Evaluation of polycrystalline silicon after Excimer laser annealing by Retardation measurement method

Nakcho Choi, Eungtaek Kim, Kie Hyun Nam, Deokhoi Kim and Beohm Rock Choi
Samsung Display Co., Ltd., Yongin-City, Korea

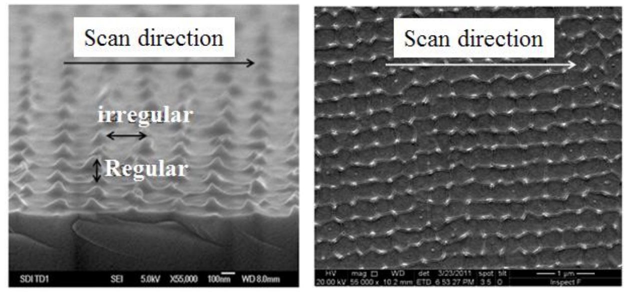
Abstract
The excimer laser annealing (ELA) process is one of the important processes in Low Temperature Polycrystalline Silicon (LTPS) and the optimization of laser intensity and scan pitch in ELA process are the key technology to make good performance in OLED panel. However, the visual inspection through human eye has been used to find the Optimum ELA energy density (OPED) because of the fast inspection speed and accuracy. As the size of glass in LTPS is increasing, the need of a new inspection method has been raised. So the measurement of retardation which has been used in liquid crystals' cell gap measuring was applied to evaluate the degree of crystallization in polycrystalline silicon(p-Si) made from the ELA process for the first time. The origin of the retardation is estimated as a Laser-induced periodic surface structure (LIPSS).

Author Keywords
Excimer laser annealing (ELA), Laser-induced periodic surface structure (LIPSS)

1. Introduction
After the study of p-Si using ELA [1] James S. Im and H. J. Kim discussed how grain growth and abrupt grain size decrease with ELA energy. [2] He explained that to maximize the average grain size, it is necessary to irradiate laser to amorphous silicon layer with a sufficient amount of energy so that a completely non-nucleated nucleus is present in the lower part of the a-Si. Huck Lim et al. [3] and James B. Boyce et al. have shown that the intensity of the (111) peak of Si and the grain size and mobility are proportional. [4] However, since such an assay method for destroying or damaging the substrate is not suitable as a real-time inspection method in the ELA manufacturing process, the inspection used in manufacturing is a visual test in which inspectors watch an image reflected by a light diagonal to a periodic protrusion at Optimized Process Energy Density (OPED) was determined by observing vertical line stain and reflectance uniformity.

In this paper, we introduce optical retardation analysis method which has physical meaning of alignment of Si lattice in protrusions as well as has quantitative values

2. Experiment and Result
Transistor (TR) design is decided according to the resolution and requirement characteristics of AMOLED products. Due to the periodicity between the pitch of TR and the pitch of ELA, moiré stains are generated, so the ELA scan pitch is limited. Therefore, the energy of the OPED region during the ELA process differs when the pixel pitch is changed for each product. In general, the shape of the Laser-induced periodic surface structure (LIPSS) is shown in Figure. 1. Regular periodic intervals exist in the long axis direction of the laser, but there are irregular intervals in the scanning direction. This is explained by H. M. van Driel [5] and S. E. Clark [6], which is generated by p-polarized laser and s-polarized laser, respectively.



(a) (b)

Figure 1. SEM image of a Laser-induced periodic surface structure (a) tilted (b) top

In this paper, we propose a hypothesis that micro-stress induced retardation occurs when Si is melted and crystallized, and that this is concentrated in the vicinity of the hillock and has a large phase difference.

