Ion-Beam-Induced Recrystallization in Si(100) Studied with Slow Positron Annihilation and Rutherford Backscattering and Channeling

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Ion-beam-induced crystallization in silicon preamorphized by Ge-ion implantation was studied by combined means of Rutherford backscattering and channeling, and positron annihilation. The epitaxial regrowth of amorphous surface layers in a ⟨100⟩ Si substrate has been studied with irradiation of 400-keV Ar^+ ions at the temperature of 400 °C. The ion-beam-induced epitaxy was found to result in a drastic increase in the positron lifetime to a maximum value of 400 psec in the recrystallized silicon layer. It is demonstrated that vacancy migration is promoted during the epitaxial recrystallization to form defect complexes like trivacancies and/or quadrivacancies.

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An annealing process that occurs during ion irradiation has been reported by many authors [1] to be effective on already existing damage. Even amorphous layers, formed by an earlier ion implantation or deposition of films on single-crystal substrates, can be regrown with irradiation at slightly elevated temperature. The phenomenon is classified as ion-beam-induced solid-phase epitaxial growth (SPEG), where the regrowth of an amorphous layer proceeds epitaxially from an adjacent crystalline seed region. Although most studies have been done on SPEG of Si and GaAs with Rutherford backscattering (RBS) and channeling analysis [2,3], details of the SPEG mechanism are yet to be determined. During recent years much progress has been made in positron annihilation studies on solid materials because of the advances in the production of relatively intense, low-energy positron beams and its application for semiconductor physics [4]. In the present work a combined study of the annihilation measurement of slow positrons and of RBS and channeling has been done to gain more insight into the SPEG or defect-annealing mechanism, because it is expected that positron annihilation gives clear information about the atomic configuration of vacancy-type defects.

A time-bunched slow positron beam, with energy variable from 0.4 to 25 keV and variable pulse period, was used to take lifetime spectra in the near surface region of ion-implanted silicon. The slow positron system generates a high-intensity-pulse positron beam with a frequency of 12.5 MHz, using the intense positron source from the ETL linear accelerator; details may be found in a recent paper [5]. Lifetime spectra were obtained by measuring the time interval between the timing signal of the pulsing system and the timing signal of an annihilation γ ray, detected with a BaF_2 scintillator.

Samples used in this study were float-zone-grown (FZ) nondoped *n*-type (100) Si wafers. The Ge^+ implantation for amorphization was performed at room temperature with an energy of 130 keV and a fluence up to 7.0×10^{14} ions/cm^2. Furthermore, after the preamorphization the Si samples were implanted with 18-keV B^+ ions to a fluence of 1.75×10^{14} ions/cm^2. B ions were implanted to examine the crystalline property in the regrown Si layer through electrical activation of the *p*-type dopant. 400-keV Ar^+ irradiation with current density of 1 μA/cm^2 was subsequently performed to induce SPEG in the temperature range from 300 to 435 °C. The extent of SPEG was determined by Rutherford backscattering and channeling analysis, which was performed with a 1.5-MeV He^+ beam using a VdG accelerator. Table I summarizes the projected ranges for 130-keV Ge, 18-keV B, and 400-keV Ar ion implantation, along with other parameters, which were calculated by the TRIM code.

The slow positron pulsing system enables us to take lifetime spectra of variable-energy positrons with high count rates, high peak-to-background ratio, a wide time range, and good time resolution. Figure 1 shows typical lifetime spectra measured with two incident energies of slow positrons, 0.9 and 2.6 keV, before and after Ar irradiation to a fluence of 8×10^{15} ions/cm^2 at 400 °C. The energies of 0.9 and 2.6 keV correspond to 15 and 79 nm in mean penetration depth, respectively; the depth Z_p of the positrons was calculated by $Z_p[\text{nm}]=40E_p^{1.6}/\rho$, where E_p [keV] is the incident positron energy and ρ [g/cm^3] is the mass density of the sample material. It is remarkable that both spectra indicate the development of longer-lived components in the SPEG layer than in the initial amorphized zone prior to Ar irradiation. After the

TABLE I. Implantation parameters for Ge^+, B^+, and Ar^+ ions.

