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Investigation of thermal stability of Si$_{0.7}$Ge$_{0.3}$Si stacked multilayer with As ion-implantation

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Abstract

The effect of As ion implantation on the stability of SiGe/Si multilayer was systematically studied. The atomic percentage of Ge in as-grown SiGe layer was 30% in this work. A thermally stable Si$_{0.7}$Ge$_{0.3}$/Si multilayer with As ion implantation was attained when the rapid thermal annealing (RTA) treatment temperature did not exceed 850 °C. Significant Ge diffusion was observed for the SiGe/Si multilayer with As ion implantation when the RTA temperature was 900 °C or above. However, minor Ge diffusion was attained for the SiGe/Si multilayer without As ion implantation when the RTA treatment temperature was 900 °C. Therefore, compared with samples without As ion implantation, the stability window of the SiGe/Si multilayer with As ion implantation should be further reduced to 850 °C. As ion implantation plays a critical role in the stability of SiGe/Si multilayer, as it promotes the diffusion of Ge. Consequently, based on the stability of the SiGe/Si multilayer, the highest RTA treatment temperature of 850 °C is proposed for the gate-all-around (GAA) device fabrication process.

1. Introduction

As logic devices scale to 5 nm nodes, SiGe channel materials are becoming popular to extend the use of Si for gate-all-around (GAA) devices due to their higher hole mobility, greater compatibility with present mainstream Si platforms, and better negative bias temperature instability (NBTI) performances than those of Si [1–3]. Moreover, SiGe/Si multilayers can be used as the cores of GAA devices with multichannels and vertically stacked SiGe, which exhibit superior ratios of $I_{on}$ to $I_{off}$ due to their channel stacking [4, 5]. Since the melting points of SiGe materials are lower than that of Si, a treatment with a lower thermal budget should be implemented for shallow trench isolation (STI) annealing or source and drain (S/D) annealing [6]. Furthermore, the stability of the SiGe/Si multilayer will also have an impact on its Si or SiGe channel release. A sharp interface of the SiGe/Si multilayer with no significant Ge diffusion must be maintained after STI and S/D activation annealing. Therefore, it is crucial to investigate the thermal stability of SiGe/Si multilayers for the GAA devices. To date, some studies have been performed on epitaxial growth [7], rapid thermal annealing (RTA) treatment [8], selective etching of SiGe/Si stacked multilayers [9, 10], and SiGe GAA device fabrication [11, 12]. However, there are few detailed reports on the effect of S/D ion implantation and activation on the stability of SiGe/Si multilayers.

In this work, the effect of As ion implantation on the stability of SiGe/Si multilayers was examined in detail. The atomic percentage of Ge in the SiGe/Si multilayer was 30%. The highest thermal budget treatment of the SiGe/Si multilayers was verified for GAA device fabrication.

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2. Experiment

After a standard HF-last cleaning, an H$_2$ pre-baking treatment was applied at 825 °C to attain a good surface of the 8-inch Si substrate. Two sets Si$_{0.7}$Ge$_{0.3}$/Si multilayers were then epitaxially grown at 650 °C using reduced pressure chemical vapor deposition. The partial pressure of the SiH$_4$ was 40 mTorr for the Si layer growth[13]. And the partial pressures of dichlorosilane and GeH$_4$ were 80 and 30 mTorr for the Si$_{0.7}$Ge$_{0.3}$ layer growth. Two sets of Si$_{0.7}$Ge$_{0.3}$/Si multilayers were prepared by appropriately alternating the exposure to dichlorosilane and GeH$_4$ gases and SiH$_4$ gas. As implantation at 7 keV/1.76 $\times$ 15 cm$^{-2}$ followed by an activation process using an RTA treatment in an N$_2$ ambient was employed to simulate the effect of S/D implantation and the activation process. The RTA treatment temperature ranged from 800 to 950 °C and the treatment time was 30 s.

The interfacial morphologies, thickness, and crystalline quality of the SiGe/Si multilayer were directly analyzed using high angle annular dark field scanning transmission electron microscopy (HAADF-STEM). The crystalline quality was also qualitatively detected by high-resolution X-ray diffraction (HRXRD) in the vicinity of the Si (004) Bragg peaks. Moreover, the Ge and As profiles in the SiGe/Si multilayer samples were obtained via secondary ion mass spectrometry (SMIS) analysis.

3. Results and discussion

Initially, As ion implantation followed by different RTA activation treatments was implemented on blank SiGe/Si multilayer epitaxial wafers. Their sheet resistance values are shown in figure 1. The sheet resistance values exhibited a downward trend as the temperature of the RTA treatment increased. For example, the sheet resistance decreased from 388.56 to 162.95 ohm/sq as the RTA treatment temperature increased from 800 to 950 °C. However, the lowest sheet resistance of the SiGe/Si multilayer with the As ion implantation under 950 °C RTA activation treatment may not be the optimal process conditions for the SiGe GAA device fabrication. In addition to the sheet resistance performance, the stability of the Si$_{0.7}$Ge$_{0.3}$/Si multilayer is also very critical for the release of Si or SiGe channel channels, and finally has an impact on the final electrical performance of the GAA device. Therefore, the stability of the Si$_{0.7}$Ge$_{0.3}$/Si multilayer postafter As implantation under different RTA treatmenttreatments will discusbe discussed in detail in the following parts. below.

