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Solid-phase Epitaxy of Silicon Amorphized by Implantation of the Alkali Elements Rubidium and Cesium

R. Maier*, V. Häublein[†], H. Ryssel^{*,†}, H. Völlm^{**}, D. Feil^{**}, H. Seidel^{**} and L. Frey^{*,†}

**Lehrstuhl für Elektronische Bauelemente (LEB), Universität Erlangen-Nürnberg, Cauerstrasse 6, 91058 Erlangen, Germany*

†Fraunhofer-Institut für Integrierte Systeme und Bauelementetechnologie (IISB), Schottkystrasse 10, 91058 Erlangen, Germany

***Lehrstuhl für Mikromechanik, Mikrofluidik/ Mikroaktorik (LMM), Universität des Saarlandes, Campus A5.1, 66123 Saarbrücken, Germany*

Abstract. The redistribution of implanted Rb and Cs profiles in amorphous silicon during solid-phase epitaxial recrystallization has been investigated by Rutherford backscattering spectroscopy and secondary ion mass spectroscopy. For the implantation dose used in these experiments, the alkali atoms segregate at the a-Si/c-Si interface during annealing resulting in concentration peaks near the interface. In this way, the alkali atoms are moved towards the surface. Rutherford backscattering spectroscopy in ion channeling configuration was performed to measure average recrystallization rates of the amorphous silicon layers. Preliminary studies on the influence of the alkali atoms on the solid-phase epitaxial regrowth rate reveal a strong retardation compared to the intrinsic recrystallization rate.

Keywords: ion implantation, amorphous, solid-phase epitaxy, redistribution, alkali, rubidium, cesium

PACS: 61.72.uf, 81.15.Np, 64.75.Qr

INTRODUCTION

Local doping of semiconductor wafers during fabrication of ULSI devices is the most widespread application of ion implantation. The main advantages are short process times, high homogeneity and reproducibility, prevention of high process temperatures, possibility of implantation through thin layers, and possibility of profile engineering. The main disadvantage is the introduction of damage during implantation. Depending on the mass of the implanted ions and on the temperature of the crystalline Si target an amorphous layer is formed by exceeding a critical implantation dose. The recrystallization of the amorphous Si layer can be achieved by solid-phase epitaxy which is a thermally activated process [1]. In the intrinsic case where Si is amorphized by self ion implantation, the activation energy is 2.3 eV [1]. The regrowth rate is strongly dependent on the crystalline orientation of the underlying Si substrate. In <100> direction, the rate is the highest and in <111> direction the lowest [2]. The influence of impurities on the recrystallization rate of amorphous Si has been intensively investigated in the past. In a certain concentration range, electrically active elements like B and P are known to have an increasing effect [3, 4, 5] on the SPER (solid-phase epitaxial regrowth) rate whereas the elements C, N, and O can retard it [6]. The recrystallization behavior of silicon amorphized by implantation of Rb and Cs has not been investigated so

far. Preliminary results are shown in this work.

EXPERIMENTAL

Sample preparation

The experiments were performed using two FZ-grown p-type silicon wafers of <100>-orientation and 4-6 Ωcm resistivity. One wafer was implanted with $2 \times 10^{15} \text{ Cs cm}^{-2}$ using an energy of 180 keV. The other wafer was implanted with $2 \times 10^{15} \text{ Rb cm}^{-2}$ using an energy of 50 keV. The wafers were partially covered with SiO_2 during implantation to leave unimplanted parts. These parts are necessary for RBS (Rutherford backscattering spectroscopy) in channeling configuration. To reduce recrystallization during implantation, the beam current was held at 40 μA resulting in an introduced power of 7.2 W for the maximum implantation energy mentioned above.

To avoid a parasitic influence on the SPER rate of elements other than the alkali elements, contamination sources were eliminated as much as possible. Oxygen contamination via recoil implantation from scattering oxide will lead to a high oxygen subsurface concentration [7] with strong retarding influence on the SPER rate [6]. Therefore, a scattering oxide mask was not used and implantations were performed at an angle of 7° to reduce

channeling. An HF-Dip for removal of native oxide was performed just before implantations. The wafers were cut into 1.5 cm² pieces. The samples were annealed in a RTP (rapid thermal processing) system. The main advantages of this annealing system in comparison to annealing in a furnace are fast heat-up and cool-down rates. Very short temperature plateaus at elevated temperatures can be realized with well defined heating characteristics. Three samples of each wafer were taken. Two of the Cs implanted samples were annealed at 600°C for 2 min and for 10 min, respectively. One sample was kept as implanted for comparison. The Rb implanted samples were annealed at 550°C for 30 min and 60 min, respectively. One sample also remained untreated for comparison.

Analysis

To obtain the distributions of the alkali elements, all samples were measured by SIMS (secondary ion mass spectroscopy). For a comparison, the samples implanted with Cs were also analyzed by RBS. The thickness of the amorphous layers was determined by channeling measurements.

The RBS and channeling measurements were performed using a 2 MeV ⁴He-beam obtained from a 5 MeV Van de Graaff accelerator. The backscattered particles were detected at a scattering angle of 165°. Channeling spectra from the unimplanted and implanted parts of the samples were collected with a dose of 20 μC. Subsequently, a rotated random spectrum was collected on the implanted area with a tilt of 7°. The impurity distributions were determined by collecting backscattering spectra with a tilt of 70°.

