Plasma beam alignment for the large-area substrates: Equipment and process

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Abstract — We have developed an effective method for liquid-crystal alignment of the large-area substrates. This method is based on the oblique treatment of the alignment substrates with a "sheet" of accelerated plasma generated by the anode layer source of the "race track" geometry. During this treatment, the substrate or source is cyclically translated in the direction perpendicular to the plasma "sheet." This method provides planar, tilted, and vertical liquid-crystal alignment with excellent uniformity and reproducibility and easy axis control in the azimuthal and polar planes.

Keywords — *Liquid-cyrstal alignment, plasma processing, plasma source, anode layer thruster.*

1 Introduction

Modern LCD technologies set strong demands for liquid-crystal (LC) alignment. It should be highly uniform (even on the microscopic level) and stable as well as posses strongly determined alignment parameters, such as pretilt angle and anchoring energy. The electro-optic performance sets additional demands, such as acceptable residual DC voltage and voltage holding ratio parameters, which partially relate to alignment conditions and alignment materials. These requirements should be satisfied for the large-area substrates used in modern LCD manufacturing. Nowadays, LCD production equipment operates with Gen 6 substrates of a size of 1500×1600 mm^2. The Gen 7 substrates are planned to be 1870×2200 mm^2 in size.

With increasing substrate size the traditional rubbing procedure satisfies the demands listed above less and less. For this reason, the development of a new alignment process that overcomes the intrinsic problems of rubbing alignment is of great necessity. Among the most promising candidates, the group of particle-beam methods is especially intriguing. In these methods, the surface of the alignment substrate is obliquely treated with a flux of particles (atoms, ions, electrons, or mixtures thereof), which causes anisotropic material deposition or etching of the substrate. The deposition might be direct (thermal deposition,[1] *etc.*) or indirect (ion-beam sputtering[2] *etc.*). The etching procedure for the LC alignment was first applied by M. J. Little *et al.*[3] They obliquely treated aligning films with the ion fluxes of high energy (1–3 keV). Similar treatment conditions were also used by Z. M. Sun *et al.*[4] Special interest to the etching procedure arose recently after publication by the IBM group (NY, U.S.A.)[5,6]. The idea of the IBM authors is based on treatment with ions of low energy, which modifies only the very top layer of the aligning film. To realize this, the ion beam from a Kaufman-type ion source was utilized. The high-quality alignment with strong anchoring and a controllable pretilt angle was achieved.

Later on, the IOP group (Kyiv, Ukraine)[7–9] demonstrated that results rather similar to the results of IBM group might be obtained by substitution of the ion beam with a beam of accelerated plasma generated by a source known as the anode layer thruster (ALT) or a source with closed electron drift. Noteworthy is that plasma processing of LC substrates within a glow discharge was previously widely experimented to vary the zenital anchoring energy and the pretilt angle of LC[10–15]. However, this isotropic processing can never generate a planar or tilted LC alignment. G. J. Sprokel and R. M. Gibson[16] achieved planar/tilted LC alignment by processing alignment substrates with a directed plasma flux. In their experiments, a modified rf plasma etcher was used, in which the reactive plasma was extracted and carried onto substrates by a gas stream. In contrast to this principle, the Kyiv group utilized the sources in which plasma flux is extracted electrically. Moreover, plasma ions that resulted in ion parameters comparable to those in the IBM experiments were also electrically accelerated.

In addition to the advantages of the IBM method, two alignment modes were realized. In the first mode, easy axis is confined to the plane of plasma incidence and tilted towards the incidence direction. In the second mode, easy axis is perpendicular to the incidence plane. The first aligning mode is rather similar to the mode observed by the IMB group. In this mode, the LC pretilt angle is non-zero and can be controlled by the incidence angle of the plasma beam and the irradiation dose. In the second mode, the LC pretilt angle is zero independent of the irradiation conditions. With an increase in the irradiation dose, the anchoring transition from the first to the second mode occurs through the transient two-fold degenerated alignment.[17] Together with the KSU group (Kent, OH, U.S.A.),[18] we revealed that aniso-

