E-PAPER DISPLAYS

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E-Paper Displays

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Series Editor's Foreword

Paper is the medium which has dominated the presentation of both the written word and graphics for two thousand years. The happy partnership of paper with printing was first developed in China before being adopted in the Western world in the Middle Ages and it initiated the first information explosion. Perhaps no other invention has had such a fundamental influence on the development of human society and way of life. Printed books and periodicals are attractive, affordable, and so familiar that we can truly pay attention to the contents alone, and overlook the qualities of the physical page. With this cultural and technical background, it is not surprising that printed paper is widely regarded as a reference point for electronic display technologies and since the introduction of the first flat panel displays, achieving paper-like performance has been a common dream and aspiration of engineers. At the same time, users have bemoaned the shortcomings of electronic displays and the poor reading experience offered by early generations of displays.

In the present volume, Professor Bo-Ru Yang has brought together an outstanding selection of authors to examine the technologies which aspire to mimic the properties of printed paper. It is fair to say that no electronic display can yet rival all the desirable characteristics of paper, and a basic question which arose at an early point in the planning of the volume, was which technologies or aspects of performance should be included. Professor Yang and his team have taken an inclusive approach. In this book the reader will find accounts of displays which offer different combinations of desirable properties including paper-like appearance under ambient light, long-term image storage with zero or ultra-low power consumption, light weight and flexibility, and the ability to accept user input with the ease of pencil on paper. It follows that a wide range of display technologies are included, with an emphasis on device modes which offer ambient light viewability. Several liquid crystal modes, both with and without polarizer, can provide image storage either intrinsic to the display or in ultra-low power drive electronics. Meanwhile, displays based on electrophoretic or electrowetting effects can offer outstanding optical appearance under a wide range of ambient lighting. Innovative and emerging displays are also considered, with a chapter on phase-change displays offering an early view of the potential of this new development. Of course, physics of operation, the fabrication, engineering and especially the addressing characteristics of each display mode can be very different, and these issues are comprehensively covered, with special attention to those aspects of the devices which are less well covered in earlier sources. Other, user-related properties of the devices—the difficulty of providing high quality reflective colour, and the relation of the display performance to human perception of image quality and metrology are carefully considered.

In the 21st century, our priorities regarding electronic displays have changed. Excellent optical performance is today taken for granted while convenience, light weight and long battery life have increasingly driven user approval. Especially, the environmental impact of every activity we undertake, now demands scrutiny. Printed media are major consumers of environmental resources including energy, timber, carbon emissions and chemical residues while electronic devices have the potential to reduce or eliminate these problems—but only if they are responsibly manufactured and accepted by users sufficiently to displace print over a long period of use and wide range of use cases. Paper-like display quality can really make a difference to the world. The present book provides a comprehensive and authoritative overview of the field, authored by leading experts on each aspect of the subject, and I believe it will offer a most valuable source of reference to display professionals and advanced students, for many years to come.

Ian Sage
Malvern

Editor’s Preface

With the advent of the Internet of Things (IoT), devices and objects around us are being equipped with built-in sensors and electronics which allow them to analyse and share information in real time, in the manner we associate with intelligent organisms. It follows that vast numbers of devices will be fitted with displays to present the information. The needs of such autonomous miniature devices mean that displays with low power consumption, excellent sunlight readability, and geometrical conformability which are compatible with low-cost fabrication methods, are becoming critical components in future IoT environments. E-paper displays have the inherent advantages of reflective operation, zero-power bistability, and in many cases they can be fabricated by printing-based processes. Therefore, they are regarded as among the most promising display technologies for these applications. Furthermore, many recent applications, such as fixed and mobile signage for transport, advertising billboards, architectural coatings, wrapped vehicles, e-readers, retail labelling, dynamic artworks, and many others, have started to exploit the unique advantages of E-paper.

