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Formation of uniaxially strained SiGe by selective ion implantation technique

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ABSTRACT

Uniaxially strained SiGe layers were fabricated with a newly developed selective-ion-implantation technique. The SiGe layer was grown on the Si substrate, into which laterally selective ion-implantation with stripe pattern was carried out prior to the SiGe growth. A strain-relaxation of the SiGe layer was largely enhanced due to ion-implantation-induced defects selectively in the ion-implanted area while it was hardly enhanced in the neighboring unimplanted area. However, micro-Raman mapping and X-ray diffraction reciprocal space mapping measurements obviously revealed that the relaxed SiGe in the implanted area remarkably influenced a strain state of the neighboring strained SiGe in the unimplanted area, that is, the strain along the stripe line direction was highly relieved due to the stress caused by the neighboring relaxed SiGe while the strain in the direction perpendicular to the line was well maintained. As a result, highly asymmetric strain state, that is, uniaxial strain was realized, where 4 times different relaxation ratios in the two directions were observed. These results indicate that the selective-ion-implantation technique developed in this study has a high potential to realize uniaxially strained Si/Ge channel devices with high mobility.

In recent years, an importance of channel strain engineering has been increasing for continuing MOSFET performance improvements and new technologies are still required for further developments. Currently, one of the most important strain-engineered channels is a strained-Si channel with locally process-induced strain (called local strain), which has achieved mobility enhancements of both electron and hole [1]. Induced uniaxial strain plays an important role for the mobility enhancements [2]. On the other hand, strained channels with so-called global strain induced across a whole wafer are formed by growing them on SiGe strain-relaxed buffer layers called virtual substrates. The global strain has many advantages, such as, its much superior stability, controllability and independence on device processes. One critical drawback of the global strain technique based on Si/Ge hetero structures, however, is the inability to induce uniaxial strain. Therefore, development of new techniques to realize uniaxially strained Si/Ge heterostructures is considered to be the most attractive and challenging technology to enjoy both benefits.

In this study, we propose a novel technique to form uniaxially strained SiGe layers based on ion-implantation technique [3–7]. We have been developing ion implantation technique for fabrication of thin SiGe strain-relaxed layers and have demonstrated that ion-implantation-induced defects acting as dislocation sources can largely enhance the strain-relaxation of thin SiGe layers [5–7]. Here, we applied this technique to local controlling of strain by means of introducing the defects selectively. A SiGe grown on defect-induced area is selectively relaxed while a SiGe on unimplanted area remains to be strained. Thus, the relaxed and strained SiGe regions can be created simultaneously on one planar SiGe/Si substrate, where both regions are expected to interact with each other, leading to generation of anisotropic strain states. We demonstrate that the uniaxially strained SiGe can be realized by selective-ion-implantation with µm-order stripe line patterns.

Fig. 1 depicts the sample structure fabricated in this study. A SiO_2 film was firstly deposited on a Si substrate by plasma enhanced chemical vapor deposition (PECVD) and a stripe pattern consisting of 2-µm-width lines and spaces was defined by standard photolithography process. Through this SiO_2 mask window, Ar^+ ions were selectively implanted into the Si substrate prior to SiGe growth. In the following, we call this selectively ion-implanted Si substrate as SII-Si. The implantation condition was an energy of 25 keV and a dose of $1\times10^{15}\,cm^{-2}$. The ion implantation was followed by recrystallization annealing at 700 °C for 10 min in N_2 atmosphere. After this annealing process, end-of-range defects remain only in selectively ion-implanted areas. Next, a $Si_{0.73}Ge_{0.27}$ layer with the thickness of 60 nm was epitaxially grown uniformly on the whole region of the SII-Si by gas source molecular beam epitaxy at 500 °C. At this stage, it is

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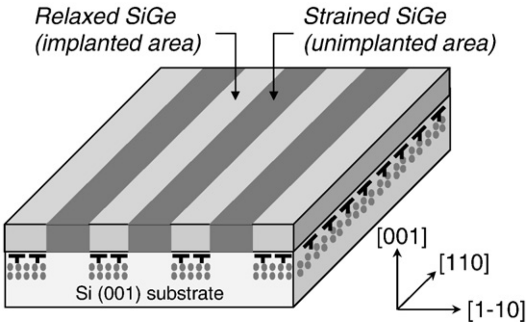

Fig. 1. The schematic of the fabricated sample structure. The stripe width is 2 µm.

expected that the strain relaxation of SiGe hardly takes place and the SiGe layer is compressively strained both in implanted and unimplanted areas. To cause the stain relaxation, the sample was next subjected to post growth annealing at 900 °C in N_2 atmosphere. During this annealing process, the strain relaxation is expected to proceed only in the ion-implanted area due to the implantation-induced defects working as dislocation generation sources while the compressive strain still remains in the unimplanted area without such dislocation sources. It was confirmed by atomic force microscope (AFM) that SiGe surfaces for both regions were very smooth with rms roughness less than 1.0 nm even after the annealing process. As references, the same structures were formed with the same procedures on the Si substrate that was globally ion-implanted without the stripe patterning (referred as GII-Si) and on the Si substrate without ion-implantation (referred as unimplanted Si). Two-dimensional (2D) micro Raman mapping measurement was employed to precisely evaluate lateral strain-field distributions of the SiGe layer. A 514.5 nm wavelength line of an Ar laser was used for excitation in backscattering geometry. A laser spot size was focused to 1 µm^2. X-ray diffraction (XRD) reciprocal space mapping was performed to evaluate anisotropic strain states. Incident X-ray beam direction was fixed to be along or perpendicular to the stripe pattern line direction in order to estimate strains of each direction. The size of the processed area, which is fully covered by periodically aligned line-and-space patterns, was much larger than the X-ray beam spot so that lattice information of unprocessed region should not be incorporated into XRD results.

