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FEATURE ARTICLE

Devices and materials for high-performance mobile liquid crystal displays

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Mobile liquid crystal displays (LCDs), often playing a role in hand-held computers, have become indispensable electronic tools to human beings in modern society. Innovative technological developments in the devices and materials have paved a successful road toward the development of mobile LCDs. Herein, after reviewing the trends and performance requirements of mobile LCDs, organic–inorganic materials as the key components of high performance mobile LCDs are addressed. Additionally, the developing trends in mobile LCDs are discussed with respect to these materials.

I.   Historical background

The advent of the portable notebook computer during the early 1990s was partially due to the unique characteristics of liquid crystal displays (LCDs), including exceptional image quality with normal direction, power consumption, thinness, and lightness.[1] Early on the super-twisted nematic (STN) LC mode was adopted with passive matrix driving. However, high information content was difficult to display using this technique, which was rapidly replaced by thin-film-transistor (TFT)-LCDs around the mid-1990s. Currently, TFT-LCDs are only used in mobile, notebook, monitor, and television displays for high information content. As a result of the success stories of TFT-LCDs in notebook displays, the simple, low resolution displays in many mobile electronic devices have been replaced by high resolution TFT-LCDs.[2] Moreover, the appearance of mobile devices such as mobile phones, personal digital assistants, and electronic dictionaries has shifted toward more compact, lighter styles.

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Seung Hee Lee received his B.S. degree in Physics from Chonbuk National University in 1989 and Ph.D. degree from the Physics Department of Kent State University in 1994. In 1995, he joined the LCD division at Hyundai Electronics. In the company, he invented and commercialized new liquid-crystal devices, with so-called "Fringe-Field Switching (FFS)" mode which have become the main LC devices in most high resolution/performance LCDs. He was awarded "King of the Invention" twice in the company. In September of 2001, he became a professor at Chonbuk National University in Jeonju, Korea. He was selected "SID Fellow" in 2008 and received the "Special Recognition Award" from SID in 2012. His main research fields are non-emissive electro-optic devices and functional materials.

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Surjya Sarathi Bhattacharyya

II. Trends and requirements of mobile LCDs

Recently, the explosive debut of smart mobile phones with mobile telephone functionality and features of a personal computer has encouraged engineers to write a new history on mobile devices. In order for LCDs to better facilitate the connection between human beings and machines, improved displays with larger size and higher resolution for providing high information content need to be developed.[2,3] In particular, very high resolution LCDs are required where the pixel density would be on the order of 320 pixels per inch (ppi) in screen sizes less than 4″ (known as "Retina Display") such that the human retina cannot spatially distinguish the pixels (the minimum units displaying information). In general, high-resolution TFT-LCDs result in a very low LCD panel transmittance because the number of signal lines blocking incident light increases with increasing resolution. The low transmittance of LCDs requires strong backlight intensity, which results in high power consumption. Therefore, the breakthrough LCD design should be adopted with the proper choice of LC mode with high light efficiency and low operating voltage to minimize power consumption. In addition to these requirements, the LCDs should have wide-viewing-angles in order to be compatible with both portrait and landscape styles. Since most mobile LCDs are becoming touch-sensitive displays, the LC director should be stable under external pressure, and it should not show any touch traces such as pooling or bruising. Therefore, choosing the right LC device or mode to meet the above mentioned requirements is critical. The key requirements of high performance mobile LCDs are summarized below.

Key features of mobile LCDs and key requirements of devices and materials:

-High brightness: high transmittance pixel structure and high light efficiency materials.

-High resolution over 320 ppi: high transmittance pixel structure, LC mode, and materials.

-Low power consumption: high light efficiency of the LC mode and low operating LC.

-High image quality: wide-viewing-angle LC mode and high color gamut.

-Slim/lightweight design: thinner and lighter materials.

-Touchscreen display: no image quality change under external pressure.

III. Structure of a TFT-LCD and its related materials

Fig. 1 shows a schematic cell structure of a TFT-LCD, except for the attachments related to the driving circuits and touchscreens. A light source is always required in LCDs as they are non-emissive. In order to achieve excellent transmission quality, especially in the normal direction, many optical films such as a reflection film, light guiding plate, diffuser film, prism sheet, and luminance improvement films are required. Since LCDs use LC molecules for the modulation of polarized light, polarizers should exist on both sides of the glass substrate. In order for the LC molecules to control the polarized light, they should be aligned uniformly over the whole area of the display with the help of an alignment layer. The LC molecules should be driven by a TFT when displaying high information content. In addition, the LC molecule itself does not produce color; therefore, a color filter with a striped array of red, green, and blue pigments dispersed in the photoresist exists with a black matrix, which absorbs unwanted light for a high contrast ratio display. The thickness of the LC layer is controlled using either plastic ball spacers or an organic column (photo) spacer, and the LC is sealed with sealants.

