SECOND EDITION

# INTRODUCTION TO FLAT PANEL DISPLAYS

JIUN-HAW LEE • I-CHUN CHENG • HONG HUA • SHIN-TSON WU

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# Introduction to Flat Panel Displays

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# Introduction to Flat Panel Displays

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## Series Editor's Foreword

The first edition of *Introduction to Flat Panel Displays* has proved to be a popular and valued resource, which has been widely used both as a textbook and for reference. However, it was published over a decade ago in 2008, and established readers of the SID book series will not need reminding how fundamentally the subject matter has changed in that time. It is worth recalling that 2008 is also reported to be the first year in which worldwide sales of LCD televisions exceeded those of CRT sets.

Continuing demand for the first edition demonstrates that there is still a need for a broad-based introductory but authoritative account of flat panel displays, and it followed that the editors of the present book should consider writing a new and revised edition. It soon became clear though, that a simple revision would not be sufficient, and the volume you are holding represents a comprehensively updated and rewritten book which reflects the present state and latest developments in flat panel display technologies and applications. In order to provide the reader with a book which is a reasonable size and properly focused on contemporary topics, chapters in the first edition which described display technologies of lesser current importance – plasma and field emission devices – have been dropped. Important new chapters have been added on topics which are now central to flat panel applications: near-eye displays, reflective/e-paper displays and touch panel devices. The chapters describing the well-established, dominant display technologies such as LCDs, OLEDs, and LEDs have been comprehensively revised and updated to reflect the full range of technologies used in commercial displays and to describe the most recent important advances in these devices. Chapters describing AM backplane devices and structures, and the key principles of vision and color science have likewise been thoroughly updated to reflect their evolution and importance. Each chapter has been authored by an expert in display science, and the enthusiasm of the writers for their subjects is evident in their work. The authors' work in preparing this new edition has been virtually the same as writing a new book from the beginning, and I am grateful to all of them for their persistence and dedication to the task.

Flat panel display technology has revolutionized the ways in which we interact with electronic systems and through that, shapes the way we lead our lives. The pace of innovation shows no signs of slowing and the new cohorts of scientists and engineers who take the subject forward will need a range of training and reference works. Providing these resources is a key objective of the SID book series, and I believe that the present volume will make an important contribution to this aim.

Ian Sage
Great Malvern

# 1

# Flat Panel Displays

## 1.1 INTRODUCTION

Displays provide a man–machine interface through which information can be passed to the human visual system. The information may include pictures, animations, and movies, as well as text. One can say that the most basic functions of a display are to produce, or re-produce, colors and images. The use of ink to write, draw, or print on a paper as in a painting or a book might be regarded as the longest established display medium. However, the content of such a traditional medium is static and is typically difficult or impossible to modify or update. Also, a natural or artificial source of light, is needed for reading a book or viewing a picture. In contrast, there are now many electronic display technologies, which use an electronic signal to create images on a panel and stimulate the eyes. In this chapter, we first introduce flat panel display (FPD) classifications in terms of emissive and non-emissive displays, where non-emissive displays include both transmissive and reflective displays. Then, specifications of FPDs will be outlined. Finally, the FPD technologies described in the later chapters of this book will be briefly introduced.

Displays can be subdivided into emissive and non-emissive technologies. Emissive displays emit light from each pixel which forms a part of the image on the panel. On the other hand, non-emissive displays modulate light by means of absorption, reflection, refraction, and scattering, to display colors and images. For a non-emissive display, a light source is needed. Such non-emissive displays can then be further classified into transmissive and reflective types. In historical terms, one of the most successful technologies for home entertainment has been the cathode ray tube (CRT), which enabled the widespread adoption of television (TV). It exhibits the advantages of being self-emissive and offering wide viewing angle, fast response, good color saturation, long lifetime, and good image quality. However, one of its major disadvantages is its size and bulk. The depth of a CRT is roughly equal to the length or width of the panel. For example, for a 19 in. (38.6 cm × 30.0 cm) CRT with aspect ratio of 4 : 3 the depth of a monitor is about 40 cm. Hence, it is hardly portable; its bulky size and heavy weight limit its applications.

In this book, we introduce various types of FPDs. As the name implies, these displays have a relatively thin profile, several centimeters or less, which is largely independent of the screen diagonal. Specifying a display or the design and optimization of a display-based product require selection of an appropriate technology, and are strongly dependent on the application and intended conditions of use. These issues, together with the intense pace of FPD development, which has made available many options and variations of the different display types, have made a thorough understanding of displays essential for product engineers. The options can be illustrated by some typical examples. For instance, the liquid crystal display (LCD) is presently the dominant FPD technology and is available with diagonal sizes ranging from less than 1 in. (microdisplay) to over 100 in. Such a display is usually driven by thin-film-transistors (TFTs). The liquid crystal cell acts as a light modulator which does not itself emit light. Hence, a backlight module is usually used behind a transmissive LCD panel to form a complete display module. In most LCDs, two crossed polarizers are employed which can provide a high contrast ratio. However, the use of polarizers limits the maximum optical transmittance to about 35–40%, unless a polarization conversion scheme is implemented. Moreover, at oblique angles the

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optical performance of the assembly is degraded by two important effects. Firstly the projections of optic axes of two crossed polarizers onto the E vector of the light are no longer perpendicular to each other when light is incident at an oblique angle, so it is difficult to maintain a good dark state in the display over a wide viewing cone. Secondly, the liquid crystal (LC) is a birefringent medium, which means that electro-optic effects based on switching an LC are dependent on the relative directions of the incident light and the LC alignment in the cell. Hence, achieving a wide viewing angle and uniform color rendering in an LCD requires special care. To achieve wide-view, multi-domain architectures and phase compensation films (either uniaxial or biaxial) are commonly used; one for compensating the light leakage of crossed polarizer at large angles and another for compensating the birefringent LC layer. Using this phase compensation technique, transmissive multi-domain LCDs exhibit a high contrast ratio, high resolution, crisp image, vivid colors (when using quantum dots or narrow-band light emitting diodes), and a wide viewing angle. It is still possible for the displayed images to be washed out under direct sunlight. For example, if we use a smartphone or notebook computer in the high ambient light conditions found outdoors in clear weather, the images may not be readable. This is because the reflected sunlight from the LCD surface is much brighter than that transmitted from the backlight, so the ambient contrast ratio is greatly reduced. A broadband anti-reflection coating and adaptive brightness control help improve the sunlight readability.

Another approach to improve sunlight readability is to use reflective LCDs [1]. A reflective LCD uses ambient light to illuminate the displayed images. It does not need a backlight, so its weight, thickness, and power consumption are reduced. A wrist watch is such an example. Most reflective LCDs have inferior performance compared to transmissive ones in terms of contrast ratio, color saturation, and viewing angle. Moreover, in fully dark conditions a reflective LCD is not readable at all. As a result, its application is rather limited.

