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A Review of Electronic Paper Display Technologies from the Standpoint of SID Symposium Digests

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ABSTRACT

A history of an electronic paper display technologies are reviewed by analyzing the Society for Information Display (SID) Symposium Digests. It is believed that the history starts from 1997, but there was a pioneer earlier than 1997, who reported an electrophoretic display at SID Conference in 1977.

About a hundred proceedings of SID conferences are analyzed in total, and are classified into several original technologies applied to electronic papers and development stages.

One of conclusions of this paper is, so typical and widely alleged, that there are a lot of unfinished business and we just open the first page of the Last Book.

INTRODUCTION

A history of an electronic display began from 1897 when Karl Ferdinand Braun invented the cathode ray tube (CRT), which progressed through the inventions by Boris Lvovich Rosing (1907), John Logie Baird (1925), and Kenjro Takayanagi (1926) to the first television broadcasting by British Broadcasting Company (BBC) in 1936 [1]. The end of the progress was led by Sony which discontinued the production of Trinitron in 2008. It will bring an end to 111 year-history of CRT. But its broadcasting system will exist as an information system.

The first observations of liquid crystalline or mesomorphic behavior were made towards the end of the 19th century by Reinitzer and Lehmann[2]. MERCK in Germany started selling liquid crystals in 1904. Several thousands of organic compounds are now known to form liquid crystals. But it took eighty years until RCA made the first public appearance of primitive liquid crystal display (LCD) in 1968. After the appearance, during only eight years, Sharp applied LCDs for their first pocket electronic calculator and Seiko developed practical LCD for their wristwatch. After the invention of the calculator, it took fourteen years for Sharp to launch out the first 2.6-inch LCD-TV in the world in 1987 [3]. In TV market worldwide, annual production of color LCD-TV outnumbered CRT-TV in 2005 [1].

Plasma display panel (PDP) was invented by D.

L. Bitzer and H. G. Slottow at Illinois University in 1968. Because the thickness of PDP is one tenth of CRT and the weight of PDP is one sixth of CRT, PDP was expected for a long time to be the next generation display post CRT, but 50-inch PDP-TV went on in 1997 at last [3].

Just then, J. M. Jacobson, MIT, presented his latest working paper, “Electrophoretic Ink” at SID Symposium and established E Ink Corporation [4].

GODMOTHER of ELECTRONIC PAPER

In 1998 at SID symposium, N. K. Sheridon et al. of PARC explained, boiled down to, about as follows: Plane paper scatters light diffusely and efficiently, allowing for high contrast, high resolution images that can be viewed from broad angles without glare caused by specular reflection, in contrast, electronic display media can provide the extra benefits of reusability and easy integration into digital electronic systems. Electronic display media used in such a fashion can be called “electronic paper” [5].

Their contribution was to recognize the paper is a exquisite reflective display and to give a name to it, although their invention “Gyricon” was received a fair amount of attention but did not yield practical applications.

Meanwhile, in 1997, J. M. Jacobson, who invented the electrophoretic ink, made a presentation as follows: The objective of our research is to develop an electronically addressable ink which can be printed onto arbitrary substrates, including flexible ones. The ink should be bistable and provide high contrast over a rage of viewing angles [4].

And he submitted a paper about “The Last Book”, which was an electronic book comprised of hundreds of electronically addressable display pages printed on real paper substrates (Fig.1) [6]. He also had a patent application on “Electronic Book with Multiple Page Displays”. This filing of patent application took ten years to be issued as a patent [7]. It will be perceptible that the patent is made from his obsessiveness.

Those were how the electrophoretic ink, the electronic paper, and the electronic book were born in the years straddling 1997.

