Overview

Introduction

Display Measurements

Displays (LCD, OLED, E-Paper)

3D, Touch, Interfaces

Summary & Outlook

Some pictures etc. are courtesy of the companies named on the picture, others from, e.g., SID, …
High End Embedded System Hardware

Focus of this chapter except e-o and glass topics
Typical Design Flow of System with Display

1. Product specification, idea
2. Data to be displayed
3. Display resolution
4. Screen size
5. Display technology
6. Price, supply chain, ...
7. Mechanics; production, ...
8. Environment (T, illuminance, …), application
9. User input

Start of design

Redesign, optimization

Graphics controller, µC, software, OS, …
Typical Design Flow of System with Display

- Product specification, idea
  - Data to be displayed
    - Display resolution
      - Screen size
        - Display technology
          - Price, supply chain, …

- User input
  - Keyboard, mouse, touch

- Viewing conditions
  - Environment (T, illuminance, …), application
    - Display Metrology
      - Display Effects

- Display Market
  - Display driving & interfaces
    - Graphics controller, µC, software, OS, …

- GUI / HMI
  - Redesign, optimization

This § § Introduction

Mechanics; production, …
Display Fundamentals

Cross section of a typical (color) display

Front plane

Electro-optical layer

Back plane

Substrate, barrier layer, polarizer, …
Color filter (option)

LCD, OLED, e-paper, …

Matrix drive, TFT, electronics

Substrate, barrier layer, polarizer, backlight, …

Electro-optical layer decides on display characteristics like bistability, image quality, environmental conditions, …
Typical FPD Principles (EO Layer)

- **Light Switching** (AM LCD): $U \Rightarrow$ transmission (luminance)
- **Emissive** (OLED): $I \Rightarrow$ luminance
- **Reflective** (LCD, E-Paper): $U \Rightarrow$ reflection (luminance)
Display Technologies Overview

- **Reflective**
  Examples: "simple" monochrome LCDs, e-paper

- **Emissive**
  Examples: OLED, Plasma (PDP), LCDs with backlight
Display Technologies Overview

• Reflective
  Principle: Reflects ambient light
  → sunlight readability, lowest power consumption („green displays“)
  Examples: “simple” monochrome LCDs, e-paper

• Emissive
  Principle: Each pixel generates light by current
  → Good in indoor applications, high power consumption
  Examples: OLED, Plasma (PDP), LCDs with backlight

There is no display technology suitable for all applications!
→ Evaluate acc. applications → Opportunities for skilled people
Consequences for Display Technologies

Criteria: \( \eta \) and \( r \)

“High Power vs. no color”
(2014)

<table>
<thead>
<tr>
<th>Emissive</th>
<th>Reflective</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Examples</strong></td>
<td>AMLCD, OLED, PDP, …</td>
</tr>
</tbody>
</table>
| **Improvements** | • Rise e-o efficiency \( \eta \)  
• Optimize subassemblies | • Rise reflectance \( r \)  
• Add frontlight |
| **Merits** | Multimedia, mass production | Bistable ➔ lowest power |
| **Issues** | Bright light, power consumption | Multimedia, professional |
| **Benefit** | Multimedia @ reasonable power | B/W @ lowest power |
Displays - From Segmented to E-Signage

Size, price, complexity, …

Monochrome graphics

Color graphics

Direct drive  MUX  Passive Matrix  Active Matrix

Resolution
Matrix Driving of FPD - Example LCD

Passive Matrix

- Crossings of 2 grids form pixel
- No storage of data (if not bi-stable) during frame period

Active Matrix

- Capacitor stores data during frame period
- 1 TFT psp, SXGA: 4 Mio. TFTs

Higher contrast ratio, higher resolution, more grey shades and colours

Exception: PDP

Low vs. high cost
- Low vs. high image quality

Low vs. high image quality

1 Pixel

Row 'scan'

Column 'data'

(IITO simplified example)
**AM LCD - Module**  
A display is more than just glass …

Electronics within module is called “panel electronics”

*: Backlight for LCD, frontlight for e-paper
none for emissive displays
AM LCD – Module - Explanation

• Module: Consists of panel electronics and display glass

• Display glass: eo-layer, TFTs, color filter, …

• Panel electronics: All electronic circuitry within module like column and row driver, timing controller, power supply, interface, e-o correction

• Interface: Data to be displayed sent from Graphics/Display Controller to display module. Modern interfaces have serial data stream in real time.

• Power supply: Provides all necessary voltages for panel electronics, usually 5+, most panel have single voltage input

• Timing controller: Reformats interface input data for row and column driver

• Row driver: Subsequently activates row by row (line) by pulses

• Column driver: Provides grey level voltages for subpixel for active row

• E-o transfer function / gamma correction: Adjust digitally input grey levels to voltage levels which are adapted to e-o transfer function of e-o layer

• \( V_{COM} \): LCD-frontplane voltage

• Backlight: Provides light which passes LC glass; frontlight for e-paper as this is not transparent like LCD. Emissive display generate light.
Example of Row and Column Drivers

Column (data) driver

Row (gate) driver
**Power Consumption and Cost**

- **Panel electronics**, front and backplane have similar impact on module price: ~ 25%
- Backlight draws about 75% of total power

**Typical values for 10.4” VGA Color AM LCD**

- **TFT / back plane**
- **Misc.**
- **Polarizer etc.**
- **Controller**
- **Backlight**
- **Driver ICs**
- **Front plane color filter**

- **Power consumption**
- **Timing Controller**
- **Row Driver**
- **Column Driver**
- **Backlight**

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3D, Touch, Interfaces

Summary & Outlook

• Principles
• AM LCDs (TFT)
• Backlight

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Overview

Fundamental LCD Principle

Active Matrix (full color graphics)

LED Backlights and Improvements

Improvements beyond TN LCDs

- Principle
- TN Technology
- Electro-optic curve

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**LCD (Liquid Crystal Display) Overview**

