Silicon Thin Film Crystallization Annealing System Using Blue Laser Diode

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ABSTRACT

A new silicon-crystallization-annealing system using blue laser diode (BLDA) has been developed. By selectively irradiating the LD in a redundant fiber-array arrangement, annealing of display of different pixel pitch can be implemented by a fixed fiber-array. High on/off current ratio and mobility near 300cm^2/VS has been confirmed in the TFT device of lateral-growth silicon by BLDA.

1. INTRODUCTION

The thin film transistor (TFT), which is consisted of stack of semiconductor layer, insulate layer and metal layers, has achieved great success in display industry. Adopting TFT as backplane Liquid crystal displays (LCD), organic light emitting devices (OLED) has become a trillion-dollar industry. The semiconductor of TFT can be classified to amorphous silicon, polysilicon, and oxide compound etc. Amorphous silicon TFTs are most widely utilized because it is easy to produce with less process steps, in turn lower cost. Polysilicon TFT is used in mobile displays for its higher mobility and reliability. Oxide TFT has found its application in large size OLED displays for its moderate mobility and less cost than polysilicon TFT.

With increasing attentions to mini-LED and micro-LED, improvement of TFT performance, such as higher mobility and higher on/off current ratio, is expected. Comparing to LCD, illuminating an LED display requires much more electric current, which in turn requires higher mobility of TFT. Amorphous TFT is not the candidate because it can't provide enough electric current for low mobility. Oxide TFT is one of the candidates for the backplane of mini-LED displays resulted from its success in the adoption of backplane of OLED TV displays. However, this is not true for mini-LED, comparing to OLED driving an LED pixel requires much higher current, and also because of oxide TFT device deterioration under light illumination and high bias voltage. For LTPS TFT, the excimer laser is utilized for silicon crystallization annealing. However, because the complicated optical system and requirement of expensive high-power pulse gas laser, the polysilicon TFT is limited in manufacturing using smaller substrate smaller than G6.

For large size substrate, we have developed partial laser anneal technology using excimer laser and micro-lens projection system. By using the partial laser annealing, the laser light is effectively accumulated to the TFT area, less laser tubes are required compared to conventional ELA equipment. Based on the concept of partial anneal, we have developed a new laser anneal system using blue laser diode annealing, this can further reduce the crystallization annealing cost.

Comparing to conventional ELA where the laser energy is limited, in BLDA the irradiation energy can be controlled by fluence and scan speed of the laser beam over the substrate. The crystallization process can be controlled both by irradiation and cooling speed. A rapid heating and cooling process produces polysilicon, rapid heating and slower cooling produces lateral-growth crystal which has large elongated grain size. The lateral growth crystal has smoother surface which is important to the gate insulator film of TFT device. More precise control of heating and cooling of the silicon film with support of a heat preserve SiO2 cape layer, single crystal strip has been obtained.

In this paper we will report our recent progress of development of BLDA.

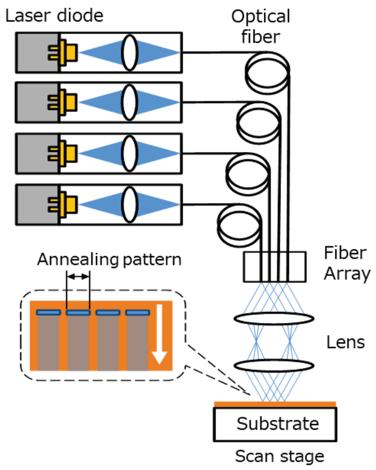

Figure 1. The optical geometry of BLDA.

2. The constitution of BLDA equipment

2.1. The configuration of optical structure

Figure 1 shows the equipment concept of BLDA. In BLDA equipment, blue light semiconductor laser diode of wave length of 450nm was utilized. The light of laser was attracted into optical fiber by a coupling module. Adoption of optical fibers make easier to construct an optical pass-way from the light source to the annealing location of the substrate. The optical

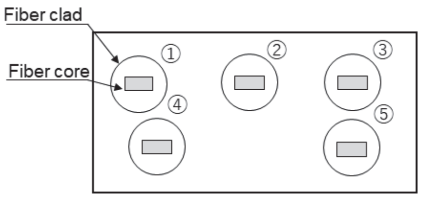

Figure 2. The 2D view of fiber array module of BLDA.

fibers also work as an integrator creating uniform optical beam intensity distribution. Multiple fibers were assembled to a fiber-array module where the output-end of all fibers were set in a plane perpendicular to the optical axis of the subsequent projection lens. Figure 2 shows one example of a fiber array, in this example, 5 fibers were aligned in two rows and three columns by a special ceramic plate, the output-end surface of the fiber array was polished after assembly, then coated with anti-reflection film.