IV. Liquid crystal modes

In TFT-LCDs, the LC device or mode determines the image quality, production cost, and manufacturing process.[4] Until the middle of the 1990s, all TFT-LCDs adopted the TN mode, in which a LC director is twisted 90° from the top to bottom substrates and reorients for switching along the vertical field

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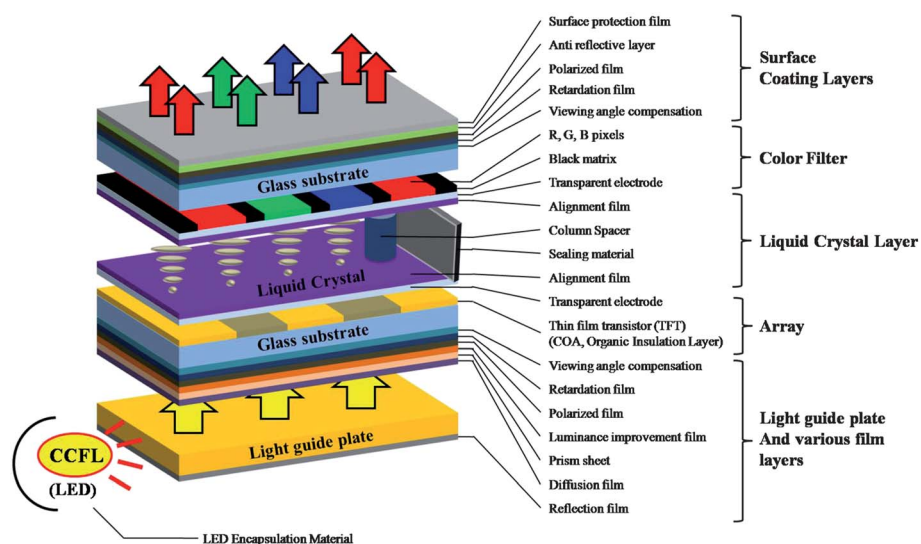
Kwang-Un Jeong

Fig. 1 Schematic cell structure of a TFT-LCD with various layers except for the driving and touchscreen parts.

direction, mainly for notebook applications. The TN mode has strong merits in terms of light efficiency and operating voltage, which are the most important display performance parameters for mobile or portable displays. However, as the size of the displays increased for monitor and television applications, a new wide-viewing-angle LC mode demonstrating high image quality in all viewing directions was needed because the displayed image quality in the TN mode becomes easily distorted at the normal axis.

In 1995, the in-plane switching (IPS) LCD was developed, in which a homogeneously aligned LC director rotates in the plane by the horizontal field, thus minimizing the distortion of images in off-normal directions.[5] An LC with positive dielectric anisotropy was used in the IPS device, and a rubbing process to achieve homogeneous alignment was required. In multi-domain vertical alignment (MVA) invented in 1997, the vertically aligned LC director tilted down in four different azimuthal directions to minimize the viewing-angle dependency of the displayed image in the normal direction.[6] In the MVA device, an LC with negative dielectric anisotropy was used, and a rubbing process was not required because polyimide with a high density side chain could induce the vertical alignment of the LC. Both devices show much improved viewing-angle performances in comparison with those employing the TN mode; however, they require higher operating voltage and have lower light efficiency than devices utilizing the TN mode.

The fringe-field switching (FFS) mode, in which a homogeneously aligned LC director rotates almost in plane but has high light efficiency and low operating voltage, as well as a wide-viewing-angle, was developed in 1998.[7] Although the FFS mode shows superior electro-optics performance, only the inventing company commercialized the device until 2004. A few years ago, IPS and MVA modes dominated the market of large-sized TFT-LCDs, and the TN mode took over the small-sized portable TFT-LCD market, while the FFS mode was applied to all kinds of displays, irrespective of size and application, though it was small in volume in the market.

The TN mode was used in the earlier days of the mobile display, especially in mobile phones. With technological developments and increasing pressure to meet consumer demand, mobile phones became multi-functional, and the image quality had to be upgraded to simultaneously display a high level of information content with wide-viewing-angle characteristics, moving pictures, and a full touch-screen base. To meet these requirements, LCDs should exhibit high image quality not only in the normal axis, but also in the off-normal axis, and they should possess a sufficiently fast response time to display moving pictures clearly. To satisfy the high image quality specifications, the IPS and MVA modes were applied to mobile displays. However, the IPS mode has a low transmittance and high operating voltage. Additionally, the VA mode[8] requires a circular polarizer to improve the transmittance, which increases cost and deteriorates viewing-angle performance, and also makes evident the dynamic instability of the LC director when an external pressure is applied for a touch function. Most importantly, as the display resolution becomes much higher than 320 ppi, the transmittance of the TN, IPS and MVA modes drops significantly, so that the power consumption of the device increases.

Many LC modes have been tested to meet the requirements of high performance and a high resolution display, and the FFS mode is the most popular (though many companies refer to it with different names). The superiority of the FFS mode over the other display driving schemes can be simply explained as follows. Fig. 2 shows a cross-sectional view of the IPS and FFS modes with the schematic molecular orientation of the LC in the white state.[9] In the IPS mode, signal and common electrodes exist only on the bottom substrates with a proper distance (l) between electrodes larger than the electrode width (w). With this structure, an in-plane field is generated between the electrodes with a bias voltage, and the field between the electrodes rotates the LC director in the plane in order to switch from black to grey scale. Hence, the device transmits light only between the electrodes, but the field intensity depends on l. In other words, a large l is favored for high transmittance, but it will increase the operating voltage. In the FFS device, a horizontal distance does not exist between the signal and common electrodes; instead, l' represents the
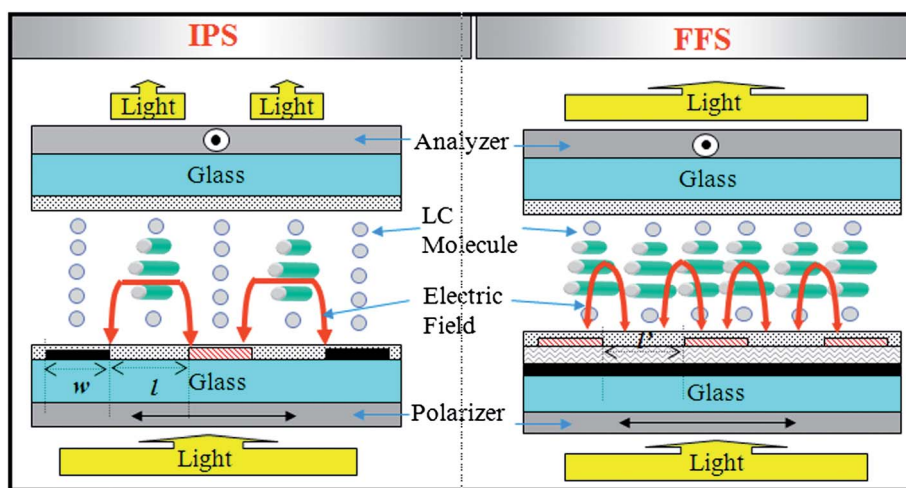
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Fig. 2 Schematic cross-sectional view of IPS and FFS modes showing the molecular orientation of an LC in the white state.