Unlike LCD and OLED technologies, E-paper display technologies have not up until now been collectively and comprehensively reviewed, and there has been no published source which can provide scientists, engineers, and users with enough broad, insightful, and up-to-date knowledge to support research and development or product integration in this field. To fill this need, the present book represents the achievement of a three-year collaboration with prestigious scholars, experts, and entrepreneurs in E-paper display fields.

In this book, we have tried to cover as extensive a range of E-paper technologies as possible. Started with the development history of electrophoretic displays, followed by the fundamental mechanisms, physical models, driving waveforms, image processing, and advanced structures of electrophoretic displays, we describe the technological details and review the development progress to show how electrophoretic E-papers become commercially successful. In addition, bistable and reflective LCDs for E-paper applications, including Cholesteric LC, Zenithally Bistable Display (ZBD), Memory in Pixel (MIP), and Optically Rewritable (ORW) LCDs are also introduced. After that, the emergent technologies such as electro-wetting, electro-chromic, and phase change materials for E-paper display applications are reported and summarized. In the last part, the special needs for metrology of E-paper displays are explained. This book covers the broad spectrum of state-of-the-art reflective and bistable E-paper technologies, and we believe it will provide an invaluable handbook and reference for researchers, advanced students, and professionals in this field.

1

The Rise, and Fall, and Rise of Electronic Paper

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1.1 Introduction

For over a thousand years, before the world of electronics, paper was the dominant medium for people to share written and later printed information. People become familiar with paper at an early age, and there is an enormous worldwide infrastructure for the production and distribution of printed material. Despite this huge built-in advantage, paper and print now fall short in providing for many demands of modern life. The past few decades have seen the emergence of electronic networks that transmit vast amounts of information, on-demand, for use in various ways. Electronic displays are a necessary part of this infrastructure, converting bits to photons and serving as the final stage of transmitting information to people.

Over the years, several electronic display technologies have waxed and waned; cathode ray tubes, plasma displays, and super twisted nematic (STN) displays come to mind. A few technologies are dominant; backlit active-matrix liquid crystal displays, active matrix organic light-emitting diode (OLED) displays, and inexpensive, passively addressed liquid crystal displays. Along the way, tens of different types of display technologies have been invented and explored, but ultimately have failed to catch on. A few displays have found a home in niche products and promise greater future application. Reflective displays, particularly electronic paper, are examples that have managed to find a place in the display ecosystem, with unique applications best served by these technologies.

This book aims to update on some of the most exciting new areas in electronic paper technology. This introductory chapter focuses primarily on electrophoretic displays (EPDs) and how they became synonymous with electronic paper. The story starts in the early 1970's, with the proposal and first demonstration of the electrophoretic movement of charged particles to make an optical effect. After intense effort, the technology was mostly abandoned, only to be resurrected by a start-up company, E Ink. Several key, and rather improbable inventions had to be made to develop a technology competitive to the dominant liquid crystal technology. Finally, the right application and ecosystem, the Amazon Kindle electronic book, was necessary to cement commercial success.

The field of reflective displays is very rich. The many other chapters in this book and recent reviews [1, 2] provide a wealth of resources for understanding the many technologies that have been developed in the quest to achieve a paper-like display. In this chapter, we will examine the following:

- A description of print-on-paper and how the optics of real paper compare with potential electronic paper competitors.

E-Paper Displays, First Edition. Edited by Bo-Ru Yang.

- A hierarchical summary of the different technical approaches for reflective displays.
- A detailed look at the historical development of EPDs, starting with the invention of the technology and ending with the introduction of the Amazon Kindle. Looking at the various developments in the context of its times, the EPD story offers some lessons in what it takes for a technology to transition from the laboratory to commercial success.

1.2 Why Electronic Paper?

Electronic paper has undoubtedly caught the imagination of the world. A Google search for electronic paper in September 2021 returns over 12 *billion* hits. This interest reflects people's love affair with paper as a medium for transmitting information. Yet, it is easy to recognise that printing ink onto dead trees is not easily compatible with today's networked world. What are the attributes of print-on-paper that make it so important?

