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40 years research and development on liquid crystal displays

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40 years research and development on liquid crystal displays

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Electronic displays, especially liquid crystal displays (LCDs), have made significant progress. In this paper, the actual situation of how the research and development of the new field was pushed forward is introduced by referring to the process of liquid crystal study related to the author's experience. In addition, the future trends of research and development on image electronics are discussed on the basis of the peculiar characteristics of humans related to information input and output ability.

1. Introduction

More than 40 years ago, the author was eager to study semiconductor technology as it was important in state-of-art electronics at that time, and joined Professor Masanobu Wada's laboratory at the Department of Electronics of Tohoku University because he was an authority on semiconductor electronics. In those days, Professor Wada predicted the progress of semiconductor technology and an information society, and the necessity of low-power, thin, and lightweight displays compatible with semiconductors. In the mean time, the liquid crystal display was proposed by Heilmeier et al.[1] and Professor Wada thought that this was the material he desired. When the author went to graduate school after one year of research on semiconductors, he was recommended by Professor Wada to study liquid crystal. This was his first encounter with liquid crystal.

2. Synthesis and purification of liquid crystal

Just after the author started to study liquid crystal, he found that there were no experimental materials, instruments, literature on liquid crystal or colleagues to discuss it with in the laboratory, and he realised what a serious choice he had made. Anyway, he had to start a fundamental study of chemistry to synthesize liquid crystal material, and visited the library of the Department of Chemistry in Tohoku University every day. It took about half a year to master the fundamental knowledge required to synthesize chemical compounds. Then, the author decided to synthesize *p*-methoxybenzylidene-*p*′-*n*-butylaniline (MBBA) as shown in Fig. 1, which was a room-temperature liquid crystal recently discovered.[2] This was again a serious choice because it was necessary to use the difficult process of the Friedel–Crafts reaction[3] at high temperatures and pressures to synthesize *p*-*n*-butylaniline, which is a composition material of MBBA.

After various difficulties related to synthesis and purification, extremely pure MBBA was successfully obtained. This took about one year from starting to study the synthesis of liquid crystal.

3. Molecular alignment of liquid crystal

After a while, the author started to study the electronic and optical properties of liquid crystal and he found that the liquid crystal molecule aligned sometimes parallel and sometimes perpendicular to the glass substrates,[4] as shown in Fig. 2, and these alignments strongly affected the electro-optical properties.[5,6] Therefore, he decided to investigate the mechanism of the molecular alignment because it was predicted that the control of alignment would become one of the most important fundamental technologies of liquid crystal displays (LCDs).

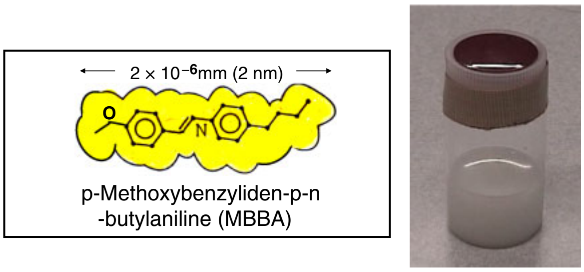

Fig. 1. (Color online) Room temperature liquid crystal, MBBA.

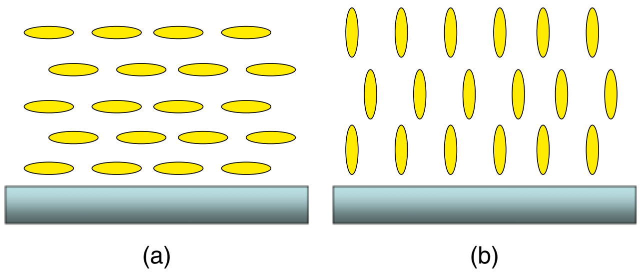

Fig. 2. (Color online) Molecular alignment of liquid crystal on the glass substrate: (a) parallel alignment and (b) perpendicular alignment.

