•Ultra-low impact energy sputtering using Dynamic Secondary Ion Mass Spectrometry

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1) Summary

- The Inductively Coupled Plasma Ion sources (ICP) provide SIMS profiling practical capability down to 75eV impact energy. The depth resolution of 0.5nm/decade is obtainable once reaching the steady state sputtering conditions.
- The first nm sputtering model needs refinement. The current model suggests a high sputter yield (removal rate) sputtering from the surface exponentially dropping to a steady state value. Thus, explaining the presence of so-called 'surface shift', the depth scale distortion observed as if the profiles are shifted toward the surface.
- The overall results show that the use of Extremely Low Impact Energy (EXLIE) conditions create near surface (depth < 2 nm) artifacts, shown as the high surface peak on the Boron depth profile. This surface peak increases while reducing the impact energy of sputtering ions.
- The comprehensive data treatment algorithm based on empirical model of sputtering and surface oxidation allows to interpret the results in some cases. The research is on-going to find sputtering conditions to minimize the near surface artifacts is needed.
- A first attempt is made using different sputtering species such as O_2, O, Ar, N2 and their mixture at low impact energy of 150eV. It is shown the steady state Si sputter yield can be increased, and surface to steady state sputter rate ratio is reducing. Thus, reducing so called 'surface shift', and eventually the surface peak within the Boron signal is reduced.

2) SIMS at Extremely Low Impact Energy

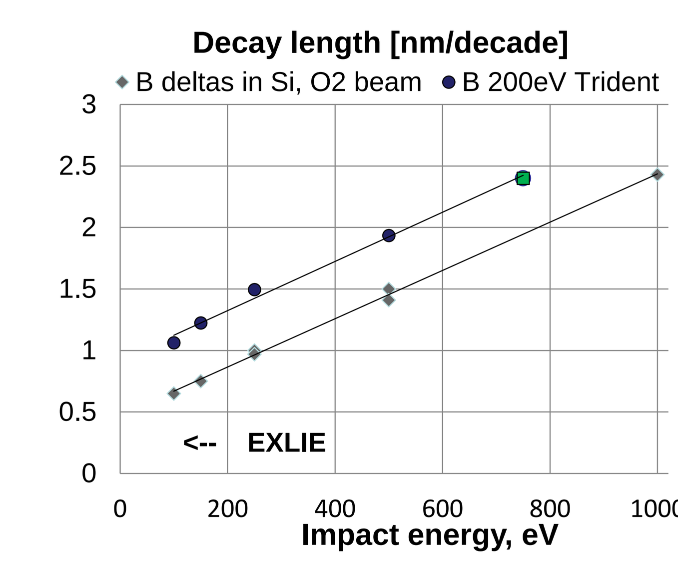


Figure 1 Depth resolution in steady state sputtering conditions is measured using B delta doped silicon standard and B implanted @200eV

Figure 2 presents the overlay of the Boron SIMS profiles recorded for O_2^+ of different impact energy in non-channeling Si implant

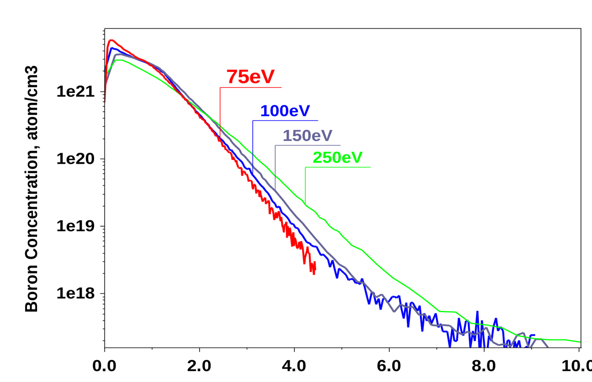
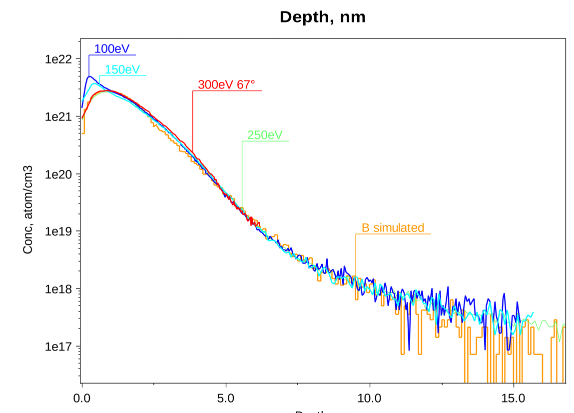


Figure 3 presents the overlay of the Boron SIMS profiles recorded for O_2^+ of different impact energy in channeling Si implant



- Main motivation for EXLIE SIMS is to increase the depth resolution, measured as the interface signal decay length in nm/decade**.**
- The lower impact energy produces the artifacts near the surface: the depth scale distortion and the surface peak, increasing with lower impact energy.

