Flexible Microelectronics; High-Resolution Active-Matrix Electrophoretic Displays

Atsushi Miyazaki [1)], Hideyuki Kawai [1)], Mitsutoshi Miyasaka [1)], Satoshi Nebashi [1)], Tatsuya Shimoda [2)] and Michael McCreary [3)]

1) Seiko Epson Corporation, Advanced Product Development Center, 281 Fujimi, Fujimi, Nagano, 399-0293 Japan
TEL +81-266-61-1221

2) Seiko Epson Corporation, Corporate R&D, 281 Fujimi, Fujimi, Nagano, 399-0293 Japan
TEL +81-266-61-1221

3) E Ink Corporation
733 Concord Avenue, Cambridge, MA 02138, USA
TEL +1-617-499-6132

Abstract

A beautiful, flexible active-matrix electrophoretic display (AM-EPD) device is reported. The flexible AM-EPD device has a 40.0 × 30.0 mm² display area, measures about 0.27 mm in thickness, weighs about 0.45 g and possesses only 20 external connections. The flexible AM-EPD device displays clear black-and-white images with 5 gray-scales on 160 × 120 pixels. The display is free from residual image problems, because we use an area-gray-scale method on 320 × 240 EPD elements, each of which is driven with binary signals. Each pixel consists of 4 EPD elements. In addition, since the response time of the electrophoretic material is as long as approximately 400 ms and since the display possesses a large number of EPD elements, we have developed a special driving method suitable for changing EPD images comfortably. A complete image is formed on the AM-EPD device, consisting of a reset frame and several, typically 6, image frames.

1. Introduction

The demand for electronic paper (e-paper), an electronic display system with paper-like features, is being driven higher as more and more electronic documents are distributed over computer networks such as the Internet. This demand has incited a wave of studies on e-paper display devices [1, 2]. Electrophoretic displays (EPDs) [3] are believed to be the most promising of the various display devices for e-paper.

EPD device meet all the requirements for e-paper applications. For example, they offer high reflectance, a good contrast ratio, a wide viewing angle, and long image stability after power is removed [4]. In addition, EPD devices have a major advantage over other display devices in that they are quite easily fabricated and, hence, can be fabricated at lower cost. EPD devices consist of a frontplane and backplane. The frontplane is a thin plastic sheet, on which an electrophretic material is coated. The backplane is either glass or a plastic plane on which a number of pixels are formed. The frontplane is laminated onto the backplane to complete the EPD device. The simple fabrication process and their excellent optical properties make EPD devices the most promising candidates for realizing an e-paper system in near future.

Two drawbacks of EPD devices are a slow response to electric signals and an inability to use passive matrix addressing. To overcome these shortcomings, we developed simple active-matrix electrophoretic displays (AM-EPDs) using low-temperature polycrystalline silicon (LTPS) thin film transistor (TFT) technology [5,6].

This paper presents beautiful high-resolution AM-EPD devices that show a slight improvement over those reported earlier [6]. Our new flexible AM-EPD devices display clear black-and-white images with 5 gray-scales. A special driving method that is suitable for AM-EPD devices with a large number of pixels is also discussed.

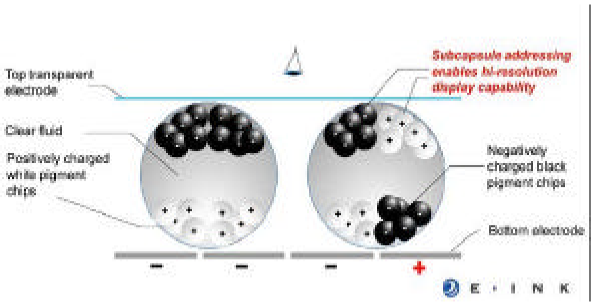
2. Device Fabrication

2.1 Backplane

Low temperature polycrystalline silicon TFTs are fabricated onto a glass substrate, using a standard LTPS TFT fabrication process. TFT device performance is high enough to allow peripheral driver circuits to be integrated onto the glass substrate, which allows us to reduce the number of external connections between the TFT active matrix substrate and outside controller circuits to 20. The TFT active matrix backplane thus fabricated is transferred onto a plastic sheet, using surface-free technology by laser ablation/annealing (SUFTLA™) [7,8]. The backplane is 0.2-mm thick. The performance of the TFT devices is perfectly preserved after the SUFTLA™ process. The peripheral driver circuits operate correctly on a plastic sheet. The circuit performance on plastic is also exactly the same as that on glass.