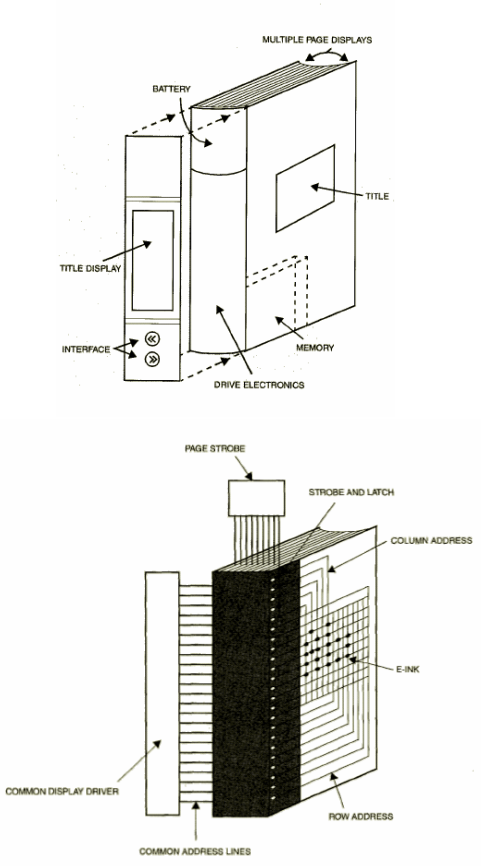

Fig.1 The Last Book [6]

CANDIDATES of TECHNOLOGY for ELECTRONIC PAPER

At SID symposium, a number of novel or emerging technologies for displays are separated from conventional sessions for the first several years. SID finally decided to add a new session for electronic paper at 2002. The words of “Electronic

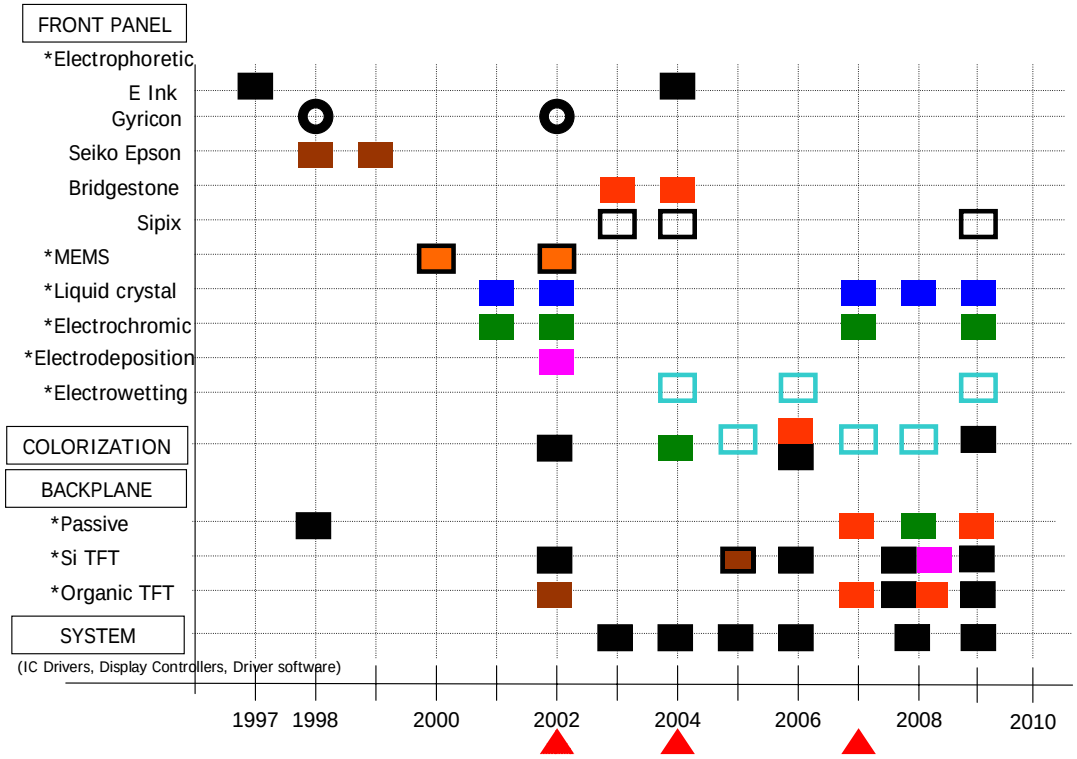

Fig.2 Classification of electronic paper technology

Paper" appeared on the official stage as a new session of SID symposium.