2.1. Polarizer Micro Scope (POM)
Generally, Dark field reflection microscope is used to observe the uniformity of the protrusions after ELA. In particular, stripe strain in the scan direction occur at intervals of about 1.5 to 3 μm, which can be observed by the reinforcement and destructive interference of light reflected from the periodic protrusions. In order to observe the striations more highly, Paul C. van der Wilt reported that polarizing microscopy is preferred and that the brightness of blue light is similar to grain size according to ELA Energy. [7] However, he did not explain why the polarized light microscope image is good to observe the striations on p-Si, but In this paper, I proposed that this is because of the optical anisotropy of poly crystalline silicone that amorphous silicon does not have. In Figure. 2(a), the a-Si region without laser irradiation is black in the cross polarizers, whereas the p-Si region is brightly lighted, which means that retardation occurs in the crystallization process. Also, when the sample of the p-Si region was rotated, it was bright and dark, which was the same phenomenon as when the liquid crystal molecules were rotated on the aligned LCD in Figure. 2(b),(c). This is due to the equation (1) that the transmittance varies with the angle between the slow axis of the anisotropic molecule and the transmittance axis of polarizer with the transmission axis of the orthogonal polarizer. In p-si, the scan direction of the laser is slow axis.

$$T = \frac{1}{2}(\sin 2\theta)^2\left(\sin\frac{\pi \mathrm{Re}}{\lambda}\right)^2 \quad (1)$$

where T, θ, Re, and represent luminance, angle between slow axis of molecule and transmittance axis of polarizer, retardation, and wavelength, respectively. [8]

As rotating sample at the fixed polarizer, POM image at 0 degree of sample (b) and POM image at 60 degree of sample (c)

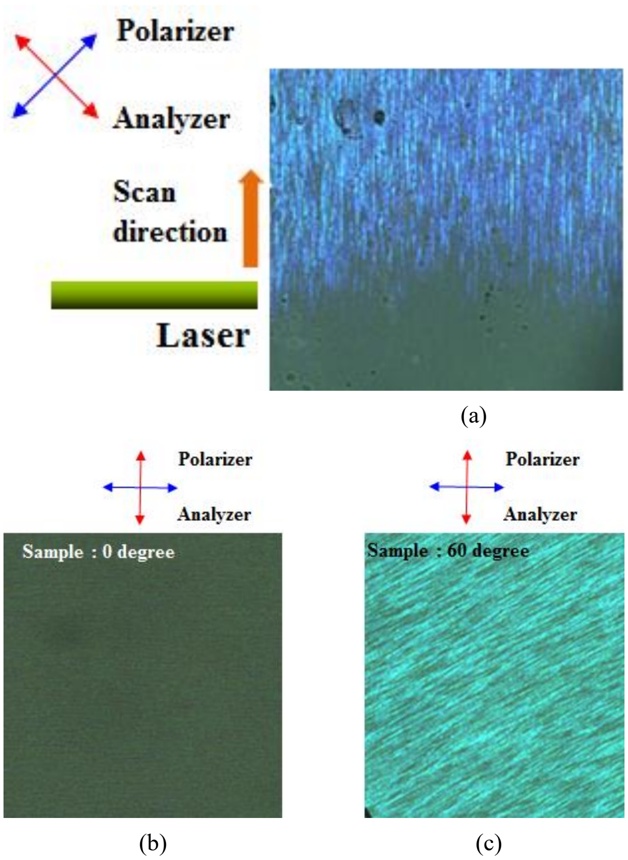


Figure 2. Polarizer optical microscope image near edge of ELA start point (a) As rotating sample at the fixed polarizer, POM image at 0 degree of sample (b) and POM image at 60 degree of sample (c)

2.2. Retardation Measurement

In order to quantitatively measure the anisotropy of the p-Si observed previously, the laser was irradiated at various energy densities on one substrate. Re and Rth were measured using the Axoscan-60H equipment of the Axometric company, which measures the cell gap and rubbing direction of the LCD. Re and Rth are shown in Equations (2), (3).

$$\mathrm{Re} = (n_x - n_y) \times d \tag{2}$$

$$R_{th} = \left(n_z - \frac{n_x + n_y}{2} \right) \times d \tag{3}$$

where Re, Rth, nx, ny, nz, and d represent in-plane retardation, out of plane retardation, x,y,z axis refractive index, and thickness, respectively.

As the ELA energy density increases, Re and Rth increase gradually, but decrease rapidly after OPED. As shown in Figure. 4, the Rth value is larger than Re and the trends of the two values coincide with each other. This is the same phenomenon that occurs when nx, ny, and nz are different from each other, such as a biaxial film of LCD. It can be assumed that the Rth is generated by the tilted Si lattice at the protrusion in Figure. 3.