5 keV primary ions were used in the SIMS measurements and the beam current was held at 1 μA. The sputter area was 2 mm × 2 mm. To minimize crater effects during measurement, the centered analyzing area in the crater bottom was reduced to 25% by blanking. The crater depth was measured using a Dektak profilometer.

RESULTS AND DISCUSSION

RBS and ion channeling

Figure 1 shows the channeling spectra indicating the amorphous layer thickness for the set of samples implanted with Cs and isothermally annealed at 600°C. The thickness of the amorphous layer after implantation was 155 nm and then reduced to 120 nm during annealing for 2 min. Compared to the recrystallization rate of 60 nm/min [1] in the intrinsic case the rate is retarded to 18 nm/min. An overall annealing for 10 min results in an

FIGURE 1. Channeling spectra showing the thickness of the amorphous layers after implantation of Cs and subsequent thermal annealing.

FIGURE 2. Backscattering spectra showing the Cs distributions after implantation and subsequent thermal annealing steps.

amorphous layer thickness of 55 nm. This reveals an additional retardation of the average SPER rate to 8 nm/min for the recrystallization of another 65 nm amorphous silicon. This nonlinearity of the SPER rate with annealing time may be explained by a Cs concentration dependent retardation of the recrystallization process. Figure 2

FIGURE 3. SIMS profiles of Cs implanted silicon and subsequent isothermal annealing.

shows the Cs distributions of the as implanted and annealed samples determined by RBS. Compared to the positions of the a/c-interfaces after annealing shown in Fig. 1, the movement of the a/c-interface during the 2 min annealing step takes place in an area with relatively low Cs concentration. Longer annealing leads to a recrystallization of an amorphous area which contains the as implanted Cs peak causing a further decreased recrystallization rate. Similar observations have been made with the elements O, C, N, and noble gases Ne, Ar, and Kr [6] where the SPER rate is also reduced by exceeding certain impurity concentrations. The SPER rate for a wide range of Cs concentrations (not shown here) was investigated and so far a complete stop of the recrystallization process could not be observed in our experiments.

During annealing a redistribution of the implanted Cs occurs which is caused by segregation at the a/c-interface during its movement through the as implanted profile. Compared to the as implanted sample the Cs distribution of the sample annealed for 2 min there is a slight difference in the profile tail. A depletion of Cs behind and an accumulation in front of the interface, whose location was determined to be at 120 nm, remained after annealing. The sample annealed for 10 min exhibits a strong redistribution during recrystallization where a big fraction of the implanted dose was pushed ahead towards the surface leading to a peak concentration 2.5 times higher than the maximum concentration directly after implantation. Here, the peak is located slightly in front of the interface which is located at 55 nm according to the can-

FIGURE 4. SIMS profiles of Rb implanted silicon and subsequent isothermal annealing.

neling analysis. The bigger distance between the positions of the accumulated peak and the interface in the 6 min annealed sample results from the depth dependent resolution of RBS.

SIMS analysis

Figure 3 shows the SIMS profiles obtained from the same set of Cs implanted samples which were analyzed by RBS and ion channeling. The redistribution after 2 min annealing could be resolved better compared to RBS. The peak positions after recrystallization are very close to the positions of the a/c-interface measured by the ion channeling experiment. For a more precise determination of the a/c-interface positions relative to the concentration peaks other analyzing methods complementary to SIMS, e.g. TEM, have to be applied.

The redistribution during SPER was also observed for the set of samples implanted with Rb, shown in Fig. 4. During the recrystallization process, more and more of the implanted dose is accumulated near the interface resulting in growing concentration peaks towards the surface. A comparison of the two peak positions also reveals a strong retardation of the SPER rate during movement of the a/c-interface through the as implanted profile. Average SPER rates were estimated assuming that during the propagation of the a/c-interface the distance to the concentration peak stays constant. Between the two peaks reordering of approximately 8 nm amorphous

silicon took place within 30 min, which is equivalent to 0.27 nm/min in the area with the highest concentration after implantation. For an estimation of the average recrystallization rate in the sample annealed for 30 min, the characteristic position in the profile at a depth of about 70 nm was used. The average SPER rate was estimated to be 1.4 nm/min. Compared to the intrinsic case with a SPER rate of 8 nm/min at 550° C the rate was retarded by a factor of 30 and 5.7, respectively.

SUMMARY

Silicon was amorphized by implantation of the alkali elements Rb and Cs and their influence on the recrystallization in $\langle 100 \rangle$ direction was investigated. Ion channeling experiments were performed to determine SPER rates in amorphous layers formed by Cs implantation. The rates are decreasing during the movement of the a/c-interface through increasing Cs concentration. Compared to the SPER rate at 600° in the intrinsic case, a retardation up to a factor of 8 was measured. During recrystallization a redistribution of Cs was observed by RBS and SIMS caused by segregation at the a/c-interface.

SIMS was applied to investigate the recrystallization behavior of Rb implanted silicon. Concentration peaks which also occur due to redistribution during SPER were used to estimate average recrystallization rates via SIMS. In comparison to the SPER rate at 550° C in the intrinsic case, a much stronger retardation up to a factor of 30 was observed.

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