Suftla Flexible Active-Matrix Electrophoretic Displays

Mitsutoshi Miyasaka, Satoshi Nebashi and Tatsuya Shimoda [1)]

Flexible Microelectronics Project, Seiko Epson Corporation, 281 Fujimi, Fujimi, Nagano, 399-0293 Japan
1) Corporate R&D, Seiko Epson Corporation, 3-3-5 Owa, Suwa, Nagano, 392-8502 Japan
E-mail: miyasaka.mitsutoshi@exc.epson.co.jp

Abstract

We have developed the world's thinnest flexible electrophoretic displays (EPDs). The thin-film displays are 95 μm thick, which is nearly the same thickness as a standard sheet of paper. Weighing 0.44g including external connection cables, these displays are also probably the world's lightest.

We have also developed 7.1-inch-diagonal (paperback-sized) high-resolution flexible EPDs. The displays are large enough to be used as practical e-paper. More than 7 million transistors work correctly on plastic, enabling us to see 3-megapixel images.

These flexible displays include active-matrix TFT devices that are fabricated using Suftla transfer technology. Suftla technology demonstrates the potential to achieve thin, flexible displays that will be used as an e-paper in the near future.

1. Introduction

Over the years technological advances have brought us devices that are progressively smaller, thinner and lighter yet are capable of handling massive amounts of data very fast while consuming less energy. This is descriptive of the recent history of technology in general, which is characterized by four general technology trends: (1) smaller and lighter; (2) massive amounts of data; (3) faster; and (4) high energy-efficiency. It is safe to assume that these technology trend rules will continue with the next generation of smaller, thinner, lighter, more powerful, faster, and energy-efficient electronic devices.

Electronic paper (e-paper) is one of the key electronic devices of the near future and promises to fire up the electronics market much like digital mobile music players have the past several years. To fulfill its promise, e-paper must be as paper-like as possible. It must also be capable of electrically rewriting high-quality images. Many researchers have been studying flexible display devices, both passive and active matrix, in an effort to develop such e-paper [1-4].

In this paper we intend to show the tremendous potential that an active-matrix electrophoretic display (AM-EPD) having integrated peripheral driver circuits and pixel switching elements has for e-paper, while referring to the four technology trends. The display we developed satisfies all the requirements posed for practical e-paper; that is, it is an energy-effective, thin, light flexible device that produces images of high quality on a large display and has few external connections.

2. Device Fabrication

The AM-EPD device consists of an EPD front-plane and an active-matrix thin film transistor (TFT) back-plane [5]. The EPD front-plane is prepared by coating a microencapsulated EPD paste on a thin polyethylentherephtalate film.

The TFT back-plane should include the peripheral driver circuits, thus eliminating the need for hard silicon ICs on the display device and minimizing the number of external connections. It is desirable to have as few external connections as possible, as securing stable electrical connections between flexible devices and flexible cables is a serious challenge. Polycrystalline silicon (polysilicon) TFT devices are used on our TFT back-plane because of the ability to integrate the peripheral circuits.

The CMOS polysilicon TFT active-matrix devices are first fabricated on a glass substrate and then transferred onto a plastic film, using Suftla transfer technology. A detailed description of Suftla technology is available elsewhere [6-8].

The AM-EPD fabrication is completed when the EPD front-plane is simply laminated onto the TFT back-plane. A vacuum-type laminator is used to avoid the formation of air-bubbles between

Fig. 1 Suftla polysilicon TFT devices formed on 30-μm-thick polyimide films

Fig. 2 World's thinnest display

front-plane and back-plane.

When we fabricate thin film displays, described in detail in the following section, we use a supporting substrate during the assembly process. When standing free and not supported by the substrate, the polysilicon TFT device transferred onto a thin plastic film warps due to residual thermal stress (Fig. 1). Figure 1 shows two TFT back-planes. The warped back-plane resting on the palm of the hand is free-standing; the other is rolled on a pen (the brown part of the pen). To facilitate the display assembly process, the plastic TFT back-plane is fixed to a transparent supporting substrate, using an ultra-violet-light (UV) degradable adhesive. After the display panel is completed, UV light is irradiated onto the adhesive from the transparent supporting substrate so that the display panel can be removed from the substrate.

