Thin Solid Films 557 (2014) 101–105

Contents lists available at ScienceDirect

Thin Solid Films

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

Fabrication of ultra-thin strained silicon on insulator by He implantation and ion cut techniques and characterization

Z.Q. Mu, Z.Y. Xue, X Wei, D. Chen, M. Zhang, Zengfeng Di *, X. Wang

State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, 865 Changning Road, Shanghai 200050, China

ARTICLE INFO

Available online 11 September 2013

Keywords:
Strained silicon
SOI
Implantation
SiGe

ABSTRACT

8-inch strained silicon on insulator (sSOI) wafer with 13 nm strained Si top layer has been obtained using He implantation, wafer bonding, layer transfer and selective etching techniques. Different from the conventional graded buffer layer with considerable thickness, the relaxed SiGe virtual substrate, which provides the lattice template for strained Si epitaxy, is achieved by the process combining He implantation and rapid thermal annealing. The strain relaxation in SiGe virtual substrate and the strain transfer from SiGe virtual substrate to the strained Si have been examined by X-ray diffraction reciprocal space mapping. The final 8-inch sSOI wafer is characterized for stress uniformity, thickness uniformity, crystalline quality, defect density and surface roughness using a variety of techniques and found to be in acceptable quality for the application in advanced device fabrication.

1. Introduction

Tensile strain can enhance the carrier mobility including both electron and hole in complementary metal-oxide semiconductor field-effect transistors (CMOSFETs) devices [1,2], and silicon on insulator (SOI) technology can reduce power consumption and increase operation speed duo to its active layer insulation [3]. Strained silicon on insulator (sSOI), which combines both advantages from strained Si and SOI structure, has been considered as a potential substrate for next-generation microelectronic technology [4]. In particular, due to the fact that the scaling beyond the 22 nm node is likely to require fully depleted CMOS, sSOI with top silicon less than 20 nm is highly demanded due to its mobility gain and compatibility with mature CMOS process. Strained Si is usually obtained by the epitaxy of Si on thick SiGe graded buffer, and the final sSOI wafer is realized using wafer bonding, ion cut and selective etch back. However, the growth of thick SiGe buffer layer is time consuming. Many appropriate approaches have been developed to overcome the problems. Among them, Ge condensation technique [5], low-temperatured buffer-layer [6] and ion implantation technique [7] are the satisfactory candidates.

In the present work, the strain relaxation of thin SiGe epilayer is realized via appropriate He ion implantation and thermal annealing. The relaxed SiGe epilayer provides an ideal template for the epitaxy of strained Si, and 8 inch sSOI with 13 nm sSi has been obtained by the subsequent ion cut technique and selective etching process.

2. Experiment

A 160 nm pseudomorphic $Si_{1-x}Ge_x$ ($x = 0.25$) layer and 7 nm Si cap were grown on 200 mm Si (100) standard wafers by a commercial reduced pressure chemical vapor deposition (RPCVD) after baking the Si substrate in H_2 for native oxide desorption. 25 keV He^+ implantation (with the projected ion range (Rp) of ~220 nm simulated by SRIM) with the dose of 1×10^{16} cm^{-2} and rapid thermal annealing (RTA) at 800 °C for 1 min in N_2 ambient were performed to realize the strain relaxation of $Si_{0.75}Ge_{0.25}$ epilayer. 150 nm $Si_{0.83}Ge_{0.17}$ followed by 20 nm Si was subsequently grown on relaxed $Si_{0.75}Ge_{0.25}$ epilayer. By combining ion cut and selective etching techniques, sSOI with ultrathin strained silicon (13 nm) was obtained eventually. The amount of strain relaxation was determined by high resolution four-crystal X-ray diffraction reciprocal space mapping (HR-RSM) using a Philips X'pert instrument with Cu K_α radiation ($\lambda = 1.5406$ Å) and UV Raman spectroscopy (Model: HORIBA Jobin Yvon HR800). The surface roughness was characterized using contact mode atomic force microscopy (AFM) (Model: MultiMode NS-3a, Veeco). Cross-sectional transmission electron microscopy (XTEM) (Model: Tecnai G2 F20 S-Twin, FEI) was used to examine the microstructures. The XTEM specimens were prepared by Ar ion milling and the XTEM images were taken with an operating voltage of 200 kV.

3. Result and discussion

3.1. $Si_{1-x}Ge_x$ relaxation

In order to suppress strain relaxation, the designed thickness of the grown $Si_{1-x}Ge_x$ layer is below the critical thickness according to R. People [8]. In order to obtain the precise information of the $Si_{1-x}Ge_x$

---

* Corresponding author.
E-mail address: zfdi@mail.sim.ac.cn (Z. Di).

0040-6090/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tsf.2013.08.119

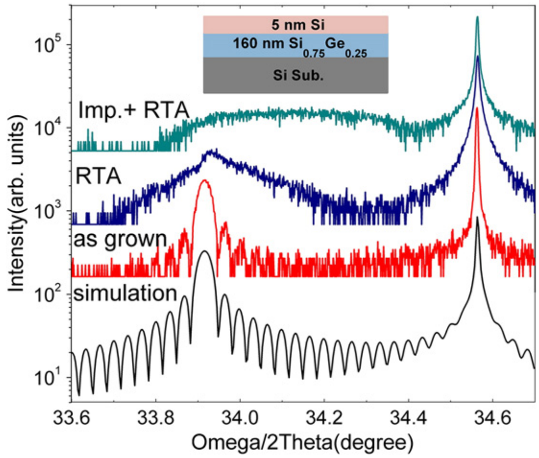

Fig. 1. The (004) rocking curves of the $Si_{0.75}Ge_{0.25}$/Si structure with different treatments including He implantation & RTA and RTA solely. The simulation data is also plotted for comparison.

layer including the thickness, composition, strain and crystalline quality, the (004) X-ray rocking curves are compared with the simulation curve, as shown in Fig. 1. A distinct peak corresponding to $Si_{1-x}Ge_x$ epilayer is located at 33.9 degrees, which agrees well with the simulation data, indicating the $Si_{1-x}Ge_x$ epilayer possesses the composition and thickness as expected. The interference fringes at both sides of the $Si_{1-x}Ge_x$ peak, which come from the abrupt interface, imply that there is almost no strain relaxation in the perfect pseudomorphic $Si_{1-x}Ge_x$ layer.