- Have reached (mostly) professional maturity
- Range from Segment 8 over MUX and b/w graphics to high res full color

- Many "specials" like round, 16:3 and transparent
**Multimedia Displays**

## LCD Evolution

<table>
<thead>
<tr>
<th>1888</th>
<th>1980’s</th>
<th>1990’s</th>
<th>2000’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>From small size displays for characters to large area displays for graphics and movies</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Active Matrix**
  - Low temp. p-Si TFT-LCD
  - LCD TV

- **Active Matrix a-Si TFT-LCD**

- **Passive Matrix LCD**

- **Segment LCD**

- **Discovery of LC materials**
Forth wave after TV: Digital Signage, flexible displays? Both applications are not large enough (areawise) to cover up a saturated TV market!
**LCD Cross Section**

**Principle**: Voltage driven 'switching' of light

- (Back-) Light
- Polarizer
- Glass 1 mm
- ITO 50 nm
- LC 10 µm
- Alignment layer 50 nm
- Spacer
- Analyzer
- TFT plane (back plane)
- CF plane (front plane)

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Basic Technologies

- **Reflective**
  (low resolution and monochrome)
  + Power consumption
  - Night vision
  Mainstream for low res.

- **Transflective**
  (good performance but too expensive)
  + Power consumption
  + Night & day vision

- **Transmissive**
  (high resolution and color)
  + Vivid Colors
  - Power consumption
  - Daylight vision
  Mainstream for high res.
Characteristics of Liquid Crystals

• Chemistry

Liquid crystal is a special material with a “4th” phase (solid, liquid, gaseous). In this 4th phase the solid phase properties “orientation” (crystal, fixed positions of molecules) and the liquid characteristics (moveable, no fixed positions) are combined. Furthermore they can orientate parallel to an electric field.

• Mechanics

• Physics

- Effects in electric field

LC molecule align to electric field:
- Mechanical orientation within ms
- Induced charge adapt within ns
TN (90°) : Light Guide Principle

TN: Twisted nematic + twist angle

Positive Mode

- Voltage driven
- Direct Drive & Active Matrix
- Contrast: Difference of luminance

Negative mode:
Turn polarizer by 90°
**TN 90° : Light Guide Principle**

TN 90°: Twisted nematic LC with 90° helix (no voltage)

**Polarizer**: Let only polarized part of light pass in its direction

**Alignment layer**: Set Orientation direction of LC

**ITO**: Indium Tin Oxide, a transparent conducting material (use in all displays)

**LC**: Forms helix **without voltage**, polarized light “follows” LC orientation

Light orientation is the same as polarizer orientation at the “bottom” of the pixel → light passes polarizer → pixel is “white”

With “high” **driving voltage**:  
LC orientates to E-field set by voltage  
No helix, polarized light orientation is unchanged, lower polarizer cannot be “passed” → pixel is “black”
Electro-Optic Curve (EOC) of LC

Luminance /Transmission

Pixel

90 %

10 %

0

Driving Voltage

eo curve

Slope and Shape:
- Viewing Angle
- Twist
- Pre-tilt
- T
- LC Type
- ...

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Grey Scale: Adjust Electro-Optical Curve of LCD to $L \sim D^\gamma$

Input grey levels $D_{\text{Input}}$ must be modified by Transfer Function in a way that its modified grey levels $D_{\text{LCD}}$ result with the electro-optical curve of the LCD in the gamma curve $L \sim GL^\gamma$.

Example: The luminance of $D_{\text{Input}} = 0.5$ is about 0.2. If this would be $D_{\text{LCD}}$, it would result in about 0.95 of $L_{\text{max}}$. The Transfer Function modifies $D_{\text{Input}} = 0.5$ to $D_{\text{LCD}} = 0.55$ which then provides the correct luminance with 0.2.
Summary: LCD Fundamentals

- Liquid crystals are a special material with a fourth state of matter (plasma is the fifth state – both are used for displays!)
- An LCD consists of several layers with mostly glass as a substrate
- Twisted Nematic $90^\circ$ is used for all LCDs except TV-panels
- LCDs are voltage driven
- Electro-optic curve has many dependencies which have to be respected (or optimized) for good performance like viewing angle, response time, …
Summary

• Liquid crystals are a special material with a 4\textsuperscript{th} state (solid-liquid).
• With polarizer, alignment layer and transparent electrodes a basic LCD is made.

- LCD is voltage driven.
- Twisted Nematic 90° (TN 90°) is used for Seg 8, low MUX and many AM LCDs.
- IPS, xVA is used for high quality LCDs (see below).
Overview

- Fundamental LCD Principle
- Active Matrix (full color graphics)
- LED Backlights and Improvements
- Improvements beyond TN LCDs

Some pictures etc. are courtesy of the companies named on the picture, others from, e.g., SID, ...
AM LCD Fundamentals
AM LCD Side View

AM LCDs are often named as “TFTs”. TFT is just the type of the AM transistor design. AMOLEDs are built with TFTs as well.

Driving Circuit Unit

LCD Panel

Polarizer

Color Filter

Substrate

Align.

ITO

TFT Array

Substrate

Diffusors

Light guide

Backlight and Chassis Unit

Contact

Seal

LC

Spacer

TFT

Glás

Black Matrix

Color Filter

Substrate
Active Matrix Subpixel

- Scan and data signal on one plate
- 1 TFT per pixel (AM OLED ≥ 2)
- Capacitor stores pixel voltage (data) during frame time

- 1 pixel = 3 RGB subpixel
- Aperture ratio ≈ 60%
- SXGA: 1280 x 1024 x 3 TFTs
  ≈ 4 Mio. TFTs
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**LCD Backlight Requirements**

- High luminance
- Uniformity of luminance
- High dimming ratio (e.g. automotive)
- Low power consumption
- Low profile
- Low weight
- Low heating
- Choice of color
- Extended temperature range
- High life time
- Low cost
- …

All these requirements cannot be fulfilled by a single technology!
Backlight System

Diffuser and BEF sheets make inhomogeneous backlight distribution uniform. BEF stack can be optimized for luminance (efficiency) or viewing angle!
Luminance Loss for AMLCD

Light efficiency: 
\[ \eta = 0.6 \times 0.4 \times 0.7 \times 0.3 \approx 5\% \]

White light is RGB filtered, only 1/3 of white intensity passes.

