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Preparation of Crystalline $Si_{1-x}Ge_x$ Thin Films by Pulsed Ion-Beam Evaporation

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Abstract - Thin films of single phase, polycrystalline silicon germanium ($Si_{1-x}Ge_x$) were prepared by ion-beam evaporation (IBE) using Si-Ge multi-phase targets. After irradiation of the targets by a pulsed light ion beam with peak energy of 1 MV, 450 and 480 nm thick films were deposited on Si single crystal and quartz glass substrates, respectively. From XRD analysis, the thin films consisted of a single phase $Si_{1-x}Ge_x$, whose composition is close to those of the targets.

Keywords: high deposition rate, polycrystalline silicon germanium ($Si_{1-x}Ge_x$) thin films, pulsed ion-beam evaporation, single phase, room temperature

1. Introduction

Complementary metal-oxide-semiconductor structures are commonly used in large scale and high-speed devices. For decreasing feature size and increasing clock speed, it is essential that electrical properties including electron and hole mobility in the devices be improved. Although silicon occupies a dominant position in the materials used for the devices, the required properties are nearing those for silicon. Thus, new materials must be developed for the devices.

Silicon germanium ($Si_{1-x}Ge_x$) has been paid much attention to because of its high hole mobility [1]. Numerous researches have been performed to establish deposition processes to prepare not only epitaxially grown $Si_{1-x}Ge_x$ p-channels [2] but also polycrystalline $Si_{1-x}Ge_x$ gates [3]. For preparation of the $Si_{1-x}Ge_x$ gates, it is required to drive dopants and to activate carriers in the gates by sample annealing, which could be harmful for the devices. Thus, other processes to deposit the $Si_{1-x}Ge_x$ thin films have been studied.

A novel thin film preparation method of ion-beam evaporation (IBE) was developed [4]. This method utilizes a high power, pulsed ion beam generated in a pulsed power generator [5]. The ion beam was focused on a target, which yields high-density plasma. Then, the plasma was deposited on the surface of substrates that are placed facing toward the target. By the IBE method, various thin films were obtained with an instantaneous deposition rate of a few mm/s. Furthermore, crystallized TiFe, B_4C [6-8] and $SrAl_2O_4$ [9-11] thin films were successfully prepared without substrate heating or sample annealing.

Recently, polycrystalline Si thin films were prepared by IBE on Si single crystals at room temperature [12, 13]. It is expected that polycrystalline $Si_{1-x}Ge_x$ thin films can also be obtained by IBE. In the present paper, we report the characteristics of polycrystalline $Si_{1-x}Ge_x$ thin films prepared at room temperature, i.e., without heating the substrate, by a high-density ablation plasma produced by IBE. The crystallization and the deposition rate of thin films prepared at different Ge composition rates of target and substrate are investigated. The crystallinity and the deposition rate of the as-deposited thin films were examined by powder X-ray diffraction (XRD) and scanning electron microscopy (SEM).

2. Experimental Setup and Method

Thin films were prepared in a pulsed ion beam generator ('ETIGO-II'). Ion beam and deposition chambers are schematically shown in Fig. 1. A voltage of 1 MV (peak) with pulse width of ~50 ns and current of 70 kA was applied between the cathode and the anode, which was covered with a polyethylene sheet (flashboard). The application of the pulsed voltage produced a pulsed light ion beam. From the measurement by energy spectrometer, the ion species has been found to be mostly comprised of protons (approximately 75%), with the remainder consisting of carbons. The ion beam was geometrically focused on one of the sintered $Si_{0.5}Ge_{0.5}$ and $Si_{0.8}Ge_{0.2}$ targets, which was located at 180 mm from the anode. The ion beam irradiation produced ablation plasma from the surface of the target. Substrates of (100) Si single crystal and quartz glass were placed at 70 mm from the target. The ablation plasma was then deposited on the substrates and the ion beam was irradiated on the target.

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The substrates were kept in a vacuum of 2 × 10^{-4} Torr and at room temperature.

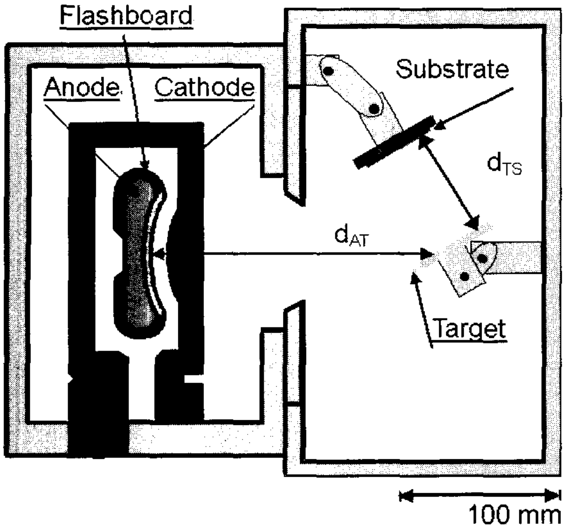


Fig. 1 Experimental setup for thin film deposition.

