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GeC film with high substitutional carbon concentration formed by ion implantation and solid phase epitaxy for strained Ge n-MOSFETs

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Dear editor,

Ge is considered as a promising channel material to replace Si because of its high carrier mobility than Si and compatibility with conventional Si process [1–3]. Strain engineering has been widely used in Si-based devices and can also be adopted in Ge-based devices to extend scaling limits and further improve device performance. It has been reported that electron and hole mobility of Ge are boosted by compressive and tensile strain, respectively [4]. Although strained Ge p-MOSFETs have been experimentally demonstrated, there are few reports on strained Ge n-MOSFETs. In order to introduce tensile strain in the channel of Ge n-MOSFETs, embedded source/drain (S/D) with smaller lattice constant than Ge as tensile stressors is an effective method. Among tensile stressor materials, GeC is a promising candidate due to its large lattice mismatch with Ge, which could induce high tensile strain in the channel. In spite of the advantages of GeC, there are still some challenges for the application of GeC into high performance devices, such as the low substitutional carbon concentration (C_{sub}) in Ge. Firstly, the equilibrium solid solubility of C in Ge is extremely low ($\sim 10^8$ atoms/cm^3) [5]. Secondly, the Ge-C bond length (∼1.9 Å) is shorter than Ge-Ge bond (2.41 Å), which means large strain around substitutional C atoms in Ge [6]. The strain may be relieved by forming interstitial C atoms, which has been observed in Si [7]. In addition, subsequent thermal processes are likely to precipitate C atoms out from substitutional sites, resulting in the reduction of C_{sub} [8]. So it is very important to improve C_{sub} in GeC film.

A simple and effective method of solid phase epitaxy (SPE) is proposed and experimentally demonstrated to improve C_{sub} in GeC film by employing Ge^+ and C^+ implantation followed by rapid thermal annealing (RTA). The impact of SPE on C_{sub} and re-crystallization of GeC film is investigated. The dependence of C_{sub} and re-crystallization on annealing temperature and time is also demonstrated. Finally, the possible mechanism is discussed.

Experiment. The n-type Ge (100) substrates were used as the starting wafers. After cleaned by diluted hydrochloric acid (HCl), Ge^+ pre-amorphous implantation (PAI) of 40 keV, 1×10^{14} cm^{-2} and C^+ implantation of 7 keV, 5×10^{15} cm^{-2} were performed. The wafer with only C^+ implantation was set as control sample. Finally, RTA was performed in nitrogen ambient to realize the solid phase epitaxial regrowth of GeC at the temperature of 400°C–600°C with the time of 60–600 s.

Results and discussion. In order to study the effectiveness of SPE process on enhancing C_{sub}

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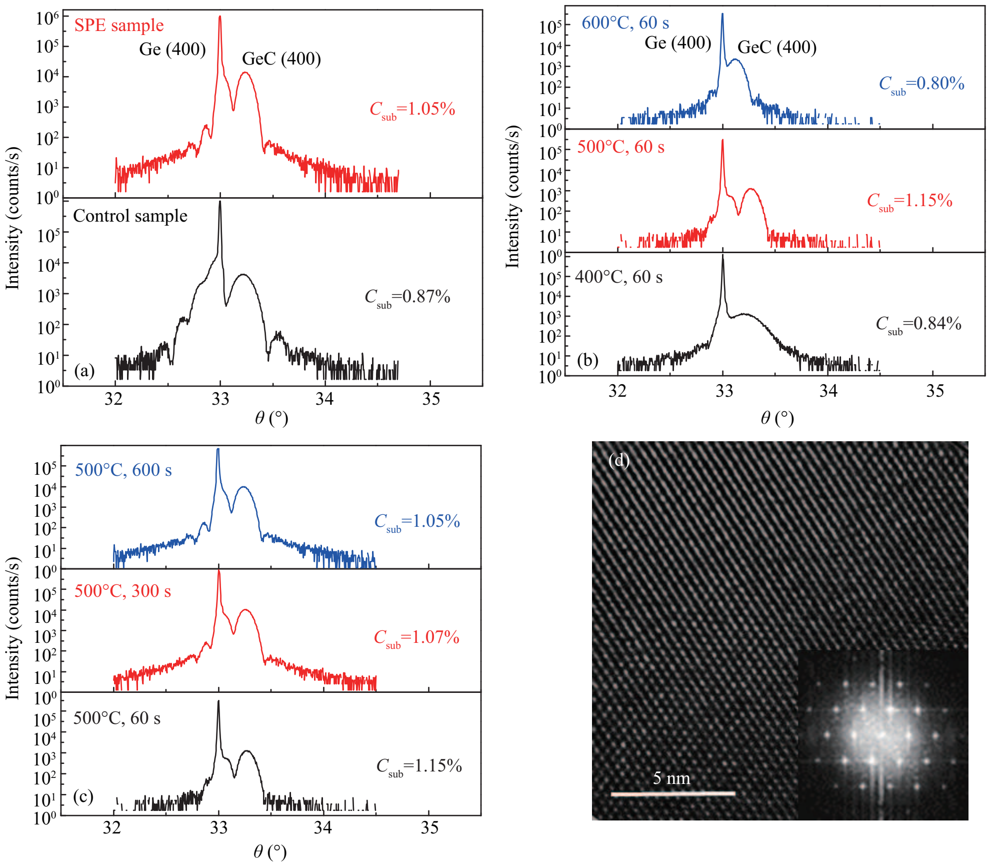

