Flexi-e: Side-by-Side Manufacturing of Flexible Displays and Glass TFT-LCDs

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Abstract

Electronic Paper Displays (EPDs) incorporating electrophoretic foils have made digital reading as pleasant as reading normal print. We will report on progress to replace glass-based displays with light and robust plastic EPDs using only a few extra process steps in a standard TFT-LCD factory.

1. Introduction

The first flexible Active Matrix (AM) displays were made more than ten years ago on plastic substrates using Thin Film Diodes as the switching elements [1]. Since then, flexible displays have been made with almost every possible combination of stainless steel or plastic substrates and TFTs made with amorphous silicon (a-Si), Low Temperature Polycrystalline Silicon (LTPS), polymer or inorganic oxide semiconductors. These have been used to drive LCDs, OLEDs and electrophoretic displays [2]. Market surveys show that there is a large demand for flexible displays, particularly for handheld and mobile applications [3]. Despite this demand and the long standing ability to make flexible displays in laboratories, none have yet appeared on the market. This shows that it is not straightforward to transfer the fabrication of flexible displays from research into mass production.

To address these issues we have developed the Flexi-e method for making flexible displays. Flexi-e is based on the EPLaR process, originally developed by Philips Research and later transferred to PVI [4]. It was designed to make high quality demonstrators in the laboratory, but equal importance was given to industrial and commercial issues. This included how to manufacture attractive flexible displays with high yield and high throughput in a factory with the minimum development of new manufacturing equipment and processes. For commercial reasons we decided that it was important to develop a technology that would be used in displays with a rapid route to market, but which in the longer term could be used in as many different types of flexible displays and flexible electronics as possible.

In this paper we will begin by discussing the merits of different flexible display technologies and explain why we chose electrophoretic displays for our first products. We will then describe the Flexi-e process and present its current status for mass production.

2. Flexible Display Technologies

In the mid-90s, when work on flexible displays started, the only active matrix displays in production were Twisted Nematic LCDS, so it was natural that the first flexible displays made in laboratories were also LCDs. However, while LCDs are well-suited to glass substrates, they pose problems for use in flexible displays. Transmissive LCDs need substrates that have high optical transmission over the complete visible spectrum and negligible birefringence. This has restricted flexible LCDs to a range of plastics that are not compatible with standard processing in TFT-LCD factories. For instance, PES and PAR have been used by a number of groups, but have a maximum process temperature of 200°C or lower [1]. This means that the a-Si deposition temperature on these substrates is more than 100ºC below the normal deposition temperature used for manufacturing glass TFT-LCDs, resulting in devices with poor electrical stability [5]. It is also difficult to keep accurate cell spacing with two flexible substrates, which is essential for LCDs [6]. Glass displays are used in almost every mobile phone made today, so flexible LCDs must compete directly with glass TFT-LCDs, which are highly developed to give superb display performance.

The second kind of active matrix display to be developed used reflective electrophoretic foils, in particular those made by the E-Ink company [7]. E-Ink foils are bistable, so that they only draw power when the image is being changed. They show black and white images that have a similar appearance to paper. This makes them ideal for use in e-Books, with long battery life due to low power consumption and without the eye strain that is often associated with reading from LCDs. Faster colour versions have been demonstrated in research [8]. E-Ink foils can be laminated directly onto rigid or flexible substrates. The beauty of this for display manufacturers is that the active matrix array can be developed independently, with no constraints on TFT process conditions, substrate type, colour or transparency. There are no concerns about the flexibility of the foils because E-Ink is made by a roll-to-roll process.

E-Ink foils are already used in e-Books on glass TFT substrates. They have a slow refresh rate and the TFTs are completely hidden by the reflective E-Ink foil. This means that the TFTs can be very large and have low mobilities, particularly when they are used in small displays or with large pixels.

Combining E-Ink foils with flexible TFT arrays has the advantage of making the e-Book thinner, lighter and more robust, while at the same time having the same visual performance as glass based e-Books. E-Ink first reported on flexible AM electrophoretic displays with Lucent using polymer TFTs in 2001 [9] and they recently listed seven other companies that they have collaborated with to make flexible electrophoretic displays [8]. Both plastic and stainless steel substrates were used along with a-Si, LTPS, polymer and inorganic oxide TFTs. The large number of demonstrators emphasizes that it is manufacturing issues, not fundamental technical issues, which has delayed the manufacture of flexible e-Books.