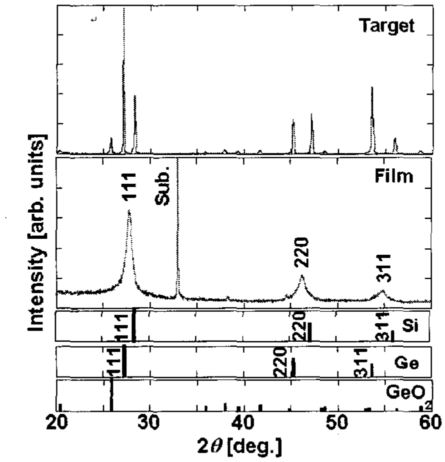
Thickness of the thin films was measured using cross-sectional scanning electron microscopy images. Phases in the as-deposited thin films were identified by XRD. From the peak positions, lattice parameters of $Si_{1-x}Ge_x$ phase were measured. Using the known relationship between the lattice parameter and composition [14], the compositions of the thin films were estimated. Typical experimental conditions are presented in Table 1.

Table 1 Typical experimental conditions.

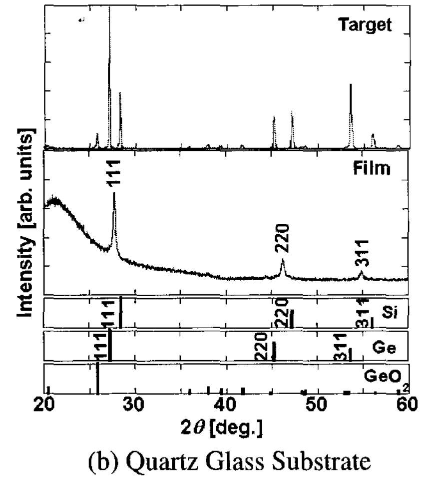
main component of ions	protons (H^+)
beam voltage	1 MV
beam current	70 kA
energy density on target	50 J/cm^2
d_{AT} (anode-target distance)	180 mm
d_{TS} (target-substrate distance)	70 mm
target angle	45°
substrate	Si, Quartz Glass
pressure	10^{-4} Torr
substrate temperature	R. T.
number of ion-beam shots	1

3. Results and Discussion

After one shot of the ion beam irradiation on the $Si_{0.5}Ge_{0.5}$ and $Si_{0.8}Ge_{0.2}$ targets, 480 and 450 nm thick films were deposited on Si single crystal substrates. XRD patterns for a thin film using a $Si_{0.5}Ge_{0.5}$ target are shown in Fig. 2 (a). Diffraction angles of all peaks are located between those of the Si and Ge phases. Peaks for other phases remain undetected. Thus, it was evident that a single phase $Si_{1-x}Ge_x$ thin film was obtained by IBE. Note that the targets consisted of Si, Ge and GeO_2 phases. Germanium oxide may be reduced in the vacuum chamber. Furthermore, the Si and Ge phase must be mixed in the ablation plasma following ion irradiation of the target, forming a single $Si_{1-x}Ge_x$ phase. An XRD pattern for a thin film prepared using a $Si_{0.8}Ge_{0.2}$ target is shown in Fig. 3 (a). Similar to the XRD pattern in Fig. 2 (a), $Si_{1-x}Ge_x$ is the only phase detected in the thin film. Compared to the pattern in Fig. 2 (a), diffraction angles for the peaks were shifted to higher angles.



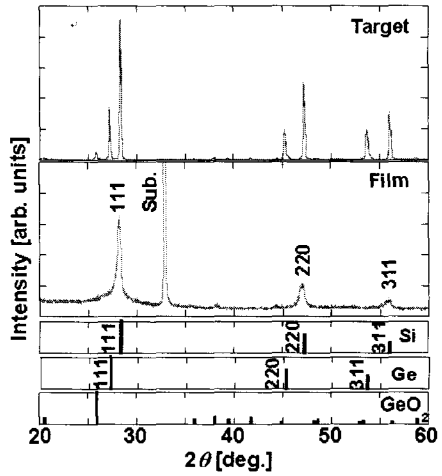
(a) Si Substrate



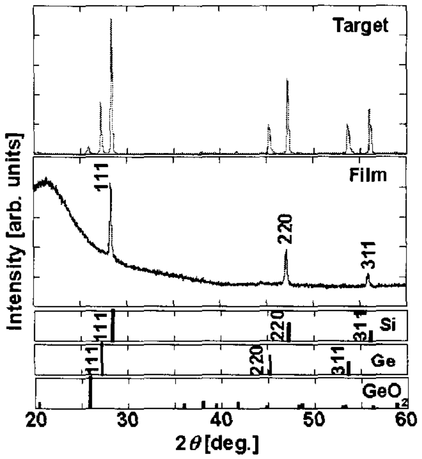
(b) Quartz Glass Substrate

Fig. 2 XRD patterns for $Si_{0.5}Ge_{0.5}$ thin films prepared on (a) quartz glass and (b) Si single crystal substrates. XRD patterns for the target and peak positions for Si, Ge and GeO_2 phases are also presented.

