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Nucleation of the pi-cell operating state: a comparison of techniques

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It is well known that the operating state (e.g. bend or V state) of a pi-cell must be nucleated prior to operation. For direct view liquid crystal display applications, such as direct view TV, low voltage nucleation of the operating state is necessary. A brief description of existing nucleation techniques is presented, followed by a detailed consideration of three low voltage nucleation techniques. The concept behind these techniques and their observed performance is described. Possible areas for further work are included.

1. Introduction

In standard pi-cell configurations, the operating state (referred to as the bend or V state) is not the global energy minimum state at 0 V, instead it is the non-operating state (the splayed or H state) that is the global energy minimum at 0 V [1–4]. At voltages greater than the stability voltage, ie. the voltage at which the Gibbs free energy of the splay state equals that of the bend state. (V_{st}) the bend state becomes the global energy minimum state. The bend and splay states are topologically distinct from each other. The bend state must therefore be nucleated prior to operation, i.e. the bend state must be initiated (creation of $S = \pm \frac{1}{2}$ disclinations) and grown (movement of disclination) under the application of a voltage until the splayed state is fully removed. If the splay state is not fully removed, it will return once the voltage is reduced below V_{st}. Several routes to nucleate the bend state in a pi-cell or to overcome the need for nucleation have already been described in the literature:

(1) Voltage nucleation and stabilization [5, 6]. This method utilizes a (high) voltage (>10 V) to nucleate the bend state. Although a suitable method for many LCD applications, the high voltages are not compatible with TFT-drivers used in direct view LCD application.

(2) Spacer nucleation [7, 8]. Cooling the device from the isotropic phase to the nematic phase under an applied voltage provides (by adsorption) an anisotropic structure around the spacers. Upon application of a voltage, these spacers are able to nucleate the bend state, and in the absence of a voltage have been observed to stabilize the bend state. Ideally, the spacers should be positioned outside the active pixel aperture to prevent reduction of the contrast ratio of the display.

(3) Network polymerization [9–11]. A method to prevent the return of the splay state at low voltages, which eliminate any need for re-nucleation, consists of nucleating the bend state via a high voltage and then stabilizing it by the polymerization of a network under this voltage condition. Although a useful technique, it does not overcome the initial high voltages requirement while the *in situ* polymerization can lead to ionic contamination [12] and possible image sticking.

(4) High surface tilts [13–15]. High surface tilts can stabilize the bend state at 0 V. However at these high surface tilts the performance of the device is significantly affected; for example, at high surface tilts relaxation times are increased and electro-optic modulation is reduced.

(5) Twist state [16]. Chiral doping the liquid crystal (LC) to a thickness-to-pitch ratio (*d*/*p*) greater than 0.25 stabilizes a 180° twist state. The utilization of a twisted configuration eliminates the requirement for nucleation of the bend state, as the 180° twist state adopts a configuration similar to the bend state at high voltages. However, at low voltages the twisted configuration significantly affects the voltage–transmission

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curve, limiting the switchable range to higher voltages. Alternative methods of driving this mode, e.g. dynamic driving [17], may overcome the effects of the twist configuration at low voltages but these need further investigation.

2. Nucleation

Three nucleation techniques are now considered, these attempt to achieve low voltage nucleation of the bend state (i.e. TFT compatible nucleation techniques) by stabilizing within predetermined 'nucleation' regions a bend state, or a state topologically equivalent to the bend state at 0 V (for clarity any state topologically equivalent to the bend state is here referred to as the 'bend state'). Outside these nucleation regions, the splay state remains the energetically favourable state at 0 V. The coexistence of the splay and bend states at 0 V ensures the presence of the $S = \pm ½$ disclination at 0 V. This means that high voltages are no longer required as the voltage need only be greater than the stability voltage (V_{st}) for the bend state domain to grow [15], e.g. $V > 1.5$ V. Positioning the nucleation regions within the inter-pixel gaps means the active pixel regions retain the performance that make the pi-cell a desirable mode for LCD applications, e.g. optical modulation and response times. The three nucleation techniques considered are: (1) HAN nucleation, (2) thickness-to-pitch (*d*/*p*) nucleation, (3) LVAA nucleation.

