Feature

Research on Flexible Display Systems

1. Introduction

Research on flat panel displays (FPD), which started in the 1960s, has finally reached the commercialization stage in the form of large plasma display panels (PDPs) and liquid crystal displays (LCDs). This research will hopefully lead to FPDs with larger displays, higher picture quality, lower power consumption, and lower prices. A spin-off of this trend is the growing demand for enhanced picture quality broadcasting in media such as Hi-Vision (HDTV) and in data services. In the future, broadcasting, communications, personal computers will have fused together to form a common media by which interactive broadcasting and mobile reception via digital terrestrial broadcasting will be available in most areas. The demand for ubiquitous and easy-to-use displays as human interfaces will also increase. One of these interfaces will be a lightweight, flexible display that can be rolled up or folded. It might be possible for anyone to carry a large home display device simply by rolling it up.

While the dream of a flexible display has a long history, roll-up and paper-like displays are now estimated to be commercially feasible by around 2014. It has also become apparent that the advent of flexible display systems will have a significant impact on the market, not only because of the ubiquitous and convenient systems that could be supported, but also because of the potential to provide unconventional visual effects that are not possible with conventional systems. Moreover, the manufacturing technology for these displays will likely be low-cost and environmentally friendly.

Studies on display systems and materials have just begun, and it is unwise to give definitive statements about such a display system for television. That said, however, the following pages describing the issues and prospects of flexible displays will hopefully give the reader an overall introduction to the present research.

2. Impact of Flexible Displays

The move from the cathode ray tube (CRT) display to the FPD is a major transition; electron beam scanning systems are rapidly being replaced with matrix displays (a sequential display with a cell structure corresponding to pixel dots). The main effects of this transition are a significant space saving that makes large wall-mountable TV screens practical and enhanced mobility, as in the case of the laptop computer. A flexible display system is expected to have a significant impact, i.e., beyond that of conventional FPD systems. That impact is detailed below.

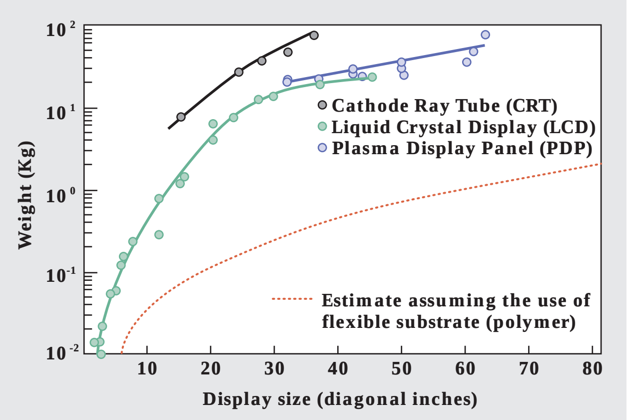

Figure 1: Relationship between display weight and screen size

1) Ubiquitous, Convenient System

The weight of a 40-inch diagonal flexible display constructed on a 0.2-mm-thick plastic substrate would be approximately 500 g. This is two orders of magnitude lighter than a conventional wall-mounted PDP, LCD, or CRT display (Figure 1). Its volume would be at least three orders of magnitude smaller than that of a CRT display. It will be able to be rolled up or folded, transported anywhere, and operated indoors or outside. These characteristics will drastically diversify TV viewing styles and promote the distribution of the contents.

2) Fusion of Medias

A display device is an essential piece of hardware for a variety of media, including broadcasting, communications, and personal computers. Accordingly, if a display device possesses paper-like properties, electric media and paper media will fuse to diversify viewing styles. Moreover, if a flexible display is equipped with an information storage function, e.g., printing of TV screen image, it will open up an array of application possibilities.

