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Oriented Growth of Location-Controlled Si Crystal Grains Using Ni Nano-Imprint and Excimer Laser Annealing

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1. Introduction

Low temperature polycrystalline-Si (poly-Si) thin-film transistors (TFTs) are being extensively studied to realize advanced system-on-panel and three-dimensional LSI. The performance of poly-Si TFTs has been significantly enhanced by eliminating grain boundaries from the TFT channel region providing channel electron as high as 600 cm^2/Vs. The improvement was achieved by controlling the location of large crystal grains. Several methods based on excimer laser annealing (ELA) have been proposed for location control[1,2]. However, the orientation control of Si grains has not been reported yet. The next challenge in creating high-mobility and low-variation TFTs is to control the crystallographic orientation of location-controlled Si grains, since carrier mobility and gate interface properties change with surface orientation of Si crystals. When the orientation control becomes possible, the integration of highly functional circuits will be greatly facilitated. In the recent article[3], we reported results of proof-of-concept to realize the control of two-dimensional location and surface orientation of Si crystal grains by combining Ni nano-imprint and ELA. In this report, we describe detailed results of this novel process. In particular, we discuss the crystalline quality and deviation of crystal orientation of the Si grains.

2. Experimental

The concept of the new process is as follows (see Fig. 1): An array of seed crystals for ELA grain growth is formed in the first Si layer by using the metal (Ni) nano-imprint technique[4], where the surface orientation of the seed is determined by the lowest surface free energy of silicide. The second Si layer is then deposited to make the Si film thickness required for TFT fabrication. ELA is applied to grow grains from the oriented seed crystals. The first layer was found to be necessary to keep the seed crystals unmelted at the film/substrate-SiO_2 interface[3,5].

In the experiment, the first a-Si layer (25 nm) was vacuum evaporated with an e-gun on SiO_2/Si substrate followed by heating *in-situ* at 400°C for 1 h for densification. Ni nano-imprint was carried out in such a way that the Ni-coated tip-array was faced down to the a-Si film surface and pressed (pressure: 0.15 MPa). As a result, a small amount of Ni was transferred at desired positions. After detaching the tip array, Ni-induced solid phase crystallization was carried out at 450°C for 20 h in a N_2 ambient. $NiSi_2$ crystallites can be formed at temperatures below 400°C by heating the Ni/a-Si system. The $NiSi_2$ precipitates are octahedra bounded by eight {111} faces, and the lattice mismatch between $NiSi_2$ and Si is only 0.4%. Therefore, a Si crystal grain epitaxially grows on one of eight {111} faces of the $NiSi_2$. As a result, the surface orientation of Si seed crystals becomes {111} in this method, whereas the in-plane orientation becomes random. The size of Si seed crystals thus formed was 70 nm. After eliminating Ni or Ni-silicide using chemical treatment, the second a-Si layer (75 nm) was deposited. Finally, a single pulse of XeCl excimer laser light (λ=308 nm, duration: 20 ns) was irradiated at room temperature.

3. Results and Discussion

Figure 2(a) shows an optical-microscope view of the Si film after laser irradiation at 400 mJ/cm^2. We can see that crystal grains appear at the sites imprinted with the tips which are arrayed in a square lattice pattern. Figure 2(b) shows a crystal morphology of a grain grown by the above-mentioned method after Secco's etching, showing that approximately 2 μm sized crystal grain is formed. The laser-irradiated regions of the film start to melt from the surface. Spectroscopic ellipsometry measurement showed that the absorption coefficient α of both c-Si(111) and a-Si was approximately 1.5×10^6 cm^{-1} at the wavelength λ of 308 nm. Therefore, a solid-phase nanocrystallite survives at an imprinted site whereas the surrounding a-Si regions completely melt owing to differences in melting point and thermal conductivity. The unmelted crystallite that functions as a seed crystal preferentially grows after the laser irradiation ceases. At the same time, the heat generated from the completely melted regions flows to the seed region and, therefore, radial lateral growth occurs. As a result, the nucleation and growth at controlled positions are enhanced in ELA. These results suggest that the location control of Si crystal nucleation in ELA is certainly realized by Ni nano-imprint and a following Ni-induced crystallization.

We analyzed the crystallographic orientation of the location-controlled grains and boundaries in the grain interiors using the electron back-scattering pattern (EBSP) technique. Figure 3(b) shows 111 pole figure of all the location-controlled grains, which clearly demonstrate that {111}-oriented crystal grains can be grown on amorphous SiO_2 substrate by using the proposed process. Besides, the EBSP orientation map shown in Fig. 3(a) reveals that the vast majority of the grains are single-crystal grains while some misorientations and resultant boundaries are also involved.

To characterize the orientation controllability of the process, we evaluated the distribution of the crystal orientation of the grown grains. The results are shown in Figs. 4(a)-4(c). The horizontal axis shows the angle deviation of {111} crystal axis of grains from the surface normal direction. The histogram shows measured data and the curve shows its Gaussian fit. In case of the sample prepared by Ni nano-imprint and solid phase crystallization (SPC) at 590°C for 9 h as seed crystals [Fig. 4(a)], the orientation of all the seed crystal distributes less than 7°. On the other hand, in case of the ELA annealed (400 mJ/cm^2) sample [Fig. 4(b)], the orientation of all the location-controlled grain distributes over about 10°. These results indicate that the deviation in crystal orientation generated primarily during the solidification process of ELA and results in generation of sub-boundaries. In order to confirm this, we have also prepared true-single crystal seed by processing SOI (details will be reported at the conference) and similar ELA process was applied. The resultant orientation distribution is shown in Fig. 4(c), which shows the generation of significant angular spread from the original single crystal seeds.

