Introduction to Microdisplays

David Armitage
Consultant, Los Altos, California, USA

Ian Underwood
MicroEmissive Displays Ltd, Edinburgh, UK

Shin-Tson Wu
University of Central Florida, Florida, USA

John Wiley & Sons, Ltd

Introduction to Microdisplays

Wiley-SID Series in Display Technology

Series Editor:
Anthony C. Lowe

Consultant Editor:
Michael A. Kriss

Display Systems:
Design and Applications
Lindsay W. Macdonald and **Anthony C. Lowe (Eds)**

Electronic Display Measurement:
Concepts, Techniques and Instrumentation
Peter A. Keller

Projection Displays
Edward H. Stupp and **Matthew S. Brennesholz**

Liquid Crystal Displays:
Addressing Schemes and Electro-Optical Effects
Ernst Lueder

Reflective Liquid Crystal Displays
Shin-Tson Wu and **Deng-Ke Yang**

Colour Engineering:
Achieving Device Independent Colour
Phil Green and **Lindsay MacDonald (Eds)**

Display Interfaces:
Fundamentals and Standards
Robert L. Myers

Digital Image Display:
Algorithms and Implementation
Gheorghe Berbecel

Flexible Flat Panel Displays
Gregory Crawford (Ed.)

Polarization Engineering for LCD Projection
Michel G. Robinson, Jianmin Chen, and **Gary D. Sharp**

Fundamentals of Liquid Crystal Devices
Deng-Ke Yang and **Shin-Tson Wu**

Introduction to Microsdisplays
David Armitage, Ian Underwood and **Shin-Tson Wu**

Introduction to Microdisplays

David Armitage
Consultant, Los Altos, California, USA

Ian Underwood
MicroEmissive Displays Ltd, Edinburgh, UK

Shin-Tson Wu
University of Central Florida, Florida, USA

John Wiley & Sons, Ltd

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wiley.com

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 6045 Freemont Blvd, Mississauga, ONT, L5R 4J3

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN-13 978-0-470-85281-1 (HB)
ISBN-10 0-470-85281-X (HB)

Typeset in 9/11 pt Times by Thomson Digital
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

Contents

Series Editor's Foreword

There is an old saying that good things are worth waiting for and that is certainly true of this latest addition to the Wiley-SID Series. I only wonder at its title; the authors have been modest; this is much more than an Introduction. It is an in-depth treatment of the subject written by three experts in the field with extensive academic backgrounds, but with very differing experience outside academia. David Armitage has been a consultant to the industry for more than 20 years, Ian Underwood has founded and successfully floated his company on the London Stock Exchange and Shin-Tson Wu, after many years in industry, has returned to academia. Between them the authors bring a range of different and complementary knowledge and backgrounds to this work.

In the late 1970s, when David Armitage and I were working in IBM Research Division on liquid crystal effects for what would become known as LCOS displays, I do not believe that either of us anticipated the impact microdisplay technology would have or the economic importance it would achieve in the display industry. It is the basis of digital cinema, projection TV, computer projectors, near-to eye displays and some aspects of digital signage. The projection technologies that have become commercially successful on a large scale have been transmissive or reflective liquid crystal and micromechanical devices; the first based on polysilicon or transferred crystalline silicon and the other two on CMOS technology. Slower growth has occurred in head mounted and virtual reality displays. However, emissive OLED microdisplay technology is now appearing on the market and will surely drive increased growth of near-to-eye displays. It is a given that a dynamic and growing market will encourage the development of improvements to the existing technologies and the invention of new ones.

The book covers this commercially important and technologically diverse subject to a depth which will benefit engineers at many levels from practitioners in the field to potential users of microdisplays. The introduction provides a useful review of human factors, specifications, display technologies and applications. The second chapter covers all aspects of analog and digital addressing schemes for LCDs, DMDs and OLEDs and the next two discuss reflective and transmissive backplane technologies. There follow three chapters which deal respectively with transmissive LC microdisplays, reflective LC microdisplays and LCD assembly and testing. The next two chapters discuss the two important microdisplay technologies other than LCD; micromechanical and emissive (predominantly OLED) devices. The book concludes with two chapters on optical and psychophysical aspects of projection and near-to-eye systems.

Coverage of the subject is comprehensive not just in the sense that all the technical issues are addressed but because significant practical information relating to the economics of manufacturing and assurance of product reliability are also included. General bibliographies are provided where appropriate and each chapter contains comprehensive references.

This twelfth book in the series is the first to deal exclusively with microdisplays and creates a welcome extension of our coverage into this important area.

Anthony Lowe

Series Editor
Braishfield, UK

Preface

Devices that are now recognized as "microdisplays" have been around for many years, although the name itself is more recent. Initially, helmet-mounted miniature CRTs with magnifying optics delivered an image to an individual viewer, such as an aircraft pilot confined to a small cockpit. Personal display development demanded smaller, lighter-weight, lower-voltage alternatives to the CRT. In recent years, display designers have been presented with a range of microdisplay options satisfying many of their demands.