3. Thin Film Display

The electronic devices in the next generation must be thin and lightweight, according to the first technology trend. Suftla clears this requirement without facing a serious problem [9], because the polysilicon TFT devices are transferred after being completed on a glass substrate.

Figure 2 shows a photograph of the world's thinnest, and likely its lightest, practical flexible thin film EPD device. With a paper-like total thickness of only 95 μm (62 μm for the EPD front-plane and 33 μm for the TFT back-plane), the device not only can be rolled but also displays clear images. The device weighs 0.44g, including external connection cables weighing 0.2g. The actual display area thus weighs only 0.24g, as compared to 0.14g for paper of the same size.

The display, which measures 42.2 mm in length and 31.7 mm in width, has 320 × 240 pixels. Thus the resolution is 192 ppi. Data- and scan drivers operate at 3.3V and EPD pixels are driven at 8.0V. Due to the good EPD properties, a contrast ratio of more than 10 is obtained even at the low voltage value of 8V. This contrast ratio is sufficiently high to enable the device to be used as e-paper. The frame frequency is 6.7 Hz so that one page is immediately rewritten.

Devices that are quite thin and lightweight are easily fabricated using Suftla. The devices also satisfy another important basic requirement of e-paper: high-quality images can be electrically rewritten even when the device is rolled up.

4. Paperback-sized Display

4-1. Specifications

Electronic devices in the next generation must integrate highly functional circuits and handle huge amounts of data, according to the second technology trend. From a viewpoint of e-paper this trend can be interpreted as meaning that an e-paper device must be large enough and have a resolution that is high enough to allow easy reading. Suftla has already cleared hurdles on the path to circuit integration and data-crunching power, as we have developed high-resolution 7.1-inch-diagonal flexible EPD devices (Fig. 3) [10].

The device is nearly the same size as a page in a

Fig. 3 Paperback-sized display

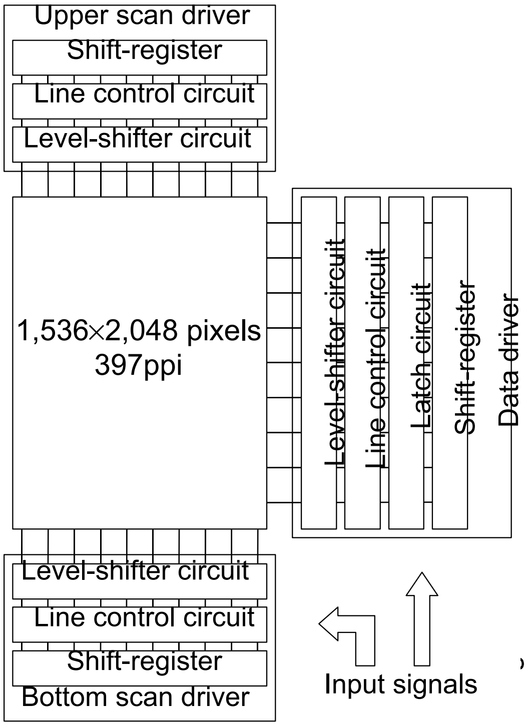

Fig. 4 Block diagram of the paper-back sized display

paperback, a best fit for reading with a hand-held device. Specifically, the display area measures 131 mm in length and 98 mm in width. It has 2,048 × 1,536 (= 3,145,728) pixels, resulting in a resolution of 397 ppi. The resolution is high enough to produce crisp, clear images. The thickness of the bare display (EPD front-plane and TFT back-plane) is 0.43 mm. An actual display device laminated with 100-μm-thick protection films has a total thickness of 0.63 mm. The device has 40 external connections on the bottom right corner of the display (the brown ribbon seen in Fig. 3). The total weight of the device is 11.3g, including the protection films and the brown ribbon. The display size, weight and shape satisfy the requirements for a practical e-paper.