3) Visual Effects of Curved Display

Some movie theaters have curved screens and there are subjective evaluation results showing that a slightly curved display (a concave surface as viewed by an observer) is preferable to a flat display. Some research using simulation method also supports the idea that a curved display presents a stronger sensation of reality. A curved display can attain a larger viewing angle, which could lead to an enhanced sensation of reality even with a relatively small display device. Since there have been no systematic or extensive experiments conducted using a direct-view-type display, it is also anticipated that a flexible display system will serve as a research tool for such visual effects. The capability of displaying images on a surface with an arbitrary degree of curvature will contribute to a wide range of applications in the medical, transportation, and educational fields, among others.

4) Low-energy, Low-cost Manufacturing Technology

The current PDP system employs a manufacturing process that requires temperatures of 400°C to 500°C during the screen-printing, firing, and vacuum-sealing steps. Present LCDs, which use amorphous silicon thin film transistor (a-Si TFT) for driving, must be fabricated at high temperature (up to 300°C). The present technology also uses up a lot of raw materials, e.g., a massive amount of glass substrate. On the other hand, flexible displays using a plastic substrate can be manufactured at near ambient temperature, and very little raw material is used up for the approximately 0.2-mm-thick substrate. The flexibility of the plastic substrate and display material will enable space-saving production through rolling technology such as roll up and roll over. Beyond the benefits of lower costs, these fabrication technologies would have less impact on the environment.

3. Research Trends in Display Systems and Materials

Table 1 shows a list of examples of potential flexible display systems that can be fabricated with a plastic substrate. The basic display principles can be classified according to five aspects: 1) electroluminescent (EL) systems, 2) external optical modulation systems based on liquid crystal molecular orientation changes by an electric field, 3) reflected light modulation systems caused by colored particle shifts and rotation in electric or magnetic fields, 4) reflected light modulation systems by electrochemical (thermal) response, and 5) mechanical external optical modulation systems. There are several systems and materials proposed for each principle. Among these, liquid crystal, except for liquid crystal film, and 3), 4), and 5) are the lines of research that have been advanced for realizing an electronic paper device for still-picture presentation. This section will give a brief explanation of the principles and features of each technology.

1) Electroluminescent (EL) Systems

A typical example of this system is organic EL devices as first conceived by C. W. Tang et al. of the Eastman Kodak Company in 1987. Enthusiastic development followed, with devices initially employing low-molecular-number materials (a single molecule with several dozen to several hundreds of atoms in it). These early materials were hard-to-bend and thus were not suitable for a flexible display. Recently though, they have been used in cellular phone displays. Flexible high-molecular-number materials soon caught up in sophistication, and today there is little characteristic difference between these materials. A simple illustration of the basic principle of EL light emission is shown in Figure 2. Energy is input to cause molecules in the luminous layer to reach a high energy state when electrons and holes (electron empty shells) injected from the positive and negative electrodes are recombined in the

Table 1: Flexible display scheme and material comparison

Basic display principle	Light-emissive/ Non light emissive	Display system	Material scheme details	Response speed	Gray-scale display	Reduced power-consumption	Enhanced resolution	Large display
Electroluminescence (EL)	Self-emissive	Organic EL	Polymer material	◎	◎	△	◎	○
External optical modulation by liquid crystal molecular orientation change	Transmissive Reflective	Liquid crystal	Cholestric LC	×	△	○	○	○
			STN LC	×	○	○	○	○
			Ferroelectric LC	◎	×	○	○	○
			Polymer LC	○	×	○	○	○
			LC film	◎	◎	○	○	○
Color particle shift/ rotation	Reflective	Electrophoretic	Microcapsule	×	○	◎	△	○
			In-Plane	×	○	◎	△	○
		Magnetophoretic		×	△	◎	△	○
		Toner		×	△	◎	△	○
		Electronic Liquid Powder		◎	△	◎	△	○
		Electric field deposition		×	△	◎	△	○
		Twist ball	Electrostatic	○	△	◎	△	○
			Magnetic	○	△	◎	△	○
Molecular Color response	Reflective	Thermal		×	△	×	△	○
		Electric field color development		×	△	○	△	○
Mechanical external light modulation	Reflective	Optical interference reflective		◎	○	○	◎	△
		Movable film		◎	○	○	△	○