Technologies for electronic paper are classified according to electro-optical properties by SID. These are electophoretic, MEMS, liquid crystals, electrochromic, electrodeposition, and electrowetting. These are summarized in Fig.2. As just described, many specific technologies are tested for accomplishing an idea of electronic paper.

The electronic paper display is a one of flat panel displays (FPD), which basic structure is consisted of three elements, that is, front panel, display layer, and back plane. In many cases, both front panel and display layer are integrated into one architecture.

Fig.2 shows also the progress of technologies from basic researches to practical applications along with front panel, backplane, and system. The system in Fig.2 means, in this instance, the integration of IC drivers, display controllers, and driver software.

In Fig.2 matrix, if a technology plot, which has same color, goes from top left to bottom right, the technology will be considered to edge closer to final practical use. If a technology plot goes flatline from left to right, it will be remaining research level or will result in less innovation. Disappeared technologies in the symposium from 1997 to 2009 are excluded from the matrix.

From above expectation, the matrix (Fig.2) shows that there are two technologies which will be reaching final stage of practical applications for electric paper. These are E Ink's technology and Bridgestone's one.

ELECTROPHORETIC INK

What was the electrophoretic ink, which J. M. Jacobson invented as electronically addressable ink,

was microencapsulated electrophoresis dispersion in which white pigment particles were dispersed in dyed solvent. The first generation of electrophoretic ink in 1997 had one kind of pigment particles in a microcapsule as shown in Fig.3.

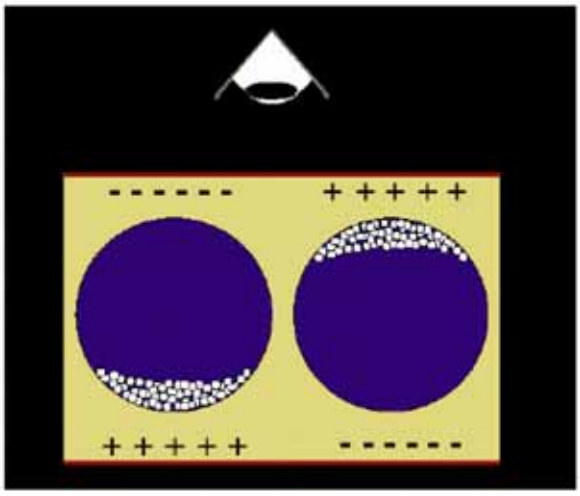

Fig.3 Microencapsulated Electrophoretic Ink

Only on the basis of the SID proceedings among, somewhere down the line, by 2002 at the latest, the electrophoretic ink had binary blend of pigment particles in solvent [8], that is, white and black pigments.

In 1998, E Ink made a presentation titled “A Printed and Rollable Bistable Electronic Display” [9]. At the same time, H. Kawai, NOK Corp., presented an electrophoretic display using microcapsulated suspension [10]. It is implied that E Ink adhered to Jacobson’s policy but NOK might challenge itself to make a new electronic display.

But, in 1999, NOK redirected their course of development and presented a rewritable sheet by photoconductor drum like a copier, which was the concept of the first monochrome rewritable paper [11]. On the other hand, E Ink fell into a deep sleep of their presentation until 2002.

In 2000, Canon and IBM presented new type of electrophoretic displays respectively. But they did not deliver the second presentation thereafter [12] [13]. Iridigm Display presented for the first time MEMS display. It is interesting that they named it “Digital Paper” although its substrate was made of glass (Fig.4) [14].

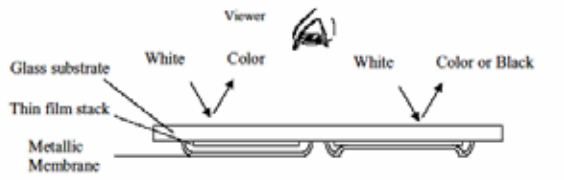

Fig.4 Iridigm Digital Paper [14]

In 2001, Fuji Xerox presented photoaddressable cholesteric liquid crystal display, which was the first concept of color rewritable paper [17].