Thin films were also deposited on quartz glass substrates. XRD patterns for the thin films are shown in Figs. 2 (b) and 3 (b). Similar to the results for thin films prepared on Si single crystal substrates, all peaks are for the $Si_{1-x}Ge_x$ phase. From these outcomes, single-phase $Si_{1-x}Ge_x$ thin films were obtained on both Si single crystal and quartz glass substrates.



(a) Si Substrate



(b) Quartz Glass Substrate

Fig. 3 RD patterns for $Si_{0.8}Ge_{0.2}$ thin films prepared on (a) quartz glass and (b) Si single crystal substrates. XRD patterns for the target and peak positions for Si, Ge and GeO_2 phases are also presented.

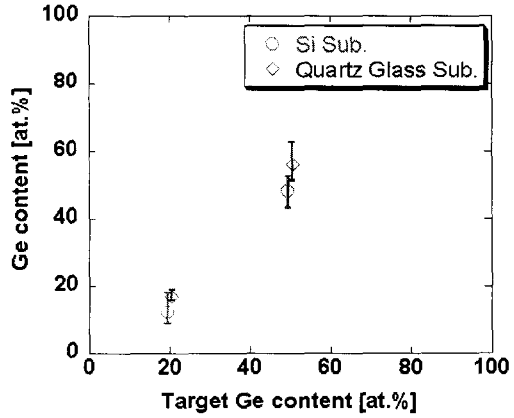
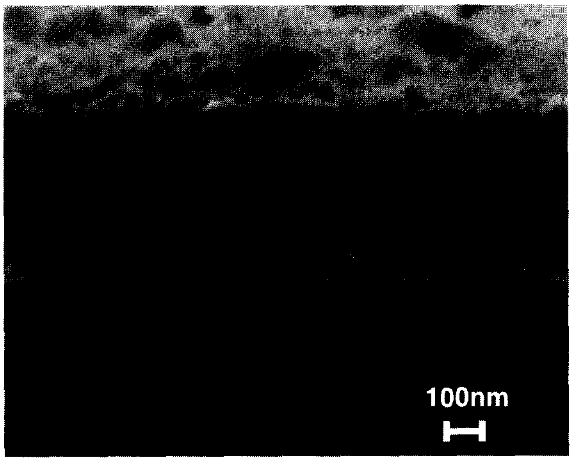


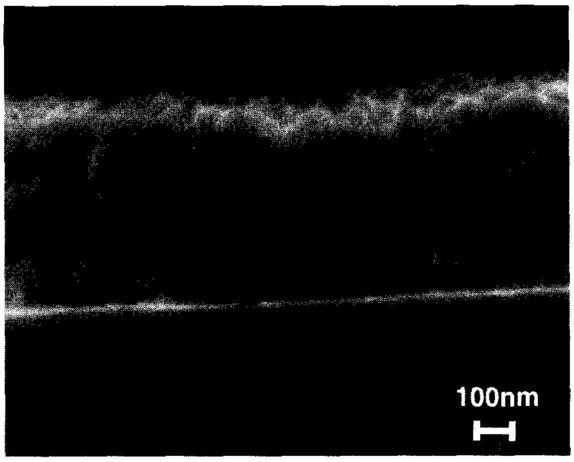
Fig. 4 Ge content (x) estimated from lattice parameters and Ge content in the targets.

From peak positions for the $Si_{1-x}Ge_x$ phase, lattice parameters were calculated and plotted against the composition of the target in Fig. 4. The estimated compositions of the thin films are close to those of the targets. It is concluded that a novel process to prepare polycrystalline $Si_{1-x}Ge_x$ thin films with different compositions were successfully developed by IBE.

Fig. 5 presents the cross-sectional SEM images of the films deposited on the silicon substrate by using the targets of (a) $Si_{0.8}Ge_{0.2}$ and (b) $Si_{0.5}Ge_{0.5}$. From these figures, it is found that a good crystallinity and high density film can be prepared by IBE without any thermal treatments. The deposition rates of polycrystalline $Si_{1-x}Ge_x$ thin films were estimated to be about 450 and 480 nm/shot, respectively.



(a) $Si_{0.8}Ge_{0.2}$ target



(b) $Si_{0.5}Ge_{0.5}$ target

Fig. 5 Cross-sectional SEM images of the films deposited on the silicon substrate by using the (a) $Si_{0.8}Ge_{0.2}$ target and the (b) $Si_{0.5}Ge_{0.5}$ target.

4. Conclusion

Using the intense pulsed ion beam evaporation technique and Si-Ge multi-phase targets, we have succeeded in the preparation of single phase, polycrystalline silicon germanium ($Si_{1-x}Ge_x$) thin films without impurities on the silicon or the quartz glass. High crystallinity and deposition rate have been achieved without substrate heating or post thermal annealing. From XRD analysis, the thin films consisted of a single phase $Si_{1-x}Ge_x$, whose composition is similar to those of the targets.

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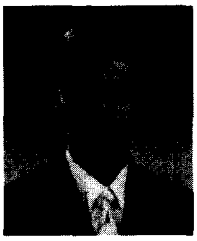

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