2.2 Frontplane

To form the frontplane, which is approximately 0.07-mm-thick, a microencapsulated electrophoretic material and polymer binder are coated on a polyethylene terephthalate film that possesses a thin indium tin oxide (ITO) layer. These are then combined with an adhesive layer. The microencapsulated electrophoretic material contains charged black and white pigments in a clear fluid. EPD devices operate on the principle of electrophoresis, wherein charged particles suspended in a clear liquid migrate under the influence of an electric field (Figure 1). In this particular EPD, when a



negative electric voltage is applied to a bottom electrode, the black particles are attracted to the top transparent electrode, where they become visible to the user as a black spot. White spots can be seen when the opposite polarity of voltage is applied.

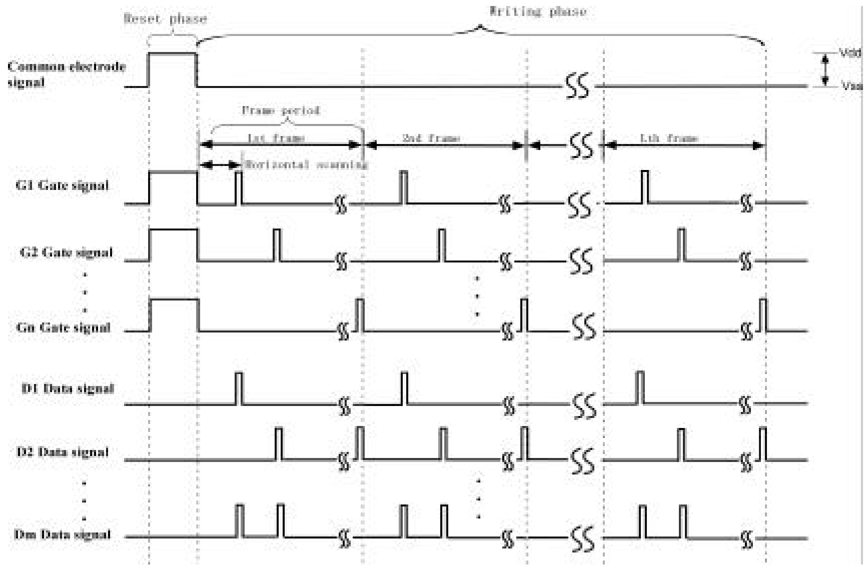
2.3 Fabrication of a Flexible AM-EPD Device

The frontplane and backplane are laminated together with a vacuum-type laminator to form a complete flexible AM-EPD device. The device measures about *0.27* mm in thickness and weighs about *0.45* g.

2.4 Device Specifications

The specifications of the AM-EPD device are summarized in Table 1. The flexible AM-EPD device has a display area of 40.0 mm $\times$ 30.0 mm. The display area is in a matrix form and contains 320 $\times$ 240 electrophoretic display elements (EPD elements). Each EPD element possesses a switch TFT and an element electrode. Between the element electrode on the backplane and the ITO layer on the frontplane is an electrophoretic material. The switching TFT is used to introduce binary signals, i.e. either completely black signals or completely white signals, into the element electrode. Since binary signals are used, the flexible AM-EPD device is free from residual image problems.

One pixel of the flexible AM-EPD device consists of 4 EPD elements to realize 5 gray-scale. When all the EPD elements of a pixel are in a white state, the pixel shows a completely white image (Level 0). Conversely, when all the EPD elements of a pixel are in a black state, the pixel shows a completely black image (Level 4). When one of the 4 EPD elements in a pixel is in a black state and the other 3 EPD elements are in a white state, the pixel shows a near-white gray image (Level 1). The 5 gray-scales are thus produced in this way. Since each pixel consists of 4 EPD elements, the flexible AM-EPD device possesses 160 $\times$ 120 pixels.



3. Optical Properties of the AM-EPD Device

3.1 Driving Method

A complete image consisting of a reset frame (a reset phase) and several image frames (a writing phase) is formed on the flexible AM-EPD device (Figure 2). During the reset phase the previous image on the device is erased and replaced by a completely white frame. All the EPD elements on the backplane are at low potential, and the ITO layer on the frontplane is at high potential in the reset phase. During the writing phase a new image is formed on the device. Pixels that must show white stay at low potential, but the potential of pixels that must show black changes from low to high during the writing phase.