Only light with same polarization as polarizer pass.
AM LCD Optimizations: Selected topics

η: Backlight

No CF for sequential color backlight

Intelligent dimming

Increase $\eta_{\text{LED}}$

η = 5%

L: Transmission

Light CF or RGBW (gamut $\downarrow$)

Rise aperture

Directional films

Front Polarizer

ITO Coated Glass

Color Filter (30%)

Liquid Crystal Layer

Active Matrix (70%)

Rear Polarizer (40%)

Light Guiding Plane (60%)

100%
Improving Backlights

- **Simpler stack**
  
- **BEFs**
  
> Enhances perpendicular luminance at the price of viewing angle degradations.

Great for many applications -

Source: 3M
Backlight & Colour Filter Fundamentals

Backlight spectrum \times \text{ colour filter spectra} = \text{ Light output spectra}

Match backlight spectra and colour filter transmission spectra for maximum light output with respect to colour management.
White LED - Backlight & Color Filter

WLED tolerances shift white point (and color co-ordinates)
LED – Backlight Power Saving Methods

• Adaptive light output by ambient light sensor (also applicable for CCFL)
• Local dimming (image content)
• Sequential color (no color filter, 1/3 of pixel [TFTs, …], higher aperture, …)
• Power savings up to 90%
LED – Backlight: Adaptive Light Output

Power Savings by Ambient Light Sensor
To detect the amounts of lights available & adjust display brightness accordingly to save power.
Power Saving strongly depends on image:
dark images – large savings vs. bright image virtual no saving
## LED – Backlight: Dimming

Dimming by WLEDs or RGB LEDs (with 2D color dimming ~ 80% *)

When LEDs are dimmed, grey levels of pixels have to be increased

### Power consumption

<table>
<thead>
<tr>
<th>Dimming</th>
<th>No</th>
<th>0D</th>
<th>1D</th>
<th>2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>All LEDs</td>
<td>100 %</td>
<td>80%</td>
<td>70%</td>
<td>50%*</td>
</tr>
</tbody>
</table>

### Principle

<table>
<thead>
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<th>1D</th>
<th>2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>All LEDs</td>
<td>100 % ON</td>
<td>All LEDs dimmed</td>
<td>LED in lines, # of lines drvs</td>
<td>LED matrix, h x v drivers</td>
</tr>
</tbody>
</table>

### Visualization

(white ≡ yellow)

- **No**: All LEDs 100% ON
- **0D**: All LEDs dimmed
- **1D**: LED in lines, # of lines drvs
- **2D**: LED matrix, h x v drivers
LED Backlight Dimming  Not yet implemented in most professional AM LCDs

Without  with dimming

Same image quality but 60% less power

0 138 W  54 W

0 138 W  90 W
LED – Backlight: Adaptive Local Dimming

**Traditional Full-On LED**

**Individual LED On/Off & Level Control**

High Contrast

- $L_{\text{max}} = 630 \text{ cd/m}^2$
- $L_{\text{min}} = 0.03 \text{ cd/m}^2$

$\rightarrow C_R = 630 / 0.03 = 21,000$

Power Saving 50% avg. (image dependant)
AM LCD Power Reduction

Conventional 60 Hz WLED LCD:
- 250% Reduction

FSC. Field sequential color
Stencil: L + some color, R,G,B

- Reductions refer to video
- Static content = less savings

Source: Wu, UCFO
LCDs Improvements

4.5” World’s Slimmest HD

- Characteristics
  - Resolution: 720 x RGB x 1280 (329 ppi)
  - Outline Dimension: 58.71(H) x 107.22(V) mm
  - Thickness: 0.99(T) mm
  - Luminance: 400 cd/m²
  - Color Gamut: 70%
  - Structure

![Conventional vs Ultra Slim Diagram]

47” World’s Lowest Power Consumption Backlight

- Characteristics
  - Power Consumption: 19 Watt (Backlight)
  - Luminance: 350nit
  - Active Screen Size: 1039.7(H) x 584.8(V)
  - Resolution: 1920 x RGB x 1080
  - Maximized Efficiency Technology

- High Transmittance Panel
- High Efficiency LED
- 1 LED Array (Vertical)
- High Efficiency LGP
- Efficiency Improvement Design
- 3 Sheet Structure

![47” FHD Low Power BLU Image]
Slim LED Backlight LCD Examples

... demonstrators and in mass production

Curved displays may remain as “only” advantage of OLEDs.

Total thickness (LCD + backlight) 1 … 5 mm if optimized for slim line.
Summary: LCD Backlights

• A backlight technology which fulfils all requirements of backlights is not available but OLED area backlights can come close.

• 100% LED backlights for small displays but more and more manufacturers switch to LED, even for LCD TV (LED TV as labelled by SAMSUNG).

• LED backlights offer unique advantages of power saving methods.
Summary

• Main requirements for backlights are:
  - Efficiency (low heat)
  - Uniformity (BEFs)
  - Lifetime (cooling)
  - No LED color shifts

• Improve efficiency (≈ 5% transmission) of Color AM LCDs.
• Professional LCDs are mostly equipped with LED backlight.

