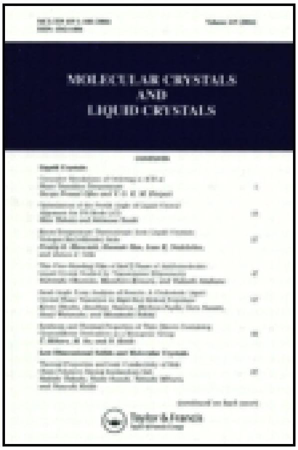

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Evaluation of Pretilt Angle and Polar Anchoring Strength of Amorphous Alignment Liquid Crystal Display from Capacitance Versus Applied Voltage Measurement

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The pretilt angle and the anchoring strength are important parameters in liquid crystal displays (LCDs). However, in the case of amorphous LCDs (a-LCDs), it is difficult to evaluate these parameters by means of conventional measurement method due to non-uniformity of the LC directors. In this paper, we report the simultaneous evaluation method of the pretilt angle and the polar angle anchoring strength of a-LCDs by fitting the theoretical values based on the elastic continuum theory to the data obtained by the measurement of capacitance versus applied voltage (C-V) characteristics. We evaluate the pretilt angle and the polar anchoring strength of a-LCD using the polyimide alignment films. We confirm the pretilt angle and the polar anchoring strength of a-LCD are strongly dependent on surface energy of the polyimide alignment film.

Keywords: amorphous LCD; pretilt angle; polar anchoring strength; capacitance versus applied voltage characteristics; liquid crystal

1. INTRODUCTION

Amorphous liquid crystal displays (a-LCDs) exhibit the following several superiorities: the simplicity in the production (prepared by the non-rubbing technology); the wide and homogeneous viewing angular characteristics that is free from contrast inversion occurring in the vertical direction; the optical transmission versus applied voltage characteristics free from the viewing angle dependence, which provides a benefit for the gray scale operation; and excellent voltage holding ratio that is necessary for TFT-driven twisted nematic LCDs [1]. On the other hand, it is difficult to evaluate pretilt angle and polar angle anchoring strength of the a-LCD by conventional measurement method due to the non-uniformity of LC alignment. It is needless to say that the pretilt angle and the polar angle anchoring strength are very important parameters in LCDs. Many methods of measuring the polar angle anchoring strength such as surface disclination [2,3], wedge cell [4,5], Freedericksz transition [6,7], high field [8-10] have been given based on various phenomena. Koyama and Akahane proposed a method [11] which is based on the measurement of cell capacitance change with an external field. This method can be applicable to the simultaneous evaluation of the pretilt angle and the polar angle anchoring strength without depending on the azimuthal orientation of the LC director. Therefore, we try to apply this method to the evaluation of the pretilt angle and the polar angle anchoring strength of the a-LCD.

2. PRINCIPLES

We assume that the surface energy is given by

$$F_S = \frac{1}{2} A_\theta \sin^2(\theta_0 - \theta_p) \tag{1}$$

where A_θ is a polar anchoring strength, θ_p is a pretilt angle of the easy axis, and θ_0 is a tilt angle of LC director at the surface.

Using the elastic continuum theory of nematic liquid crystals, we obtain the relation between a normalized applied voltage v, θ_0 and θ_m (the tilt angle at the mid-plane of the cell) as

$$v = \frac{2}{\pi}\left(1 + \gamma \sin^2\theta_m\right)^{1/2} \int_{\theta_0}^{\theta_m} \left[\frac{1 + \kappa \sin^2\theta}{(1 + \gamma \sin^2\theta)(\sin^2\theta_m - \sin^2\theta)}\right]^{1/2} d\theta \tag{2}$$

and

$$\left[\frac{(1 + \kappa \sin^2\theta_0)(\sin^2\theta_m - \sin^2\theta_0)}{1 + \gamma \sin^2\theta_0}\right]^{1/2} \int_{\theta_0}^{\theta_m} \left[\frac{(1 + \gamma \sin^2\theta)(1 + \kappa \sin^2\theta)}{\sin^2\theta_m - \sin^2\theta}\right]^{1/2} d\theta = \frac{1}{4}\beta \sin 2(\theta_0 - \theta_p) \tag{3}$$

where

$$\gamma \equiv \frac{\varepsilon_{//} - \varepsilon_{\perp}}{\varepsilon_{\perp}} = \frac{\Delta\varepsilon}{\varepsilon_{\perp}}, \tag{4}$$

