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HIGH ACCURACY SIMS DOPANT PROFILING IN HETEROJUNCTION SiGe/Si STRUCTURES

Paul K. Chu[1], Salman Mitha[2], and Stephen P. Smith[2]
[1] Dept. of Physics & Materials Science, City University of Hong Kong
83 Tat Chee Avenue, Kowloon, Hong Kong
[2] Charles Evans & Associates
301 Chesapeake Drive, Redwood City, CA 94063, USA

1. Introduction

$Si_{1-x}Ge_x$ heterostructures are found in high-speed and high-frequency microelectronics devices such as heterojunction bipolar transistors (HBT), modulation-doped heterojunction field effect transistors (MODFETs) with high mobilility [1]. Typical high-performance SiGe/Si heterostructure devices employ a $Si_{1-x}Ge_x$ alloy layer with thickness below 100 nm and dopant concentrations in the range of 10^{16} to 10^{20} atoms/cm^3. The performance of these devices requires accurate positioning of the dopants with respect to the alloy layers. However, due to dopant segregation during epitaxial growth and other poorly understood dopant incorporation issues that can adversely affect device quality and yield, the empirical determination of the dopant profiles is crucial to device engineering and reliability diagnosis.

Empirical investigation of these structures requires an analytical technique that offers both high depth resolution and sensitivity. Secondary ion mass spectrometry (SIMS) is a widely accepted depth profiling technique for dopants. During a typical SIMS analysis, either oxygen or cesium ion bombardment is used to optimize the secondary ion yields of electropositive (p-type) dopants or electronegative (n-type) dopants. Hence, the dopants are usually measured individually under different conditions [2]. The profiles are then quantified using implant standards and subsequently reconstructed by overlaying the results from the separate analyses. Typically, a matrix marker is used to align the interface. However, due to the differences in sputtering rates and depth resolution under oxygen and cesium ion bombardment, accurate alignment of the p-type and n-type dopants with respect to the alloyed layer is difficult.

In this work, we present a depth profiling technique using SIMS by which boron (p-type dopant), phosphorus (n-type dopant), and germanium (matrix or interface marker) can be monitored simultaneously. A thin $Si_{1-x}Ge_x$ epitaxial film is analyzed using a low energy oxygen ion beam and oxygen backfill. We show that under these conditions, it is possible to achieve excellent depth resolution and detection limits for dopants at the same time. Detection limits on the order of 10^{15} atoms/cm^3 can be achieved for both B and P while simultaneously aligning the dopant profiles relative to the Ge profile with an accuracy of better than 5 nm.

2. Experimental

The analysis was conducted using a CAMECA IMS-4f microanalyzer. The primary O_2^+ primary ions were mass filtered and accelerated to a voltage of 7.5 kV. The $Si_{1-x}Ge_x/Si$ sample was biased to +4.5 kV, and so the relative impact energy was 3 kV. Hence, the net bombarding energy of each oxygen particle was 1.5 keV. To remove the surface transient and other related matrix effects, an oxygen leak was used. The oxygen backfill pressure was adjusted until the matrix ion yield was flat at the onset of the depth profile. The use of the oxygen leak also enhanced the positive ion yields of $^{11}B^+$ and $^{31}P^+$, the species monitored in the depth profile [3]. $^{72}Ge^+$ was measured simultaneously to delineate the structure and determine the depth resolution. High mass resolution conditions were employed to eliminate mass interferences such as $^{30}Si^1H^+$ for $^{31}P^+$. The instrumental transmission was maximized. The oxygen ion beam was rastered to an area of 500 μm x 500 μm while the secondary ion signals were acquired from a 400 μm x 400 μm region in the center of the crater using the dynamic transfer optics. As the oxygen ion beam was tightly focused, the crater wall as observed by stylus profilometric measurement was quite steep. No depth resolution degradation due to secondary ions emanating from crater walls and crater edges was observed.

3. Results and discussion

One of the advantages of the technique is that all three elements, B, P, and Ge, are monitored simultaneously using one set of instrumental conditions. Accurate dopant profile alignment can thus be assured. In addition, under the oxygen leak environment, the ion yield of phosphorus can be substantially improved. Fig. 1 depicts the depth profiles of a $Si_{1-x}Ge_x/Si$ heterostructure. The B and P profiles are referenced to the left-hand-side concentration scale whereas the Ge composition is plotted versus the right-hand-side atomic % axis. Quantification of the B and P profiles is accomplished by relative sensitivity factors derived from reference implants in SiGe alloy standards. The relationship between the relative sensitivity factors and Si:Ge ratios has been investigated in prior studies [4-6]. The Ge concentration was determined from a separate analysis employing the $CsGe^+$ ion which has been shown to exhibit much less matrix dependence [7]. No RBS (Rutherford backscattering spectrometry) cross referencing is conducted here for the $Si_{1-x}Ge_x$ is quite thin and the continuously varying Ge content in the film makes accurate RBS analysis quite difficult.