As mentioned above, SID symposium decided to hold a new session as Electronic Paper in 2002. At the session, every kind presentation for electronic paper was collected again, as if it was an alumni meeting, except E Ink. E Ink was still growing up. They delivered three presentations. The first one was regarding image stability with TFT [15], second one was for energy consumption property [16], and last one was for colorization by color filter [8]. They started to use the phrase “Microencapsulated Electrophoretic Display” (MEPD). Another bottom line is that Seiko-Epson and Plastic Logic in their joint names presented organic thin film transistor (OTFT) with their ink-jet system for MEPD (Fig.5) [18]. After this year, 2002, E Ink turned gradually their interest from the development of the front panel to that of the backplane and system.

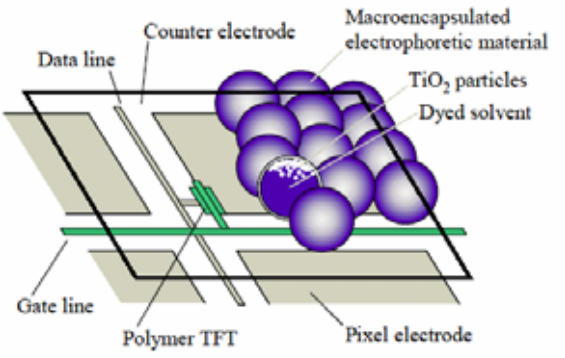

Fig.5 OTFT by Seiko-Epson and Plastic Logic

QUICK RESPONSE LIQUID POWDER

In 2003, Bridgestone disclosed at SID symposium "Quick Response Liquid Powder Display" (QR-LPD). They developed electrophoretic powder which behaved like liquid in the atmosphere and moved quickly by electric field (Fig.6) [19]. The most distinctive property of the powder was the quick respond time, which was for video rate and enormously faster than that of the electrophoretic ink (Fig.7).

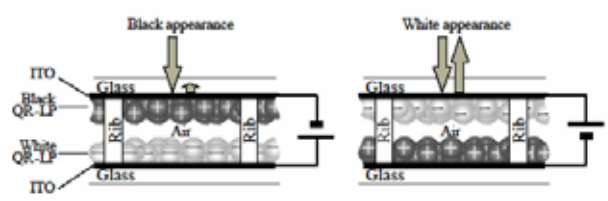

Fig.6 QR-LPD architecture [19]

The Bridgestone's presentation stunned E Ink. E Ink was taught by Jacobson's reemergence to develop their faster response electrophoretic ink and made a presentation titled "Towards Video-rate Microencapsulated Dual-Particle Electrophoretic Displays," in 2004 [20].

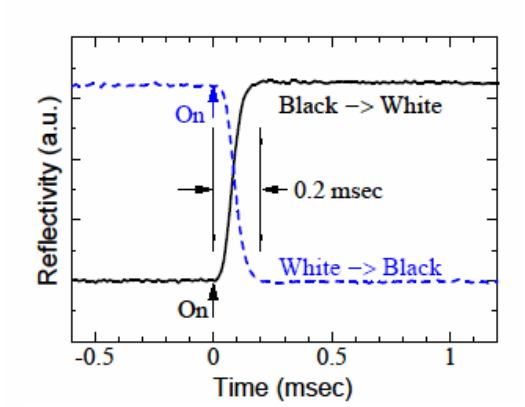

Fig.7 Response time of QR-LPD [19]

Another interesting presentation in 2003 was made by Sipix Imaging. They developed a roll-to roll manufacturing processes to make a flexible array of unique cell structures named Microcup to wall electrophoretic dispersion in its cell seamlessly (Fig.8) [21]. This manufacturing process captivated printing companies in Japan. But as they did not find TFT manufacture as a business partner for so long, they fed their way into segmented electrode display and developed numerical displays for smart cards.