To overcome the sunlight readability issue while maintaining high image quality, a hybrid display termed a transflective liquid crystal display (TR-LCD) has been developed [2]. In a TR-LCD, each pixel is subdivided into two sub-pixels which provide, respectively, transmissive (T) and reflective (R) functions. The area ratio between T and R can be adjusted depending on the applications. For example, if the display is mostly used out of doors, then a design which has 80% reflective area and 20% transmissive area might be used. In contrast, if the display is mostly used indoors, then we can use 80% transmissive area and 20% reflective area. Within this TR-LCD family, there are various designs: double cell gap versus single cell gap, and double TFTs versus single TFT. These approaches attempt to solve the optical path-length disparity between the T and R sub-pixels. In the transmissive mode, the light from the backlight unit passes through the LC layer once, but in the reflective mode the ambient light traverses the LC medium twice. To balance the optical path-length, we can make the cell gap of the T sub-pixels twice as thick as that of the R sub-pixels. This is the dual cell gap approach. The single cell gap approach, however, has a uniform cell gap throughout the T and R regions. To balance the different optical path-lengths, several approaches have been developed, e.g. dual TFTs, dual fields (providing a stronger field for the T region and a weaker field in the R region), and dual alignments. Although TR-LCDs can improve sunlight readability, the fabrication process is much more complicated and the performance inferior to transmissive devices. Therefore, TR-LCD has not been widely adopted in products.

Light-emitting diodes (LEDs) consist of a semiconductor p–n junction, fabricated on a crystalline substrate. Under a forward bias, electrons and holes are injected into the device where they recombine and emit light. The emission wavelength of the LED is determined by the bandgap of the semiconductor. For longer wavelength (such as red and yellow) emission, an AlGaInP-based semiconductor is needed. Three group III (Al, Ga, and In) and one group IV (P) atoms are needed to allow tuning of the emission wavelength and lattice-matching to the substrate (e.g. GaAs). However, for shorter wavelength (green and blue) emission, it was not easy to find a lattice-matched substrate. Besides, there were other technological difficulties in fabricating nitride-based LEDs such as p-type doping and InGaN growth. In recognition of their successful demonstration of the InGaN-based blue LED, Professor Isamu Akasaki, Professor Hiroshi Amano, and Professor Shuji Nakamura were awarded the Nobel Prize in Physics in 2014. By combining the blue LED with phosphors, white emission is possible from a single chip. LEDs have been used for many display and lighting applications, such as traffic lights, very large diagonal (over 100 in.) signage, backlights of LCD, and general lighting, due to their long lifetime and high efficiency. A detailed description of LEDs from the viewpoints of materials, devices, fabrication, and applications will be presented in Chapter 5.

In Chapter 6, organic light-emitting devices (OLEDs) will be introduced. The operating principle of OLEDs is quite similar to that of the LED. It is also an electroluminescence (EL) device, but fabricated from organic materials rather than a semiconductor. In contrast to LEDs, it is not necessary to fabricate OLEDs on a crystalline substrate. From the manufacturing viewpoint, the OLED is similar to an LCD because it can be fabricated on a very large glass substrate. Apart from the usual glass substrate, OLEDs can be also fabricated on a flexible substrate if suitable processes are used. The device structure of the OLED is quite simple, comprising a stack of thin organic layers (~200 nm) sandwiched by anode and cathode electrodes. When transparent conductors are used for both the anode and cathode, a transparent display can be fabricated, while a metallic cathode layer can provide a mirror-like appearance. When the OLED is not activated the panel appears highly reflective, while information displayed on the OLED is superimposed on the mirror-like background. In addition to displays, OLEDs can provide a flat, large-area, and diffuse light source for general illumination. This is quite different from LED lighting which provides a point source and highly directional emission of light.

In Chapter 7, the basic working principles of several reflective display technologies, including electrophoretic displays, reflective liquid crystal displays, interferometric modulator displays and electrowetting displays, will be reviewed. These reflective displays do not require an internal light source. They possess some attractive features, providing low eye strain, low power consumption, and excellent optical contrast under high ambient light levels, and are favored for portable reading applications and for outdoor use. Some reflective displays require the image being displayed to be constantly refreshed, while some are bistable and retain the image without power. In bistable displays, energy is only consumed during switching operations. In addition, some have a video-rate switching capability, while others are more suitable for displaying still images. Today most monochrome reflective display technologies match the typical contrast ratio standard of 10 : 1 for printed images on paper, but the reflectance of their bright states are still less than the typical value of 80% for white paper. Many color reflective displays rely on color filters or side-by-side pixel subdivision. However, to achieve color images with good brightness and saturation, multiple colors within the same pixel area is desirable.

By fabricating a display on a flexible substrate rather than rigid glass, flexible displays (using technologies including LCD, OLED, and electrophoretic effects) can be fabricated with the advantages of being thin, robust, and lightweight.

Most FPDs have been developed to provide a format for direct-view applications, such as TVs, computer monitors, laptop screens, tablets, and smart phones. However, several FPD technologies including LCDs and OLEDs, can readily be made into microdisplays with panel sizes less than 1 in. and pixel sizes of tens of microns or less. Such microdisplays are not suitable for direct-viewing, but they have found applications in an emerging class of head-mounted displays (HMDs) which are key enablers for virtual reality and augmented reality systems. In Chapter 8, the working principles and recent development of head-mounted displays will be reviewed. Unlike a direct-view display, an HMD system requires an optical system to collect light from a microdisplay source and couple it into the viewer's eye. The system may use a single microdisplay and optical system to display a two-dimensional image to one eye, yielding a monocular information display. Alternatively, it may be configured with a microdisplay and viewing optics for each eye, yielding a binocular system with the capability of rendering stereoscopic views. In some of the most advanced HMD systems, each set of optics may be capable of rendering light fields which replicate the configuration of light rays originating from a real scene, enabling a true 3D viewing experience. The proximity of an HMD system to the eye allows it to be configured into one of two different types – either an immersive or a see-through display. An immersive HMD blocks a user's view of the real world and places the user in a purely computer-rendered virtual environment, creating the immersive visual experience known as virtual reality. A see-through HMD, on the other hand, blends views of the real world and a computer-rendered digital environment, creating an experience variously known as augmented reality, mixed reality or increasingly as spatial computing. Chapter 8 will start with a brief introduction to the optical principles of HMD systems and an overview of historical developments, then follow with a brief review of the human visual system parameters critical to the design of an HMD system. It will then review paraxial optical specifications, common miniature display sources, optical principles and architectures, summarize optical design methods and optical performance specifications critical to HMD system design, and the chapter concludes with a review of several emerging HMD technologies with advanced capabilities, such as eyetracking, addressable focus cues, occlusion capability, high dynamic range, and light field rendering.

A touch panel (TP) is not a "flat panel display." However, it provides an intuitive interface which provides input to the machine, and provides an enhancement to many displays which is critical to their application. In some cases, a single touch sensing function is enough, such as in an automatic teller machine (ATM). On the other hand, a multi-touch function is needed for controlling many mobile devices (such as mobile phones and tablet computers). Usually, electrical parameters (such as resistance or capacitance values) of the TP are changed by touch and the x–y positions at which these changes occur provide the input function. So, a TP must be transparent to allow mounting on top of the display, and a separate TP increases the thickness of the display module. Integration of the TP and the display can reduce the module thickness. TP technologies will be introduced in Chapter 9.