$$\kappa \equiv \frac{K_3 - K_1}{K_1}, \tag{5}$$

$$\beta = \frac{A_\theta d}{K_1}, \tag{6}$$

$$V_c \equiv \pi\left(\frac{K_1}{\Delta\varepsilon}\right)^{1/2}, \tag{7}$$

$$v \equiv \frac{V}{V_c}. \tag{8}$$

The cell capacitance is given by

$$\frac{C}{C_\perp} = \frac{2}{\pi}\left(1 + \gamma\sin^2\theta_m\right)^{1/2}\frac{1}{v}\int_{\theta_0}^{\theta_m}\left[\frac{\left(1+\gamma\sin^2\theta\right)\left(1+\kappa\sin^2\theta\right)}{\sin^2\theta_m - \sin^2\theta}\right]^{1/2} d\theta \tag{9}$$

where

$$C_\perp = \frac{\varepsilon_\perp S}{d}. \tag{10}$$

The applied voltage dependence of θ_m and θ_0 is obtained by eqs. (2) and (3). Then, the applied voltage dependence of the cell capacitance is calculated by eq. (9).

When θ_p is zero, clear threshold voltage of Freedericksz transition V_{th} exist even anchoring strength is finite, and Vth depend on ß. In order to introduce relationship between V_{th} and ß, we consider a limitation of θ_m to zero and obtain as follows:

$$\beta = \pi v_{th}\tan\frac{\pi v_{th}}{2}, \quad v_{th} \equiv \frac{V_{th}}{V_c}. \tag{11}$$

In addition to the Freedericksz transition, LC alignment transition from splay-bend alignment to homeotropic alignment occurs at high voltage (saturation voltage V_s). In order to introduce relationship between V_s and ß, we consider a limitation of θ_0 to $\pi/2$ and obtain

$$\beta = \pi(1+\kappa)^{1/2} v_s \tanh\left[\frac{\pi v_s}{2(1+\kappa)^{1/2}}\right], \quad v_s = \frac{V_s}{V_c} \tag{12}$$

According to eq. (11) and eq. (12), relationship between ß with normalized voltage of Freedericksz transition of the threshold voltage and the saturation voltage are calculated as shown in Figure 1, respectively. The threshold voltage curve is saturates when ß is larger than 10. On the other hand, the saturation voltage curve does not saturate. Therefore, it is found that the measurement of the saturation voltage field is suitable for evaluation of anchoring strength. So in this paper, we evaluate the anchoring strength at the saturation voltage.

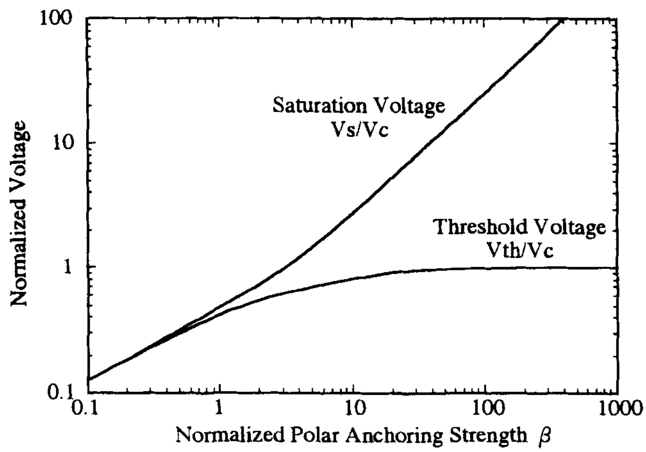

FIGURE 1 Normalized polar anchoring strength dependence of the threshold voltage and the saturated voltage.

3. EXPERIMENTAL

3.1 Measurement system

The C-V measurement system is very simple as is shown in Figure 2 schematically. Figure 3 shows C-V characteristics of an LCD measured by C-V measurement system and LCR meter (HP4284A) which is on the market. These C-V characteristics of the LCD measured by different systems show rather good agreement. This indicates that the C-V measurement system has a high precision as well as LCR meter. The C-V region, then this system is suitable for measuring the cell capacitance of the saturation voltage.

