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Investigation of silicon-germanium fins fabricated using germanium condensation on vertical compliant structures

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We report the formation of defect-free SiGe vertical heterostructures using Ge condensation on vertical SiGe structures. To evaluate the effectiveness of substrate compliance in vertical structures, SiGe fins of various widths were subjected to Ge condensation. This formed vertical fin heterostructures comprising a SiGe core region sandwiched by Ge-rich regions. Using cross-sectional transmission electron microscopy (TEM), wide fins were found to contain more dislocations than narrower fins, in which we observed few or no dislocations. Lattice strain analysis using high-resolution TEM image analysis was used to confirm that strain relaxation has occurred. In the wide fins (noncompliant substrate), strain relaxation was dislocation mediated. In the narrow fins, substrate compliance enabled strain relaxation in the Ge-rich layer with reduced dislocation formation. Hence, we also demonstrated the formation of a strain-relaxed homogeneous SiGe fin (~90% Ge concentration) with no observable dislocations. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2151257]

Ge condensation is a phenomenon which occurs in SiGe alloys during thermal oxidation, in which Si is selectively incorporated into the thermal oxide, causing a pileup of Ge at the oxidation front. During Ge condensation of crystalline SiGe, the condensed Ge-rich layer, being lattice mismatched with the substrate, develops high stress. This typically culminates in the formation of dislocations.[1] Most Ge condensation experiments have been carried out on planar substrates with (001) surface orientations. Although work on (110) substrates has been reported,[2] there was no detailed defect and lattice strain analysis. A significant dislocation density in strained germanium-on-insulator (GOI) substrates, fabricated by Ge condensation of epitaxially grown SiGe on silicon-on-insulator (SOI) substrates, was reported.[3] This may be attributed to the low effective compliance of conventional SOI substrates below oxide viscous flow temperatures.[4–6] To this end, there have also been efforts to improve SOI substrate compliance at relatively lower temperatures by incorporating boron into the buried oxide layer, so as to reduce oxide reflow temperatures.[7,8] Nevertheless, the use of SOI with either conventional oxide or boron-doped oxide imposes limitations on the substrate quality for carrier-depleted GOI device fabrication. A free-standing planar thin film is another approach to realize substrate compliance, but its viability may be limited by fabrication difficulties, structural fragility, and strained-induced film warping.[9,10] Conversely, a vertical free-standing thin film, such as the Si fin body in a fin field-effect transistor (FinFET), can be a practically feasible compliant substrate. The formation of fins is free from the earlier-mentioned limitations, since it has been shown to be compatible with complementary metal-oxide-semiconductor (CMOS) processes. Such vertical structures will also be resistant to strain-induced warping due to their structural symmetry. In this work, the Ge condensation was applied to SiGe fins of various fin widths. The Ge concentration, dislocation density, and lattice strain in these vertical structures were investigated. Their relationship with fin widths in the context of substrate compliance is discussed in this letter.

SiGe wafers with (001) surface orientation were used in this experiment. Each wafer comprised an epitaxially grown strain-relaxed $Si_{0.85}Ge_{0.15}$ layer (thickness of ~0.5 μm) on a graded SiGe buffer layer (thickness of 2 μm) on Si substrate. Fin patterns of various widths (80–650 nm) were formed using 248 nm lithography, photoresist trimming, and reactive ion etch (RIE) of SiGe. The fin height is typically about 480 nm. The patterned SiGe wafers were subjected to dry thermal oxidation at 875 °C for different durations. The oxidation temperature was chosen to be below the melting point of pure germanium yet sufficiently high to ensure that no germanium was incorporated into the thermal oxide.

