Flexible Display ; Low Temperature Processes for Plastic LCDs

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Flexible displays such as plastic-based liquid crystal displays (LCDs) and organic light-emitting diode displays (OLEDDs) have been researched and developed at KETI since 1997. The plastic film substrate is very weak to heat and pressure compared to glass substrate, that its fabrication process is limited to 110℃ and low pressure. The ITO films were deposited on the bare plastic film substrate by rf-magnetron sputtering. Moreover, in order to maintain uniform cell gap and pressure on the plastic film substrate, we utilized newly-invented jig and fabrication process. Electro-optical characteristics were better than or equivalent to those of typical glass LCDs though it is thinner, lighter-weight, and more robust than glass LCDs.

Keywords : Plastic film, LCD, ITO, Cell gap, Chip bonding

1. INTRODUCTION

There is an increasing demand for displays based on plastic film substrates due to the potential advantages of the displays using plastic film substrates, such as light weight, thinness and reduced incidence of breakage. As well, the use of plastic film substrates will enable a new product concept such as curved or flexible displays. The advantages of plastic film substrates compared to glass substrates are greater flexibility and reduced sensitivity to flaws and defects, however, plastic film substrates have considerably low thermal resistance, shrinkage problem and relatively high electrical resistance. Since the characteristics of plastic and glass substrates are quite different, it is recognized that modifications in materials, substrate handling practices and processes used in LCD fabrication are necessary to produce plastic-based LCDs.

2. PLASTIC FILM SUBSTRATES

2.1 Deposition of Indium Tin Oxide on plastic film substrate

Indium tin oxide (ITO) thin films (1000±100Å) with excellent electrical resistance, optical transmittance and etching property were deposited on a plastic film substrate by rf-magnetron sputtering. The plastic substrates were polycarbonate and polyethersulfone films with gas barrier layer and anti glare coating. The electrical resistance varied from 15Ω/θ to 30Ω/θ. Electrical resistance of ITO films on the plastic film substrate is more sensitive to oxygen contents than other deposition conditions. Transmittance is higher than 75-80% in the visible range. It is similar to that of ITO coated glass. Annealing and substrate temperature affect mainly the etching property and transmittance at short wavelength range. Fig. 1 shows the dependence of transmittance on the oxygen contents. Wet etching rate was improved by the vacuum annealing at 180℃ and 120℃ in polyethersulfone and polycarbonate substrates, respectively. In these experiments, optimum properties of plastic film substrate were obtained under 0.2% oxygen contents, vacuum annealing and substrate temperature at 180℃ for polyethersulfone material (120℃ for polycarbonate material).

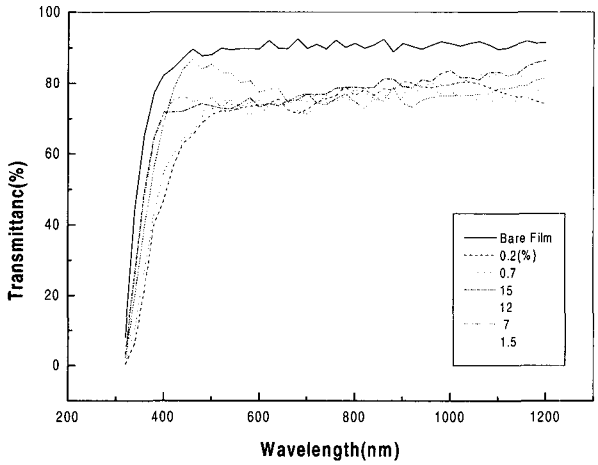

Fig. 1. Dependence of transmittance on oxygen contents.

2.2 Characteristics of plastic film substrates

To use plastic film substrates in STN (super twisted nematic) LCD, optical properties, thermal properties and mechanical properties must be considered. Since STN LCD utilizes optical birefringence phenomenon, the substrates are required to be optically isotropic and have low optical retardation and high transmission. Thermal properties of plastic film substrates are critical because high temperature applied in conventional LCD processes causes deformation and distortion of plastic substrate. These processes can also cause considerable problems such as substrate shrinkage and crack in ITO films due to the difference of thermal displacements between plastic substrate and ITO thin film. Fig. 2 shows the difference of thermal displacements between abrupt and stepped heating. It was accomplished by measuring the changes

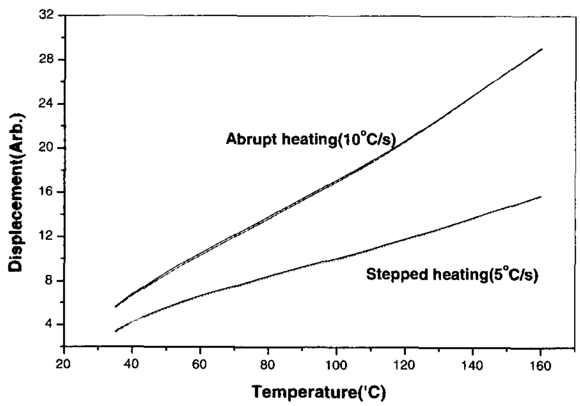

Fig. 2. Relationship between thermal displacement of substrates and heating temperature.