Projectile	Incident energy (keV)	Projected depth (nm)	Standard deviation (nm)	Damage depth (nm)
Ge^+	130	92	33	54
B^+	18	65	25	55
Ar^+	400	386	132	303

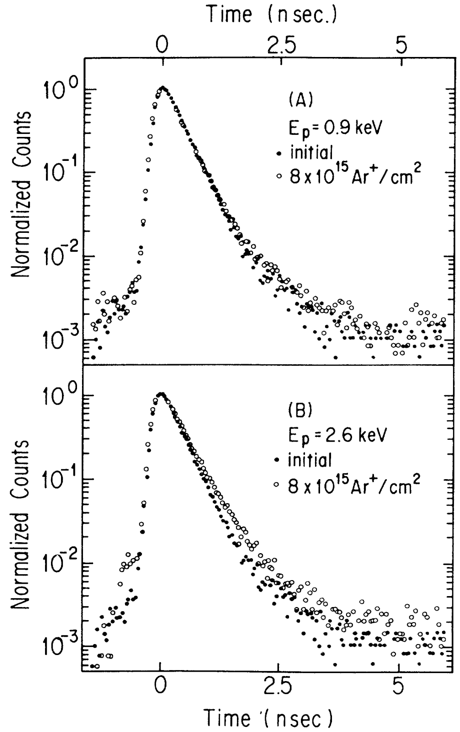

FIG. 1. Positron lifetime spectra of the Si(100), as amorphized (solid circle) and after Ar irradiation (open circle), taken with incident positrons energies of (a) 0.9 keV and (b) 2.6 keV.

epitaxial regrowth one might expect that the lifetime would become shorter and closer to the bulk lifetime, since RBS measurements show evidence of amorphous to crystalline recovery in the same sample. The lifetime spectra were analyzed using the program POSITRONFIT [6], and the fitting was done assuming a single component for the lifetime. The mean values of the lifetime are presented in the following figures.

Figure 2 shows the behavior of the positron lifetime as a function of the incident positron energy or mean penetration depth for the amorphized Si, before and after Ar irradiation at a target temperature of 400 °C. The vertical lines A and B in the figure denote the location of the amorphous/crystalline (a/c) interface after and before the Ar irradiation, respectively, while the line C corresponds to the damage peak due to Ar bombardment as shown in Fig. 3. It is noted that the lifetimes in both cases still show large values of 280 and 285 psec at the highest positron energy of 21.5 keV (2 μm in depth); the value of 224 psec was confirmed for the defect-free Si substrate with the present system of slow positrons [5]. It is likely that even at such a deep penetration the positrons may be under the influence of the damaged surface layers. On the one hand, it turns out that the lifetime increases to the highest value of about 400 psec in the region between the lines A and B, i.e., the SPEG layer recrystallized with Ar irradiation to a fluence of 8×10^{15}

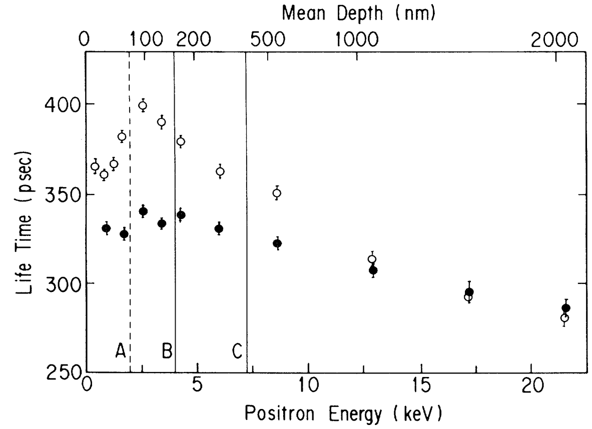

FIG. 2. Mean lifetime vs incident positron energy or mean stopping depth for the as-amorphized Si (solid circle) and that after Ar irradiation (open circle). The vertical lines A and B denote the amorphous/crystalline interface after and before Ar irradiation, obtained from RBS measurements, and the line C denotes the peak position of Ar damage.

ions/cm^2.