The flat panel dominance of direct view displays continues at small scale with advances in microdisplay projectors. Conference rooms quickly adopted the new lightweight projectors, replacing 35 mm slide shows and overhead transparencies with electronic images. Home TV projection followed, and today cinema projection is converting to microdisplays. Cinema is the most demanding application and shows electronic projection at its best, but at considerable expense. Film is long gone from home projection, which provides a huge potential market to support development and manufacturing of microdisplay projectors. The blossoming of high-definition television (HDTV), requiring higher resolution and larger screens, enhances the quest for market share amongst competing TV systems. Microdisplays are basic components of projection, having great influence on performance and price.

Display technology brings together a number of disciplines – chemistry, physics, materials science, electronics, mechanical engineering, optics, and others – in addition to which it involves other specialized areas such as visual perception and psychology. In 2002, Shin-Tson Wu, recognizing the need for a book bringing together various aspects of microdisplay design, fabrication, and application, invited David Armitage to co-author the work. The series editor, Tony Lowe, suggested that a third author, Ian Underwood, be added. The team would thus bring together a range of knowledge and experience that allows them to explain performance and clarify issues in microdisplay technologies and applications. In total, the authors of this book have injected more than 60 person-years of experience in microdisplay technology and applications into writing it. Responsibility for the structure and content of each individual chapter has resided with the author having the most relevant experience in the given topic area. General coordination of material and structure fell to David Armitage. As a guideline, we have erred a little on the side of repetition from chapter to chapter in order to allow each chapter to be read without too much cross-referencing to other chapters.

As part of the SID series, the book serves the display community, but also accommodates readers unfamiliar with display details. Many engaged in the display industry concentrate on a particular discipline such as electronics or optics; others are limited to segments such as direct-view LCD, or plasma display. The book offers easy access to microdisplay details for readers seeking to broaden their background.

We examine the dominant microdisplay forms in detail, revealing their strengths and weaknesses. Microdisplays that once attracted attention are discussed briefly, noting the reasons for their decline. Others that are in the early stages of development are mentioned in relation to their promise. A range of basic projection system designs are discussed in relation to different microdisplay types. Other important projection components, such as light sources and polarizing beam-splitters, relate to microdisplay aspects. The need to provide compactness and viewing comfort as well as magnification complicates the optics of personal displays. A review of several successful designs includes output-pupil expansion techniques to enhance viewing comfort.

The introduction places microdisplays in context and discusses human factors such as visual acuity and flicker that influence the design of all display systems. The second chapter is concerned with electronic addressing methods, particularly the digital techniques supported by silicon backplane devices. A chapter devoted to silicon technology charts development of the silicon backplane structure with evolution of the silicon fabrication industry in general. The chapter on transmission microdisplays highlights the challenge of maintaining a high aperture ratio under pressure of shrinking pixel size. Two chapters on liquid crystals cover the design options and address the field fringing issues of concern in microdisplays. The chapter devoted to the burgeoning field of electromechanical systems emphasizes the development of the DMD microdisplay. An emissive microdisplays chapter is dominated by OLED development to complete the coverage of microdisplay devices. The final chapters are devoted to applications areas – projection then near-to-eye.

The authors thank Tony Lowe (Editor) and Mike Jin (SpatiaLight) for their initial comments on the content and structure of the book. We thank members of the display community for supplying pictures and diagrams that enliven and clarify the text. We are particularly indebted to: Larry Hornbeck (Texas Instruments); Bob Melcher (Syntax-Brillian Corporation); Professor Ifor Samuel (St Andrews University); Professor Bill Crossland (Cambridge University); Dr Euan Smith and Terry Nicklin (Cambridge Display Technology Ltd) for supply of, and permission to reproduce, information and diagrams relating to polymer OLED materials and devices; MicroEmissive Displays Ltd for supply of, and permission to reproduce, information and diagrams relating to polymer OLED microdisplays; the University of Edinburgh for supply of, and permission to reproduce, information and diagrams relating to LCOS backplanes. Ian Underwood offers his grateful thanks to colleagues including Dr Georg Bodammer, Dr Alastair Buckley, Dr Dwayne Burns, Dr Christophe Miremont and Graeme Kelly for their helpful feedback on his drafts. Shin-Tson Wu is indebted to his post doctors and students for technical assistance, especially Dr. Xinyu Zhu and Dr. Simon Fan-Chiang for providing the simulation results.

About the Authors

David Armitage pursued academic interests in semiconductor and liquid crystal physics, leading to microdisplay activity at IBM and Lockheed Corporation. For many years, he has consulted in microdisplay development and applications. He has numerous publications on semiconductors, liquid crystals, and displays. Academic qualifications include PhD (Physics), Bath University, UK; MS (Physics), University of Newcastle-upon-Tyne, UK; BS (EE), Durham University, UK.