distance between the signal electrodes. In general, the thickness of the passivation layer between the signal and the common electrodes is less than 1 μm (l is more than a few μm in the IPS mode), so that a much stronger horizontal field is generated in the FFS mode than in the IPS mode near the edges of the signal electrodes when the same voltage is applied. For the FFS mode, the LC director also rotates nearly in the plane as in the IPS mode, doing so above the surface of the whole electrode, and at lower operating voltage than in the IPS mode. Consequently, the FFS mode has a wide-viewing-angle and high transmittance simultaneously with a low operating voltage. These characteristics are highly favored for mobile or portable LCDs with low power consumption and high image quality.[2,10]

At present, the LC with positive dielectric anisotropy is mainly used in the FFS mode owing to its low operating voltage and fast response time. However, commercialization of the FFS mode using the LC with negative dielectric anisotropy is under research because it can yield higher transmittance than the positive LC.

V. Materials for mobile TFT-LCDs

1. Liquid crystal

The LC material properties play a key role in determining the electro-optic performance of the device. LC mixtures with low threshold (V_{th}) or operating voltage are advantageous for LCDs, especially in mobile applications, because the usage of lower voltages reduces the power consumption. Generally, V_{th} has the following relationship with the physical properties of the LC:[11]

$$V_{th} \approx \sqrt{\frac{K_{eff}}{\Delta\varepsilon}},\qquad(1)$$

where K_{eff} and $\Delta\varepsilon$ are the effective elastic constant and dielectric anisotropy of LCs, respectively. Hence, V_{th} can be reduced by tailoring the elastic constants and/or dielectric anisotropy of the LC mixture. However, a reduction in the V_{th} *via* the effective elastic constants does not play a major role. The more effective way to reduce V_{th} is by systematic development of materials with high dielectric anisotropy while keeping the rotational viscosity

(γ_1) low for a fast response time, in parallel with the development of new LC mixture concepts.

In addition to the operating voltage, the response time of the LC plays a decisive role, especially in the case of moving picture reproduction. The frame rate of current mobile LCDs is 60 Hz, which requires a response time less than 16 ms for the proper reproduction of moving pictures. The time required for reorientation of the LC molecules during the rising and decaying process is called the rising (τ_{on}) and decaying time (τ_{off}), respectively. The τ_{on} is proportional to the amplitude of the applied voltage and γ_1 of the LC. On the other hand, τ_{off} is mainly associated with γ_1, the cell gap (d), and K_{eff}, with the following relationship:

$$\tau_{off} \approx \frac{\gamma_1 \cdot d^2}{K_{eff}}.\qquad(2)$$

To achieve a very fast response time, the reduction of d is absolutely needed since τ_{off} is proportional to the square of d. However, reducing d to less than 3 μm would result in a production yield sacrifice. Hence, the magnitude of the switching time parameter γ_1/K_{eff} needs to be minimized in order to achieve a faster response time. The development of LC materials exhibiting lower γ_1 is most effective during application because an increase in the elastic constant leads to a higher operating voltage, reduced low temperature stability, and a higher γ_1.[12] Therefore, LC mixtures with low γ_1 and high $\Delta\varepsilon$ are prerequisites for the latest mobile applications.

In addition to the above-mentioned requirements, LC mixtures with a relatively wider nematic temperature range and higher T_{ni} value are more necessary in mobile applications than in television or LCD monitors because the consumer requires extensive indoor–outdoor compatibility, even under extreme weather conditions. In mobile LCDs, a T_{ni} higher than 80 °C is favored; however, an LC with a higher T_{ni} has an intrinsic trend of exhibiting a higher γ_1 than that with a lower T_{ni}. Therefore, new LC materials with a relatively high T_{ni} and a controlled magnitude of γ_1 need to be developed.

The trade-off between rotational viscosity and dielectric anisotropy of LCs. For mobile and stand-alone applications, the

driving voltage has to be reduced to ensure low power consumption. This can be achieved by using high dielectric anisotropy mixtures with a newly designed LC molecular structure.

The LC molecular structure based on the trifluoro end group has a large dipole moment, resulting in a high value of $\Delta\varepsilon$. Generally, molecules with polar end groups have a bigger impact in low V_{th} mixture development. Using LCs with end groups of increasing polarity seems to be an appropriate method for the development of low V_{th} LC mixtures. However, an increase in the dielectric anisotropy of a mixture tends to increase the rotational viscosity, resulting in different typical switching times for different LC molecules and their mixtures. Fig. 3 shows the empirical correlation between γ_1 and $\Delta\varepsilon$ of an LC mixture.[13] The structural elements (side chain, rings, linking groups, and end groups) influence the physical properties of the LC molecule. Strong polar end groups such as $-O-CF_3$, $-O-CF_2$, and $-CF_3$ extend the molecular long axis, which directly results in an increase in γ_1. The corresponding reduction in switching time is acceptable for a limited number of mobile applications.

