Epi SiGe Application using METRION® in-line SIMS System

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Abstract

The epitaxial process is a well-established deposition technique in semiconductor fabrication because it enables the ability to achieve much higher doping concentrations than can be obtained via ion implantation. As we move toward <5nm technology, a key process for enabling gate-all-around FET (GAAFET) is the stacked multi-lattice of Silicon (Si) and Silicon-germanium (SiGe) epi process for constructing the nanosheets.

Germanium (Ge) content in SiGe correlates to channel stress, and the germanium fraction (Ge%) has been increasing steadily as we move towards smaller technology nodes. When stress is high, epi layers can suffer from multiple problems such as defect formation, facet formation, non-uniform strain, etc. The challenge is greater when moving from planar to 3D structures, where uniformity of strain and control of defect density are important. Often, multiple epi layers of SiGe with varying thicknesses, Ge%, and Boron doping are deposited to optimize the device structure and process integration.

Enabling process control on the layer thickness, Ge%, and Boron doping concentration in these complicated SiGeB epi stacks is critical in high-volume manufacturing (HVM), and there is no single in-line metrology that is able to do the measurement.

This paper describes how in-line Secondary Ion Mass Spectrometry (SIMS) could be a solution to this problem by providing material composition profiles as a function of depth – resulting in thickness, Ge% and Boron concentration data from each nanosheet.

Background and Introduction

The epitaxial process is commonly used in creating the source-drain region of transistors. As strain engineering is adopted at around 90nm, chipmakers started using blanket epitaxial process to integrate Silicon-germanium (SiGe) stressors in PMOS transistors. The lattice mismatch induced by SiGe boosted hole mobility and drive current. As a device shrinks, a similar epi process that incorporates carbon in silicon is also used to apply strain engineering for NMOS devices. In some processes, addition of boron or phosphorous dopants during the epi process enables the ability to achieve much higher doping concentrations than can be obtained via ion implantation. As we move toward <5nm technology, a key process for enabling gate-all-around FET (GAAFET) is the stacked multi-lattice of Silicon (Si) and SiGe epi process for constructing the nanosheets.

In the development of CMOS source/drain in advanced technology nodes, in-situ Boron doped SiGe epitaxy has been widely used, initially in planar devices and more recently applied to FinFETs. This allows FinFETs to benefit from an improved short channel effect, which allows for lower contact resistance thanks to significantly higher in-situ doping levels. The need for increased doping levels in FinFET source/drain architecture can be addressed via an optimized in-situ doped epitaxy process. The relationship between germanium and boron incorporation results in an inverse relationship between the two, where increasing Germanium incorporation will typically lower Boron doping, and increasing Boron doping incorporation results in a lower Germanium concentration.[1]

Metrology Challenges

In strain engineering, Germanium (Ge) content in SiGe correlates to the amount of channel stress applied, and the Ge% has been increasing steadily as we move towards smaller technology node, as shown in Figure 1. When stress is high, epi layers can suffer from multiple problems such as defects formation, facet formation, non-uniform strain, etc. The challenge is greater when moving from planar to 3D structures, where uniformity of strain and control of defect density are important. Often, multiple epi layers of SiGe with varying thicknesses, Ge%, and Boron doping are deposited to optimize the device structure and process integration. For example, a Si-cap layer is deposited on top of the SiGe layer as sacrificial layer for the subsequent silicide formation process to reduce contact resistance, without introducing defects to the SiGeB layer. Being able to do process control on the thicknesses, Ge%, and Boron doping in these complicated SiGeB epi stacks is critical in high-volume manufacturing (HVM), and there is no single in-line metrology that is able to do the measurement.

