

FERROELECTRIC LIQUID CRYSTAL DEVICE AND
METHOD OF DRIVING THE SAME

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The present invention relates to a liquid crystal device and, more particularly, to a ferroelectric liquid crystal device having both a high-speed response characteristic and a memory effect and a method of driving the same.

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It is expected that a ferroelectric liquid crystal is applied to a high-speed liquid crystal shutter for a printer and large-capacity display by utilizing its memory effect and high-speed response characteristic.

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Most of ferroelectric liquid crystal devices manufactured as test samples so far are those in which a ferroelectric liquid crystal is sandwiched between two glass plates each having alignment films composed of rubbed organic polymer films or oblique deposited inorganic insulating member as of SiO on opposing surfaces. For example, Japanese Patent Laid-Open No. 62-173433 discloses a liquid crystal device using a rubbed polyimide thin film. In a liquid crystal device of this type, all the liquid crystal molecules are aligned in the same direction to be

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parallel to the glass substrate surfaces, i.e., in a uniform aligned state upon application of a voltage. When a driving voltage is reset to zero, the uniform alignment is disordered, and the liquid crystal molecules define a twisted structure between the glass substrates, i.e., are in a twisted aligned state. As a result, a memory effect is considerably impaired.

In contrast to this, as in a method disclosed in Japanese Patent Laid-Open No. 62-250418, a liquid crystal device in which two substrates having alignment films formed by SiO oblique deposition are arranged so that each direction of deposition in the same inclination state can provide a memory effect. However, memory nonuniformity locally occurs, and uniform switching characteristics are difficult to obtain.

Japanese Patent Laid-Open No. 62-160420 discloses a liquid crystal device in which stable states of liquid crystal molecules include two different uniform aligned states and a twisted aligned state. It is demonstrated that this liquid crystal device does not much suffer from display nonuniformity caused by memory nonuniformity. However, a definite structure of a liquid crystal device which can take three stable display states and a satisfactory method of driving the same have not been developed yet.

Another problem posed in a practical application of a ferroelectric liquid crystal device is that a bright state of a ferroelectric liquid crystal device is undesirably colored in a variety of colors depending on refractive index anisotropy of liquid crystal molecules and a thickness of a liquid crystal layer, and the ferroelectric liquid crystal device is not easy to perform black-and-white display.

Furthermore, when a ferroelectric liquid crystal device is put into a practical application, continuous gray scale control of a transmittance in a multiplex driving mode poses a serious technical problem. For example, Japanese Patent Laid-Open No. 62-160420 tries gray scale display in the multiplex driving mode by utilizing three states, i.e., two different uniform aligned states and a twisted aligned state. However, in this prior art, only three gray scale levels can be displayed. Japanese Patent Laid-Open No. 59-193427 discloses a technique in which the number of driving pulses is changed to cause bistable states to coexist, thereby making an attempt of gray scale display. However, according to the experiments of the present inventors, halftone level changed over time in the multiplex driving mode, and stable halftone display could not be obtained.

It is a first object of the present invention to provide a ferroelectric liquid crystal device which has a good memory effect and memory uniformity, and can provide a
5 bright state closer to white.

It is a second object of the present invention to provide a method of driving the ferroelectric liquid crystal device attained by the first object.

It is a third object of the present invention to
10 provide a method of driving a ferroelectric liquid crystal device which can precisely reproduce continuous gray scale levels even in a multiplex driving mode.

In order to achieve the first object, the present invention provides a new structure and driving method of a
15 liquid crystal device which has a twisted aligned state as one stable state.

In order to realize a liquid crystal device which has a stable twisted aligned state and two uniform aligned state, alignment films of an inorganic insulating member
20 are formed by oblique deposition on opposing surfaces of a pair of substrates having transparent electrodes on the opposing surfaces so that each direction of the deposition is reverse, and a ferroelectric liquid crystal is sandwiched between the substrates, so that a thickness of the

liquid crystal layer is set to fall within the range of 1.5 μm to 4 μm .

Furthermore, in order to achieve the second object, the twisted aligned state and one of the two uniform aligned states of the liquid crystal device are used as two
5 stable states to perform binary photoelectric control.