The author and several supervised students have successfully clarified the molecular alignment mechanism: The microstructure of the substrate surface, such as the orientation state of the organic molecules coated or adsorbed on the surface, had a dominant effect on the molecular alignment of liquid crystal,[7] as shown in Fig. 3, which was based on the molecular interaction between the liquid crystal and the surface.[8,9] Furthermore, a method of measuring the surface alignment force (anchoring strength)[10,11] and surface order parameter of liquid crystal[12] was established. In addition, it was found that there was a strong correlation among the surface microstructure, anchoring strength, and surface order parameter.[12–15] However, the author will skip the details as space is limited, and move the subject to LCDs.

4. Dawn of the LCD and its application products

With the progress of technology of integrated circuits (ICs),

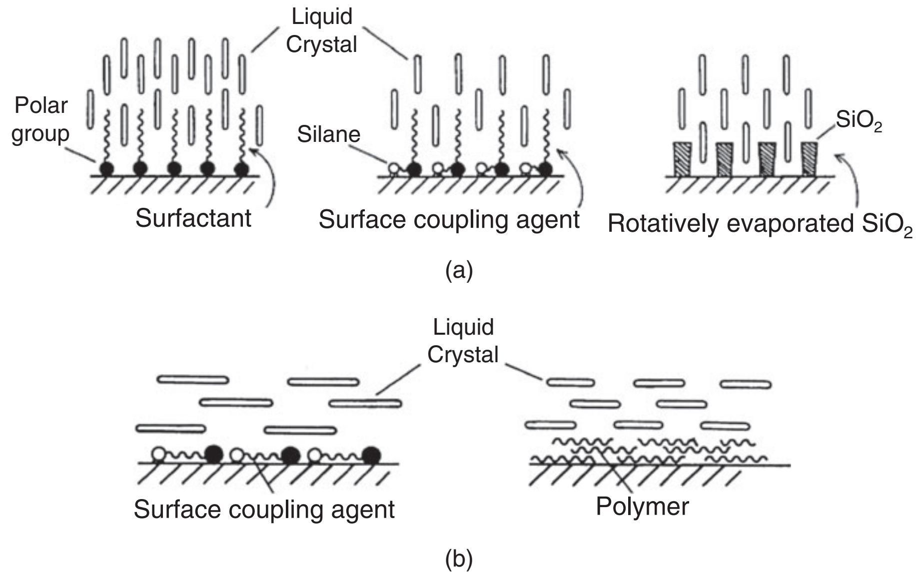

Fig. 3. Alignment control of liquid crystal on the substrate surface: (a) parallel alignment and (b) perpendicular alignment.

Fig. 4. (Color online) Pocket-size electronic LC-calculator (Sharp, 1973).

calculators became a pocket size from a table top type in 1972, and were widely used. However, the consumption of batteries was intense and the reduction of power consumption became an important subject. In the meantime, Sharp Corp. mass-produced a significantly low power calculator using LCD and CMOS-IC in 1973,[16] as shown in Fig. 4, and it spread rapidly. The LCD was well suited for CMOS technology, and their combination produced new products one after another from the 1970s through the 1980s, by taking advantage of the features such as low voltage, low current and high integration (Table I). The products included an electronic typewriter and a word processor equipped with LCDs of several lines character display. Thereafter, a laptop computer began to be developed. For this application, the LCD with scanning line numbers of about 60 was used at first. Then, it became the main subject of LCD research to increase this number up to about 500.

5. Limit of the LCD

The direct matrix drive LCDs used for the character displays in those days, had a severe problem in that the contrast decreased with the increase in scanning line number,[17,18] as shown in Fig. 5, and this dilemma was thought to be inevitable. Rumors began that this was the limit of LCDs, and that there would be no future for them. The liquid crystal sessions of every society declined rapidly. The author was also advised by some professors and his peers that he should quit liquid crystal research as soon as possible because organic materials as well as liquid materials had never been used for the active device of electronics. Then, he looked for new areas of research other than liquid crystal for several years. However, one day, he noticed that he had been observing liquid crystal with the eyes of an outsider, and that the future of the liquid crystal depended on his effort. Therefore, he decided to stay in the liquid crystal research field.

Table I. Appearance of the new products by the collaboration of the LCD and semiconductor from the 1970s through the 1980s.