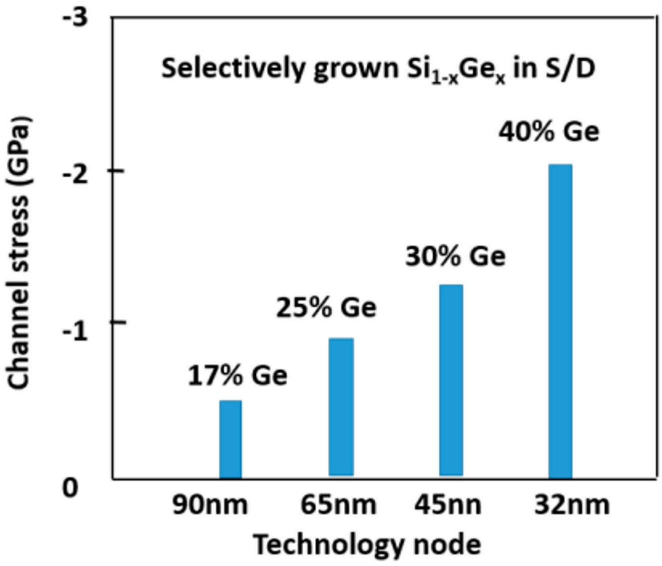

Figure 1. Evolution of Ge content in SiGe source/drain[2]

One of the techniques used in monitoring the epi deposited SiGeB films is Secondary Ion Mass Spectroscopy (SIMS). By sputtering with a focused primary ion beam, and collecting the ejected secondary ions from the sample, SIMS can determine the composition and thicknesses for complicated multilayer film stacks, as illustrated in Figure 2. As SIMS is typically only available in an analytical lab outside of the fabrication environment, the current process controls are done on test wafers, where broken sample pieces are measured with traditional lab SIMS equipment. The turnaround time is often long, and the results often do not reflect the actual production conditions on actual product wafers. It is known in some cases that, while the control charts are in good standing, the product has failed to meet its specification.

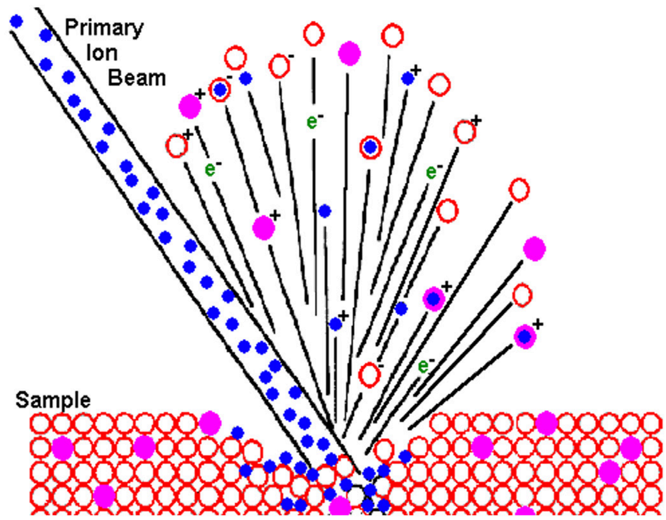

Figure 2. Basic principle of secondary ion mass spectrometry (SIMS): A primary ion beam is sputtered through sample surface layers, resulting in ejection of secondary ions, which are then separated by mass spectrometry and analyzed.
Image Source: Evans Analytical Group

METRION®

Nova's METRION® is a 300mm wafer-level in-line SIMS metrology system developed to seamlessly integrate with an automated high-volume manufacturing (HVM) fabrication environment. It is a fully automated, recipe-driven metrology tool utilizing a Magnetic Sector mass analyzer to provide high quality dynamic SIMS depth profiles. It has an O2 ion source that ranges from low to medium to high in beam energy for a variety of applications. Because METRION® utilizes a low voltage secondary ion extraction field, it enables stable and repeatable measurements within a 50um x 50um metrology pad on product wafers. With multiple detectors, METRION® can measure multiple species simultaneously through the entire film stack, providing high data density capable of achieving higher depth resolution. Process automation with built-in film analysis and recipe management make the system easy to use and shorten the time to data.

Epi SiGeB Application

Here we present analysis results of x5 static measurement of B doped SiGe layer measured using 500eV primary energy on a 50x50 micron raster area (see figure 3). The repeatability of mean B concentration, Ge fraction and SiGe thickness measured at ~1% RSD.