## 1.2 EMISSIVE AND NON-EMISSIVE DISPLAYS

Both emissive and non-emissive FPDs have been developed. In emissive displays, each pixel emits light with a different intensity and color which stimulate the human eyes directly. CRTs, LED panels, and OLEDs are emissive displays. When the luminance of the panel viewed from different directions is constant, the device is called a Lambertian emitter and this represents an ideal performance for an emissive display because it results in a wide viewing angle performance. Due to the self-emissive characteristics, it can be used in conditions of very low ambient light. When such displays are turned off, they are completely dark (ignoring any ambient reflections). Hence, the display contrast ratio (see also Section 1.3.3) under low ambient light can be very high. On the other hand, displays which do not emit light themselves are called non-emissive displays. An LCD is a non-emissive display in which the liquid crystal molecules in each pixel work as a light switch, independently of the other pixels. An external voltage reorients the LC director which controls an optical phase retardation. As a result, light incident from the backlight unit or from the ambient is modulated. Most high-contrast LCDs use two crossed polarizers. The applied voltage controls the transmittance of the light through the polarizers. If the light source is behind the display panel, the display is termed a *transmissive* display. On the other hand, it is also possible to use the ambient light as the illumination source, imitating the principle of traditional media, such as reading a book, and the device is then called a *reflective* display. Different technologies for reflective displays such as electrophoretic, interferometric modulators, and electrowetting displays as well as LCDs will be introduced in Chapter 7. Since no extra light source is needed in a reflective display, its power consumption is relatively low. Under high ambient light conditions, images on emissive displays and transmissive LCDs can be washed out. In contrast, reflective displays exhibit a higher luminance as the ambient light increases. However, they cannot be used in dark conditions. Hence, transflective LCDs have been developed, which will be described in Chapter 4.

## 1.3 DISPLAY SPECIFICATIONS

In this section, we introduce some specifications which are generally used to describe and evaluate FPDs in terms of their mechanical, electrical, and optical characteristics. FPDs can be smaller than 1 in. for projection displays, 2–6 in. for cell phones, 7–9 in. for car navigation, ~8–20 in. for tablets and notebooks, ~10–25 in. for desktop computers, and ~30–110 in. for direct-view TVs. For different FPDs, their requirements for pixel resolution also differ. Luminance and color are two important characteristics which directly affect the display performances. Dependencies of these two parameters on viewing angle as well as image uniformity, device lifetime, and response time should be addressed when describing the performances of a FPD. Contrast ratio is another important parameter, which strongly depends on the ambient environment.

### 1.3.1 Physical Parameters

The basic physical parameters of a FPD include the display size, aspect ratio, resolution, and pixel format. The size of a display is typically specified by the diagonal length, in units of inches. For example, a 15 in. display indicates that the diagonal of the viewable area is 38.1 cm. Display formats, include landscape, square, and portrait types, corresponding to display widths larger than, equal to, and smaller than the height, respectively. Most monitors and TVs use a landscape format with the width-to-height ratio, also called the "aspect ratio," of 4 : 3, 16 : 9, or 16 : 10, typically.

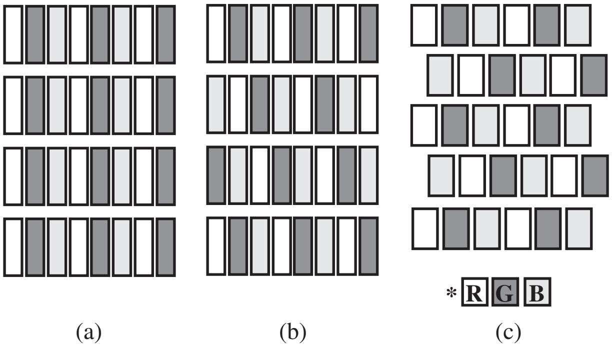
FPDs typically provide a rectangular "dot matrix" of addressable pixels which can display images and characters. To increase image quality, one may use more pixels in a display. Table 1.1 lists some standard resolutions of FPDs. For example, video graphics array (VGA) indicates a display 640 pixels in width and 480 in height. The aspect ratio is 4 : 3. Higher resolution typically (but not necessarily) provides better image quality. The HD series includes several wide screen standards with an aspect ratio of 16 : 9. FHD has a resolution of 1920 × 1080, which may be abbreviated as 2K1K. Doubling the pixels count in columns and rows results in 4× the resolution, which is termed UHD, 4K2K, or 4K. Similarly, an 8K standard is proposed with still higher resolution. Once the resolution, display size, and aspect ratio are known, one may obtain the pitch of pixels. For example, a 5.5 in. display with aspect ratio of 16 : 9 and FHD resolution has a pitch of ~63 μm. Or, we can use pixel per inch (ppi) to describe the pixel density of the display. The above example corresponds to ~401 ppi.

In the case of an HMD system for VR or AR applications, a microdisplay source is used. Although the pixel resolution of the microdisplay is a critical contributor to the system performance, the image resolution perceived by the viewer also depends on the optical magnification of the viewing optics. For instance in an HMD system, a VGA resolution microdisplay can produce an image with an apparent angular resolution equivalent to or better than an image provided via a FHD microdisplay if the optical magnification to the VGA panel is substantially lower than that to the FHD panel, this angular resolution being traded off against the field of view of the image. More detailed discussion on the resolution metrics of HMD systems can be found in Chapter 8.

Note that not all of the panel area contributes to the displayed image; the active area of each pixel is normally surrounded by a small inactive area occupied by inter-electrode gaps and possibly other structures such as stray light barriers. One can define the "fill factor" or "aperture ratio" as the ratio of the active display area in a pixel over the whole pixel size, with its maximum value of 100%. Also, for a full-color display, at least three primary colors are needed to compose a color pixel. Hence, each color pixel is divided into three subpixels, red, green, and blue (RGB) which share the total pixel area. For example, if we assume that a color pixel has

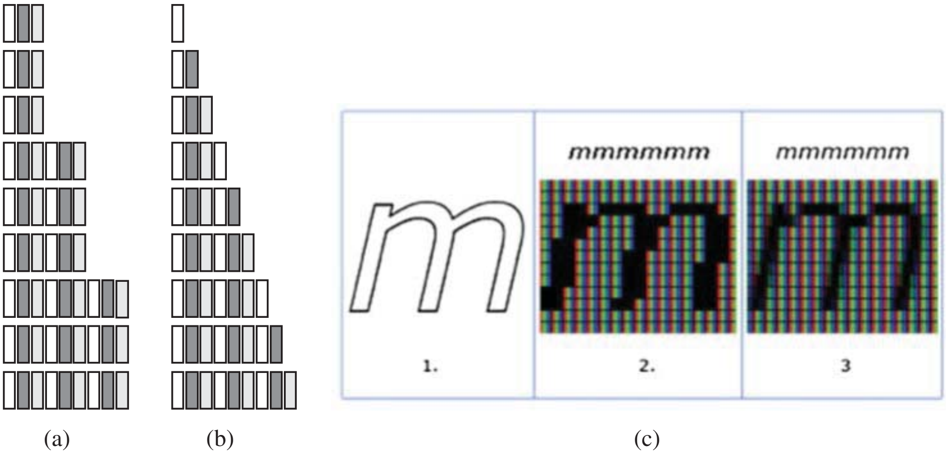
**Table 1.1** Resolution of FPDs.

| Abbreviation | Full name | Resolution |
|---|---|---|
| VGA | Video graphics array | 640 × 480 |
| SVGA | Super video graphics array | 800 × 600 |
| XGA | Extended graphics array | 1024 × 768 |
| HD | High definition | 1280 × 720 |
| FHD | Full high definition | 1920 × 1080 |
| UHD (4K) | Ultra-high definition | 3840 × 2160 |
| 8K | | 7680 × 4320 |



(a) (b) (c)

**Figure 1.1** Subpixel layout of a FPD: (a) stripe, (b) mosaic, and (c) delta configurations.



(a) (b) (c)

**Figure 1.2** (a) White (red + green + blue) pixels lit-on at the edge of the slope, and (b) with subpixel rendering in a stripe configuration. (c) "*m*" in italic (2) without and (3) with subpixel rendering on a display [3].

a size of 63 μm × 63 μm, then the dimension of each subpixel will be 21 μm × 63 μm. If the area of each active, switchable sub-pixel which contributes to light emission or transmission is 18 μm × 60 μm, then the fill factor will be ~82%.