The basic challenge of developing a low V_{th} LC material or mixture is the formation of polar LC mixtures with low rotational viscosity. For this purpose, quantum-mechanical calculations to predict the interaction of LCs with freely moving ions and experiments have been performed to elucidate the interaction of the LC with peripheral materials such as orientation layers.[13]

The development history of positive dielectric anisotropic LC materials for mobile applications. Fig. 4 gives an overview of the development of the main polar material class for TFT-LCD applications.[14] A comparative physical property investigation of the LC substance with a CF_2O linkage and formerly used polar compounds such as ester or dioxane reveals a significantly higher dielectric anisotropy, as well as a lower rotational viscosity.

Developments in recent years have resulted in a clear enhancement of polarity with respect to the former referenced materials. Using LC materials containing the CF_2O linkage moiety, the driving voltage can be remarkably decreased with moderate switching times, or the switching times, which are proportional to γ_1, can be significantly improved for a given threshold voltage.
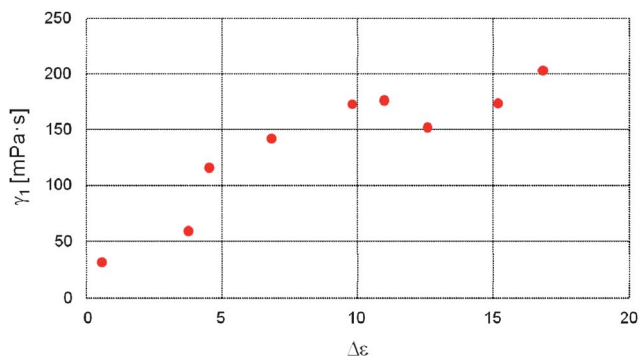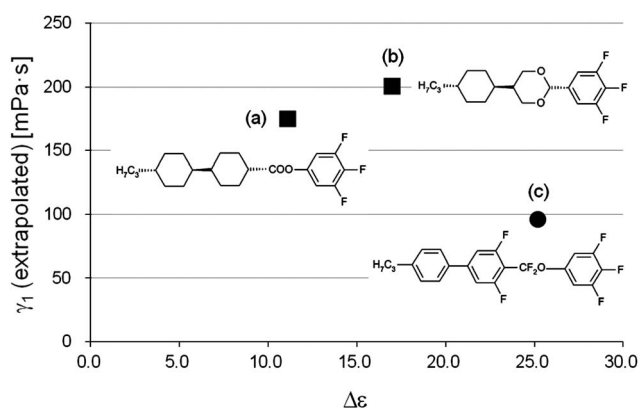

Fig. 4 Rotational viscosity as a function of the dielectric anisotropy of representative polar LC materials and their molecular structures: (a) ester, (b) dioxane, and (c) CF_2O.

A novel LC with low V_{th} for mobile applications. Various high dielectric anisotropic LC molecules were developed after the introduction of the CF_2O linking group,[15,16] which has a strong impact on LC technology. By introducing the new, highly polar four-ring compounds shown in Fig. 5, a new efficient source of polarity was found.[16,17] The trifluoro end group enhances the longitudinal dipolar contribution and eliminates the lateral dipolar influence. The main purpose of fluorination at a linking group is to enhance the positive dielectric anisotropy. The use of the CF_2O linking group delivers remarkable results in the design of materials with positive dielectric anisotropy. The basic four-ring structure is called LC (Fig. 5).

This type of new polar compound combines a wide nematic range and high clearing temperature, high dielectric anisotropy, high birefringence, and high chemical stability. The development of new polar materials results in the enhancement of polarity and clearing point with respect to previously used polar materials. The physical properties of the new polar materials in comparison to those of the former polar materials are summarized in Fig. 6. As depicted, two new polar material classes, LC1[15,16] and LC2,[17] were identified with an improved ratio of rotational viscosity to clearing point. Along with the improvement, the trade-off between the polarity and clearing point has been partly compensated by the usage of new high dielectric anisotropic LC materials. In summary, these new materials with a very high polarity and high clearing point can be used for the improvement of positive $\Delta\varepsilon$ mixtures.

The impact of the new polar materials on the LC mixtures for TN and IPS/FFS devices is shown in Fig. 7. For the range of the threshold voltage parameter shown, the new materials show a clear improvement in the switching time parameter γ_1/K_{eff}. The new polar material LC already improves the switching time
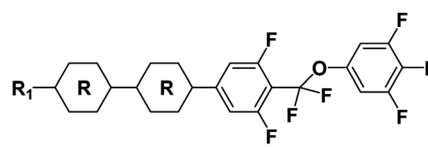

Fig. 3 Rotational viscosity as a function of the dielectric anisotropy of LC mixtures.

Fig. 5 New polar LC materials with a CF_2O linking group and trifluoro end group.