3) Sputter rate variation near surface under EXLIE conditions

- In order to correct for the near surface SR variation between Si and SiO_2, a concept of a **Sputter Rate Variation (SRV) curve** has been applied for the depth scale calibration procedure. It consists in a **point-to-point SR correction** based on the knowledge of **SR(Si), the ratio SR(SiO_2)/SR(Si)**.
- SRV correction technique does not address the origin of SR variation during the pre-equilibrium sputter regime. The surface shift and the initial spike are caused by an enhanced sputter yield in the transient. **SR correction function in transient region, in a generalized exponential form** as proposed in [1] is applied. Two SRV curves combination (steady state SiO_2/Si SR ratio and transient SR correction curves) allows accurately quantify a number of different samples cases: from native oxide on silicon to a relatively thick oxide layer on annealed implanted structure. Simplified formula for time to depth scale calibration is presented by the formula:

$$D(\tau)=\int_{0}^{\tau 1}(\beta e^{-\tau\cdot SR_{SiO2}/D_{trans}}+\int_{\tau 1}^{\tau 2} SR_{SiO2}(\tau)+\int_{\tau 2}^{\tau 3} SR_{SiO2/Si}(\tau)+\int_{\tau 3}^{\tau 4} SR_{Si}(\tau))d\tau$$

Where D_{trans} , β are empirical constants, SR_{SiO2} is the sputter rate in silicon oxide; SR_{Si} is the sputter rate in silicon, $SR_{SiO2/Si}(t)$ is the sputter rate variation law through the SiO_2 / Si interface. **[2]**

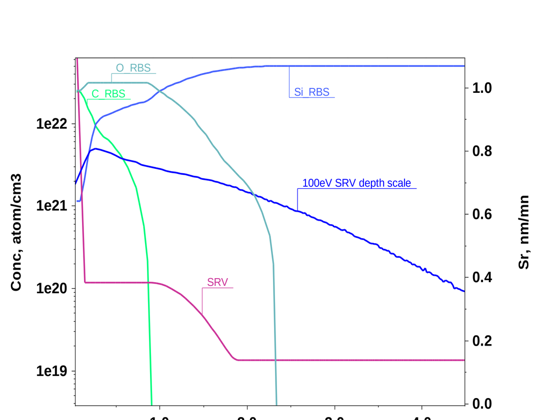


Figure 4: Sputter rate variation SRV curve near the surface. A correlation with C and O can be served for model refining

- The stoichiometry of the native oxide is very often unknown, with inclusion of organic and non-organic contaminations. The **Figure 4** profiles suggests the presence of Carbon in the termination layer. The high variability of sputter rate, and possible the ion yield, within the first nm might be correlated with carbon through unknown mechanism.

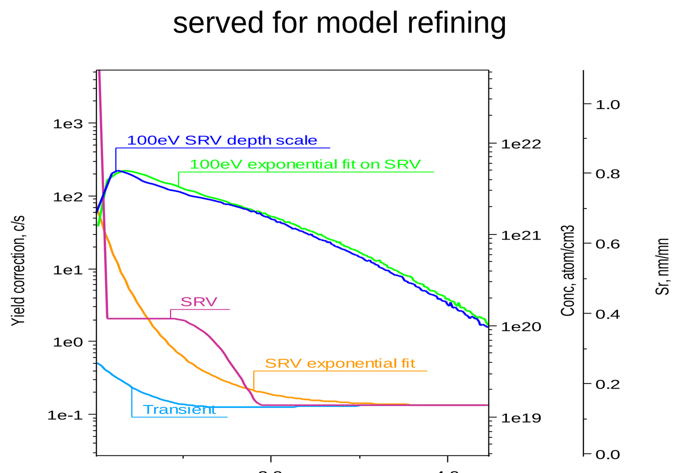


Figure 5: The SRV can be simplified using the exponential fit instead [1]. The transient function is a product of SRV and ion yield variation

- The sputter rate variation function can be replaced by its exponential fit, according to **[1]**.
- The application is limited to some native oxide terminated Si samples.