The phenomenon of Ge condensation to enhance Ge concentration in three-dimensional SiGe structures is illustrated in Fig. 1. Cross-sectional transmission electron microscopy (TEM) micrographs of two fins with different fin widths (W_{fin}) are shown in Fig. 2. These fins had been subjected to 12 h of dry oxidation. It is observed that Ge condensation occurs for both (001) and (110) surfaces. Due to rejection of Ge from the oxide, the local Ge condensation rates are directly related to the local oxidation rates. The local oxidation rates are in turn dependent on surface orientation and presence of local stress. Oxidation rates are typi-

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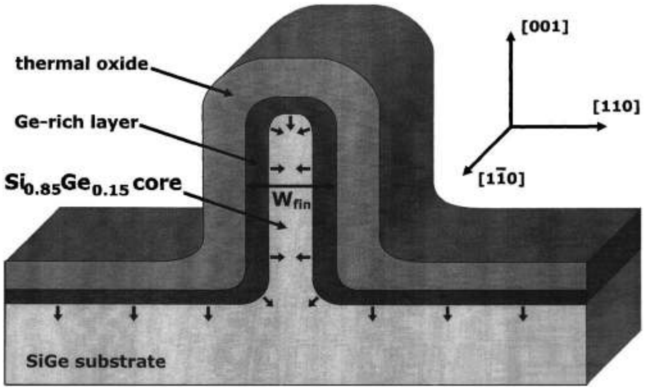

FIG. 1. Cross-sectional schematic of a SiGe fin heterostructure during Ge condensation. The piling up of Ge at the oxidation front to form a Ge-rich layer is shown. As oxidation proceeds, the Ge-rich layer increases in thickness and the fin width (W_{fin}) decreases. This also results in decreasing $Si_{0.85}Ge_{0.15}$ core thickness (T_{core}).

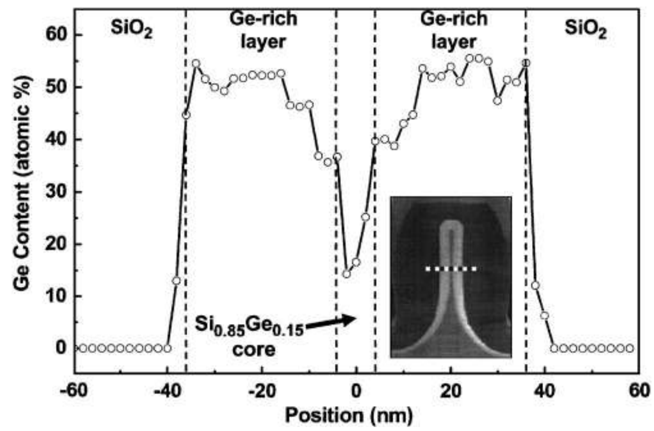

FIG. 3. Ge concentration profile across a medium-width SiGe fin (W_{fin} =70 nm, see inset) that has undergone 18 h of Ge condensation. The Ge concentration within the Ge-rich layer is quite uniform. The Ge concentration profile is observed to be rather abrupt at the interface between the Ge-rich layer and the $Si_{0.85}Ge_{0.15}$ substrate.

cally higher on the (110) surface as compared to the (001) surface. Low-temperature oxidation below oxide viscous flow temperatures (~950 °C) also generates stress, which tends to build up in the corners of the structures and reduces the local oxidation rates.[11] Energy dispersive spectrometry (EDS) was used to estimate the atomic Ge concentration in different regions. The condensed Ge-rich regions, with Ge concentration in the range 40–55 %, are visually distinguishable from uncondensed regions with Ge concentration of about 15%. Figure 2(a) shows a medium-width SiGe fin (W_{fin}=100 nm). The Ge concentration values at several locations are shown. The Ge concentration values ranges from 39.1% to 48.7% in the Ge-rich layer and remains at around 15% in uncondensed SiGe regions. Figure 2(b) shows a narrower fin (W_{fin}=45 nm). Due to the smaller fin width, the Ge-rich layers from opposite sides of the fin have merged homogeneously at the top portion of the fin. The Ge concentration in the merged portion is also observed to be higher—ranging from 50.7% to 56.3%. With further Ge condensation, the Ge concentration can be increased further.