HRXRD spectra analysis was firstly employed to evaluate the effect of the As ion implantation and activation process on the stability of the SiGe/Si multilayer. Figure 2 shows the HRXRD results of the as-grown sample, and the samples prepared via As ion implantation combined with an activation process under different RTA treatment temperatures. The peaks of the samples with implanted As ions and activation treatment temperature of 800 °C–850 °C were comparable to those of the as-grown samples. These samples produced a series of high-intensity satellite peaks and small-intensity thickness fringes, which were a characteristic of high-quality pseudomorphic multilayers with abrupt interfaces. Moreover, when the activation annealing treatment...
temperature increased to 900 or 950 °C, the peak intensity decreased, became broader, and finally disappeared. At the same time, the peak position of SiGe shifted toward the Si substrate peak. These signatures directly proved that as the RTA treatment temperature increased to 900 °C or above, the SiGe/Si multilayer with the As ion implantation could suffer from thermal stability issues due to the rapid Ge diffusion between the SiGe and Si layers [8, 14]. Furthermore, the lowest sheet resistance of the As ion implantation sample under 950 °C RTA activation was not acceptable in terms of the stability of SiGe/Si multilayer.

To decouple the effect of the S/D implantation and activation on the stability of the SiGe/Si multilayer, only an RTA treatment temperature from 800 to 950 °C was implemented on some SiGe/Si multilayer samples. Their HRXRD results around the (004) Bragg peaks are presented in figure 3. The peaks of the RTA-treatment-only samples under 800 °C, 850 °C and 900 °C were comparable to those of the as-grown sample. Meanwhile, the intensity of one of the SiGe peaks was significantly reduced as the activation annealing treatment increased to 950 °C. However, its peak profile was still better than that of the samples with As ion implantation under 900 or 950 °C RTA treatment. These results indicated that the impact on the stability of the SiGe/Si multilayer samples without As ion implantation was small when the RTA treatment temperature did not exceed 900 °C. Therefore, compared to the samples without As ion implantation, the highest tolerable temperature of the As ion implantation samples was reduced from 900 to 850 °C from the perspective of thermal stability. Namely, the As ion implantation had a significant impact on the microstructure of the SiGe/Si multilayer when its RTA treatment temperature was higher than 850 °C.

To further examine the effect of S/D implantation and activation on the crystal quality, and the interfacial morphologies of the SiGe/Si multilayer, the HAADF-STEM images of the as-grown SiGe/Si multilayer, samples with As ion implantation treated by RTA at 850 and 950 °C and samples only treated by RTA at 950 °C are shown.
The XRD results shown in figures 2 and 3 can be well explained by the HAADF-STEM results. Compared with the as-grown samples, the thickness difference of each SiGe layer was less than 2 nm, and thin and distinct interfaces between the SiGe and Si were only observed for the sample with As ion implantation and 850 °C RTA treatment. For the sample with As ion implantation and 950 °C RTA treatment, the SiGe and Si layer interfaces were damaged, and the sample behaved as a homogeneous SiGe alloy due to the rapid diffusion of Ge between SiGe and Si layers [15]. The total thickness of the SiGe/Si stacked multilayers increased to 81.6 nm. Meanwhile, each SiGe layer was only ~6 nm wider for the the 950 °C RTA-treatment-only sample shown in figure 4(d), whose only difference was that there was no As ion implantation compared with the sample in figure 4(c). These results directly proved that the As ion implantation further promoted the Ge diffusion when the RTA treatment temperature is higher than 850 °C. Therefore, As ion implantation into an SiGe/Si multilayer may further reduce its thermal stability window.

Meanwhile, SMIS analysis was employed to quantitatively study the diffusion of Ge between the SiGe and Si layers caused by the As ion implantation under different RTA activation temperatures. Figure 5 presents the As and Ge profiles of the SiGe/Si multilayer samples with and without As ion implantation under RTA treatment of 850 and 950 °C. Furthermore, the simulated As profile in the Si/SiGe stack post-implantation by SRIM without any RTA treatment obtained by SRIM is also presented in the figure 5. For the sample treated by the 850 °C RTA treatment, the Ge concentration of the SiGe layer of the SiGe/Si multilayer with As ion implantation was almost comparable to that of the sample with no As ion implantation. This signature indicated that minor Ge diffusion could be attained for the samples with or without As ion implantation as an RTA treatment of 850 °C. The concentration and distribution of As dropped from $2 \times 21 \text{ cm}^{-3}$ to $7.5 \times 19 \text{ cm}^{-3}$ at the interface between the top Si and upper SiGe layers. This may have been related to the transient retarded diffusion of As in the SiGe compared to that in the Si layer [16].

For the sample treated by 950 °C RTA, the Ge diffusion of the sample with the As ion implantation was worse than that without As ion implantation. Moreover, the Ge concentration of the top and bottom SiGe layers decreased by 12.5% and 3%, respectively. Ge element diffusion of the upper SiGe layer was more significant than that of the bottom SiGe, since the As diffused from the top to the bottom. Furthermore, its concentration and depth of As is $\sim 1 \times 20 \text{ cm}^{-3}$ and 76 nm, respectively. Thus, the diffusion of As could promote rapid Ge diffusion. The stability window of the SiGe/Si multilayer was further reduced from 900 °C to 850 °C. Finally,
considering the S/D implantation and activation process, the highest thermal budget temperature of the GAA device fabrication was confirmed to be 850 °C.

4. Conclusion

In summary, As ion implantation caused serious rapid diffusion of Ge for the SiGe/Si multilayers when the RTA treatment temperature was 900 °C or above. However, minor Ge diffusion and good stability of the SiGe/Si multilayers with the As ion implantation were attained when the RTA treatment temperature did not exceed 850 °C. Consequently, based on the SiGe/Si multilayer stability analysis, the highest tolerable temperature for the RTA treatment of 850 °C is proposed for the GAA device fabrication.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Figure 5. Ge and As profiles of SiGe/Si multilayer for RTA treatment at different temperatures.
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