

SIMS Modular Approach To Ultra-Low Energy Implants For Accurate TCAD Process Simulation Modeling

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Abstract – The use of technology computer-aided design (TCAD) for IC design, technology development and semiconductor fabrication has grown. The motivation of new users of TCAD is to solve technology problems in the shortest time possible and at the lowest cost. TCAD programs allow process flows, as well as device and circuit performance to be simulated using a combination of simulation tools. TCAD modeling of MOS (metal oxide semiconductor) and bipolar technologies requires selective SIMS (secondary ion mass spectrometry) measurements for calibration. In this work we present the SIMS modular approach to TCAD simulation modeling. We will illustrate the principle of the SIMS module approach with examples of ULE implants of boron, arsenic, and phosphorus that were unannealed and annealed. Our study showed that for a given S/D (source/drain) implant, several combinations of SIMS instruments and analytical conditions were needed to extract different criteria of the implant. In general, magnetic sector spectrometers are required for surface accuracy and quadrupole spectrometers are required for improved depth resolution.

I. INTRODUCTION

MOS (metal oxide semiconductor) integrated circuit technology is currently heading towards very short transistor channel lengths of the order of 0.1 microns. To fabricate these devices very shallow S/D (source/drain) implants with energies as low as 1 keV and below, are necessary [1]. SIMS continues to be the most widely used technique for characterizing S/D implants [2]. However, new SIMS instrumentation and analytical approaches must be developed for SIMS to remain the analytical technique of choice.

In this work we present the SIMS modular approach to S/D engineering and TCAD (technology computer-aided-design) modeling. The principle of the SIMS modular approach is illustrated with examples of ULE implants of boron, arsenic, and phosphorus that were unannealed and annealed. Our study showed that for a given S/D implant, several combinations of SIMS instruments and analytical conditions were needed to extract different criteria of the implant.

II. SIMS MODULAR APPROACH

A dynamic SIMS analysis is a “package” comprised of a mass spectrometer and an analytical protocol. Quadrupole and magnetic sector instruments are two types of mass spectrometers that are frequently used. And, there are many SIMS analytical protocols. With the many possible combinations of mass spectrometers and analytical protocols, it is often difficult to agree on what is the correct SIMS analysis. The SIMS modular approach addresses the circumstance that for a given sample, several SIMS analyses may be required depending on the criteria of interest. For example, the criteria of the experiment may be for surface quantitative accuracy or for junction depth determination. There will generally be one SIMS analysis that may be optimized to characterize the criteria of interest. The SIMS modular approach therefore evolves around the different combinations of mass spectrometers and analytical protocols.

A. SIMS Mass Spectrometer

Two types of mass spectrometers are commonly used for ion implant characterization [2]. They are the quadrupole and magnetic sector instruments. Fig. 1 shows their relationship for dynamic SIMS applications within the SIMS family tree.

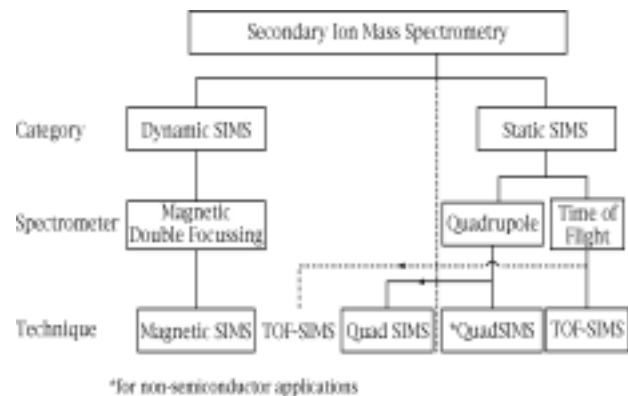


Fig. 1. SIMS family tree.

The key features of the quadrupole and magnetic sector instruments for implant characterization are as follows. Quadrupole instruments have low energy (≥ 200 eV), primary ion bombardment capability. This capability derives from their static SIMS heritage and allows them to perform analyses with excellent depth resolution (≤ 3 nm). The strength of magnetic sector instruments is their high mass resolution capability, ≥ 8000 mass resolving power. This asset allows them to measure arsenic and phosphorus with excellent detection limits ($\leq 1 \times 10^{15}$ at/cm²). As a passing remark, Time-of-Flight SIMS (TOF-SIMS) is presently under development for dynamic SIMS applications [3,4].