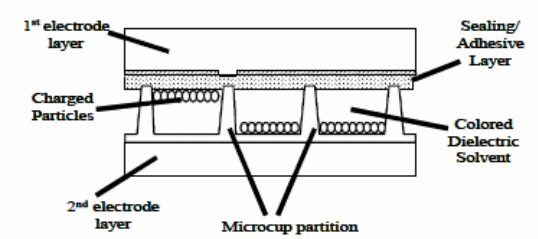

Fig. 8 Microcup structure [21]

In 2004, Bridgestone made a presentation for a polymer film based flexible display using QR-LPD technology [22]. A thickness of the display was about 0.3 mm, which was expected to bring a step closer to a flexible electronic paper (Fig.9). And its honeycomb-rib structure seemed to be durable for deformation of the display (Fig.10).

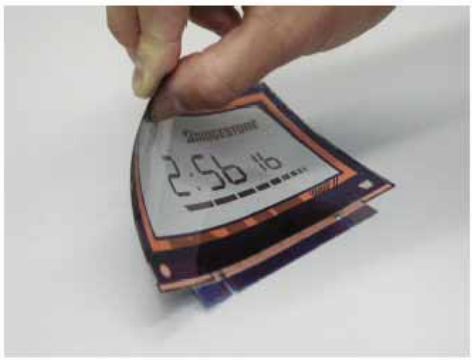

Fig.9 Bridgestone's flexible display [22]

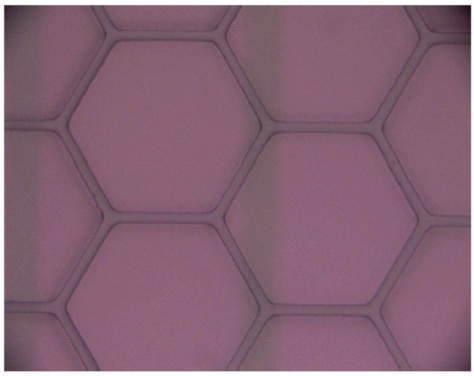

Fig.10 honeycomb-structure [22]
(rib width: 10 micron, rib height: 50 micron)

In a business field, Sony LIBRIe and Matsushita Sigma Book were launched on the market in Japan. They found before long to be failed in business in Japan because their business models adhered fundamentally to conventional book business to avoid friction with existing book stores in Japan. But it is noticeable that Sony showed the first model

Fig.11 Sony LIBRIe, the first model of electronic book in the world (2004) [23]

of electronic book in the world, although Sony made only one page of Jacobson's last book which contains multiple pages of electronic paper.

In 2005, there were significant advances of backplane technology, which were "Surface Free Technology by Laser Ablation" (SUFTLA) by Seiko-Epson [24] and "Electronics on Plastic by Laser Release" (EPLaR) by Philips [25]. Both SUTLA and EPLaR are in the category of transfer technology for TFT to flexible substrates.

There was another feature of 2005, that E Ink stated to use the phrase "electronic paper" instead of MEPD which was stuck around for long. This was a prediction for the next year.

In 2006, Bridgestone made a presentation for area color flexible electronic paper display using QR-LPD technology and revealed their roll-to-roll process (Fig.12) [26]. This color is characterized by using both color powder and white powder except black. In other words, these powder themselves were reflective. On the other hand, E Ink, as late-news paper, presented a color MEPD using

Fig.12 Bridgestone's flexible color electronic paper

color filter which had R, G, B, and white with the idea of Pentile making apparent reflection increase [27]. The long-waited Sony Reader using the electrophoretic ink was launched on the market in the U, S. A., October, 2006 for the biggest seller of the Christmas business.

