Applied Surface Science 255 (2008) 1345–1347

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Silicon isotope superlattices: Ideal SIMS standards for shallow junction characterization

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ARTICLE INFO

Article history:
Available online 8 May 2008

Keywords:
Silicon
Isotopes
Superlattices
Shallow junction
SIMS

ABSTRACT

We present a silicon isotope superlattice structure that we believe to be the most ideal secondary ion mass spectrometry standard sample for the dopant concentration depth profiling required for characterization of the shallow junction formed by ion implantation. The precisely stacked alternating layers of silicon isotopes function as a depth ruler. Therefore, it enables us to calibrate the depth scale of dopant based on the positions of silicon isotopes. We show the depth profiles of silicon isotopes and arsenic in the arsenic ion-implanted silicon isotope superlattice as a representing example.

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1. Introduction

Boron (B) or arsenic (As) ion implantation is widely used for the formation of shallow junctions in silicon (Si) transistors. The depth profiles of dopants are routinely obtained by secondary ion mass spectrometry (SIMS) technique [1,2]. The determination of dopant distributions in shallow junctions of source/drain region in complementary metal-oxide-semiconductor becomes critical especially near the surface region because the precise profiles of dopants are not well understood in such transient region. The profile shape strongly depends on the energy and incident angle of a primary ion due to the atomic mixing. It has been reported that the accurate profile shape of dopant is obtained by the reduction of the primary ion energy in SIMS measurement [3]. Furthermore, changing incident angle, backside-SIMS measurement, and mathematical deconvolution technique have been studied extensively in order to obtain the real profile shape [4–6]. Another problem is that the sputtering rate variation distorts the depth scale calibrated by sputtering time and crater depth because the sputtering rate is assumed to be constant during SIMS measurement. In the past, a multi-delta-layer sample, such as B delta-doped Si, was employed to evaluate the sputtering rate variation. The study reveals that the variation causes near the surface region [7–11]. However, the problem of the change sputtering rate between the matrix Si and delta-doped B region disqualifies such B-delta-layer samples to be the ideal SIMS standards. This prompted Wittmaack and Poker to utilize alternating layers of Si isotopes that guaranteed the constant sputtering rate throughout the doped region [12]. Naturally available Si (^{nat}Si) is composed of three stable isotopes in fixed proportions (^{28}Si: 92.2%, ^{29}Si: 4.7%, ^{30}Si: 3.1%), i.e., isotopic separation followed by alternating depositions allows for formation of a Si single crystal with alternating mass variations. Although Wittmaack and Poker employed ion beam deposition to form alternating Si isotope layers, which most likely lead to poor crystalline quality, their proof-of-concept experiment to apply Si isotopes as SIMS depth markers was very successful [12]. Our isotope superlattice has been prepared by molecular beam epitaxy (MBE) and guarantees the crystallinity as good as that of commercial Si wafers [13,14]. Therefore, it allows for shallow SIMS depth profiling with a constant sputtering rate. Our much short periodicity of isotope superlattices than those reported in Ref. [12] allow for the shallow SIMS depth profiling. Implantation of dopants into the Si isotopes superlattices followed by SIMS analysis allows for the simultaneous observation of the dopant and alternating Si isotope marker depth profiles. Therefore, the isotope depth marker enables us to calibrate the depth scale of the dopant profiles. Furthermore, the sample is useful for the calibration of the atomic mixing because our Si isotopes superlattice has the interface abruptness better than two atomic layers. The smearing of the SIMS profiles between adjacent Si isotope layers originates from the SIMS atomic mixing rather than sample itself. Thus, this paper presents the short-period Si

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doi:10.1016/j.apsusc.2008.05.016