Table 1 shows three important features of quadrupole and magnetic sector spectrometers that can influence the accuracy of ultra-shallow implant measurements. It is important to realize that the quadrupole instruments can control the primary ion energy and incidence angle independently. This capability is key to optimizing instrumental conditions for sputter rate changes, surface roughening, and depth resolution [5]. With the magnetic sector instruments (e.g. Cameca), both these variables are interrelated.

TABLE I

COMPARISON OF QUADRUPOLE AND MAGNETIC SIMS CAPABILITIES FOR ULTRA-SHALLOW IMPLANT MEASUREMENTS

Quadrupole	Magnetic Sector
Low mass resolution	High mass resolution
Variable primary incident angle (0° - 90°)	Predetermined incident angle (21° - 65°)
Primary beam energy (0.20-12 keV)	Primary beam energy (1.8 - 22 keV)

B. SIMS Analytical Protocol

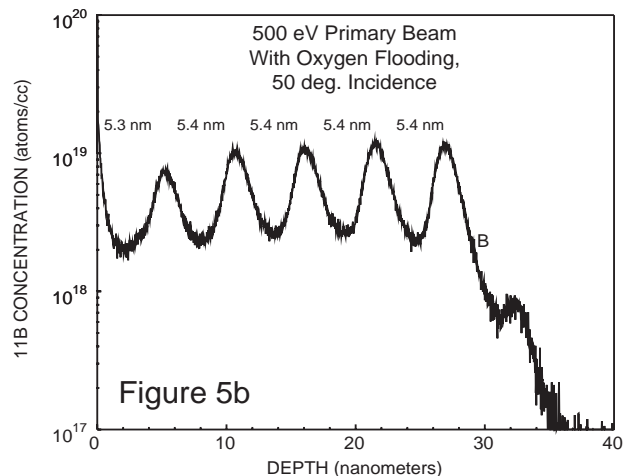
There are many SIMS analytical protocols. For example, (I) ASTM F 1366 - a test method for measuring oxygen contribution in heavily doped silicon substrates; (II) ASTM F 723 - a test method for measuring boron contamination in heavily doped N-type silicon substrates, and (III) ASTM F 1617 - a test method for measuring surface sodium, aluminum, potassium, and iron on silicon and Epi substrates. Some protocols, such as ASTM F 1366 and F 723, may be performed only with a specific SIMS instrument type. Other protocols, such as ASTM F 1617, may be performed with either type of SIMS mass spectrometers. The point being made, for our discussion here, is that the SIMS instrument type can be an integral part of the analytical protocol.

The choice of a particular analytical protocol invariably depends on the type of mass spectrometer available. Only very well equipped analytical laboratories will possess the full suite of SIMS instruments. In practice, identical results can be observed using any type of mass spectrometer operating with a specific analytical protocol. Similarly, with the same

type of mass spectrometer identical results can be attained using different analytical protocols.

For ultra-shallow implant measurements, it is essential there be no sputter rate changes and surface roughening during the SIMS analysis, typically to a depth of 10 nm. Quadrupole instruments are most suited to this type of application because of their capability to optimize beam energy and incidence angle independently. Atomika, a quadrupole instrument manufacturer, has stated that accurate measurement of ultra-shallow boron implants can be made at normal incidence (O_2^+) without oxygen flooding [6]. Magee et al. [5] recently used a MBE sample with 5.4 nm internal marker layers to demonstrate accurate measurements taken with a PHI quadrupole instrument at 50 degrees incidence to the surface normal (O_2^+ , 500 eV) with oxygen flooding. Clearly, if the correct analytical protocol is used, either quadrupole instruments by the two manufacturers is appropriate for ultra-shallow implant measurements.

Fig. 2. Boron profile of five-delta layer sample taken at 500 eV, O_2^+ bombardment at 50 degrees, with oxygen flooding.



III. EXPERIMENTAL

Boron, arsenic, and phosphorus implants in silicon are used as test samples to demonstrate the principle of SIMS Modular Approach. The SIMS measurements were made using a PHI 6650 equipped with a low energy, primary ion gun (125 eV/atom) and an upgraded Cameca 4f IMS. Cs^+ and O_2^+ primary ion sources were available on both instruments. Ion counts were converted to concentration using relative sensitivity factors calculated from reference implant materials. Boron secondary implant standards were calibrated to a Standard Reference Material, NIST SRM #2137, providing an absolute accuracy of $\pm 6\%$. Arsenic and phosphorus secondary implant standards were calibrated to a consensus reference implant material, ConRef, providing an absolute accuracy of $\pm 15\%$. The data acquisition time was converted to depth by measuring the analytical crater depths using a Tencor P-10.