Figure 3 shows the EDS-derived Ge concentration profile across a 70-nm-wide fin after 18 h of Ge condensation. The Ge concentration within the Ge-rich layer is quite uniform (~50%). The Ge concentration profile is abrupt at the interface (heterojunction) between the Ge-rich layer and the $Si_{0.85}Ge_{0.15}$ core. The concentration profile is a result of competing dynamics of the processes such as oxidation of SiGe, Ge segregation out of the oxide region, and Ge diffusion in SiGe with varying Ge concentration. The abrupt concentration profile at the heterojunction is consistent with the fact that Ge self-diffusion is five orders of magnitude faster than Ge diffusion in pure Si (Ref. 12). Considering the Ge-rich layer to be of a uniform concentration of 50%, the lattice mismatch between the Ge-rich layer and the $Si_{0.85}Ge_{0.15}$ core will be ~1.5%, according to Vegard's law. This mismatch will result in high strain in either or both of the layers, depending on relative layer thicknesses. However, it is reasonable to expect that the strain will be relaxed via the formation of dislocations when layer thicknesses exceed a certain critical thickness. The dislocation density was investigated using TEM. Figure 4 shows the cross-sectional TEM micrographs of three fins of different fin widths after 18 h of Ge condensation.

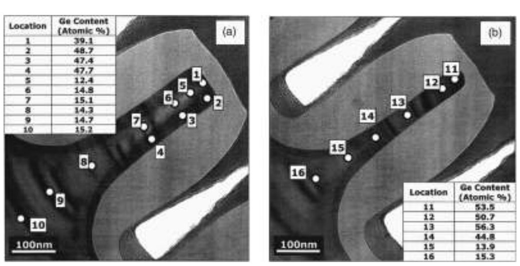

FIG. 2. Cross-sectional TEM images of two SiGe fins after 12 h of Ge condensation. The oxidation temperature of 875 °C is below the viscous flow temperature of thermal oxide of about 950 °C, resulting in the unique geometry of the thermal oxide encapsulating the fin. The vertical sidewall surfaces of the SiGe fins also appear to be very smooth, making them suitable for FinFET applications where sidewall surface roughness would degrade carrier mobility dramatically at high electric field. The Ge atomic concentration values obtained by EDS at several locations in each fin are shown. (a) A wider fin (W_{fin}=100 nm) showing the Ge-rich layer and the sandwiched $Si_{0.85}Ge_{0.15}$ core. (b) A narrower fin (W_{fin}=45 nm) in which the Ge-rich layers have merged from opposite sides of the fin.

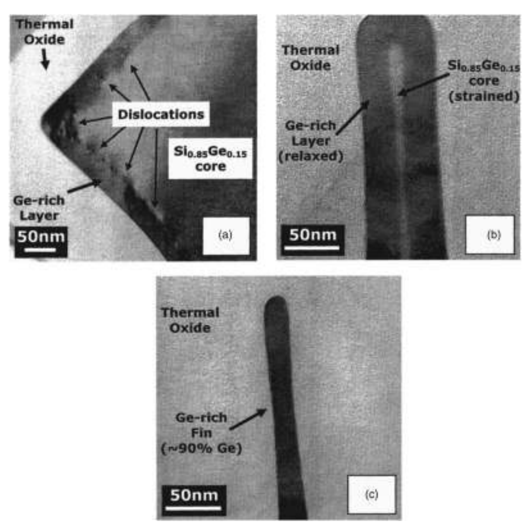

FIG. 4. Cross-sectional TEM images highlighting dislocations in three SiGe fins of different fin widths (W_{fin}) after 18 h of Ge condensation. (a) A wide fin (W_{fin}=480 nm) with a high dislocation density at the interface between the Ge-rich layer and the $Si_{0.85}Ge_{0.15}$ core. (b) A medium-width (W_{fin} =70 nm) fin with a much lower dislocation density. (c) A narrow homogeneous Ge-rich fin (W_{fin}=20 nm, ~90% Ge concentration) showing no observable dislocations.