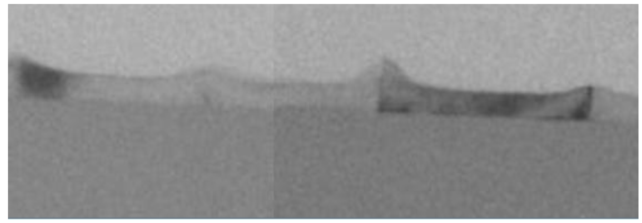


Figure 3. TEM image of p-Si

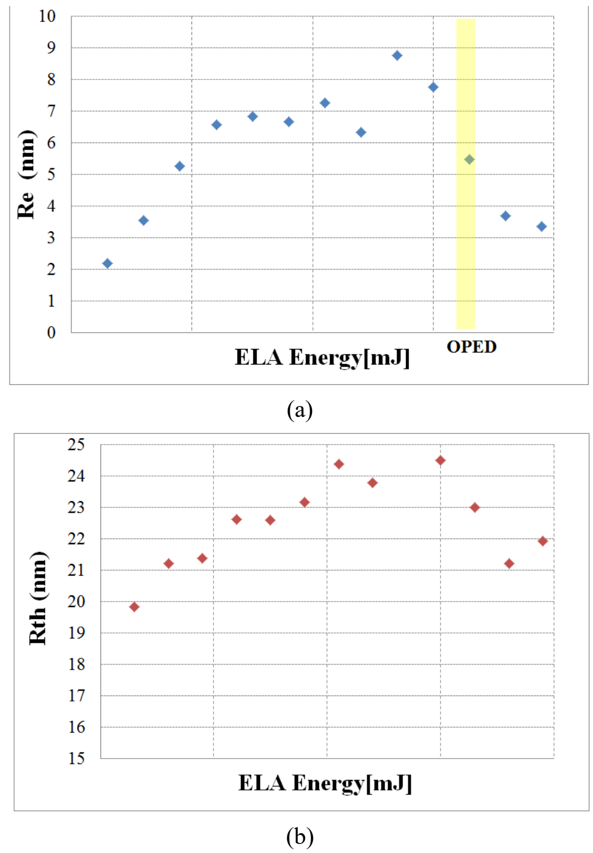


Figure 4. Re(a) and Rth(b) according to ELA energy density

The crystal orientation of lattices in each grain is different, and randomness does not produce retardation. As a result, the cause of the anisotropy is assumed to be due to the alignment of grain boundaries in the laser scan direction.

2.3. FEM Stress simulation

It is assumed that the cause of retardation is concentrated stress near the protrusion. Then we simulated stress-induced retardation near the protrusion by a commercial Finite Element method (FEM) simulation program (FlexPde). The simulation conditions are shown in Table. 1, the thickness of p-Si is 50 nm, and the thickness of SiO_2 is 300 nm. The protrusions were simplified to triangular pillars. Shear stresses were calculated for p-Si when the temperature difference at the top and bottom was 1000 ° C for two types of shapes with and without protrusions. Simulation results show that shear stress was not large in p-Si in the structure with no protrusions, but shear stress was large at the interface of the protrusions when the protrusions were present. (Figure. 5 c, f) When the thermal expansion coefficients of the two materials are different, the volume change due to the temperature difference causes local stress. When the surface protrusion structure is present, the stress is concentrated at the protrusion structure boundary.

Table 1. Simulation conditions (FlexPDE)

	Thermal conductivity [W m^{-1} K^{-1}]	Young's modulus [GPa]	Expansion coefficient [°C^{-1}]	Poisson's Ratio
p-Si	67	169	4.3×10^{-6}	0.22
SiO_2	1.3	66	5.6×10^{-7}	0.17

3. Impact

In this study, we investigated the anisotropic tendencies occurring in the periodic protrusions of p-Si by using phase retardation, and proposed this measurement method that can replace the visual human inspection that determines the OPED of the ELA process.

.

4. References

[1] T. Sameshima and S. Usui, Mater. Res. Sot. Symp. Proc. **71**, 435 (1986).