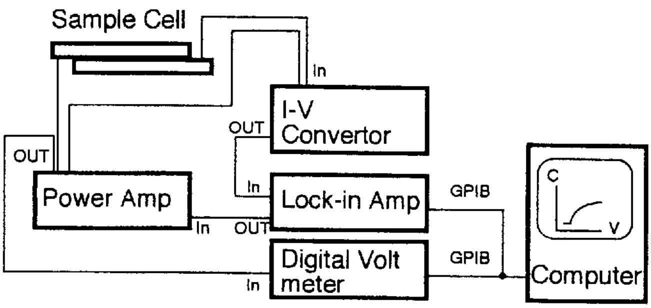

FIGURE 2 C-V measurement system.

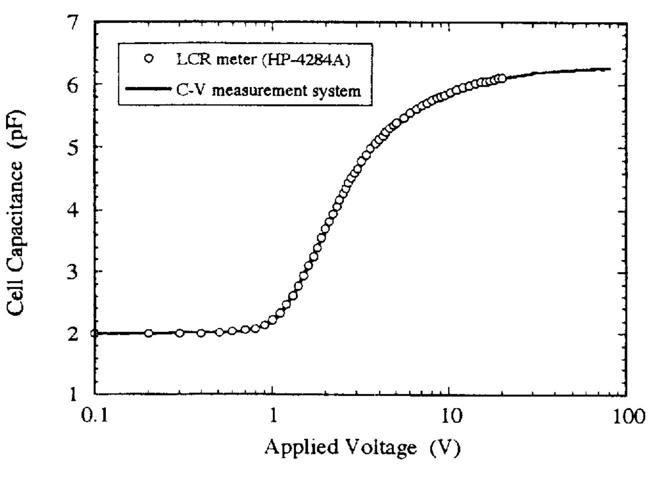

FIGURE 3 C-V characteristics of the cell measured by C-V measurement system and LCR meter (HP4284A).

3.2 LCD preparation and measurement condition

The nematic liquid crystal material used in our experiment was fluorinated type mixture. No chiral material was added to the liquid crystal. Three types of polyimide alignment films were used (PI-A to C: Nissan chem. Ind.). PI-A is a very low pretilt angle type polyimide film and used for preparing strong anchoring cell (standard sample). PI-B is an alkyl branched type polyimide film, and used for preparing rubbed and a-LCDs. PI-C whose surface energy is controllable by annealing temperature is used for preparing a-LCDs with various annealing temperature. The thickness of these polyimide films were controlled to be as thin as possible (thinner than 10nm) in order to avoid the influence of film capacitance. The rubbing direction of the rubbed LCD was adjusted to be an anti-parallel alignment. The cell thickness was 5.6μm except for standard sample. The cooling rate of the a-LCDs at the isotropic-nematic phase transition after LC injection were controlled from -0.34°C/min to -313°C/min. In order to observe display properties of a-LCDs, a-TN-LCDs were prepared under same cell condition except for doping a chiral dopant (S-811, Merck) in the nematic liquid crystal material. The concentration of the chiral dopant was adjusted so as to be d/p=1/4, where p stand for the chiral pitch. In C-V measurement, AC voltage up to 120V with 1000 kilohertz was applied to LCDs.

In order to measure the pretilt angle and the anchoring strength of LCDs, LC material properties must be measured exactly by using strong anchoring cell with zero pretilt. In our experiment, we used the cell (standard sample) as a strong anchoring whose cell thickness was thick (50μm) and alignment film was rubbed PI-A film with low pretilt (0.6°). We measured the nematic LC material properties by using the standard sample as shown in Table 1.

TABLE 1 Nematic LC material properties necessary for the simulations

Threshold Voltage [V]	1.23
$\gamma=\Delta\varepsilon/\varepsilon\perp$	2.547
κ=(K3-K1)/K1	1.033

4. RESULTS AND DISCUSSION

4.1 C-V characteristics of strong anchoring cell

Figure 4 shows measured C-V characteristics of the standard sample and calculated C-V characteristics by applying the nematic LC material properties shown in Table 1. In Figure 4, the horizontal axis is Vc/V, and the vertical axis is C/Cs; solid square plot is measured data; broken line and solid line are calculated data whose anchoring strengths are infinity and pretilt angle are 0.01° and 0.6°, respectively. Measured and calculated C-V characteristics show perfect agreement. Therefore, we confirm that the standard sample can be regarded as a strongly anchoring and very low pretilt angle cell.