Figure 1 (Color online) HRXRD and HRTEM results of samples. (a) HRXRD spectrum obtained from sample without and with SPE at 500°C, 600 s, HRXRD spectrum of sample with SPE at (b) different annealing temperature (400°C–600°C) and (c) different annealing time (60–600 s), (d) HRTEM pictures of SPE sample formed at the optimal condition.

and film quality of GeC, high resolution X-ray diffraction (HRXRD) and high resolution transmission electron microscope (HRTEM) were carried out, as shown in Figure 1. Figure 1(a) shows the HRXRD spectrum of SPE sample and control sample formed at the same annealing condition (500°C, 600 s). Compared with the control sample, SPE sample shows higher intensity and smaller full width at half maximum (FWHM) of GeC (400) diffraction peak, indicating better GeC film of SPE sample compared with control sample. Calculated from HRXRD spectrum, $C_{\rm sub}$ of SPE sample and the control sample are 1.05% and 0.87%, respectively. So $C_{\rm sub}$ of GeC is improved by about 21% by this method. For SPE sample, a continuous amorphous layer is formed by Ge^{+} PAI. SPE annealing enables the re-crystallization of amorphous layer at relatively low temperature with high crystal quality [9]. Therefore, $C_{\rm sub}$ and film quality of GeC is effectively improved by SPE, possibly due to better defect recovery during the solid phase epitaxial regrowth.

As C atoms are easy to precipitate during RTA, lower annealing temperature and shorter annealing time are expected for the minimum loss of substitutional C atoms in GeC film. However, GeC could not be completely re-crystallized at too low annealing temperature or too short annealing time. Therefore, the SPE annealing condition should be optimized to obtain both high $C_{\rm sub}$ and fully re-crystallized GeC film. So RTA was performed at different temperature (400°C–600°C) and different time (60–600 s). Figure 1(b) and (c) show the HRXRD spectrum of SPE sample formed at different annealing temperature and time. As seen from Figure 1(b), GeC (400) diffraction peak is observed at 400°C. However, the GeC (400) diffraction peak is weak and $C_{\rm sub}$ is low, indicating that the GeC film has not been fully re-crystallized. As annealing temperature rises to 500°C, GeC (400) diffraction peak intensity is obviously enhanced, indicating the significant improvement of film quality of GeC. And $C_{\rm sub}$ significantly increases to 1.15%. As annealing temperature further rises to 600°C, GeC (400) diffraction peak intensity does not show obvious improvement. While $C_{\rm sub}$ decreases from 1.15% to 0.80%, possibly due to the precipitation of C atoms at relatively high annealing temperature. That is, complete re-crystallization of GeC has been realized at the annealing temperature of 500°C. Both high C_{sub} and film quality of GeC are obtained at the relatively low temperature of 500°C. Thus, annealing temperature is optimized to be 500°C. As seen in Figure 1(c), GeC (400) diffraction peak intensity shows no obvious difference as annealing time increases from 60 s to 600 s. That is, GeC film has been fully re-crystallized under the annealing time of 60 s. C_{sub} does not obviously change with annealing time increase due to that C precipitation is mainly determined by annealing temperature. Therefore, the annealing temperature and time are optimized to be 500°C and 60 s, respectively. High C_{sub} of 1.15% and film quality of GeC are realized under the optimal SPE annealing condition.

To further confirm the crystallinity of GeC formed at optimized annealing condition, HRTEM measurement was performed. HRTEM pictures of SPE sample formed at the optimized annealing condition (500°C, 60 s) is shown in Figure 1(d). As seen from the picture, no observable defects are seen. And the rhombus reciprocal lattice point in the FFT image indicates the single crystal state of the annealed sample. Therefore, GeC film can be fully re-crystallized under the optimized annealing condition.

Conclusion. A method of SPE is proposed and experimentally demonstrated to fabricate single crystalline GeC film with high C_{sub} on Ge substrate. The solid phase epitaxy of GeC alloy is realized by Ge^+ and C^+ ion implantation followed by RTA. C_{sub} of SPE sample is improved by 21% compared to that of control sample. Fully re-crystallized GeC film with high C_{sub} of 1.15% is obtained under the optimized SPE annealing condition. Therefore, this method shows high C_{sub} and good film quality of GeC, which is compatible with CMOS process, indicating great potential for strained Ge n-MOSFETs.

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Supporting information Appendix A. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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