Different layouts of RGB subpixels are possible, as shown in Figure 1.1. A stripe configuration, is straightforward and makes fabrication and driving circuit design relatively easy. However, for a given display area and resolution it provides a poor color mixing performance. Both mosaic and delta configurations make the fabrication process and/or the driving circuits more complicated, but the resulting image quality is higher because of their better color mixing capabilities.

When displaying an oblique black-on-white pattern on a display with a stripe subpixel configuration as shown in Figure 1.2, a clear sawtooth can be seen at the edge. However, because each pixel is formed of three subpixels, these can be switched on in a controlled sequence from the top to the bottom such that edge of the pattern appears smoother – a technique called "subpixel rendering." [3] Obviously, the colors at the edges of some rows are no longer white. For the first and the fourth rows, the red subpixel is switched on at the edge while for the second and the fifth rows, red and green emission results in a yellow color at the edge. This is called a "color fringing artifact." Figure 1.3 shows the letter "*m*" in italic, without and with subpixel rendering. A smoother edge can be clearly seen when subpixel rendering is used. Advanced sub-pixel rendering algorithms not only switch different sub-pixels on or off at an oblique edge, but also adjust their luminance values to optimize the visual quality of the image.

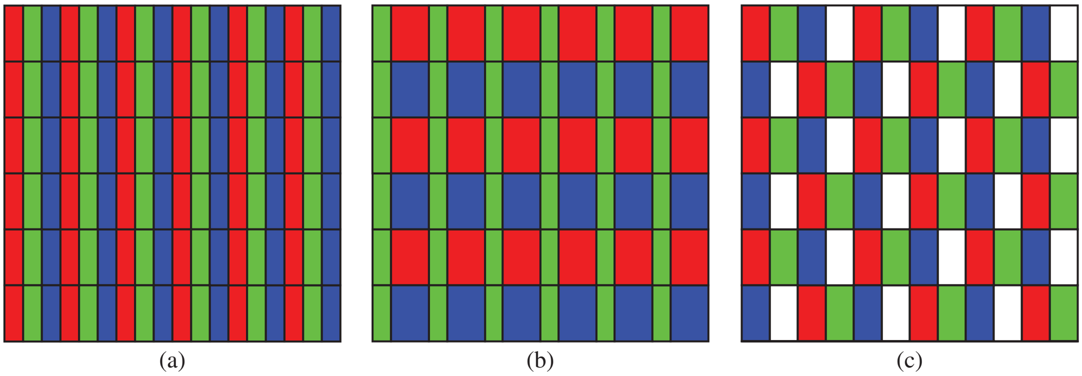


**Figure 1.3** (a) stripe, (b) PenTile™ RGRB, and (c) PenTile RGBW configurations [3].

There are three kinds of photoreceptor cells in human eyes, which respond to long, medium, and short wavelength regions of the visible spectrum. That is the major reason we use red, green, and blue as three primaries for the display and will be discussed further in Chapter 2. The arrangement of the photoreceptor cells does not correspond to a stripe configuration. Besides this, the numbers for different types of cell are not the same. The PenTile™ configuration has been proposed to mimic the layout of different photoreceptors in the eye to achieve better color mixing [4]. Here, "Pen" is a contraction of the Greek prefix "penta" meaning five and indicates that five subpixels form a pixel. There are many possible formats; Figure 1.3b shows one of them which is called the RGBG format. Combined with the subpixel rendering technique, a high display resolution can be obtained with a larger subpixel size. Figure 1.3a,b show the stripe and PenTile layouts with the same resolution. One can see that PenTile configuration allows larger red and blue subpixels. This is important for some displays, such as OLEDs, because it is not easy to reduce the subpixel size during fabrication. Hence, the PenTile arrangement can relax the design rules required in manufacture of displays for a given resolution. Also for OLED displays, the lifetime of the blue sub-pixel is an issue and by enlarging the blue emitting region its current density can be reduced and its lifetime extended. Another type of PenTile pattern is the RGBW arrangement, shown in Figure 1.3c. Here, a white subpixel is added alongside the three primary colors. In some displays such as LCD, where different colors are obtained by filtering unwanted colors from a white backlight, the blocked light is responsible for a major loss in efficiency. With the introduction of the white subpixel, the efficiency can be raised.

A device in which the pixel density is increased to the point where the human eye cannot resolve the individual pixels, is called a "retina display." This implies a very high resolution so that when projected onto the retina of the eye, the pixel density is higher than that of the photoreceptors in the retina. Evidently, a higher ppi is required for displays such as phones which are used closer to the eye, in order to satisfy the requirement for a retina display. Typically, ~300 ppi is required for a phone with a typical viewing distance of ~30 cm. With larger viewing distances such as those normal when watching a TV, a larger pixel is acceptable in a retina display. A detailed illustration of retina displays will be presented in Chapter 2.

### 1.3.2 Brightness and Color

Luminance and color gamut are two of the most important optical characteristics of a FPD. A display with high luminance looks dazzling under dark conditions. On the other hand, a display with insufficient brightness appears washed out under high ambient light levels. Typically, the luminance of a FPD should be as bright as (or a little brighter than) real objects under the ambient light in which the display is used. In an ordinary indoor environment, a monitor has a luminance of 200–300 cd $m^{-2}$. For a large screen TV, a higher luminance (500–1000 cd $m^{-2}$) may be needed. A FPD is used to produce or reproduce colors, hence, the number of colors a FPD can display, and how closely the color displayed on a FPD matches that of the real object (color fidelity) are two important characteristics to judge display performance. Since the color on a FPD is produced by mixing together (at least) three primary colors, i.e. RGB, more "pure" (narrow-band) primaries result in a broader range of colors which can be displayed, which is called the "color gamut" (see Section 2.4.5). As well as the usual three primaries (red, green, and blue), more primaries (such as yellow and cyan) can be added into the subpixels and can further broaden the color gamut. Besides, with suitable design of the driving method, the power consumption of the display can be reduced simultaneously [5, 6]. The perceived range of brightness from dark to bright can be divided into equal steps defined by numbers with 2, 4, 8, or more bits, which are called "gray levels" or collectively a "gray scale" (see Section 2.4.3). For example, a FPD can display 16 million colors ($2^8 \times 2^8 \times 2^8 \sim 16.8$ M) when each RGB subpixel can show 256 (8 bit) gray levels.