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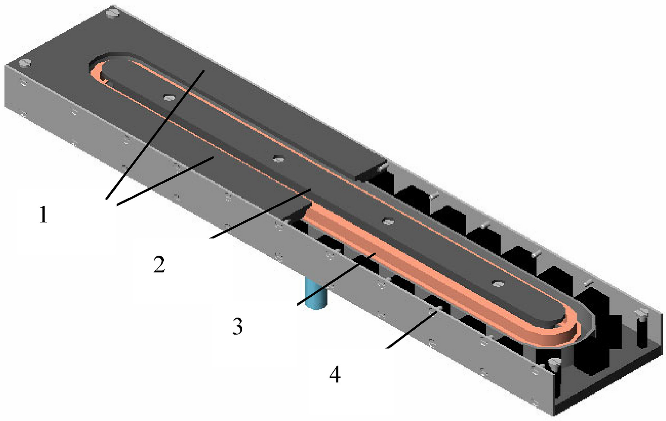

FIGURE 1 — The ALT used in our study. 1 – outer cathodes; 2 – inner cathode; 3 – anode; 4 – permanent magnets.

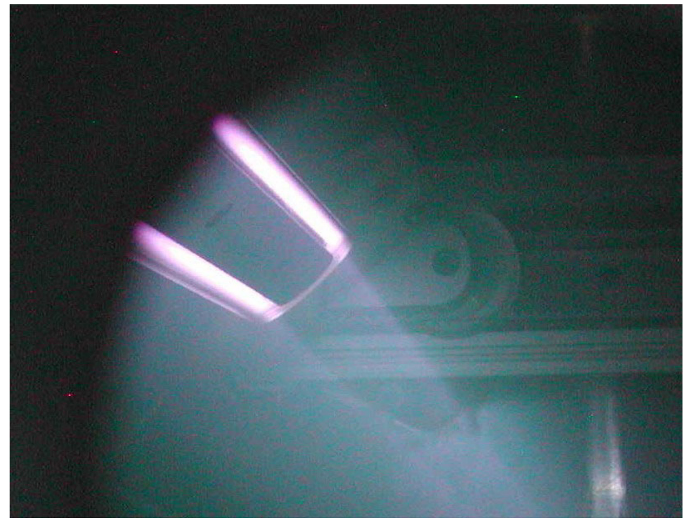

FIGURE 3 — A segment of the plasma-irradiation setup. One can see the ALT mounted on the vacuum scanner and a pair of plasma "sheets."

tropy of the surface relief is a rather important factor for LC alignment and anchoring transition on the plasma-beam-treated substrates.

In the present research, we evaluated the capability of ALT treatment of the LC alignment on large-area surfaces. For this purpose, extended ALT and the translation irradiation regime are combined. The alignment peculiarities revealed in the dynamic irradiation regime are discussed. The alignment uniformity of the enlarged substrates was studied. The obtained results allow us to draw very encouraging conclusions regarding the application of ALT for the generation of LC alignment of the large-area surfaces.

2 Experimental details

2.1 Plasma irradiation setup

We utilized an anode layer thruster with a "race track" shaped discharge area. The general construction of this source is presented in Fig. 1. The source contains inner and outer cathodes and anodes, which define the size and the shape of the discharge channel. At the outer cathode, the source contains permanent magnets. The magnetic circuit formed by the steel body and cathodes is interrupted by a glow discharge gap. Due to this construction, ion flux is formed in crossed electric (**E**) and magnetic (**H**) fields immediately within the discharge channel, and thus is part of the dc plasma generated in the discharge area. ALT is characterized by the high efficiency of plasma extrusion that allows us to use this source as the thruster. Basically, ALT was developed in the former Soviet Union as an engine for orbital correction of space satellites. Also, it was adapted for etching and sputtering purposes. The details of construction, characteristics, and principles of operation of this device can be found elsewhere.[19]

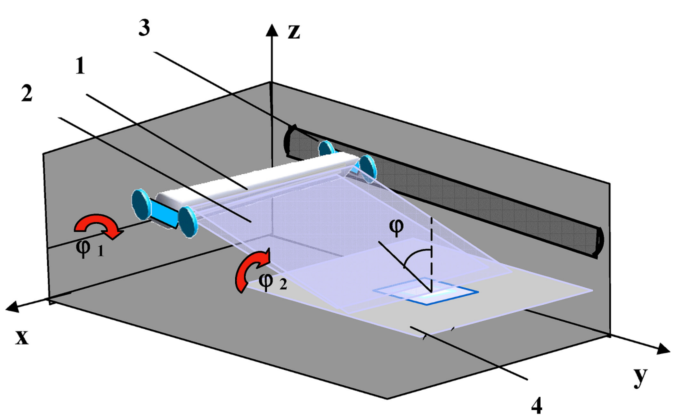

FIGURE 2 — Scheme of the irradiation setup. 1 – ALT; 2 – plasma "sheet"; 3 – scanning system providing ALT translation in y direction; 4 – platform with substrates. φ_1 and φ_2 denote the rotational degrees of freedom of ALT and the holder, which determine the incidence angle of plasma flux, φ.