sation. Figure 4(a) shows a wide fin (W_{fin}=480 nm). It is observed that a large number of dislocations are present at the heterojunction between the Ge-rich layer and the $Si_{0.85}Ge_{0.15}$ core of the fin. A larger number of dislocations are found in the fin corners, possibly due to higher localized strain. The dislocation density at the (110) heterojunction is estimated to be about $\sim 40\ \mu m^{-1}$. Figure 4(b) shows a medium-width fin (W_{fin}=70 nm) in which much fewer dislocations ($\sim 8\ \mu m^{-1}$) are found at the (110) heterojunction as compared to the wide fin. No dislocations are observed at the heterojunction even in the fin corners. Since the lateral thicknesses of the Ge-rich layer [$T_{(\text{Ge-rich layer})}$] in both fins are almost identical, the difference between these two fins lies in the lateral thickness of the sandwiched $Si_{0.85}Ge_{0.15}$ core [$T_{core}=W_{fin}-2\times T_{(\text{Ge-rich layer})}$]. We can thus hypothesize that the thin $Si_{0.85}Ge_{0.15}$ core ($T_{core}<15$ nm) in the medium-width fin exhibits compliance and complies easily with the lattice constant of the Ge-rich layer. If this is the case, the core will be highly strained and few dislocations will be formed. This is consistent with reported results regarding epitaxial growth of a thick SiGe layer on thin Si membranes.[13] Figure 4(c) shows a narrow fin (W_{fin} =20 nm). The Ge-rich layers from opposite sides of the fin have merged to form a homogeneous Ge-rich fin in which no dislocations are observed. During Ge condensation, core compliance played a dominant role in strain relaxation, resulting in a very low dislocation density ($<1\ \mu m^{-1}$). The Ge concentration in this fin is found to be ~90%.

To further examine the compliant nature of the sandwiched $Si_{0.85}Ge_{0.15}$ core, a combination of high-resolution transmission electron microscopy (HRTEM) and fast fourier-transform (FFT) diffractogram[14] was used to derive the lattice mismatch between the Ge-rich layer and the $Si_{0.85}Ge_{0.15}$ core for each of the two wider fins (W_{fin}=70 nm, 480 nm). In short, this technique requires analysis using high-resolution lattice images of the heterojunctions. With the help of FFT diffractograms, the relative lattice constants of the heterolayers were extracted and used to derive the lattice mismatch. If the heterolayers are both relaxed, the lattice mismatch will be ~1.5%, according to Vegard's law. For the wide fin (W_{fin}=480 nm), the lattice mismatch was derived from the analysis to be 1.3 ± 0.3 %, which is close to the value of 1.5%. This clearly points to dislocation-mediated strain relaxation in these heterolayers, which is expected of a non-compliant substrate. For the medium-width fin (W_{fin} =70 nm), the lattice mismatch was derived to be only 0.5 ± 0.3 %, suggesting the existence of a large amount of strain ($\sim 1\pm0.3$ %). For a face-centered-cubic (FCC) lattice, the ratio $a_{[110]}/a_{[001]}$ (where $a_{[110]}$ is the atomic spacing in the [110] direction and $a_{[001]}$ is the atomic spacing in the [001] direction) has a value of $\sqrt{2}$. Strain causes distortion of the cubic lattice and the deviation of this ratio from $\sqrt{2}$. For the medium-width fin (W_{fin}=70 nm), the ratio $a_{[110]}/a_{[001]}$ of the Ge-rich layer was calculated to be within 0.15% of $\sqrt{2}$. This indicates that the Ge-rich layer is almost strain free and the majority of the strain is present in the $Si_{0.85}Ge_{0.15}$ core, thus confirming the compliant nature of the core. In the case of the narrow homogeneous fin (W_{fin}=20 nm) with 90% Ge concentration, the ratio was also within 0.15% of $\sqrt{2}$, indicating its strain-relaxed nature.

In conclusion, narrow SiGe fins demonstrated substrate compliance during Ge condensation. The effect of substrate compliance allowed the condensed Ge-rich layer on opposite sides of a SiGe fin to relax with greatly reduced dislocation formation. This was further evidenced by the formation of dislocation-free Ge-rich fins with ~90% Ge content. These results can be useful for engineering FinFETs or nanowire-FETs employing high mobility channel material such as strained Si, SiGe, and/or Ge, as CMOS technology scales beyond the 45-nm technology generation.

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