### 1.3.3 Contrast Ratio

The device contrast ratio (CR) of a FPD is defined as:

$$CR = L_\mathrm{w}/L_\mathrm{b} CR = L_w/L_b, \tag{1.1}$$

where $L_\mathrm{w}$ and $L_\mathrm{b}$ are the luminances of the white and black states, respectively. A higher CR requires a higher on/off ratio and hence potentially better image quality and higher color saturation. When CR is equal to or below 1, the information content of a FPD is lost or inverted. For most emissive displays, the off-state luminance is zero. Hence, the contrast ratio is infinite under perfectly dark viewing conditions. However, under ambient light conditions, surface reflections from the display mean that Eq. (1.1) should be modified to:

$$\mathrm{CR_A} = (L_\mathrm{w} + L_\mathrm{ar})/(L_\mathrm{b} + L_\mathrm{ar}), \tag{1.2}$$

where $\mathrm{CR_A}$ stands for the ambient contrast ratio, and $L_\mathrm{ar}$ is the luminance from ambient reflection. From Eq. (1.2), as the ambient reflection increases, $\mathrm{CR_A}$ decreases sharply. To maintain a high ambient contrast under increasing ambient light levels, one can: (i) increase the on-state luminance, and (ii) reduce the reflectance of the display surface. However, under a very high ambient such as outdoor sunlight, luminance from the direct sun is 4 orders of magnitude higher than a FPD, which severely washes out the information content of any emissive or transmissive FPD. Sunlight readability is an important issue especially for mobile displays. On the other hand, an adequate ambient light is required for viewing conventional media such as a book or newspaper. A similar consideration applies to reflective displays, such as reflective LCDs.

### 1.3.4 Spatial and Temporal Characteristics

Uniformity of a FPD refers to any unwanted change in the luminance and color over a display area. Human eyes are sensitive to luminance and color differences. For example, a 5% luminance difference is noticeable between two adjacent pixels. In the case of a gradual change, human eyes can tolerate up to 20% luminance change over the whole display.

Optical characteristics (luminance and color) may also change at different viewing angles. For Lambertian emitters, such as CRTs, the viewing angle performance is quite good. The emission profile of LEDs and OLEDs can be engineered by packaging and optimizing their layer structure, respectively. However, the viewing angle of LCDs requires careful attention because LC materials are birefringent and crossed polarizers are no longer crossed when viewed at oblique angles. There are several ways to quantify the viewing angle of a FPD. For example, one may masure the viewing cone with: (i) a luminance threshold, (ii) a minimum contrast ratio, say 10 : 1, or (iii) a specified maximum value of color shift. In some cases the contrast ratio viewed at oblique angle can be smaller than 1, resulting in "gray level inversion."

Response time is another important metric. If a FPD has a slow response time, one may see blurred images of fast moving objects. By switching the pixel from "off" to "on" and from "on" to "off," one can obtain rise and fall times, respectively which are typically specified between 10% and 90% luminance levels,. One may also define the response time from one to another gray level – the so-called "gray-to-gray" (GTG) response time. Most displayed scenes contain extensive areas of different luminance pixels, so the GTG response time is more meaningful. For LCDs, this GTG response time may be much longer than the black-white rise and fall time [7]. The TFT matrix used to address many FPDs provides a voltage set-and-hold function. This is quite different from the CRT's impulse type response, and requires a different metric to characterize it. Therefore, a motion picture response time (MPRT) [8] is commonly used to define the response time of a TFT LCD, which will be further discussed in Chapters 2 and 4.

After a long period of operation, the luminance of a FPD (especially for emissive display) may decay. If a fixed pattern is displayed on an emissive panel for a long period of time, then all the pixels are turned on to display a blank white screen, one can see a "ghost image" of the fixed pattern displayed with a lower brightness, which is called a "residual image" or "burn-in." As mentioned before, human eye can detect less than 5% nonuniformity between two adjacent pixels. Hence the lifetime of a FPD is crucial for static images. An alternative solution is to use only moving pictures, rather than static images for information display. Then the luminances of all the pixels decay uniformly, since the average on time for all pixels is the same.

### 1.3.5 Efficiency and Power Consumption

Power consumption is a key parameter, especially for mobile displays, as it affects the battery life. For displays with wall-plug electrical input, lower power consumption implies a lower heat generation, which means heat dissipation is easier and "green" environment targets can be met more easily. Typically, one uses the unit lm/W to describe power efficacy of a FPD (see Section 2.2). A portable display with lower power consumption leads to a longer battery life. For notebooks and TVs, a high optical efficiency also translates into less heat dissipation and a lower electricity bill. Thermal management in a small chassis device is an important issue. Energy Star is a program which defines the "power consumption" for electronic products, such as displays (https://www.energystar.gov). For example, in Energy Star Display Specification 7.1 (released in April 2017), the maximum power consumption of the display under on-state operation is defined, which is related to the screen area and the maximum luminance of the display. For example, the maximum power consumption of a 60 in. TV with aspect ratio 4 : 3 and maximum luminance 500 cd/m$^2$ should be less than 144 W.

### 1.3.6 Flexible Displays

A FPD is usually fabricated on thin glass plates which provide a rather rigid substrate. On the other hand, conventional media are printed on paper, which is flexible. An important current research and development theme is fabrication of FPDs on a flexible substrate, to provide a conformable or "paper-like" display [9]. Compared to glass-based FPDs, flexible displays are thin and lightweight. In addition, flexible displays can potentially be fabricated by a roll-to-roll process at low cost. Potential substrates for flexible FPDs include ultra-thin glass, plastic, and stainless steel. A bendable ultra-thin glass substrate is possible, but the cost is high. Plastic substrates are suitable for flexible displays, but the highest temperature which can be tolerated in the manufacturing process is typically lower than 200 °C. A stainless steel substrate is bendable, and resistant to high temperatures, however, it is opaque and therefore not suitable for transmissive displays. There are many technical bottlenecks for flexible FPDs, such as material selection, fabrication processes, device configurations, display packaging and measurement.

## 1.4 APPLICATIONS OF FLAT PANEL DISPLAYS

The following sections briefly outline the applications of each technology. Details will be described in the related chapters.

### 1.4.1 Liquid Crystal Displays

Although LC materials were discovered more than a century ago [10, 11], their useful electro-optic effects and stable materials are developed only in late 1960s and 1970s. In the early stage, passive matrix LCDs were adopted in electronic calculators and wrist watches [12]. With the advance of thin film transistors [13], color filters [14], and low voltage LC effects [15], active matrix LCDs gradually penetrated into the market of notebook computers, desktop monitors, and televisions. Today, LCDs have found widespread uses in our everyday life, including smartphones, tablets, virtual reality and augmented reality displays, automotive displays, navigation systems, notebook computers, desktop monitors, and large screen TVs [16].

To satisfy this wide range of applications, three types of LCDs have been developed: transmissive, reflective, and transflective. Transmissive LCDs can be further separated into projection and direct-view devices. In a high-resolution smartphone display, the pixel size is around 30–40 μm. Thus, the TFT aperture ratio becomes particularly important because it limits the light throughput [17]. To enlarge the aperture ratio, poly-silicon (p-Si) TFTs are commonly used because their electron mobility is about two orders of magnitude higher than that of amorphous (a-Si) silicon. High mobility allows a smaller TFT to be used which, in turn, enlarges the aperture ratio. For a detailed structure of a TFT LCD, please see Figure 4.1.

For a large-sized LCD TV, say 65 in. diagonal, 16 : 9 aspect ratio, and 3840 × 2160 resolution, the pixel size is about 350 μm by 350 μm, which is much larger than that of a microdisplay. Thus, a-Si silicon is adequate although its electron mobility is relatively low. Amorphous silicon is easy to fabricate and has good uniformity. Thus, a-Si TFT dominates large screen LCD panel market.