To process huge amounts of image data, the data- and scan drivers include 8 parallel 256-staged shift-register circuits and a single 1,536-staged shift-register circuit, respectively. Both drivers also include line control circuits and level-shifter circuits (Fig. 4). The line control circuit in the scan driver prevents display image crosstalk [11]. The data driver also includes latch circuits so as to enable the digital line-at-a-time driving mode. The data driver is formed on the right-hand side of the device while a couple of scan drivers are formed on the upper- and bottom sides of the device. Since one scan line is connected to 2,048 pixel TFTs, thus having a large load-capacitance value, the scan signal is supplied onto the selected scan line both from the upper- and bottom scan drivers simultaneously. The width of the data- and scan drivers is less than 5 mm, so the actual device is 143 mm long and 108 mm wide.

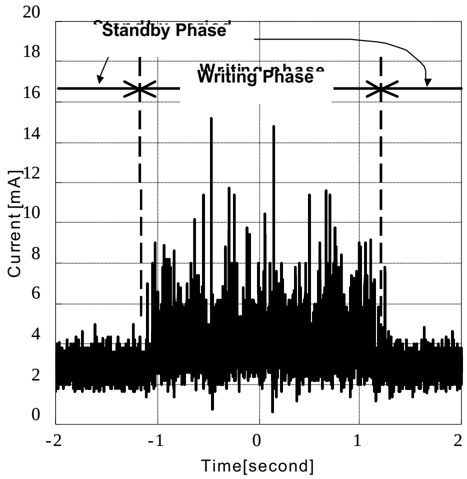

Fig. 5 Electric current consumed during the writing phase on the paper-back sized display

A total of more than 7 million transistors are formed on the plastic because the data- and scan drivers handle massive amounts of data and the display presents high quality images. All these transistors work correctly on plastic, enabling the thin, flexible device to display 3-megapixel images.

4-2. Energy Consumption

The electronic devices in the next generation must operate fast and consume less energy, according to the third and fourth technology trends. Low energy consumption is particularly critical for an e-paper system, which will be used in portable products with a small battery. Our Suftla e-paper device satisfies this requirement.

An image shown on the EPD device is inherently bi-stable in nature. An image drawn on the EPD screen is held even after power is removed. The system should effectively utilize the bi-stable nature of the EPD device to minimize the total energy consumption of the e-paper system.

When the e-paper system is used in real situations, there will be a transitional rewriting period before documents shown on the display are read (a reading period). Only during the rewriting period is electricity supplied to our Suftla e-paper device; no electricity is supplied during the reading period, so energy consumption is minimized. The rewriting period starts with an initializing phase that follows an erasing phase and a writing phase. When the electricity is supplied to the Suftla e-paper device, all the register outputs in the scan drivers are set in a low state in the initializing phase. This is because not all register outputs are fixed to a low state immediately after the electricity is supplied. The erasing phase erases the previous image to make the entire display area white. A new image is drawn during the writing phase. In order to obtain a high contrast ratio, the same image is drawn twice with an interval of 0.2 seconds [12]. The writing phase stretches over 2.2 seconds under the present conditions. However, this phase can be shortened, if the conditions are optimized. Therefore, the electricity is supplied to our Suftla e-paper device at most for a few seconds of the rewriting period while we are reading 1-page document on the e-paper system.