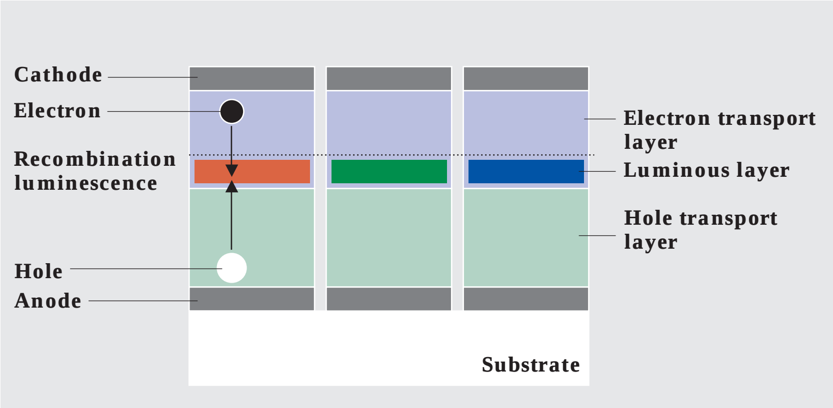

Figure 2: Basic structure and display principle of organic EL

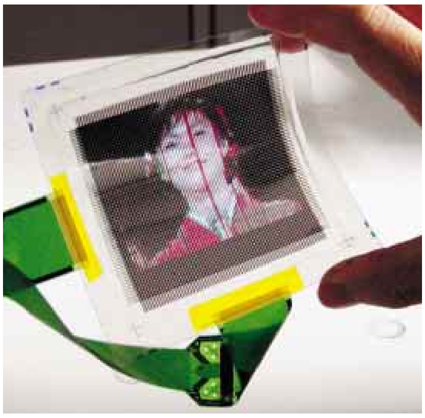

Figure 3: Flexible organic EL display

luminous layer. The energy is emitted as light when the state returns to the normal, stable one. A broad range of trials are being made on these materials and on device structures for them. Their quick response (1 ms or less) and self-emissive characteristic are promising features for high-quality moving-image displays. Figure 3 shows an example of flexible organic EL display developed by NHK using white light-emitting phosphorescent polymers and RGB color filters. Both low molecular number and high molecular number systems face significant challenges in attaining sufficient luminous efficiency (reduced power consumption), device life, and economy.

2) Liquid Crystal (LC) Systems

Several LC materials have been developed. Figure 4 shows one, optical writing cholestric liquid crystal, when an electric field is applied (not applied) perpendicular to the substrate. When no electric field is applied, a structure appears in which the molecules are aligned such that their long axes to rotate about the substrate perpendicular [Figure 4 (a): Planer structure]. This allows selective reflection of light at a wavelength corresponding to the pitch of the rotation (interference reflection). A low applied electric field causes the rotating axes to turn 90 degrees, allowing light to be transmitted [Figure 4 (b): Focal conic structure]. This orientation is maintained even after the electric field ceases. A higher electric field will align the long axes uniformly in the direction of the electric field, further improving the optical transmittance [Figure 4 (c): Homeotropic structure]. The structure changes to a planar one after the electric field is removed. An image can be displayed by controlling these three orientation states. This scheme has the drawback of a high drive voltage.

