

Recent Patents on Liquid Crystal Alignment

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Abstract: The fabrication of liquid crystal devices requires a reproducible and accurate method of aligning the LC on the surface of the electrodes. Rubbed polyimide surfaces have been successfully employed but suffer disadvantages. Recent developments in technology have seen new methods based on ion and plasma bombardment, UV exposure and electron irradiation. In addition, there has been much activity in achieving LC alignment through doping of the LC itself with suitable agents. Here, we review the recent developments in LC alignment technology and the patent literature in this area.

Keywords: Liquid crystal, homeotropic, nematic, vertical alignment, pre-tilt angle.

INTRODUCTION

Liquid crystal displays (LCDs) have developed into one of the most dominant information display devices in the marketplace and are common place in most portable electronic equipment, large display systems, photonic devices etc. In the area of flat panel displays for home entertainment, LCDs continue to develop and evolve. Up until 2003 the market for direct view flat panel televisions was segmented clearly with LCD sets available only to a maximum size of 30 inches whereas plasma display panels (PDP) were available up to 61 inches. The markets are now converging as LCD TVs grow larger and reduce the cost advantage of PDP. PDP remain the choice for sets larger than 45 inches (maximum size is now 103 inches), while LCD TVs are rapidly replacing cathode ray tube (CRT) sets smaller than 35 inches and 108 inch LCD sets are now available. The predicted global revenue for large-sized LCD panels (10 inches and greater) in 2007 is \$66 Bn and by 2011 will exceed \$100 Bn [1].

CRT TVs are still the largest market worldwide, but LCD and PDP are expected to eventually become dominant. However, rear-projection TVs, an alternative to the flat-panel LCD and plasma sets, are expected to survive through new lighting technologies, such as electrode-less lamps, light-emitting diodes (LEDs), and lasers. Other potentially competitive technologies include Organic Light Emitting Diodes (OLED). OLED is a wafer-thin, super bright technology that employs light-producing polymers instead of backlit liquid crystals.

PDP and LCD are therefore the two major technologies in flat panel display and both incorporate fixed matrix technologies but produce images by different methods. Currently, PDP has advantages in the areas of (a) larger screen sizes, (b) more accurate image reproduction, colour accuracy, contrast and brightness, (c) ability to display fast moving images without motion artefacts. LCD relies on matrix switches which typically have a switching time of the order of 1/30 sec and leaves image trails on the screen. There is an intense research and development effort in LCD

technology to address these drawbacks, and if sufficiently successful will see increasing dominance of LCD in the marketplace.

Liquid Crystal Displays (LCDs) are then, developing into the major technology for information display and Flat Panel Display (FDP) technology. Increasingly LCDs are replacing CRT monitors and finding many applications in mobile instruments. From an historical perspective, RCA invented the first LCD and a patent was applied for in 1967. Subsequently, Japanese industry has dominated LCD and flat panel display technology in general. The LCD development history was summarised by Ijichi and Hirasawa [1] in terms of three phases:

- Phase 1: 1960s-1970s; basic concepts of LCD and driving methods developed
- Phase II: 1980-1995; new methods developed to improve stability and enable production
- Phase III: 1995-present; the market for image display technology rapidly expanded and development aimed at improving quality.

PRE-TILT ANGLE AND LC DISPLAYS

The LC display comprises a thin liquid layer sandwiched between a pair of glass substrates. Some LC displays employ polymer substrates to produce flexible displays. The device usually incorporates one or two polarizing elements that in combination with the LC layer and electrical biasing can optically modulate the optical path of the LC film that results in a variation in transmittance/opacity or reflectance of the LC display and modulates the pixel intensity. In an active matrix LC display, independently addressable thin film transistors are fabricated on the substrate. In a backlit display, the light is modulated by the biasing electronics to lighten or darken the pixels. In a reflective display, the reflectance is modulated. If the molecule tilt direction is not uniform in the activated state, the brightness is highly non-uniform. In order to avoid this effect, a small pre-tilt angle is required and homeotropic alignment is achieved. An additional problem arises when the pre-tilt angle is too high such that the contrast ratio and threshold level are decreased. The pre-tilt angle should have a value greater than ~ 0.5 degrees otherwise the LC molecules may tilt in diametrically

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opposite directions when the voltage is suddenly applied. If the pre-tilt angle is too high, the birefringence due to the pre-tilt of the LC molecules will cause a light leakage in the dark state and reduce the contrast ratio. In all devices, one or more alignment surfaces are employed that bias the molecules of the LC toward a specific spatial alignment or orientation.

LC materials are anisotropic and for electro-optic applications are rod-shaped molecules with axial dependent optical properties. The LC material is of three main types: nematic, cholesteric and smectic. Furthermore, the molecules exhibit some long range order such that locally, similar orientations may be adopted. The local orientation of the long axis of the LC molecule is referred to as the "director". The alignment types of LC molecules may be divided into two categories: (i) homogeneous, or planar (director parallel to the cell walls), (ii) homeotropic or vertical (director perpendicular to the cell walls). A third category can be defined where the director is tilted with respect to the cell walls which is of the greatest industrial interest since the tilted alignment aids in the switching of the cell in operation. Here, the LC is arranged on the surface of the electrode with a pre-determined angle of pre-tilt by means of an alignment layer. The techniques employed in producing this defined alignment of the LC are of critical importance in the manufacture of LC devices. The alignment ensures that a single domain is formed throughout the LC which otherwise leads to disclinations (dis-continuities in orientation), optical scattering and ultimately degradation of the optical performance of the device. Homeotropic alignment is used in LC displays, rear-projection TV's, optical devices etc. and typically LC with negative dielectric anisotropy is used.