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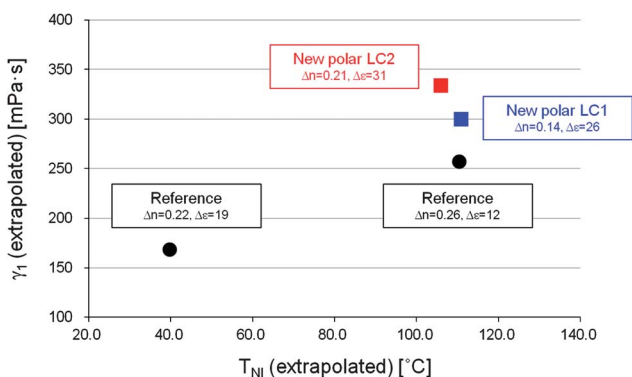
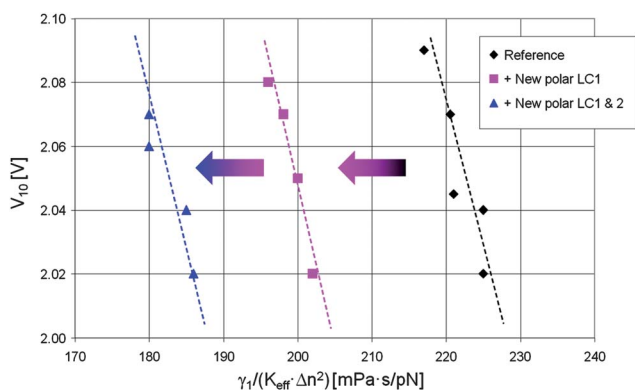**Fig. 6** Clearing point and rotational viscosity of new polar materials.

Fig. 7 The improvement in V_{th} and switching time using new polar materials in a typical positive $\Delta\varepsilon$ mixture.

significantly, but an additional γ_1/K_{eff} reduction can be achieved by the combination of a new polar LC1 and LC2.

Fig. 8 shows the advantage of using the new high polarity materials in a typical mobile application target having a wide operating temperature, with a T_{ni} of around 80 °C and a low temperature stability (LTS) of around −30 °C in bulk. By using the new high polar materials, γ_1 can be clearly improved for the entire $\Delta\varepsilon$ range. Specifically, additional improvement on γ_1 was identified in a higher $\Delta\varepsilon$ range. Therefore, these materials are suitable for the mobile application mixture, which must have a low driving voltage and fast response time.
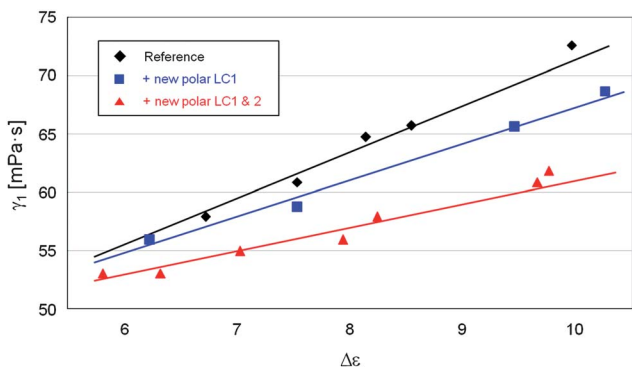

Fig. 8 Performance benefits of LC mixtures with new high polar materials.

Since mobile LCDs are often used in an outdoor environment, a proper response time even at the very low temperature of −20 °C is required. As shown in Fig. 9, LC1 showed more improvement compared to the reference sample, and with the combination of a highly polar LC1 and further improvement in γ_1, this result was also observed at very low temperatures with a T_{ni} of around 90 °C.

Reliability. Introducing these new polar materials enhanced the electro-optic performance of the new LC mixtures. For the LC to be utilized in TFT-LCDs, its reliability, including parameters such as the voltage-holding ratio (VHR), needs to be evaluated. The VHR is defined as the ratio of the voltages at a pixel at the end and the beginning of the frame time.[18] Typically, VHR values are correlated with electrostatic potentials. Fig. 10 shows space filling models of the new polar LC material. Electrostatic potentials are presented using a color code; blue represents a positive electrostatic potential, and red corresponds to a negative electrostatic potential. The red centers indicate strong electrostatic centers favoring strong interactions with cations. The absence of a red center denotes a relatively high VHR value for this compound, which could also be confirmed experimentally.

The VHR of LC mixtures with and without new CF_2O linked materials has been evaluated at 100 °C under thermal stress where the mixtures were kept at 150 °C for 4 h. As indicated in Fig. 11, the new mixture with new LC materials exhibits a slightly better VHR than those without new LC materials before and after exposure to thermal stress. This proves that the new mixture with the new polar LC materials LC1 and LC2 shows excellent reliability under thermal stress.

The future of LC materials. As mentioned in the device section, the FFS mode is expected to dominate the future mobile LCD market. At present, an LC with a positive $\Delta\varepsilon$ is mainly used. However, the LC has some disadvantages, such as a lower transmittance and less physical stability of its disclination lines according to the applied voltage, compared to those using an LC with a negative $\Delta\varepsilon$.[19] At present, an LC with a negative $\Delta\varepsilon$ is used in the VA mode; however, the magnitude of $\Delta\varepsilon$ is much smaller
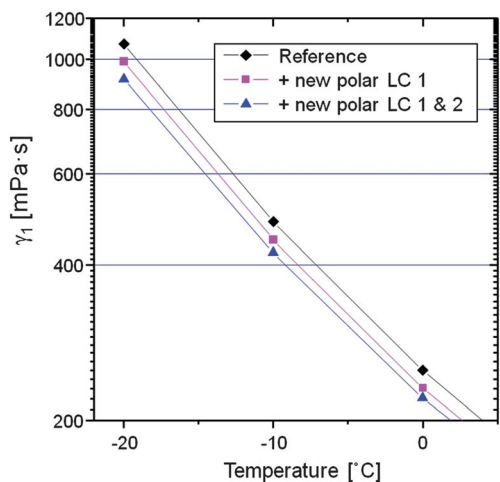

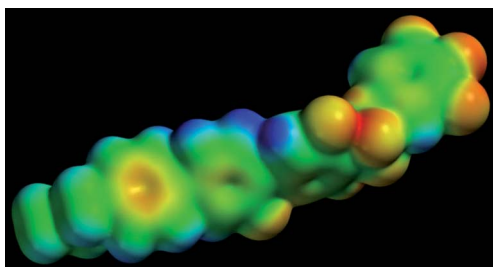**Fig. 9** Rotational viscosity changes at low temperatures.