The assumption has been made that the increase of the positron lifetime over the bulk value is proportional to the number of vacancies in the defect cluster, and positrons trapped in divacancies were reported to have a lifetime of 325 psec, and in quadrivacancies, 435 psec [7]. The room temperature irradiation of crystalline Si with heavy ions is known to yield the formation of divacancies as the predominant vacancy defects [8]; the observations support the present results because the lifetime is estimated as about 330 psec in the Si layer amorphized with Ge implantation. On the other hand, a different magnitude of lifetime components of 400–500 psec was observed in de-

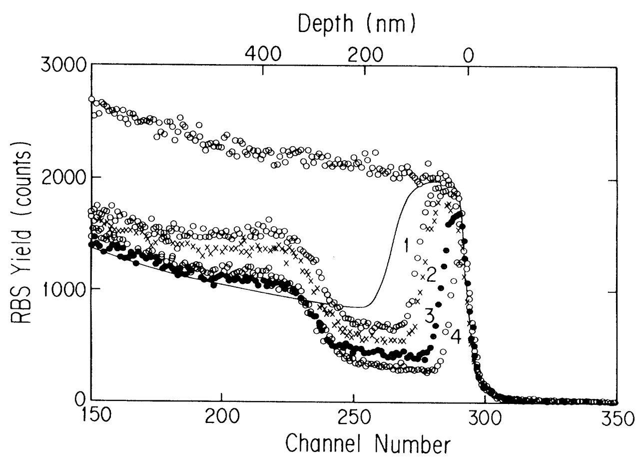

FIG. 3. RBS-channeling spectra of Ge^+-preamorphized ⟨100⟩ Si irradiated with an Ar dose of $8\times10^{15}/cm^2$ at temperatures of (1) 300 °C, (2) 345 °C, (3) 400 °C, and (4) 435 °C. The solid curve denotes the spectrum of as-amorphized Si.

posited amorphous Si films and attributed to trapping in microvoids with such a size as five vacancies [9]. During thermal annealing, while the divacancies in the irradiated Si migrate and change the defect distribution between 573 and 823 K, the voids in the films were reported to shrink and be annealed above 500 °C [8,9]. In this work the increase of the lifetime due to irradiation at 400 °C has been observed to be about 60 psec in the recrystallized region (the *A-B* zone) and about 40 psec in the amorphous region (the ordinate-*A* zone). Therefore, it is suggested that the vacancy migration and recombination at the elevated temperature are promoted in a somewhat different way in both the amorphous region and SPEG layer, leading to the formation of defect complexes during irradiation.

The channeling analysis of the SPEG induced by Ar irradiation is shown in Fig. 3 for ⟨100⟩-oriented Si substrates. The aligned spectra refer to 400-keV Ar irradiation of 8×10^{15} ions/cm^2 at various substrate temperatures. An apparent ion-induced epitaxial recrytallization is seen; that is, after irradiation at a temperature of 400 °C the channeling spectrum indicates a movement of the a/c interface from the initial depth of 145 to 55 nm in depth by the recrystallization. It is noted that the minimum backscattering yield χ_{min} was estimated as 9% in the SPEG layer at 400 °C. The extent of SPEG was estimated from the regrowth process in Fig. 3, and the activation energy was obtained as 0.22 eV from an Arrhenius plot of the regrowth rate. This value is lower by 1 order of magnitude compared to the activation energy due to thermal annealing without ion beams and in good agreement with values reported elsewhere [2]. However, the result appears to be in contrast with positron annihilation measurements because vacancy clustering is observed in the latter experiments. It should be noted that RBS-channeling is sensitive to the interstitial-type defects whereas positrons are highly sensitive for detecting vacancies and identifying their configuration. The result from Figs. 2 and 3 is that in the SPEG zone there remains an amount of vacancy clusters, plus additional defects such as interstitials, dislocations, and so on.

