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Generation of pretilt angle in NLCs and EO characteristics of a photo-aligned TN-LCD with oblique non-polarized UV light irradiation on a polyimide surface

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We have investigated the generation of pretilt angle for a nematic liquid crystal (NLC) alignment in cells with oblique non-polarized ultraviolet (UV) light irradiation on polyimide (PI) surfaces. It was found that monodomain alignment of the NLC is obtained with an incident angle of 70° and 75° on the PI surface. It is considered that this alignment may be attributed to the anisotropic dispersion force due to photo-depolymerization of polymer on PI surfaces. Also, the generated NLC pretilt angles are all about 3° at an incident angle of 70° and 75° for 1 h irradiation. Next, we observed that the voltage–transmittance characteristics for a photo-aligned twisted nematic (TN) LCD with an incident angle of 80° on a PI surface were excellent. Also, we measured that the voltage-holding-ratio (VHR) of a photo-aligned TN-LCD is about 94%; it is almost same as obtained for rubbing-aligned TN-LCDs. Finally, the slow response time of photo-aligned TN-LCDs is attributable to their weak anchoring strength.

1. Introduction

Liquid crystal displays (LCDs) are the dominant flat panel display technology. The successful operation of LCDs requires uniform alignment and controlled pretilt of the LC on substrate surfaces. Most LCDs with pretilted homogeneous LC alignment are prepared by using rubbed polyimide (PI) surfaces. The leading technology for LCD is based on twisted nematic (TN) LCDs [1]. Director pretilt prevents the creation of reverse tilted disclinations in TN-LCDs. Pretilt is also important to avoid stripe domains in super (S) TN-LCDs [2]. The generation of pretilt angle in NLCs on various alignment layers by unidirectional rubbing has been demonstrated and discussed by many investigators [3–7]. Rubbed polymer surfaces have been widely used to align LC molecules. Currently, rubbing-free techniques for LC alignment are needed in thin film transistor (TFT)-LCD fabrication. In a previous paper, we reported that TFTs are damaged by the electrostatic induced during rubbing [8]. The photo-alignment method for LC alignment is expected to achieve high resolution LCDs; Gibbons *et al.* have reported a new method for LC alignment using polarized laser light [9]. Also, the pretilt angle on Langmuir–Blodgett films has been controlled by regulation of the fraction of *trans*-azobenzene units, using light wavelength tuning [10].

More recently, LC alignment with polarized UV light irradiation of poly(vinyl)cinnamate surfaces has been reported [11–13]. The photo-polymerization reaction of a photo-polymer with polarized UV light has been shown to induce uniaxial orientation of NLCs on poly(vinyl)cinnamate surfaces. LC alignment by polarized UV light irradiation of PI surfaces has also been reported [14–16]. The photo-depolymerization of PI main chains parallel to the electric field of deep polarized UV light (257 nm), causing an anisotropic dispersion force, is discussed in [14]. Finally, Yamamoto *et al.* have reported LC alignment in a cell with oblique irradiation of non-polarized UV light on PI surfaces [17]. The generated pretilt angle of the NLC is about 0.8° on PI surfaces with side chains. However, this pretilt is not enough to avoid reverse tilted disclination in a TN-LCD. Most recently, we reported the generation of 3° pretilt in NLCs with oblique non-polarized UV irradiation of PI surfaces [18]. The detailed mechanism of LC alignment by the photo-alignment method has not yet been explained.

In this study, we report pretilt angle generation and the electro-optical (EO) performance of TN-LCDs photo-aligned by oblique non-polarized UV light irradiation of PI surfaces.

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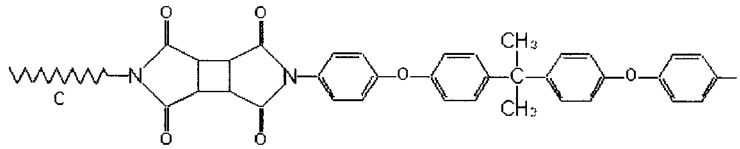


Figure 1. Chemical structure of the polymer.

