Applied Surface Science 256 (2010) 3499–3502

Contents lists available at ScienceDirect

Applied Surface Science

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

Strain relaxation in nano-patterned strained-Si/SiGe heterostructure on insulator

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ARTICLE INFO

Article history:
Received 2 December 2009
Received in revised form 18 December 2009
Accepted 18 December 2009
Available online 28 December 2009

PACS:
68.55.Ag
81.15.−z
68.37.Lp

Keywords:
Strained silicon
SiGe
Strain relaxation
Raman spectroscopy

ABSTRACT

In order to evaluate the strain stability, arrays of strained Si/SiGe nano-stripes and nano-pillars were fabricated by Electron-Beam Lithography (EBL) and Reactive-Ion Etching (RIE). The strain relaxation in the patterned strained Si on SiGe-on-insulator (SGOI) was investigated by high-resolution UV micro-Raman spectroscopy. The Raman measurements before and after patterning indicate that most of the strain in the top strained Si is maintained until scaling down to 300 nm, and relaxation of <15% is observed in pillars with a dimension of 150 nm × 150 nm. In the nano-patterned heterostructure strained Si/SiGe, the observed relaxation is small, which is mainly attributed to the fully relaxed and dislocation-free SiGe virtual substrate fabricated by modified Ge condensation.

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1. Introduction

The strained silicon based on silicon-on-insulator (SOI) technology is an attractive material for low-power, small-sized metal-oxide-semiconductor field effect transistors (MOSFETs). SOI circuits have lots of merits such as simpler fabrication, free of latch-up, reduced junction capacitance and reverse body effect. Strained silicon allows for enhanced carrier mobility due to the band-structure modification induced by in-plane tensile strain, as compared to conventional Si [1]. Since the carrier mobility enhancement is based on strain engineering, it is essential to retain the strain in the strained layers during the device fabrication process. Consequently, with MOS device dimensions scaling down to sub-micron and deep sub-micron, the behavior of the strained state of Si layers after nanopatterning is of significant technological importance [2].

Lei et al. have investigated 30 nm thick strained silicon stripes and pillars directly on insulator using UV-Raman spectroscopy [3]. Their results indicated that the patterning would induce 100% lateral strain relaxation in stripes (90 nm) and total relaxation in pillars (80 nm × 170 nm). However, Himcinschi et al. reported that strained silicon round pillars with diameters from 100 to 500 nm on strain-relaxed SiGe/graded SiGe were partially relaxed [4]. In these patterned samples with different structures, the strain relaxation occurs early (in 500 nm round pillars) and rapidly (100% in 170 nm stripes), which means that strained Si will lose its chief advantage in ever-smaller devices.

In this work the strain relaxation of nano-stripes and nano-pillars in strained silicon film was studied. Different from the previous studies using a thick graded SiGe buffer layer, the strained Si layer was grown on a thin relaxed-SiGe on insulator (relaxed-SGOI) fabricated by a modified Ge condensation technology [5–8]. The evolution of the strain in patterned strained Si nanostructures with different dimensions was analyzed by means of UV-Raman spectroscopy, because the reduced penetration depth of UV light in Si improves considerably the detection of the strain localized close to Si surface [9,10].

2. Experiment

The strain relaxed SiGe virtual substrate was fabricated by dry oxidation of a sandwiched Si/SiGe/Si structure on SiO_2/Si substrate [5–8]. The biaxially tensile strained silicon was then epitaxially grown by ultra-high-vacuum chemical-vapor-deposi-

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doi:10.1016/j.apsusc.2009.12.063

