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Crystallization of a-Si Films with Smooth Surfaces by Using Blue Multi-Laser Diode Annealing

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Crystallization of ∼50-nm-thick amorphous Si (a-Si) with a smooth surface was achieved by using Blue Multi-Laser Diode Annealing (BLDA). The a-Si films were deposited by using RF sputtering with Ne gas or by using plasma enhanced chemical vapor deposition (PE-CVD) and were annealed by using BLDA with CW scanning. After the films had been annealed a relatively low laser power below 4 W, the root-mean-square (RMS) roughness deduced from the atomic force microscopy (AFM) results for the surfaces of the Si films was slightly increased, but smoothness was within 3 nm despite the conditions under which the films had been crystallized. BLDA has a potential to realize next-generation poly-Si thin film transistors (TFTs).

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I. INTRODUCTION

High-crystallinity poly-Si films are required for a system on glass (SoG) and a system on panel (SoP) [1–4], and the grain size, as well as the contained trap states density, in the Si film should be uniform over a large area. Excimer laser annealing (ELA) has been widely used to crystallize amorphous Si (a-Si) film [4–10]. However, ELA has difficulty in that it is expensive. Moreover, the surface morphology is formed during liquid-phase crystallization within several hundred nanoseconds. We have proposed Blue Multi-Laser Diode Annealing (BLDA) [11–13] because of its low cost for the thin film transistor (TFT) production and the high stability of the laser source for use as an irradiation beam. In principal, because semiconductor diodes are small, the optical systems can be designed to be compact and to have high input power. Also, the consumption of gasses such as Xe and Cl is not needed. Recently, we proposed a low-cost TFT fabrication process without impurity doping. The device can be formed by using a sputtering technique not only for the channel but also for the gate insulator without the need to adopt chemical vapor deposition (CVD) process [14]. In our previous work, we reported the effective crystallization of a-Si on a glass substrate and on a polyimide sheet by using BLDA [11–22]. In this work, we focus on the crystallinity and the surface roughness of Si films crystallized by using BLDA. Differences between the two deposition methods, RF sputtering and plasma enhanced chemical vapor deposition (PE-CVD), are also discussed.

II. EXPERIMENTS

Amorphous silicon (a-Si) films of 50 nm in thickness were deposited on a glass substrate by using a radio frequency (RF) sputtering machine with a semi-intrinsic Si target (n-type: 5 − 10 Ωcm) or a phosphorous-doped Si target (0.0013 − 0.0016 Ωcm) at room temperature. To realize stable crystallization, we optimized deposition with a Ne gas flow rate of 13 sccm and gas working pressures of 1.4 mTorr. As Ne atoms are lighter and their atomic radius is smaller than these of Ar, Ne gas can much easily effuse at a lower annealing temperature during crystallization [15, 23]. Prior to Si layer deposition, a buffer layer of 50-nm-thick SiO_2 was deposited on the glass substrate by RF sputtering with Ar gas. For comparison, a-Si:H films of 40 nm in thickness were deposited by using plasma enhanced chemical vapor deposition (PE-CVD) at 360 °C. After the deposition, dehydrogenation was performed at 550 °C for 1 hour.

For crystallization, the films were annealed using a semiconductor blue laser diode with a 445-nm wavelength in the continuous wave (CW) mode. The samples were placed on a high-precision computer-controlled x-y stage, and the laser beam of 600 × 2.4 μm^2 with a top-flat power profile along the long axis was focused onto the surface of the Si films and scanned in a direction

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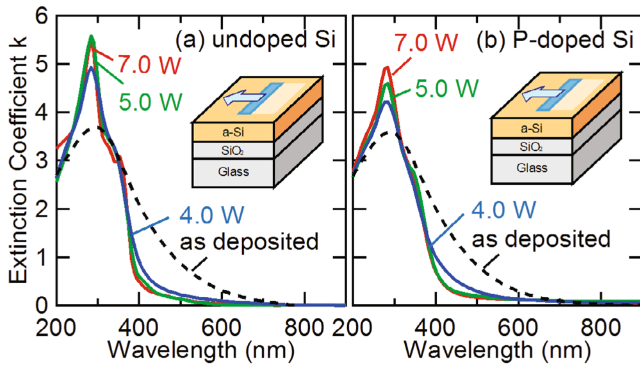

Fig. 1. (Color online) Extinction coefficient spectra of (a) undoped and (b) P-doped Si films deposited by using PE-CVD.