3. HAN nucleation

This nucleation technique consists of patterning the surface tilt (zenithal alignment orientation) to stabilize a bend state within defined nucleation regions at 0 V. The technique is viable, as high surface tilts are known to stabilize the bend state at 0 V [15]. Importantly, high surface tilt (homeotropic) on only one surface, a hybrid-aligned-nematic (HAN) configuration, has been found effective [18]. A schematic diagram of a HAN nucleation region adjacent to an active area is shown in figure 1.

Figure 2 shows a test sample consisting of 30 × 30 μm^2 HAN nucleation regions spaced 300 μm apart. The 5 μm cell gap is filled with LC E7 (Merck Ltd). On application of a voltage greater than 1.6 V across the LC layer, the bend state domain grows from the nucleation regions; figure 2 shows the bend state domains growing on application of 2 V. It was observed that in some instances the disclination became pinned at the alignment surface, in such cases the removal and reapplication of the voltage successfully unpinned the disclination.

The LC mixture E7 is well characterized and widely used in research; however, it is unsuitable for active matrix addressing. Therefore the HAN nucleation technique was re-investigated using the LC mixture ZLI 6000-100 (Merck Ltd); successful nucleation was again observed. Figure 3 is a sequence of photographs showing the bend state nucleating from 200 μm wide HAN nucleation strips spaced 200 μm apart.

Successful nucleation of the bend state via the HAN technique has been observed in different cell gaps (range investigated 2–10 μm) and for different nucleation region widths (range investigated 30–300 μm). Successful nucleation has also been observed over a range of temperatures (−5 to 60°C). However, it has been found that at high temperatures (typically within ~20°C of the LC clearing point) the domain boundary (disclination) sometimes becomes pinned and fails to grow on application of a voltage. The increased occurrence of domain growth failure at higher temperatures has yet to be understood, however it is suspected to be due to the particular alignment layers used in this HAN nucleation technique investigation. The HAN nucleation technique has been found to be a robust nucleation technique working effectively over

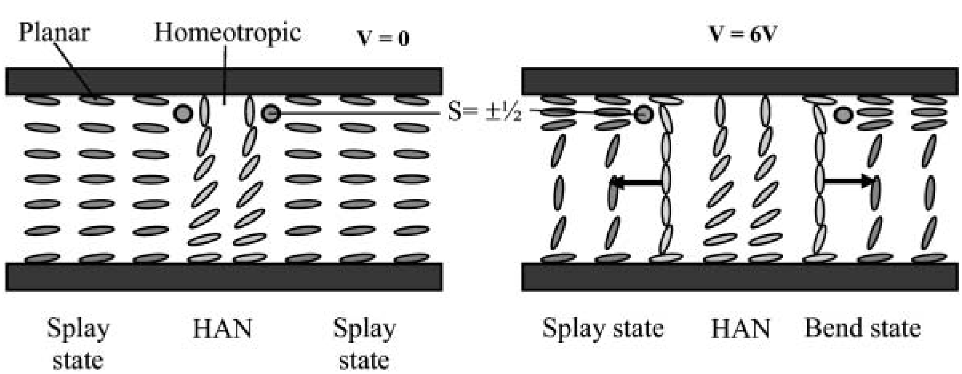

Figure 1. Schematic representation of the HAN nucleation technique. One surface has a patterned planar–homeotropic alignment. At 0 V, the splay state (red) and HAN state (yellow) coexist, on application of a suitable voltage the bend state (green) domain grows.