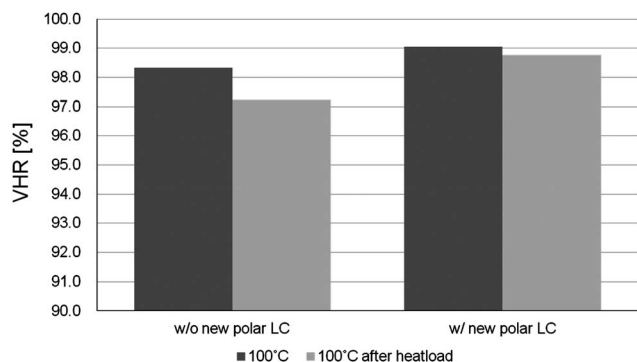**Fig. 10** Space filling model of a new polar LC material, LC2.

Fig. 11 VHR changes according to the presence of new polar materials after 4 h and at a 150 °C heat load.

(approximately less than −4) compared to that of an LC with a positive $\Delta\varepsilon$. Additionally, γ_1 of the negative LC is much higher than that of the positive LC because the negative LC molecule consists of a polar group perpendicular to the long axis of the LC. This indicates that when a negative LC is used for the FFS mode, the LCD would show a relatively higher operating voltage and slower response time compared to that of the positive LC. Nevertheless, the negative LC is still attractive because it has a higher transmittance than that of the positive LC with a stable field-respondent reorientation,[19a] especially in super high resolution LCDs. Therefore, developing a negative LC that yields a very low switching time parameter and large $\Delta\varepsilon$ would bring a new generation of LCDs showing superior performance to LCDs fabricated with positive LC.

2. The alignment layer of the LC

An alignment film with a thickness less than approximately 100 nm is required to align the LC in the proper direction. Thermally and mechanically stable polyimides or poly(amic acids) exhibiting strong anchoring interactions with the LC molecules are often used. Some key requirements for the alignment layer include a high VHR and low residual DC in order to provide strong resistance against image sticking. In present LCDs, especially in the IPS and FFS modes, the uniaxial orientation of the LC molecules has mainly been achieved by rubbing the alignment film. However, this rubbing technique has a critical drawback in that it generates static electricity in the polymer film, which results in the attraction of dust particles that deteriorate precise LCDs.[20] Alternatively, most of the present high image quality LCDs use organic column spacers instead of ball spacers to keep the LC layer uniform because the existence of

ball spacers in an active area disturbs the orientation of the LC, resulting in a deterioration of the image quality. Since the column spacers exist above signal lines instead of active areas, they do not affect the image quality of the display in general. However, as the resolution of the display goes up, the cross-sectional size of the column spacers is no longer negligible, affecting the uniform alignment of the LC achieved by the rubbing process. Since the rubbing is not performed directionally, unrubbed active areas on one side of the column spacer opposite the rubbing direction exist, and these dead zones lower the contrast ratio of the displayed image.

Photoalignment. To replace the contact rubbing alignment method, many noncontact LC alignment methods, such as ion beam exposure on a diamond-like carbon layer,[21] oblique evaporation of SiO,[22] and a micro-grooved surface,[23] were proposed. Nevertheless, from a practical viewpoint, the LC photoalignment technique was a candidate to replace rubbing LC alignment technology (Fig. 12).[24] Since the report from Gibbons et al. in 1991,[25] photoalignment research has boomed, and the achievement of photoalignment using poly(vinyl cinnamate) by Schadt et al.[26] triggered commercialization trials of this technology by many LCD companies between 1995 and 2000. At that time, the development of wide-viewing-angle LC modes was a hot issue, and the photoalignment technology made multi-domain LC alignment possible with multiple UV exposures. However, commercialization was not successful due to the image sticking problem originating from the weak anchoring energy of the photoalignment layer and a high level of residual DC.

On the other hand, multi-domain types of VA mode are widely used in LC-television applications. The formation of multiple domains by photoalignment technology has several advantages, including a fast response time and high transmittance, and recently, this technology was commercialized by Sharp Co. in 2010.[27] Nevertheless, a homogeneous photoalignment method has not yet been commercialized for LCDs to our knowledge, and the adoption of this technology for IPS/FFS LCDs will be indispensable to achieve uniform alignment and high image quality in high resolution LCDs. The durable LC molecular orientation exhibiting optical anisotropy can be achieved by the surface-assisted photoalignment of passive photochromic units (Fig. 13).[28] One of the best examples of applying the surface-assisted photoalignment technique is the fabrication of a film patterned retarder (FPR) for 3D LCD.[29] However, the types of photochromic chemicals are limited, and the reliability of the LC
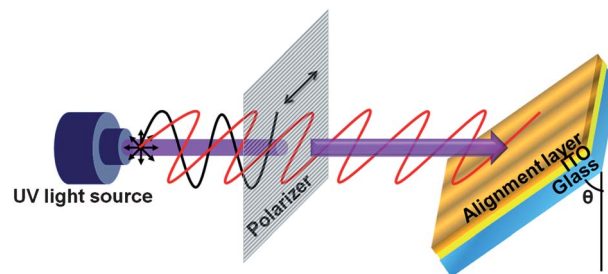