A method of driving the liquid crystal device for performing the binary photoelectric control is as follows. That is, a pair of positive and negative pulses having a
10 magnitude capable of changing an aligned state from one of the two uniform aligned states to the other are applied across the transparent electrodes in order to set the uniform aligned state that is one of the two stable states for binary control. In order to set the twisted aligned state
15 as the other of the two stable states for binary control, the same positive and negative pulses used for setting the uniform aligned state are applied first, and a pair of pulses in which a product of a voltage value and a pulse width is decreased stepwise so as not to set the other uniform aligned state are then applied.
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In order to achieve the third object, a voltage signal in which a product of a voltage peak value and a pulse width is modulated is applied across transparent electrodes of the ferroelectric liquid crystal device, in
25 which the twisted and two uniform aligned states are

sufficiently stable, to control a coexistence ratio of twisted and uniform aligned states, thereby achieving continuous gray scale display.

5 Fig. 1 is a sectional view showing an embodiment of a ferroelectric liquid crystal device according to the present invention;

Fig. 2 is a view for explaining movements of liquid crystal molecules;

10 Figs. 3(a), 3(b), and 3(c) are views respectively showing two uniform aligned states and a twisted aligned state of the liquid crystal device;

Fig. 4 is a view showing the positional relationship between liquid crystal molecule arrays and a
15 polarizer;

Fig. 5 is a table showing transmission light characteristics corresponding to aligned states of liquid crystal molecules and driving waveforms for selecting the corresponding aligned states;

20 Fig. 6 is a chart showing driving signal waveforms for matrix-driving the ferroelectric liquid crystal device according to the present invention;

Figs. 7A, 7B, and 7C are waveform charts showing fluctuations of stable states of ferroelectric liquid crystal device in a multiplex driving mode;
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Fig. 8 is a table showing multiplex driving waveforms of the ferroelectric liquid crystal device according to the present invention; and

5 Figs. 9(a) and 9(b) are charts for explaining an optical response of the ferroelectric liquid crystal device in the multiplex driving mode.

The present invention will be described hereinafter with reference to the accompanying drawings.

10 Fig. 1 is a sectional view showing an embodiment of a ferroelectric liquid crystal device according to the present invention.

15 1,200-Å thick In_2O_3 transparent electrodes 3 are deposited on opposing surfaces of opposing glass substrates 1 and 2. SiO inclined alignment layers 4 are deposited on the transparent electrodes to have opposite inclined states. A gap between the two alignment layers 4 is set to fall within the range of 1.5 μm to 4.0 μm .

20 A liquid crystal mixture 6 which contains 40 wt.% or more of an ester ferroelectric liquid crystal (e.g., a liquid crystal composition CS-1014 available from Chisso Corp.) which is easily aligned by the SiO inclined alignment layers 4 is filled in a liquid crystal cell constituted by the two glass substrates 1 and 2 and epoxy
25 resin seals 5 arranged at two ends of the two glass

substrates. Polarization plates 7 and 8 in a crossed
nicols state are arranged outside the glass substrates 1
and 2. A heater 9 for holding a constant temperature of
the liquid crystal device is attached to the outer surface
5 of one polarizer 8.

The liquid crystal device in which the
ferroelectric liquid crystal is sandwiched between the two
glass substrates having the alignment layers of an inorgan-
ic insulating member oblique deposited in opposite di-
10 rections has different liquid crystal aligned states de-
pending on the thickness of the liquid crystal layer.

Fig. 2 shows movements of ferroelectric liquid
crystal molecules. A liquid crystal molecule M (an
elongated hatched portion) can take three positions, i.e.,
15 a position P_1 on a near side of a cone 100 (indicated by a
solid line), a position P_2 on a far side of the cone 100
(opposite side indicated by a broken line), and an interme-
diate position therebetween.