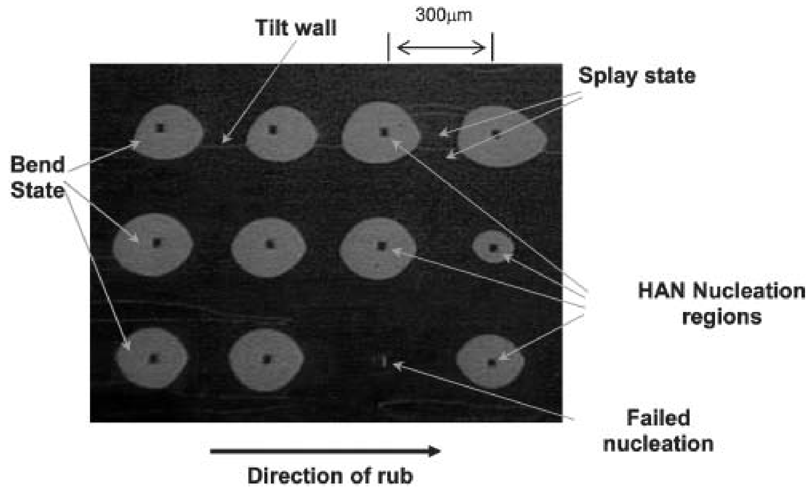

Figure 2. Photograph showing nucleation of the bend state from $30 \times 30\,\mu m^2$ HAN square nucleation regions on application of 2 V. The cell gap is 5 μm, filled with E7; surface tilt within the active region is 12°. Observe the presence of tilt walls within the splay state.

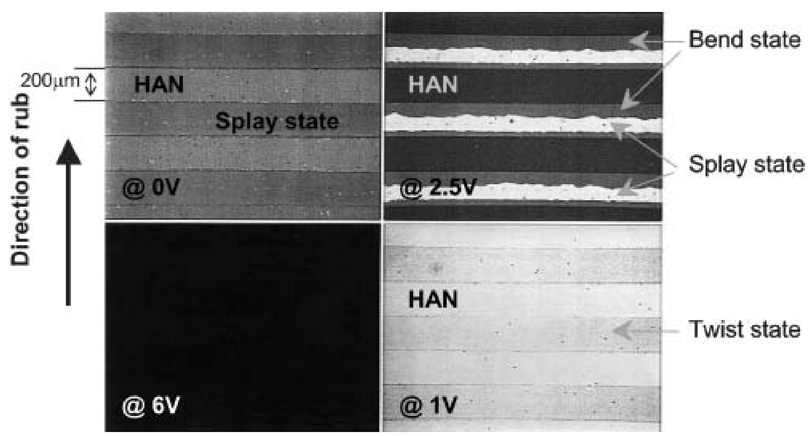

Figure 3. Photomicrographs (in sequence) showing nucleation of the bend state from the 200 μm wide HAN nucleation regions at various voltages. The cell gap is 4.7 μm (filled with LC ZLI 6000-100) and the surface tilt in the parallel aligned region is 8°. The bend state is fully nucleated in the 6 V photomicrographs. At 1 V the bend state relaxes to the twist state.

a range of conditions, with the exception of high temperatures. This nucleation technique is considered applicable to direct view pi-cell LCDs.

Ishihara *et al*. [19] and Tsuboyama *et al*. [20] have also investigated the use of high surface tilts within a pi-cell. Ishihara *et al*. utilize a phase separation method to obtain a mixture of planar and homeotropic alignment within a pi-cell. This technique provides regions of planar and homeotropic alignment randomly distributed over both the pixel and inter-pixel gap, detrimentally affecting the performance (response times and contrast ratio) of the pi-cell device. Alternatively, Tsuboyama *et al*. introduce high surface tilt within a region surrounding the pixel region intended to stabilize the twist (bend) state at 0 V within the pixel region. Additionally, Nagae *et al*. have more recently presented a similar high surface tilt nucleation concept [21].

4. Thickness-to-pitch (*d*/*p*) nucleation

This nucleation technique utilizes the principle that for $d/p>0.25$ the 180° twist state is stable at 0 V [16], and therefore nucleation becomes unnecessary. However, the detrimental effects associated with $d/p>0.25$ make it desirable to find routes substantially to reduce the d/p in the active pixel regions. A loss of maximum brightness associated with $d/p\neq 0$, especially $d/p>0.25$, means a trade-off between response time and brighter (thicker) cells due to the inherent twist. A nucleation technique with differing LC layer thickness (cell gap) between the active (d_{ACT}) and nucleation regions

(d_{NUC}), (more specifically, $d_{ACT} < d_{NUC}$ where $d_{NUC}/p > 0.25$ [22]) is considered in figure 4. Ideally, the d/p within the active area (d_{ACT}) is made as low as possible to reduce the detrimental effect of d/p on the performance of the pi-cell LCD. This configuration establishes an $S = \pm ½$ disclination at 0 V so that low voltage nucleation is obtained. An advantage of $d/p > 0$ in the active region is that the splay state takes longer to regrow at 0 V.