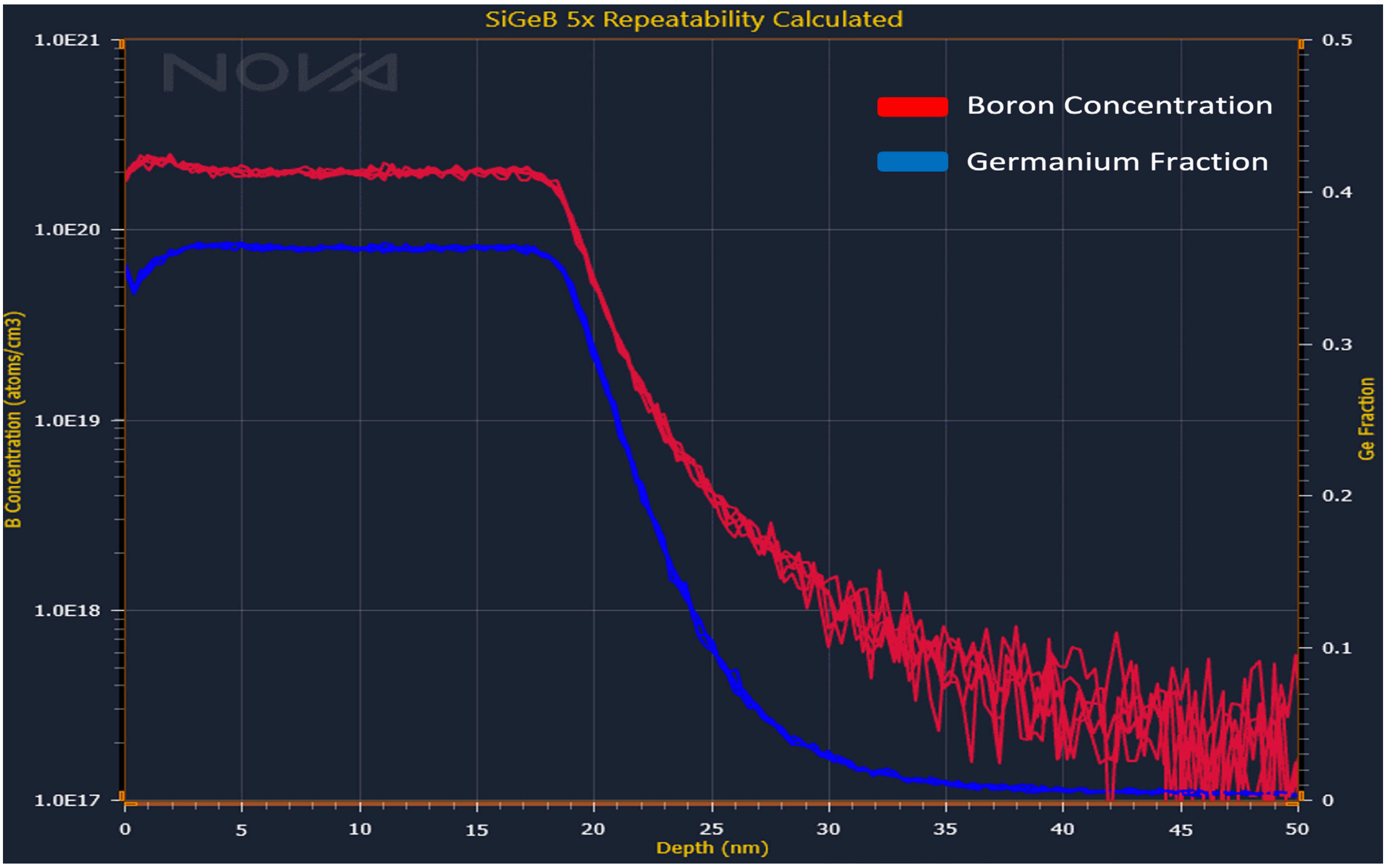

Figure 3. Repeatability of B concentration and Ge fraction measured in B doped SiGe epitaxy with METRION® at 500eV primary beam energy.

Depending on the required depth resolution, sputtering conditions are adjusted. For relatively thick films (> 100 nm) with no strict interface resolution requirement, an impact energy of 1keV is typically used. However, at these energies, thin layers are often sputtered through without sufficient data density to characterize the layer. For thinner doped films, much lower primary ion energies are needed for more accurate characterization. The use of low primary beam energy allows METRION® to achieve extremely good depth resolution. To demonstrate this, we acquired multiple SIMS depth profiles on a SiGe multi lattice using a 250eV primary beam energy and 50x50um raster size, as shown in Figure 4. The Si and Ge depth profiles show three distinct SiGe layers with Ge fraction decreasing from layer 1 to layer 3 and the use of a low primary energy beam allows for superior depth resolution.