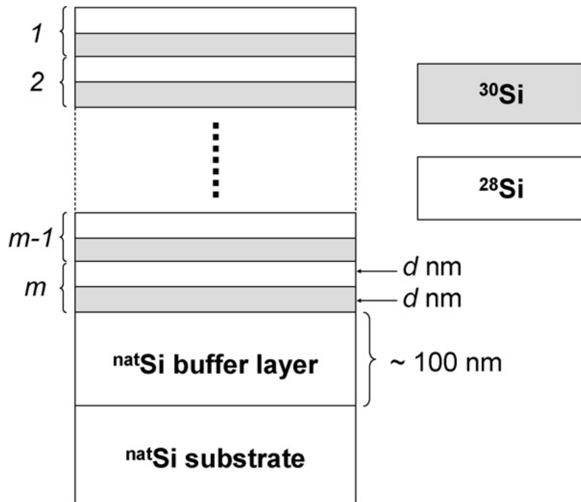

Fig. 1. Schematic illustration of ^{28}Si(d nm)/^{30}Si(d nm) isotope superlattice structure.

isotope superlattice structure that we believe to be the most ideal SIMS standard sample for the dopant concentration depth profiling required for characterization of the shallow junction formed by ion implantation.

2. Experiment

We prepared a ^{28}Si/^{30}Si isotope superlattice grown by solid-source MBE as described in Refs. [13,14]. In short, floating-zone 2-in. ^{nat}Si(0 0 1) substrate was of high resistivity ($\rho > 2000\ \Omega$ cm, n-type), onto which a buffer layer of ~100 nm was formed before the growth of the alternating layers of isotopically pure ^{28}Si and ^{30}Si. Fig. 1 illustrates an example of the superlattice structure, ^{28}Si and ^{30}Si layers with each thickness of d nm. We implanted $^{75}As^{+}$ into such superlattice sample in the condition at an energy of 25 keV, which corresponds to the projected range of ~20 nm, and with doses of 1×10^{13}–1×10^{15} cm^{-2} at room temperature. The depth profiles of the samples were measured by ATOMIKA SIMS-4000 instrument using cesium ion (Cs^{+}) primary ion beam at energies ranging from 1 to 5 keV with 45° incident angle.

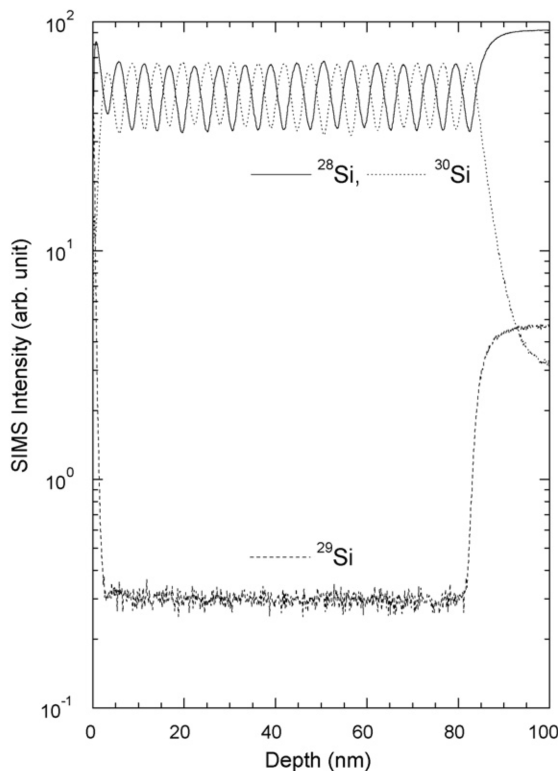

Fig. 2. SIMS depth profiles of ^{28}Si (solid curve), ^{29}Si (broken curve), and ^{30}Si (dotted curve) in the ^{28}Si(2.7 nm)/^{30}Si(2.7 nm) isotope superlattice. The primary ion energy was Cs^{+} 1 keV. The incident angle was 45°.