4) B correction under EXLIE conditions

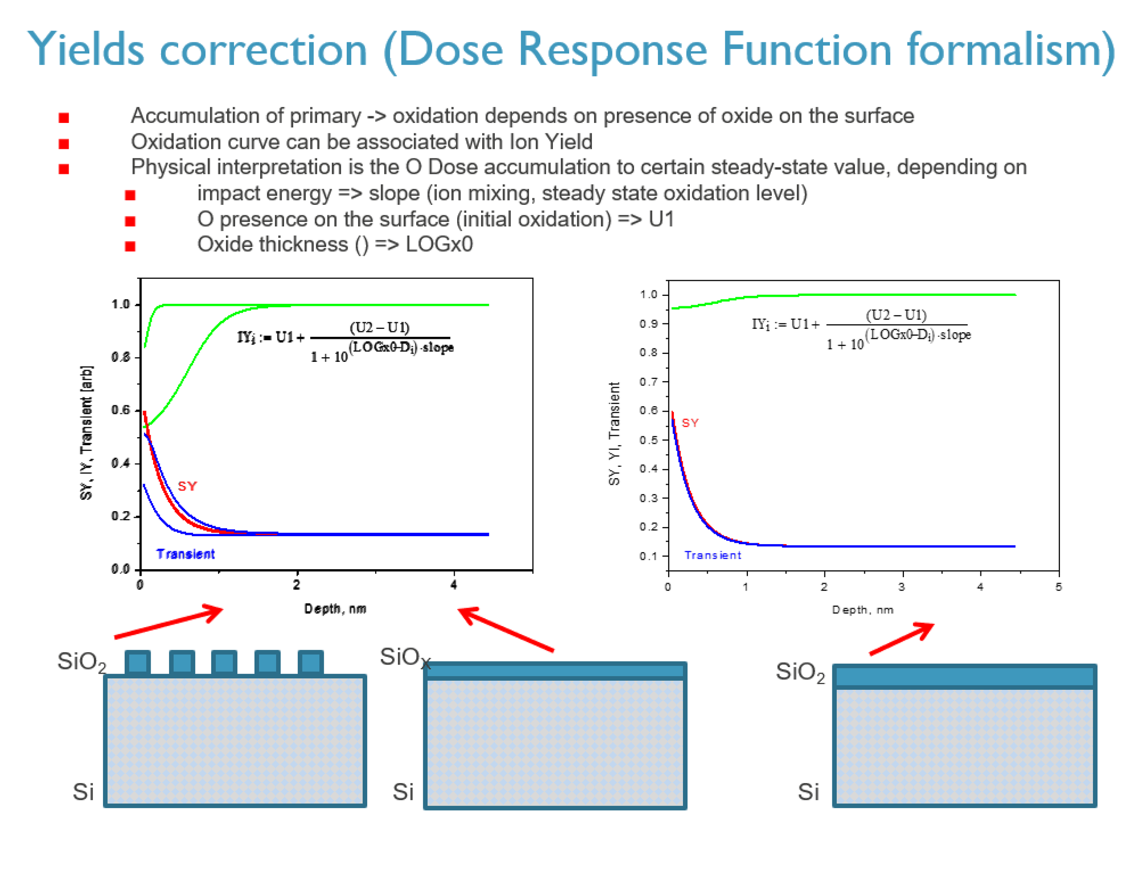


Figure 6 The transient function is a product of Sputter Yield and Ion Yield, taking into account the terminating oxide (soup) property and sputtering beam oxidizing dose.

- **Figure 6** presents the transient function creation based on sputter yield and ion yield variation curves product.
- The SIMS profile to be quantified by applying:

i) depth scale correction the Sputter yield variation function.

ii) concentration scale correction by normalizing the B^+ intensity point to point by transient curve (Sputter Yield x Ion Yield). Ion yield curve is empirically created using the native oxide properties and ion beam oxidation property (O fluence, energy, angle) using the dose response function formalism.

- The good agreement between the fully corrected SIMS profile and the ERDA profile gives a good confidence in the SIMS data for Boron 200eV implants through different native and thermal oxide layers.

5) EXLIE conditions development; non-oxidizing conditions research.

- Most results for very low impact energy sputtering with SIMS were obtained using O_2 + primary beam. This is to provide the surface oxidation to maximize the ion yield and, in some cases, reducing the surface roughness developing under ion beam. However, the use of extreme low impact energy regime is known for very low sputter rate in steady state sputtering, with big variation through the first nm stack containing so-called native oxide layer.
- The measurements of sputter yield at low energy regime using N_2, Ar and Ar+ N_2 gas mix with O_2 show the possibility to improve the sputter yield while using very low impact energy sputtering beam.

- The Sputter yield increases with O fluence reduction in the primary beam.
- The O_2(20%)+N_2(80%) and O_2(10%)/N_2(80%)/Ar(10%) gas mixtures are used in experiment.

