Tight adhesion of plastic substrates for cell gap stability in flexible LCDs

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Abstract
We developed tight adhesion techniques of two plastic substrates to maintain cell gap stability for rugged flexible LCDs. By combining rigid spacers and several adhesion materials, we demonstrated mechanically very stable flexible LCDs against pressure and bending.

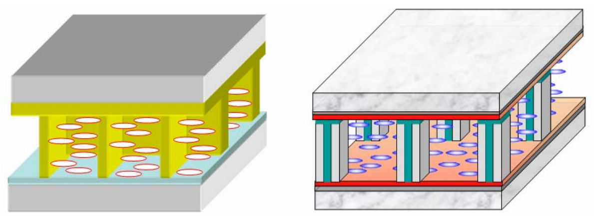
1. Introduction

Conventional liquid crystal (LC) electro-optical (EO) devices, such as flat panel displays, are prepared by sandwiching the LC between two glass substrates coated with transparent indium-tin-oxide (ITO) electrode pattern with an overlay of rubbed polymer alignment layer to facilitate alignment of the LC's optical axis in a predetermined configuration. One of primary role of the substrates is to support LC molecular orientation and shield it from external influences such as mechanical bending or compression, which alter the thickness of the LC layer and arrangement of LC molecules in a manner that is detrimental to optical properties and performance of such devices.

Recently, flexible displays have been widely and extensively studied for the purpose of use in applications such as smart cards, PDA, and head mount displays because of their lighter weight, thinner packaging, flexibility, and reduced manufacturing cost through continuous roll processing. Among various kinds of flexible displays, plastic LCDs have advantages in their efficient light-control capabilities with low power consumption[1-4]. However, there exist basic obstacles in fabrication as well as operation of plastic LCDs due to the flexibility of substrates. One is mechanical instability of LC molecules, and the other is adhesion of two substrates because flexible displays always experience bending and folding stress[5].

In order to overcome the above problems, we have proposed pixel-isolated LC (PILC) mode by photo-polymerization induced phase separation from LCs and pre-polymer composite material[6,7]. Although the LC molecules in this mode are well confined inside pixel and shows good mechanical stabilities, LC alignment can not be free since rubbing is possible only for one substrate. To achieve various kind of LC operating mode, it is required to control the LC alignment from both substrates. In order to solve the problem, we proposed adhesion techniques using rigid spacers to give mechanical as well as bending stabilities for rugged flexible displays as shown in Fig. 1. The easiest way to bond two sheets of plastics is using epoxy as a bonding material. In order to do that, the adhesive materials were typically placed on top of rigid spacers before assembling process. However, the epoxy infiltrate into the pixel due to the low viscosity of adhesive material. Therefore, we have to prevent the leakage of bonding materials into the pixel, because the leaking epoxy will degrade LC alignment in the pixel area and reduce the EO performance of LCDs.

In this presentation, we proposed new adhesion techniques to prevent the leakage of epoxy as well as provide mechanical stability



(a) **(b)**

Fig. 1 Schematic diagrams of cell structures with (a) PILC mode and (b) proposed technique with rigid spacers

2. PILC structure with agarose composite

First of all, we used composite bonding materials of UV curable epoxy and agarose. Agarose is a natural colloid extracted from sea weed and used to make gels. Since agarose gels have large pore size, we used as a container of epoxy to prevent leakage. At first, we fabricated microstructures on one plastic substrate using stamping method. The microstructures maintain cell gap and isolate LCs. The used agarose is high-gel-strength type (gel point (1.5%):36.0^{O}C±1.5^{O}C, remelting point (1.5%):88.0^{O}C ±1.5^{O}C, gel strength(1%)≥ 1200 gm/cm^2, gel strength (1.5%) ≥ 2500gm/cm^2, and moisture < 7%). SK-9 (Summer Optical) is used as a bonding epoxy. We added EDTA (ethylene diamimetetraacetic) to the mixture of distilled water and agarose of powder. The EDTA helps bonding polymer being scattered well. The initial muddy mixture is changed to the clear state at the temperature of 150^{O}C. We spin-coated at the 6500 rpm during 50sec on the substrate after the mixture cooled down until 60^{O}C. Owing to the transition between gel- and liquid-state of viscosity as temperature, we can easily fabricate without flooding or infiltration of bonding material.