IV. RESULTS AND DISCUSSION

A. Boron

Fig. 3 shows an overlay plot of four $^{11}\text{B}^+$ implants of 5, 2, 1, and 0.5 keV at 5×10^{14} at/cm in pre-amorphized silicon. Good depth resolution was achieved with a low O_2 primary beam energy of 500 eV with a quadrupole spectrometer.

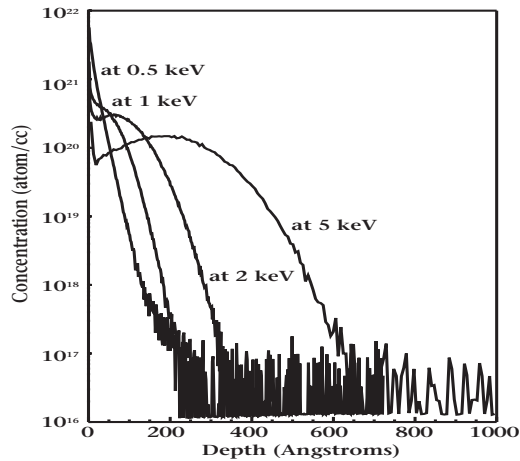


Fig. 3

Fig. 4 shows two depth profiles acquired from an annealed sample using magnetic sector and quadrupole spectrometers. If the criteria is for accurate distribution a quadrupole spectrometer with a low energy ion gun is the instrument of choice. However, if junction depth is the criteria a magnetic sector spectrometer is a better choice because the signal-to-noise ratio in the depth profile is lower and the sputter rate is higher (more samples can be analyzed in a given time). Fig. 3.

Fig. 4.

B. Arsenic

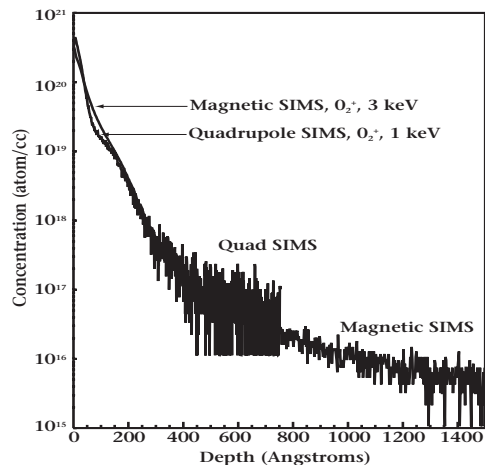


Fig. 5 shows an overlay plot of three SIMS profiles of arsenic implanted with 3×10^{14} at/cm² at 2 keV. It is evident from this figure that for extracting junction depths at 1×10^{17} at/cm³ a quadrupole spectrometer is required.

Fig. 5

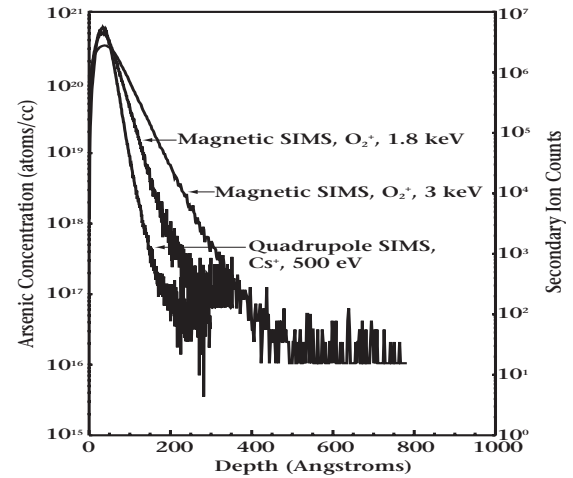


Fig. 6 shows depth profiles acquired with quadrupole and magnetic spectrometers of arsenic annealed at 1000°C for 10 s. Improved depth resolution is observed with a quadrupole spectrometer. However, accurate near-surface quantification and distribution are possible only with a magnetic spectrometer using high mass resolution. The quadrupole SIMS depth profile shows a molecular mass contribution of $^{30}\text{Si}^{29}\text{Si}^{16}\text{O}$ to mass ^{75}As at the near-surface and would result in an incorrect total dose value.