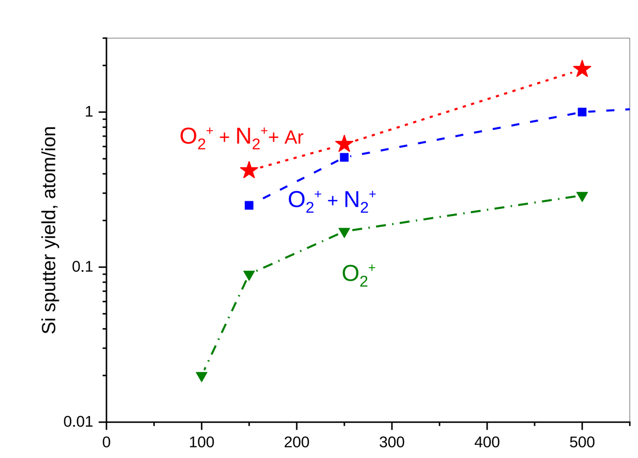


Figure 7 Si sputter yield on impact energy of primary bombardment species, including the monoatomic and molecular ions

- The non-oxidizing sputtering conditions produce less pronounced 'surface shift', the depth scale distortion due to high sputter rate in first seconds of sputtering. It is also reducing the ion yield variation, thus the high surface peak observed in Boron depth profile with extreme low impact energy.

- The Ar^+ and O^+ show biggest surface shift.
- The smallest surface shift is observed using the gas mix O_2(10%)/N_2(80%)/Ar(10%).
- The surface peak, related to the ion yield variation is reduced for Ar^+, O^+, and $(O_2+N_2+Ar)^+$ gas mixture. Thus, supporting the suggestion of oxygen fluence influence on sputter rate variation and ion yield variation within the first nm

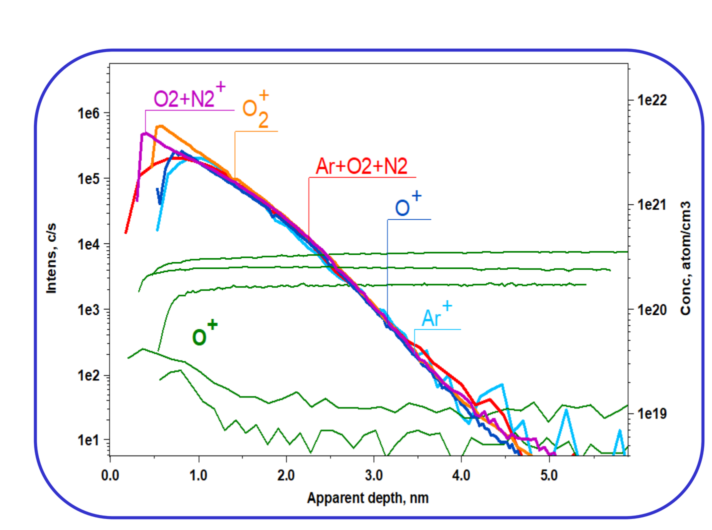


Figure 8 The B+ and O+ depth profile using 'apparent depth scale (using only SR at steady state) using 150eV sputtering conditions.

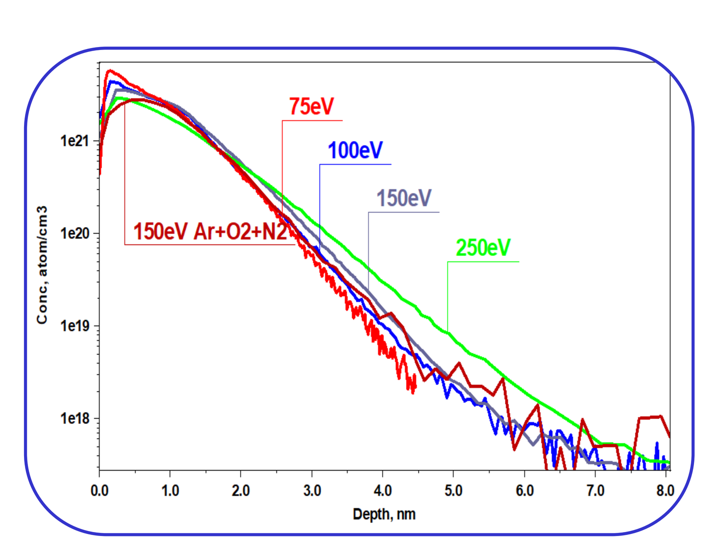


Figure 9 Boron depth profile with depth scale correction according to formula 1, varying the empirical constant β to match the known distribution shown in **Figure 2**.

- The less distorted depth Boron profile, in both scales, is obtained using the ion beam produced from the gas mixture: $(O_2+N_2+Ar)^+$.
- The real elemental composition of the beam needs to be controlled by primary beam mass filtering system.
- Production of the gas mix plasma is not trivial instrumental problem, which need to be addressed to benefit the experimental results above.

References: [1] M.G. Dowset at al. , Phys. Rev. B 65, 113412 (2002) , [2] A. Merkulov& al, pp.7215-7217, Surf. Interface Analysis, p522-524 , 43, 2011.