Fig. 2 shows schematic illustration of sample fabrication process. The alignment layer was spin-coated followed by rubbing. We used the micro-contact printing method in order to place the composite materials of epoxy and agarose on microstructures. We dropped LCs on microstructure and laminate with plastic substrate. For tight adhesion of two substrates, we exposed UV for polymerization of epoxy.

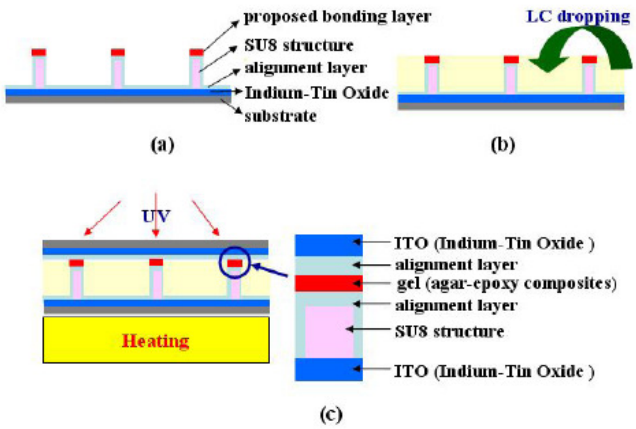
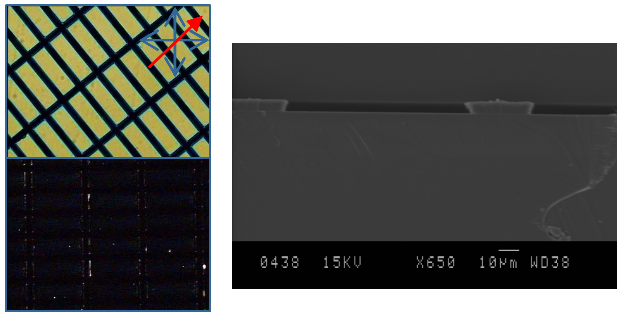


Fig. 2 Schematic illustration of fabrication process. (a) preparing bonding layer on microstructures with a micro-contact method, (b) dropping LC, and (c) curing of bonding material using UV light.

Fig. 3 shows the optical microscopic images of the sample at white and dark states and cross sectional SEM image. We found that slight light leakages from the boundary of microstructures. It may due to the miss alignment of LCs by the morphology of microstructures. And it is very clear that the top and bottom substrates are tightly bonding each other and no leakages of epoxy.



(a) **(b)**

Fig. 3 (a) Microscopic and (b) SEM images of the fabricated sample.

3. Modification of rigid spacers

As we mentioned above, the rigid spacers with epoxy only will leak epoxy into the pixel when we laminate plastic substrate. In order to prevent the leakage, we need new type of rigid spacers. We designed rigid spacers with 4 column pillars[8] which isolate epoxy by capillary action. We used two kinds of adhesive materials. One is UV curable epoxy and the other is thermally curable epoxy.

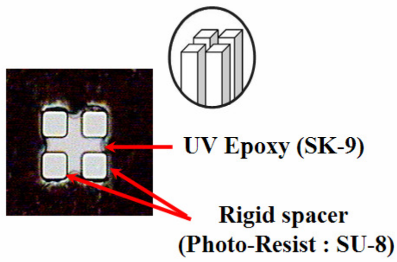


Fig. 4 Microscopic images of bonding structure with UV curable epoxy and multicolumn rigid spacers

The UV curable epoxy SK-9 was placed on rigid spacers using micro-printing method. Fig. 4 shows the optical microscopic image of rigid spacers after assembling. As we expected, the SK-9 is well confined inside the multicolumn structure. From the result, we found that the modification of rigid spacers is prevented effectively the leakage of epoxy even without mixing with other materials. However, since the rigid spacers are placed under black matrix, it is not possible to expose UV light. In order to solve the problem, we used thermally curable epoxy instead of UV curable epoxy. We used NOA83H (Norland Co.) as thermally curable epoxy. Since the material has large flow viscosity which makes it difficult to process using micro-contact method or spin casting, we used THF(Tetrahydrofuran) as a solvent with different weigh ratio.