of substrate thickness using a dilatometer system. The difference between ITO film and plastic substrate induced distortion of the substrate and stress on the ITO film. As shown in Fig. 2, thermal displacements could be reduced by stepped heating process. The displacements of substrates with relatively abrupt heating show much steeper slopes compared to those of stepped heating substrates. The low thermal displacement induced lower stress in ITO films on the substrates. In addition to thermal resistance, it is essential that substrates have to resist variety of chemical solutions utilized in LCD process. We routinely tested for organic solvents and acids frequently used in LCD process. Table 1 shows chemical stability of the plastic film substrates. The mechanical properties of plastic and glass substrates are different and these differences underlie the advantages of plastic film substrates in portable display devices. Plastic film substrates are less brittle, more flexible and lighter than glass. On the contrary, flexibility can causes some problems in maintaining cell gap, chip bonding process and others.

Table 1. Chemical stability of plastic film substrates.

5% HCL	Stable
5% NaOH	Stable
Isopropyl alcohol	Stable
Acetone	Stable
NMP	Stable
Distilled water	Stable
γ-Butyrolactone	Stable

3. FABRICATION OF PLASTIC FILM LCD MODULE

3.1 Fabrication of the cell

Figure 3 shows the cross-sectional view of a plastic film STN LCD developed by KETI. It is a transflective cell with a transmissive polarizer, a compensation film on the top substrate and a transflective polarizer on the bottom substrate. As the substrate material we used 100 ㎛ thick polycarbonate substrate coated with 1000-1100Å ITO layer showing optical retardation of 30nm at 550nm. As described above, the surface of plastic film substrate is non-uniform and non-rigidness. It is very important to maintain flatness of the substrate surface. Because most of fabrication processes need to fix the substrate on a stage with vacuum press, conventional vacuum zone line damages the flatness of the substrate surface. It can cause problems such as grooves on plastic film substrate, which results in non-uniform coating, exposure, rubbing and etc. In order to avoid these problems, we devised a new vacuum chuck with micro vacuum holes in the fabrication process. The ITO electrode was patterned by photolithography process, LC alignment layer was printed by flexographic printing and the printed polyimide was cured in an oven at temperature below 110℃. Rubbing was done with a velvet coated roller. Because plastic film substrates have more electro-static force than glass substrates, we expected higher pre-tilt angle could be obtained with the same process condition. Fig. 4 shows the influence of substrate materials and number of rubbing process on the pre-tilt angle. In this experiment, we obtained higher pre-tilt angle with plastic film substrates than that of glass substrates by 1 ~ 2 degrees with the same process conditions.

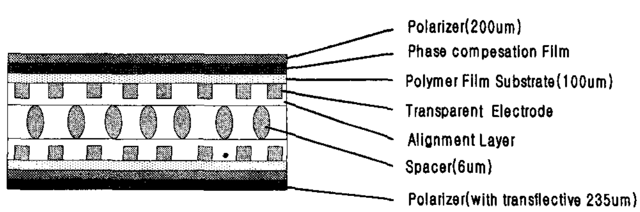

Fig. 3. Cross-section of a plastic film STN LCD.

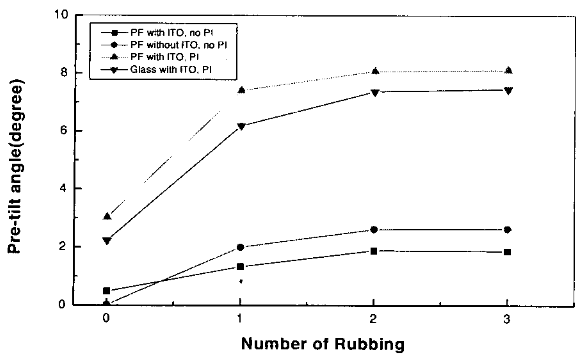

Fig. 4. Influence of substrate materials and number of rubbing process on the pre-tilt angle.

3.2 Cell gap control

Due to the non-flatness and non-rigidness of plastic film substrates, plastic film LCD requires spacers more immobile in order to maintain uniform cell gap and high mechanical stability. The spacers coated with resin were adopted in this process and cured at 100℃. Also due to the same characteristics of plastic film substrates, it is difficult to make displays having a uniform cell gap by conventional vacuum filling method. Non-flatness and flexibility of plastic film substrates form a vacant area in the cell and the spacers in this vacant area tend to move to the edge of the cell after the filling process. Hence, the area without spacers has different cell gap as shown in Fig. 5 and it results in considerable color difference. To overcome this problem, we have developed a new pressing and filling methods, which use two flat and transparent substrates as supports. These two supports fix plastic film substrates using surface tension of water or glycerin placed between the supports and plastic film substrates. We used a glass substrate as a support and this method was adopted to measure the pre-tilt angle and others.