A strain state and its in-plane distribution in the SiGe layer formed on the SII-Si were firstly evaluated by means of two-dimensional (2D) Raman mapping measurement. Raman spectra were obtained at each scanning position and Raman shift of Si–Si mode of SiGe, which changes very sensitively with the strain of SiGe, was precisely determined by a fitting and plotted at each position. Fig. 2 shows obtained 20 × 20 µm^2 Raman mapping images of the sample (a) before and (b) after annealing. Even before annealing, two areas with different amounts of strain are distinguishable. The ion-implanted area exhibits lower wavenumbers (dark contrast) while the unimplanted area does higher wavenumbers (bright contrast). This difference becomes more significant after annealing as obviously seen in Fig. 2(b) where the implanted and unimplanted areas exhibit Raman shift wavenumbers around 507.5 and 509.0 cm^{-1}, respectively. These observations mean that strain relaxation is significantly enhanced after annealing only in the implanted area, but not in the unimplanted area, indicating that two different SiGe films containing small and large strains can be simultaneously created on the one continuous planar wafer by means of the selective defect introduction. For comparison, the reference sample formed on unimplanted Si was also evaluated by Raman measurement and Raman shift peak of 512.5 cm^{-1} was obtained, which corresponds to almost full strain. A remarkable fact is that the peak obtained from the unimplanted area of the sample formed on SII-Si (509.0 cm^{-1}) is markedly lower than that obtained from the reference sample formed on unimplanted Si (512.5 cm^{-1}), which indicates that the compressive strain of the former is smaller than that of the latter. In other words, the compressive strain of SiGe pseudomorphically grown on unimplanted Si is largely relieved in the presence of the neighboring relaxed SiGe in the implanted area while almost full strain is maintained without the neighboring relaxed SiGe. Therefore, it can be said that the neighboring relaxed SiGe markedly affects the strain state of the strained SiGe. It is considered that shear stress along stripe direction supplied by the neighboring relaxed SiGe is responsible for the observed strain relaxation in the unimplanted area, where generation of anisotropic (uniaxial) strain is highly expected.

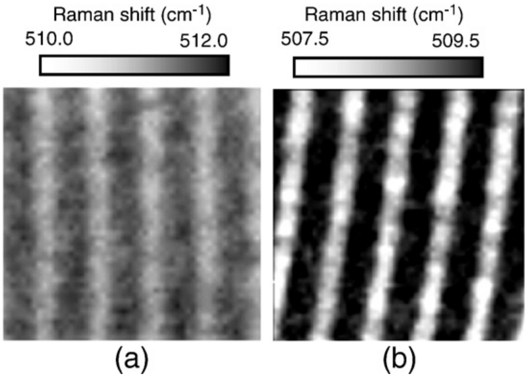

Fig. 2. 20 × 20 µm^2 Raman mapping images of the SiGe layer formed on the selectively ion-implanted Si substrate (a) before and (b) after post growth annealing. Scale ranges are 2.0 cm^{-1}.

XRD reciprocal space mapping (RSM) measurements were next carried out to precisely characterize anisotropic strain states. The measurement configuration is illustrated in Fig. 3. RSM images around [2–24] and [224] diffraction points measured with the incident X-ray beam direction perpendicular to and along the stripe line pattern direction [110], respectively, are shown in Figs. 3 (a) and (b). In [2–24] RSM (Fig. 3(a)), two peaks associated with SiGe are obviously observed in addition to a Si substrate peak. One broad peak around Q_x of 0.519 Å^{-1} corresponds to a partially relaxed SiGe while another sharp peak exhibiting almost the same Q_x as the Si substrate is related to an almost fully strained SiGe. With previous Raman results taken into account, the relaxed and strained SiGe peaks are reasonably assigned to the implanted and unimplanted areas, respectively. On the contrary, a markedly different feature is obviously observed in [224] RSM as shown in Fig. 3 (b). The signal related to the strained SiGe is completely absent while only the relaxed-SiGe related peak is observed. It is considered that the SiGe in both implanted and unimplanted areas are relaxed to a similar extent, making it difficult to separate the peaks coming from the two areas. This is a clear evidence that the SiGe in the unimplanted area is strained only along [1–10] direction but relaxed along [110] direction, that is, the uniaxial strain is realized in the unimplanted area.

For a quantitative analysis of the strain states, the obtained peak values in [2–24] RSM were converted into the lattice constants and associated strains of SiGe along [001] direction ($\varepsilon_{[001]}$) and [1–10] direction ($\varepsilon_{[1-10]}$). From the elastic theory [8], the strain along [110] direction ($\varepsilon_{[110]}$) can be derived utilizing the experimentally obtained $\varepsilon_{[001]}$ and $\varepsilon_{[1-10]}$, and resultantly, relaxation ratios ($R_{[001]}$, $R_{[1-10]}$ and $R_{[110]}$) corresponding to each direction can be obtained as well. The relationship between $R_{[110]}$ and $R_{[1-10]}$ ($\varepsilon_{[110]}$ and $\varepsilon_{[1-10]}$) is plotted in Fig. 4. For comparison, relaxation ratios obtained from the reference samples fabricated on GII–Si and unimplanted Si are also plotted in this figure. For the reference sample formed on unimplanted Si, both $R_{[110]}$ and $R_{[1-10]}$ are seen to be nearly zero before and after annealing. This indicates that the strain relaxation of SiGe is almost suppressed without ion implantation even after annealing, which agrees with aforementioned Raman results. On the other hand, for the reference