- Paper is a reflective medium that automatically adapts to changing lighting
- Unlike most emissive displays, paper can be easily read in bright sunlight.
- The appearance of paper is relatively constant over different viewing angles, without significant shifts in luminance or color.
- Paper can be lightweight and flexible. The user can easily annotate it. with a pen or pencil.
- Paper is inexpensive
- Paper can be archived.

Nevertheless, physical paper cannot be instantly updated with information from electronic networks or easily serve as an interface with electronic devices. Today's backlit LCDs and OLED displays are ubiquitous as a means of transmitting information, but with the limitations that emissive displays possess, including eyestrain and low visibility in sunlight. Electronic paper can combine the power of electronic devices and networks with all the attributes of paper.

So what strategies can be taken to enable electronic paper? It is instructive to understand the composition and design of print-on-paper and see how many of these properties can be converted to something under electronic control to compete with printed media.

1.3 Brightness, Color, and Resolution

Conventional, non-electronic paper consists of a mat of tightly pressed fibers, most commonly derived from parchment or wood pulp. The combination of fibers and embedded air pockets scatter light and provide the reflective characteristics of paper. Historically, additives to the paper pulp during fabrication have also provided glossiness, color, aid in manufacture, or other desirable characteristics (Figure 1.1).

Compared to a white optical standard, the perceived reflectivity of paper often ranges from 50–80%, but can be even higher. The whiteness or brightness of paper depends on several factors, including the density of fibers, the paper thickness, the presence of additives such as titanium dioxide, clays, or fluorescent agents, and whether the viewing surface is made glossy through calendaring and coatings. The color of light reflected from white paper may differ somewhat from a perfect reflector due to the fluorescing whiteners' presence, or some underlying color absorbance from the paper. The human eye readily accommodates for these changes, though, so the perception of consistent color and lightness of a page relative to its surroundings is easily achieved (Figure 1.2).

Print-on-paper consists of drops of colored ink impregnated into the paper fiber. It is straightforward to devise dyes and pigments that absorb red, green, or blue. To generate the color characteristics of print, the CMYK subtractive color system can be used (Figure 1.3). The colors in print are usually comprised of cyan (absorb red), magenta (absorb green), and yellow (absorb blue) (Figure 1.4). Black pigment (the K in CMYK) is also commonly used, as it is challenging to achieve a neutral black color by mixing cyan, magenta, and yellow.

Figure 1.1 Arches 100% cotton rag paper. Scanning electron microscope image @100×. *Source:* http://paperproject.org [3] Used with permission of CJ Kazilek.

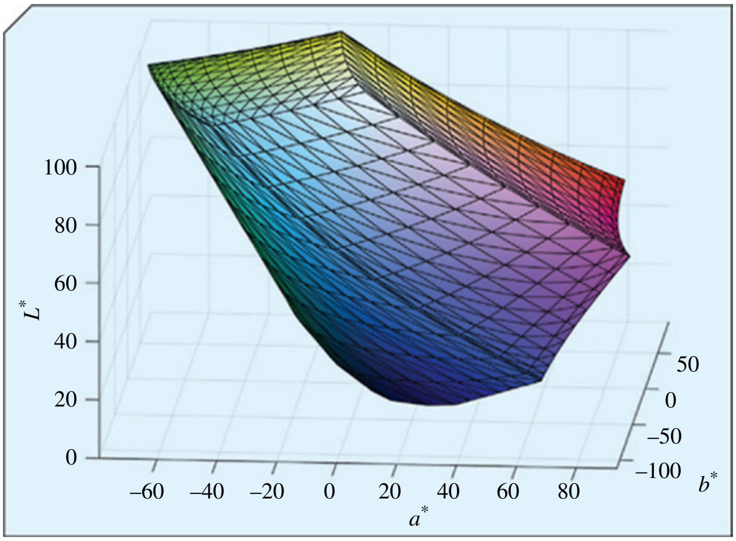

Figure 1.2 CIELAB color system [4] John Wiley & Sons.