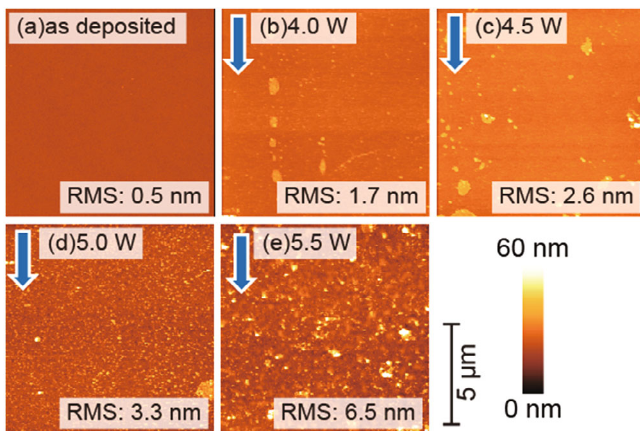

Fig. 2. (Color online) Surface morphologies before and after BLDA of undoped Si deposited by using PE-CVD.

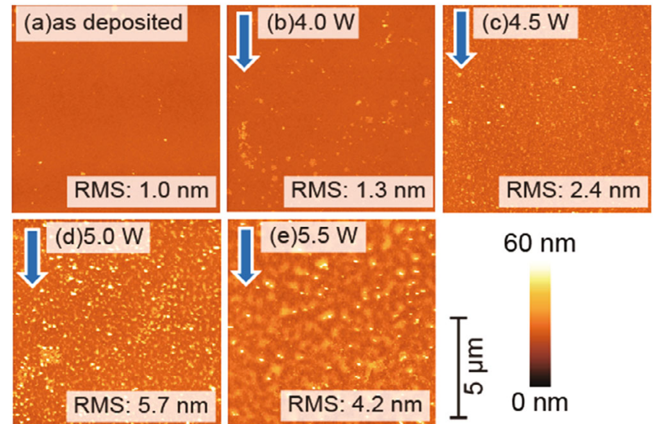

Fig. 3. (Color online) Surface morphologies before and after BLDA of P-doped Si deposited by PE-CVD.

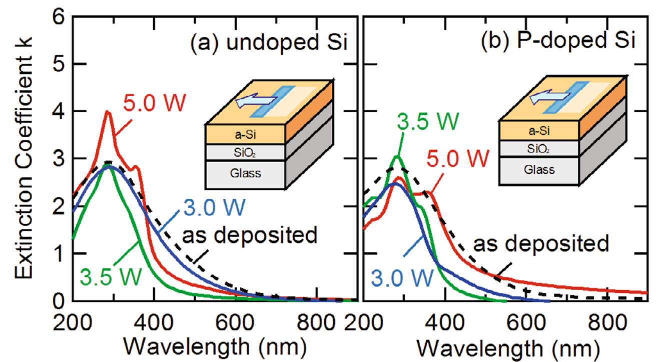

Fig. 4. (Color online) Extinction coefficient spectra of (a) undoped and (b) P-doped Si films deposited by using RF sputtering.

perpendicular to the long axis at a rather high speed of 500 mm/s in an atmospheric ambient. The laser power was controlled to be in the range from 3.0 to 7.0 W [11, 12, 15, 16]. For the analysis of the film's quality and optical properties, spectroscopic ellipsometry (SE; SOPRA ES4G) was used to evaluate the thickness (d), the refractive index (n), the extinction coefficient (k) and the crystallinity in the Si film. Atomic force microscopy (AFM; SII E-sweep) was also performed to observe the crystal grain structure and the surface roughness.

III. RESULTS AND DISCUSSION

Figure 1 shows the extinction coefficient spectra of Si films deposited by using PE-CVD, as obtained from SE analyses before and after BLDA. The peaks at 280 nm (E_2, 4.4 eV) and 360 nm (E_1, 3.4 eV) of the extinction coefficient spectra, which indicate band formation induced by the crystallization of the Si film [24, 25], are higher and sharper after BLDA.

Figures 2 and 3 show the surface morphologies of Si films before and after BLDA, as obtained by using AFM. In both cases, undoped and P-doped Si film, the surface roughness was slightly increased due to the effective crystallization after BLDA. Also, the root-mean-square (RMS) roughness was less than that of conventional ELA, especially for an atmospheric ambient. In the case of ELA in an atmospheric ambient, the RMS roughness were 10 nm or higher after crystallization [9, 10]. Furthermore, for laser powers below 4.5 W, the RMS roughnesses were around 3 nm or less.