2. Experimental

Figure 1 shows the chemical structure of the PI material used in this study. The PI films were coated on indium tin oxide (ITO) coated glass substrates by spin-coating, and were imidized at 250°C for 1 h. The thickness of the PI layers was about 500 Å. The oblique non-polarized UV irradiation system (power: 1 kW) is shown in figure 2. The substrates were irradiated for 3 h using UV light at a wavelength of 365 nm. To measure the pretilt angle, the LC was assembled in sandwich-type cells with antiparallel-UV irradiation direction. All the cells had an LC layer thickness of 60 μm. After assembly, the cells were filled with an NLC consisting of a fluorinated mixture (T_c = 87°C) in the nematic phase; the cells were then annealed in the isotropic phase for 30 min. The photo-aligned TN-LCD was assembled using oblique (80°) non-polarized UV light irradiation of the PI surface. The LC layer thickness was about 5 μm. The LC orientation capability was evaluated by observation of optical microscopic textures and by the generation of pretilt angles. To measure pretilt angles, the crystal rotation method was used; measurements were made at room temperature. The surface morphology of the PI surface was observed by using atomic force microscopy (AFM). We also observed the EO characteristics of the photo-aligned and rubbing-aligned TN-LCDs.

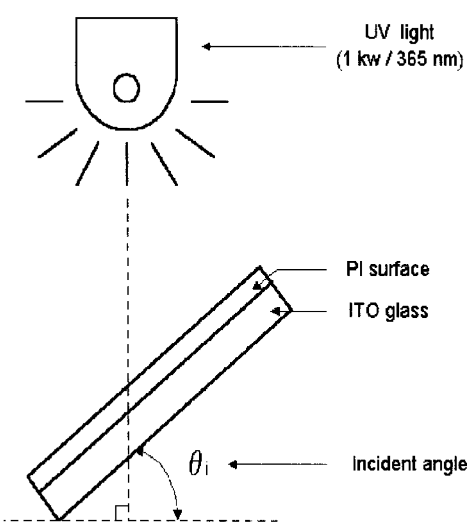


Figure 2. Schematic diagram of UV light irradiation system.

3. Results and discussion

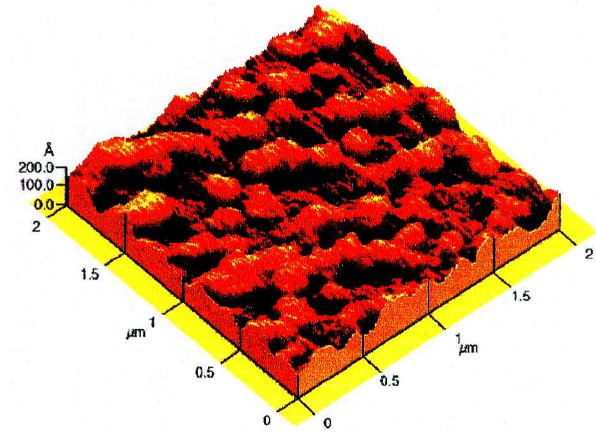
Figure 3 shows the AFM images of PI surfaces with side chain (*a*) unrubbed (*b*) rubbed, and (*c*) with oblique (70°) non-polarized UV light irradiation. It can be seen that the micro-groove structure has not been formed with the oblique non-polarized UV irradiation. Also, we observed a micro-groove structure along the rubbing direction on the rubbed PI surface for medium rubbing strength (RS) (RS = 262 mm) as shown in figure 3(*b*); this is similar to the results of previous work [18, 19].

We next measured an induced optical retardation of about 0.05° with oblique non-polarized UV light irradiation on the PI surface. In a previous paper, we reported that the induced optical retardation is about 1.3° on a rubbed PI surface with side chain [5]. It is considered that the induced optical retardation with oblique non-polarized UV is small compared with the rubbed PI surface because the former is attributable to photo-depolymerization of the polymer.