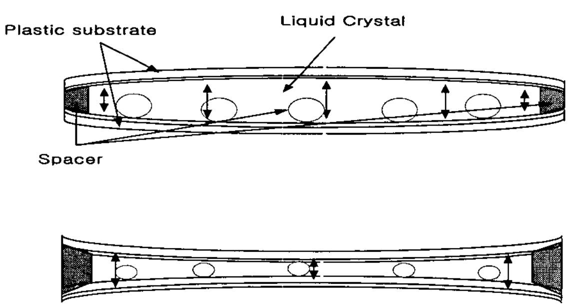

Fig. 5. Problems caused by flexibility of plastic film substrate.

The evidence of different cell gaps was obtained by measuring capacitance of a cell with patterned test electrodes. In glass substrates, the difference of cell gap was about 0.1 ~ 0.3 ㎛. In plastic film substrates the difference of cell gap was 1.5 ~ 2 ㎛ with conventional method, 0.5 ~ 0.7 ㎛ with adhesive spacers and 0.2 ~ 0.4 ㎛ with a new method and adhesive spacers. Fig. 6 shows the experimental results. With this new method, we could achieve uniform cell gap similar to that of a glass cell. The uniform cell gap was maintained after ±20° bending test using a bending test machine with down head. From this experiment, it is considered that the pressure loaded in the hot press process make the spacers to be stuck in the cell.

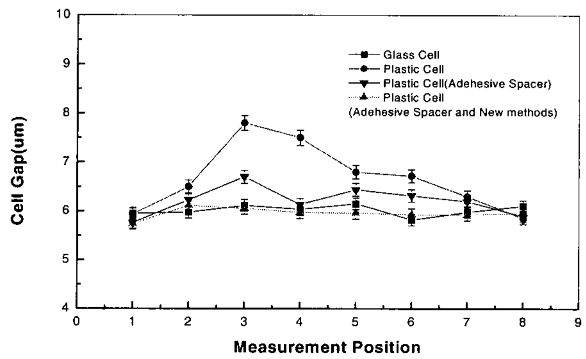

Fig. 6. Cell gap measurements.

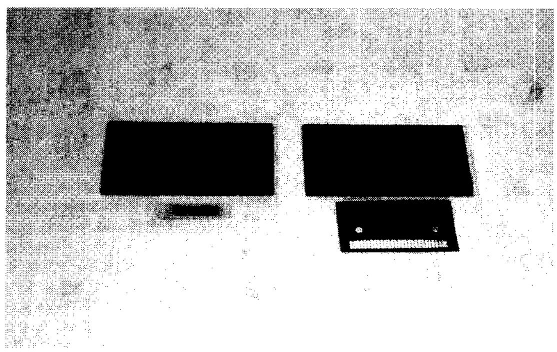

Fig. 7. Plastic film STN LCD module.

As described above, another main problem of plastic film substrates is the low thermal resistance. This flaw is critical in the process of main sealing and curing of the alignment layer. So, we used materials having low temperature curing state and optimized the curing time. Also, to minimize the shrinkage caused by abrupt heating, temperature was increased by step heating.

3.3 Chip bonding

The last process of plastic film LCD module is the interconnection of plastic film LCD to a driving circuit. The plastic film LCD was connected with a driving circuit board by thermally activated anisotropic conductive films (ACFs) with more elastic conductive particles that were developed for plastic film LCD. Fig. 7 demonstrates the transflective type plastic film STN LCD developed in this work. A new technology realizing interconnection between plastic film LCD panel and a driving circuit was developed under the new stepped processing condition of low temperature and pressure with ACFs developed for plastic film LCDs. Figure 8. shows the connection resistance of these new methods and materials. The conduction failure of interconnection of the two resulted from elasticity, low thermal resistance and high thermal expansion of plastic film substrates. Penetration of conductive particles into ITO electrode reduces the contact area and increases contact resistance. This increase of contact resistance in the worst case resulted in open circuit. In this reason, we utilized more elastic conductive particles and measured the difference of penetration depth between conventional conductive particles and more elastic ones. Conductive particles with elasticity similar to the plastic film substrate did not damage the ITO electrode on plastic film substrates, and low temperature and pressure stepped process also did not deform the surface of plastic film substrates. As a result, highly reliable interconnection with minimum contact resistance was accomplished. Through these process and newly developed methods, we successfully fabricated 2-inch plastic film STN LCD.

