



Application of Deconvolution to Boron Depth Profiling in SiGe Hetero Structures

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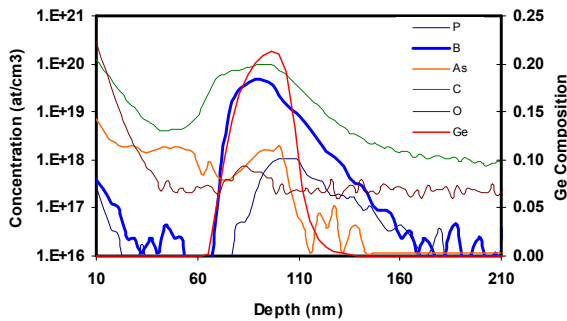
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Specialists in Materials Characterization

INTRODUCTION

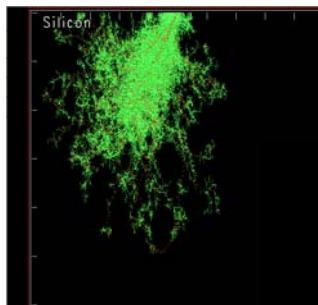
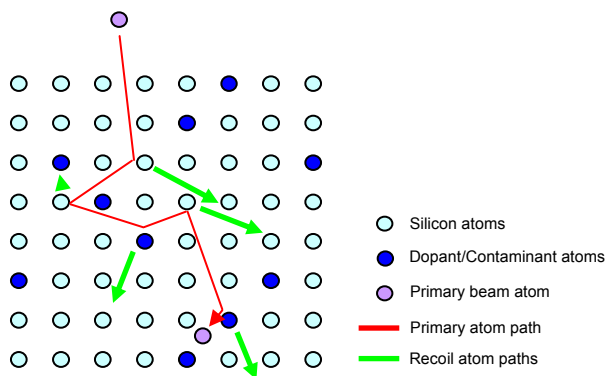
- The advantage: The analysis of SiGe heterostructures by SIMS using Cs ion bombardment is to provide information for all relevant species such as B, C, O, Si, P, As and Ge in a single profile.
- The challenge: Boron depth profile is distorted due to Cs enhanced chemical segregation.
- The solutions:
 1. Measure B with low energy O₂ bombardment.
 2. Use deconvolution to remove the chemical segregation effect due to Cs bombardment.

Figure 1: Si/SiGe/Si Heterostructure



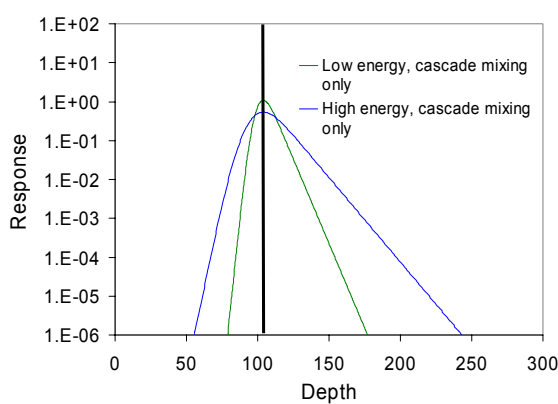
- Typical SIMS profiles acquired on a Si/SiGe/Si sample using a Cs primary beam.
- Boron profile exhibits a slow decay tail due to Cs enhanced chemical segregation.
- The tail is absent when O₂ primary beam is used.
- SiGe layer is graded and Ge composition fraction is shown referenced to the right axis.

WHAT IS ION BEAM MIXING?



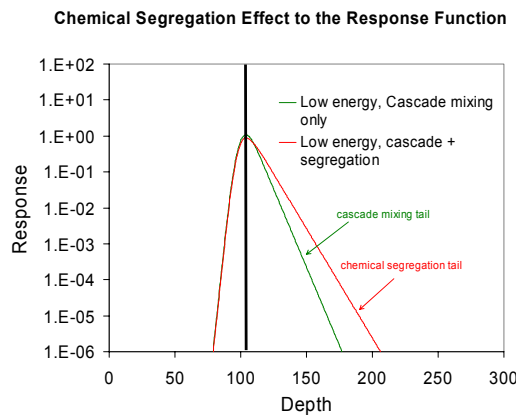
- Recoil collisions between the primary beam atom and the matrix atoms cause movement that is generally deeper.
- Cascade collisions between matrix atoms and matrix atoms cause movement in all directions.