The length of "race track" of our source was 508 mm, while the length of linear section was about 470 mm. The low power of discharge allowed us to refuse cooling lines. It lightened the source and let us to avoid the use of hoses supplying cooling liquid. This altogether increased the system reliability. The system scheme is presented in Fig. 2, while Fig. 3 depicts the part of our system, which contains source and plasma beams. Source mounting allows rotation around the horizontal x axis and cycling translation across the plasma "sheet" (along the y axis, Fig. 2). The holder of the substrates had similar degrees of freedom: rotation around the x axis and cycling translation along the y axis. This flexible construction allowed us to realize two translation regimes: (1) the horizontal and static position of the aligning substrate and the cycling translation of the ALT tilted with respect to horizontal level; (2) the horizontal static position of the plasma source and the tilted moving position of the substrate. Both methods provide oblique treatment of the aligning substrate in the dynamic regime.

The working gas was argon. It was let immediately in a vacuum chamber. The gas pressure p was 3×10^{-4} Torr. The anode potential U was 600 V. At these conditions, the ion current density in the sample position was 6–8 μA/cm^2. The angle of plasma beam incidence φ (shown in Fig. 2) was 70°. These treatment parameters were optimized earlier for small-area substrates.[7–9,18] The time of irradiation was varied between 1 and 20 min. The speed of translation was 1–5 cm/sec.

2.2 Samples

For aligning substrates, we used bare glass slides and ITO-coated glass slides with polyimide (PI 2555 from Dupont) or a-C:H aligning layers. To achieve vertical alignment (VA), we also used films of fluorinated poyimides (PI-F) specially designed. Two sizes of the aligning substrates were chosen. The regular size was 20 × 30 mm^2. These substrates were placed in different parts of a 450 × 450 mm^2 holder plate (see Fig. 2) in order to determine the treatment uniformity of the holder's area. We also used 120 × 150 mm^2 substrates for the cell preparation. Two types of LC cells have been prepared: (1) one substrate was irradiated by a plasma beam, while the second substrate has a rubbed polyimide layer (asymmetric cells); and (2) both substrates are irradiated with a plasma beam and assembled in an antiparallel fashion (symmetric cells). The asymmetric cells were prepared with the aim of determining the direction of the LC alignment on the plasma-treated substrate. The symmetric cells were used to measure the pretilt angle by using a crystal rotation method. The cell gap was kept with spacers of 6 and 20 μm in diameter. We used an LC with $\Delta\varepsilon > 0$ (K 15 and ZLI2293 from Merck) and with $\Delta\varepsilon < 0$ (MJ961180 from Merck Japan). The in-plane uniformity of the LC alignment was tested by sample observation using a viewing box or a polarizing microscope. The out-of-plane uniformity was judged from the measurement of the LC pretilt angle.

3 Alignment results

In this section, we first consider the alignment modes realized in a sample translation regime and after that the alignment uniformity in these modes.

3.1 Tilted and planar alignment modes

In the beginning, it is reasonable to determine whether the mode sequence, first mode – twofold degenerated alignment – second mode, realized with an increase in the exposure dose in a static irradiation regime,[17,18] is also observed in the translation regime of the irradiation. Figure 4 shows two sets of asymmetric cells in which the plasma-treated substrates (tested substrates) are processed over a different time in the second translation regime (Section 2.1). Set (a) corresponds to the cells filled with LC K15 ($\Delta\varepsilon > 0$), while set (b) corresponds to the cells filled with LC MJ961180 ($\Delta\varepsilon < 0$). The tested substrates were placed in the same place of holder, in order to provide equal irradiation condi-