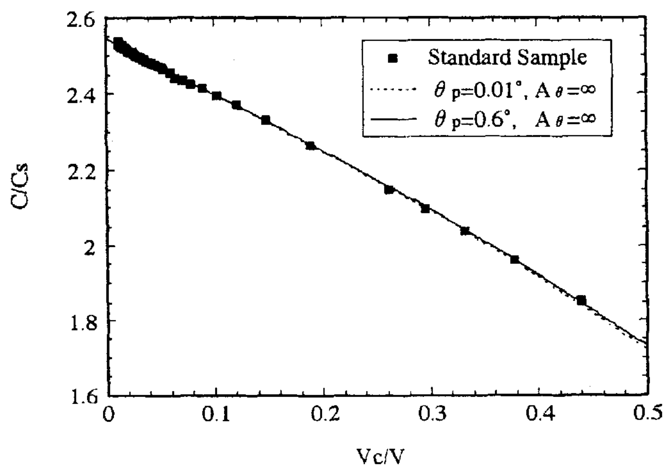

FIGURE 4 C-V characteristics of the standard sample (PI-A).

4.2 Influence of the disclination lines

Figure 5 shows microscopic textures of a-LCDs. As shown in Figure 5, these a-LCDs have non-uniform alignment, and the domain size of the alignment can be controlled by cooling rate of the a-LCDs at the LC phase transition from isotropic to nematic phase. When the voltages are applied to the a-LCDs, innumerable reverse tilt disclination lines appear as is shown in Figure 6. And the density of the disclination lines is lower as the cooling rate is slower. This disclination lines disappear with higher electric voltage (>6V).

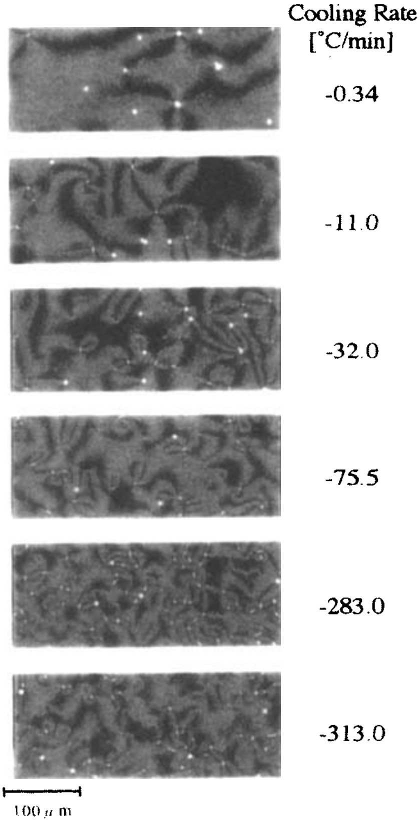

FIGURE 5 Microscopic textures of a-LCDs (V=0V).

See Color Plate XIII at the back of this issue.

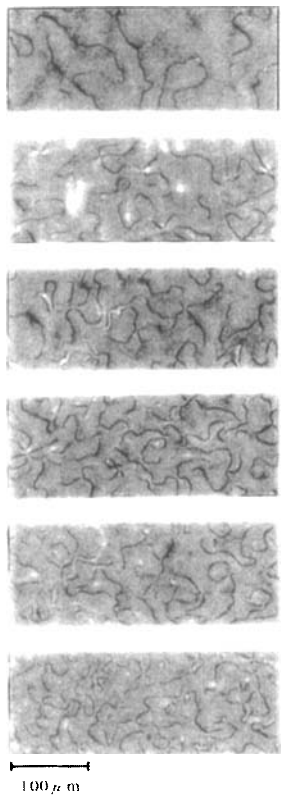

FIGURE 6 Microscopic textures of a-LCDs (V=3V).

See Color Plate XIV at the back of this issue.

In order to study the influence of existence of the disclination lines to the C-V characteristics, we measured the C-V characteristics of rapid cooling (-283°C/min) a-LCD, slow cooling (-0.34°C/min) a-LCD and rubbed LCD (with no reverse tilt disclination lines), as shown in Figure 7.

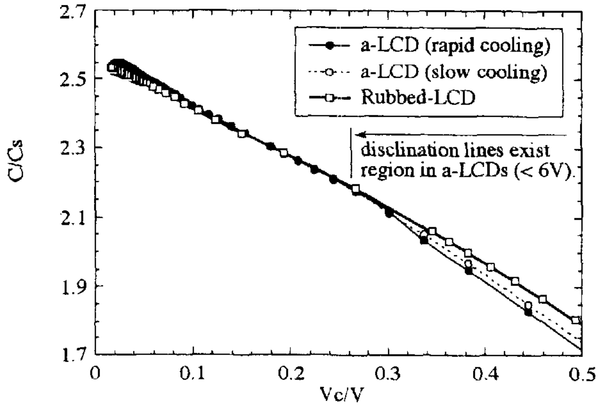

FIGURE 7 C-V characteristics of amorphous alignment LCDs (rapid and slow cooling LCD) and rubbed LCD.