The pre-tilt angle of high resolution TN-LCD should be controlled around 5 degrees in order to prevent disclination. Direct view VA display is required to be completely homeotropic whereas the VA projection type LCD requires a certain pre-tilt angle in order to prevent disclination. Therefore high quality LCD always requires accurate control of the surface alignment and there is considerable research and development aimed at achieving controllable pre-tilt angles.

A standard method for producing alignment, particularly on polymer surfaces, is the rubbing method. Here, a surface coated with polyimide or other polymer film is physically

rubbed using a velvet cloth to produce a directional or anisotropic template for LC molecules. The method has several drawbacks including potential contamination, static charge generation, mechanical damage, and non-uniformity over large substrate areas. There exists, therefore, a need to develop a non-contact alignment method that is suitable for large scale production processing.

ALIGNMENT OF LIQUID CRYSTALS

The common industrial method for LC alignment is based on the mechanical rubbing of a polyimide surface. The method of aligning liquid crystals by rubbing polymer surfaces is well established and references exist that can be traced to as early as 1907 [2] and 1911 [3]. However, the physics of the process is by no mean understood [4] although Stöhr [5,6] has explained the effect in terms of the minimum energy state of the interaction of the LC and oriented polymer surface which corresponds to maximum directional overlap of the respective anisotropic charge distributions. Using NEXAFS (Near Edge X-ray Absorption Spectroscopy) he found that there was a preferred molecular orientation at the surface of the rubbed polymer film. It is this orientation that is the microscopic origin of the LC alignment [7]. The preferred LC alignment direction (parallel to the rubbing direction) as well as the direction of out-of-plane LC pre-tilt is explained in terms of preferential orientation of phenyl rings. The molecular orientation arises from a preferential alignment of a polymer chain segment parallel to the rubbing direction, which is caused by a pulling action of the rubbing fibres of the rubbing roller.

Alignment control structures have also been used to promote homeotropic alignment in LC cells [6]. These structures take the form of 10-15 micron-sized sloping projections and /or slits on the surface of the cell structures around which the LC material aligns (Fig. 1). The cells can be constructed such that the alignment structures induce four different LC alignment regions within a given pixel to improve the field of view of the device.

EVAPORATION METHODS

The rubbing technique has advantages and disadvantages, the former being simplicity and the latter including debris produced by the rubbing process, uneven wear of the roller

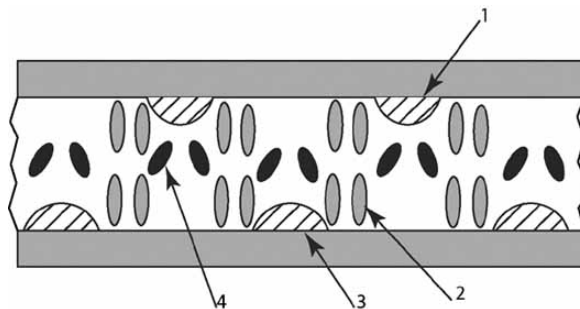


Fig. (1). LC may be aligned using control structures on the surface of the transparent glass substrates in the form of projections or slits. In the case of LC with negative anisotropy of the dielectric constant, and in the absence of any applied voltage, the LC molecules are aligned in the direction perpendicular to the vertical alignment layers and perpendicular to the projections. When the voltage is applied, the LC aligns perpendicular to the electric field and lies substantially parallel to the substrate surfaces. When the substrate is not treated (i.e. rubbed) the direction in which the LC molecules lie is random and their behaviour unstable. However, in the region of the projections, the LC molecules align as if pre-tilted. Schematic cross-section showing a liquid crystal display apparatus of the vertical orientation type with alignment control structures (1. substrate, 2. LC aligned perpendicular to the substrate, 3. alignment projections, 4. LC aligned perpendicular to the projections. [6].

and the relatively high temperatures required for curing the polyimide layer. At least 17 alternative methods for LC alignment have been investigated [8] including PVD and CVD [9]. Oblique evaporation [10] has also been employed for industrial deposition of inorganic alignment layers such as silicon oxide.

It has been recognised since at least 1977 that LC alignment is correlated with the deposition angle of silicon monoxide. When deposited at angles exceeding 75° , striations and scales are observed in the film structure which influence the alignment and tilt angle of nematic LC [10]. A refinement of this process was patented in 1993 [11] in which silicon dioxide was evaporated onto obliquely orientated substrates and the depositing SiO_2 simultaneously bombarded with 500 eV O_2^+ ions. The ion assisted process was then repeated after rotating the substrates through 90° in the substrate plane. The resulting structure was found to produce homeotropic cells with higher contrast ratio and greater temperature stability. More recently, Lu [12] produced homeotropic and tilted homeotropic LC alignment during the oblique deposition of SiO_2 (and other dielectric materials) by electron beam evaporation. By masking the substrate and rotation, different areas of the surface are coated with the alignment layer. This approach enables the formation of a multi-domain homeotropic-alignment, liquid crystal display device. The principal difficulty with conventional evaporation techniques for depositing alignment layers onto obliquely orientated substrates is that of maintaining a uniform angular distribution of depositing atoms at the substrate and hence a uniformly deposited layer. Tatsushi, *et al.* [13] describe a method in which the uniformity of the deposition process is further improved by employing a system of rotating collimating slits between the evaporation source and the obliquely arranged substrates.

Sputtering has also been used to prepare alignment layers [14]. A long throw sputtering method describes a process whereby the substrate is placed at a distance greater than 20 cm from the sputtering source and a collimator inserted between the source and substrate. The sputtered film (dielectric SiO_2 , SiO_x or diamond-like carbon) is then deposited onto the substrate (cell surface) whilst the substrate is tilted at an oblique angle to produce a pre-tilt angle of the LC. The efficacy of this approach in controlling LC pre-tilt angle is not described.