Another scheme is one that sandwiches ordinary super-twisted nematic (STN) liquid crystal between plastic substrates. Unfortunately this scheme has a slow response of several dozen ms. To overcome this problem, a high-molecular-number liquid crystal material was developed that connects ferroelectric liquid crystal (FLC) with a side chain of monopolymer. The high-speed FLC is then sandwiched between plastic substrates. However, these systems can be used only for a binary gray-scale display. Contrary to these, a new liquid crystal material (liquid crystal film) with both high-speed response and gray-scale

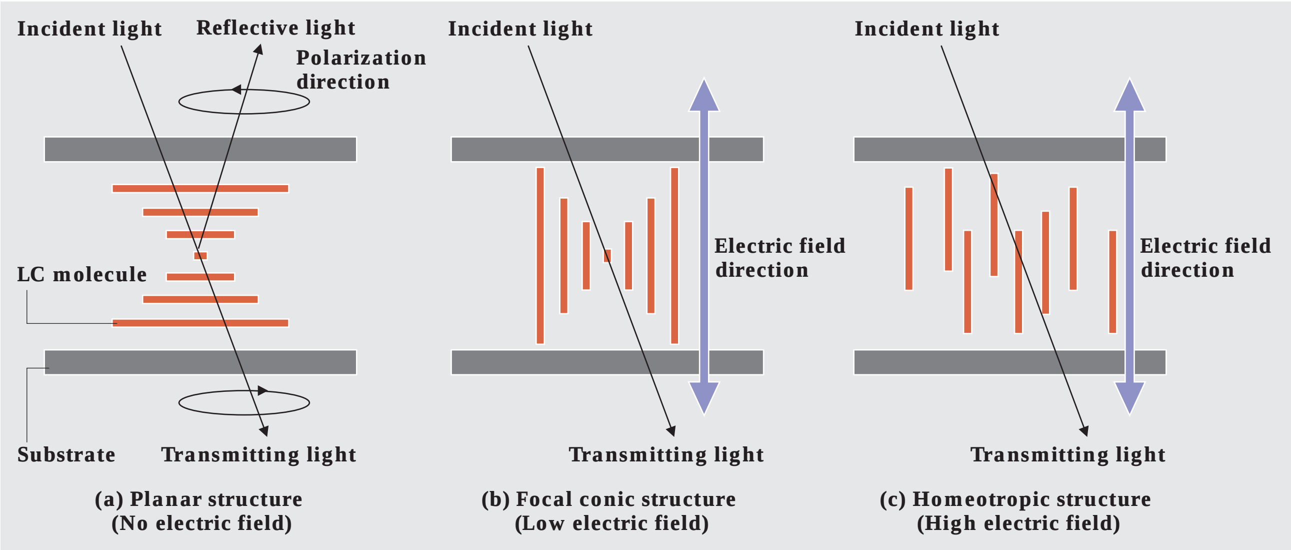

Figure 4: Molecular orientation change by applying electric field and display principle of Cholestric LC

display capability has been developed. This flexible material is composed of the polymer network and the ferroelectric liquid crystal. An example of flexible LC display developed by NHK is shown in Figure 5.

Figure 5: Flexible LC display

3) Moving Particle Systems

This is an electrophoretic image display (EPID) system. The first such system was developed in the 1970s, and EPID has recently become a lively topic after the advent of new materials. A typical example is the microcapsule structure (Figure 6), which uses pigment particle sealed in polymer micro-capsules. The pigment particles are positively or negatively charged according to its color, and to obtain enough contrast to operate as a reflective-type device, these particles are moved closer to the front substrate or to the rear substrate by applying an external electrical field. A color device can be constructed by using either colored particles or colored fluid. Systems which move colored particles horizontally near a substrate surface or rotate spheres (colored in semi-sphere units) include the twist ball system and the toner system. Another recent development is a display in which polymer powder can be traveled rapidly under the electric field. This system is said to have a high-speed response to complement the electrophoretic image display's general merits of high contrast and good image retention.