At the low voltage region (<6V), where the disclination lines exist, the capacitance values of the two types of a-LCDs are lower than those of rubbed LCD. Furthermore, the capacitance values of rapid cooling a-LCD are lower than those of slow cooling a-LCD. From these results, we found that the higher density of the disclination lines causes the lower capacitance value of the LCD. When lower voltage is applied to a-LCDs, the existence of the disclination lines degrades the precision of C-V measurement. However, when higher voltage (>6V) is applied to a-LCDs, the disclination lines disappear and the capacitance values of a-LCDs show almost the same as those of the rubbed LCD except saturation region (about Vc/V<0.15), as shown in Figure 7. There is no influence of the disclination lines at high voltage region except for the influence of the polar anchoring strength. Therefore, the disclination lines, which are observed in a-LCDs, do not affect the precision of C-V characteristics at high voltage region.

4.3 C-V characteristics of rubbed LCD with PI-B

Figure 8 shows measured and calculated C-V characteristics of rubbed LCD. We obtained the best fitting when θp=2.4°, Aθ=1×10^{-3} [J/m^2]. The pretilt angle of rubbed LCD evaluated by C-V method shows good agreement with that of same LCD evaluated by crystal rotation method.

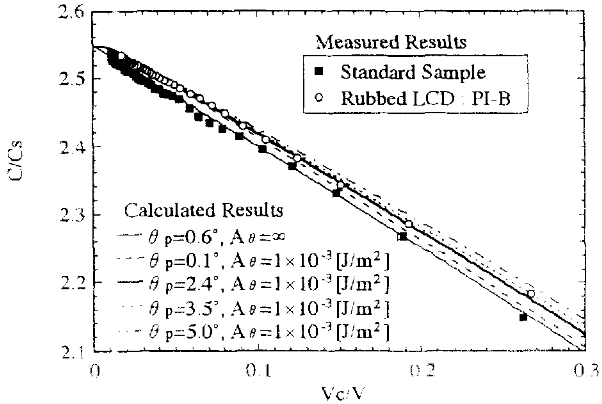

FIGURE 8 Measured and calculated C-V characteristics of rubbed LCD (PI-B).

4.4 C-V characteristics of a-LCD with PI-B

Figure 9 shows measured and calculated C-V characteristics of a-LCD. We obtained the best fitting when θp=0.1°, Aθ=6×10^{-4} [J/m^2]. The pretilt angle of a-LCD is perfectly zero and the polar angle anchoring strength of the a-LCD is relatively lower than that of rubbed LCD. The result of pretilt angle indicates all LC molecules in the a-LCD are aligned perfectly parallel to the substrate plane in spite of the use of the alkyl branched type of polyimide film.

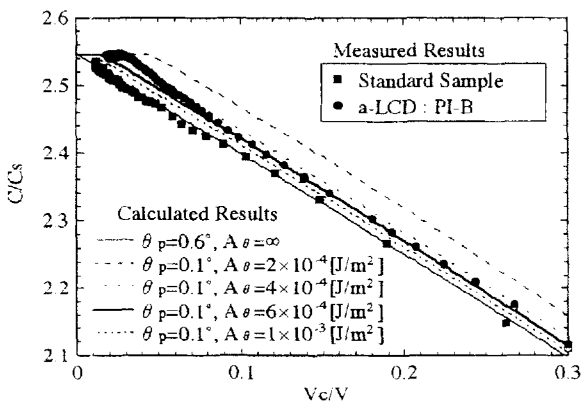

FIGURE 9 Measured and calculated C-V characteristics of a-LCD (PI-B).

4.5 C-V characteristics of a-LCD with PI-C

Figure 10 shows measured and calculated C-V characteristics of a-LCD with PI-C. From Figure 10, the pretilt angle and the polar anchoring strength of a-LCD are controlled by the annealing temperature of PI-C from 0.1° to 5.0° and from 2×10^{-4} to 5×10^{-4} [J/m^2], respectively. As shown in Figure 11, the surface energy of PI-C is lower as annealing temperature of PI-C is higher. Therefore, the pretilt angle and the anchoring strength of a-LCD is higher and weaker as the surface energy of polyimide film is lower.