Methods to obtain a variation in cell gap will depend on the type of LCD. In the case of reflective active matrix LCDs for projection or helmet mounted display applications, the via-hole structures already present could be used; this is a small hole or gap in the insulator of a reflective display through which the TFT is connected to the pixel electrode. However, in conventional transmissive direct view LCDs it would be necessary to fabricate the step structures. The microphotograph in figure 5 shows successful low voltage nucleation with voltages as low as 2 V. The LC used was E7 doped with chiral dopant R1011 (Merck Ltd) and the surface tilt was 5°. The cell gaps were $d_{NUC} = 6\,\mu m$ and $d_{ACT} = 4\,\mu m$, corresponding to a d/p of ~ 0.17 within the active region and a $d/p = 0.26$ within the nucleation region. The thickness-to-pitch nucleation technique has been demonstrated and provides a viable option for LCDs with intrinsic cell gap variations, e.g. via holes and rough reflectors [23].

5. Lateral variation in azimuthal alignment (LVAA) nucleation

This nucleation technique involves nucleation regions whose azimuthal alignment orientation is different from that within the active regions, such that within the nucleation regions a state topologically equivalent to a bend state is stabilized at 0 V [24]. The alignment within the active regions supports a splay state at 0 V.

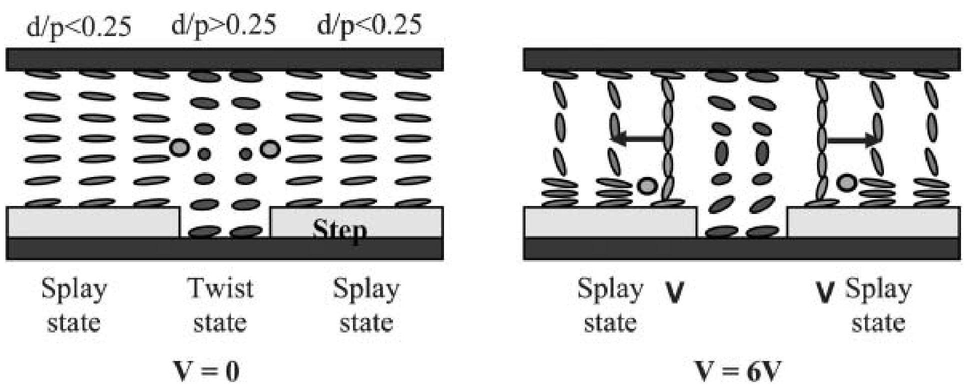

Figure 4. Schematic representation of the thickness-to-pitch nucleation technique. At 0 V, the splay state (red) and twist state (blue) co-exist, so that the bend state (green) grows on application of a suitable voltage.

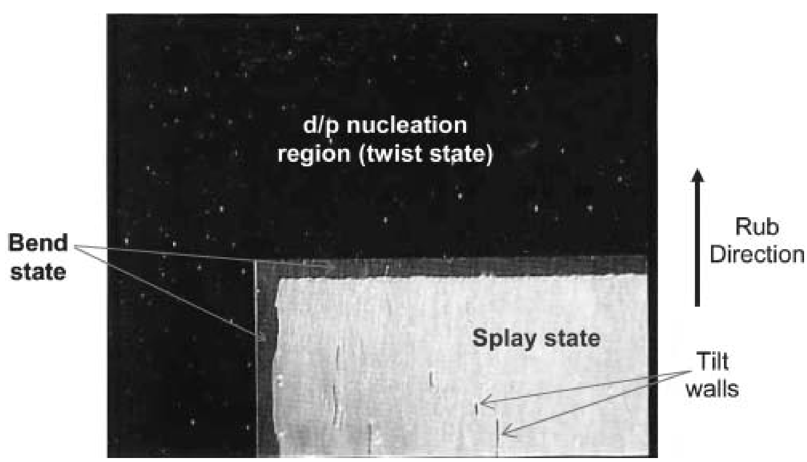

Figure 5. Photomicrograph (×5 objective) of d/p nucleation test cell under applied voltage. The test cell is positioned between crossed polarizers, with its alignment direction parallel to one of the transmission axes of the polarizers. The bend state domain is seen growing from the twist state nucleation region.