ION AND PLASMA BEAM ALIGNMENT

Among the vacuum-based techniques, the use of ion and plasma beams is attractive due to the potential for large scale production [15-39]. The use of ion beam irradiation for LC alignment can be traced back to around 1979 [15] and the use of plasma beam irradiation to 1986 [33].

The directed ion beam technology has been used to irradiate a DLC film (a-C:H) on the substrate, typically with low energy Ar ions [16-32] (Fig. 2). Conceptually, the DLC is regarded as a random mixture of carbon rings bonded together with no preferred direction or alignment. When bombarded the C-C bonds and rings perpendicular to the ion beam direction and with a higher probability for destruction are destroyed and re-formed in an orientation with lower cross section for destruction. NEXAFS reveals that ion

irradiated surfaces of DLC exhibit a preferential orientation of its sigma bonds parallel to the ion beam direction and π bonds perpendicular to the beam direction [25]. Continued bombardment results in an increase in surface sputtering, eventual randomisation of the surface and an associated decrease in pre-tilt angle. Aligned surfaces can be over written by irradiating from a different direction. (Fig. 3) shows the typical range of LC pre-tilt angles achievable with ion beam irradiation of polymer coated substrates [25]. The process may also be simplified in that the DLC layer and preferred orientation of bonds can be achieved in a single step by introducing a carbon gas such as methane or acetylene into the ion gun and depositing the film at a preferred angle of incidence directly onto the substrate

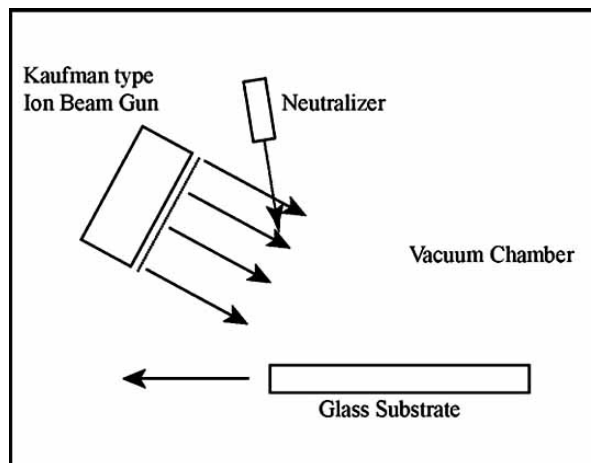


Fig. (2). Schematic of the ion beam irradiation system for LC alignment [24]. The glass substrate is moving with respect to an ion beam gun mounted at a defined angle of incidence. The ions strike the substrate (coated with diamond-like carbon) with a defined energy of 50-500 eV and dose in the range 1×10^{14} - 1×10^{15} ions cm^{-2} , and induce a specific pre-tilt angle of up to 10 degrees for the LC molecules.

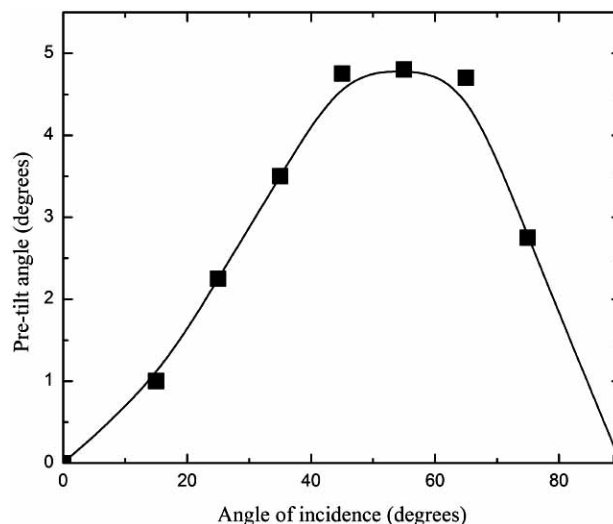


Fig. (3). The pre-tilt angle for DLC coated glass may be controlled by ion-beam irradiation angle. The measured pre-tilt angle as a function of the argon ion beam incident angle for constant ion dose (1×10^{15} ions/ cm^2) on the surface of DLC coated glass [24].

The pre-tilt angle of IB/DLC alignment is not stable and tends to decrease in contact with moisture and air. The pre-tilt angle decreases as a function of storage time in vacuum sealed LC cells and further degrades under UV or violet radiation [24]. Several patents describe methods for improving the anchoring of LC on carbon alignment layers. One such method [26] exposes a diamond-like carbon (DLC) alignment layer to atomic hydrogen which has the effect of passivating the surface. The substrate is held over a hot tungsten filament (held at 1800°K) in a hydrogen atmosphere. The hydrogen is dissociated into hydrogen atoms and contacts the carbon surface. NEXAFS studies revealed that the presence of C-H bonding and also that C-C bonding was increased. Subsequent exposure of the passivated layers showed negligible reduction in C-C bonding whereas non-passivated films indicated a significant reduction in C-C bonds and appearance of carbonyl (C=O) and carboxyl (O=C-OH) peaks in the NEXAFS spectra.

The ion beam method has been used for industrial scale production of polymer-based alignment surfaces utilising all types of inert gas ions [27,28], modified ion gun geometries for uniform irradiation [29] (Fig. 4), and multiple substrate irradiation at differing angles [30-32].