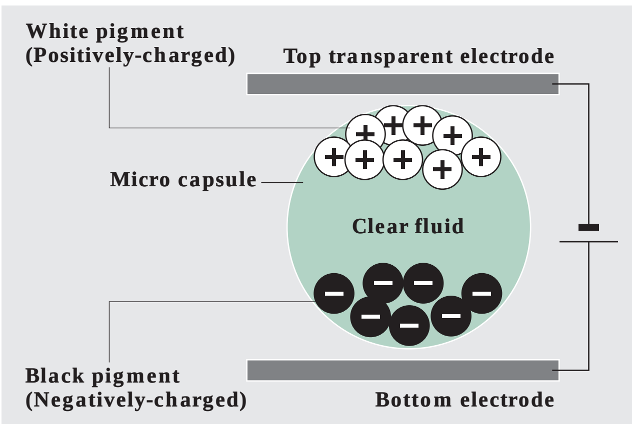

Figure 6: Basic structure and display principle of microcapsule electrophoretic image display

4) Electrochemical and Thermal Change systems

This system is exploited by electrodeposition displays (EDD). For a typical EDD, silver ions are electrodeposited onto an electrode from an electrolyte solution under an applied voltage to reflect outside light. A recent device shows a high reflectivity (73%) at a low voltage. Electrochromic displays (ECD) first appeared in the 1970s and the early ones worked by exploiting electrochemical oxidation-reduction to produce an optical absorption spectrum change in a material. A recent prototype display based on viologen had a slow response, indicating the difficulties of creating moving image displays with this method. A wide range of thermal image rewriting systems has also been pursued. A typical scheme is one that controls color response by the temperature of leuco dye (Figure 7). This dye is employed in thermal recording: it is colorless by itself, but responds to a developer at a high temperature. The developed color can be diminished when it is returned to a certain lower temperature, with the developer separating from the dye. This scheme can attain high-contrast images with good image retention performance, yet its slow response makes it difficult to display moving images.

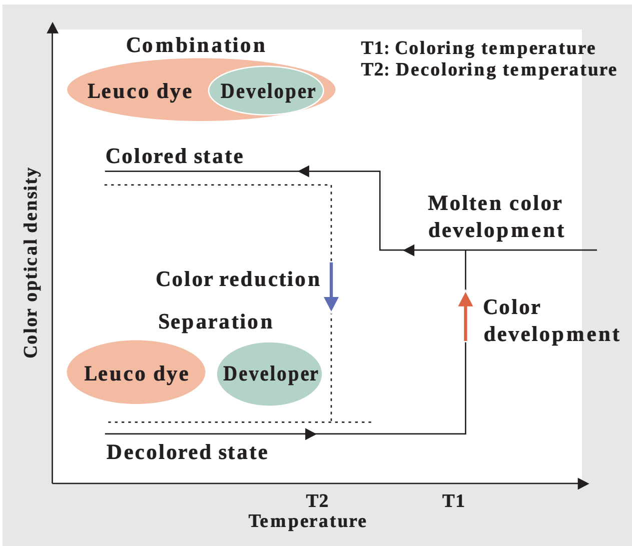

Figure 7: Leuco dye color development/reduction reaction

5) Mechanical External Light Modulation Systems

Micro-electromechanical systems (MEMS) use semiconductor fine processing technology to form mechanical rather than electrical components. The digital micro-mirror device (DMD) is one of MEMS for a projection display and has already made it to the market. A DMD is manufactured with micron-sized square micro-movable mirrors corresponding to pixel dots, modulating incident light by tilting the mirrors for each pixel dot. Similar to this is research on a reflective display that modulates external light using a mechanical device (Figure 8). It consists of a conductive thin film over a glass substrate, with a variable-

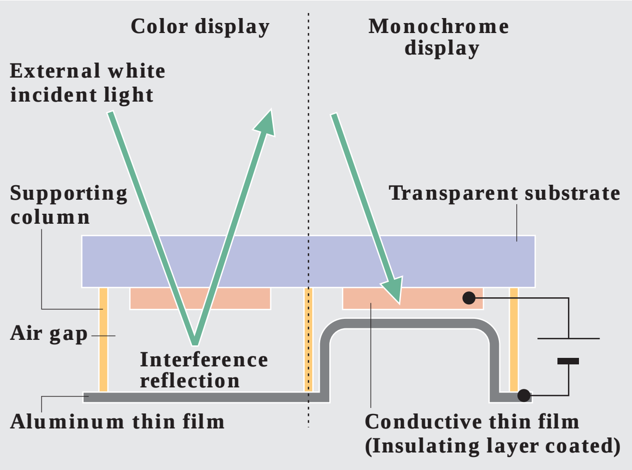

Figure 8: Structure and display principle of MEMS optical interference reflective display

