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Fabrication of dislocation-free Si films under uniaxial tension on porous Si compliant substrates

Jeehwan Kim *, Jae Young Lee, Ya-Hong Xie

Department of Materials Science and Engineering, University of California at Los Angeles, Box 951595, Los Angeles, California 90095-1595, United States

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Abstract

This paper presents a method for fabricating uniaxially as well as biaxially strained Si films on porous Si substrates. Single crystalline Si films of ~150 nm thickness on top of porous Si substrate can be routinely obtained by self-limiting anodization of heavily doped p-type substrates with epitaxially grown thin Si overlayers. The typical structure of our samples has the porous Si region in square shape in the center of the sample surrounded by bulk Si analogous to a picture in a frame. The porous Si region undergoes volume expansion upon oxidation at low temperature (~500 °C) in steam. The rigid bulk Si frame constrains the porous Si region preventing it from expansion along the direction of the substrate surface. The expansion can be either uniaxial or biaxial along the sample surface if two opposite stripes of bulk Si or all four sides are removed. In this report, we describe uniaxial tensile strain of 0.83% observed in a 150 nm thick Si film without dislocation or crack.
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Keywords: Strained silicon; Uniaxial strain; Dislocation-free; Porous silicon

1. Introduction

Strained Si has become an integral part of modern complementary metal-oxide-semiconductor (CMOS) technology. The mobility enhancement of a strained Si channel is dependent on the mode of strain (biaxial/uniaxial), the sign of strain (compressive/tensile), and the magnitude of strain. With respect to the sign of strain, tensile strain enhances the mobility of both holes and electrons, while compressive strain only enhances hole mobility. For both tensile and compressive strain, the uniaxial mode of strain is more advantageous for the following reasons. The mobility enhancement under uniaxial strain results in larger drive current of Si metal-oxide-semiconductor field effect transistors (MOSFETs) [1]. For n-channel MOSFETs, the threshold voltage shift under uniaxial tension is further reduced compared to that under biaxial tension [2]. A common method for adjusting the threshold voltage shift under biaxial tension is to increase the doping level. However, the increased doping level diminishes the strain-induced enhancement of electron mobility. Recently, a process-induced local strain method has been incorporated into the 90 nm logic technology [3]. It employs uniaxial compressive strain induced by epitaxial growths of SiGe into recessed source and drain pockets, and uniaxial tensile strain induced by a high stress nitride capping layer [3]. The high level of compressive strain effectively improves hole mobility in the p-channel up to 90% even under high gate overdrive. In contrast, the electron mobility enhancement in n-channel MOSFETs is significantly smaller than that in the p-channel. This is due to the fact that tensile strain achievable by using the nitride capping layer is rather limited compared to the values of global strain achievable by using compositionally graded SiGe buffer layers (>1%) [4]. However, relatively high density of threading dislocations originating from within the SiGe buffers and the self-heating effect due to reduced-thermal conductivity of the SiGe buffer are undesirable for microelectronic devices application [4]. Moreover, this method only allows for biaxial strain. H. Yin et al. demonstrated a method for fabricating uniaxially relaxed SiGe buffer layers without dislocations by relaxation of a rectangular island of strained SiGe film on top of a borophosphorosilicate glass (BPSG)

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* Corresponding author.
E-mail address: jhkim03@ucla.edu (J. Kim).

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layer above the glass flow temperature of ~800 °C [5]. Although this method allows to grow uniaxially strained Si on a SiGe template, uniform strain can be obtained only for small lateral dimension (typically <100 µm). Moreover, the high concentration (10^{21-22} cm^{-3}) of boron and phosphorous in BPSG causes unintentional doping into device level due to out-diffusion during prolonged annealing of BPSG above glass flow temperatures.

In this study, we introduce a method for achieving a high level of uniaxial strain in thin Si films without utilizing SiGe templates. Dislocations are never introduced during the fabrication process. Moreover, uniaxially strained Si films are obtained in an entire substrate area. Dislocation-free strained Si with a high level of strain is fabricated via low temperature oxidation of a porous Si (PS) substrate with a thin Si film. Geometrical manipulation of the sample structure results in either uniaxial strain or biaxial strain of 0.83% in a 150 nm Si film on the PS substrate without the formation of dislocations or cracks.

