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Enhanced relaxation of SiGe layers by He implantation supported by in situ ultrasonic treatments

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Abstract

Helium implantation-enhanced strain relaxation of SiGe layers grown pseudomorphically on Si substrates is an interesting alternative for the creation of strained Si CMOS structures. Here we demonstrate the application of additional in situ ultrasonic treatment (UST) during He ion implantation for the formation of relaxed $Si_{0.8}Ge_{0.2}$ buffer layers. By Raman spectroscopy and X-ray diffraction we show increased relaxation of the SiGe layers under the influence of UST. A rectangular dislocation network with a high dislocation density of about 10^9–$10^{10}\,cm^{-2}$ concentrated near the interface between the SiGe layer and the Si substrate is shown by TEM for 100 nm SiGe/Si heterostructures after heat treatment at 750 °C, 60 s. Application of ultrasonic waves during He implantation keeps a low surface roughness of about 0.5 nm.

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1. Introduction

Strained silicon (Si) layers show enhanced mobility of holes and electrons and represent therefore an interesting channel material for advanced CMOS technologies [1]. One possibility to introduce biaxial strain in a manner compatible with existing technologies is the pseudomorphic hetero-epitaxial growth of Si layers on strain-relaxed SiGe layers with a larger lattice constant compared to pure Si. It was demonstrated that thin SiGe layers grown on Si substrates with thicknesses of 80–150 nm can be strain relaxed by H or He ion implantation and thermal annealing [2]. An implantation-induced defect band about 100–200 nm below the SiGe/Si substrate interface promotes strain relaxation of the SiGe layer, maintaining a high surface quality (rms roughness below 1 nm) and reaching low threading dislocation densities.

However, the degree of relaxation depends strongly on technology treatments and still needs improvement without increasing the density of threading dislocations.

Ultrasonic treatment (UST) of Si wafers during ion implantation changes the point defect distribution and influences the behavior of defects during post-implantation annealing. It was shown [3] that UST allows one to lower the amorphization threshold and stimulates diffusion of Si interstitials. Changing intensity and frequency of the ultrasonic waves allows one to modify the kinetics of defect formation.

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In this contribution we show that ultrasonic treatment applied during He implantation can improve the relaxation of strained SiGe layers on Si. This widens the processing window, improves layer quality and simplifies optional overgrowth.

2. Experimental

We used rapid thermal chemical vapor deposition (RPCVD) to grow metastable 100 and 300 nm thick $Si_{0.8}Ge_{0.2}$ buffer layers on 200 mm Si(1 0 0) wafers. Parts of the wafers were subsequently implanted with He ions (50 keV) with doses of $1–8 \times 10^{15}\,cm^{-2}$. During implantation several samples were supposed to ultrasonic waves with a frequency of 5.6 MHz and a power of $0.01–1\,W/cm^2$. Subsequently, the samples were annealed in Ar at temperatures between 650 °C and 850 °C for 60 s.

The strain and strain relaxation in the layers were measured with Raman spectroscopy, using excitation at a wavelength of 488 nm, and double-crystal X-ray diffraction (XRD) in symmetric and asymmetric geometries. The defect structure was investigated by transmission electron microscopy (TEM) at 200 keV in a Phillips CM200. The surface roughness was evaluated by atomic force microscopy (AFM) in a D 5000/Nanoscope III from Digital Instruments.

3. Results and discussion

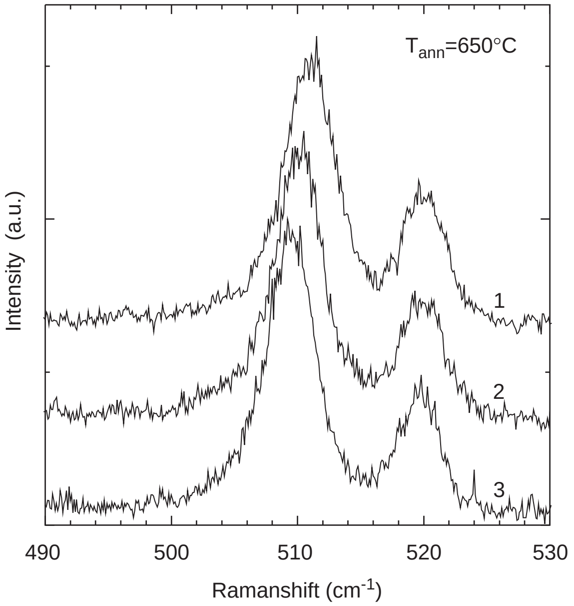

Fig. 1. Raman spectra for samples after annealing at 650°C: without He implantation (1), with He implantation (2) ($D = 5 \times 10^{15}\,cm^{-2}$), He implantation with UST (3).