The third type of AM displays to be developed were Organic Light Emitting Displays (OLEDs). In many ways AM-OLEDs have the ultimate in display performance, being capable of vivid, full-colour video speed images. However, they are still at a relatively early stage of development and there are a number of technical issues that need to be solved before they are ready for mass production in flexible displays. These issues include the need for further TFT improvements, OLED and TFT stability [10] and problems with current OLED deposition techniques for mass production. However, upward emitting OLEDs and electrophoretic displays share the advantage that the TFTs and substrates can be optimized separately from the display because they do not form part of the optical path.

Due to the attractiveness of flexible e-Books and the comparatively simple technology needed we decided to concentrate on electrophoretic displays as the first Flexi-e product. Research has also been carried out on a range of different devices to develop the basic technology for a range of future products for Flexi-e and the EPLaR process For instance, flexible single colour AM-OLEDs with a-Si TFTs [11] and LTPS TFT circuits on plastic [4] have been demonstrated by the European Community FlexiDis consortium

3. The Flexi-e Process for EPDs

The main steps in making AM electrophoretic displays on glass are TFT processing, followed by lamination of the electrophoretic foil and connections to the drive electronics. The TFT process for electrophoretic displays is identical to processing for LCDs. A Field Shielded Pixel design, which incorporates a polymer layer between the TFT and the pixel, is used to allow the pixel to extend over the pixel and data lines without suffering from capacitive cross-talk. The electrophoretic foil is laminated directly onto the TFT array, so that the ITO pixels form one electrode of the electrophoretic cells.

The Flexi-e process closely follows the process for making glass electrophoretic displays, but with some additional process steps. It begins by applying a 10 μm thick polyimide layer to a standard glass substrate. As long as the correct interface treatments are used in conjunction with the correct type of polyimide and curing schedule then the polyimide adheres very strongly to the glass substrate. It can withstand all of the standard temperatures and processes used for making TFTs on glass substrates. In addition, the polyimide only increases the substrate thickness by about 1.4% and the weight of the substrate by less than 1%. Together these mean polyimide coated substrates can be used in a TFT factory with standard processing and using all of the existing automated handling and mass production equipment. In particular, the TFT deposition temperature is not changed, so that the TFTs have the same electrical characteristics and stability as standard a-Si TFTs on glass.

Electrophoretic foils and electrical interconnects are laminated onto the Flexi-e substrates after TFT array fabrication using the same equipment and process settings that are used for glass electrophoretic displays. At this stage we have fully working electrophoretic displays on glass, but with a thin polyimide layer between the glass and the bottom of the TFT array. The polyimide is then released from the glass substrate using a laser process and the polyimide becomes the plastic substrate for the flexible display.

Fig. 1 Photograph of nine Flexi-e TFT arrays on a 370 x 470 mm substrate.

Flexi-e displays were made in the PVI Gen 2.5 factory in Hsinchu alongside e-Books and LCDs on glass. Figure 1 shows a photograph of a Flexi-e substrate at the end of the TFT array process. After this the arrays would have been inspected, followed by lamination of the electrophoretic foils.

4. Electrical Characteristics

Flexi-e displays were made in the PVI factory using standard mask sets and processing conditions. Figure 2 shows transfer characteristics measured on test TFTs from a standard glass substrate and a Flexi-e display after laser release. We can see that the TFT characteristics were almost identical. We also carried out D.C. stability measurements at elevated temperatures and high gate fields. Again, the results were effectively the same for laser released Flexi-e TFTs and test devices on glass. This shows that Flexi-e TFTs should have the same performance, lifetime and stability as a-Si TFTs in LCDs and e-Books.

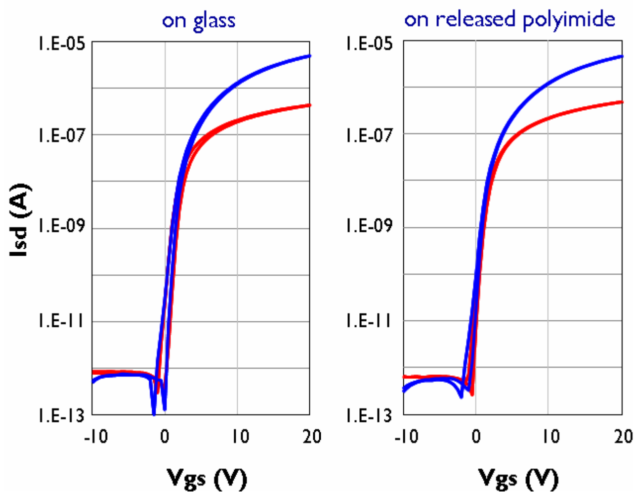

Fig. 2 Transfer characteristics of test TFTs on glass and from a laser released Flexi-e display. The TFTs had a W/L of 50/5 and the source-drain voltages were 1 and 10 V.