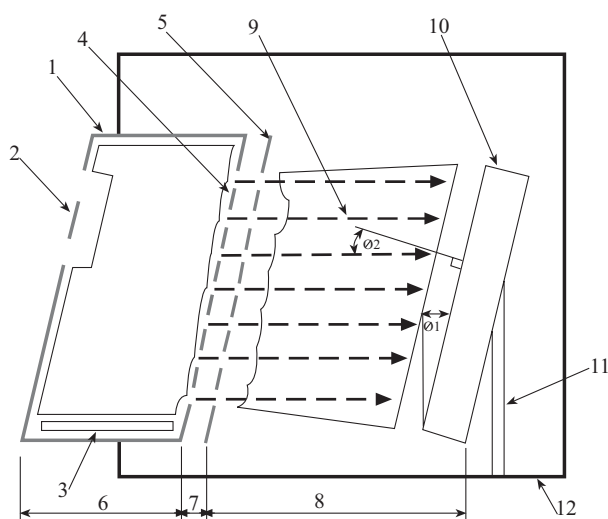


Fig. (4). Ion beam irradiation may be used to provide a non-contact means of providing LC alignment on a polyimide-based organic coated substrate. The resulting pretilt angle is dependent upon the irradiation angle (as in figure 3). A twisted nematic (TN) LCD requires a pre-tilt angle of 5 degrees and in-plane switching (IPS) LCD one of 2 degrees. The appropriate angle is then selected by means of the appropriate angle of incidence of 50 and 20 degrees respectively.

Optimised geometry for ion beam irradiation device [29]

1. ion beam source, 2. cathode, 3. discharge electrode, 4. discharge grid, 5. ion accelerator grid, 6. plasma generation region, 7. ion beam acceleration region, 8. irradiation region, 9. ion beam, 10. substrate, 11. substrate holder, 12. vacuum chamber.

In the case of plasma beams [33-38], two types of alignment are produced; (1) tilted planar (with a small pre-tilt $\theta \leq 10^\circ$) and (2) strictly planar (zero tilt) with different geometrical (easy axis directions) and energetic (strength of anchoring) properties. In the case of a-C:H films, the

mechanism of alignment is also thought to be a result of the modification of surface chemical bonds. The movement of a scanning plasma source breaks the aromatic rings and creates dangling carbon bonds that subsequently form directional C-O bonds on the surface. It is these bonds that are considered to favour LC alignment [32]. (Fig. 5) shows a schematic diagram of a typical plasma beam irradiation system used to treat two substrates simultaneously. The pre-tilt angles obtained on a range of substrates including polymers and glass is shown in (Fig. 6).

Generally, it is considered that any method that creates a statistically significant orientation order at the surface of a carbo-naceous material can be used for LC alignment. Even amorphous materials may have strong orientation because of the strong directional nature of unsaturated carbon bonds.

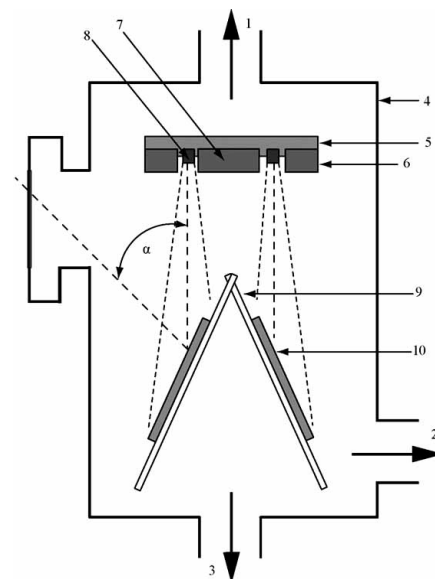


Fig. (5). Plasma beam irradiation system used for producing pretilt angles on substrates. 1, 2, 3. vacuum valves, 4. vacuum chamber, 5. plasma source, 6. outer cathode, 7. inner cathode, 8. anode, 9. substrate holder, 10. substrate [35].

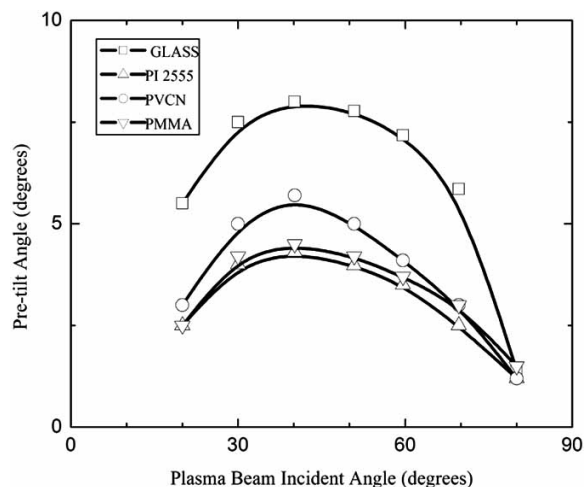


Fig. (6). The pre-tilt angle versus the plasma beam angle of incidence for different substrates irradiated by the plasma beam process.

Negative dielectric liquid crystal will align vertically when van der Waals interactions are the dominant force. These forces are short range and will be overridden by any other influences such as grooves or π -electron coupling resulting in non-vertical alignment. DLC is used for homogeneous alignment with ion beam treatment and the π -electrons from carbon rings are responsible for alignment. The π - π interactions of the carbon rings dominate the van der Waals forces and the alignment is planar. However, in amorphous silicon (a-Si), SiO_x and SiN_x materials π -electron loops are not formed and perpendicular alignment is observed. This observation forms the basis for the work of Andry *et al.* [24].