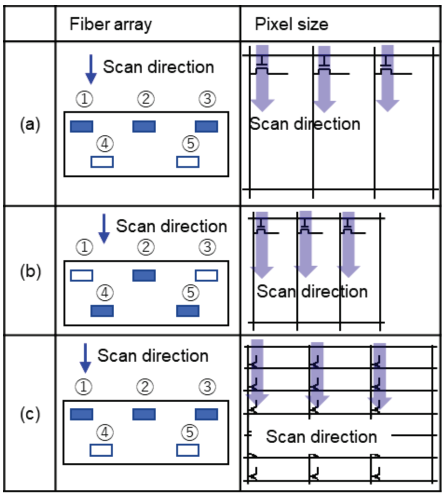

Figure 3. Mechanism for fixed fiber array to implement Annealing of display of different pixel pitch.

In BLDA annealing, partial annealing was applied, where the light energy of laser was condensed into a narrow area where the TFT channel was created. By utilizing partial annealing, the energy efficiency can be increased significantly. Whereas for BLDA where the distance between laser beams is fixed, a special mechanism is required to implement annealing of displays of different pixel pitch. Figure 3 indicates one example of our proposal of annealing of displays with different pixel pitch using a fiber-array of fixed pitch. In the example, five laser beams were assembled in the fiber-array, for any special pixel pitch only part of all beams was with laser irradiated, as in case (a), the upper row three beams were utilized for wider pixel pitch, in case (b) three beams of two rows was utilized for a narrower pixel pitch, in case (c) the upper three beams were utilized, however scanned in a perpendicular direction. By the mechanism mentioned above, multiple displays of different pixel pitch can be annealed using one fiber-array, this prevent frequent fiber-array replacement in the manufacturing lines.

2.2. Control and system of BLDA

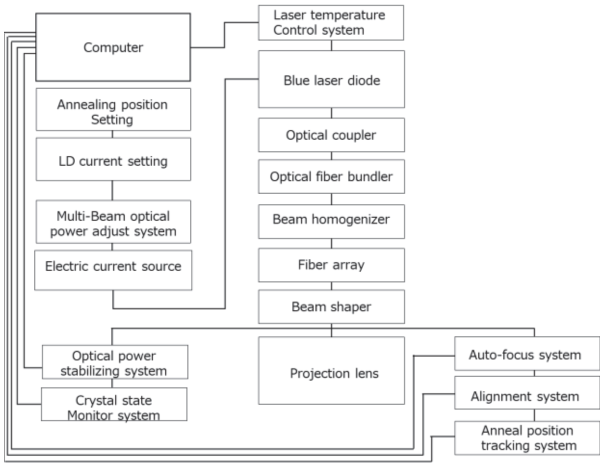

Figure 4. System diagram of BLDA.

Figure 4 shows the system diagram of BLDA equipment. In our BLDA equipment, the light of each one laser is projected to specified location of the substrate. Any specified location can be annealed with necessary energy, creating desired crystal. This would be helpful for TFT backplane designs to realize electric devices which require different mobility in different locations of the TFT backplane, it is impossible in conventional laser annealing using uniform large laser beam. Whereas the difference of optical power caused by deviation of characteristics of each laser would give rise to the difference of desired crystal. Equal optical power of all beams should be maintained for a uniform crystal in entire substrate. Therefor the optical characteristics of each should be precisely measured. The current of each laser should be precisely controlled regarding the optical power of the beam. In our BLDA equipment the current is determined based on the power measurement of all lasers and the results is stored in lookup tables of the system. A feedback system is adopted to maintain the laser optical power stability.

The other important control of BLDA is the focus position of the projection lens. As in figure 1 in our BLDA equipment the annealing beam is a conjugate image of the output surface of fiber array. A reduction projection optical lens is adopted, the depth of focus (DOF) is about the range of several micron meters. To realize a stable optical power and beam distribution, the substrate should be controlled in-between the DOF. The distance between lens and substrate is measured simultaneously during anneal using laser displacement meter, the distance is constantly adjusted in entire anneal process.

In our BLDA, a positioning mechanism consisted of precise stage, camera and real time position correcting system, is adopted for guarantee the anneal positions in the partial annealing. An anneal state monitoring mechanism comprised of microscope and analyzing software is also utilized in the BLDA equipment.