Figs. 3(a) to 3(c) are views showing possible liq-
20 uid crystal aligned states of the liquid crystal molecules
in the ferroelectric liquid crystal device. Figs. 3(a) and
3(b) show uniform aligned states, and Fig. 3(c) shows a
twisted aligned state. In Figs. 3(a) to 3(c), a bar with a
mark "o" indicates a case wherein a liquid crystal molecule
25 takes the position P_1 of the cone 100, as shown in Fig. 2,

a bar with a mark " $\square$ " indicates a case wherein a liquid crystal molecule takes the position P_2 , and a bar with no mark indicates a case wherein a liquid crystal molecule takes an intermediate position between the positions P_1 and P_2 . In Figs. 3(a) to 3(c), reference numerals 1 and 2 denote the glass substrates; and 4, the alignment layers. In the uniform aligned state shown in Fig. 3(a), only liquid crystal molecules near the glass substrate interfaces are twisted counterclockwise. The twisted aligned state shown in Fig. 3(c) includes both counterclockwise and clockwise twisted aligned states. It is experimentally revealed that the aligned states shown in Figs. 3(a), 3(b), and 3(c) have different stable states depending on the thickness of the liquid crystal layer. More specifically, when the thickness of the liquid crystal layer is 4 μm or more, and a positive or negative voltage is applied thereto, liquid crystal molecules are aligned once in the uniform aligned state shown in Fig. 3(a) or 3(b). However, when a voltage is reset to zero, the liquid crystal molecules tend to be stable in only the twisted aligned state shown in Fig. 3(c). In contrast to this, when the thickness of the liquid crystal layer is set to be 1.5 μm or less, both the aligned states shown in Figs. 3(a) and 3(b) maintain those upon application of a voltage after the voltage is reset to zero, that is, a so-called bistable state can be exhibited.

However, the stability of these states tends to be deviated to one state. More specifically, threshold voltage largely varies locally, resulting in nonuniformity of memory characteristics. When the thickness of the liquid crystal layer falls within the range of 1.5 μm to 4 μm , according to the experimental results of the present inventors, three stable aligned states shown in Figs. 3(a), 3(b), and 3(c) can be independently present. Since the aligned state shown in Fig. 3(c) corresponds to an intermediate state of the uniform aligned states shown in Figs. 3(a) and 3(b), it can be easily obtained by application of positive and negative voltages decreasing a peak value or a pulse width while switching the aligned states shown in Figs. 3(a) and 3(b). Thereafter, this state can be semipermanently maintained unless another voltage is applied. Furthermore, since the intermediate state shown in Fig. 3(c) is present, write voltages of the uniform aligned states shown in Figs. 3(a) and 3(b) can have almost the same values, and nonuniformity of memory characteristics can be considerably eliminated.

To summarize changes in aligned states of a liquid crystal depending on the thickness of the liquid crystal layer, when the liquid crystal layer has a thickness of 4 μm or more, a monostable state of only the twisted aligned state tends to be established. When the thickness

falls within the range of $1.5\text{ }\mu\text{m}$ to $4\text{ }\mu\text{m}$, the three stable states, i.e., the two uniform aligned states and the twisted aligned state are established. When the thickness of the liquid crystal layer is decreased below $1.5\text{ }\mu\text{m}$, only
5 the two uniform aligned states are stable, but asymmetry memory characteristics locally occur. On the other hand, when the ferroelectric liquid crystal device is switched using the twisted aligned state and the uniform aligned states, coloring of a bright state can be eliminated as
10 compared to conventional switching between only the uniform aligned states, and clear black-and-white display can be attained. This is because the twisted aligned state has different optical characteristics from those of the uniform aligned states. That is, since liquid crystal molecules
15 are aligned in a twisted state unlike in the uniform aligned state in which liquid crystal molecules are aligned in one direction between the upper and lower substrates, light rotates when it passes through the liquid crystal device. Fig. 4 shows aligned states of liquid crystal molecules. As shown in Fig. 4, when the polarizers are arranged on the upper and lower substrates so that an axis of
20 polarization 44 in the crossed nicols state coincides with a direction of liquid crystal molecules 41 in one uniform aligned state, a dark state is established by the aligned state of the liquid crystal molecules 41, thus obtaining
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black level of the polarizers whose polarization directions are perpendicular to each other.