a

b

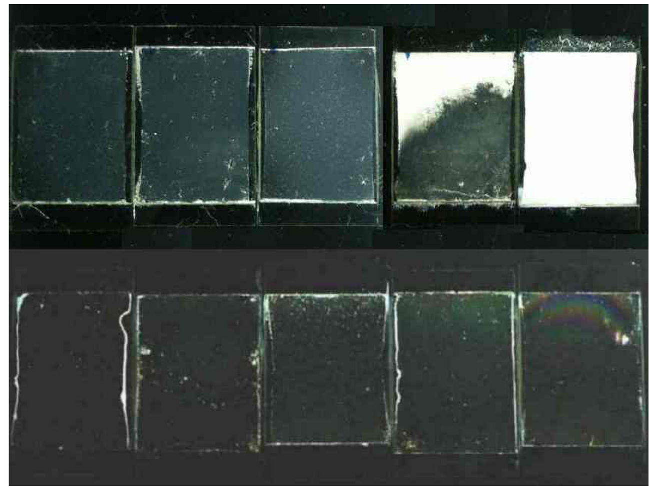

FIGURE 4 — Two sets of asymmetric cells viewed between two crossed polarizers. The tested PI substrates in the cells have been irradiated during 1, 2, 4, 5, and 10 min [set (a)] and 1, 2, 10, 20, and 40 min [set (b)], respectively. Irradiation conditions: cycling regime (v = 1 cm/sec), α = 70°, j = 8 μA/cm^2, E = 600 eV. The cell gap is 20 μm. The cells are filled with LC K15 [set (a)] and MJ961180 [set (b)].

tions. In the set (a), with an increase of irradiation time, the anchoring transition from the first to the second alignment mode occurs. Within 5–8 minutes of irradiation, the sample contained areas with the first and second modes, *i.e.*, the first and the second mode coexist. No other transition types of alignment (such as two-fold degenerated alignment observed in the static regime), except the coexisting first and second modes, were detected. It might be caused by the very narrow range of the exposure doses needed for the transition alignment modes. This range can be easily achieved only in a static irradiation regime characterized by a broad current density distribution in a direction perpendicular to plasma "sheet." At the same time, it is difficult to fall into this range by using dynamic irradiation.

The set (b) in Fig. 4 corresponds to LC MJ961180. Surprisingly, no transition from the first to the second mode for this LC occurs, even for rather high irradiation times. The alignment in the first mode remains unchanged with a pretilt angle θ = 20–30° that only slightly depends on the dose.

The observed difference in the alignment trends of LC with positive and negative dielectric anisotropy was earlier detected for obliquely deposited SiO_2 coatings. According to Ref. 20, at shallow-angle deposition, both LC with $\Delta\varepsilon > 0$ and LC with $\Delta\varepsilon < 0$ are aligned in the first mode. The difference is only in the value of the pretilt angle, which is small (θ < 2°) for the LC with $\Delta\varepsilon > 0$ and high (θ = 87–90°) for the LC with $\Delta\varepsilon < 0$. With the increase in the deposition angle (measured from the substrate), the LC with $\Delta\varepsilon > 0$ undergoes an alignment transition from the first to the second mode, while the LC with $\Delta\varepsilon < 0$ preserves the first mode of alignment. The planar or almost planar alignment of $\Delta\varepsilon > 0$ LC and homeotropic or almost homeotropic alignment of $\Delta\varepsilon < 0$ LC might be explained by a strong dipole–dipole interactions between the liquid crystal and