Fig. 12 Schematic description of the surface-assisted photoalignment technique.
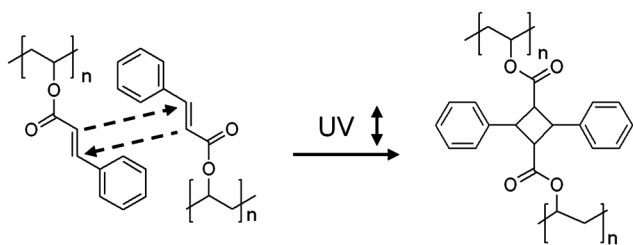
Fig. 13 Photochromic materials for the photoalignment of LC molecules: cross-linkable cinnamate-based materials.

molecular orientation is not sufficient compared to that afforded by the rubbing LC alignment technology.[26–28] Therefore, new types of photochromic chemicals having good reliability should be developed for a high performance mobile LCD.

In the IPS/FFS mode, achieving strong azimuthal anchoring energy in the photoalignment layer comparable to that of the rubbing case is very important for minimizing the image sticking issue; however, a zero pretilt angle is favored, unlike in the TN or VA mode. Increasing the anchoring energy of the photoalignment has been proposed such that a minute amount of reactive mesogen (RM) is mixed in the LC, and then the LC cell is exposed to UV light. After the diffusion of RM to the surfaces, UV or thermal polymerization results in the formation of an additional polymer layer on the existing polymer layer.[30] Furthermore, it was reported that the formation of this additional layer reduces the residual DC in the IPS cell.[31] We believe that the next generation of high resolution LCDs with the FFS mode will adopt this technology.

3. Color filter

The color gamut or reproduction ratio of mobile LCDs is very high, at least over 50%, comparable to that of an LC-television. The color gamut is mainly determined by the color purity of the color filter and light. The intrinsic characteristic of the color filter is that the color purity is inversely proportional to the transmittance. Therefore, the adoption of a high purity color filter will give a very low transmittance such that the overall panel transmittance becomes very low, which can increase the power consumption of the LCDs. Currently, color filters for LCDs are manufactured utilizing the pigment dispersion method (Fig. 14a–c), considered to be an economical, reliable, and convenient process.[32] Mobile LCDs often used outdoors have a need for a higher brightness and contrast ratio of the color filters compared to those made of pigment-based color photoresists (PRs). As a potential solution, an organic dye-based color PR has been attempted because it can yield high transmittance and color purity (Fig. 14d–f).[33] However, the thermal, optical, and chemical stabilities of organic dyes should be further improved to enable the use of organic dyes for the manufacturing of patterned color filters.[34]

4. Glass substrates

The non-alkaline and borosilicate type of glass made by the fusion or floating manufacturing method is used in TFT-LCDs. At present, glasses with a thickness of 0.5 mm are mainly used in mass production due to the handling issues associated with current production lines. A display that is lightweight and thin needs to be developed for use in mobile LCDs. To reduce the weight and thickness of the display, the outside of the glass should be etched after the LC cell fabrication process.

A wet chemical etching process is currently applied for glass etching, and high-rate glass etching in a hydrofluoric (HF) and hydrochloric (HCl) acid solution mixture has been recently reported.[35] With this approach, the glass is thinned from 0.5 mm to about 0.2 mm or less, such that the total 1.0 mm thickness of two glass substrates can be reduced to 0.4 mm, while at the same time reducing the weight of the glass.[36]

Ideally, uniform etching of amorphous glass should result in a defect-free, smooth surface. However, the imperfect etching process combined with residual stresses generated in the glass leads to rough surfaces.[37] The irregular surface of the glass substrate is one of the main reasons for light scattering and distortion of the polarized light, which deteriorates the image performance of LCDs. Therefore, state-of-the-art micromachining or dry etching post-processes are needed for achieving a smooth surface.[38]

5. Polarizers

The polarizer is a key material that controls the polarization of light, strongly affecting the transmittance and contrast ratio of the LCD. Presently, LCDs contain an absorptive dichroic film with an iodine base. Though this film shows a high transmittance above 40% and an excellent polarization efficiency greater than 99.99%, a new type of polarizer with a better transmittance of more than 45% and a proper level of polarization efficiency needs to be developed. This is especially true in mobile LCDs in order to decrease power consumption. From a mechanical perspective, thinning the polarizer is also important in mobile LCDs to decrease the thickness of a single protective film (triacetyl cellulose: TAC), which can now be reduced to 40 μm.

Since two polarizers are mechanically attached to the outside of two glass substrates, the total thickness of the polarizers is not negligible. A great deal of research has been performed on the coatable polarizer using lyotropic chromonic LCs,[39] such that it can be located inside of the glass substrates surrounding the LC layer. Although the technology is not yet mature enough for mass production due to the low level of polarization efficiency and thermal reliability, this approach represents a breakthrough in the thinness of LCDs.

VI. Next generation mobile TFT-LCDs

In the last two decades, simple, large, and monocolor mobile LCDs have been transformed into multifunctional, compact, and full color displays, known as "smart phones." We believe that the evolution of mobile LCDs has not yet stopped, and that there are greater challenges to increasing their functionality, such as the development of *3D display*, *flexible display*, *viewing-angle control display*, and *transflective display*. The necessities of such functions are explained below.