• Power saving by
  - Ambient light sensor
  - Local dimming, …
• Standard only for high end LCD TV.
Overview

Fundamental LCD Principle

Active Matrix (full color graphics)

LED Backlights and Improvements

Improvements beyond TN LCDs

Some pictures etc. are courtesy of the companies named on the picture, others from, e.g., SID, ...
Improvement of Viewing Angle (I)

- **TN**
  - Black: White
  - Electrode
  - Polarizer
  - Glass substrate
  - Cheap laptop, monitor, phone

- **VA**
  - Black: White
  - Electrode
  - Polarizer
  - Glass substrate
  - TV, professional

- **IPS**
  - Black: White
  - Electrode
  - Polarizer
  - Glass substrate
  - Smartphone, tablet, automotive, TV
Improvement of Viewing Angle (II)

<table>
<thead>
<tr>
<th></th>
<th>TN</th>
<th>VA</th>
<th>IPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low driving voltage</td>
<td>High contrast ratio</td>
<td>Very wide viewing angle</td>
</tr>
<tr>
<td>viewing</td>
<td>Limited viewing angle</td>
<td>Wide viewing angle</td>
<td>Slow response speed</td>
</tr>
<tr>
<td>angle</td>
<td></td>
<td>Fast response speed</td>
<td>Low brightness</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TN: Twisted nematic  
IPS: In plane switching  
VA: Vertical alignment

VA and IPS at higher cost and risk of image sticking
Improvement of Viewing Angle: TN 90°

4 Subdomains per Subp

Film on LCD

Backlight Foil

Iso - Contrast Plots

4 domain TN 1 domain TN

Standard TN 90°

Standard stack

TN 90° + FUJI film

Improved
Improvement of Viewing Angle: \textbf{In Plane Switching}

E-field is not between front- and back plane as for TN. ITO electrodes are only on backplane for IPS.
Improvement of Viewing Angle: Multi Domain Vertical Alignment

- E-field between protrusions
- Multi domain results in great viewing angle performance
LCDs Improvements

High Color Gamut
27" QHD PLS

High resolution & “unlimited” viewing angle
RGBW Color Approach

- Merits of RGBW:
  - Power saving
  - Larger maximum white luminance than RGB

Shortcomings:
- Higher cost (4 TFTs)
- Shrink of gamut

2013: Implemented in some automotive and smartphone LCDs.

SONY XPERIA Smartphone
**Improvements: Color Filters**

- **Color Filters**
  - E-INK
  - Poor color reproduction (see § E-Paper)
  - Higher luminance but lower power!

### Table: 12.1" XGA

<table>
<thead>
<tr>
<th>Pattern</th>
<th>RGB stripe</th>
<th>RGBW square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>1024 x 3 x 768</td>
<td>1024 x 2 x 768 x2</td>
</tr>
<tr>
<td>Brightness</td>
<td>500 nits</td>
<td>500 nits</td>
</tr>
<tr>
<td>Power Consumption (W)</td>
<td>14.5</td>
<td>10.1</td>
</tr>
</tbody>
</table>

- 30%
## RGBW Case Study for Outdoor E-Signage / Automotive

<table>
<thead>
<tr>
<th>Requirement, Application</th>
<th>Suitable? Range</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor Luminance ($L_{\text{White}}$) and CR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color reproduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feasibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Outlook for LCDs

• Improve “weaknesses“
  - Viewing angle towards OLEDs ➔ IPS, VA
  - Response time towards OLEDs ➔ Overdrive
  - Bright light readability towards EP ➔ RGBW

• Reduce power consumption (“green”)
e.g. by backlight dimming, RGBW, film stack, …

• Reflective low res LCDs ➔

• Some market for transparent LCDs
• 4k x 2k resolution (QHD) and beyond
• Massive rise of AM LCD fabs in China
• Joint ventures and mergers like “New Japan Display” will rise in future

Adapt methods from high end LCD TVs for professional displays

Watch markets and manufacturers
Summary & Questions

• What makes LCDs so unique and universal for display applications?

• What are the main issues to solve for LCDs?

• What are today's hot topics when promoting LCDs?

• Issues of LCDs where other display technologies are superior:
  - Ambient light performance: e-paper but no color
    (for low res: reflective LCDs)
  - Response time & viewing angle, depth: OLED but higher cost

→ LCDs are the most universal technology today and is available
  from 8 Segment (< 0.5”) to Quad HD, large size (up to 108”)
  at best price and optimized for special requirements like automotive!
Summary

• Various LCs are optimized for different applications.
• Overdrive reduces and equals G2G response time.

• LCDs are the most universal technology today and are available from 8 Segm. (< 0.5”) to Quad HD (> 100”) at best price.

To be improved:
- Sunlight perform.
- Depth (but 5” FHD: 1 mm)
- Efficiency
- Cost for customized
# Summary: Technologies vs. Applications

<table>
<thead>
<tr>
<th>Requirement, Application</th>
<th>Suitable? Range</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viewing distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color, video</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viewing angle</td>
<td></td>
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</tr>
<tr>
<td>Feasibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trends</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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Displays (LCD, OLED, E-Paper)

3D, Touch, Interfaces

Summary & Outlook

- OLED fundamentals
- OLED displays
- AM OLED vs. AM LCD

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OLED Market Forecast

Source: IHS OLED Market Tracker
AM OLED vs. AM LCD Price

### Mobile displays

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Price/cm² (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTPS AMOLED (Galaxy S Series)</td>
<td>1.01</td>
</tr>
<tr>
<td>LTPS LCD (iPhone Series)</td>
<td>1.02</td>
</tr>
<tr>
<td>a-Si LCD (iPad Series)</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Source: iSuppli, Samsung Securities

Ratio:

- 1 : 1
- 1 : 0.5

### TV

MP 3D
55” LCD
2012

d=3cm

$8000

$4500

$2500

$1200

$2000

Source: Display Search 2012

55” LCD TV, 240Hz, 3D, LED Backlight, Slim
OLEDs in Mass Production

Passive Matrix since about 2005, mainly MP3 players

Limit in resolution etc. similar to PM LCDs.

Active Matrix since about 2010, mainly mobile phones

Issues: High resolution (ppi) and uniformity of TFTs.