On the other hand, a bright state established by the uniform aligned states of liquid crystal molecules 42 is colored, and transmission light T is expressed by equation (1) as a function of refractive index anisotropy Δn of a liquid crystal, a thickness d of a liquid crystal layer, and a wavelength λ of the transmission light:

$$T = \sin^2(\pi \Delta n d / \lambda) \quad \dots (1)$$

With respect to a Δn value of 0.15 of a typical ferroelectric liquid crystal, when d exceeds 2 μm , coloring considerably occurs; when $d = 2.5 \mu\text{m}$, a bright state is colored in yellow; when $d = 3 \mu\text{m}$, red; and when $d = 4 \mu\text{m}$, light blue. In contrast to this, a coloring phenomenon is eliminated due to optical rotation in the twisted aligned state in which liquid crystal molecules 43 in Fig. 4 are continuously changed. In this case, when $d = 2.5 \mu\text{m}$, a bright state is colored in white; when $d = 3 \mu\text{m}$, cream; and when $d = 4 \mu\text{m}$, light yellow. Thus, up to the thickness of the liquid crystal layer of about 4 μm , a ferroelectric liquid crystal device which can perform black-and-white display almost free from coloring can be obtained by switching the twisted aligned state and the uniform aligned states.

Fig. 5 shows operation modes of a liquid crystal device which has a thickness of a liquid crystal layer of $3.0\text{ }\mu\text{m}$, and is formed of the ferroelectric liquid crystal composition CS-1014 available from Chisso Corp.

5 A uniform aligned state (a) with reddish transmission light is obtained by a positive-negative symmetrical voltage waveform having a pulse width of 1 ms and peak values of $-2V_0$ and $2V_0$ ($V_0 = 15\text{ V}$). A uniform aligned state (b) of black level is obtained by a symmetrical voltage waveform having the same pulse width as above and peak values of $2V_0$ and $-2V_0$. Furthermore, a twisted aligned state (c) with transmission light almost close to white is obtained by a symmetrical voltage waveform whose peak values are decreased like $2V_0$, $-2V_0$, V_0 , and $-V_0$. When the value of the first positive/negative value ($2V_0$) equals to 10 30 V, if the peak value of the second pulse is 5 to 20 V, an aligned state is changed to the twisted aligned state. These three aligned states (a), (b), and (c) are semipermanently stable unless another voltage is applied, 15 and there is no local variation in conversion voltage among these states, thus allowing a satisfactory switching operation. The present inventors examined 10 to 20 kinds of liquid crystal material mixtures containing ester ferroelectric liquid crystals, and found that the thickness 20 of the liquid crystal layer with which the aligned states 25

(a), (b), and (c) could stably appear without nonuniformity
fell within the range of $1.5\ \mu\text{m}$ to $4.0\ \mu\text{m}$, and preferably
fell within the range of $2\ \mu\text{m}$ to $3.5\ \mu\text{m}$. When the liquid
crystal layer had a thickness falling within this range,
5 the aligned states exhibited almost identical stable states
without nonuniformity.

The present inventors prepared a 2.7" ferroelectric
liquid crystal device having 128 scanning electrodes and
160 signal electrodes under the condition described in the
10 above embodiment, being $3.0\ \mu\text{m}$ thickness of the liquid
crystal layer and using the liquid crystal composition
CS-1014, and tried actual driving display. As driving
waveforms, as shown in Fig. 6, two pairs of posi-
tive-negative symmetrical voltage waveforms in which volt-
15 age peak values and pulse widths are decreased are applied
to the scanning electrodes ($T_1, T_2, T_3, \dots$). A nega-
tive-positive symmetrical waveform is applied to the signal
electrodes ($S_1, S_2, \dots$) in a write mode of a white state,
and a positive-negative symmetrical waveform is applied in
20 a write mode of a black state. A pixel T_1-S_1 selected in a
white state is once set in a uniform aligned black state
written by a positive-negative symmetrical voltage waveform
having a peak value of $20V_0$ and a pulse width of $2t_0$, and
is then converted to a twisted aligned white state by a
25 positive-negative symmetrical voltage waveform having a

peak value of $5V_0$ exceeding a threshold value for converting an aligned state to a twisted state and a pulse width of t_0 . This state is not disturbed by a bias voltage in a non-selection mode of $\pm V_0$, and the pixel T_1-S_1 is kept in the white state. On the other hand, a pixel T_2-S_1 selected in a black state is converted to black level by a $\pm 20V_0$ voltage waveform, and thereafter, the uniform black state is not disturbed by a $\pm 3V_0$ voltage waveform. Thus, the pixel T_2-S_1 is kept at black level. In particular, as a result of the experiments for $V_0 = 1.5$ V and $t = 4$ ms, black-and-white display having a contrast ratio = 10 could be obtained, which was impossible to obtain in switching between uniform aligned states when the thickness of the conventional liquid crystal layer = 3 μm .