Figure 1.3 Color separation of an image into its CMYK components, and the final printed image. The absence of a color is white.

Figure 1.4 Subtractive color mixing. Cyan and magenta overlap to make blue, cyan, and yellow overlap to make green, yellow, and magenta overlap to make red, and all three mixed together provide black.

To achieve a wider color gamut, inkjet printing may use six or more colors to print. Additionally, spot color printing can deposit specialty inks (such as fluorescent pigments) that currently have no analog in emissive displays.

Depending on the industry, a variety of different color spaces and metrics have been developed for printed and reflected color. For example, the CIE 1976 (L*a*b*) color space is widely used to measure reflective colors and print. The human perception of lightness is measured by L*, which roughly scales as the cube root as the reflected luminance level.

For color reproduction in the print industries, the SNAP standard (Specifications for Newspaper Advertising Production) and SWOP standard (Specifications for Web Offset Publications) are widely used [1]. These print standards are rarely applied to electronic displays, though the advent of colored reflective displays approaching print-like appearance could change this situation.

Grayscale in printing is achieved using halftones (Figure 1.5). Each dot on a printed page defines an area where smaller halftone dots are printed. The more halftone dots, the deeper the color or darker the black while white is the absence of halftone dots. The smaller the dots, the higher the resolution. Print is often defined in lines per inch.″ Some examples of everyday printed objects include:

- Newspaper (monochrome) – 65–100 LPI
- Books and magazines (color) – 120–150 LPI
- Art books (color) – 175–250 LPI
- Photorealistic inkjet printer (color) – 250–300 LPI

Likewise, the resolution-defined dot for color printing consists of multiple prints of smaller dots. The combination of different colors and black and the underlying brightness and color of the paper provide the specific color and lightness of that dot.

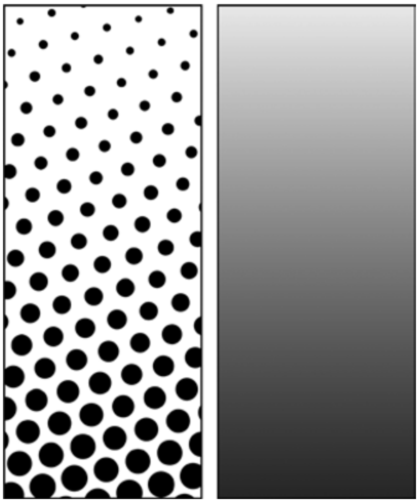

Figure 1.5 Examples of halftone dots of variable size, enabling grayscale [5] / Slippens / Public Domain.

With inkjet printing, commercial printers can also control the size of the drop, such as achieving four different sizes (Figure 1.6). The number of achievable gray levels is a combination of the number and size of the printed dots within the equivalent printed pixel [6, 7].

1.4 Reflectivity and Viewing Angle

An important aspect of paper is that the image printed on the page appears to have constant lightness and color irrespective of the viewing angle and lighting conditions. If the paper is glossy, there may be some glare from the surface, but that reflectance rarely interferes with the user interacting with the page. The near-constant appearance of the printed page is representative of Lambertian reflectance. The underlying paper scatters light, impinging onto the surface from many angles and then reflected uniformly into all spatial angles. Whether the page is illuminated by a collimated source such as a light bulb in a dark room or a more uniform source such as a cloudy sky, the distribution of reflected light from the paper does