Most professional OLED projects failed.
55” OLED TVs in Mass Production (Flat and Curved)

LG

SAMSUNG (stopped in May 2014)
OLED Module

- Emissive display technology (ambient light performance, Burn-In)
- Advantages: “unlimited” viewing angle, superfast response time
- Thin (thinner as AM LCD as no backlight required)
- Current driven (basic function similar to LEDs)
- Panel electronics and interface similar/same as for LCDs
- OLED display modules similar/same as for LCD: Direct, MUX, PM, AM
## Small Molecule Stack

![Diagram of a Small Molecule Stack]

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>150 nm</td>
</tr>
<tr>
<td>Electron Injection Layer (EIL)</td>
<td>200 nm</td>
</tr>
<tr>
<td>Electron Transport Layer (ETL)</td>
<td>35 nm</td>
</tr>
<tr>
<td>Emitting Layer (EML)</td>
<td></td>
</tr>
<tr>
<td>Hole Transport Layer (HTL)</td>
<td>50 nm</td>
</tr>
<tr>
<td>Hole Injection Layer (HIL)</td>
<td>20 nm</td>
</tr>
<tr>
<td>Anode</td>
<td>100 nm</td>
</tr>
<tr>
<td>Substrate</td>
<td></td>
</tr>
</tbody>
</table>

First idea of OLED was to have only 1 layer!
Influences on OLED Lifetime

Temperature

![Graph showing the influence of temperature on OLED lifetime.](image)

Luminance

![Graph showing the influence of luminance on OLED lifetime.](image)

25 °C: 20,000 h $\Rightarrow$ 500 h

Initial Luminance in cd/m²

Outdoor!
Examples of Direct Drive and PM - Module

Direct Drive

- From electronics point of view very similar to LCD.
- Several manufacturers of character and low res graphics OLED modules exist.
- Practical limits of PM OLEDs: < 2”, < 128 rows

Sources: Display Lab
Active Matrix Color OLED

Only few companies have mature LTPS process!
Active Matrix for High Resolution and/or Image Quality

Non-Emissive (LCD, E Ink)

- Voltage drive
- 1 TFT pP (6 Mio for HDTV)
- Aperture \( \approx 70\% \)

Self-Emissive (OLED)

- Current drive
- \( \geq 2 \) TFTs pP (uniformity)
- Aperture \( \approx 30\% \) higher for top emission (inverted stack)

AM LCD simpler than AM OLED
Active Matrix OLEDs: Driving - # of TFTs

Voltage Drive: Low Uniformity

- Power
- Storage Capacitor
- Address TFT
- Data
- Scan
- Drive TFT
- OLED

Current Drive: High Uniformity

- Power
- Address TFT
- Storage Capacitor
- Data
- Scan
- Drive TFT
- OLED
## OLED Approaches to Full Colour

<table>
<thead>
<tr>
<th>RGB Emitters</th>
<th>Colour Filters + White Emitter</th>
<th>Colour Changing Media</th>
</tr>
</thead>
<tbody>
<tr>
<td>![RGB Emitters Diagram]</td>
<td>![Colour Filters Diagram]</td>
<td>![Colour Changing Diagram]</td>
</tr>
<tr>
<td>+ Power efficient</td>
<td>+ Colour filter like LCD</td>
<td>+ Homogeneous aging of emitter</td>
</tr>
<tr>
<td>+ No patterning of emitter</td>
<td>+ Homogeneous aging</td>
<td>+ More efficient than filters</td>
</tr>
<tr>
<td>+ Synergies OLED lighting</td>
<td></td>
<td>+ No patterning of emitter</td>
</tr>
<tr>
<td>Stopped for OLED TV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Differential aging</td>
<td>- Inefficient (energy)</td>
<td>- Stable blue emitter necessary</td>
</tr>
<tr>
<td>- Patterning process difficult</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SAMSUNG**

**LG**
RGBW OLED by LG

- Basics see §LCD

- Merits:
  - Power saving
  - Larger maximum white luminance than RGB
  - “New” for marketing

- Shortcomings:
  - Higher cost
  - Lower gamut for bright images
OLEDs vs. LCDs: Color – Quantum Dots

Spectral tuning of LED backlight by QD foils:
Easy to customize as wavelength depends on QD size.
Mass production: Sony, Kindle

Source: KB, 3M
OLEDs vs. LCDs for Color AM - Displays

OLED*

- Polarizer
- Glass
- Colour filter
- OLED / LC layer
- 4 vs. 1 TFT p.P.
- Glass
- Polarizer
- Backlight

Appr. same price

LCD

- Polarizer
- Glass
- Colour filter
- OLED / LC layer
- 4 vs. 1 TFT p.P.
- Glass
- Polarizer
- Backlight

*: Top emitting, white emitter

Same price ?

Lifetime, no burn in, … !

Production process costs of OLED layers ?
# OLED vs. LCD

<table>
<thead>
<tr>
<th>OLED strengths = LCD weaknesses</th>
<th>LCD improvements (done &amp; prototype status)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viewing angle</td>
<td>IPS, VA, multi-domain (all in MP)</td>
</tr>
<tr>
<td>Response time</td>
<td>&gt; 3ms, Blue Phase LC &lt; 1 ms</td>
</tr>
<tr>
<td>Gamut</td>
<td>Quantum Dot Backlight</td>
</tr>
<tr>
<td>Thin, light</td>
<td>Backlight needed, but slim today</td>
</tr>
<tr>
<td></td>
<td>(mobile panel &lt; 1mm, 42“ : 2.6 mm)</td>
</tr>
<tr>
<td>Efficiency (image dependent)</td>
<td>Sequential color backlight, polarizer-free</td>
</tr>
</tbody>
</table>

OLED seems to be superior in some topics over LCD but LCD has cost advantage and new approaches.