Fig. 1 shows Raman spectra of annealed SiGe/ Si heterostructures (300 nm SiGe layer) without He implantation (1), with He implantation (2) and with additional in situ UST during implantation (3). We observe a shift of the Si–Si band in the SiGe layer towards lower frequencies by about $0.8\,cm^{-1}$ for the He-implanted samples, indicating additional relaxation. The UST enhances this shift ($1.4\,cm^{-1}$) showing increased relaxation in the corresponding samples.

Figs. 2(a–d) show TEM micrographs of the implanted and annealed (750 °C, 60 s) samples (thickness of the SiGe layer 100 nm) (a,c) without UST and (b,d) with UST. The plan view micrographs (Figs. 2a,b) demonstrate the formation of a dense rectangular misfit dislocation network responsible for the high degree of relaxation. The density is estimated to be in the range of $10^9–10^{10}\,cm^{-2}$. Unfortunately, the statistics from the TEM migrographs is not sufficient to make a final conclusion about a density difference between the sample with and without UST. With the given heat treatment a significant part of the He is expected to disappear due to outdiffusion, this explains the absence of He bubbles in Figs. 2c and d.

Fig. 2c shows that the misfit dislocation network is located in a very thin transition layer at the interface between the Si substrate and the relaxed SiGe layer. The lateral spacing between the dislocations is in the range of 20–100 nm. The density of possible threading dislocations is too low to be investigated exactly by TEM. The localization of the network near the interface and the low density of threading dislocations indicate advantages of the given method of relaxation compared to graded buffer layer growth. From the TEM work we do not see any disadvantages for the application of UST. In general, sample bowing was less in the case of TEM samples with UST. This could be a result of lower stress in the UST samples. AFM measurements indicate a slightly increased surface roughness for the UST samples (Figs. 2e,f). In the case of 100 nm SiGe/Si heterostuctures the RMS roughness values for the UST relaxed layer could be kept below 0.6 nm in comparison to 0.5 nm without UST. These results and the increased degree of relaxation (see Raman and XRD data) support a perspective application of UST for the fabrication of relaxed SiGe layers.

Fig. 3 shows XRD spectra of 300 nm SiGe/Si samples in different stages of technological treatments: as-grown (1), as-implanted (2) without UST, as-implanted (3) with UST, annealed after implantation without UST (4), and with UST (5). By the arrows in Fig. 3 the theoretical position of completely relaxed (R) and coherently strained (S) layers are indicated.