Ian Underwood entered the field of LCOS as a postgraduate student in 1983. For the next 16 years he was part of a research group that pioneered advances in LCOS devices and applications. In 1999 he shifted his attention to P-OLED microdisplays when he co-founded MicroEmissive Displays which he continues to serve today as Director of Strategic Marketing. Personal distinctions include a Fulbright Fellowship held at the University of Colorado (1991), the Ben Sturgeon Award of the UK chapter of SID (2000), seminar presenter at the SID Annual Meeting (2000 to 2004), the Alfred Woodhead best paper award of the UK chapter of SID (2002 and 2004), Ernst & Young Emerging Entrepreneur of the Year (2003), Fellow of the Royal Society of Edinburgh (2004), the Gannochy Award for Innovation of the Royal Society of Edinburgh (2004), and a keynote address on Microdisplays at Eurodisplay IDRC in 2005. In 2004 he was named Professor of Electronic Displays at the University of Edinburgh.

Shin-Tson Wu is a PREP professor at the College of Optics and Photonics, University of Central Florida (UCF). Prior to joining UCF in 2001, Dr Wu worked at Hughes Research Laboratories (Malibu, California) for 18 years. He received his PhD from the University of Southern California and his BS in physics from National Taiwan University. His studies at UCF concentrate on liquid crystal displays, liquid crystal materials, foveated imaging, tunable-focus liquid crystal/liquid lenses, bio-photonics, and laser beam steering. Dr Wu is a Fellow of the IEEE, SID, and OSA. He has co-authored **three** books: *Fundamentals of Liquid Crystal Devices* (Wiley-SID, 2006), *Reflective Liquid Crystal Displays* (Wiley-SID, 2001), and *Optics and Nonlinear Optics of Liquid Crystals* (World Scientific, 1993), **five** book chapters, and over 300 papers.

1 Introduction

1.1 Microdisplays

Advances in several technologies related to projection displays and near-to-eye (NTE) displays have intensified interest in these areas. Development of the microdisplay is a key technology. The term "miniature display" does not distinguish small displays, such as watch displays, from displays designed with magnification in mind as indicated in Figure 1.1.[1] Microdisplays are a natural extension of the familiar microfilm, where magnification is essential to readout. A coarse image is recognizable on a microdisplay, but the full resolution is only discernable with the aid of magnification. The term "microdisplay" now in general use means a compact display designed for use with a magnification system. Microdisplay projectors have taken over the consumer market from CRT projection displays that have long dominated large-screen television. NTE products such as camera viewfinders and head-mounted displays evolve with microdisplay developments.

The direct-view CRT display has grown bigger and better over the years. Competing flat panel technologies such as liquid crystal and plasma displays have followed a similar path. Conversely, microdisplays have become smaller, in step with the shrinkage in microelectronics. NTE displays have progressed from miniature CRTs to lightweight microdisplays with superior characteristics. Attractive image quality and improvements in viewing comfort have opened up a commercial market for NTE displays. Figure 1.2 shows an early head-mounted display (HMD) designed for the consumer market, employing dual liquid crystal microdisplays. The unit weighs 150 gm and simulates a 52-inch diagonal color image viewed from a distance of 7 ft with resolution $260 \times 346 \times 3$ RGB pixels.

The vacuum tube nature of the CRT has made it difficult to expand in scale over the years, and now appears to be saturating at a cumbersome 40-inch diagonal. Projection displays powered by special-purpose compact CRTs overcame the size limitation. In comparison, the simple slide projector provided a much better image, and obviously with the invention of a suitable "electronic slide" (microdisplay) would be the basis of a new video projection technology. A wide variety of electro-optic devices has struggled to fill the microdisplay role in projectors. The current choices,

Introduction to Microdisplays D. Armitage, I. Underwood and S-T. Wu

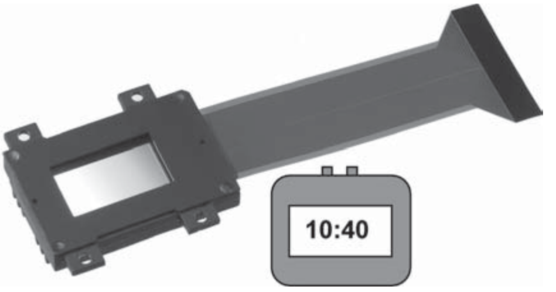

Figure 1.1 Miniature watch display compared with microdisplay having 9 μm pixel pitch, 1920 × 1080 resolution giving active area 0.78-inch diameter. Reprinted courtesy of Sony Corporation

liquid crystal and micromechanical devices, have proved commercially viable and will be difficult to displace. Price continues to exert a downward pressure on microdisplay area, due to the device cost and the influence of area on system cost. Figure 1.3 shows a portable business projector weighing 2.4 lb, with dimensions 2.6 × 6.1 × 7.8 inch, employing a single micromechanical microdisplay of 1024 × 768 resolution, diagonal 0.7 inches (DMD™), projecting full-color 1500 ANSI lumens at contrast ratio 1100:1.