New application	LCD
Calculator	Numeric: 5–10 digits
Electronic typewriter	Alphabet: 1–2 lines
Word processor	Chinese character: 1–5 lines
Personal computer	Scanning line number: 60–120 lines

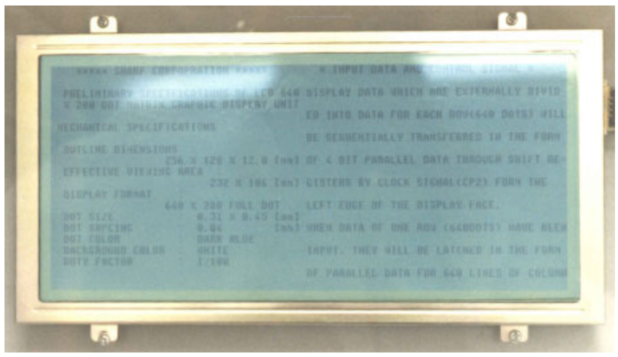

Fig. 5. (Color online) Decrease in contrast ratio of the direct-matrix LCD with increase in scanning line number.

Fig. 6. (Color online) Matrix LCD using double-STN in which the contrast ratio improved significantly (EPSON at Electronic Show '87).

In the mean time the contrast of LCDs with large scanning line numbers was significantly improved by the discovery of the supertwisted birefringent effect (SBE),[19,20] supertwisted nematic liquid crystal (STN),[21] double-STN,[22,23] as shown in Fig. 6, and film-compensated STN.[24–28] In addition, an amorphous silicon thin-film transistor was devised[29] and it promoted the development of an active matrix LCD,[30–33] which drastically solved the above-mentioned fundamental problem of LCDs.

On the other hand, the author worried about what kind of research he should do as a researcher of a university with very poor manpower and research funds compared with companies. Then, he decided to challenge a prospective theme that would become one of the most important themes in ten years, even though it would be very difficult, and fixed his attention on realizing full-color LCDs.

6. Color LCDs

There had been many methods proposed to obtain color LCDs as follows.

- Guest–host mode[34]
- Selective reflection of cholesteric liquid crystal[35]
- Birefringence mode such as deformation of vertical alignment phase (DAP)[36,37] and electrically controlled birefringence (ECB)[38,39]
- DAP + cholesteric liquid crystal[40]
- Twisted nematic cell (TN-cell)[41] + color polarizers[42,43]
- TN-cell + retardation films[43,44]
- Optical rotatory dispersion of chiral nematic liquid crystal[45,46]
- CRT + liquid crystal shutter (field sequential)[47–50]
- Flat CRT + LCD (field sequential)[51]

However, it seemed that none of them were practical. Then, almost all possible ideas to realize color LCDs were examined, and a solution to use the-three-primary-color mixture system was finally reached. There are two systems, as shown in Fig. 7; the additive mixture type using red, green, and blue, which are called the primary colors of light, and the subtractive mixture type using cyan, magenta, and yellow, which are called the primary colors of paints. Since the liquid crystal does not emit light, the author thought that it was natural to use the subtractive mixture type the same as paints. In this case, the structure shown in Fig. 8[50,52] was obtained using a guest–host-type LCD[34,53–55] with dichroic dyes of three primary colors, and its trial production was successfully carried out.[50,52] However, it was predicted that this type of LCD would not be practical for future high-resolution color LCDs, because color parallax occurred in oblique observation.

Then, the author continued to look for another solution to this problem, and finally arrived at the idea to change the arrangement of color elements, as shown in Fig. 9; namely, the three primary colors were arranged laterally.[56,57] Only by this change, the color mixture became of the additive type and the primary colors changed to red, green, and blue [Fig. 9(b)]. Figure 10 shows the actual structure of this color LCD using the additive type mixture. It was composed of a usual black-and-white LCD and color filters formed inside

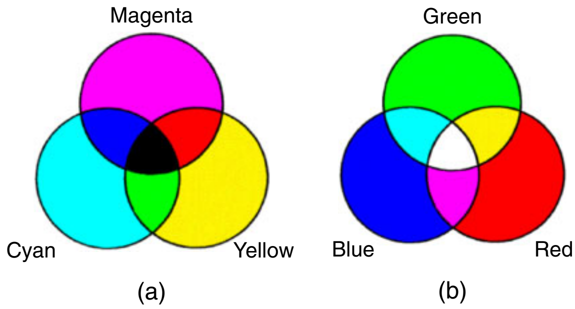

Fig. 7. (Color online) Principles of two types of color mixture: (a) subtractive color mixture and (b) additive color mixture.