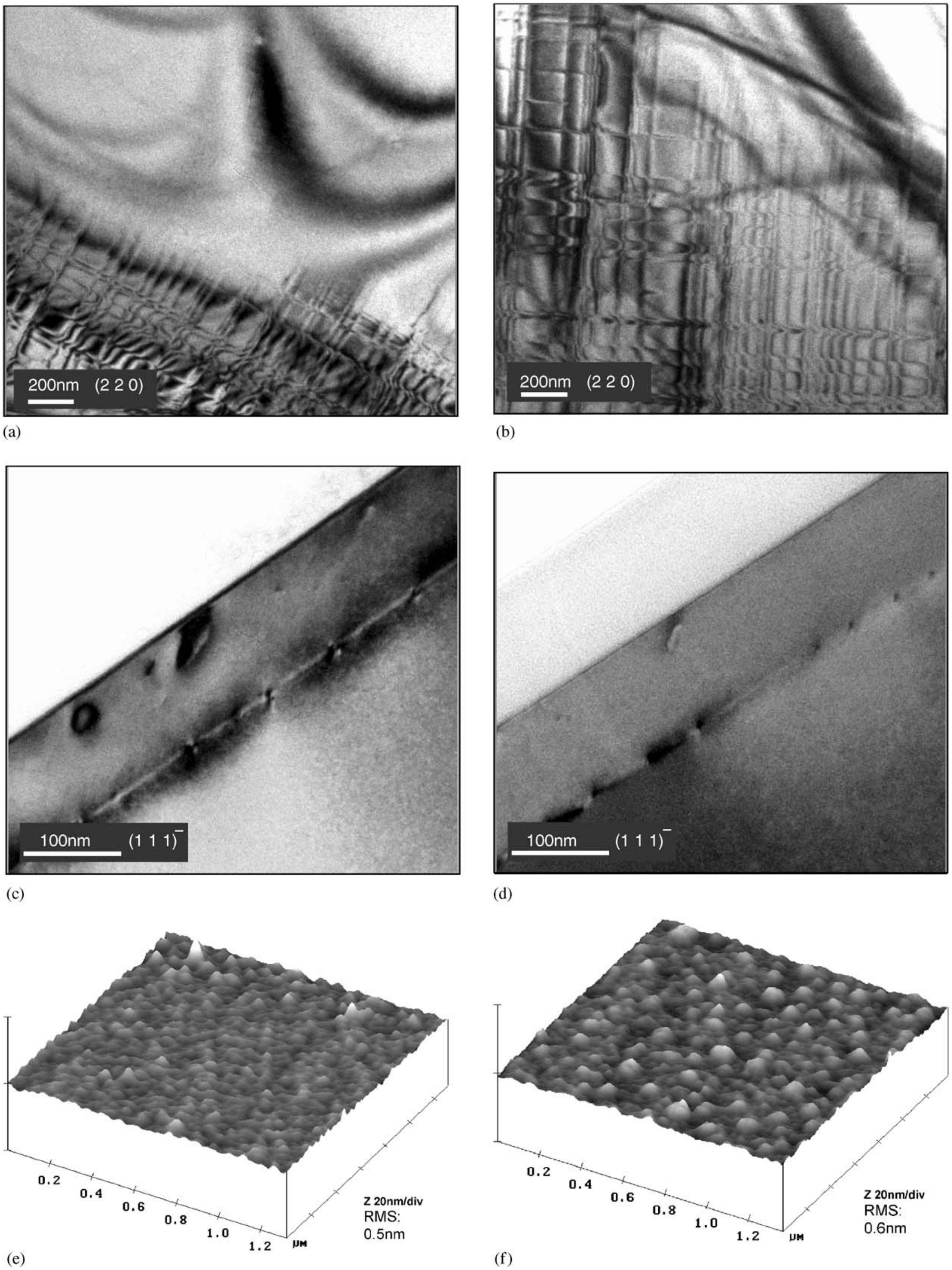

Fig. 2. TEM micrographs of the defect structure in 100 nm SiGe/Si samples after relaxation annealing (750 °C, 60 s): (a,b) plan view TEM under [2 2 0] bright-field imaging conditions; (c,d) XTEM under [1 1 $\bar{1}$] imaging conditions; (a,c) sample without UST, (b,d) samples with UST, (e,f) corresponding AFM surface plots, (e) without UST, (f) with UST.

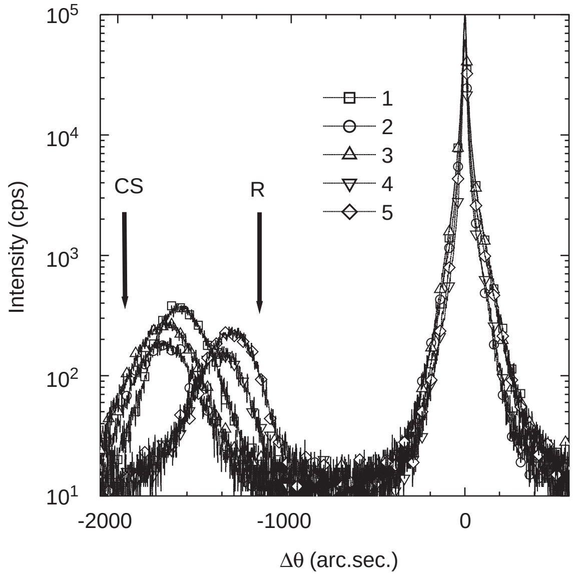

Fig. 3. X-ray diffraction curves for samples with different treatment: as-grown (1), as-implanted (2) without UST, as-implanted (3) with UST, annealed after implantation without UST (4), and with UST (5). The theoretical position of diffraction curves for completely relaxed (R) and coherently strained (CS) layers are indicated by the arrows.