Rear projection TV is a huge consumer market that drives the development of microdisplays. The latest products employ folded optic systems that reduce the unit depth to about 8 inches eroding the

Figure 1.2 Head-mounted microdisplay GT270. Reprinted courtesy of Canon Inc.

Figure 1.3 Microdisplay portable business projector LP70+. Reprinted courtesy of InFocus Corp.

space advantage of flat panel displays. The highest quality products produce the best images of any display technology. Figure 1.4 shows a 65-inch diagonal rear projection TV, employing three XGA LCOS microdisplays: luminance 450 cd/m^2, contrast ratio 2000, weight 95 lb.

1.2 Human Factors

The display engineer needs some knowledge of human vision to understand display performance and comfort for a given application. An engineering specification of human vision provides details of resolution, sensitivity, response time, and wavelength dependence. Luminance measured in candela/m^2 (lumen/steradian/m^2) is a measure related to our sensation of brightness. The lumen is a photometric unit of light flux derived from the product of the eye's wavelength sensitivity and radiant power,

Figure 1.4 Microdisplay rear-projection TV model BR768HC. Reprinted courtesy of Syntax-Brillian Corp.

giving the visual response to different wavelengths directly. At peak wavelength sensitivity 555 nm, flux in lumens = 683(radiant flux in watts); the same radiant flux at any other wavelength is worth fewer lumens, falling to zero lumens outside the visible wavelength range. Ambient light, contrast, and color saturation also influence our sense of brightness.

1.2.1 Color

Perception of color depends on wavelength in a complicated way that allows three primary wavelengths to represent a wide color gamut according to the luminance values of the primaries. Red, green, and blue primaries (RGB) optimize the color gamut. An even wider gamut of colors follows from the addition of more primaries. The narrower the spectral range of each primary color, the more saturated the primary color becomes.

Reduction to three primaries is of great utility in electronic displays, where picture elements (pixels) grouped in RGB triads below visual resolution merge to provide a full-color display. Color pixels are standard for direct-view CRT, flat panel displays, and some microdisplays. One of the options in projector design is to superimpose primary color images on the screen, to achieve full color. Each primary has a dedicated microdisplay, requiring three microdisplays for this parallel color system. Alternatively, color sequential display systems exploit the eye's response time by presenting the primary colors in rapid succession to give the perception of a single color represented by the primaries. One microdisplay can handle the sequence of colors, but it must operate at high frame rate. Eye movement during the color sequence will cause some separation of primary colors on the retina, perceived as color breakup. Eye movement sets a lower limit on the color field rate needed to suppress color breakup.

Color temperature is a measure of the spectral distribution of a light source, by comparison with the temperature of equivalent black body radiation. A color temperature of 6504 K represents average daylight. An arc-lamp source can be adjusted to a given color temperature by spectral filtering, with some sacrifice in output. Primary color separation requires filtering, where strong color saturation incurs further loss. Some compromise between color temperature, color saturation, and luminance is required. Color vision is lost at low light level $<10^{-4}\,\mathrm{cd/m^2}$; display engineering is essentially concerned with substantially higher luminance levels to provide good color vision.

1.2.2 Resolution

Display costs generally increase with resolution, making it wasteful to provide display resolution beyond viewer requirements. Light level, modulation depth, and wavelength of the signal influence eye resolution, peaking at maximum sensitivity 555 nm. The response to one-dimensional sinusoidal luminance patterns characterizes eye resolution as a function of spatial frequency (u), luminance (L), and contrast (C).

$$\textit{Contrast ratio} \quad CR = \frac{L_{\max}}{L_{\min}} \tag{1.1}$$

$$\textit{Contrast} \quad C = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} = \frac{CR-1}{CR+1} \to 1 - \frac{1}{CR} \tag{1.2}$$

$$\textit{Perception boundary} \quad L = L_{\mathrm{av}}\left[1 + C_{\min}\sin u\right] \quad L_{\mathrm{av}} = \frac{L_{\max} + L_{\min}}{2} \tag{1.3}$$

The contrast sensitivity function $S(u, L_{\mathrm{av}}) = 1/C_{\min}$, where $C_{\min}$ is the minimum contrast required to perceive the sinusoidal fringes at spatial frequency u and average luminance L_{av}. Contrast sensitivity plots reveal the most sensitive spatial frequency and upper frequency cutoff. Figure 1.5 shows contrast