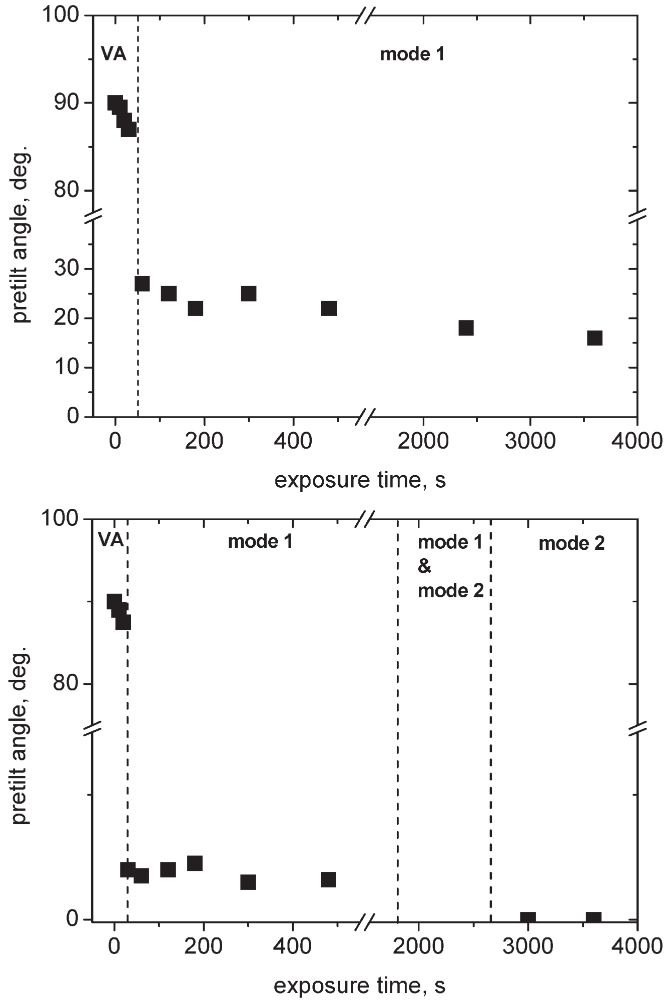

FIGURE 5 — Pretilt angle *vs.* plasma-exposure time curves for LC MJ961180 [set (a)] and LC K15 [set (b)] on PI-F aligning films. Exposure conditions of the substrates: cycling regime (v = 2 cm/sec), α = 70°, j = 0.4 μA/cm^2, E = 600 eV.

the substrate. Since dipoles of LC molecules and substrate tend to be aligned parallel to each other, LC with $\Delta\varepsilon > 0$ (dipole moment directed along the molecular axis) and LC with $\Delta\varepsilon < 0$ (dipole moment is directed perpendicularly to the molecular axis) demonstrate different types of alignment. Although a detailed model of the alignment is absent, it is clear that the dielectric anisotropy seems to be an important factor in the alignment mechanisms of plasma-etched substrates, similar to the alignment on the SiO_2 aligning substrates.

3.2 Vertical-alignment mode

It is well known that the vertical alignment of the LC can be observed on some hydrophobic aligning films. To generate a uniform deviation of the LC from the homeotropic direction, the aligning substrates are usually softly rubbed or obliquely exposed to actinic light.[21] It is reasonable to assume that low dose exposure to a plasma beam should cause effects similar to that of the light treatment. To check

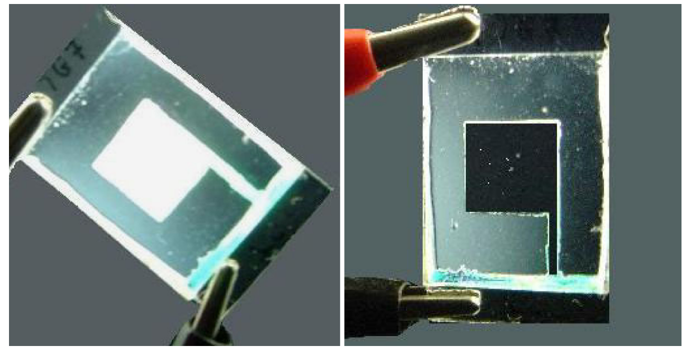

FIGURE 6 — Photographs of symmetric LC cell (d = 20 μm) filled with LC MJ961180 viewed between two crossed polarizers. Aligning coating is fluorinated polyimide treated with a plasma flux. Treatment conditions: α = 70°, j = 0.4 μA/cm^2, t = 10 sec, E = 600 eV. ITO electrode is patterned so that electric field (8 V, 1 kHz) is applied to the central rectangular part of the cell.

this idea, we chose a polyimide providing homeotropic alignment of LC MJ961180 ($\Delta\varepsilon < 0$) and LC K15 ($\Delta\varepsilon > 0$). We also reduced the current density to only 0.4 μA/cm^2 in order to minimize the influence of the plasma, which usually results in a decrease in surface hydrophobicity. Figure 5 shows the pretilt angle as a function of plasma exposure time for these conditions. One can see that low exposure times (5–20 sec) result in a VA (θ = 97–99°) of both LC MJ961180 [set (a)] and LC K15 [set (b)]. Figure 6 shows two photos of VA LC cell (LC MJ961180) with the parts in the field off and the field on state. One can see that field application causes reorientation from VA to the uniform planar alignment of LC layer. With these results, VA is for the first time achieved by the plasma/ion beam processing of the aligning substrates.