[2] James S. Im and H. J. Kim. Phase transformation mechanisms in excimer laser crystallization of amorphous silicon films. Applied Physics Letters, **63(14)**,1969–1971(1993)

[3] Huck Lim. et al. Journal of the Korean Physical Society **48**, S47~S50 (2006)

[4] James B. Boyce and Ping Mei. Laser crystallization for polycrystalline silicon device applications. In R. A. Street, editor, Technology and Applications of Amorphous Silicon, pages 94–146. Springer, 2000.

[5] H. M. van Driel, J. E. Sipe, and Jeff F. Young, Laser-Induced Periodic Surface Structure on Solids: A Universal Phenomenon, PHYSICAL REVIEW LETTERS **49**, 1955 (1982)

[6] S. E. Clark and D. C. Emmony, Ultraviolet-laser-induced periodic surface structures, PHYSICAL REVIEW B **40**, 2031 (1989)

[7] Paul C. van der Wilt, Excimer-Laser Annealing: Microstructure Evolution and a Novel Characterization Technique, SID 2014 DIGEST, 149–152 (2014)

[8] Pochi Yeh, Claire Gu, Optics of Liquid Crystal Displays (Wiley, New York, USA, 2006) p118.

[9] D. Rosenblatt, A.Sharon, A.A.Friesem, IEEE Journal of Quantum Electronics **33**, 2308 (1997)

[10] S. He. et al., Applied Physics Letters **89**, 111909 (2006)

[11] Naoto Matsuo, Materials Transactions **46**, 1958 (2005)

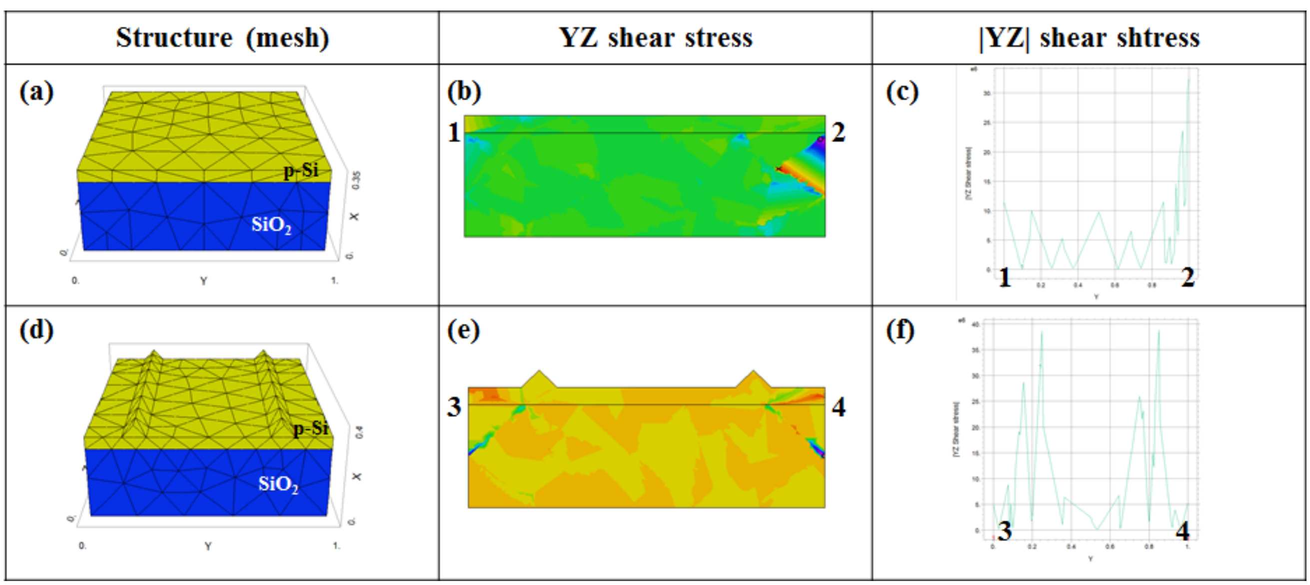


Figure 5. Two kinds structures with hillock and without hillock
Mesh image (a),(d) Result of shear stress simulation cross sectional image (b),(e) and intensity of YZ shear stress (c),(f)