After He implantation and RTA, the dislocation loops emitted by the over-pressurized He-filled nano-cavities promote strain relaxation via both the propagation of two threading dislocation segments through the epilayer and the extension of the misfit dislocation segment located at the SiGe/Si heterointerface [9,10]. As shown in Fig. 1, the $Si_{0.75}Ge_{0.25}$ peak becomes much broad and shifts towards the peak of Si substrate, indicating a large part of strain is relaxed after He implantation and annealing. The strain relaxation introduces the formation of misfit dislocation network along the SiGe/Si interface[11], which increases the interface roughness, thus resulting in the disappearance of the interference fringes. In comparison, the relative shift of the diffraction peak corresponding to $Si_{0.75}Ge_{0.25}$ with RTA solely is not significant, so the strain stored in $Si_{0.75}Ge_{0.25}$ epilayer cannot be relaxed by RTA sufficiently.

To characterize the strain relaxation quantitatively and more precisely, a series of two-dimensional HR-RSMs near asymmetric (113) reflection are shown in Fig. 2. The asymmetric (113) HR-RSMs of the samples give more details of the mosaic structures in the epi-layers. Q_x is parallel to the surface, and Q_y is perpendicular to the surface. Q_x, Q_y can be calculated by:

$$Q_x = 2\gamma_E sin\theta \cdot sin(\theta - \omega) \tag{1}$$

$$Q_y = 2\gamma_E sin\theta cos(\theta - \omega) \tag{2}$$

where γ_E is the radius of the Ewald sphere. For a (113) reflection, the in-plane $a_\parallel$ and out-of-plane $a_\perp$ lattice constants are given by $a_\parallel = \sqrt{2}/Q_x$ and $a_\perp = 3/Q_y$ [12,13].

In Fig. 2(a), the $Si_{0.75}Ge_{0.25}$ peak from the as grown sample is essentially aligned in the Q_x direction with the substrate peak, indicating the as grown $Si_{0.75}Ge_{0.25}$ is fully strained and commensurated with the substrate. In addition, the thickness fringes emerging periodically spaced between the epilayer diffraction peak and the substrate diffraction peak imply the high crystalline quality of the epilayer. For the RTA treated sample as shown in Fig. 2(b), the $Si_{0.75}Ge_{0.25}$ peak-intensity distribution is much broadened, but the position of maximum intensity still aligns in the Q_x direction of the substrate peak with a subtle shift. The small shift of $Si_{0.75}Ge_{0.25}$ peak corresponds to the strain relaxation of 14%, thus most of the strain still exists after RTA process. In Fig. 2(c), after the He implantation and RTA treatment, the peaks corresponding

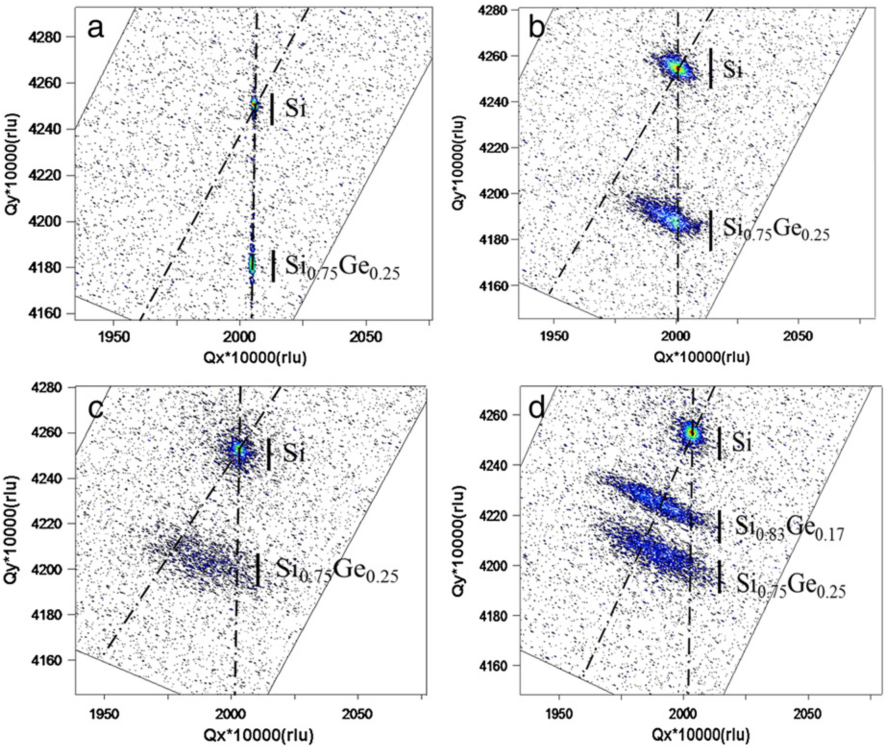

Fig. 2. Asymmetric (113) HR-RSMs of the $Si_{0.75}Ge_{0.25}$/Si structure with different treatments: (a) as grown; (b) RTA solely; (c) He implantation & RTA; (d) He implantation & RTA followed by the epitaxy of $Si_{0.83}Ge_{0.17}$ and Si.