It is possible to tailor the pre-tilt angle by combining inorganic material with homeotropic alignment tendencies (Si, SiO_x , Si_xN_y) with one with homogeneous alignment tendencies (carbon or SiC) in the appropriate concentrations [24]. For example, the pre-tilt angle for a-C:H is > 15 degrees, and unstable. The pre-tilt angle for a-Si is < 0.5 degrees and stable. A combination of both can increase the pre-tilt angle to a stable 1.5 degrees. The bombardment of a surface layer of SiO_x for example with N_2^+ ions can introduce sufficient nitrogen to form SiO_xN_y . SiN_y produces a more planar pre-tilt angle compared to SiO_x and therefore suitable tuning of the composition can increase the pre-tilt angle. Similarly, the stoichiometry of the material may be adjusted during deposition e.g. SiC_x where x is controlled during sputter deposition and the pre-tilt angle tuned to a predetermined value.

The bombardment of substrate surfaces with energetic particles from plasma or ion beam sources can lead to changes in the surface topography from ion/particle-surface interactions. Several studies of the influence of ion bombardment on surface roughening and smoothing reveal that for small angles of incidence (near to normal) ripples are formed which are perpendicular to the beam direction and for angles closer to grazing incidence the ripples are parallel to the beam direction. This behaviour is successfully predicted by the Bradley-Harper theory [40] and has been refined by Toma *et al.* [41,42] to predict fluence dependence (time) on the wavelength and roughness that evolves. Chason and Mayer [43] have also reported on the curious effect of roughening produced by low energy Xe and then smoothing again by bombardment with 1 keV H^+ ions. The precise mechanism was unknown.

PARTICLE BEAM AND PHOTON METHODS OF ALIGNMENT

US patent 7105845 B2 [44] describes a new process that does not involve the use of plasmas or ion beam beams and does not require the use of expensive and complex vacuum equipment. This patent describes a method in which the substrate, either organic or inorganic, is irradiated with an electron beam (Fig. 7). For electron beam energies of 1 MeV or higher, the particle range in air is of the order of 1 meter. This enables the substrate to be in atmosphere and to be irradiated directly by the electron beam. The substrate may be obliquely orientated with respect to the electron flux during irradiation. The authors have detected alignment of LC on the irradiated surfaces and relate the phenomenon to

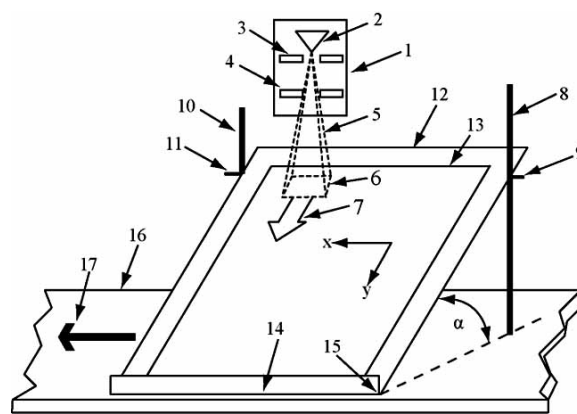


Fig. (7). Liquid crystal alignment using electron beam exposure. (1. electron source, 2. filament, 3. anode, 4. acceleration grid, 5. electron beam, 6. processing area, 7. rastering direction, 8. support, 9. pin, 10. Sup-port, 11. pin, 12. substrate plane, 13. substrate, 14. front edge, 15. substrate retaining edge, 16. linear track, 17. direction of travel).[43].

an electron stimulated chemical reaction that can break specific chemical bonds in the substrate and induce local rearrangement of atoms or molecular groups. The resultant rearrangement introduces a degree of physical and chemical anisotropy to the surface. In the case of polymeric substrates, the biphenyl rings that have a direction perpendicular to the electron beam direction have a higher cross-section for interaction with the beam and are preferentially damaged relative to the bi-phenyl rings that lie in a parallel direction to the beam. This may, therefore, account for the anisotropic effect on irradiated polymers. As an example, a successful alignment layer was produced on a 2.4 m x 1.2 m polymer substrate with 0.7 MeV electron bombardment at an angle of incidence of 80° . The authors suggest that other types of radiation such as X-ray or γ -ray as well as proton beams may also produce similar effects.

Photo-alignment methods have also been used to produce alignment layers in LC devices [45]. When linearly polarised light UV is normally incident on a photosensitive polymer such as polyvinylcinamate, the surface becomes photo-polymerised due to cross linking between polymer molecules. The bonding direction of the photo-polymer molecules depends on the direction of the linearly polarised UV light and hence the LC is aligned according to the bonding direction. When the surface is irradiated again at an angle of incidence θ with linear polarised light, whose polarisation direction is perpendicular to the first UV light, a pre-tilt angle of the alignment layer is formed [46]. The magnitude of the pre-tilt angle is dependent upon the irradiation angle θ and values of pre-tilt angles of 0.15° , 0.26° and 0.30° are possible for irradiation angles of 30° , 40° and 60° respectively. A refinement of this approach was patented by Reznikov, *et al.* [47, 48]. Here the authors claim that by irradiating with firstly linearly polarised light at normal incidence and then non-nonpolarised light at an angle to the substrate the resulting structure can be both aligned and the magnitude of the pre-tilt angle varied according to the exposure time (Fig. 8,9). Furthermore, the pre-tilt angle