In our paperback-sized display the peripheral driver circuits operate at 3.3V and the pixel circuits operate at 6.0V. Figure 5 shows the electric current consumed during the writing phase. (Standby phases just before and after the writing phase are for this measurement. In the standby phases, the electricity is supplied to the device, but the peripheral drivers are not working.) The electric current consumption depends on what kind of images are shown on the display. For example, when the paperback-sized display shows an all-black image from corner to corner, it consumes approximately 12.3 mA. In contrast, when an all-white image is shown on the display, the current consumption is approximately 3.6 mA. This is because an all-white image is introduced as the erasing phase immediately prior to the writing phase, and during the writing phase the white pixels are kept on [12]. Only the black pixels are actually rewritten during the writing phase. The result of Fig. 5 is obtained when a typical text image is shown on the display. The average current consumption when the text image is shown is approximately 3.9 mA. Correspondingly, the total energy consumed in the drawing of 1 page of text in the writing phase is 12.9×10^{-6} Watt-hours, a negligible power draw compared to the 2 Watt-hour energy capacity of an AA-sized alkaline cell battery. Therefore, used in a real e-paper system, our display would consume a sufficiently modest amount of power; the bulk of the power would be consumed by non-display parts in the e-paper system, such as the microprocessor and memory circuits.

5. Conclusions

Referring to the four technology trends, a practical e-paper system must (1) be thin and light; (2) be large and have high-resolution for easy reading; (3) have peripheral drivers formed on the back-plane; and (4) operate at low voltage. Suftla technology meets all these requirements, as we have developed 95-μm-thick thin film displays and paperback-sized high-resolution flexible displays that operate at high energy efficiency.

Suftla technology will be a driving force behind the nascent e-paper business and flexible microelectronics industry.

6. Acknowledgments

The authors gratefully acknowledge E Ink Co. for providing the EPD front planes.

They also gratefully acknowledge Hitachi Chemical Co. Ltd. and Zeon Co. for providing the plastic sheets.

This research is supported in part by the New Energy and Industrial Development Organization (NEDO), Japan.

7. References

[1] G. H. Gelinck, H. E. A. Huitema, M. van Mil, E. van Veenendaal, P. J. G. van Lieshout and F. J. Touwslager, *SID 05 Digest*, (2005), p. 6.

[2] S-H. Paek, K. L. Kim, H-S. Seo, Y-S Jeong, S-Y Yi, S-Y. Lee, N-B. Choi, S-H. Kim, C-D. Kim and I-J. Chung, *SID 06 Digest*, (2006), p. 1834.

[3] I. French, D. McCulloch, I. Boerefijn and N. Kooyman, *SID 05 Digest*, (2005), p. 1364.

[4] R. Hattori, S. Yamada, Y. Masuda and N. Nihei, **J. SID** 04 **12/1**, (2004), 75.

[5] A. Miyazaki, H. Kawai, M. Miyasaka, S. Inoue, T. Shimoda, *IMID 04 Digest*, (2004), p. 153.

[6] T. Shimoda and S. Inoue, *IEDM 99 Tech. Digest*, (1999), p. 289.

[7] S. Utsunomiya, T. Kamakura, M. Kasuga, M. Kimura, W. Miyazawa, S. Inoue and T. Shimoda, *SID 03 Digest*, (2003), p. 864.

[8] M. Miyasaka and T. Shimoda, *IMID 03 Digest*, (2003), p. 61.

[9] T. Kodaira, S. Hirabayashi, Y. Komatsu, S. Utsunomiya, M. Miyasaka, H. Kawai, S. Nebashi, S. Inoue and T. Shimoda, *IDW/AD 05* (2005), p. 869.

[10] Y. Komatsu, H. Kawai, T. Kodaira, S. Hirabayashi, M. Miyasaka, S. Nebashi and T. Shimoda, *SID 06 Digest*, (2006), p. 1830.

[11] Y. Komatsu, H. Kawai, M. Miyasaka, T. Kodaira, S. Nebashi and T. Shimoda, *The 2nd Int. TFT Conf.* (2006), p.184.

[12] A. Miyazaki, H. Kawai, M. Miyasaka, S. Inoue, T. Shimoda and M. McCreary, *IMID 05 Digest*, (2005), p. 575.