As a plastic substrate, ITO-coated PES films were used in our experiment. Both of the ITO-coated PES substrates were spin-coated with a homogeneous alignment layer and unidirectionally rubbed. The multicolumn rigid spacers of SU-8 were formed on one of the substrate. The mixture of NOA83H and THF solution was transferred to rigid spacers using micro-printing method. We prebaked the sample for the evaporation of solvent. Fig. 5 shows the schematic illustration of preparing rigid spacers with epoxy by micro-contact printing. The fabrication process is the same as Fig.2 except thermal curing after assembling.

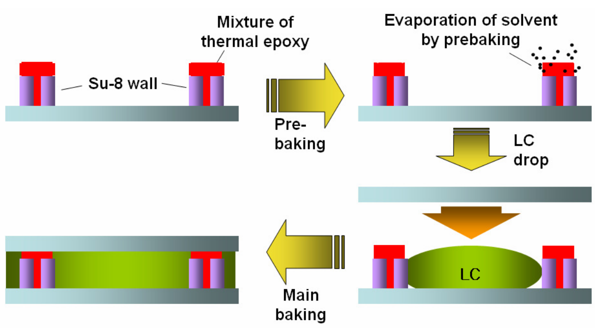


Fig . 5 Schematic illustration of fabrication of flexible LCD using thermal curable adhesive.

Fig. 6 shows microscopic and SEM images of bonding structures with different conditions. In the process, prebaking condition is affected on the bonding structure profoundly. We used two different prebaking conditions; one is performed at the temperature of 67^{O}C during 30 minutes (Fig. 6(a)) and the other is 80^{O}C during 20 minutes (Fig. 6(b)). For the condition (a), the viscosity of bonding mixture is as low as to flow inside the multicolumn structure by capillary effect. Whereas for condition (b), the solvent evaporated fast enough to remain epoxy on the rigid spacers. Moreover, the epoxy at high temperature may start solidification which increases the viscosity as enough as preventing the leakage of epoxy. It means that we can use single column rigid spacer if we control carefully the temperature condition.

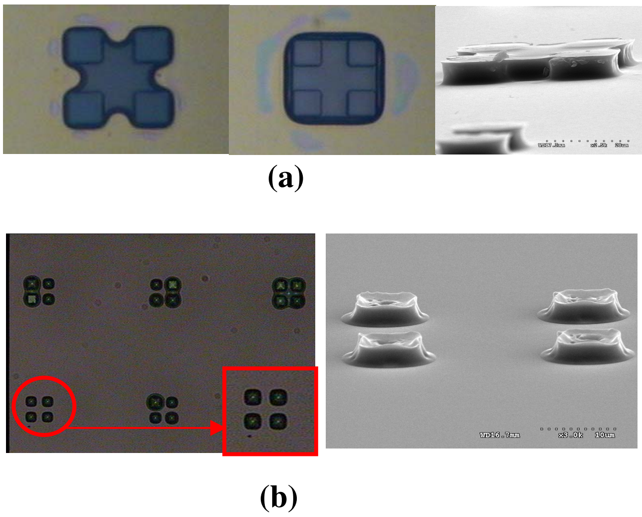


Fig. 6 Optical and SEM images of bonding structure after curing.