Similarly, reflective LCDs can also be divided into projection and direct-view displays. In projection displays using Liquid-Crystal-on-Silicon (LCoS) [18], the pixel size can be as small as 4 μm because of the high electron mobility of crystalline silicon (c-Si). In an LCoS panel, the electronic driving circuits are hidden beneath the metallic (aluminum) reflector. Therefore, the aperture ratio can reach >90% and the displayed picture is quite smooth. On the other hand, most reflective direct-view LCDs use a-Si TFTs and a circular polarizer. Its sunlight readability is excellent, but it is not readable in a dark ambient. Therefore, a thin front light is needed for reflective direct-view LCDs.

To obtain a high quality transmissive display and good sunlight readability, a hybrid TR-LCD has been developed. In a TR-LCD, each pixel is divided into two sub-pixels: one for transmissive and another for reflective display [19]. In a dark to normal ambient, the backlight is turned on and the TR-LCD works as a transmissive display. Under direct sunlight, TR-LCD works in the reflective mode. Therefore, its dynamic range is wide and its functionality does not depend on the ambient lighting condition. TR-LCD can overcome sunlight readability issues, but its fabrication is much more complicated and the cost is higher than its transmissive counterpart. As a result, its application is limited. For a detailed discussion of TR-LCDs, please refer to Chapter 4.

### 1.4.2 Light-Emitting Diodes

The LED is an electroluminescent (EL) device based on crystalline semiconductors [20]. To convert electrical to optical power, one has to inject carriers into the LED through electrodes, which then recombine to give light. The emission wavelength is mainly determined by the semiconductor material, and can be fine-tuned by device design.

Since it is difficult to grow large size single crystals, the wafer diameter of LEDs is limited to about 8 in. After device processing, LEDs are diced from the wafer followed by a packaging process. The size of a single packaged LED is typically several millimeters, which means that the pixel size of an LED panel is large, and suitable for use in huge area displays. Due to their self-emissive characteristic, LEDs are commonly used for large displays, such as outdoor signage (mono color, multi-color, and full color), traffic signals, and general lighting to replace light bulbs. Compared to conventional devices using light bulbs, LED displays exhibit the advantages of lower power consumption, greater robustness, longer lifetime, and lower driving voltage (so safer). There are also many outdoor screens with diagonals over 100 in. which consist of millions of LED pixels.

Rather than providing a display itself, an LED can be also used as the light source, such as in a backlight module for an LCD, and for general lighting. Compared to the conventional cold cathode fluorescent lamp (CCFL), which resembles a thin fluorescent tube, LED exhibits a better color performance, longer lifetime, and faster response. Another important motivation to use LEDs in LCD backlighting is that the mercury in CCFLs is harmful to the environment. When using LEDs for general lighting applications, a broad emission spectrum is preferred to simulate natural light, such as sunlight, and obtain a faithful color rendering of the reflective objects (Section 2.4.6). This is quite different from the requirements for LED displays and LCD backlights, which usually need a narrow spectrum.

### 1.4.3 Organic Light-Emitting Devices

The OLED is also an EL device, like the LED, except its materials are organic thin films with amorphous structures [21]. Amorphous organic materials have a much lower carrier mobility (typically five order of magnitude lower) than crystalline semiconductors, which results in a higher driving voltage for OLEDs. Besides, the operational lifetime of OLEDs is one order of magnitude shorter than semiconductor LEDs. However, due to its amorphous characteristics, fabrication of large size panels (e.g. 55 in.) is possible.

Since the conductivity of amorphous organic materials is very low, very thin organic films (100–200 nm in total) are required to reduce the driving voltage to a reasonable value (i.e. <10 V). It is quite a challenge in thin film formation, especially for large size substrates. Several fabrication technologies have been proposed, such as physical vapor deposition, spin-coating, ink-jet printing, and laser-assisted patterning. OLEDs are widely used in display applications (such as TVs and mobile phones). Besides, OLEDs can be used in lighting applications [22, 23]. Two advantages of OLEDs are: (i) low process temperature, and (ii) compatibility with different substrate materials, which makes them suitable for flexible displays. One of the strategies for OLED development is to improve the device performance (especially driving voltage and lifetime) to match (or at least approach) those of LEDs. Due to their large size fabrication capability, the potential manufacturing cost of OLEDs is lower than LEDs. Because OLEDs have some advantages in performance and fabrication cost over LEDs, it has a chance to replace LEDs in some applications since they are both EL devices with similar operational principles.

### 1.4.4 Reflective Displays

A wide variety of reflective display technologies are available today. They are quite different in working principles and performance. Some of them, such as interferometric modulator displays, electrowetting displays and guest-host polymer dispersed liquid crystal displays exhibit fast response and are capable of video frame rate operation. However, most of them are still some way from commercial success because of their poor color gamut and relatively high power consumption for video rate operation. On the other hand, bistable reflective display technologies with sufficiently good reflectivity and contrast ratio, such as electrophoretic displays and cholesteric liquid crystal displays, are attractive for displaying (quasi)static images where a low switching speed is not a major concern. With the advantages of low power consumption and good outdoor readability, these reflective displays are suitable for portable reading devices, wearable or mobile devices and signage applications. For instance, electrophoretic technologies have been adopted in many e-book readers and electronic paper displays. Because many of the reflective display technologies can be made thin and flexible, they are suited to billboards, signage and shelf-edge labels. In the application of wearable or mobile devices, these low-power paper-like reflective display technologies have been incorporated into an electronic paper watch, electronic wristband, and similar devices. For detailed discussions of the above-mentioned reflective displays, please refer to Chapter 7.

### 1.4.5 Head-Mounted Displays

Head-mounted displays (HMDs), also known as head-worn or near-eye displays, are typically attached in close proximity to a user's eye and require an optical system to couple the light from a microdisplay source into the user's eye. The basic principles of an HMD system can be dated back to 1830s when Sir Charles Wheatstone proposed the concept of the stereoscope for viewing a pair of static photographs with slight disparities. Through over a century of technical development, the stereoscope has evolved into a new class of display technology enabling a new paradigm of applications. Instead of static photographs and simple mirrors, modern HMD systems enjoy a wide range of choices of electronic displays as the image sources, a wide range of advanced optics technologies in the optical viewer, and a wide range of sensing, computing, and communication capabilities.

A modern HMD system can be as simple as a microdisplay source plus a single magnifier-like eyepiece, providing a monocular display for information access and navigation. It can also be configured into a very sophisticated system integrating not only advanced microdisplays and optics but also a suite of advanced sensors and computing hardware and software, yielding a computing platform for advanced missions and visual experiences. Some advanced HMD systems go beyond the traditional route of displaying a 2D image or rendering a 3D perception of depth via binocular viewing, and create a true 3D viewing experience via light field rendering.

Over many decades of development, HMD technology has become a key enabler for virtual reality and augmented reality applications. To satisfy the needs of VR and AR applications, two types of HMDs have been developed: immersive and see-through. Immersive HMDs, primarily used for VR systems, block a user's view of the real world and immerse him or her in a purely computer-rendered virtual environment. See-through HMDs, mainly used for AR systems, blend views of the real world and a computer-rendered digital world digitally or optically. Both types of HMD technology share most of the same fundamental optical principles and requirements, but see-through HMDs, especially those providing optical see-through, confront many unique optical challenges. For instance, an optical combiner which combines the light paths of the real-world and virtual world views, plays a critical role in the architecture of optical see-through HMDs. It can be as simple as a beamsplitter or as sophisticated as a holographic waveguide.