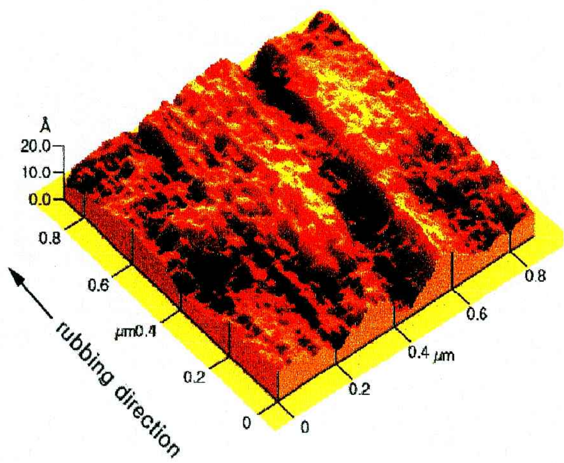
Figure 4 shows a microphotograph of the NLC in a cell aligned with oblique (80°) non-polarized UV light irradiation on the PI surface for 2 h (between crossed Nicols); monodomain alignment of the NLC is observed. In a previous paper, we reported that disclination is observed after oblique non-polarized UV light irradiation on a PI surface with side chain for 3 h [18]. It is considered that the monodomain alignment of the NLC depends on the UV irradiation time.

Liquid crystal alignment with oblique non-polarized UV light irradiation on the PI surface is shown in figure 5. We suggest that the aligned NLC is parallel to the incident direction (p-wave) of UV light. Therefore, we consider that the NLC alignment is due to photo-depolymerization of the polymer with oblique non-polarized UV light irradiation on PI surfaces [14–18].

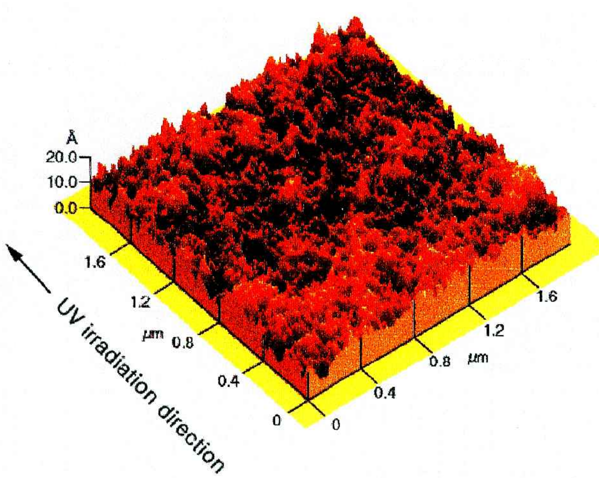
Figure 6 shows the transmittance versus pretilt angle for two angles of incidence of non-polarized UV light: (*a*) incident angle of 75° for 1 h, and (*b*) incident angle of 80° for 2 h. The generated NLC pretilt angle as a function of angle of incidence is shown in figure 7. The generated NLC pretilt angle is greater than 3° with an incident angle of 70° and 75° for 1 h, as shown in figure 7(*a*); it decreases above 80°. We consider that this pretilt angle is almost same as obtained with the rubbed PI surface with side chain [5]. In a previous result, the generated NLC pretilt angle was about 1° with oblique



(*a*)



(*b*)



(*c*)

Figure 3. AFM images on PI surface: (*a*) unrubbed PI, (*b*) rubbed PI, (*c*) oblique non-polarized UV light irradiation on Pi.

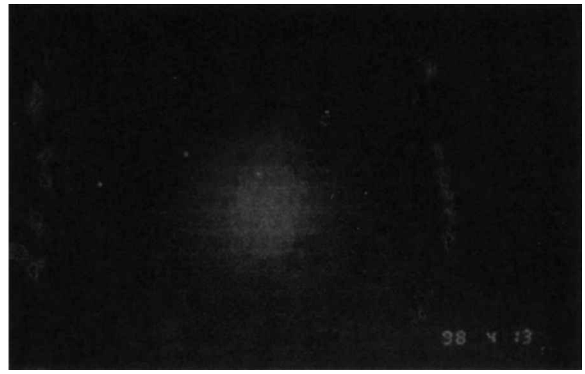


Figure 4. Microphotograph of aligned NLC in a cell with oblique non-polarized UV light irradiation of 80° on a PI surface (between crossed Nicols).