OLED drawbacks: complex backplane, color, … (power for TV)
OLEDs vs. LCDs: Power Consumption

Small Size (~ 5“)

OLED: 459 mW

LCD: 648 mW

Large Size (~ 55“)

55” TV

OLED: 150 – 600 mW

LCD: > 500 mW

Power /W

OLED: 170 – 250 W

LCD: 100 – 150 W

Power consumption:
- Small size: $P_{\text{OLED}} \approx< P_{\text{LCD}}$
- Large size: $P_{\text{OLED}} \approx 2x P_{\text{LCD}}$

Advantages of OLED?
Summary “OLEDs”

- PM OLED is limited in resolution like LCD.
- AM OLED backplane is more complex than for AM LCD (cost!).
- OLED lifetime in app is most important.
- Emissive display, so negative contrast is preferred.
- Some professional PM OLEDs are available.
- AM OLEDs are in MP for mobile CE products.
## Summary: Technologies vs. Applications

<table>
<thead>
<tr>
<th>Requirement, Application</th>
<th>Suitable? Range</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viewing distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color, video</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viewing angle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feasibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trends</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Overview

Introduction

Fundamentals of Displays

Liquid Crystal Displays (LCD)

OLED, E-Paper, Touch

Summary & Outlook

Some pictures etc. are courtesy of the companies named on the picture, others from, e.g., SID, …
E-Paper Display Market Revenue Forecast

Million USD per year

Source: DISPLAYBANK, May 2009

E-book is a large but not the only market
Reflective Electro-Optic Layer Technology Overview

**Electrophoretic**
- Wet (E-INK)
- Dry
- In-plane ep
- Electro-kinetic

„Not all technologies are listed here“

**Reflective LCDs**
- Bistable TN
- Reflective TN*
- Smectic
- Guest Host
- PDLCD*
- ChLCD

**Other**
- Electro Chemical
  - Electro-Chromic*
  - Electro Deposition
- Electrowetting / -fluidic
- MEMS
- P-INK

- Many technologies, but only a few in MP, some in lab status
- Reflective TN (e.g. watches) run for years on a small battery

*: low power but not fully bistable
Why Is Color Performance of E-Paper So Poor?

100% white

Each color filter absorbs 33% (simple model)

33%

33%

Ideal reflector: 100%

Eo-layer: 30%

10%

Poor reflectivity & non-saturated color for side-by-side color (CMY stack better)

Color KINDLE: IPS LCD !!!

What is not drawn: color filter and eo-layer is passed twice. This is taken into account via %-values.
Electrophoretic Wet - Type: E-Ink

- **Principle**: Microcapsules with black and white, opposite charged particles
- **Color by RGB(W) filter**, new: “red” as third color in microcapsules

<table>
<thead>
<tr>
<th>Light State</th>
<th>Dark State</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Light State Diagram" /></td>
<td><img src="image2" alt="Dark State Diagram" /></td>
</tr>
<tr>
<td><img src="image3" alt="Electrode" /></td>
<td><img src="image4" alt="Electrode" /></td>
</tr>
</tbody>
</table>

- Most advanced technology, in mass production
- Leader in e-book readers
- Customized displays like 8-Segments are pushed
- E Ink’s e-o layer is used by many panel makers
Selected Examples: E-Ink

Positive & negative mode via software

E-Ink (left) vs. LCD (right)

Source: E Ink
Color E-Paper: E-Ink

Vivid red as third color in 2013

But not full color, only K, W, R

Source: KB
Examples of E-Ink Displays in Mass Production ≤ 2013

Sources = names

... most take only use of plastic substrate (unbreakable)!
Flexible Display Prototypes by E-Ink (2012)

E-Ink with customized mass production

Large variety of customized solutions with superior reflective performance compared to LCDs.

Source: KB
Reflective LCDs

- **Principle**: TN LC transmission is modulated by voltage
- Area color feasible, full color hardly to achieve due to low CF transmission

---

**Features:**

- In mass production since decades
- Low reflectance: ~ 20 % (monochrome)
- Flexible easy to achieve due to MUX or PM
- Segment 8 to QVGA graphics displays
- Low voltage (~ 3 V)
- Low viewing angle performance

Source: KB
Trimode TN LCD by PIXEL QI vs. E-INK

**E-Ink**: monochrome & no video, “no” power
**PIXEL QI**: monochrome (low power) or color (high power), video

### Indoor
**E-Ink**: without frontlight but readable
**PIXEL QI**: excellent & color (video) but high power (transmissive)

### Outdoor
**E-Ink**: higher white reflectivity
**PIXEL QI**: monochrome & low power (reflective)
Trimode **TN LCD by PIXEL QI**

- **Trimode** = transmissive + transflective + reflective in one display

- **Benefit**: compromises power consumption and sunlight readability

- Best color in transmissive mode

- Monochrome (incl. grey levels) for reflective mode

---

### Trimode TN LCD by PIXEL QI

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>10.1” diagonal 222.72 x 125.28 mm active area</td>
</tr>
<tr>
<td><strong>Display modes</strong></td>
<td>Transmissive, transflective, reflective</td>
</tr>
<tr>
<td>Pixel count</td>
<td>1024 x 600 color 1024 x 3 x 600 black and white</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>0.2175(h) x 0.2088 (v) mm</td>
</tr>
<tr>
<td>Pixel density</td>
<td>220 ppi</td>
</tr>
<tr>
<td>White-state reflectance</td>
<td>24%</td>
</tr>
<tr>
<td>Contrast ratio</td>
<td>&gt;100:1</td>
</tr>
<tr>
<td>Field of view</td>
<td>±45°</td>
</tr>
<tr>
<td>Color gamut</td>
<td>45% NTSC</td>
</tr>
<tr>
<td>Refresh rate</td>
<td>25 – 60 Hz</td>
</tr>
<tr>
<td>Power consumption</td>
<td>0.4W – 0.8W, reflective (30Hz, 60Hz) 1.3W – 1.7W, transflective (30 – 60) 2.2W – 2.6W transmissive (30 – 60 Hz)</td>
</tr>
<tr>
<td>Colors</td>
<td>262,144</td>
</tr>
<tr>
<td>Brightness</td>
<td>150 nits</td>
</tr>
</tbody>
</table>
Cholesteric LCDs (ChLCD)