The rapidly growing interest in VR and AR applications, the ever-increased bandwidth and accessibility of wireless networks, the miniaturization of electronics, and the ever-growing power of computers have collectively boosted the rapid development of HMD technologies in recent years. Please refer to Chapter 8 for a detailed discussion of the historic development, basic working principles, optical design fundamentals, and recent advances in head-mounted displays.

### 1.4.6 Touch Panel Technologies

When a TP is touched, an electrical, optical, or magnetic parameter is changed and the point of touch can be identified. As electrical signals, typically we can use changes of resistance or capacitance. A resistive TP consists of two substrates. The inner sides of the substrates are coated with transparent resistive layers, separated by an air gap. The outer substrate is deformable. When the resistive TP is touched, contact is made between the upper and lower conductive layers. The contact position affects the resistance value read out from the driving circuit. However, the air gap between the two substrates results in a low optical transmittance, which reduces the luminance from the display panel. An important use case is when the object which touches the TP is a finger. This can be regarded as equivalent to a capacitor connected to the ground which therefore changes the capacitance measured at the TP. That is the basic idea of the capacitive TP. With suitable design of vertical and horizontal electrodes on the substrate, self- and mutual-capacitance TPs can be obtained, respectively. Note that a conductive object such as a finger is needed to activate the touch function on a capacitive TP. When a TP is physically stacked on top of the display, it is called an "out-cell" configuration. To reduce the thickness of the TP-display module and simplify the fabrication process, on-cell and in-cell TPs have been introduced. Taking the LCD as an example, it consists of two glass substrates. By fabricating the TP onto the outer substrate, an on-cell configuration is created. Note that there is a dense array of TFTs and conductors on the bottom substrate of the TFT panel. With a suitable layout and driving scheme, a TP can be integrated inside the display, which is called the "in-cell" configuration.

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# 2

# Color Science and Engineering

## 2.1 INTRODUCTION

Display systems are used to produce and reproduce color images which makes the topic “color science and engineering” very important for evaluating their performance. Typically, the perception of colors can be treated as a four-stage process: (i) existence of a light source – either man made or natural, (ii) light-object interaction – such as reflection, absorption, and transmission, (iii) stimulation of the eyes, and (iv) recognition by the brain. Figure 2.1a, illustrates the human eye seeing the color of an object under sunlight, which is a “white” light source because its spectral bandwidth covers the entire visible range. If there was no light source, there would be no photons to stimulate the human eye and, therefore, no color could be formed. Under illumination, the object (e.g., paper in Figure 2.1a) absorbs a portion of the incident photons and reflects the rest. As shown in Figure 2.1b, there are yellow and green inks on the white paper. When incident white light illuminates the yellow ink, the “blue” component of the white light is most strongly absorbed. The reflected light contains a higher proportion of red and green wavelengths, resulting in a perception of yellow. Similarly, the green ink absorbs “red” and “blue” light. Where there is no ink, the white paper reflects all components of the white light almost equally, so it appears white. It follows from the above discussion, that the color of an object is also dependent on the spectral content of the incident light. For example, if the light source is red, then the yellow ink will have the same appearance as the white paper. After the light–object interaction, reflected photons are received by the detector; here it is a human eye. To properly describe a light wave, there are four basic parameters: intensity, wavelength, phase, and polarization. Photons with different emission wavelengths in the visible region (~380–780 nm) stimulate the photosensitive cells (cone and rod cells, as discussed later) of the eye which generate the perception of different colors, such as violet, blue, green, yellow, orange, and red. The light intensity gives the observer a perception of bright and dark. However, the human eye cannot resolve the polarization state and phase of the light.

In human eyes, in individuals with “normal”color vision, there are three different types of cone cells with different spectral sensitivities. This makes it possible to use three primary colors (red, green, and blue) to generate different (but not all) the colors and to describe the colors quantitatively [1]: this is called “trichromatic space.” In 1931, the Commission Internationale de l’Eclairage (CIE) suggested the (X, Y, Z) colorimetric system, which can specify all the colors by their distinct coordinates, and also indicates the brightness of the target object [2]. It is a convenient system for describing colors. However, the CIE 1931 system is not suitable for discussing the magnitude of the perceived difference between two colors. Besides, the 1931 system is set up to quantify the colors of self-luminous objects without any ambient reference – which is not unrealistic for some display applications. To solve this problem, the uniform color spaces are proposed (e.g., CIE 1976 ($L^*u^*v^*$)- and ($L^*a^*b^*$)-spaces). In these systems, a numerical “color difference” can be specified for two colors. In different areas of the CIE 1976 color diagrams (for example, for two similar greenish colors or for two reddish colors), just-distinguishable color difference is nearly identical in magnitude. Since the trichromatic space can be quantitatively described by CIE colorimetric systems, different colors can be produced or reproduced in a display device by mixing three primary emitters. Although the reflection spectrum of a “real” object is

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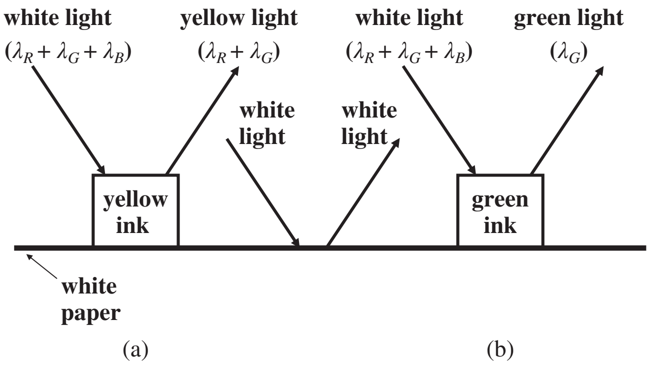

**Figure 2.1** Formation of colors.

different from the one appearing on the display, they appear the same color to the human visual system. This ability of different spectral power distributions to produce identical perceived colors, is called "metamerism."

In this chapter, we first describe photometry, then the structure of the human eye and its functionalities, followed by the formulation of colorimetry which includes the CIE standards, light sources, and finally metamerism.

## 2.2 PHOTOMETRY

Due to the spectral sensitivity of the human eye, we perceive brighter or dimmer illumination from light sources with the same optical output power (in terms of Watts) emitting at different wavelengths. Here, the photometric unit, lumen (lm), is defined as: the luminous flux ($F$) from a monochromatic light at 555 nm emitting the optical power of 1/683 W. The spectral sensitivity of the human eye can be represented as $V(\lambda)$ under the photopic region and reaches its highest sensitivity at 555 nm, which will be illustrated in Section 2.3. For example, $V(\lambda)$ is 0.1 at 650 nm, which means the sensitivity is 10× less than at 555 nm. So, 1/68.3 W is needed for monochromatic light at 650 nm to obtain 1 lm. Actually, the primary photometric unit is not "lm," but candela (cd), which is defined as one lumen per unit solid angle (lm/sr) and is called luminous intensity ($I$). The initial definition of 1 cd was the luminous intensity of a standardized plumber's candle. As shown in Figure 2.2, the candle emits light in all directions, hence we use "lm" to describe the radiant flux. When