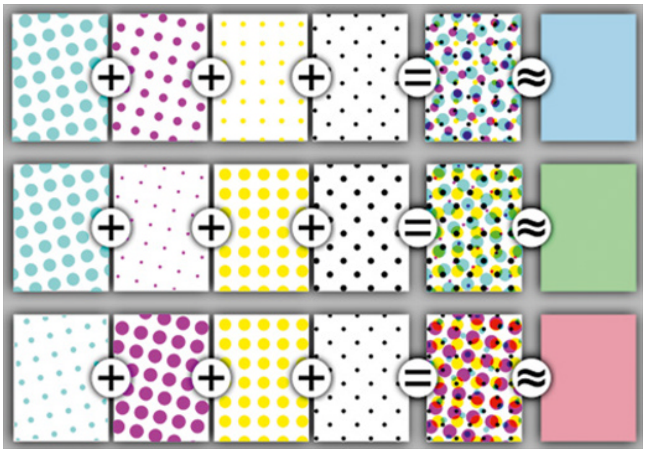

Figure 1.6 Printed color generation through printed CMYK halftones [5] / Slippens / Public Domain.

not change that much. Likewise, the amount of light scattered into the viewer's eyes for a given spot on the paper is also constant with viewing angle [8].

1.5 Translating Print-on-Paper into Electronic Paper

With this background, we can examine why designing an electronic display with the appearance of high-quality print-on-paper is challenging.

1.5.1 Brightness

Electronic displays require a transparent front sheet as the top surface of the display. This top surface (usually plastic or glass) provides a flat dielectric interface with air and degrades the optics of electronic paper in several ways.

- A significant fraction (4–10%) of light is directly reflected off the display without interacting with the display medium. This reflected light is seen as glare and degrades the contrast of the underlying display to the viewer. This reflected light also reduces the available light scattered back to the viewer. Anti-reflective coatings can reduce this reflected light, but with added cost and sometimes compromises in durability.
- Even if there is perfect diffuse reflectance, a significant fraction of that light will be trapped by internal reflectance at the display-air interface [9]. For an EPD where the dielectric phase is somewhere in the range of 1.38–1.45, the maximum amount of light that can be outcoupled from a white scattering layer, with no other absorptive losses, is predicted to be no more than 65%. These incoming and outcoupling losses limit the potential brightness of an embedded Lambertian scatterer within an electronic paper display.

There are strategies to improve the luminance of scattering-based displays by incorporating focusing optical elements with the display itself. Fleming et al. have demonstrated a display that uses a retroreflective prismatic element within the display and a black electrophoretic colloid to control the reflection from this element [10, 11]. While the reflectivity of the micro prism layer will depend on the geometric details of the source illumination, in many lighting conditions, the micro prism itself provides optical gain, and the display can appear "whiter than white."[12]. One display by Fleming et al., when illuminated by moderately collimated light, is reported to have an apparent brightness over 80%, with a 20: 1 contrast ratio. Fleming will describe more information on these types of displays in Chapter 4 of this volume. Further information about the metrology of measuring reflective display and e-paper will be described in Chapter 12.

1.5.2 Grayscale – Analog vs. Digital

High-quality images require grayscale, with 256 levels for each color channel being standard in emissive displays. Today, it is impractical to rely only on halftoning approaches to generate high-quality grayscale, which would require further subdividing each CMYK subpixel into an additional 4, 8, or 16 subpixels to maintain the native resolution. Instead, grayscale is generated using analog techniques, in which any pixel can be programmed to show intermediate reflective states between black and white. While many reflective display technologies, including EPDs, can show continuous grayscale within any pixel, maintaining accurate and uniform grayscale across all pixels is challenging. Analog gray levels are typically restricted to a number that enables uniform luminance without mura artifacts. For example, today's commercial e-paper displays from E ink are limited to 16 analog levels of gray to achieve good uniformity. However the underlying technology is capable of more gray levels [13].

Sophisticated dithering algorithms have been developed to minimize perceptual errors, some of which have been examined for use in electronic displays [14]. Dithering is analogous in many ways to halftones in print. In an electronic display, dithering sacrifices resolution to give the appearance of intermediate gray levels or to suppress non-uniformities between pixels.

1.5.3 An Overview of Approaches to Color Electronic Paper

Many inventive approaches have been proposed to achieve electronic color paper. Some designs take advantage of an electro-optical medium that can change color at the subpixel level intrinsically. Other approaches use color filters with an otherwise colorless black and white effect. Accurate and uniform grayscale is essential for high-quality images and is often very difficult to achieve.