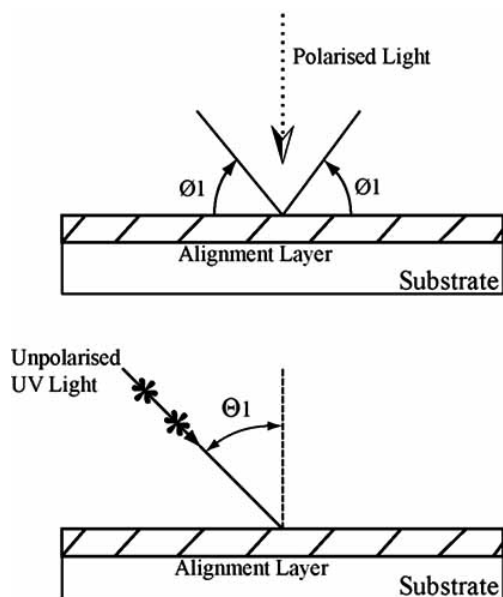


Fig. (8). Method of liquid crystal alignment by means of UV irradiation. Step 1 (upper) Linearly polarised UV irradiation is normally incident upon the alignment layer. Two symmetric and bidirectional pre-tilt angles ϕ_1 are created on either side of the alignment axis. Step 2 (lower) a second UV irradiation with unpolarised light at an oblique angle θ_1 aligns all the molecules at one of the symmetric pre-tilt angle directions, [46, 47].

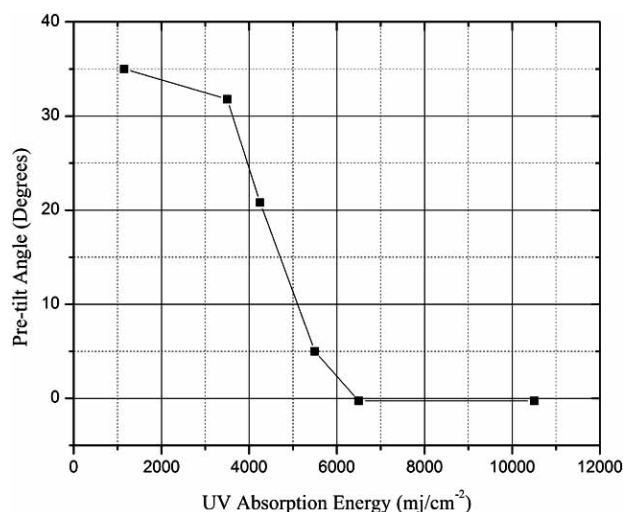


Fig. (9). The relationship between the pre-tilt angle and the UV irradiation dosage [46, 47].

can be varied over a much greater range than previously reported, from 0-35°. Multidomain LC display panels may also be fabricated using a similar technique [49].

The alignment layer may also be exposed to an interference pattern of UV light [50]. In this instance the LC will align itself according to the interference pattern on the substrate surface (Fig. 10). This photo-alignment process has

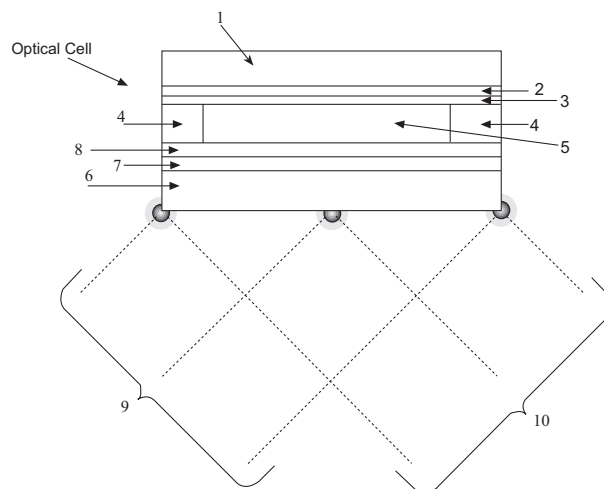


Fig. (10). An example of UV interference used to produce alignment of LC. [49].

1. optical cell, 2., electrode layer, 3. polymeric alignment layer, 4. epoxy seal, 5. cell chamber region, 6. substrate, 7., electrode, 8. alignment layer, 9, 10. linearly polarized UV beams.

been used to form planar gratings by exposing the substrate to an interference pattern generated by an Ar⁺ laser emitting at 351 nm and 350 W.

CHEMICAL AGENTS AND MIXING

There have been many patents focussed on methods for aligning LC by means of chemical agents [51]. Homeotropic alignment is achievable by doping a percentage of positive $\Delta\epsilon$ (dielectric anisotropy), neutral or negative $\Delta\epsilon$ -LC material into another negative LC material to produce a high contrast ratio homeotropic alignment of difluoro compounds or mixtures, independent of operating temperature. Generally, pure negative dielectric anisotropic LC mixtures are aligned in homeotropic LC cells at room temperature but the alignment becomes non-uniform above room temperature and the light leakage at dark state increases which results in poor contrast ratio. The stability is improved by changing the properties of the LC mixture. The negative $\Delta\epsilon$ -LC is the dominant part of the mixture. By doping some positive neutral or negative $\Delta\epsilon$ into the host negative $\Delta\epsilon$ -LC, ultra high contrast ratio is achieved and the alignment preserved at high temperature. Birefringence and viscosity of the mixture is also improved.

A LC alignment agent can include a molecule having a highly polar functional group grafted onto one end of the molecule [52]. Such agents include cyano or cyano-like groups and alignment mixtures can also contain UV stabilisers and anti-oxidants. Often the additives are rod-like LC with positive $\Delta\epsilon$ that align homogeneously on SiO_x substrates. When mixed appropriately with the target LC, they align vertically. Such chemicals are cyanobiphenyl LC from Merck, and Aldrich etc. The blending of any LC or LC mixture that has negative $\Delta\epsilon$ with LC, with a strong polar group at the molecular end, promotes vertical alignment.