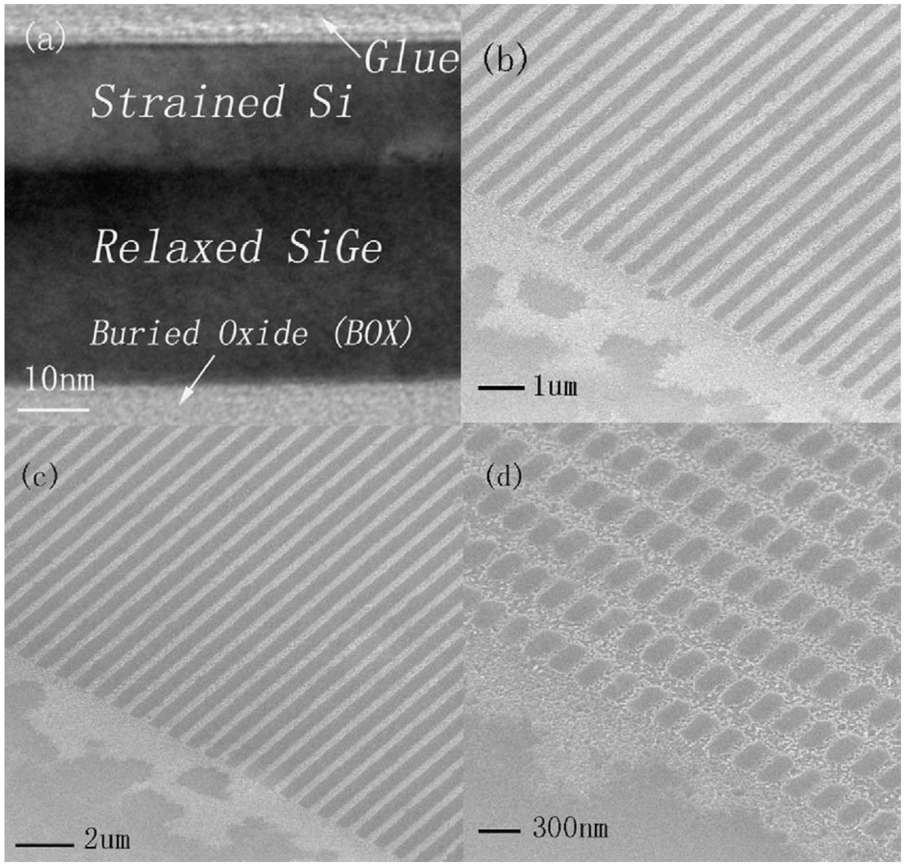

Fig. 1. (a) XTEM image of the strained Si/SiGe-OI structure, and SEM images of the same sample after patterning into (b) 150 nm, (c) 300 nm stripes, and (d) 150 nm × 300 nm pillars.

tion (UHVCVD). The thickness of strained Si is under critical thickness (~15 nm) [11] to avoid relaxation by misfit dislocations formed at the strained Si/SiGe interface. The Ge concentration in SiGe virtual substrate was determined to be 30.8% by energy dispersive X-ray spectroscopy (EDS) in conjunction with transmission electron microscopy (TEM). The fabricated 50 nm thick strained Si/SiGe multilayer was patterned into stripes and pillars using Electron-Beam Lithography (EBL) on 100 μm × 100 μm fields. After EBL exposure and removing of photo resist, the samples were etched to buried oxide layer by means of Reactive-Ion Etching (RIE), and grating structures with 150, 200, 300, 500 nm wide stripes and pillars with 150 nm × 150 nm, 150 nm × 300 nm, 200 nm × 200 nm, 200 nm × 400 nm dimensions were fabricated. Fig. 1(a) shows a cross-sectional transmission electron microscopy (XTEM) image of the strained silicon before patterning. The measured thickness of strained Si layer is approximately 15 nm and the thickness of SiGe layer is 35 nm. Fig. 1(b)–(d) shows the sample scanning electron microscopy (SEM) images of the typical patterned strained Si stripes and pillars with different dimensions. The line and spacing uniformity is well for both stripes and pillars.

3. Results and discussion

Typical UV-Raman spectroscopy was used to analyze bulk Si, strained Si, and nano-patterned strained Si stripes and pillars with different dimensions. All the spectra were measured with a HORIBA Jobin-Yvon HR-800 Raman microscope equipped with a He–Cd laser at a wavelength of 325 nm. During the measurement, the initial laser power was 20 mW, on the sample surface it was decreased to around 1 mW. Hence, the effects of laser-induced heating on Raman measurement were slight and could be ignored, even for the patterned samples [12]. The 325 nm UV laser line used for the Raman measurements has a penetration depth of ~8 nm into Si [13]. Thus in the case of the unpatterned sample where the thickness of strained Si layer is ~15 nm, the Raman spectrum will show just the phonon from the strained Si and no signal from the underlying SiGe layer. This is further confirmed by UV-Raman spectrum for the 15 nm thick strained Si on relaxed SiGe sample, which did not show any SiGe Raman peak, indicating the setup is measuring only the top strained Si film. Since the incident laser beam was focused to a spot size of about 1 μm^2, each single Raman measurement contains contributions from more than one stripe or pillar. In Fig. 2, Raman spectra show that the Si phonon peak in bulk and strained Si is at ~520.6 and at ~510.3 cm^{-1}, respectively. The strain in the strained Si layer can be calculated using the following formula [14]:

$$\Delta\omega_{\text{Si-Si}}^{\text{StSi}} = \omega_{\text{Si-Si}}^{\text{StSi}} - \omega_{\text{Si-Si}}^{\text{bulk Si}} = b_{\text{Si-Si}}^{\text{StSi}} \cdot \varepsilon_{//}^{\text{StSi}} \quad (1)$$

where ω represents the Raman peak positions in cm^{-1} for the films, ε is the in-plane biaxial strain in % and b is the strain-phonon coefficient only related to the material [15]. For the strained Si sample before patterning, the Raman shift of Si phonon peak position corresponds to a strain of ~1.27%.

However, for the patterned strained Si samples, the SiGe is exposed from the edges of the patterned structures, then, the interfering signal must be concerned, because the Raman shift of Si–Si vibration mode from SiGe is close to the one from the strained Si layer. In Fig. 3, a typical Raman spectrum of the patterned strained Si pillar (150 nm × 150 nm) is displayed, with a bulk Si and the SiGe virtual substrate spectra for reference. For the

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