5. Flexi-E displays

Shrinkage and swelling can be an issue with many plastic substrates [1]. A major advantage of Flexi-e is that the polyimide layer has no measurable effect on the dimensions of the composite substrate because it is so thin and well anchored to the glass substrate. This means that the design rules for Flexi-e displays are exactly the same as design rules for TFT arrays on glass. To fabricate Flexi-e displays we used standard mask sets designed for glass substrates.

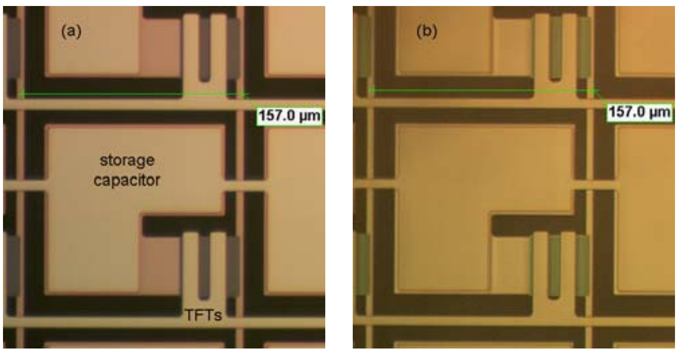

Fig. 3 Photographs or electrophoretic display pixels taken through the substrate. Fig. 3(a) was on glass and Fig. 3(b) was taken through a laser released Flexi-e polyimide substrate.

Figure 3(a) shows a photograph of a standard electrophoretic display pixel made on a glass substrate and Figure 3(b) shows a Flexi-e pixel after laser release. Two TFTs in series are used for each pixel to minimize leakage currents.

We have made Flexi-e displays in a range of different sizes. Figure 4(a) shows a 1.9” Flexi-e display that has been optimized in size and resolution for Edge of Shelf Label (ESL) applications to show text or barcodes. Figure 4(b) shows a 9.7” display that can be used for larger e-Books, e-Textbooks or e-Newspapers. We have also made 5” and 6” displays that are suitable for PDAs and e-Books.

Fig. 4(a) 1.9” Flexi-e display after being addressed and removed from the driving electronics.

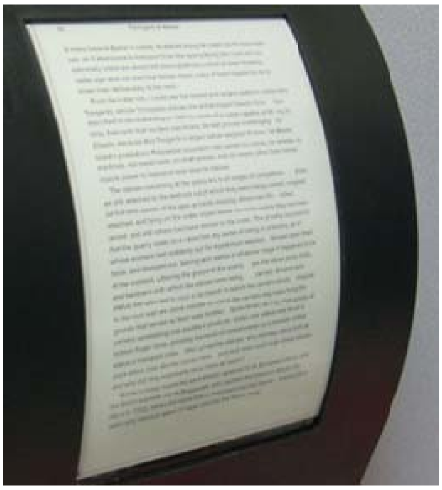

Fig. 4(b) 9.7” Flexi-e display in a curved holder being actively driven.

6. Conclusions

We are developing the Flexi-e process in a standard TFT-LCD factory alongside production of glass displays. We demonstrated that flexible displays can be made using standard designs and TFT processes. The electrical characteristics and stability of TFTs on laser-released plastic substrates were effectively the same as TFTs made on glass. This means that Flexi-e TFTs will have the same performance, reliability and stability as a-Si TFTs made directly on glass, whose utility has been shown in many millions of LC-TVs, laptops, mobile phones etc. Flexi-e electrophoretic displays will be in production in 2009 for products such as e-Books, e-Newspapers and ESLs.

In the future we will benefit from further improvements in electrophoretic display technology, such as the development of full-colour displays and video rates. Flexible AM-OLEDs and LTPS TFTs have been demonstrated with a similar process to Flexi-e and we expect to develop a wider range of flexible displays and flexible electronics. These will benefit from the development of expertise, processes and equipment from the industrialization of Flexi-e displays.

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