Figure 1.7 illustrates an EPD in combination with color filters [15]. The function of a color filter is to absorb portions of the visible spectrum so that reflected light is colored. RGB or CMY primary colors can blend the primaries to provide an extended color range. Grayscale is adjusted by controlling the state of the reflective medium, similar to gray in black and white displays. These displays inevitably must make trade-offs between color saturation, color space coverage, and brightness. Reasonable brightness is usually achieved at the cost of color purity and a restriction of available colors.

Another approach is the adoption of multiple color particles as electrophoretic elements [16, 17]. Different colors can be generated in each sub-pixel by mixing C, M, Y translucent particles with scattering white particles, as shown in Figure 1.8. This approach was firstly demonstrated by Fujifilm in 2012 [16], and later on by E ink [17], which named it Advanced Color ePaper (ACeP). The colored pigments have different electrophoretic mobilities and responsivities, which facilitate to shuffle the color particles with driving waveforms of different voltage and pulse widths. As shown in Figure 1.8, different primary colors can be presented by positioning the white particle layer above or underneath the translucent C, M, Y particles. Integrating the CMYW particles into a display unit, ACeP can present different colors and gray levels in each subpixel by controlling the driving waveforms.

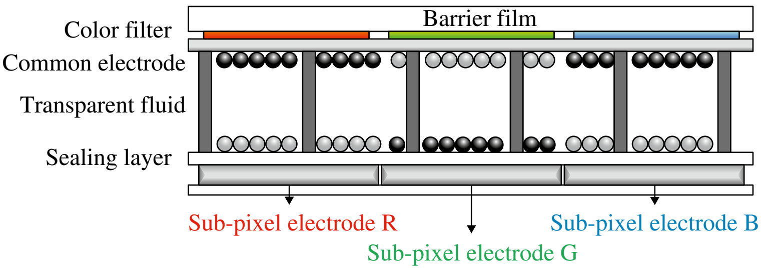

Figure 1.7 Color electrophoretic display using B/W particles and subpixel color filters [15] / John Wiely & Sons.

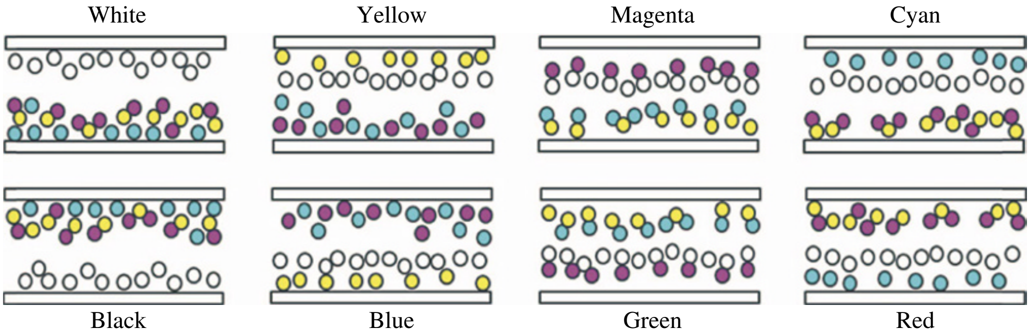

Figure 1.8 Eight primary colors of ACeP by different pigment arrangements [17] / John Wiely & Sons.

These driving waveforms are complex, and frame rates are currently slower than other EPD approaches. Nevertheless, the multiple color particle design dramatically increases the color saturation and reflective luminance achievable compared to the color filter approach. Figure 1.9 compares the color performance of these two types of color EPD prototypes [16, 17].

Many other inventive approaches have tackled the problem of making the electro-optical medium capable of switching color. Controlled lateral migration of colored fluid and particles enables a bi-primary color system. This design allows a single pixel to be changed through mixtures of color states [19].