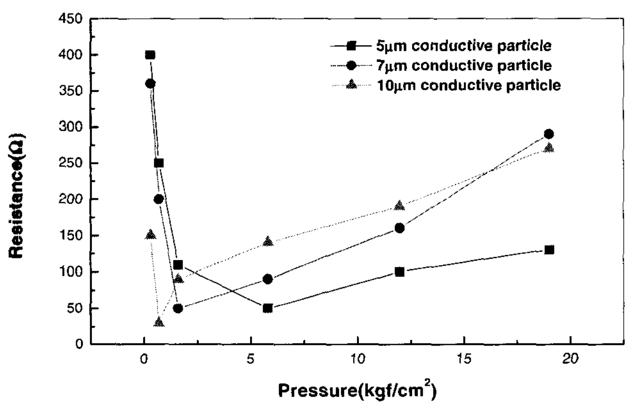

Fig. 8. Dependence of stepped loaded pressure and particle size on a connection resistance.

4. ELECTRO-OPTICAL CHARACTERISTICS AND RELIABLE TEST OF PLASTIC FILM LCD MODULE

Electro-optical characteristics of plastic film LCDs were measured by measurement equipment of LCD characteristics. The properties were better than or equivalent to those of typical glass LCDs. Response time was less than 200ms, contrast ratio was higher than 8:1 in reflective mode and viewing angle was wider than ±60°. Reliability test was accomplished in the environment and bending. Modes of environment test were temperature operating (10 cycle 200min./cycle, and -20℃~80℃), and humidity operating (RH 80%, 60℃, 120hr). Bending test was accomplished with a bending test machine at ±20°. No problems were observed in the operation and external appearance of plastic film LCDs after these tests.

5. CONCLUSION

We have demonstrated plastic film STN LCD technology which includes a new process method, and newly developed vacuum chuck and jig. The key issues of this process are low temperature stepped process and new methods to overcome flexibility and non-flatness of plastic film substrates. The electro-optical characteristics of plastic film LCD were better than or very close to those of glass LCD though its thickness was about one third and its weight was about one fifth. Considering its unique characteristics, plastic film LCD is expected to be a strong candidate in display applications for hand held electronic devices in the respects of weight and thickness.

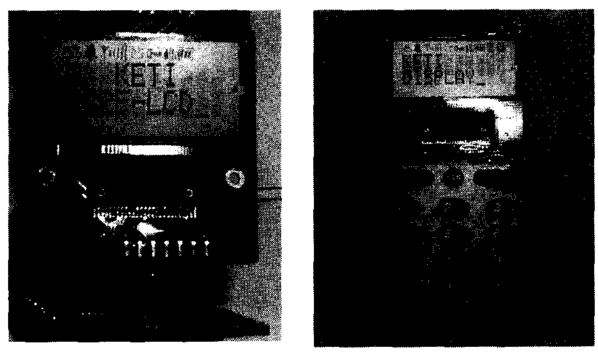

Fig. 9. Operation of 2-inch plastic film LCD developed with new methods.

FUTURE WORK

Currently active matrix displays using polymer semiconductor material as the active layer are under development. Polymer TFTs have been envisioned as a viable alternative to conventional silicon-based TFTs for future application. If the polymer TFT device can yield similar or even better performance levels to a-Si:H TFTs, the production cost of large area electronics, like flat panel displays, will be significantly reduced using roll-to-roll process. Fig. 10 shows the polymer TFT array fabricated on a polycarbonate substrate using poly (3-hexylthiophene) (P3HT) as the active layer. The P3HT layer was printed by micro-contact printing (μ-CP) method with a PDMS stamp. This printing method can be applied to roll-to-roll process and no vacuum equipments are necessary. Also, the printing process is done in room temperature condition which is a great advantage using low thermal-resistant plastic films. With this method, high performance polymer TFT device with 0.02 ~ 0.025 cm^2 / V s in saturation carrier mobility and $10^3 \sim 10^4$ in on/off current ratio was realized. From the technologies described above, plastic film LCD Fabrication and polymer TFT fabrication technologies, organic-inorganic hybrid AMLCDs and full-organic AMLCDs are now under development.

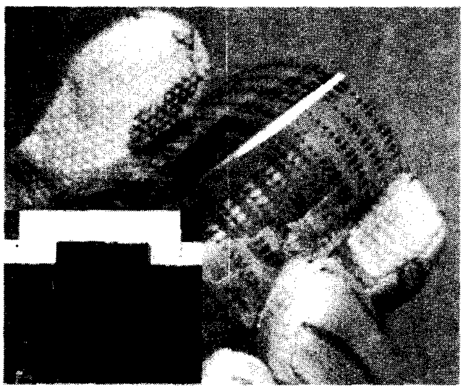

Fig. 10. Photographs of fabricated P3HT TFT device. (inset) and arrays on a polycarbonate substrate.

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