Table 1. Summary of the Reviewed Methods of Alignment

Material	Process	Technique	Pre-tilt angle [deg]	% Patents (2000-2007)
SiO _x	Oblique evaporation	Column structure	0-70	8
DLC, SiO _x , PMMA etc.	Ion Beam	Ion irradiation	0 -5	18
Glass,PVCN, PMMA	Plasma beam	Particle irradiation	2-8	3
Polyimide	UV exposure	Photoalignment	0 - 35	25
Polymer	Electron beam	Bond breaking	N.A	5
Glass	Chemical	LC mixing	90	41

An alignment layer can also be formed using an organic surfactant which is fixed in a matrix of a polymeric material or an inorganic thin film of aluminium oxide. Coates *et al.* [53] reports a typical layer thickness of about 3 microns, however, no details of performance were given.

LC aligns vertically on substrates with high or low surface energy and homeotropic alignment is achieved by reducing the surface energy of the substrate. It is the difference in surface energy of the substrate and the surface tension of the LC that promotes homeotropic alignment. Typically the surface tension of the LC is higher than the surface energy of the substrate and therefore it is feasible to achieve homeotropic alignment of LC materials on any given substrate provided the surface tension of the LC is increased sufficiently. Patent WO06131191A1 [54], describes the use of polar cellulose derivatives, in particular cellulose esters like cellulose nitrate as suitable additives for homeotropic alignment.

SUMMARY

The methods recently patented for non-contact alignment of LC molecules in display devices and (where reported) the achievable pre-tilt angles, are summarised in Table 1. The patent and scientific literature is expanding rapidly in the quest to improve performance and reliability of LCD devices due to its importance in the marketplace and the approximate distribution of patents only, over the period 2000-2007, for the processes reviewed is given in Table 1.

CURRENT & FUTURE DEVELOPMENTS

From the above review it can be seen that LC alignment methods have evolved considerably since the simple evaporative techniques used in the 1970's. Ion beam, plasma beam, electron irradiation and UV exposure techniques are all practical methods for creating alignment layers. The efficacy of each respective technique depends upon the range of the pre-tilt angle required, the stability of the alignment that can be tolerated and the use of organic or inorganic coatings. The use of chemical agents and mixing to promote alignment is also receiving increased attention due to the simplicity of the technique. Future developments may see the advent of processes that involve both the deposition of the alignment layer and the production of a pre-determined pre-tilt angle in a one-step process. Indication of this can be seen in the ion beam deposition/alignment procedures. If this approach can be realised for large scale industrial scale-up,

then this will further simplify the production LC display devices. The main technical issues will centre on production costs, throughput, scale-up etc. The present Gen 8 substrate size is 2160 x 2460 mm and the predicted Gen 10 size (by the year 2011) is 2950 x 3400 mm. The successful development of a low-cost, high throughput alignment technology will need to address all of the issues associated with this scale of substrate. Among the specific technical challenges for LCDs in the future are:

- Faster and higher quality image processing
- Improvements in LED backlight technology and associated power reduction
- Improved flexible substrates and transition to inorganic alignment layers

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REFERENCES

- [1] Ijichi T, Hirasawa R. R&D organizational process on liquid crystal display: a comparative analysis based on patents. Portland International Conference on Management of Engineering and Technology. Portland, Oregon, USA (1999).
- [2] De Gennes P.G., Prost J. The physics of liquid crystals. Oxford University Press 1993.
- [3] Mauguin MC. Sur les cristaux liquides de Lehmann. Bull Soc Fr Miner Cristall 1911; 34:71 -115.
- [4] Paek S-H, Durning CJ, Lee K-W, Lien A. A mechanistic picture of the effects of rubbing on polyimide surfaces and liquid crystal pretilt angles. J Appl Phys 1998; 83 (3): 1270-1280.
- [5] Stöhr J, Samant MG, Lüning J, *et al.* Liquid crystal alignment on carbonaceous surfaces with orientational order. Science 2001; 292: 2299-2302.
- [6] Stöhr J, Samant MG. Liquid crystal alignment by rubbed polymer surfaces: a microscopic bond orientation model. J Electron Spectr Rel Phenom 1999; 98-99:189-207.
- [7] Sasaki, T., Takeda, A., Ohmuro, K., Chida, H., Koike, Y., Nakamura, K., Tashiro, K.: US20070030421A1 (2007).
- [8] Ishihara S. How far has the molecular alignment of liquid crystals been elucidated? IEEE/OSA J Display Technol 2005; 1: 30-40.
- [9] Ong, H.L.: US20070059438A1 (2007).
- [10] Pollack JM, Haas WE, Adams JE. Topology of obliquely coated silicon monoxide layers. J Appl Phys 1977; 48: 831-833.
- [11] Shigeta, M., Shimada, T., Asami, M., Natsuhori, H., Shimizu, S., Konno, T.: US5268781 (1993).
- [12] Lu, M., Yang, K.-H.: US20026426786B1 (2002).
- [13] Tatsushi, I., Ryuichiro, U.: JP3306562A2 (2006).
- [14] Kuan, T.-S., Chang, Yi.-M., Lin, C.-T., Chan, C.-T.: US20060272938A1 (2006).
- [15] Little, M.J., Garvin, H.L., Lee, Y.-S.: US4153529 (1979).