Figure 5 demonstrates that further increase of the exposure time leads to the anchoring transition from the VA to the first alignment mode. In case of LC K15, first mode transforms to the second mode, while for the LC MJ961180 the first mode is preserved even for long exposures. The described alignment trend was confirmed for a number of polyimides containing hydrophobic fluoroalkyl or alkyl groups.

3.3 Alignment uniformity

To judge the alignment uniformity on large surfaces, we modeled them by setting small aligning substrates (20 × 30 cm^2 by size) parallel to each to other, with different places of the large holder (mosaic principle). The width of the holder was chosen to be the width of the plasma "sheet" restricted by the length of the glow discharge channel. LC alignment on different substrates was compared. For irradiation times longer then the time of one translation cycle, the in-plane alignment directions for different substrates pretty much coincide; the deviation of the easy axis is within 1° and it even decreases with a number of translation cycles. For all the substrates, we obtained the same estimate for the azimuthal anchoring energy: $W_a > 10^{-4}$ J/m^2. The anchoring

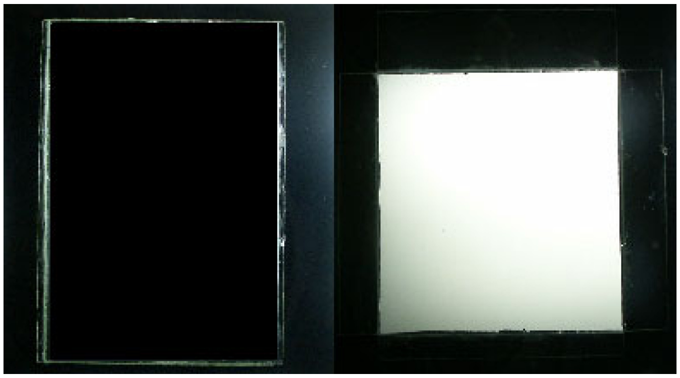

FIGURE 7 — Photos of 120 x 150 mm^2 symmetric cells (d = 15 μm) based on plasma treated PI substrates viewed between two crossed polarizers. The cells are filled with LC ZLI2293. (a) Twist angle is zero; (b) twist angle is 90°. Irradiation conditions: α = 70°, j = 8 μA/cm^2, E = 600 V, 2 min (a) and 10 min (b).

transition from the first to the second mode occurs simultaneously in all the aligning substrates. This implies a rather good uniformity of treatment and also good in-plane alignment uniformity on the hypothetical substrate with a size equal to the size of our holder (450×450 mm^2).

To check the out-of-plane uniformity, LC pretilt angle on the 20×30 cm^2 substrates was compared. The deviation of the pretilt angle for the substrates from the different places of holder was within 20%. This concerns both low tilt alignment (first mode) and high tilt alignment (VA).

Finally, Fig. 6 presents photographs of samples with increased size (12×15 cm^2) in the parallel (a) and 90°-twist (b) configuration. These photos show good in-plane alignment uniformity. The deviation of the pretilt angle within these cells is about 20%, that also confirms good out-of-plane uniformity of LC alignment.

Two methods of translation (source translation and substrate translation, Sec. 2.1) result in very similar alignment, including excellent alignment uniformity. At the same time, we prefer to translate the source in order to reduce damage risk of the large-area glass substrates characterized by a rather high fragility.

4 Conclusions

The results above demonstrate the high potential of ALT-generated "sheet"-like plasma fluxes for the alignment treatment of the large-area bounding substrates for LCDs. This method provides LC alignment with high uniformity in the azimuthal (in-plane) and polar (out-of-plane) directions. The method can be effectively used to realize low tilt alignment for the TN and IPS modes, and high tilt alignment for the VA mode. Despite studying only the alignment on the 450×450 mm^2 surfaces, limited by the length of the ALT source, we can predict high alignment uniformity on substrates with a substantially larger size. Indeed, ALT can be easily scaled and adapted for the treatment of large-area surfaces. As we predicted, these sources will be utilized not only for treatment, but also for coating of the large-area films (plasma polymers, a-C:H coatings, *etc.*) for LC alignment and, possibly, other purposes (antireflective coatings, *etc.*).

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