3. Experiment

3.1The substrate of laser annealing experiment

For laser annealing experiment of bottom-gate TFT, a low-cost glass substrate of amorphous silicon TFT was used. Copper gate metal was deposited onto the substrate, then gate pattern was created by photolithograph and etching. The substrate was then deposited with SiN_x, SiO_2, amorphous and SiO_2 silicon by CVD. The SiN_x, SiO_2 works as the gate insulator of TFT, the last SiO_2 works as a protection layer of amorphous silicon and etching stopper layer of TFT. The substrate was annealed at 500C 1 hour for dehydrogenation before laser irradiation.

For bottom-gate TFT, projection of the laser beam was 33um x 8um with stage scan speed of 800mm/S. The laser was scanned on its short axis direction. Other laser beam size was also investigated, however larger width and slow scan caused damage to the gate metal.

For top-gate TFT, glass substrate for LTPS was used. The substrate was deposited with SiN_x, SiO_2 and amorphous silicon by CVD. The SiN_x, SiO_2 works as barrier layer preventing penetration of impurities. For top-gate TFT, projection of the laser beam is 66um x 16.5um. The laser was scanned along beam short axis direction. Compared to bottom-gate TFT, wider laser beam was used for more energy accumulation.

3.2 Measurement of the silicon crystal of BLDA

The crystalline grain structure of annealed sample was analyzed using SEM and AFM. Before the measurement of crystal, the SiO_2 protection layer was etched off. The sample was then etched with special mix-solvent of Secco etching. The surface roughness of the crystal silicon was measure by AFM, after etched off the SiO2 protection layer. The crystal grain was measured after Secco etching. The grain size is defined as the apparent diameter of the circle which has the same area of the crystal grain. The cross section of all layer of TFT has been observed. The grain size only limited to the samples which no damage was found in all layers.

4. Results

4.1. Polysilicon on metal gate film by BLDA

Figure 5 shows the SEM images of the polysilicon crystal samples of bottom-gate TFT, by two different annealing conditions. Sample (a) was micro-silicon by lower power, (b) was polysilicon which average grain size was about 250nm, even high power was investigated, large-grain-size polysilicon was confirmed, however crack was found on the copper metal.

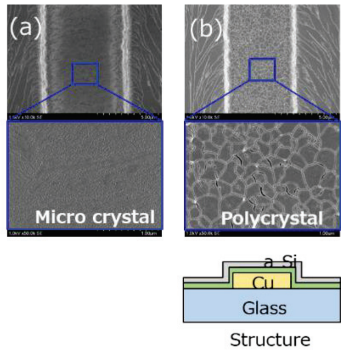

Figure 5. The SEM image of annealed amorphous silicon of bottom gate TFT.

4.2. Lateral-growth silicon by BLDA

For the precursor amorphous silicon of top gate TFT, wide variety of grain size has been obtained, depending on the laser power and scan speed. Figure 6 shows the phase diagram of silicon crystallization by BLDA. While the total irradiation optical energy was small by low laser power or fast scan, a dehydrogenated film was first confirmed. With increase of irradiated energy, micro-silicon, polysilicon, lateral-growth-silicon was confirmed before an agglomeration.

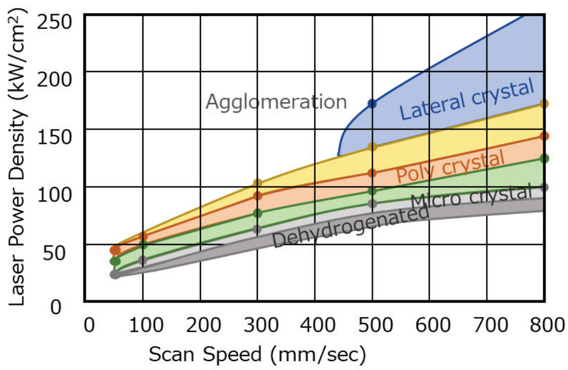

Figure 6. Crystallization phase diagram by BLDA.

In the phase diagram, the lateral crystal region is of most interest. Figure 7 shows a bird-view SEM image of a typical lateral-growth silicon. The lines in the picture is the boundary of crystalline silicon. The boundary lines have small angle to scanning direction. All grain has similar width, whereas substantial different length. Measured from the SEM image, the length of lateral region was more than 5um, it is longer than the channel length of almost all the device utilized in display backplane. Similar crystal grain shape, smaller deviation of grain width assures less deviation of the characteristics of TFT device and good functionality of electric circuit of displays. Figure 8 shows one result of transfer characteristics of TFT of lateral-growth silicon by BLDA, detail will be presented elsewhere.