The kinetic energy of the ion beam has been used to induce reaction paths for the epitaxial growth in solid phase that could not be attained without the ion beam. The competition between damage production and the induced crystallization complicates the identification of the factors responsible for the SPEG. However, the low activation energy of 0.22 eV is believed to be indicative of point defect migration, either towards the amorphous/crystalline interface and/or within the interface [2]. Divacancies are known to be mobile and anneal at substrate temperatures of more than 250 °C, but since the migration energy for divacancies is 1.2 eV in Si [7], the migration does not determine the regrowth rate. On the other hand, the double-negative vacancies diffuse with a low activation of 0.18 eV [10], and it is suggested that the vacancies move within the regrowing interface and supply nucleation sites to catalyze crystallization and/or combine with the Si interstitials whose migration energy is 0.6 eV [7]. It is supposed from the observed lifetime increase that the defects production and vacancy migration are induced in the amorphous layer due to Ar irradiation. The vacancy aggregation leads to the formation of trivacancy-type defects in the preamorphized layer where divacancy-type defects have been distributed originally, and in the regrown layer to the formation of trivacancies, quadrivacancies, and their admixtures with higher clustering of vacancies. One should note that the analytical fitting of lifetime spectra was not so good after Ar irradiation compared to that for the as-amorphized state. This means that the assumption with a single component is not accurate enough, and that vacancy clusters are distributed in multiconfigurations. However, it seems to be quite all right to consider that vacancy migration is closely correlated with the epitaxial recrystallization.

As shown in Fig. 2 the change in lifetime curve for the as-amorphized Si smears towards higher incident positron energies, whereas the amorphous layer was not formed beyond 145 nm in depth beneath the surface. To confirm the depth profiles Doppler broadening of γ annihilation radiation has been investigated with relatively intense, slow positrons emitted from a ^{22}Na source. In Fig. 4 the line shape parameter S is plotted as a function of incident positron energy. It seems that within $E_p < 5$ keV the depth profile is consistent with the lifetime measurement, but at the higher-energy side the S parameter is larger in the as-amorphized sample, i.e., larger in the defect-free substrate than in the damaged layer after Ar irradiation. The smearing of the S parameter with depth can be predicted from the observations that the half-width of positron distribution in solids becomes larger at a higher beam energy [11], and that the diffusion distance is as long as 245 nm in FZ n-type Si substrates [12]. Furthermore, the migration of positrons is affected by electric

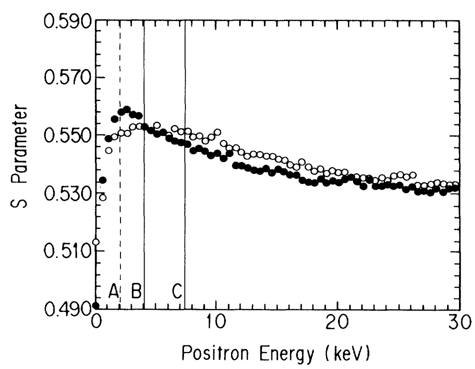

FIG. 4. Doppler broadening line shape vs incident positron energy for the as-amorphized Si (open circle) and Si after Ar irradiation (solid circle). The vertical lines *A*, *B*, and *C* have the same meaning as in Fig. 2.

fields which could be induced at the interface due to the implanted borons in the Si substrates [12]. It is likely that the line shape parameter may respond to the defect concentration and distribution in a different way from the lifetime increase when the defects distribute with various complexes.

The electrical properties in the recrystallized Si samples were measured with van der Pauw technique. The electrical activation of implanted B atoms was estimated to be as low as 10% even in the layer with the best crystalline recovery from the amorphous state, which was epitaxially regrown by Ar irradiation to a fluence of 1.3×10^{16} ions/cm^2 at 435 °C and showed a χ_{min} value of 7.8%. Furthermore, the low electrical activation of the dopant has been observed to result in a lowering of conversion temperature from the *p*- to *n*-type conduction to 285 K [13]. The low activation of dopant B suggests that the substitution of B into Si lattice sites is not sufficient and some crystalline defects remain in the ion-beam-induced SPEG layer, in qualitative agreement with the observations by the slow positron annihilation.

In summary, lifetime spectroscopy measurements by a slow positron system have been applied to detect the residual defects in an epitaxially regrown layer on a ⟨100⟩ Si substrate. We have obtained a new result indicating the existence of vacancy clusters such as trivacancies and quadrivacancies in the regrown layer where RBS-channeling analysis shows a good recovery of crystallinity, and demonstrated the evidence that vacancy migration is correlated with ion-beam-induced SPEG. It is remarkable that the peak increase of the lifetime has been observed in the regrown layer near the amorphous/crystalline interface in the Si lattice.

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