A variety of other physical phenomena can be used to modulate reflected light electrically. The following table describes several varieties of reflective displays that have been developed over the past several decades. The fact that so many technologies have been pursued shows both the interest in the electronic paper and the difficulty in achieving a paper-like display. We compare the various reflective display technologies in Table 1.1, showing the strengths and weaknesses of the different approaches. More information on these different technologies can be found in reviews [1, 2, 20] and other chapters in this book.

Figure 1.9 Prototypes of colored electrophoretic displays: the left image uses a color filter and front light, while the middle and right images use the multiple color particles design [16–18] A. [18] Ian French, et al. 2020; B.[16] Hiji N, et.al, 2012 / John Wiley & Sons, Inc.; C.[17] Telfer S J, MD Mccreary, 2016 / John Wiley & Sons, Inc.

Table 1.1 Summary of performance and other key factors for monochrome e-Paper technologies.

	Electrophoretic (commercial)	**Electrophoretic (eTIR)**	**In-plane EPD**	**Electro kinetic**	**Liquid powder**	**Electrochromic**	**Electrowelting**	**Electro fluidic**	**MEMs (IMOD)**	**Cholesteric LC**	**PDLC**	**Reflect LCD w\ polarizer**	**Flip dot**	**Zenithal bistable device**
White, color %R	44% W [21]	60% [10]	75% [23]	~62% [15]	25 ~ 30% [28]	70% [30]	70% W [34]	72% W [37]	61% (Indoor) 80% (Outdoor) [40]	40% [35]	50% W	42% W [43]	80% [45]	39% [48]
Black %R	3% [21]	4% [10]	3% [23]	2%	3 ~ 4%[28]	–	3–5%	<3% [37]	>3% [35]	5% [35]	5%	2%	6%	2% [48]
Contrast ratio	~15 : 1 [21]	15 : 1 [10]	23 : 1 [23]	30 : 1	8 : 1	38.1 : 1 [31]	>35 : 1 [35]	>30 : 1 [37]	15 : 1	8 : 1 [35]	10 : 1	>20 : 1 [43]	13.3 : 1	20 : 1 [48]
Lambertian	Yes	Partial [10]	Yes	Yes	Yes	Yes	Partial	Yes	No	Partial	No	Partial	Yes	Partial[48]
mono SNAP/ SWOP	–	Maybe SWOP [10]	Maybe SWOP [23]	SNAP	–	Maybe SWOP [30]	SNAP [34]	SNAP	SNAP	–	Maybe SNAP	Maybe SNAP [43]	–	–
Driving voltage	15	2–4 [11]	<10	~5 [26]	40–70	1.4 [31]	15 ~ 20	10–20	5–10	(lab) < 4 (product) 25–40 [41]	5	~3 [43]	4 ~ 125[46]	20
Bistable	Yes	Yes [10]	No	No	Yes	Yes [32]	Yes [34]	Yes	Yes	Yes	No (Yes with matrix)	Yes	Yes	yes
Switching speed (msec)	100's	(33 fps) 33 [10]	15 (100 V) 30 (40 V) [24]	<300 [27]	<0.2 [29]	<10 [33]	10	~4 [38]	0.01's	300 (vertical) 5 (in-plane) [41]	51 [42]	48 [43]	~66 [47]	20 ms
Matrix drive	AM	AM [11]	AM, PM	AM	PM	PM	AM	AM, PM	PM	PM	AM	PM	–	AM [49]
Greyscale approach	Pulse	Pulse [10]	Analog/ Pulse	Pulse	Multi-write	–	Analog/Partial filling/Spatial dithering [36]	Pulse	Spatial/ Temporal	Pulse	Analog	Halftone	Pulse	Analog [49]
Grayscale bit level	4	4 [10]	5 (~30) [25]	>4 [27]	2	6 [30]	4	4 [39]	6	4	8 (60 Hz) 1 (6 Hz) [42]	2 [44]	1	4 [49]