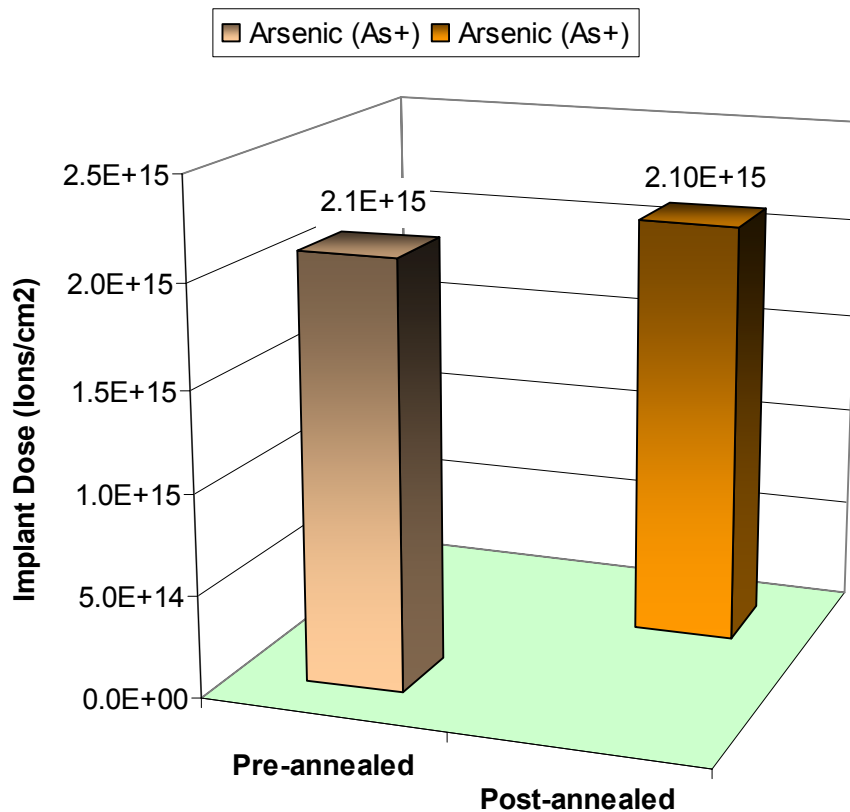


Figure 4. Results obtained with low energy As⁺ implanted at identical dose before and after thermal annealing; no difference is observed.

Simultaneous Analysis of Metal and Dopant Cross Contamination

Finally, in addition to dopant dose measurement for ULE ion implantation, SARIS™ LA ICP-MS can also be used to simultaneously monitor all metallic contaminants without ion source modification. The metal contaminants commonly found in the substrate during ion implantation include aluminum (Al), iron (Fe), chromium (Cr), nickel (Ni), and titanium (Ti). Inadvertent contamination due either to sputter erosion or implanter construction material out-gassing can adversely affect electric properties of devices. SARIS™ LA ICP-MS has also been found helpful for engineers in evaluating multi-purpose ion implanters to avoid unintentional dopant cross contamination during ion implantation.

Summary

Utilizing a different solid sampling strategy and an efficient ionization process, we have developed an alternative dose analysis methodology for quantitative analysis of LE and ULE shallow implants. Although typically the domain of SIMS, the coupling of LA for sampling and detection via ICP-MS as SARIS™ permits advantages and functionality not previously available. These advantages include extremely fast sample analysis and the simultaneous availability of all metallic contamination concentrations without ion source modification. More importantly, quantification of total dopant doses by SARIS™ LA ICP-MS does not depend on depth profiling resolution and surface condition, thereby ensuring the measurement accuracy for ULE implants. Total dose data obtained by SARIS™ LA ICP-MS for shallow $^{11}\text{B}^+$ and $^{75}\text{As}^+$ implants are presented in this paper along with results that show SARIS™ is not affected by surface oxides on the wafer, thermal annealing process, or the presence of co-implanted species such as high concentration fluorine, a feature very important when analyzing high dose BF_2^+ ion implants.

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