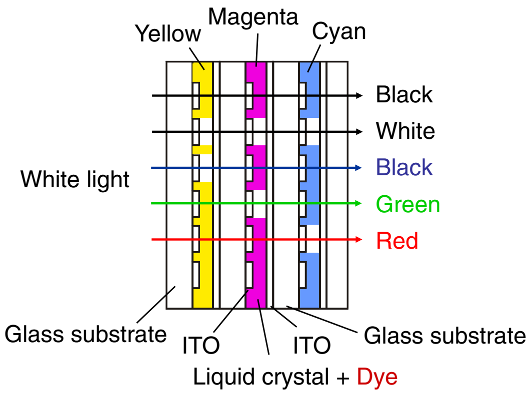

Fig. 8. (Color online) Color LCD using the subtractive color mixture.

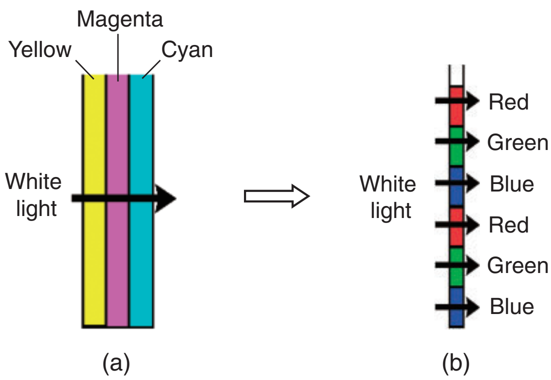

Fig. 9. (Color) Change in arrangement of the three primary colors from stacking to lateral alignment: (a) subtractive color mixture and (b) additive color mixture.

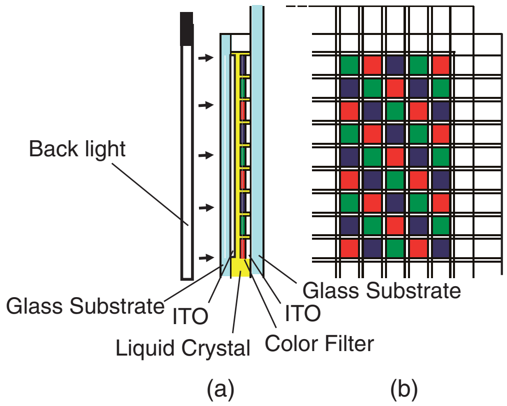

Fig. 10. (Color) Color LCD using the additive color mixture: (a) cross section and (b) top view.

Fig. 11. (Color online) Color LC televisions, notebook PCs, PC monitors, and smartphones using color LCD with color filter and back light.

the LCD cell to prevent the above mentioned parallax.[56,57] By this method, the full color LCD with the possibility of high-resolution display was achieved successfully. However, when the author first presented this proposal, there were several severe objections. They were summarized as the following two problems. One of them was poor color purity, as was known in usual nonemissive materials such as printed papers. The other one was the relatively high power consumption due to the back light. The first problem of the color purity was considered to be solved as it was related to the spectrum and would be controllable, while the second problem of power consumption was an inevitable subject at that time.

Nevertheless, this method was adopted by many researchers of LCD,[30–33,58,59] and has recently been widely used for liquid crystal televisions, notebook PCs, display monitors, and smartphones, as shown in Fig. 11, in which the first problem of color purity has been solved, as was expected. However, the second problem of power consumption has not yet been solved sufficiently. Therefore, the author decided to search for a solution to this problem and has been continuing this research.