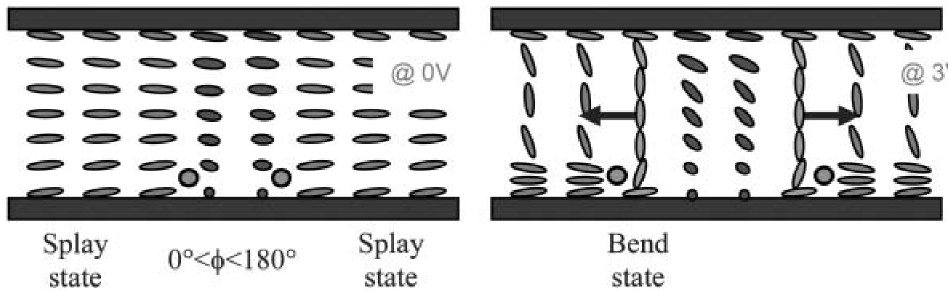

Figure 6. Schematic representation of the LVAA nucleation technique. At 0 V, the splay state (red) and twist state (blue) co-exist, so that the bend state (green) grows on application of a suitable low voltage.

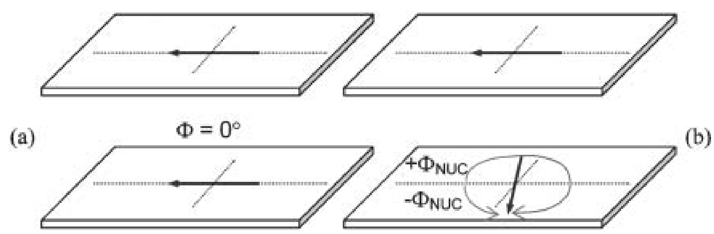

Figure 7. Schematic representations of example orientation angles with respect to the rubbing direction in a pi-cell: (*a*) active area $\Phi = 0°$ and (*b*) nucleation area Φ_{NUC}.

Figures 6 and 7 show schematically the concept behind this nucleation technique.

The azimuthal orientation (Φ) between the top and bottom substrates within the active regions is 0°, i.e. parallel alignment. Clearly, for $\Phi = 0°$ and $d/p = 0$ the splay state is the energetically preferred state at 0 V. From energy considerations (surface tilt $\cong 0°$) the azimuthal orientation within the nucleation regions (Φ_{NUC}) required to stabilize a bend state at 0 V can be determined for various d/p by satisfying the expressions (1) and (2):

$$\left(\frac{\Phi_{NUC}}{360} + 0.25\right) < \frac{d}{p} < \left(\frac{\Phi_{NUC}}{360} + 0.75\right) \quad (1)$$

$$\left(\frac{\Phi_{NUC}}{360} - 0.75\right) < \frac{d}{p} < \left(\frac{\Phi_{NUC}}{360} - 0.25\right) \quad (2)$$

where Φ_{NUC} is the angle between the alignment orientation on the top and bottom substrates within the LVAA nucleation region, see figure 7.

Expressions (1) and (2) are used to determine the range of orientation angles Φ_{NUC} that provide a bend state for $d/p < |0.25|$. Figure 8 summarizes the range of orientation angles Φ_{NUC} suitable for nucleation of the bend state for a $d/p < |0.25|$, specific examples are listed in table 1. From these it can be seen that there are many possible configurations, some of which require a small amount of chiral dopant (i.e. $d/p \neq 0$) to bias the