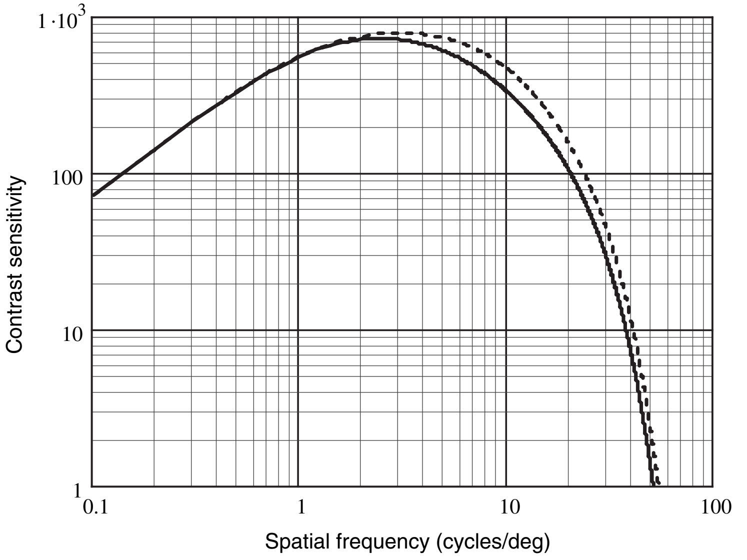

Figure 1.5 Contrast sensitivity for luminance: solid line 100 cd/m^2; dotted line 900 cd/m^2

sensitivity plots appropriate to displays. The plots are generated from formulae derived from a signal processing description of human vision, with parameters fitted to reported data.[2] Peak contrast sensitivity is about 4 cycles/deg, and cutoff about 60 cycles/deg, consistent with a limiting angular resolution of 0.5 minute of arc applicable to edge detection, and comparable with an accepted average value of 1 minute for human visual acuity. Increase in luminance provides a small increase in resolution at display luminance levels. The frequency cutoff corresponds to foveal vision, which is limited to about 2 degrees field of view. Eye and head movement compensate the limited field of view of the eye at high resolution, creating the impression of high resolution over a wide angle. Restriction of natural eye and head movement has a disturbing effect on vision that can result in eyestrain and discomfort.

The lower sensitivity of non-foveal vision contributes to the decline in sensitivity at low spatial frequency, where the spatial wavelength extends beyond the foveal range. Further low-frequency attenuation occurs at the neural processing level. Gradual variation in luminance of order 50% from the center to boundary of a display may not be noticeable, while shifts less than 1% are obvious at sensitive spatial frequencies. Color uniformity is similarly sensitive to spatial frequency. Moreover, we are more sensitive to color change than luminance change at low spatial frequency, making color uniformity more difficult to achieve in display systems.

Correlation in the visual process, known as hyperacuity, allows perception of an object's positional accuracy well beyond visual acuity. Vernier acuity is the ability to detect misalignment in lines and objects, which can be an order of magnitude higher than visual acuity. Spatial aliasing associated with pixelation gives rise to jaggy diagonal lines, detected by vernier acuity before perception of pixelation in general. Reducing pixel size below visual acuity may not suppress all the effects of pixelation.[3]

1.2.3 Flicker

Fluctuations in display luminance give rise to an annoying flicker. Frame-by-frame writing of electronic displays requires sufficient frame rate to avoid flicker. The early movies picked up the name flicks due to inadequate frame rate. With increase of flicker frequency, flicker attenuates, approaching

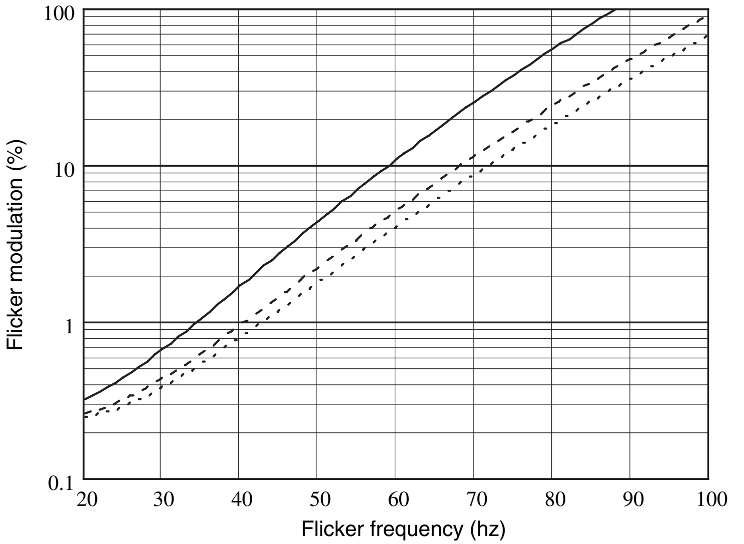

Figure 1.6 Threshold modulation for 50% probability of seeing flicker on a full white screen. Average luminance: solid line 100 cd/m^2; broken line 500 cd/m^2; dotted line 900 cd/m^2

threshold perception at a critical flicker frequency (CFF). Threshold perception is the level at which 50% of the population will detect flicker. Experimental studies of the dependence of flicker perception on luminance, modulation level, and frequency enable the elimination of display flicker.