2. Experimental procedure

Fig. 1 shows experimental procedures to fabricate strained Si films. A 150 nm thick intrinsic Si film is grown on a (100) heavily doped p-type (p++) Si substrate (ρ=0.001–0.005 Ω cm, $N_A = 2\times10^{19}-10^{20}$ cm^{-3}) using a Riber EVA-32 molecular-beam epitaxy (MBE) system at 550 °C (Fig. 1(a)). The samples are cleaved along [110] directions into a square shape (1.5 cm × 1.5 cm). The samples are anodized in a double tank electrochemical cell filled with a 1:1 volume ratio solution of HF (49%) to ethanol (Fig. 1(b)). The p++ substrate with the intrinsic thin Si film is inserted between two half-cells for isolation and platinum foils are immersed at both sides. The anodization current of 50 mA/cm^2 flows through the substrate via connecting platinum foils to a power supply. In order to form PS from the back-side of the Si substrate, anodic current is required at the back-side of the substrate. Anodization front is expected to progress from the back-side of the substrate and stops at the interface between an intrinsic thin Si film and a p++ substrate. The complete anodization of the p++ substrate upon adequate over-anodization is verified using a cross-sectional scanning electron microscope (SEM) [Hitachi S4700 field emission SEM]. The sample is subsequently oxidized at 500 °C in steam (Fig. 1(c)). The oxidation-induced volume expansion of the PS substrate is transferred into the thin Si film as a tensile strain. Since entire process for applying stress into the thin Si films is performed at a low temperature, the films can be highly strained avoiding the formation of dislocations or cracks. The sample structure is geometrically manipulated to tune the mode of strain (uniaxial vs biaxial). The schematics of this processing sequence are shown in Fig. 2. Only the center part of the p++ substrate is anodized with a square-shaped mask that protects the edges of the samples from coming in contact with the HF solution. This produces a square block of PS located at the center of the wafer, leaving a rigid bulk Si frame as shown in Fig. 2(a). It is well known that low temperature oxidation of PS does induce substantial volume expansion. The direction of the volume expansion can be controlled by preferential removal of these edges using a wafer dicing saw. The removal of all four sides of the bulk Si frame allows biaxial strain to be induced in the Si film (sample 1—Fig. 2(b)), whereas removing two opposite sides of the frame allows for uniaxial strain (sample 2—Fig. 2(c)) upon oxidation. The amount of strain in the thin Si film is measured with a Renishaw microscope Raman spectrometer. The laser penetration depth of the Raman measurement is approximately 200 nm.

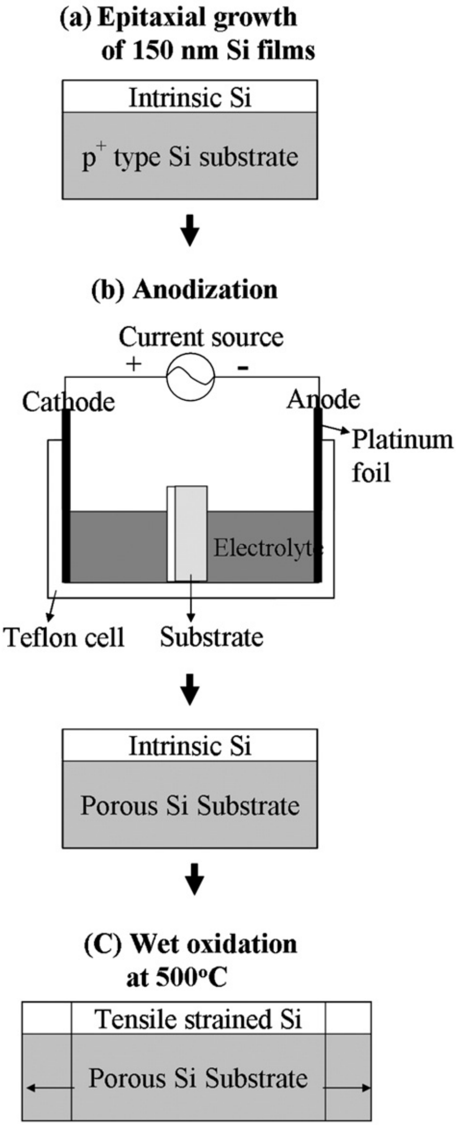

Fig. 1. Schematics of the process to fabricate a strained Si film on a porous Si compliant substrate.

3. Results and discussion

M. Ligeon et al. [6] experimentally observed that when p− and p+ Si are coupled together, the p+ Si with the doping level greater than 3×10^{18} cm^{-3} shows infinite anodization selectivity for the p− Si with the doping level of 10^{15} cm^{-3}. In this study, the background doping level from our MBE system is

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