As described in the above embodiment, a ferroelectric liquid crystal device which has a thickness of a liquid crystal layer of 1.5 μm to 4.0 μm and can take three stable states according to the present invention can perform a satisfactory switching operation having uniform memory characteristics, and can realize black-and-white display which cannot be realized by a conventional ferroelectric liquid crystal display device having a thickness of a liquid crystal layer of 2 μm or more.

A driving method for gray scale control using a ferroelectric liquid crystal device according to the present invention will be described below.

The temperature of a liquid crystal device was set by the heater 9 (Fig. 11) at a temperature lower by about 15°C than an upper limit temperature of a chiral smectic phase within a temperature range of the chiral smectic phase. This is because when a multiplex driving test waveform of a selection voltage $\pm V_0$ shown in Fig. 7A is applied, a driving temperature $T_{\min}$ for minimizing fluctuation of a stable state shown in Fig. 7B falls within the range of 10°C to 20°C lower than the upper limit temperature of the chiral smectic phase within the temperature range of the chiral smectic phase exhibiting ferroelectric characteristics, as shown in Fig. 7C.

At the driving temperature, multiplex driving was performed using a combination of scanning electrode waveforms and 5-pulse signal waveforms obtained by modulating the voltage peak values shown in Fig. 8 under the conditions of $V_0 = 10$ V and a pulse width of 60 μ s. Figs. 9(a) and 9(b) show operation characteristics of the ferroelectric liquid crystal device in the multiplex driving mode. Fig. 9(a) shows a driving voltage waveform, and Fig. 9(b) shows a transmission light intensity. Reference numeral 31 denotes a voltage waveform in a selection

period; 32 to 34 in Fig. 9(b), extracted voltage waveforms
of different gray scale levels. With this driving method,
precise halftone display could be attained to have a
black-and-white level contrast ratio of 1 to 12. When liq-
5 uid crystal devices adopting ferroelectric liquid crystals
Felix005 and Felix009 available from HOECHST Corp. were
used, precise halftone display could be similarly attained.

According to this embodiment, since the three sta-
ble states can coexist, continuous halftone display can be
10 precisely attained.

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CLAIMS

1. A ferroelectric liquid crystal device in which a ferroelectric liquid crystal is sandwiched between a pair of substrates having transparent electrodes on opposing surfaces thereof, and in which said ferroelectric liquid crystal can take three stable states comprising a twisted aligned state and two uniform aligned states, wherein alignment films of an inorganic insulating material, which are inclined with respect to surfaces of said substrates and have opposite inclination directions are formed on the opposing surfaces of said pair of substrates, and the thickness of the liquid crystal layer between said substrates is set to fall within a range of 1.5 μm to 4 μm .

2. An device according to claim 1, wherein binary photoelectric control is performed using the twisted aligned state and one of the two uniform aligned states.

3. A method of driving the ferroelectric liquid crystal device of claim 2, wherein a pair of positive and negative pulses having a magnitude enough to change one of the two uniform aligned states to the other are applied across said transparent electrodes to set one uniform aligned state, and at least one or more pair of positive and negative pulses in which a product of a voltage value and a pulse width is decreased stepwise so as not to be changed to the other uniform aligned state are applied



across said transparent electrodes, thereby setting the twisted aligned state.

4. A method of driving the ferroelectric liquid crystal device of claim 1, wherein a voltage signal in which a product of a voltage peak value and a pulse width is modulated is applied across said transparent electrodes of said ferroelectric liquid crystal device to control a coexistence ratio of twisted and uniform aligned states, thereby achieving continuous gray scale display.

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