The model for human vision referred to earlier generates Figure 1.6, on inserting typical parameters for threshold perception.[2] The flicker modulation m is of sinusoidal form $[1 + m \cdot \cos(2\pi wt)]$, at frequency w hertz. For non-sinusoidal flicker, m is the value of the fundamental Fourier component. The flicker parameters generating Figure 1.6 assume the worst case of a completely white screen at full brightness, a severe test of flicker compared with typical video projection. Perceptible flicker modulation decreases with increase of luminance, demanding a higher flicker frequency for suppression. An adjustment of the model parameters will give plots for a lower probability of flicker perception, predicting display conditions to eliminate flicker for essentially the entire population.

1.2.4 Contrast Ratio

Contrast is an important characteristic of image quality; low-contrast images have a washed-out appearance. Contrast sensitivity plots such as Figure 1.5 show that high contrast is required to achieve limiting eye resolution. High contrast ratio in all primary color channels promotes strong color saturation, and eliminates low-level color distortion, e.g. true black rather than dark purple.

The eye adapts to changes in average luminance, enhancing the visibility of dark scenes in a movie. To maintain image quality in dark scenes requires adequate contrast ratio at low luminance, implying high contrast at full luminance. Cinema-quality imaging requires $CR > 1000$ to reveal detail in dark scenes.

Ambient light reflecting from the display surface sets a minimum luminance level, requiring higher display luminance for a given CR. Screen luminance <60 cd/m^2 is accommodated by low lighting in a cinema supporting $CR > 1000$. Monitor displays designed for typical office lighting favor luminance of 150 cd/m^2 or higher, and light reflected from the screen may degrade $CR < 50$. Outdoor displays exposed to sunlight demand extreme luminance, prompting the development of reflective displays that exploit the high luminance environment. Shielded viewing inherent to NTE displays makes them insensitive to ambient light.

1.2.5 Grayscale

Analog displays such as CRT and LCD are continuously variable, making grayscale accuracy an issue of stability and noise. The advantages of digital systems result in a digital video signal converted to analog form to drive an analog display. Digital look-up tables (LUTs) assure the correct analog drive level, but digital bit-depth limits the number of gray levels. Making any display part of a digital system imposes grayscale quantization. Displays with only on/off luminance capability are inherently digital and achieve grayscale by pulse width modulation (PWM), averaging to the desired gray level over a frame period. Binary pulse code modulation generates equally spaced luminance levels over the luminance range; a poor match to the eye with an approximately logarithmic response to luminance, requiring progressively increasing steps in luminance for a perceptually uniform grayscale.

An inadequate number of gray levels gives rise to a contouring artifact in regions of near uniform luminance (e.g. image of sky), where the minimum quantized step is visible as an edge depicting the luminance contour.[4] A similar effect in color quantization appears as color contour boundaries, described as posterizing. At a given light level, fewer than 100 gray levels are required to avoid luminance contouring, provided the gray level steps are perceptually uniform, i.e. logarithmic. To provide adequate grayscale in dark scenes requires enhanced gray level count; cinema quality demands 1000 perceptually uniform gray levels.

Video image L_{in} transmitted with video signal voltage encoded $V_s \propto L_{in}^{0.455}$, to match typical receiving CRT luminance characteristic $L_{out} \propto V_s^{2.64}$, gives overall $L_{out} \propto L_{in}^{1.2}$. The display gamma ($\gamma = 2.64$) is adjusted to the viewer's preference of image gamma. The image gamma determines the distribution of grey levels in an image, where adjustment of gamma allows the viewer to optimize the appearance according to taste and viewing conditions. Video image gamma is typically set to 1.2, consistent with dimly lit viewing conditions; however, choice varies with image as well as individual.[2] It is interesting that fidelity in display engineering is usually overridden by viewer preference in choice of gamma. A similar distortion appears in choice of color temperature. Our vision evolved in response to daylight, making that the natural choice. However, given an adjustment in color temperature we will generally make color temperature higher than daylight, enhancing the blue region of the image spectrum.

1.2.6 Viewing Comfort

Adequate luminance and resolution are basic requirements for any display. The viewer's eyesight determines the upper limit on resolution. Tolerance to lower resolution depends on the information content of the display. The eye adapts to a wide range of luminance, making acceptable luminance dependent on ambient lighting and spurious display reflectance. Obviously, the display should be well engineered and in good working order, free from flicker and noticeable distortion. Direct-view displays should be set slightly below eye level, at a distance about two or three times the screen diagonal. Image quality is sensitive to viewing angle in some displays, and generally favors on-axis viewing.