4. Mechanical stability

We tested mechanical stability of plastic LCDs fabricated with multi-column rigid spacers. We prepared two kinds of plastic LCDs samples. One is normal sample where the cell gap is maintained by conventional ball spacers. The other is plastic LCD sample using multi-column rigid spacer with epoxy. We can see clearly stabilities against point pressure using sharp tip for two samples as shown in Fig. 7. In normal sample, LC alignment is severely distorted due to cell gap instability and the distortion propagate to the bulk LC. On the other hand, the rigid spacers keep the LC alignment well against external pressure.

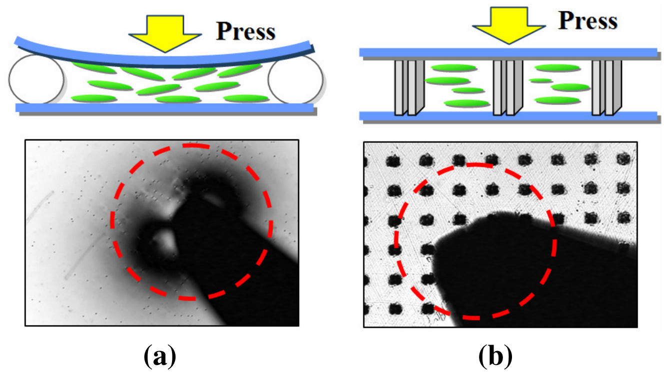


Fig. 7 Test of mechanical stability of plastic LCD samples (a) without and (b) with rigid spacers.

We also measured the EO characteristics of plastic LCD sample under external bending stress. As previously reported[9], the V-T (voltage-transmittance) curve of normal plastic sample under bending stress deformed significantly due to by instability of LC alignment and cell gap variation. Fig. 8 shows the V-T curve of our plastic LCD sample with rigid spacers under bending and exhibit almost same behavior as pixel isolated LC mode. It means that the LC alignment is maintained under bending stress which is one of the key requirements for flexible LCDs.

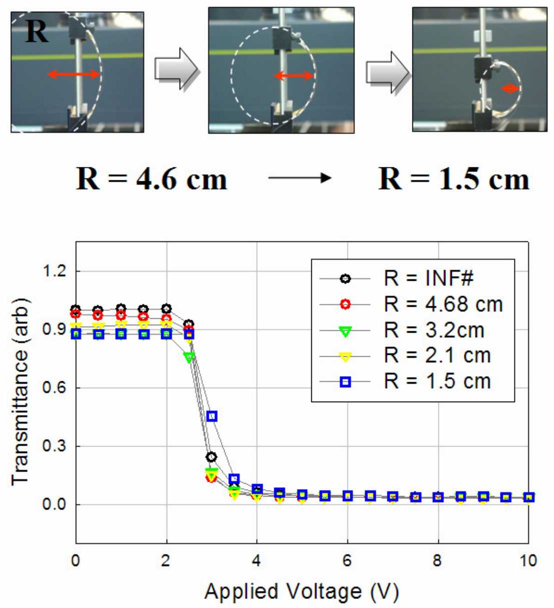


Fig. 8 V-T characteristics of plastic sample with rigid spacers under bending stress.

Fig. 9 shows the prototype of 3-inch sized plastic LCDs. Even with severe bending, the plastic LCDs working very well.

Fig. 9 3-inch size of plastic LCD sample.

5. Concluding Remarks

In summary, we have demonstrated tight adhesion technologies for rugged flexible LCDs. For the tight adhesion of two plastic substrates, we used composite materials of epoxy as a bonding material and agarose as a container. The composite materials show good adhesion and prevent the leakage of epoxy. In other approach, we modified rigid spacers with epoxy. It shows very good mechanical stability against pressure and bending. Since the rigid spacer technology is already used in conventional LCD with glass substrates, our proposed technology can be easily applied to the LCDs with plastic substrates. Moreover, the fabrication process can be easily applicable to roll-to-roll process. We believe that our adhesion technology as well as supporting structures can be one of promising technologies in the fabrication of flexible LCDs.

6. Acknowledgements

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7. References

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