7. Development of the low-power LCDs

7.1 Field sequential color LCD without color filter

To solve the problem of the power consumption of the color LCD, the color filter was removed; namely, a monochrome

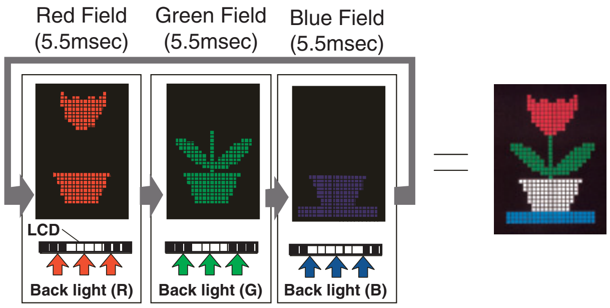

Fig. 12. (Color) Field sequential color LCD without color filter.

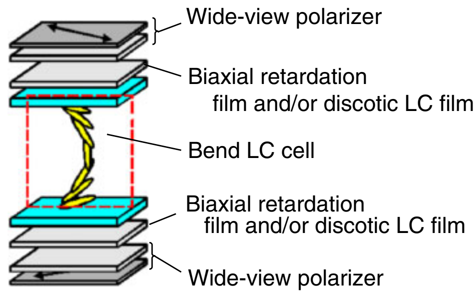

Fig. 13. (Color online) Structure of the OCB-cell with wide viewing angle and fast response.

LCD and back lights of red, green, and blue were used, as shown in Fig. 12.[60–63] The three color back lights were turned on sequentially and the color image of LCD was changed quickly according to the back light color. This method has the advantages of several times higher brightness (or lower back light energy) and three times higher resolution than the current color filter type. In this method, it was necessary to use an LCD with a response time shorter than 5 ms, which is 10 to 50 times faster than the conventional LCD. The author and coworkers fortunately developed the optically compensated bend cell (OCB-cell), as shown in Fig. 13.[64–66] This LCD had bend alignment of liquid crystal molecules, which was first proposed by Bos et al.[67] However, the bend alignment was unstable and he used this device as an alternative switching device of retardation to obtain multicolor operation of the oscilloscope.[47] To solve the instability of the bend alignment, the authors[64,65] theoretically analyzed the free energy as a function of voltage and found that the bend alignment became stable by using bias voltage. Then, the retardation of the bend-aligned liquid crystal cell was three-dimensionally compensated by using biaxial retardation films, as shown in Fig. 13. As a result, the OCB-cell obtained a very wide viewing angle and an extremely fast response (1–5 ms).

This field sequential color LCD was successively researched and developed as the Local Collective Research Development Program of Aomori Prefecture supported by Japan Science and Technology Agency (JST), and has been test-fabricated successfully,[68–72] as shown in Fig. 14. Although it has not yet been put into practice, it is expected as the next-generation LCD.

7.2 Reflective color LCD without back light

For the further-low-power LCD, a reflective color LCD

Fig. 14. (Color online) Field sequential color LCD (15 in. XGA) fabricated as an experiment.

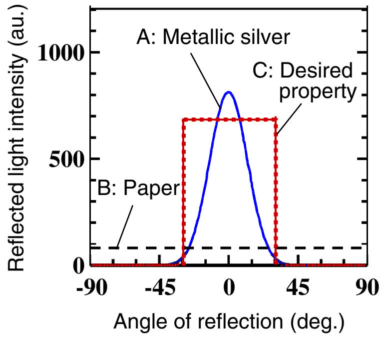

Fig. 16. (Color online) Reflective properties of metallic silver, paper, and the desired LCD.

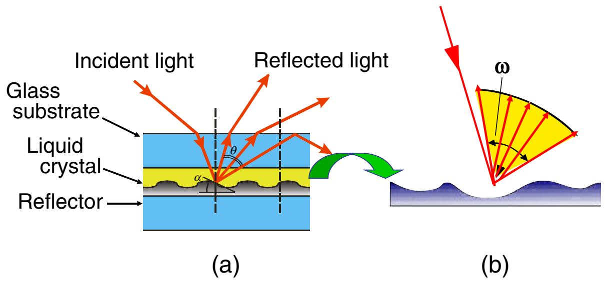

Fig. 15. (Color online) Reflective color LCDs with two types of metal reflector: (a) rough surface and (b) parabolic structure with random size keeping similar figures.