- **Principle**: Special liquid crystal, no polarizer, PM
- Color by dedicated LC reflection

---

**Title Slide**

**Graph**

**Images**

*BMGMIS, MAGINK*

*KENT*

*FUJITSU*
### SHARP MEMORY LCDs

- Polymer Network Liquid Crystal
- Polarizer free → high reflectance

<table>
<thead>
<tr>
<th>Display Mode</th>
<th>New RLCD</th>
<th>Conventional RLCD</th>
<th>Electrophoretic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table by SHARP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Monochrome</strong></td>
<td><strong>Color</strong></td>
<td><strong>Color</strong></td>
<td><strong>Monochrome</strong></td>
</tr>
<tr>
<td>Number of Pixels</td>
<td>96 × 96</td>
<td>96 × 3 × 96</td>
<td>96 × 3 × 96</td>
</tr>
<tr>
<td>Integrated Reflectance</td>
<td>50%</td>
<td>20%</td>
<td>11%</td>
</tr>
<tr>
<td>Chromaticity (x, y)</td>
<td>(0.310, 0.333)</td>
<td>(0.310, 0.335)</td>
<td>(0.308, 0.341)</td>
</tr>
<tr>
<td>Contrast Ratio</td>
<td>10:1</td>
<td>5:1</td>
<td>15:1</td>
</tr>
<tr>
<td>Drive Voltage</td>
<td>5 V</td>
<td>5 V</td>
<td>&lt; 5 V</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>10 μW @ 1 Hz</td>
<td>25 μW @ 1 Hz</td>
<td>2 mW</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20°C to +70°C</td>
<td>-20°C to +70°C</td>
<td>-20°C to +70°C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>-30°C to +80°C</td>
<td>-30°C to +80°C</td>
<td>-30°C to +80°C</td>
</tr>
<tr>
<td>Response Time</td>
<td>100 ms</td>
<td>100 ms</td>
<td>50 ms</td>
</tr>
</tbody>
</table>
QUALCOMM MIRASOL

- **Principle**: Electro-mechanical modulation of optical cavity (no CFs needed)
- **Color by optical interference of reflected light**
- **R&D since > 10y, low volume MB already started**

Reflectivity ~ 30%
Gamut ~ 10%
**Electrochromic Displays**

- **Principle**: Color changes by charging
- **Color by liquids incl. stacking (RICOH)**

**Features:**
- Reversible color change depending on charging state
- Direct, PM and AM
- Low voltage (~ 1.2 V)
- Slow update (seconds)

**Sources = names**

AVESO  
RICOH
**Electrowetting Displays: Selected Prototypes, No MP**

- **LIQUAVISTA**
  - (PHILIPS → LIQUAVISTA → SAMSUNG → AMAZON)
  - 6.2” SVGA AM

- **ADT**
  - Bistable Indicator
  - 7”

- **GAMMA DYNAMICS**
  - ~100 DPI prototype, ~10,000 pixels

(Sources: Companies, KB)
Electrokinetic by HP: R&D

Movement of the particles

Figure 2: Zero-energy e-Skin: electrokinetic panels (made by HP) powered by photovoltaic cells

Figure 2. Schematic of HP’s Proprietary Electronic Ink.

3(a). Colored State  
3(b) Transparent State
### Typical Reflectance Values of Reflective Displays

<table>
<thead>
<tr>
<th>Display Technology</th>
<th>White State Reflectance of Monochrome Display *</th>
</tr>
</thead>
<tbody>
<tr>
<td>„White paper“</td>
<td>80 %</td>
</tr>
<tr>
<td>„News paper“</td>
<td>55 %</td>
</tr>
<tr>
<td>Reflective TN 90°</td>
<td>25 %</td>
</tr>
<tr>
<td>Ch LCD</td>
<td>40 %</td>
</tr>
<tr>
<td>E-Ink</td>
<td>40 %</td>
</tr>
<tr>
<td>Electrowetting</td>
<td>60 %</td>
</tr>
<tr>
<td>Electrochromic</td>
<td>30 %</td>
</tr>
<tr>
<td>In-plane electrophoretic</td>
<td>70 %</td>
</tr>
</tbody>
</table>

*: Typical values from various sources
Summary “E-Paper”

- Most of reflective displays are mono-chrome and low res.
- Optical performance of some reflective techniques better than reflective LCDs
- Many reflective and bistable display technologies exist.
- Some are already in MP, others in prototype phase.

- Reflective displays bottom line:
  - Sunlight readable
  - Low power
  - Plastic feasible
  - E INK competitive to reflective LCDs
E-Paper Applications Overview for Replacing Paper

High content & function

High cost

Small size

Large size

Watch

Smart phone?

E-book

Billboards

Price tags

Status control

Low cost

Low content & function
Meters … Watches basing on E-Ink’s EO-Layer

The latest designs from Phosphor Watches use displays based on E Ink technology

Lowest power & reflectivity enables new designs and functionality

Red brick wall Feasible but yet limited acceptance

Sources = names
Smart Cards

Main requirements:

- Durability
- Bendable
- No power
  (change only when in reader or limited power to change for RFID)

Amount of money if the display fails e.g. 8888.88?

Smart cards like money card would be pushed if equipped with a display!