We use a digital line-at-a-time mode for introducing image data into the EPD elements in the writing phase. In the first part of a horizontal scan period image data are transferred on a data-driver (X-driver). During this period no gate line is selected. In the second part of the horizontal scan period one gate-line is selected by a scan-driver (Y-driver), and image data that were transferred and latched in the data-driver are introduced simultaneously into the EPD elements that connect to the selected gate-line. This method perfectly prevents a cross-talk problem, because the image data introduced into a horizontal line are completely isolated from those introduced into the next horizontal line.

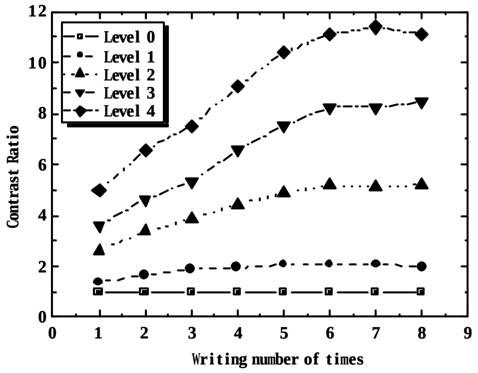
The response time of our electrophoretic material is approximately 400 ms. If it takes longer than the response time to complete an image frame, a vertical scan line appears on the AM-EPD device when images are changed. A writing phase consisting of several image frames, typically 6, is used to solve this problem. Each image frame has the same image data. The same image is repeatedly introduced into the EPD elements. Since one horizontal period is set to 1 ms, and since there are 240 scan lines on our display, it takes 240 ms to make an image frame. One image frame is therefore shorter than the response time of the electrophoretic material, so the vertical scan line is not seen. On the contrary a new image appears across the whole display area simultaneously. This driving method is the most comfortable for changing images.

Table 1. AM-EPD device specifications

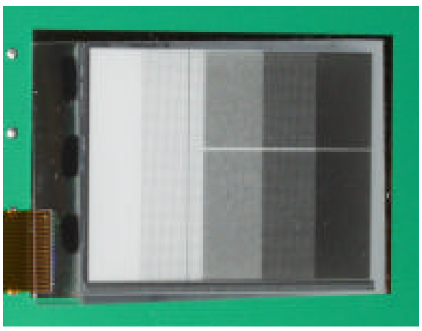
Number of EPD elements	320? 40 elements
EPD elements pitch	125 µm (200 dpi)
Number of pixels	160? 20 pixels
Pixel pitch	250 µm (100 ppi)
Operation Voltage	9 V
External connection	20
Driver	Built-in
Thickness	0.27 mm
weight	0.45g

3.2 Optical properties

Since our TFT has a high on-current value of more than 10 μA, and a capacitor in each EPD element has a capacitance value of approximately 5 pF,



10 μs of a selection period for the switch TFT is long enough to charge the capacitor. This means one image frame (1 ms of horizontal scan period) could theoretically display a beautiful picture on the flexible AM-EPD, but in reality we need more than 5 image frames. Figure 3 shows contrast ratio dependence on the number of image frames. This figure clearly indicates that the contrast ratio improves as the number of image frames increases and reaches saturation over 6 image frames. Figure 4 illustrates a 5 gray-scale chart. This image is formed with one reset frame and 6 image frames. A pixel contains 4 EPD elements of 125 μm × 125 μm and therefore its size is 250 μm × 250 μm. Because of the small pixel size, 5



gray-scales are successfully shown. Although the reason that more than 6 image frames is needed is not yet clear, the flexible AM-EPD device still successfully displays beautiful images. The EPD element driving voltage was 9 volts.

A beautiful image is comfortably shown on an AM-EPD device when short image frames are repeatedly introduced. This driving method will be especially important when AM-EPD devices possess a huge number of pixels and the horizontal scan period becomes shorter.

3.3 Flexible AM-EPD Device Image

Figure 5 shows a photograph of the flexible AM-EPD device. Although connecting a flexible backplane to input signal terminals is problematic, the backplane has only 20 external connections. The backplane was thus easily connected to input signal terminals and produces a successful image. The display is flexible and bendable. It is also confirmed that the flexible AM-EPD device retains images even after power is cut off.

4. Conclusion

Beautiful, high-resolution, flexible AM-EPD devices have been fabricated, and a driving method suitable for AM-EPD devices has been developed. The advantage of using bendable, thin, lightweight film substrates has been demonstrated. In addition, 5 gray-scales were accomplished by using area gray scale, and effectiveness of a continual writing method was confirmed. The device is worthy of practical e-paper. Although the current flexible AM-EPD device is small, this study represents a giant leap forward for e-paper.

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