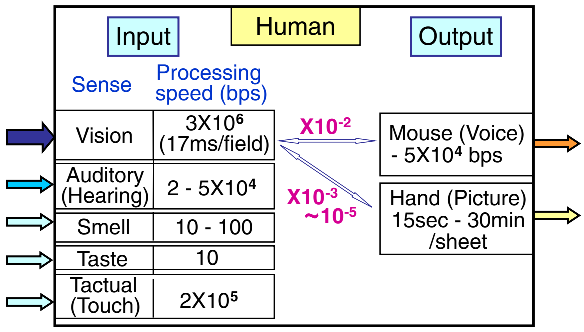

Fig. 17. (Color online) Information input and output functions of humans and their processing speed.

without a back light[73] has been devised and developed, as shown in Fig. 15(a). To increase brightness, the diffusing angle of the reflected light was limited within a certain range. Such a property was obtained by using a metal reflector with a suitable roughness, which was designed by theoretical calculation.[74,75] As a result, a significantly high brightness of the reflected light was obtained, while the LCD became metallic silver, different from the desired paper-like display. Then, this characteristic was analyzed, and the reason for this was found to be the strong dependence of the reflection intensity as a function of angle, as shown by curve A in Fig. 16, which was quite different from that of white paper (see curve B in Fig. 16). The authors tried to find the surface microstructure that provides constant reflectance like paper but within ±30° from the specular direction by theoretical calculation, as shown by curve C in Fig. 16. Then, the solution was found to be a parabolic structure.[76,77] The size of the parabolic structure should be changed randomly with keeping a similar figure, as shown in Fig. 15(b), to prevent diffraction that occurs in the case of the periodic structure.

Subsequently, in cooperation with Sharp Corp. and other companies, the reflective color LCD was actually developed,[78] and several years later, it was put into practical use as personal digital assistants (PDAs), portable game machines, and mobile phones. It induced a new business of small LCDs with high added value, and has progressed to the recent small LCDs with ultrahigh resolution for smartphones and tablets.

8. Future trends of the image information

Finally, the future progress of the man-machine interface is discussed. Humans obtain ambient information through the five senses. Among them, the sense of vision is dominant and more than 85% of the ambient information is input as visual information. This is related to the processing speed of the five human senses, as shown in Fig. 17, which is described on the basis of Ref. 79. The processing speed of sight is about 3 Mbps, which is the highest among the five senses, and is followed by the senses of hearing, smell, and taste, which are respectively 2 orders, 5 orders, and 5 to 6 orders lower than that of vision. The processing speed of tactile sense is relatively higher for some reasons, but still one order lower than that of vision.

On the basis of these characteristics, a telephone with low transmission information was developed and became mainstream in the 1880s when the electronic technology was immature. Then, with the progress of electronic technology, the facsimile, which transmitted a still image, spread in the 1980s, and the internet, which transmitted a brief animation or motional image, spread in the 1990s. It is expected in the next generation that visual communication, which uses video images, will replace text communication methods such as e-mail.

From this point of view, it should be noted that humans have a major problem in communication ability. As shown in Fig. 17, the ability of human image input using the vision is remarkabley superior, but the ability of image output is very poor. For example, it takes around 15 s to 30 min to draw one picture, which is three to five orders slower than the visual input ability. Because of this unbalance, humans mainly use voice for output, and the information is compressed by using language. However, it takes many years to learn a language, especially a foreign language.

At present, there is no clear solution to this big problem of unbalance between input and output abilities, while in the future, electronics will solve it by using touch panel, pen input, voice recognition, detectors of human's natural performance including eye motion, and detectors of thinking or brain activity. In addition, it is expected that the internet will intervene here.

At present, various industries such as consumer electronics, medical, and automobile are isolated from each other as they have been developed independently. The internet will combine these industries, and a huge industrial field will be born. In this new industrial field, image information will play an important role.

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