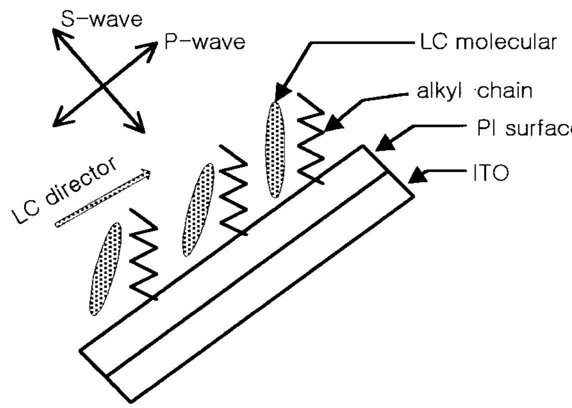


Figure 5. Liquid crystal alignment with oblique non-polarized UV light irradiation on PI surface.

non-polarized UV light irradiation of 80° on the PI surface for 3 h; this is almost the same as that given by Yamamoto *et al.* [17]. From these results, we consider that the NLC pretilt angles can be attributed to the interaction between the LC molecules and the polymer surface due to photo-depolymerization of polymer during UV light irradiation. Also, the NLC pretilt angle increases with increasing angle of incidence of UV light for a 2 h period, as shown in figure 7(*b*). Moreover, the NLC pretilt angle increases with increasing the irradiation time above 80° as shown in figures 7(*a*) and (*b*). The energy density of UV light decreases with increasing incident angle and increases with increasing irradiation time. Therefore, we consider that NLC pretilt angle generation above 80° requires much more irradiation time, as shown in figure 6(*a*). Consequently, we suggest that the pretilt angle strongly depends on the angle of incidence and the UV irradiation time.

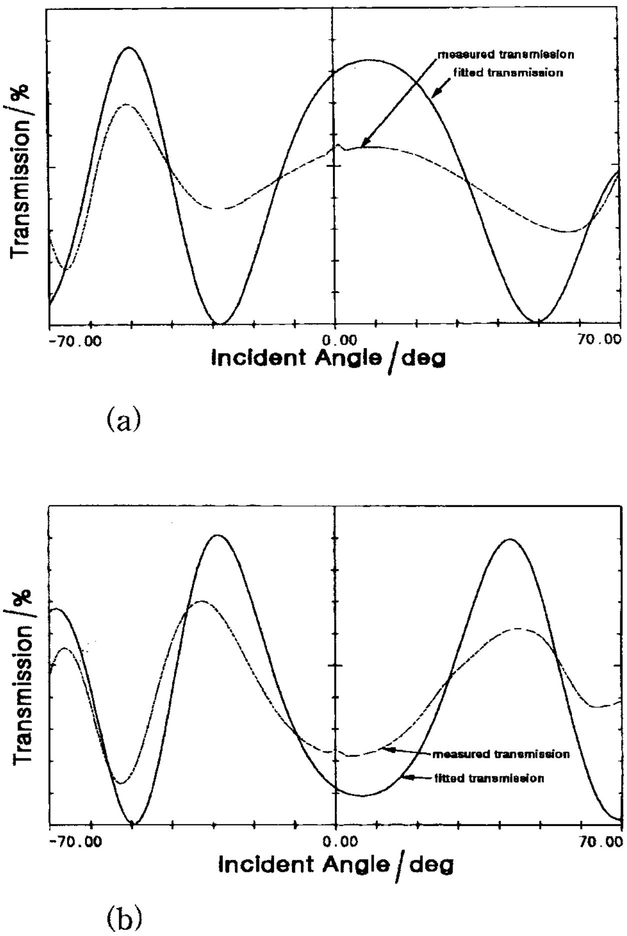


Figure 6. Transmission versus pretilt angle: (*a*) angle of incidence 75°, 1 h irradiation; (*b*) angle of incidence 80°, 2 h irradiation.