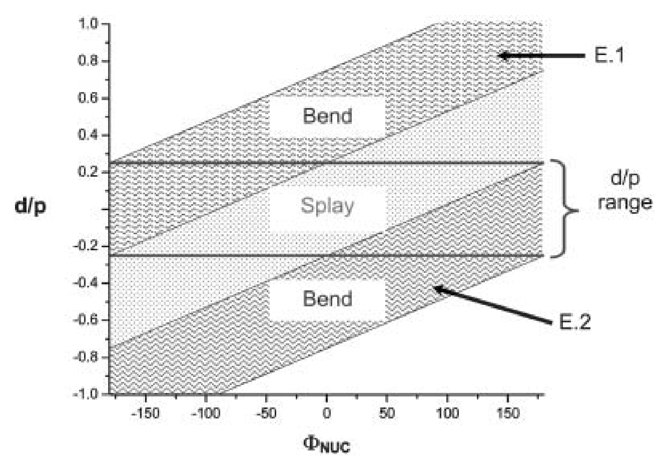

Figure 8. Range of angles (Φ_{NUC}) and d/p values that stabilize a bend state at 0 V based on expressions (1) and (2).

Table 1. Example of the ranges for d/p and Φ_{NUC} that stabilize a bend state.

d/p	Minimum Φ_{NUC} (1)	Maximum Φ_{NUC} (1)	Minimum Φ_{NUC} (2)	Maximum Φ_{NUC} (2)
0.2	−198	−18	162	342
0.1	−234	−54	126	306
0	−270	−90	90	270
−0.1	−306	−126	54	234
−0.2	−342	−162	18	198

direction of twist or to support a twist greater than 90°. Expressions (1) and (2) have assumed zero surface tilt, in practice the Φ_{NUC}–d/p range is slightly modified by the surface tilt and LC used.

A range of configurations in which one of the alignment layers remains uniform (homogeneous), while the other is patterned, was fabricated and tested. Table 2 summarizes the range of Φ_{NUC} angles investigated and whether a splay or bend configuration was stable within the nucleation region at 0 V. The test cells consisted of 6 μm cell gaps with surface tilts of 7.5°, filled with the LC E7 either non-doped or chirally doped with S811 or R811 (Merck Ltd.). Table 2 summarizes the observation or not of low voltage nucleation.

Successful nucleation of the bend state was expected for all test cells in which the bend state was stable within the nucleation region at 0 V (by selecting the direction of alignment Φ_{NUC}, the direction of twist and the chiral dopant concentration added to the LC), with particular interest in cases with $d/p \ll |0.25|$. The experimental results confirmed that Φ_{NUC} in the range of 0° to ~94° agreed with the assumption that low voltage nucleation would be obtained when a bend state is stable within the LVAA nucleation region at 0 V. Examples of successful low voltage nucleation are shown in figures 9 and 10. In contrast, nucleation was observed in none of the test cells with Φ_{NUC} in the range ~95° to 180°, even though the bend state was stable within the nucleation region at 0 V. This observation contradicts the notion that nucleation is aided by incorporating a nucleation region with antiparallel alignment [25]. Although initially surprising, consideration of the director configurations within these test cells provides a possible explanation: large Φ_{NUC} values have director configurations in which the $S = \pm ½$ defect occurs within the proximity of the surface discontinuity, increasing the likelihood of the surface discontinuity pinning the defect. Conversely, small Φ_{NUC} values have director configurations in which the $S = \pm ½$ defect occurs within the bulk of the LC layer and hence the defect is less likely to become pinned by the surface discontinuity. This could be investigated numerically by solving the Beris–Edwards (tensor order parameter) formulation of nematohydrodynamics in two or three dimensions, building upon the work of Denniston *et al.* [26, 27].

Table 2. Example of the range of LVAA configurations fabricated and tested. The symbols (√) and (×) indicate whether low voltage nucleation of the bend state is obtained or not; S and B indicate whether a splay or bend state is stable within the nucleation region at Φ V.