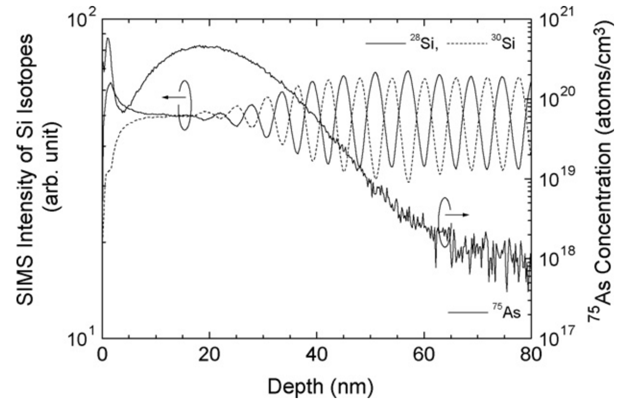

Fig. 3. SIMS depth profiles of ^{28}Si, ^{30}Si, and ^{75}As in the Si isotope superlattice implanted with $^{75}As^{+}$ at 25 keV with the dose of 1×10^{15} cm^{-2}.

3. Results and discussion

Fig. 2 shows the SIMS depth profiles of ^{28}Si, ^{29}Si, and ^{30}Si in the 15-period ^{28}Si/^{30}Si isotope superlattice (d = 2.7 nm). The primary ion condition was Cs^{+} 1 keV at 45°. As we expected, the oscillations of ^{28}Si and ^{30}Si are clearly observed as a function of the depth to ~80 nm. Depletion of the ^{29}Si concentration is also confirmed. ^{nat}Si layer appears in the region deeper than ~80 nm. Note that every ^{28}Si/^{30}Si interface has the abruptness of the order 0.3 nm (interdiffusion corresponding to less than two atomic layers) [14]. The average thicknesses of Si isotope layers are determined independently by Raman spectroscopy. When we increased the primary ion energies ranging from 1 to 5 keV, the amplitudes of the SIMS intensity oscillations of the ^{28}Si and ^{30}Si profiles became smaller due to the atomic mixing. Therefore, the rounding (smearing) of the ^{28}Si and ^{30}Si profiles in Fig. 2 allows us to quantitatively analyze the degree of unwanted atomic mixing during SIMS measurements (SIMS artifacts). The depth profiles of ^{28}Si and ^{30}Si alternate with the periodicity $2d$ = 5.4 nm in accordance with our design, and they serve as ideal depth scales.

Fig. 3 shows the depth profiles of ^{28}Si, ^{30}Si, and ^{75}As in the superlattice implanted by As ions at 25 keV with the dose of 1×10^{15} cm^{-2}. Now a part of the profiles is perturbed by the large number of implanted As, and, therefore, the ^{28}Si and ^{30}Si periodicities from the surface to 50 nm are heavily altered. When we implanted As ions at much lower dose conditions, the perturbation of the ^{28}Si and ^{30}Si profiles became smaller due to little atomic mixing during the As implantation. Here, we stress that the remaining alternating profiles of ^{28}Si and ^{30}Si continue to serve as the excellent and complete depth scales for implanted As and the altered profiles from the surface to 50 nm allows to calculate precisely how much in length Si atoms are displaced as a function of the depth. Evaluation of the Si mixing by As implantation using this isotope structure is reported elsewhere [15–17].

4. Summary

We presented a Si isotope superlattice structure that we believe to be the most ideal SIMS standard sample for the dopant concentration depth profiling required for characterization of the shallow junction formed by ion implantation. The alternating layers of isotopes play as a ruler. Therefore, the depth marker enables us to calibrate the depth scale based on the positions of Si isotopes. We showed the simultaneously obtained profiles of Si isotopes and As in the As ion-implanted Si isotope superlattice.

Acknowledgments

We acknowledge T. Mouri, Dr. T. Okui, and Prof. Y. Shiraki for the technical support. This work has been supported in part by the Research Program on Collaborative Development of Innovative Seeds by JST, the Special Coordination Funds for Promoting Science and Technology for INQIE, and a Grant-in-Aid for the Global Center of Excellence for High-Level Global Cooperation for Leading-Edge Platform on Access Spaces from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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