4. Conclusion

We proposed and demonstrated the crystal-orientation and position controlled growth of Si grains using the combination of Ni nano-imprint and ELA. The results of EBSP analysis clearly indicate that the epitaxial growth from the seeds at controlled positions takes place during resolidification of Si melted by ELA. The maximum substrate temperature in our proposed process is 450°C, which meets the requirement of low temperature process. The process will greatly facilitate the integration of highly functional circuits using TFT technology.

Acknowledgment

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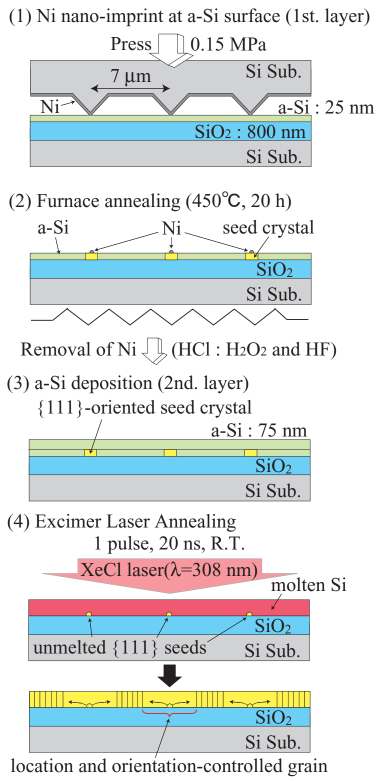

Figure 1: Process steps of combination of Ni nano-imprint and excimer laser annealing with Si double-layer process.

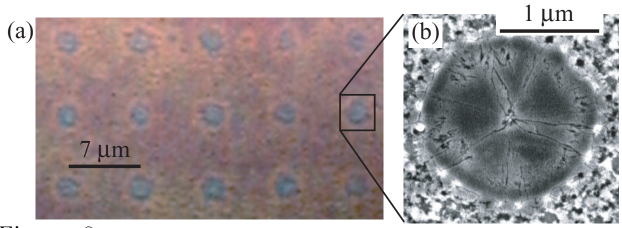

Figure 2: Optical-microscope view (a) and SEM image (b) of location-controlled grains crystallized by the Ni nano-imprint and ELA at 400 mJ/cm^2 of the double-layer Si. The SEM image was taken after Secco's etching.

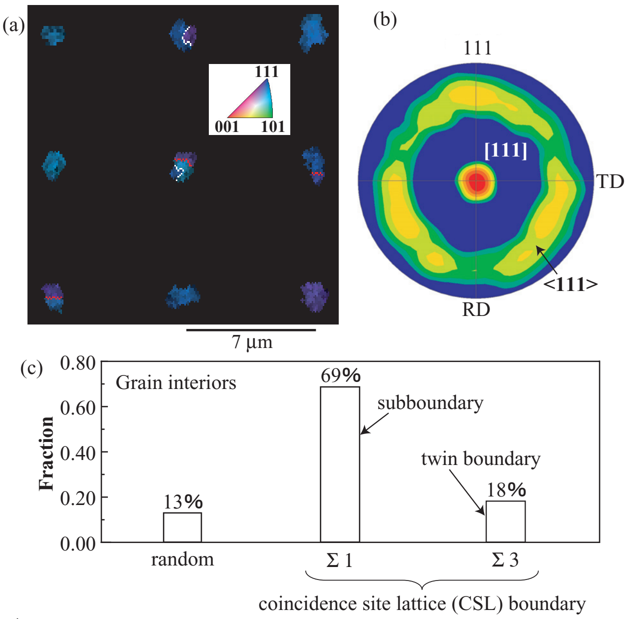

Figure 3: (a) EBSP orientation map of arrayed grains grown by the combination of Ni nano-imprint and ELA with Si double-layer process. (b) 111 pole figure taken from the same area as (a), showing the formation of the {111}-oriented grains. (c) Classification of boundaries in the grain interiors.

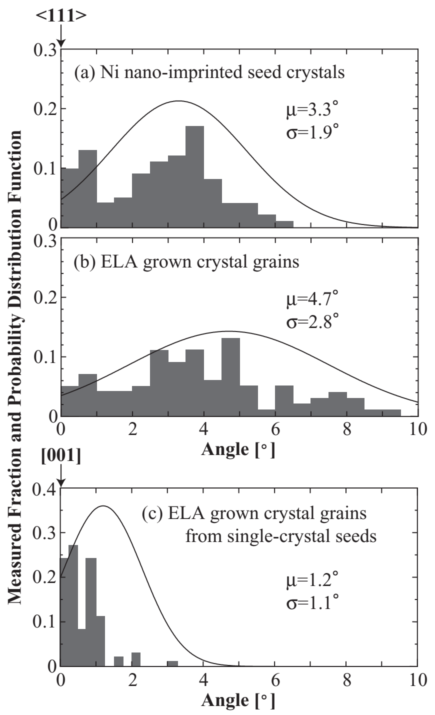

Figure 4: Histograms represent the orientation distribution of location-controlled grains. The horizontal axis represents angles from ⟨111⟩ direction (0°). (a) is the result for seed crystals formed by Ni nano-imprint and following SPC (590°C for 9 h), (b) is that for ELA grown location-controlled grains, and (c) is that obtained from a sample prepared using SOI(001) single-crystal seed. So the horizontal axis in Fig. 4(c) represents angles from [001] direction.