form thin metal film (aluminum) underneath this conductive thin film, separated by an air gap between them. Both the thin film and metal film are coated with an insulating layer. For this arrangement, the device reflects light at a wavelength determined by the interference based on the gap. When a voltage is applied between the thin film and metal film, an electrostatic force causes the metal film to cave in the side of the conductive thin film. At this moment, the device absorbs light. The current technology can make a dot size approximately 25μm square. Color displays with RGB dots of differing air gap sizes have been test manufactured. They have a response of several microseconds, which is adequate for displaying moving images. Moreover, their operating voltage is low (approximately 11 V).

Other mechanical systems include one that moves a micro-cantilever closer or farther from an electrode by using voltage to obtain contrast. This is a promising system for constructing large displays with high contrast and good image retention. While the mechanical modulation system, which combines these micro-precision mechanisms and electrostatic drive devices, does not have adequate flexibility at this stage, the potential for improvement remains because new materials and structures are actively sought in many research fields.

4. Challenges and Prospects for a Flexible Display System

As mentioned above, there are a diverse range of candidate display systems and materials for flexible display. A flexible TV display will require nearly the same performance level as that of ordinary FPDs. Considering that future digital broadcasting will center on HDTV, the final target would naturally be a screen capable of displaying HDTV. Reaching this goal will thus entail breakthroughs in reducing power consumption, a thorough investigation of human factors, and new materials. Above all, the picture quality of flexible screens has to be increased.

1) Enhanced Picture Quality

Unlike conventional electronic paper, which has mainly been studied with an eye to developing still-picture displays, a flexible TV must have a high-speed response and gray-scale capability. Table 1 indicates that the organic EL, liquid crystal film, and mechanical modulation systems are promising in this regard. The organic EL device is especially promising because it is the only self-emissive device. Liquid crystal film can use backlighting, obviating the need for external light. On the other hand, reflective systems, such as the electrophoretic and electrochemical/thermal systems and the mechanical modulation scheme, cannot be viewed in dim conditions without an external light and require high reflectivity. In their favor, these schemes have high image retention performance, whereas organic EL and liquid crystal film devices require a memory function, namely active-drive TFTs, to retain large images of sufficient quality. Advances in LCDs and organic EL using an ordinary glass substrate have led to high-performance TFTs based on amorphous silicon and low-temperature polysilicon. Such TFT devices must be made flexible if they are to be incorporated into a flexible display. Organic TFT characteristics, for example, carrier mobility, have shown significant improvement in the past ten years, nearly reaching the levels of amorphous silicon. Organic TFTs have yet to equal the performance of low-temperature polysilicon TFTs.

Further improvements aimed at the picture quality of organic EL devices will depend on whether luminous efficiency and device lifetime can be steeply increased. Success will depend on multi-literal research, especially on new materials and structures. Regarding liquid crystal film, a device structure optimized for large color display, reflective or transmissive, must be sought. Better reflectivity and response are also desirable for reflective displays.

2) Power Consumption Reduction

9.4% of the residential power consumption (2% of the total power demand in Japan) in fiscal 2000 was power for TVs. A 50 to 60 inch PDP consumes 377 to 635 W and a 32 to 45 inch LCD uses 169 to 250 W (module only). Even larger FPDs are being constructed, and future increases in their numbers and operating time will present a significant burden on our energy supplies. Every effort needs to be made to suppress the display's power consumption. This need is especially evident in the case of flexible displays for outdoor applications, since these will be battery-operated. Although the reflective systems in Table 1, such as liquid crystal, electrophoretic, electrochemical/thermal response, and mechanical modulation are low power consumption systems, attaining highly efficient light emission is still a problem for organic EL devices. Our laboratories have succeeded in realizing higher efficiency light emission by using phosphorescence, which bears the promise of reduced power consumption.