The degree of relaxation R is defined as

$$R = (a^{\top}_{\mathrm{SiGe}} - a_{\mathrm{Si}})/(a^{\parallel}_{\mathrm{SiGe}} - a_{\mathrm{Si}}) \times 100\%, \tag{1}$$

where $a^{\top}_{\mathrm{SiGe}}$, $a^{\parallel}_{\mathrm{SiGe}}$–the lattice parameters of the SiGe layer perpendicular and parallel to the substrate, respectively, and a_{Si} is the lattice parameter of Si.

Due to the large, supercritical thickness of the as-deposited 300 nm SiGe layers, we observe relaxation already in the as-deposited layers. Values up to 48% were measured by X-ray diffractometry for the 300 nm thick SiGe layers. Obviously, relaxation takes place during layer growth at temperatures of about 600 °C. For the 100 nm thick SiGe layers the relaxation after deposition was below 5%, and XRD shows nearly pseudomorphically strained SiGe layers. Short annealing of the unimplanted structures at temperatures below 650 °C does not increase the degree of relaxation significantly. At temperatures above 750 °C additional substantial relaxation processes take place.

We observed that the implantation of He atoms increases the stress in the layered structure dependent on the implanted dose. This is one reason for increased relaxation in these structures. More importantly due to precipitate and bubble formation additional relaxation mechanisms are activated for the implanted samples compared to relaxation occurring during the growth of thick graded buffer layers. We found a degree of relaxation up to values of 72% after annealing of the He-implanted samples.

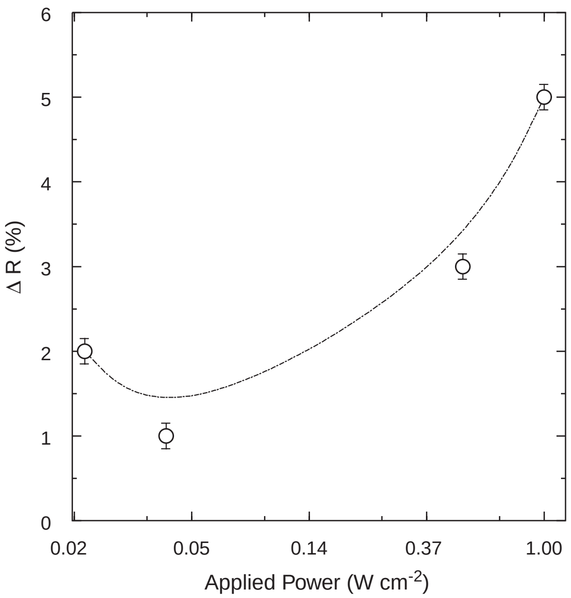

Fig. 4. Differences in the degree of relaxation as a function of the applied UST power.

Ultrasonic waves during implantation stimulate the diffusion of Si interstitials into the bulk of the substrate. They might also stimulate the diffusion of He atoms and influence the kinetics of bubble and precipitate formation during subsequent heat treatments, e.g. by clustering. This is expected to influence the generation of misfit dislocations in the layered structure.

As visible from Fig. 3, the use of UST allows one to increase the relaxation (see Fig. 3, curve (5)) under identical implantation doses and annealing conditions. Values up to $R = 82\%$ were determined for samples with 300 nm SiGe layers. It is interesting to mention that the level of stress in the as-implanted structure is even slightly less than without UST. More work is in progress to investigate differences in the relaxation mechanism under the influence of UST.

It is expected that the effect of UST will depend on the amplitude and frequency of the ultrasonic waves. The influence of the amplitude is demonstrated in Fig. 4, changing the applied voltage from 0.5 to 10 V. We observe a difference of relaxation up to 5%. The minimum value at 2 V needs further investigation.

Work is in progress to determine the influence of the UST frequency on the relaxation process.

4. Summary

We investigated the application of in situ ultrasonic treatment during He ion implantation for the formation of relaxed SiGe buffer layers on Si substrates. By Raman spectroscopy and XRD, we found increased relaxation of the SiGe layers under the influence of UST. A rectangular dislocation network with a high dislocation density of about 10^9–$10^{10}\,\mathrm{cm}^{-2}$ near the interface between the SiGe layer and the Si substrate was revealed by TEM for 100 nm SiGe/Si heterostructures after heat treatment at 750 °C, 60 s. The threading dislocation density was low enough to be investigated by TEM. Application of ultrasonic waves during He implantation increased the degree of relaxation and maintained low surface roughness of about 0.6 nm. It is expected that this will improve the properties of pseudomorphically strained Si layers on top of the relaxed SiGe layer for advanced CMOS technologies.

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