Viewing comfort in head-mounted displays is much more sophisticated than in direct-view displays. Weight, size and balance have no counterpart in direct view, but are critical to HMD tolerance. Total-emersion HMDs concentrate vision on the display, shutting out all extraneous light to provide an artificial reality experience. It is very difficult to simulate normal vision effectively over a realistic field of view, including eye and head movement. Inadequate simulation gives rise to motion sickness and other discomforts known collectively as simulator sickness.

Partial-emersion HMDs allow some vision of the outside world, which preserves the viewer's orientation, and are tolerable for much longer periods, even when the outside view is restricted to peripheral vision. Eliminating the influence of head movement on the displayed image makes eye movement do all the work in scanning the image. A field of view in excess of about 35 degrees induces intolerable eye fatigue due to the scanning effort. Viewing discomfort is a difficult barrier to overcome for the HMD to gain general acceptance. The interest in wearable computers and portable internet displays provides an incentive for further development and innovation in HMDs.

1.3 Display Specifications

A display designer emphasizes resolution, luminance, etc., according to the targeted application.[5] In marketing the display, a list of specifications identifies its value in various applications.

1.3.1 Resolution and Size

Modulation transfer function (MTF) has the same functional form as Equation (1.1) for contrast, and describes the decline in contrast with spatial frequency in cycles/mm = (line pair)/mm = lp/mm. MTF is the standard method of describing the resolution of optical components such as a projection lens, and the product of component MTFs gives the overall MTF. Display resolution determined by raster scan or pixel count cannot be expressed in MTF form without loss of mathematical rigor. The number of TV lines or pixel array size characterizes display resolution. The video graphic adapter (VGA) notation, listed in Table 1.1, identifies standard pixel array formats, extended by inclusion of the high-definition television notation.

Screen diagonal characterizes the display size, a legacy of the early circular screen CRT. The cost of a direct-view display increases more rapidly than the area, since the defect probability and assembly problems increase. Plasma displays have demonstrated the largest diagonal in excess of 100 inches, followed closely by LCDs. The size and performance of flat panel displays competes with projection TV. When manufacturing costs have settled down, price will determine the target market for projection, now set at >40 inches diagonal. TV displays viewed at a distance two or three times the screen diameter barely resolve (1 arc min acuity) pixels at WXGA resolution, while computer monitors viewed at a distance comparable to screen diameter just resolve WUXGA. Higher visual acuity of lines and edges favors extended display resolution. HDTV at 1080 × 1920 resolution may pull the viewer closer to the screen, intensifying the experience, particularly for sporting events.

1.3.2 Luminance and Color Saturation

In CRT projectors and plasma flat panels, the peak luminance cannot be maintained over the entire screen due to limited power dissipation. A peak luminance and an average luminance should be specified. Consumer CRT projectors deliver an average of about 200 lumens to the screen and require high screen gain for adequate luminance of about 350 cd/m^2. Projectors in general can take advantage of screen gain to increase the screen luminance in a preferred direction at the expense of lower luminance in other directions. The focusing and scattering properties designed into the screen determine its gain.

Table 1.1 Video graphic adapter designation and array size

VGA	640 × 480	SVGA	800 × 600	XGA	1024 × 768
SXGA	1280 × 1024	UXGA	1600 × 1200	QVGA	320 × 240
WXGA	1365 × 768	WUXGA	1920 × 1200	GXGA	2560 × 2048
SDTV	729 × 480	HDTV(720P)	1280 × 720	SHDTV(1080P)	1920 × 1080

Increased screen gain has the downside of enhanced speckle as well as reduced viewing angle. Front projectors specify lumens delivered to the screen, since the luminance depends on screen area and gain. Rear-projection units have built-in screens and luminance quoted over a range of viewing directions. Acceptable luminance depends on ambient lighting. Cinema projectors illuminate a large area screen to give about 60 cd/m^2 screen luminance, and require a dark ambient environment to appreciate image quality. Microdisplay projectors aim for 500 cd/m^2 or higher to accommodate the higher ambient light favored by the business and consumer markets.

Color saturation is strongest in laser or LED driven displays, with sharply defined wavelength. Dichroic filters in arc-lamp projection displays determine the color, where stronger color saturation implies lower throughput lumens. Specification of projector output luminance is sometimes inflated by quoting the value obtained before color correction. A similar tradeoff applies to LCDs using dyed pixels for color, where optical absorption introduces severe throughput loss. Phosphor characteristics limit the color saturation of plasma and CRT displays; however, color saturation is sometimes enhanced by addition of dichroic filtering in CRT projectors.

Backlighting power and throughput efficiency determine the luminance of LCDs. Improvements in throughput efficiency should improve the already high luminance of 500 cd/m^2. Plasma displays are marketed with small-area luminance beyond 500 cd/m^2. Microdisplays reduce cost by shrinking the diagonal to 0.7 inches or less. The development of small-arc projection lamps has kept pace with microdisplay contraction, maintaining the optical collimation necessary for efficient lumen throughput. We are entering an intense stage of competition for large-screen home theatre, where several technologies vie for consumer attention.