1. 3D display

At present, most mobile LCDs display two-dimensional (2D) images. Since the displays also play the role of televisions, there is
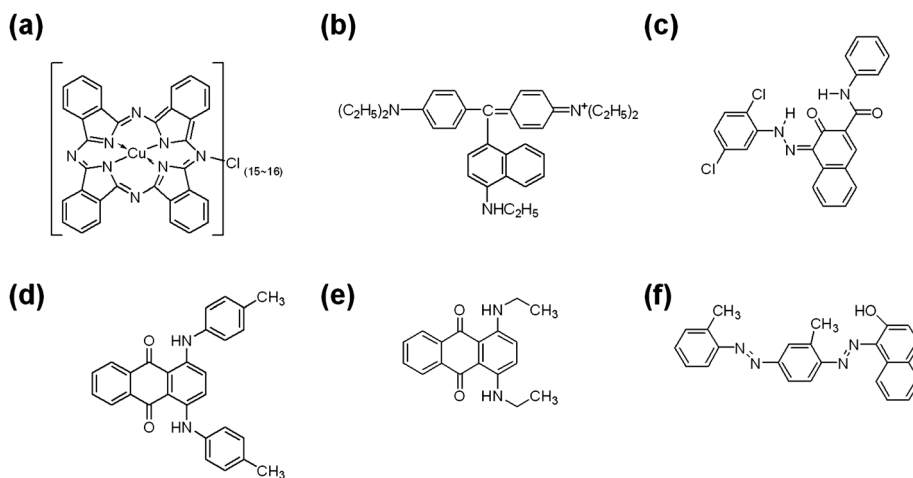
Fig. 14 Color materials used for the LCD color filters: (a) green, (b) blue, and (c) red pigments, and (d) green, (e) blue, and (f) red organic dyes.

a high demand for displaying 3D images, even in mobile LCDs. Therefore, the display should provide both 2D and 3D depending on the demands of the user, that is, there should be a switchable function from 2D to 3D. Such switching can be realized by adding one more switchable LC cell, which can be used as a switchable barrier[40] or switchable lens[41] for 3D once it is in the on state. The switchable barrier is a relatively easy approach, but the transmittance of the device is degraded so much that it results in high power consumption. Therefore, a switchable LC lens showing a relatively high transmittance is favored. In order for the LC to be utilized in the lens, the birefringence of the LC materials should be much higher than 0.2 with proper viscosity (otherwise the switching time of the LC lens is very slow). However, the performance of the LC materials is still not good enough. Another obstacle of the LC lens is the optical crosstalk between the left and right eyes because the presently proposed device could not clearly define the lens boundary. Therefore, in order for the LC lens to be adopted in future mobile LCDs, both the device and LC material performances need to be improved.

2. Flexible display

Currently, LCDs use brittle glass substrates, making them very sensitive to mechanical shock and easily breakable when dropped from pockets. Mobile LCDs with a plastic film or metal foil will not only overcome such an issue, but also reduce the weight. At present, there are many technical barriers in the manufacturing and material performance of plastic films.[42] Therefore, full mass production will take a long time to achieve, and challenges will continue to arise.

3. Viewing-angle control display

The present development trend of mobile LCDs pursues high image quality in all viewing directions. However, a case can be made for a user who wishes to protect his/her displayed content from others. For this situation, viewing-angle switchable displays from a wide to a narrow viewing angle have been proposed.[43] Nevertheless, this additional function can increase either the power consumption of the device or the cost of the products. We believe that there will be more demands for mobile LCDs in the future.

4. Transflective display

The readability of present LCDs under sunlight is quite inferior to that in an indoor environment. To overcome this problem, the brightness of mobile LCDs was recently increased to over 500 nit. However, this approach increases the power consumption of the display, but the readability performance is still not satisfactory. Therefore, transflective displays must be developed in which one pixel is divided into two subpixels, transmissive and reflective.[44] In this way, proper readability can be achieved under any environmental lighting conditions though the transmittance of the panel is sacrificed slightly. The patterning capability of LC alignment using a photoalignment layer would help improve the fabrication and electro-optic performance.

5. Field sequential display

Presently, full-color TFT-LCDs make use of color filters arranged in a striped line, in which the transmittance of the color filter is quite low, less than 40%, and the display resolution is limited due to the existence of red, green, and blue color filters. In order to overcome such problems, field sequential LCDs are needed in which a light emitting diode backlight emits red, green, and blue light in sequence one color at a time, and the LCD switches in synchrony with the backlight to form images.[45] In this way, mobile LCDs with higher transmittance and higher resolution can be realized. Nevertheless, these LCDs have not yet been commercialized due to several technical limitations. One of the most important requirements is that the response time of the LC panel should be at least three times faster than that of conventional LCDs. The present FFS or other types of LCDs have difficulty exhibiting response times in all grey levels less than 2 ms. In order to achieve this, other types of LCDs with an optically compensated bend LC mode[46] or blue phase LC[47] are under investigation, but we believe that realizing a commercialized field sequential mobile LCD would be very difficult without developing breakthrough LC technologies such as high performance LC mixtures and LC modes.

Overall, to improve the performance of current mobile LCDs and to embed the above mentioned functions in mobile LCDs, breakthroughs in LCD materials such as an LC with high dielectric anisotropy but low rotational viscosity for both the positive and negative types, an LC with high birefringence having sufficient reliability, a photoalignment layer for homogeneous alignment, high performance plastic substrates, high color purity/high transmittance color filters, and an in-cell polarizer are needed.

Acknowledgements

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