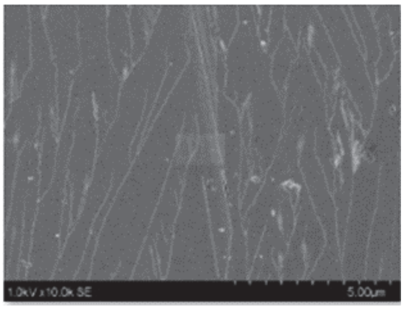

Figure 7. Lateral-growth silicon by BLDA.

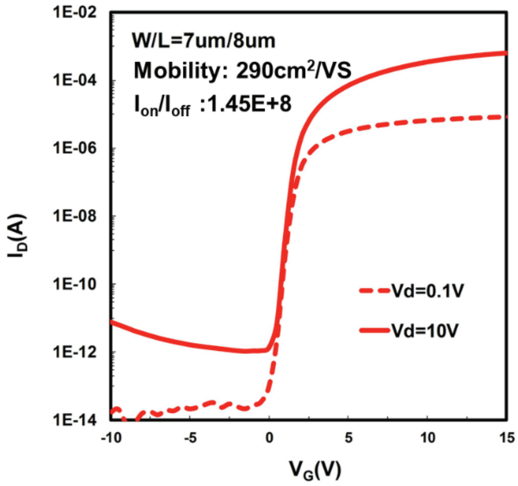

Figure 8. Transfer characteristics of TFT of lateral-growth silicon by BLDA.

4.3. Single crystal by BLDA

For more functional circuit or high performance in display or sensor circuit on the glass substrate, high quality crystal like single crystal is necessary. There are several reports about the research on laser annealing for single crystal. We have investigated BLDA annealing for single crystal using the same layer structure as previous report. The 0.5mm glass substrate which is utilized in LTPS TFT manufacturing was used. Multiple thin material layers including amorphous silicon were deposited using plasma-enhanced chemical vapor deposition (PECVD) with the

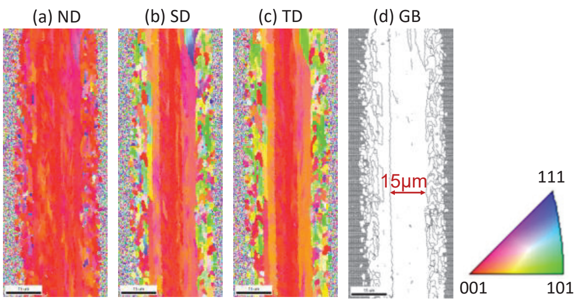

Figure 9. The inverse pole figure map (a-c) and the grain-boundaries (d) of single crystal by BLDA.

following sequence, 50 nm SiN_x, 150 nm SiO_2, 60 nm a-Si and 200 nm SiO_2. The SiN_x, and SiO_2 works as a barrier layer prevent impurities from the substrate, the SiO_2 on top of a-Si was protection layer, was believed to be effective for the orientation of facets of silicon single crystal. After deposition, dehydrogenation was carried out at 450 °C 150min using furnace oven.

Before laser crystallization of BLDA, further laser dehydrogenation was carried out with the same laser beam. The power densities of laser dehydrogenation and laser crystallization were about 23 kW/cm^2 and 35 kW/cm^2 respectively. The moving speed of the substrate while both annealing was 5 mm/S. The crystallization state was investigated using electron backscatter diffraction (EBSD; Hitachi SU6600) after dissolving the protection SiO2 layer by wet-chemical etching. Figure 9 shows the inverse pole figure (IPF) map and grain-boundaries (GB) with rotation angle greater than 15 degrees. ND, SD and TD mean normal surface direction, laser scanning direction and transverse direction respectively. The figure (d) illustrates the grain boundary. The dark area of two side of the image shows non-annealed amorphous silicon. It is apparent that there is no grain boundary in the center area, this means the center area is a single silicon crystal region. As in figure (a) – (c), a single silicon strip with length more than several hundred microns has been obtained. The crystal orientation in the beam center area was almost in accordance with {100} texture. On the contrary, it had various orientations at the periphery region.

5. Conclusion

We have developed a new silicon-crystallization-annealing system using blue laser diode (BLDA). By selectively irradiating the LD in a redundant fiber-array arrangement, annealing of display of different pixel pitch can be implemented by a fixed fiber-array. For top-gate TFT, it is possible to obtain silicon crystal from micro-crystal, polysilicon and lateral silicon. By using a SiO_2 cape layer on top of amorphous silicon, and precise control of annealing condition, silicon single crystal strip has been realized. For bottom-gate TFT, we have succeeded in obtaining large size polysilicon without any damage of copper gate metal. High on/off current ratio and mobility near 300cm^2/VS has been confirmed in a top-gate TFT of lateral-growth silicon by BLDA.

6. References

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