3) Human Factors

It is said that the replacement of paper media with electronic media will have diverse impacts in relation to human factors, such as ease of viewing and reading. One example of this is a study that showed that an objective assessment of work performance when information was presented using various electronic displays or as hard-copy on paper showed no significant difference, yet the subjective assessments from the test subjects indicated that subjects felt that information on paper was easier to see and caused less fatigue. One factor that is considered to have caused this result was the larger degree of freedom for posture while viewing the information on paper. Thus, it seems that a flexible display may have greater ease of viewing and less fatigue compared with an ordinary stationary display, since it can be viewed with different postures. The effect in this regard is not yet clear, as no operational flexible display has been constructed, but the issue will become significant as we move into a paperless world.

4) Materials Technology

Conventional broadcasting devices employ inorganic semiconductor devices such as silicon transistors, light-emitting diodes, CCDs, solid-state memories, and ultrahigh-frequency devices, and employ semiconductor processing technologies. Attaining a higher device performance depends on fabricating a device that is as small and precise as possible, and using good crystals (or amorphous film). However, we are fast approaching the physical limits of device characteristics and lithography, and will face extreme difficulty in constructing complex structures utilizing many different materials while maintaining good crystal quality. This indicates that performance improvements in future broadcasting devices, or the creation of new devices with new functions, will be increasingly difficult by using conventional technologies.

At the same time, however, organic materials are generating interest as a key material for flexible TV displays. These materials include organic EL, liquid crystal film, and organic TFT. On an organic EL device, a molecule emits light by being excited to a high-energy state, and carrier mobility is also based on the molecule's oxidation-reduction response. Organic molecular structures are equivalent in size to inorganic nano-structures, and thus, nano-scale device can be created relatively easily by employing them. By forming a nano-scale device by aligning molecules regularly as "molecular functions", rather than using micro-processing technology, will be the challenge in organic device research. The potential is there to bring about new functions and characteristics beyond the physical limitations of inorganic devices.

Although significant questions on the prospects of improving organic EL device life remain, one may take heart that the initial research on laser and light-emitting diodes consisting of inorganic III-V compound semiconductors faced a number of setbacks. These semiconductors appeared at first to be easily degraded, but the vigorous research that followed eventually overcame the deterioration or device-lifetime problems. Now they are core devices in today's information communications field. It is hoped that similar research on organic materials will also succeed. The applications of organic materials to broadcasting-related technology are being led by studies on plastic optical fiber and polymer film batteries. It is our hope that organic materials open up possibilities for significant performance improvements and new devices, including transistors, organic EL lighting, and photoconductive film. I believe that the research on flexible displays is a touchstone to the research that will follow.

5. Conclusion

A flexible display has the potential to significantly expand TV viewing styles, in addition to providing ubiquitous broadcasting services as an easy-to-use TV. In the aspect of hardware, the fact that it can be manufactured with a low-temperature, space-saving process, making it an energy-saving, resource-saving device, matches well with future environmental protection goals. Organic material also promises new functions and performance improvements for conventional inorganic material devices. The display market, including large-display televisions, will continue to grow in the future. The market for LCDs alone is estimated to reach 10 trillion yen by 2010. Therefore, the fact that a flexible display will have various applications will likely have an extensive impact, not only on broadcasting and broadcasting technology, but also on the entire electronics industry. The development of organic EL and liquid crystal film for such a diverse range of purposes will require numerous breakthroughs in efficiency and device lifetime, the construction of new device structures, and transistor improvements. Research on flexible displays at the Science & Technical Research Laboratories will embrace the challenge of pioneering new broadcasting devices based on organic materials.

(Fumio SATO, Director, Display and Optical Devices)