In addition, METRION's automated software allows for precise wafer navigation and full mapping capability. In figure 5, Ge fraction and SiGe thickness are seen to be at maximum in wafer center, at a minimum on left edge for Ge fraction and minimum on right edge for SiGe thickness.

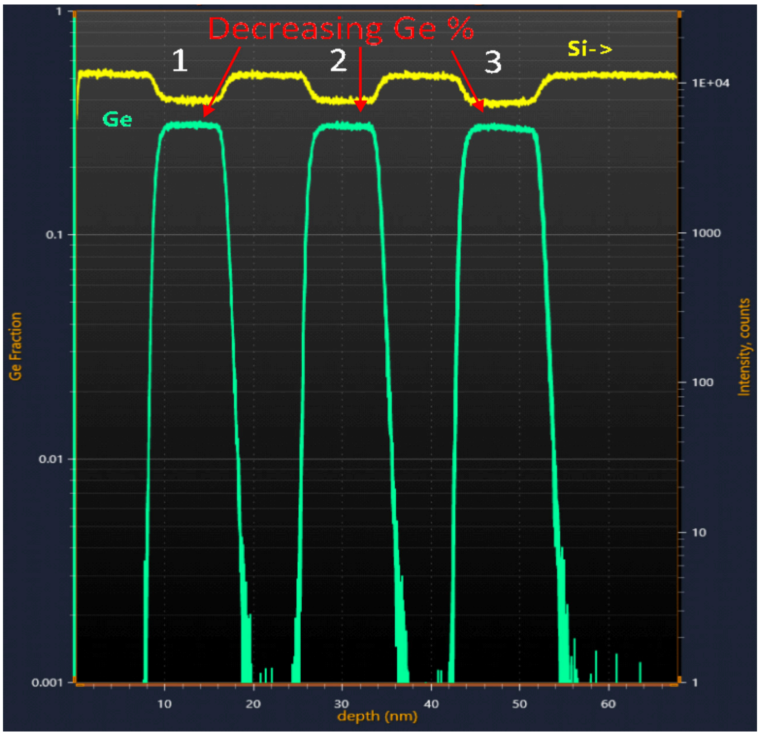

Figure 4. An overlay of x5 Si and Ge profile in a SiGe multi lattice

Ge Fraction *Thickness*

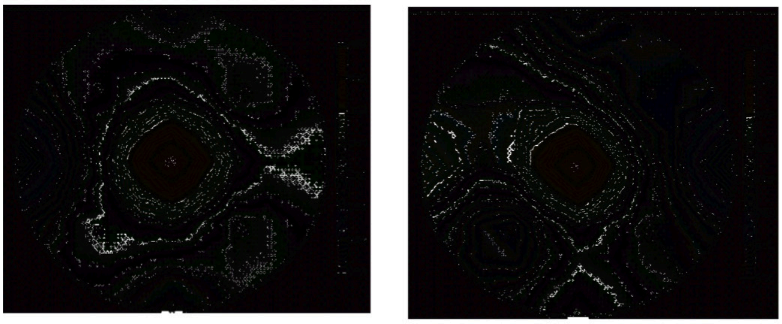

Figure 5. Wafer maps showing wafer non uniformity of mean Ge Fraction (left) and SiGe layer thickness (right).

Summary

Nova's METRION® system is an innovative SIMS platform designed for the Fab environment, seamlessly integrating into an automated factory workflow. The system is engineered to deliver wafer-based, high precision metrology results for process control in logic and memory devices. Measurements on Epitaxial SiGe films is one of the major applications which will benefit from METRION's in-line SIMS system. It will enable more relevant Statistical Process Control (SPC) of the epi process and provide in-line data correlating to electrical performance.

References

[1] Yi Qi et. al., "In-Situ Boron Doped SiGe Epitaxy Optimization for FinFET Source/Drain." ECS Transactions, 75, 8

[2] Henry H. Radamson et. al., "The Challenges of Advanced CMOS Process from 2D to 3D." Appl. Sci. 2017, 7, 1047