- [16] Chaudhari, P.: US5770826 (1998).
- [17] Lien S-C, Chaudhari P, Lacey JA, John RA, Speidell JL. Active-matrix display using ion-beam-processed polyimide film for liquid-crystal alignment. IBM Res Dev 1998 May-Jul.
- [18] Chaudhari P, Lacey JA, Lien S-C, Speidell JL. Atomic beam alignment of liquid crystals. Jpn J Appl Phys 1998; 37: L55-56.
- [19] Callegari, A.C., Chaudhari, P., Doyle, J.P., Lacey, J.A., Lien, S.-C. A., Purushothaman, S., Samant, M.G., Speidell, J.L., Stohr, J.: US20006020946 (2000).
- [20] Callegari, A.C., Chaudhari, P., Doyle, J.P., Lacey, J.A., Lien, S.-C. A., Purushothaman, S., Samant, M.G., Speidell, J.L., Stohr, J.: US20006061114 (2000).
- [21] Chaudhari, P.: US20006124914 (2000).
- [22] Chaudhari P, Lacey J, Doyle JP, *et al.* Atomic-beam alignment of inorganic materials for liquid-crystal displays. Nature 2001; 411: 56-59.
- [23] Chaudhari, P., Lacey, J.A., Lien, S.-C.: US20016195146 (2001).
- [24] Andry, P.S., Chaudhari, P., Doyle, J.P., Galligan, E.A., Lacey, J.A., Lien, S.-C.A., Lu, M.: US20036660341 (2003).
- [25] Doyle JP, Chaudhari P, Lacey JL, *et al.* Ion beam alignment for liquid crystal display fabrication. Nucl Instrum Meth 2003; B 206: 467-471.
- [26] Katoh, Y., Nalagawa, Y., Odahara, S., Samant, M.G.: US20026485614 (2002).
- [27] Ham, Y.-S.: US20050238821 (2005).
- [28] Ham, Y.-S.: US20050252440 (2005).
- [29] Ham, Y.-S.: US20050259204 (2005).
- [30] Lee, Y.B., Ham, Y.-S.: US20040124371 (2004).
- [31] Lee, Y.B., Ham, Y.-S.: US20050040346 (2005).
- [32] Gwag JS, Jhun CG, Kim JC, Yoon T-H, Lee G-D, Cho SJ. Alignment of liquid crystal on a polyimide surface exposed to an Ar ion beam. J Appl Phys 2004; 96: 257-260.
- [33] Kurchatkin, S., Mauraveva, N.A., Mamaev, A.L., Sevostyanov, V.P., Smirmova, E.I.: RU2055384C1 (1996).
- [34] Yaroshchuk O, Zakresky Yu, Dobrovolsky A, Pavlov S. Liquid crystal alignment on polymer substrates irradiated by plasma beam. Proc SPIE 2001: 4418: 49-53.
- [35] Yaroshchuk, O., Pavolov S., Mikalaiovich, R., Goncharov, O.A., Protsenko, I.M.: UA200258291 (2002).
- [36] Yaroshchuk O, Kravchuk R, Dobrovolsky A, Qiu L, Lavrentovich OD. Planar and tilted uniform alignment of liquid crystals by plasma treated substrates. Liquid Crystals 2004; 31: 859-869.
- [37] Yaroshchuk O, Kravchuk R, Dobrovolsky A, Lee C-D, Liu P-C, Lavrentovich OD. The multimode LC alignment on the substrates obliquely treated with a plasma flux. Mol Cryst Liq Cryst 2005; 433:1-12.
- [38] Yaroshchuk O, Kravchuk R, Dobrovolsky A, Liu P-C, Lee C-D. Plasma beam alignment for the large-area substrates: equipment and process. J SID 2005; 13/4: 289-294.
- [39] Wu KY, Chen C-H, Yeh C-M, *et al.* Liquid-crystal alignment on a-C:H films by nitrogen plasma beam scanning. J Appl Phys 2005; 98: 1-5.
- [40] Bradley RM, Harper JME. Theory of ripple topography induced by ion bombardment. J Vac Sci Technol 1988; A: 2390-2395.
- [41] Toma A, Buatier de Mongeot F, Buzio R, *et al.* Ion beam erosion of amorphous materials: evolution of surface morphology. Nucl Instrum Method 2005; 230: 551-554.
- [42] Granone F, Mussi V, Toma A, *et al.* Ion sputtered surfaces as templates for carbon nanotubes alignment and deformation. Nucl Instrum Methods 2005; B 230: 545-550.
- [43] Chason E, Mayer TM. Low energy ion bombardment induced roughening and smoothing of SiO₂ surfaces. Appl Phys Lett 1993; 62(4): 363-365.
- [44] Kumar, S., Vargas-Aburto, C., Wang, Q.: US20067105845B2 (2006).
- [45] Seo D-S, Choi J-H. Generation of high pretilt angle in a nematic liquid crystal with single oblique polarized UV light irradiation on polyimide surfaces. Liquid Crystals 1999; 26: 291-293.
- [46] Hashimoto T, Sugiyama T, Kataoh K, *et al.* SID 95 Digest 1995; 877.
- [47] Reznikov, Y., Yaroshchuk, O., Woo, J.W., Choi, Y.J., Yoon, K.H., Nam, M.S., Kim, J.H., Kwon, S.B.: US20047145618B2 (2004).
- [48] Reznikov, Y., Yaroshchuk, O., Woo, J.W., Choi, Y.J., Yoon, K.H., Nam, M.S., Kim, J.H., Kwon, S.B.: US20060027522A1 (2006).
- [49] Kwon, S.B., Kim, J.H., Yaroshchuk, O., Dyadyusha, A.: US20030112395A1 (2003).
- [50] Crawford, G.P., Eakin, J.N., Radcliffe, M.D.: US20077196758 (2007).
- [51] Wen, C.-H., Wu, S.-T.: US20060238696A1 (2006).
- [52] Chen, C., Bos, P.J., Andersen, J.A.: WO06121839A1 (2006).
- [53] Coates, D., Parri, O.L., Ward, J.L., Joicey, D., Wilbourn, K., Dickson, C., Scott, J.: US20077170575 (2007).
- [54] Harding, R., Francis, M., Parri, O.L., Graham, D.G., Marden, S.A.: WO06131191A1 (2006).