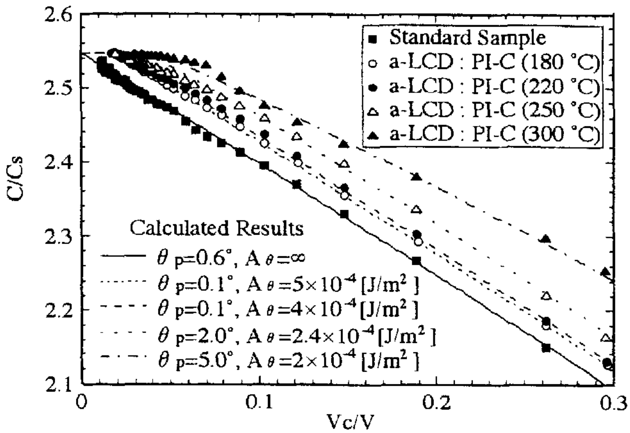

FIGURE 10 Measured and calculated C-V characteristics of a-LCD (PI-C).

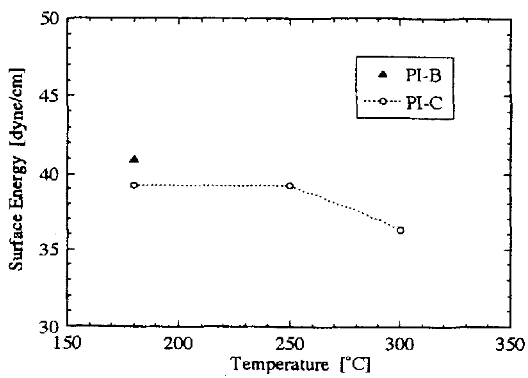

FIGURE 11 Annealing temperature dependence of surface energy of PI-C.

Figure 12 shows transmittance versus applied voltage (T-V) characteristics of a-TN-LCDs which are prepared by using PI-C. From Figure 12, threshold voltage and off-transmittance of a-TN-LCD depend on the annealing temperature of PI-C. This tendency of T-V characteristics is consistent with the annealing temperature dependence of pretilt angle of a-LCDs.

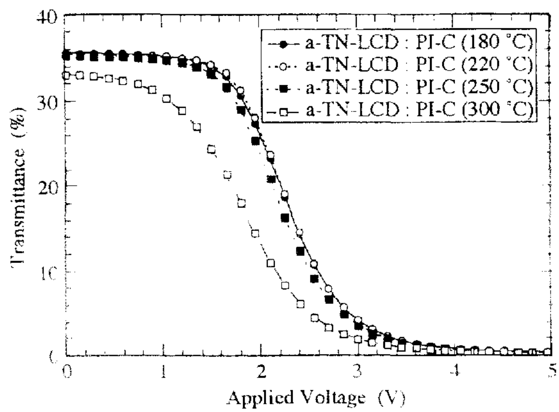

FIGURE 12 Transmittance versus applied voltage (T-V) characteristics of a-TN-LCDs (PI-C).

Table 2 shows response performance of a-TN-LCDs which cell prepared by using PI-C. From Table 2, rise time is faster and decay time is slower as the annealing temperature of PI-C is higher. This tendency of response performance is consistent with the annealing temperature dependence of the anchoring strength of a-LCDs.

TABLE 2 Response performance of a-TN-LCDs (PI-C).

Annealing Temperature of PI-C [°C]	Response Time [msec.]	
	Rise Time	Decay Time
180	9.5	21.6
220	9.1	20.3
250	8.8	22.7
300	8.5	44.0

We confirmed that the pretilt angle and the polar anchoring strength of a-LCDs are controllable by the surface energy of the polyimide alignment film.

5. CONCLUSIONS

The C-V measurement method can evaluate the pretilt angle and the polar angle anchoring strength simultaneously for various alignment LCDs such as a-LCD. The pretilt angle of rubbed LCD measured by this method shows good agreement with the value evaluated by crystal rotation method. We confirmed that the polar angle anchoring strength of the a-LCD is relatively weaker than that of rubbed LCD. In addition, we confirmed that the pretilt angle and the polar angle anchoring strength of a-LCD is controllable by the surface energy of the polyimide alignment film. The pretilt angle of a-LCD is controlled up to 5°. This result of the pretilt angle and the polar angle anchoring strength of a-LCD is consistent with the T-V characteristics and response performance of a-TN-LCDs.

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