Figure 4 shows extinction coefficient spectra for Si films deposited by RF sputtering. From the results, the films were crystallized after BLDA at power higher than 3.5 W for the undoped sample and 3.0 W for the P-doped sample. The tendency was same as that in the PE-CVD case, but the power to improve the crystallinity of the films was higher than it was for PE-CVD. Here, sputtered amorphous Si films deposited at room temperature showed relatively lower extinction coefficients compared with CVD films, so the film density seems to be low. In this case, the peaks around 280 and 360 nm after crystallization will be relatively pronounced compared with those for the CVD case.

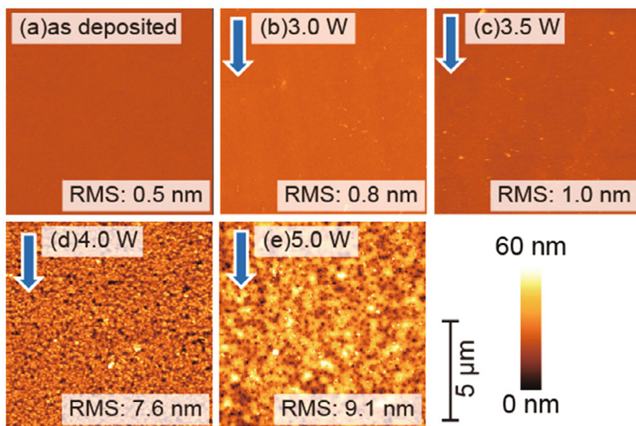

Fig. 5. (Color online) Surface morphologies before and after BLDA of undoped Si deposited by using RF sputtering.

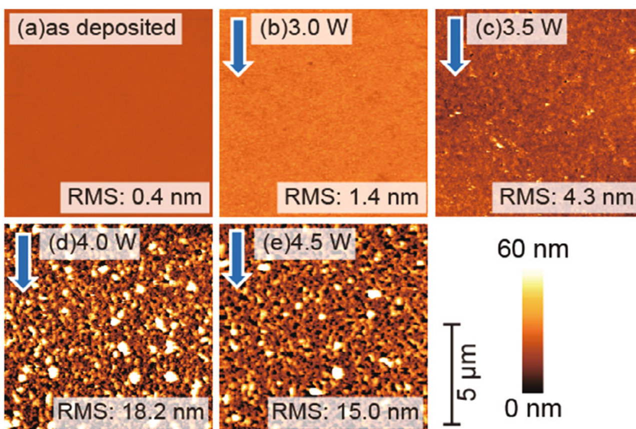

Fig. 6. (Color online) Surface morphologies before and after BLDA of P-doped Si deposited by RF sputtering.

Figure 5 shows the surface morphologies of undoped Si films deposited by RF sputtering. The morphology did not change at power below 3.5 W, and the RMS roughness was increased a little with increasing power higher than 4.0 W. Also, in our previous work, the roughness was observed to increase around 4 W [22], even though the RMS roughness was slightly different. As a result, crystallized Si films with very smooth surfaces were achieved at a laser power of 3.5 W. In the case of the P-doped Si films, the same tendency as that for the undoped Si films was obtained, as shown in Fig. 6.

The RMS roughness are summarized in Fig. 7. As a result, BLDA is an effective way to crystallize a-Si films deposited by using PE-CVD or RF sputtering. From the results of an opt-thermal analysis, which considered laser absorption and thermal conduction [15], the Si films should be crystallized in a solid phase in the considered power range, and the temperatures at the top and the bottom of the film should almost be the same at a thickness of 50 nm. Here, the nucleation rate is well known to depend on the annealing temperature in the solid phase [26,27], and nucleation is well known to occur uniformly along the depth direction of the film due to uniform heating at high temperatures. In that case, the Si films can be crystallized with small, uniform grains [11]; thus, the surface should remain smooth after the crystallization. Especially in the films prepared by using PE-CVD, a smooth surface can be obtained even at a high laser power. For the crystallization of the sputtered Si films, incorporated Ne sputtering gas diffuses out from the films more easily than Ar does it. The diffusing gas is thought to damage the films during annealing within several micro-seconds. In the case of films deposited using CVD, hydrogen is incorporated; however, the size of hydrogen molecule is small, and the contents are reduced after dehydrogenation. Thus, the surfaces of the films deposited using CVD are smooth compared to those of the films deposited using RF sputtering. On the other hand, the RMS roughness of P-doped Si films