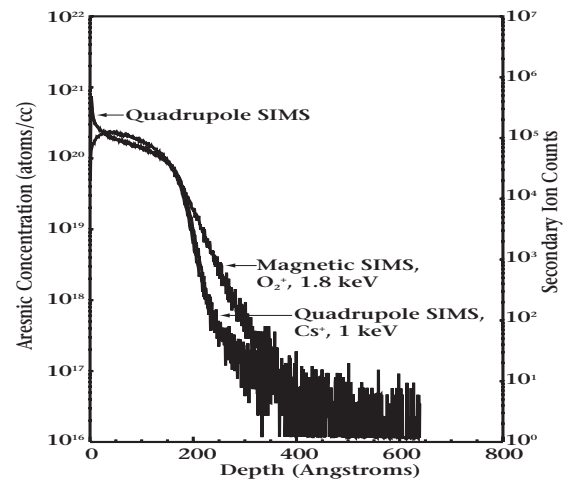


Fig. 6

C. Phosphorus

Fig. 7 and 8 illustrate that a magnetic sector spectrometer is the instrument of choice for near-surface quantification and junction depth determination. For near-surface accuracy, high mass resolution is required to mass discriminate $^{30}\text{Si}^1\text{H}$ from ^{31}P . This is apparent from the quadrupole SIMS depth profiles (unannealed and annealed samples) which show a high secondary ion signal at the near-surface. For the unannealed sample (Fig. 7) a lower detection limit is observed by the 1.8 keV magnetic SIMS depth profile compared to the 500 eV quadrupole SIMS profile with only a slight loss in depth

resolution. For the annealed sample (Fig. 8), a true distribution of the implant is acquired with either spectrometers as shown by the overlay of all three profiles acquired at different energies. The improved signal-to-noise ratio and detection sensitivity of the magnetic SIMS profiles provide for accurate junction depth characterization.

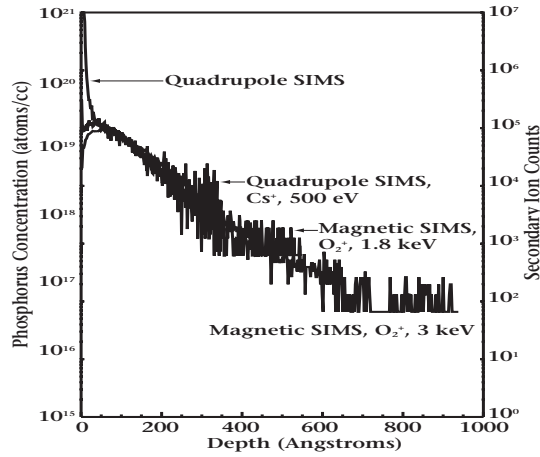


Fig. 7.

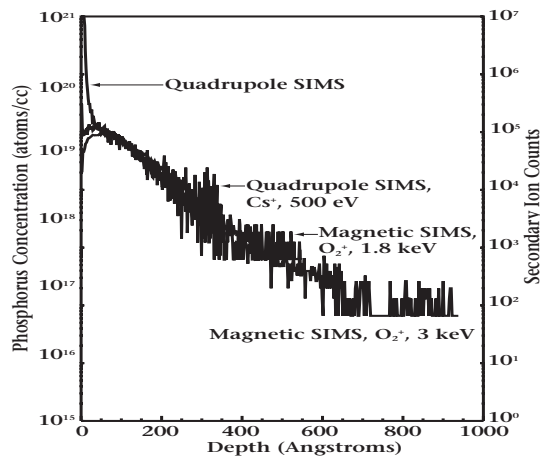


Fig. 8.

V. CONCLUSION

Many instrument parameters and protocols were evaluated to determine their validity for characterizing S/D implants. For source/drain engineering and TCAD modeling the SIMS modular approach provides the most accurate information by applying a specific analytical protocol to evaluate a specific criteria. In general, magnetic sector spectrometers are required

for surface accuracy and quadrupole spectrometers are required for improved depth resolution.

For example, to investigate junction depth and energy contamination a low primary ion energy is necessary for good depth resolution. Presently, this can only be accomplished using a quadrupole spectrometer. For surface quantitative accuracy and total dose measurements, a magnetic spectrometer is required with oxygen flooding during oblique O_2^+ primary ion bombardment. An advantage of this procedure is that high mass resolution may be used and the sputter rate is high and allows unannealed and annealed S/D

VI. REFERENCES

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