Sources = names
Electronic shelf labels

Main requirements:

- No or lowest power
- Good readability
- Low cost
- Control system enabling integration into business process

- Replace paper tags
- Business case for wireless price updates

Sources = names
Smart Phones

Main requirements:

- Foldable or rollable
- Good readability also for color

POLYMER VISION READIUS with E-Ink small MP, quitted

Slim line mobile device with large screen but potentially low acceptance without color
Smart Phones with Secondary E-Paper Display

PopSlate iPhone-5-Hülle

Mit ein paar Monaten Verspätung soll die für das iPhone 5 ausgelegte PopSlate-Hülle an den Start gehen (Preis: 129 Dollar). Vor knapp einem Jahr hatten sich die PopSlate-Macher auf dem Crowdfunding-Portal Indiegogo mit dem nötigen Geld versorgt (knapp 220.000 Dollar), nun kommen die E-Ink-Hüllen auf den Markt und können bereits vorbestellt werden. Das Ganze funktioniert so: Die Hülle wird auf die Rückseite des iPhone 5 aufgepopped und dann via App verbunden. Anschließend können eBooks,
E-Book Readers Overview (not all listed) “monochrome”

- Jinke Electronics: Hanlin eBooks versions V8, V2, V3,
- Sony Portable Reader PRS-500, Libre EBR_1000, PRS-505
- IRex Technologies: iLiad ER-0100
- Hon Hai Precision Industries: Amazon Kindle
- ERead: STAReBOOK STK101, Bookeen
- Frontech-Fujitsu: FLEPiA A4, FLEPiA A5
- Booken: cybook
- Polymer Vision: Readius
- IRiver: Iriver e-Book
- NeoLux of South Korea: NUTT
- Ricavision: Home E-Reader
- Apple: iBook
- ...

- Larger size for newspapers (eases ‘distribution’)
- E-books compete with netbooks and smart phones
- Advantage is sunlight readability and battery life
- Is this ‘enough’ to buy an additional device? (because of limited multimedia performance)
**Signs**

**Main requirements:**

- Large(r) size
- Sunlight readability
- System integration incl. wireless data transmission and solar powered

Many advantages but potentially limited acceptance without color for some applications

Sources = names
Billboards

Main requirements:

- Large size (10 m²)
- Sunlight readability
- Mullion-free
- Excellent color reproduction
- Wide viewing angle

Large market with only LED-walls as competitor

ChLCD RGB stacks, tiled:

AEGMIS

MAGINK
## Summary: Technologies vs. Applications

<table>
<thead>
<tr>
<th>Requirement, Application</th>
<th>LCD</th>
<th>OLED</th>
<th>E-Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>… 108”</td>
<td>… 55”</td>
<td>… 10”</td>
</tr>
<tr>
<td>Power consumption</td>
<td>0</td>
<td>0</td>
<td>++</td>
</tr>
<tr>
<td>Indoor</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Outdoor</td>
<td>0</td>
<td>- -</td>
<td>++</td>
</tr>
<tr>
<td>Viewing distance</td>
<td>near</td>
<td>near</td>
<td>near</td>
</tr>
<tr>
<td>Color, video</td>
<td>++</td>
<td>++</td>
<td>- -</td>
</tr>
<tr>
<td>Viewing angle</td>
<td>0</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Feasibility</td>
<td>++</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Trends</td>
<td>L ↕</td>
<td>MP ↕</td>
<td>MP ↕</td>
</tr>
</tbody>
</table>

---

**Legend:**

- **L** (Light): Lighting
- **MP** (Manufacturing Process): Manufacturing Process
- **♭** (Feasible): Feasible
- **♯** (Not Feasible): Not Feasible
- **♭♭** (High Feasible): High Feasibility
- **♯♯** (Low Feasible): Low Feasibility
- **♭♭♭** (Feasible): Feasible
- **♯♯♯** (Not Feasible): Not Feasible
- **♭♭♭♭** (High Feasible): High Feasibility
- **♯♯♯♯** (Low Feasible): Low Feasibility

Spider Chart for Mobile Display: Monochrome, 2”

- Ambient light outdoor
- Video
- Resolution
- Color
- Lifetime
- Viewing angle
- Efficiency
- Cost

Place:
- Best / worse

Materials:
- LCD
- OLED
- EP
Spider Chart for Industrial: Indoor 20”

- Ambient light outdoor
- Resolution
- Lifetime
- Efficiency
- Cost
- Viewing angle
- Color
- Video

Place best / worse:
- LCD
- LCD
- OLED
- OLED
- EP
- EP

Video: XX

Blankenbach / www.displaylabor.de / Displays / SS 2015
Spider Chart for E-Signage: Outdoor Billboard (9 m²)

Ambient light outdoor

Video

Resolution

Color

Lifetime

Viewing angle

Efficiency

Cost

Place
best / worse

LCD

OLED

LED

EP
### What Does ‘Flexible’ Mean?

<table>
<thead>
<tr>
<th>Plastic substrate</th>
<th>Conformal (bent once)</th>
<th>Bendable</th>
<th>Rollable</th>
</tr>
</thead>
</table>

... also that?

- Stretch by 45%
- Yu, UCLA, 2011
Why Flexible Displays?

1. More robust (30% of smart phone returns show broken display)
2. Thin and light weight as plastic or thin glass is used as substrate
3. Enables new form factors and products
4. Might be cheaper to manufacture (roll-to-roll vs. batch)
Curved TV Screens

- Mass production since 2013
- Only LG and SAMSUNG
- OLED most promoted
- Curved LCD since 2014
- Benefits of curved TVs:
  - Immersive feeling
  - Ergonomic as eye-to-screen distance is constant
  - Early adopters design
- Drawbacks:
  - Uncomfortable for multi user
  - OLED was promoted as “hanging on the wall” and ultrathin
Transmissive LCDs

Standard MP AM LCDs can be curved, if

- Thin glass and
- Flex foil with silicon driver ICs

are used.

BSI: Curved

SAMSUNG: MP 2014 of 65” curved LCD TV

The backlight has to be adapted.

SID 2013

Advantages of transmissive AM LCDs are:

- Easier to manufacture in terms of TFTs as AM OLEDs
- Less requirements on barrier layers for plastic substrates than OLEDs

Challenges are backlight, viewing angle, cell gap, …
**Summary “E-Paper”**

- Most of reflective displays are mono-chrome and low res.
- Optical performance of some reflective techniques better than reflective LCDs

**Electrophoretic**

- Many reflective and bistable display technologies exist.
- Some are already in MP, others in prototype phase.

**Reflective LCDs**

- Flexible displays:
  - New designs
  - “Unbreakable”
  - E Ink competitive to reflective LCDs
  - First professional applications