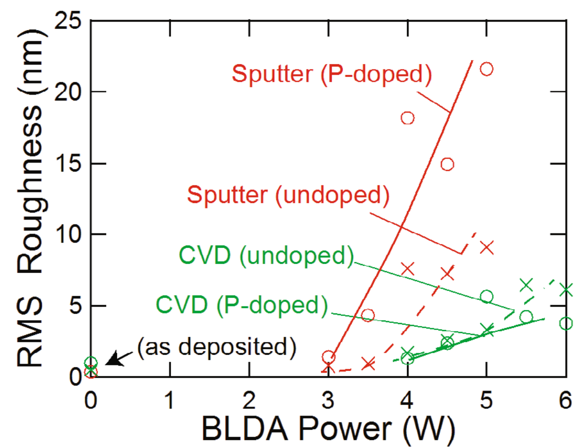

Fig. 7. (Color online) RMS roughness values obtained from AFM images.

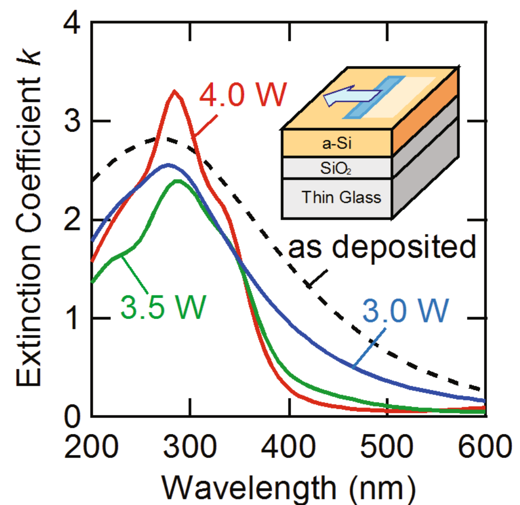

Fig. 8. (Color online) Extinction coefficient spectra of P-doped Si films deposited on flexible thin glass by using RF sputtering.

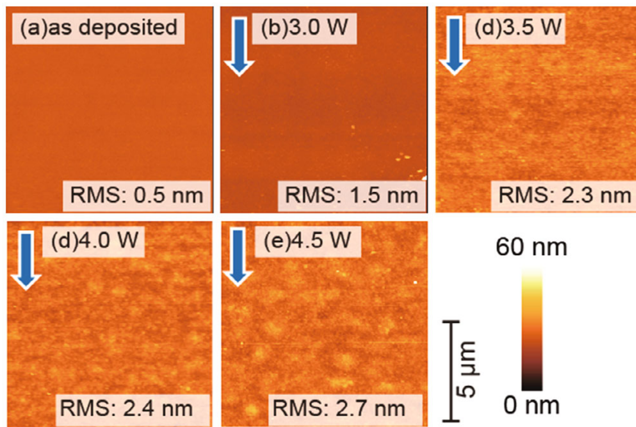

Fig. 9. (Color online) Surface morphologies before and after BLDA of P-doped Si deposited on flexible thin glass by using RF sputtering.

deposited by sputtering are higher than those of the undoped Si films. Growth rate of doped Si is higher than that of undoped Si [28]; thus, crystallization occurred and the incorporated gas diffused out at a lower laser power. The sputtered films might be damaged by the diffusion process.

Furthermore, BLDA is an effective way to crystallize Si films on flexible thin glass with a thickness of 100 μm [19]. Figures 8 and 9 show the results for Si films deposited on thin glass by RF sputtering. In this case, the Si films were crystallized at power higher than 3.5 W, and the surface smoothnesses were within 3 nm, even at a power of 4.5 W. The result seems to be related to the release of stress by a slight bending of the thin glass, but this is still under consideration.

IV. CONCLUSION

Using both PE-CVD and RF sputtering, we were able to crystallize the a-Si films with smooth surfaces by using BLDA in the CW mode. Especially at relatively low laser power, the RMS surface roughness after crystallization was kept within 3 nm. BLDA has a potential for realizing next-generation poly-Si TFTs.

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