The results demonstrate the excellent detection limit of phosphorus under the oxygen leak, high mass resolution conditions. As the typical dopant concentration in SiGe devices ranges from 10^{16} to 10^{20} atoms/cm^3, the detection limits achieved using this experimental protocol is acceptable, thereby obviating the need for a separate analysis for phosphorus using cesium ion bombardment. The oxygen leak also reduces the surface transient effects significantly, and the profile is therefore accurate from the beginning to the end.

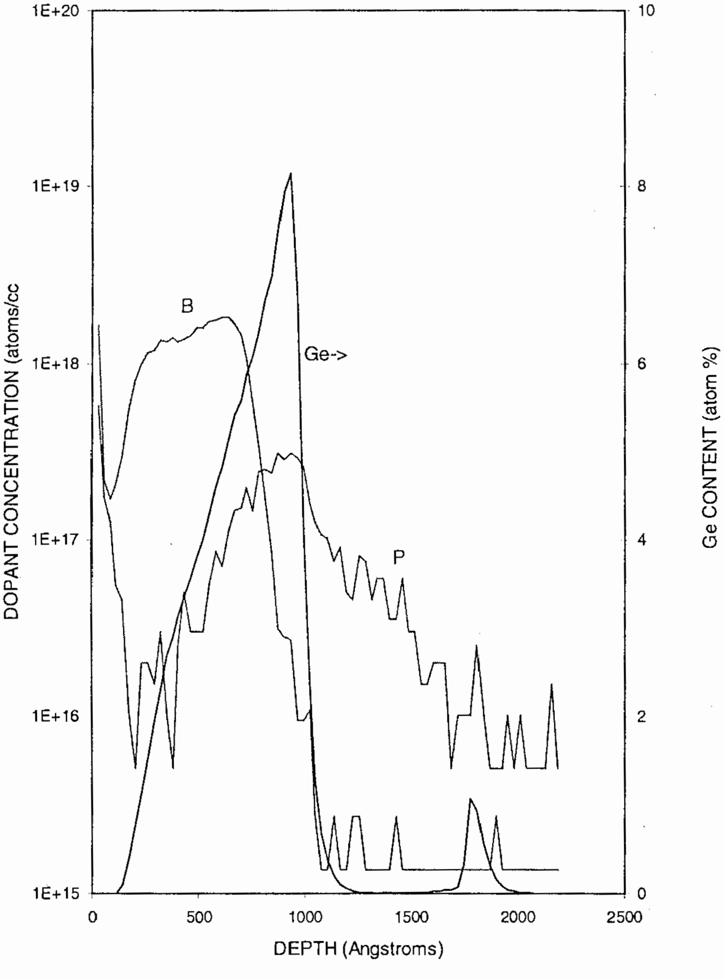

Fig. 1: High sensitivity and depth resolution depth profile of $Si_{1-x}Ge_x/Si$ heterostructure.

The use of low energy primary ion bombardment yields excellent depth resolution, and judging from the trailing edge of the Ge profile, the depth resolution is determined to be better than 5 nm and perhaps as good as a couple of nm. The intersection of the B and P profiles indicates the location of the metallurgical p-n junction. It can also be observed that for this sample, the boron is retained in the SiGe alloy layer whereas phosphorus has diffused into the silicon substrate.

In order to assess the day-to-day and instrument-to-instrument variation of the measurement protocol, the sample was analyzed four times using two different CAMECA IMS-4f instruments. The resulting profiles overlay practically on top of each other demonstrating excellent reproducibility.

4. Conclusion

Using a carefully chosen set of conditions incorporating low energy oxygen ion bombardment, high mass resolution, and oxygen leak, boron (p-type dopant), phosphorus (n-type dopant), and germanium (matrix marker) can be profiled simultaneously in a $Si_{1-x}Ge_x$ epitaxial heterostructure with excellent sensitivity and depth resolution. The B and P detection limits are on the order of 10^{15} atoms/cm^3, and the depth resolution is better than 5 nm. The metallurgical junction depth relative to the Ge alloy layer can thus be accurately determined. The analytical protocol is also applicable to other heterostructures such as $Si_{1-x}C_x$ and $Si_xGe_yC_{1-x-y}$.

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