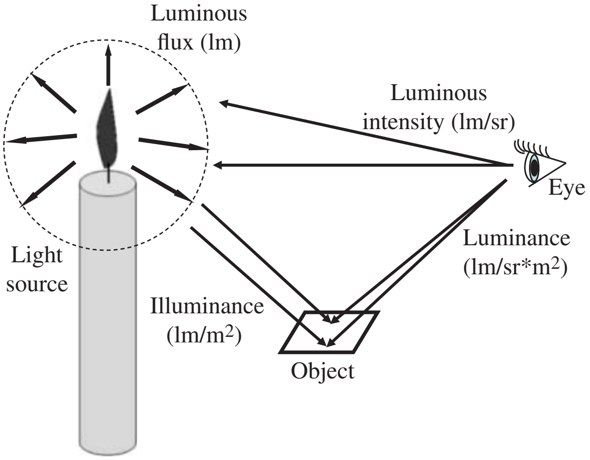

**Figure 2.2** Illustrations of photometric units.

**Table 2.1** Definitions of photometric units.

| Photometric terms | Symbol | Units | Definition |
|---|---|---|---|
| Luminous flux | $F$ | lm | lm |
| Luminous intensity | $I$ | cd | lm/sr |
| Illuminance | $M$ | lux | lm/m$^2$ |
| Luminous exitance | $E$ | lux | lm/m$^2$ |
| Luminance | $L$ | nit | cd/m$^2$ |

human eyes view the candle, they only admit light within a limited solid angle, so we receive the luminous intensity in terms of "cd." The candle can be used as a light source to illuminate an object. Then, we can define the "illuminance" ($E$) of the light source in units of lux, or lm/m$^2$. After light–object interaction, the light is modulated (reflected, transmitted, scattered, or absorbed) by the object and can be regarded as being re-emitted from the object, where apparent emission is referred to as the luminous exitance ($M$) which again has units of lux. When people see the object illuminated by the light source, the human eyes receive light only within a certain angular range, so the luminance ($L$) of the object can be defined as cd/m$^2$, or nits. Definitions of photometric units are also shown in Table 2.1.

**Example 2.1** A perfect diffuse surface means its luminance observed from different viewing angles is constant, which is also called a "Lambertian surface." For example, rough paper approximates a Lambertian surface. For a Lambertian surface (with a size $A$) illuminated by a light source with illuminance $E$, what is the luminance ($L$) of this surface? Assume this surface can perfectly reflect all the light, i.e. luminous flux of the incident beam on the surface is equal to that of the exiting light.

**Answer**

From Table 2.1, luminance ($L$, in terms of cd/m$^2$) can be also regarded as the luminous intensity ($I$; in terms of lm/sr) per unit area ($A$):

$$L = \mathrm{d}I/\mathrm{d}A \tag{2.1}$$

when viewing from a larger angle, the area looks smaller as compared to that at normal direction with a cos$\theta$ relation. $\theta$ is the angle between the viewing direction and the surface normal. That is

$$\mathrm{d}A = \mathrm{d}A_0 \cos\theta \tag{2.2}$$

where $A_0$ is the area viewing from normal direction. Because luminance of a Lambertian is the same for any viewing direction, one can obtain the luminous intensity as:

$$I = I_0 \cos\theta \tag{2.3}$$

where $I_0$ is the luminous intensity at normal direction of the surface. Incident flux to the Lambertian surface can be represented as:

$$F_{\text{in}} = EA \tag{2.4}$$

The total luminous flux which radiates from the surface is:

$$\begin{aligned} \mathrm{F}_{\text{out}} &= \int I\mathrm{d}\,\omega = \int I(\theta)\mathrm{d}\,\omega = \int\int I(\theta)\mathrm{d}\,\phi \sin\,\theta \mathrm{d}\,\theta \\ &= I_0 \int_0^{2\pi}\int_0^{\pi/2} \cos\,\theta\,\sin\,\theta \mathrm{d}\theta \mathrm{d}\phi = 2\pi I_0 \int_0^{\pi/2} \cos\,\theta\,\sin\,\theta \mathrm{d}\theta = \pi I_0 = \pi LA \end{aligned} \tag{2.5}$$

Since the luminous flux of the incident beam on the surface is equal to that of the exiting light ($F_{\text{in}} = F_{\text{out}}$), one can obtain:

$$E = \pi L \tag{2.6}$$

Typically, power efficiency (in terms of lm/W) is used to describe the efficiency of a display system. For example, if the total input electrical power (wall-plug power) of the display is 10 W and the total radiated flux is 20 lm, the power efficiency of the display is 2 lm/W. The power efficiency describes how much optical power emitted from a display (lm) which is produced by an electrical power input (W). For electroluminescence (EL) devices such as LED, current efficiency is also defined in terms of cd/A. The denominator is current, which quantifies the number of electron–hole pairs provided to the display in unit time. The electron–hole pairs recombine and generate photons which are received by human eyes (cd). For example, consider a Lambertian emitting EL display which, as above, emits a total luminous flux of 20 lm with the current = 300 mA. Then the current efficiency of the display is 21.22 cd/A.

## 2.3 THE EYE

Figure 2.3a shows a schematic diagram of a human eye [3]. The incoming light passing through the cornea, the aqueous humor, eye lens, and vitreous body, is received by the retina. Primary refraction and approximate focusing of light is achieved at the air/cornea interface. The eye lens, with a higher refractive index ($n = 1.42$) than the cornea, the aqueous humor, and vitreous body ($n = 1.33$–$1.37$), functions to focus a clear image to the retina, as shown in Figure 2.3b,c [4]. The shape of the eye lens can be adjusted by the ciliary muscle around it. Such a system can be approximately described by the Gaussian Lens formula [5]:

$$\frac{1}{d_1} + \frac{1}{d_2} = \frac{1}{f}, \tag{2.7}$$

where $d_1$ is the distance from the object to the eye lens, $d_2$ is the distance from the eye lens to the retina (which is 17 mm typically), and $f$ is the focal length. The image on the retina is totally reversed (upside-down and right–left). However, after interpretation by the brain we can recognize the images in their normal orientation in real space. When the object viewed is more distant, the eye lens becomes flatter, as shown in Figure 2.3b. On the other hand, the ciliary muscle will contract the eye lens to increase its curvature in order to focus nearby subjects, Figure 2.3c.

The retina receives the incoming photons and transfers them into bio-potential signals. After some processing within the eye, those signals are then transmitted through the optic nerve to the brain and interpreted

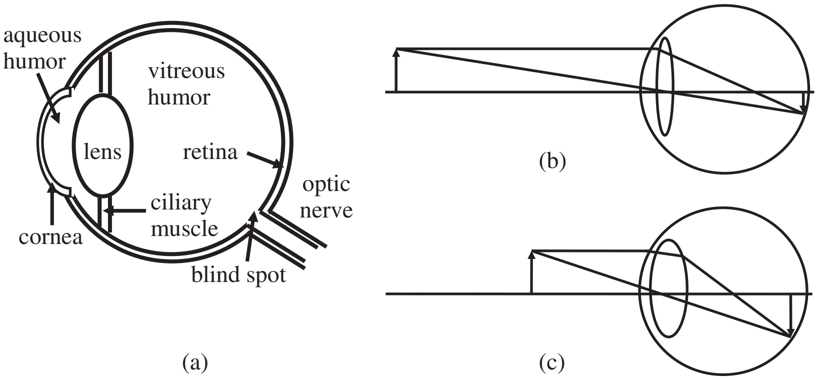

**Figure 2.3** (a) Cross section of the eye; (b) and (c): formation of image in the human eye.