1.3.3 Contrast Ratio and Grayscale

Contrast ratio is an important indication of image quality. It is quoted for dark ambient; room lighting always reduces the CR. The largest degradation in CR is associated with diffuse reflecting surfaces, such as the powder phosphors in CRTs and plasma displays. Projectors quote the serial all-on/all-off CR, along with the ANSI CR for a white/black checkerboard pattern; ANSI CR is always lower than the serial CR, due to internal light scattering, and provides a better indication of image quality. LCD CR is limited by the extinction ratio of polarizing optics and off-axis retardation dependence; however, optical compensation achieves CR > 500. Projection systems achieve CR > 1000, due to higher quality polarization optics and better compensation over the limited field angle of the projection lens. A recent development expands the effective CR by modulating the light source according to the image's average light level, to maintain excellent CR and grayscale in dark scenes.[6]

The standard 8-bit grayscale is adequate for most purposes, and applied to each primary color channel gives 24-bit color. More demanding applications such as cinema projection require 12-bit grayscale/channel. Look-up tables create appropriate luminance grayscale steps, taking into account the device characteristic. Pulse width modulation grayscale, necessary in plasma displays and other digital display devices, achieves high precision in grayscale; however, image contouring and motion artifacts associated with PWM requires an effective expansion in addressing bit depth.

1.3.4 Response Speed and Flicker

Video displays need to respond at a fast enough rate to avoid motional blurring and flicker. We are somewhat forgiving of motion blur, since our vision is less acute in observing movement. Movies shot at 24 frames/sec are acceptable, which is not very challenging for an electronic display response time. However, cinematographers structure the scenes and camera angles to minimize artifacts such as false wheel rotation; a higher frame rate is desirable. Theatres shutter the film projector to raise the flicker rate to 48 Hz or higher to suppress flicker perception. Motion picture frame time is 42 ms, but the frame changes abruptly, implying equivalent display response $\ll$42 ms to duplicate film. A video data rate of 60 frames/sec attenuates flicker, but requires response $\ll$17 ms to maintain gray level integrity and avoid trailing on fast-moving images. The response time is severely challenged in color field sequential displays, where color is formed by a rapid succession of primary color frames above the color fusion frequency of the eye. Color frame rates as high as 540 frames/sec are required to avoid color breakup caused by eye movement.

The image refresh rate introduces an intensity modulation at the refresh frequency, and half that frequency if the display mechanism is susceptible to odd/even asymmetry as in the LCD. Flicker issues are resolved in display design by minimizing the flicker modulation and raising the refresh frequency. The displayed frame rate may be doubled to reduce flicker if there is significant modulation at half frame rate.

A static image displayed for a substantial period may store some aspects of the image that persists for some time as a ‘ghost image’ superimposed on the newly addressed image. The effect is described as ghosting or image sticking. Liquid crystal displays are susceptible to image sticking due to ionic charging effects. Plasma displays are also prone to ghost image effects.

1.4 Displays in General

To place microdisplays and applications in context we discuss electronic displays in general and the shrinkage of direct-view displays into the micro domain. We restrict our attention to high-information-content displays, since there is little value in magnifying low information content capable of direct display.

1.4.1 Cathode Ray Tube

The CRT has been the dominant technology for many years. Reliability and low cost have outweighed its shortcomings, until recent developments in flat panels. The simplicity of electron-beam addressing remains appealing, but carries vacuum-tube baggage that occupies valuable space, and has become unfashionable. The shape of the tube has improved over the years, including attempts at a flat structure, but does not compare with a lightweight flat panel display. The tradeoff in luminance verses resolution is a technical limitation that is proving difficult to surmount. Diffuse reflection from the phosphor powder penalizes CR under modest room light. The direct-view CRT will play a prominent role in displays for many years and gradual improvement in performance will continue. However, flat panel performance is improving more rapidly and will continue to win market share from CRTs.

The luminance/resolution issue is more marked in projection CRTs, where inadequate luminance is the biggest drawback. Improved phosphors and the application of thin film phosphors should enhance performance. However, competitive pricing of high-quality microdisplay rear-projection HDTV is pushing the CRT units off the showroom floor. The development of large-area flat panel displays competes with projectors in general.

Miniature CRTs were developed for NTE displays such as military helmet displays. As microdisplays, they played an important role in the development of head-mounted displays, and are still in use. Microdisplays with superior performance and advantages in weight and volume have made the miniature CRT obsolete. Detailed discussion of microdisplays in later chapters excludes CRTs, because they do not provide much insight into current microdisplay development.

1.4.2 Matrix Addressed Displays

Electrode-addressed displays, such as liquid crystal displays, must use multiplex addressing to reduce the wiring complexity. Matrix addressing uses a rectangular network of electrodes similar to (x,y)