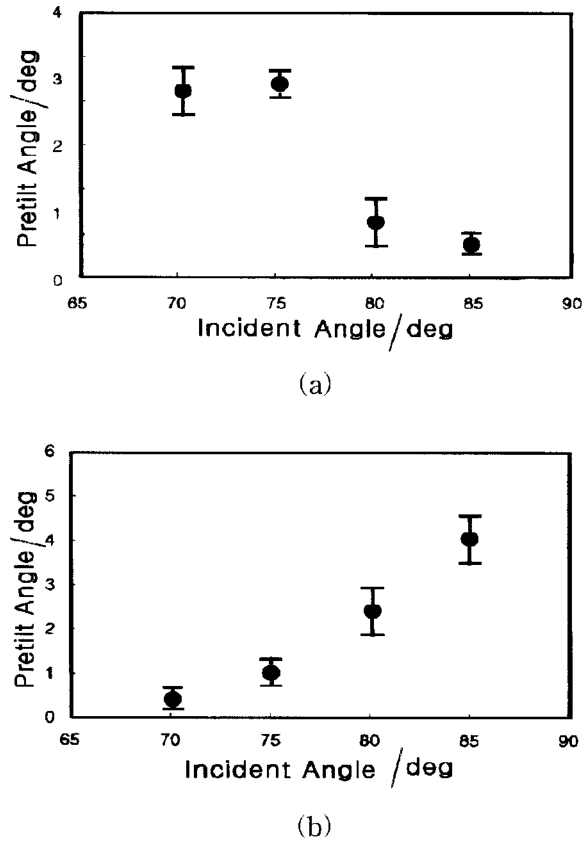
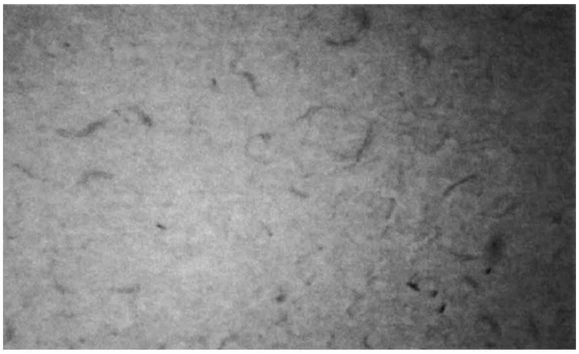


Figure 7. Generation of pretilt angle in NLC with oblique non-polarized UV light irradiation on PI surfaces as a function of incident angle: (*a*) 1 h irradiation, (*b*) 2 h irradiation.

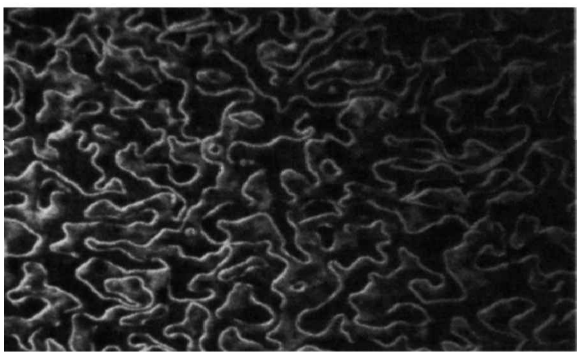
Figure 8 gives microphotographs of a photo-aligned TN-LCD with 80° oblique non-polarized UV light irradiation on a PI surface with side chain for 2 h. It is seen that reverse tilt disclinations are formed due to low pretilt angle at the on-state.

We also investigated the EO characteristics of the photo-aligned TN-LCD. Figure 9 shows the voltage-transmittance (*V-T*) characteristics of a photo-aligned TN-LCD with oblique non-polarized UV light irradiation of 80° on PI surface for 2 h, and a rubbing-aligned TN-LCD on PI surface with RS = 164 mm. Table 1 gives *V* versus *T* plots for a photo-aligned TN-LCD and a rubbing-aligned TN-LCD. The threshold voltage of the photo-aligned TN-LCD is low compared with that of the rubbing-aligned TN-LCD. The VHR of the photo-aligned TN-LCD was about 94%. It is considered that the VHR values of photo-aligned and rubbing aligned TN-LCDs are almost same.

The response time characteristics of a photo-aligned TN-LCD with oblique non-polarized UV light irradiation of 80° on PI surface for 2 h are shown in figure 10. It is seen that the curve of the photo-aligned TN-LCD is less sharp than that of the rubbing-aligned TN-LCD in their decay time characteristics. Also, a backflow effect in the photo-aligned TN-LCD is not observed. Table 2 summarizes the figure 10 results. The slow response time characteristics of the photo-aligned TN-LCD are clearly seen. Recently, Hasegawa *et al.* have reported that the polar anchoring energy of an NLC in a cell with polarized UV light irradiation on polymer (CBDA-ODA) is about 1×10^{-4} J m^{-2} [20]. In a previous paper, we reported that the polar anchoring energy of an NLC is about 1×10^{-3} J m^{-2} on a rubbed PI surface with side chain [21]. Therefore, it is considered that the anchoring strength of a photo-aligned NLC is weak in comparison with a rubbing aligned NLC. From these results, we consider that the slow response time of a photo-aligned TN-LCD may be attributed to the weak anchoring strength between the LC molecules and the polymer surface, due to depolymerization by UV light irradiation of the PI surface.