In 2007, Bridgestone developed an ultra-thin and flexible LSI driver for QR-LPD. They found that a grinded 35 μm thickness silicon LSI driver was bendable (Fig.13) [28]. At the same time, Dai Nippon Printing (DNP) presented a development of printed organic TFTs for QR-LPD. It was believed

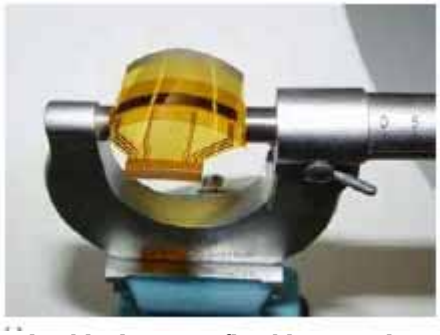

Fig.13 Flexible driver on flexible printed circuit [28]

until then to be difficult to make TFTs for high voltage driving because QR-LPD needed 80 V. DNP developed a printed AM-OTFT backplane with resolution of 50 dpi, with which they revealed the possibility for active matrix drive for QR-LPD [29]. As the result of these presentation, Bridgestone finally acquired both technology of flexible circuit and flexible AM-OTFT for QR-LPD.

In 2008, DNP made a presentation for a 10 inch flexible AM-OTFT panel for QR-LPD for motion pictures. They used a little ingenuity at increasing image reflectance of the display (Fig.14) [30]. QR-LPD is now just one step away from practical realization.

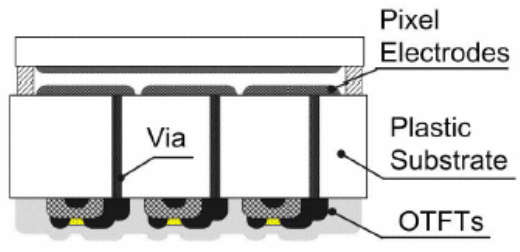

Fig.14 Double-sided backplane structure

ELECTROPHORETIC DISPLAYS

At SID symposium in 1977, twenty years prior to J. M. Jacobson, a presentation for electrophoretic displays was done by I. Ota [31], who is invited for IDW 09 at Miyazaki in Japan as a true pioneer of the electrophoretic displays [32]. He undertook his research for electrophoretic displays from 1968 at Matsushita Electronic (presently Panasonic) and had to finish it at 1976 to be engaged in another development for LCD. His patents lists are as follows: USP 3,668,106 (1972), USP 3,756,693 (1973), USP 3,729,308 (1974), USP 3,806,893 (1974), USP 3,892,568 (1975). These patent rights are already expired, but in the now the reference as a sort of bible of electrophoretic displays. And as technological genealogy, these kinds of technology seemed to be passed down to Nippon Mektron [33], NOK [10], and finally Seiko-Epson.

COCLUSION

Due to the limitation of space and the deadline of manuscript submission, although these are almost responsible for the author, this review is remaining to be outlined. On January 27, 2010, Steven Paul Jobs announced the launch of a new kind of personal mobile computer, “iPad” in coming March. The appearance of iPad will stimulate a lot of active discussion concerning the future of electronic paper displays. iPad is emissive display and on the other hand, electronic paper is non emissive display. There is large difference between these two. Human beings has been viewing for a long time, more than you will ever know, non emissive visual scenes except the sun, fires of volcano, and bonfires which they struggled to make the hard way. The human beings accustom themselves to watching and

viewing non emissive materials. They began to see emissive displays after the invention of CRT in 1907. It took only one hundred years until now, that is not completely unrelated to rigorous enforcing of the labor and environmental standards for VDT operator. Through the comprehensive and extended discussion of Electronic Paper Consortium JBMIA and a working group of ISO, it is clearing up for the author that non emissive display will be an ultimate one for human beings. From the viewpoint, we have unfinished business, because Sony Reader and Amazon Kindle are not the Last Book. All they have just done is to make only one page of the Last Book.

The author had much to learn from both Jacobson's and Sheridon's conceptual approach through reading the papers for this review. Nonetheless Isao Ota already scrutinized and developed the electrophoretic displays, there was no new concept born in Japan during the twenty years. That is, progress by inductive method can lead us merely to KAIZEN, not to innovation. We will need deductive approach leading to innovation of technology and business for electronic paper, especially in Japan.

Finally, the author has to describe something about ergonomic requirements of electronic paper displays appropriately for this symposium. It would still be unwise to conclude that the electronic paper display is nothing more than a reflective display like a reflective LCD.

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