SIMS Response Function

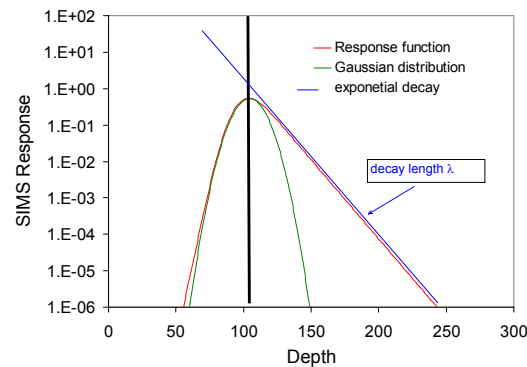


- Profiles of a delta doped sample show leading edges and trailing tails with different beam conditions.
- Heavy vertical line is the delta layer.
- The profile measured over a delta distribution is called the "SIMS response function".
- Cascade mixing widens the leading edge and trailing tail.
- The leading edge and trailing tail depend on the primary beam impact energy and the matrix.

WHAT IS ION BEAM MIXING?



- Chemical segregation only widens the trailing tail and has very little effect on the leading edge.



- The response function can be modeled with a Gaussian distribution at the peak, and with an exponential decay for the tail.

MATHEMATICAL MODEL OF THE SIMS RESPONSE FUNCTION

The SIMS response function, $G(x-x')$, is defined as the measured concentration at any given depth, x , in response to a delta doped tracer at depth, x' . For a uniform material system, the measured concentration depth profile, $N(x)$, can be expressed as a convolution of the true profile, $N_0(x)$, with its response function, $G(x-x')$:

$$N(x) = \int N_0(x')G(x-x')dx' \quad (1)$$

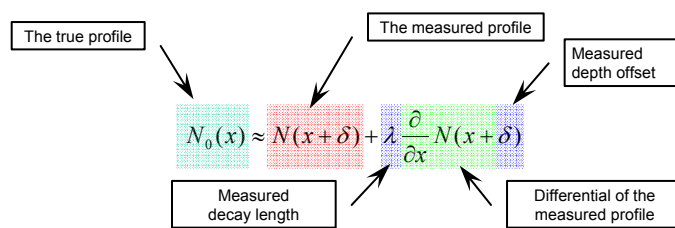
We are only going to model the exponential decay portion of the response function and can approximate this behavior as shown.

$$f(x-x') = \frac{1}{\lambda} \exp\left(-\frac{x-x'+\delta}{\lambda}\right) \quad x-x' > -\delta \quad (2)$$

By substituting (2) into (1) and solving for the true profile $N_0(x)$, we get.

$$N_0(x) \approx N(x+\delta) + \lambda \frac{\partial}{\partial x} N(x+\delta) \quad (3)$$

Reference: M.H. Yang & R. Odom, Mat. Res. Soc. Symp. Proc. Vol 669 2001 p. J4.16.1



How to determine λ and δ?

- Direct measurements of a delta doped sample.
- Determine λ from the decay tail where the ion mixing is known to be the dominating feature.
- Determine δ by aligning the deconvolved profile to a known feature.
- Energy sequence: measurements with multiple primary beam energies.