(a)



(b)

Figure 8. Microphotograph of photo-aligned TN-LCD with oblique non-polarized UV light irradiation of 80° on PI surface: (*a*) off-state, (*b*) on-state.

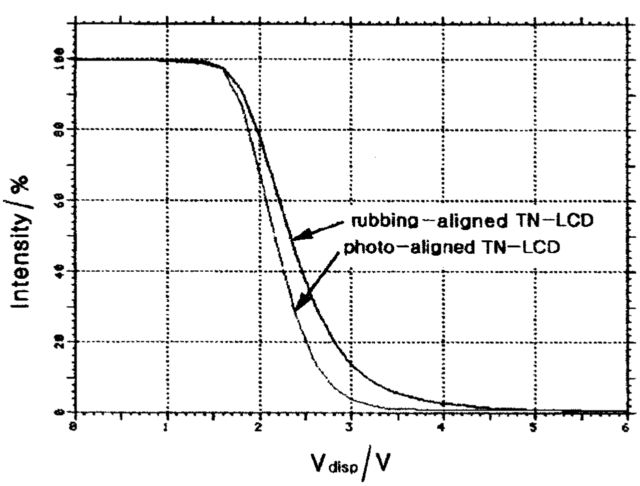


Figure 9. Voltage–transmission characteristics for a photo-aligned TN-LCD with oblique non-polarized UV light irradiation of 80° on a PI surface; and for a rubbing-aligned TN-LCD.

4. Conclusions

In summary, we have investigated the generation of NLC pretilt angle with oblique non-polarized UV light irradiation on PI surfaces. It was found that monodomain alignment of the NLC is obtained with an incident angle of 70° and 75° on a PI surface. This monodomain alignment of the NLC is attributed to the anisotropic dispersion force due to photo-depolymerization of polymer on PI surfaces. Also, the generated NLC pretilt angle strongly depends on the irradiation angle and the irradiation time of the UV light. Next, we observed that the voltage–transmittance and the VHR characteristics of a photo-aligned TN-LCD with an incidence angle of 80° on the PI surface were almost the same as obtained for a rubbing-aligned TN-LCD. Finally, the slow response time characteristics of a photo-aligned TN-LCD is attributed to the weak anchoring strength of the NLC.

Table 1. Applied voltage (V) versus transmittance for a photo-aligned TN-LCD with oblique non-polarized UV light irradiation of 80° on PI surface, and a rubbing-aligned TN-LCD.

Transmittance	Rubbing-aligned TN-LCD	Photo-aligned TN-LCD
10%	3.16	2.70
90%	1.82	1.75

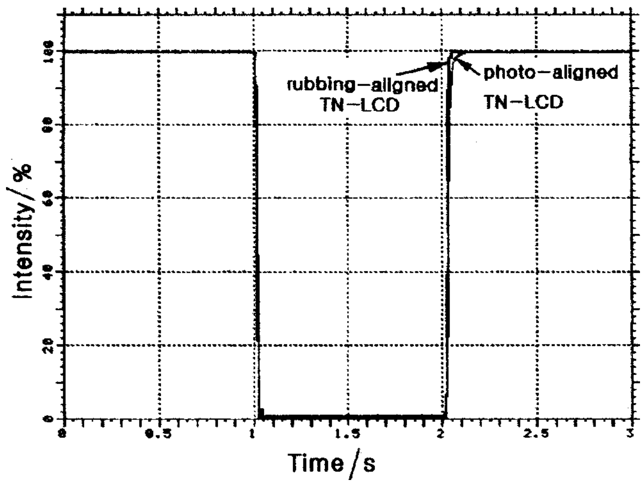


Figure 10. Response time characteristics for a photo-aligned TN-LCD with oblique non-polarized UV light irradiation of 80° on a PI surface; and for a rubbing-aligned TN-LCD.

Table 2. Response time characteristics for a photo-aligned TN-LCD with oblique non-polarized UV light irradiation of 80° on PI surface, and for a rubbing-aligned TN-LCD.

Alignment	Rising time τ_r/msec	Decay time τ_d/msec	Response time τ/msec
Rubbing	8.1	12.7	20.9
Photo	9.6	22.2	31.8

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