Φ_{NUC}/°	−0.20	−0.17	−0.05	0	0.06	0.16	0.21
180	B ×	B ×	B ×	B ×	B ×	B ×	B ×
141.5	B ×	B ×	B ×	B ×	B ×	S ×	S ×
122	B ×	B ×	B ×	B ×	B ×	S ×	S ×
93.5	B √	B √	B √	B √	S ×	S ×	S ×
76	B √	B √	B √	S ×	S ×	S ×	S ×
72	B √	B √	B √	S ×	S ×	S ×	S ×
48	B √	B √	S ×	S ×	S ×	S ×	S ×

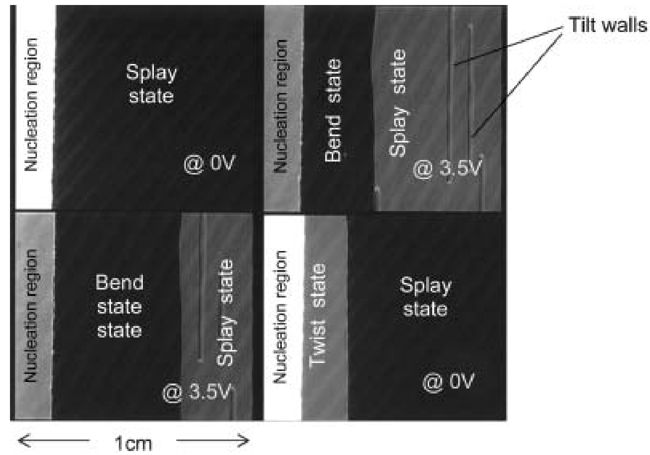

Figure 9. Photomicrograph (×100) sequence of nucleation of the bend state on application and removal of a voltage from a LVAA nucleation region. Test cell: cell gap = 6 μm, LC E7 doped with S811, $d/p = -0.06$ and $\Phi_{NUC} = 72°$.

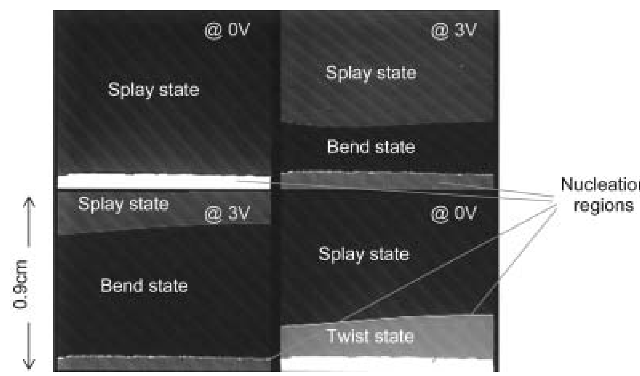

Figure 10. Sequence of the observed nucleation of the bend state on application and removal of a voltage from a LVAA nucleation region. Test cell: cell gap = 6 μm, LC E7 doped with S811, $d/p = -0.06$ and $\Phi_{NUC} = 81°$.

When considering applicability to display manufacture the results shown in table 2 are very positive; the LVAA nucleation technique is shown to provide low voltage nucleation for various configurations including those with $d/p = 0$, minimizing or avoiding the loss of brightness or addressing modifications associated with high d/p. A limited investigation of this novel LVAA nucleation technique has been repeated by researchers at Tohoku University [28, 29].

6. Summary

Three nucleation techniques for obtaining low voltage transition to the bend state in pi-cells have been considered. Experimental investigation of all three techniques demonstrated successful low voltage nucleation. Each of the nucleation techniques has its merits and design versatility, allowing the selection of a suitable nucleation technique for a specific LCD device structure and application under consideration. The HAN nucleation technique appears to be robust, working effectively over a range of conditions. The *d*/*p* nucleation technique may be suitable for devices with intrinsic cell gap variation. The LVAA nucleation technique offers many configurations, which can be obtained via conventional low tilt alignment layers readily available. Methods for patterning the azimuthal alignment direction exist, as developed for multi-domain for improved viewing angle of LCDs.

Suggested future work includes the investigation of defect and surface discontinuities in the LVAA nucleation technique by solving the Beris–Edwards (tensor order parameter) formulation of nematohydrodynamics in two or three dimensions. Additionally, the nucleation concept could be applicable to other devices in which the operating state is different from the initial 0 V state; e.g. the high tilt splay–bend mode [30, 31] and reverse doped TN mode [32].

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