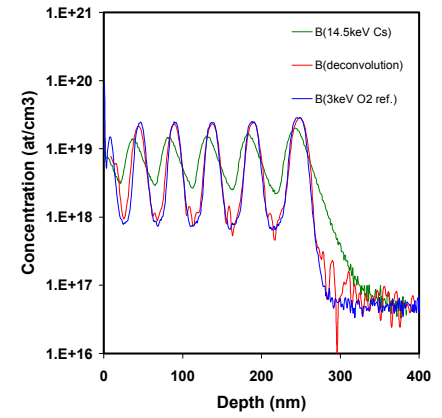
EXPERIMENTS

- SIMS measurements of a boron doped multilayer silicon sample using 14.5keV Cs bombardment on a Cameca 4f.
- SIMS measurements of boron in a Si_{0.7}Ge_{0.3} sample using 14.5keV Cs bombardment on a Cameca 4f.
- SIMS measurements of boron doped Si/SiGe/Si heterostructure sample using 3keV Cs bombardment on a Cameca 6f.
- B profiles were also measured with 3keV O₂ bombardment and are used as references to represent "true" B distributions. The ion mixing from the 3keV O₂ is sufficiently smaller than any feature size observed in the samples used in these experiments.

EXPERIMENTS

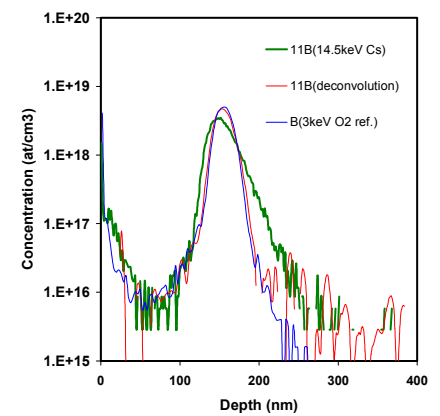
Deconvolution of Boron Profile in Silicon

- Silicon matrix
- Decay length $\lambda = 12$ nm, determined from the tail slope.
- $\delta = 12$ nm, determined by alignment of the deconvolved profile with the "true" profile measured using 3keV O₂.
- Comparison of the deconvolved profile and the "true" profile shows excellent agreement.



Deconvolution of Boron Profile in SiGe

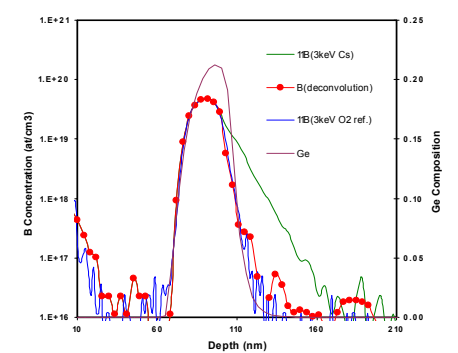
- SiGe matrix
- Ge composition is 30%.
- $\lambda = \delta = 14.5$ nm for 14.5 keV Cs, determined from the above procedure.
- Excellent agreement between the deconvolved profile and the "true" profile measured using 3keV O₂.



Issues Related to Si/SiGe/Si Heterostructure

- Sputtering rates of SiGe and Si are different.
- RSFs in SiGe and Si are different.
- Decay lengths and depth offsets of SiGe and Si are different.
- Cs enhanced chemical segregation is present and causes a long decay tail.

Deconvolution of Boron Profile in Si/SiGe/Si Heterostructure



Observations for Si/SiGe/Si Heterostructure

- C, O, Si, P, As are not shown for clarity.
- SiGe is graded, and the Ge composition is shown and referenced to the right axis indicating the layer structure.
- Boron profiles were measured using 3keV Cs and 3keV O₂, and no significant difference was observed except the B segregation tail due to Cs bombardment.
- The focus of the deconvolution procedure is to remove the segregation tail effect and accurately obtain the true profile shape for the trailing tail.
- Excellent agreement between the deconvolved profile and the "true" profile measured using 3keV O₂ is obtained for the SiGe heterostructure.

CONCLUSIONS

- Using a fairly simple approximation of residual ion mixing, we have formulated a deconvolution scheme that is simple to use and only relies on the measured profile, its derivative, and the measured SIMS depth resolution for silicon, SiGe and Si/SiGe/Si heterostructures.
- The mathematical deconvolution model shown in this work can be used to remove the Cs enhanced chemical segregation effect present in the boron tail.
- Using deconvolution, B profiles of comparable quality of O₂ bombardment can be obtained in a single profile along with C, O, Si, P, As and Ge using Cs bombardment.