Flexible and Roll-able Displays/Electronic Paper

A Brief Technology Overview

Rong-Chang (R.C.) Liang

CEO & President, Trillion Science, Mountain View, CA
Executive Advisor, BASF Electronic Materials, Germany
Advisor & Founder, SiPix Imaging, Inc., Fremont, CA
rc.liang@trillionscience.com
+1-650-934-8881 (w); +1-650-590-2407 (cell)
Toward Flexible & Rollable Displays/Electronic Paper

CRT

~ 100 years old

LCD

~ 25 years old

Flexible

Future

Technological Advancement

R.C. Liang for 08/05 SRB Meeting, Taiwan
The US DoD Flexible Display Initiative

Source: J. Pellegrino (Army Research Lab.)

R.C. Liang for 08/05 SRB Meeting, Taiwan
Recent Developments

Hitachi ePaper 07/05  400x440
Conformal, Wearable, and Rollable Displays demonstrated recently

R.C. Liang for 08/05 SRB Meeting, Taiwan
Definition of Electronic Paper

A display with the basic characteristics of printed media:

- Compatibility with flexible substrates
- No power required to maintain an image (bistability)
- Wide viewing angle
- Insensitive to ambient lighting and various humidity/temperature conditions.

And preferably,

- Low manufacturing cost
- Low Operating cost
- Format Flexibility
- Easy Converting
Paper vs. Displays

Dot density required in printed media to match the resolution of a 200 ppi display with 24-bit color (IBM)

<table>
<thead>
<tr>
<th>Consideration/Condition</th>
<th>“Equivalent” Print</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nature images with binary halftone</td>
<td>~200 lpi</td>
</tr>
<tr>
<td>Smallest reliable spot, minimum linewidth</td>
<td>~133 lpi screen; ~600 dpi</td>
</tr>
<tr>
<td>Smallest area with full grey scale (4 bit dots)</td>
<td>~800 dpi</td>
</tr>
<tr>
<td>Equivalent bit areal density</td>
<td>~ 690 dpi</td>
</tr>
</tbody>
</table>

- 400 dpi typical 100 ppi of current electronic displays.
- Inexpensive 2400 dpi printers are now available for home and office uses.

As of today, printed Media is still of much higher resolution and low cost

R.C. Liang for 08/05 SRB Meeting, Taiwan
Technical Challenges

General issues:
• Barrier properties, surface roughness and temperature resistance of substrate
• Mismatch of thermal expansion coefficients
• Flexure resistance of the electrodes
• Flexible Battery
For LCDs:
• Cell gap control during bending/rolling
• Viewing angle
• Thickness & Light Management

R.C. Liang for 08/05 SRB Meeting, Taiwan
Contrast During Bending/Rolling

- Changes of cell gap during bending may be controlled to about 50 nm by using spacers in fixed positions that are aligned with the ITO lines.

- Fixing cell gap by microcup structure is a potential solution for roll-to-roll manufacturing of flexible displays with or without polarizers.
Barrier Properties

Gas barrier performance and development target

- For packaging
- PET film
- Dry + Wet Hybrid process
- Vapor deposition method (CVD/PVD)
- For LCD
- For OLED
- MOCON method over limit

Ratio of oxygen transmission (cc/m²/day)

R.C. Liang for 08/05 SRB Meeting,
Taiwan
Polymeric substrate & barrier coatings

- Multilayer (inorganic / organic) coated Polymer
- Hard coat film plus 4 to 8 barrier layers
- Or: Single layer inorganic barrier films
- polymer / AlO_x multilayer compensates coating defects
- permeation rates below the detection limits of commercial equipment

- Vitex System Multilayer AlOx/Acrylic system
- Pioneer: SiON passivation layer
Light/Power/Thickness Management

120-250 um
90%
50-100 um
25%
1000-2000 um
85%
50-100 um
45%
130 um

155 um x2
50%
2000-3000 um

TAC
Stretched PVA
TAC
Stretched A plate (or WV film)
LCD-cell
Stretched & coated C plate (or WV film)
TAC
Stretched PVA
TAC

Polarizer
Compensation film-1
Color Filter
TFT
Compensation film-2
Polarizer

DBEF (recycle polarized light)

Diffuser
BEF (collect light)

Lamp
Light Guide
Reflector

B.C. Liang for 08/05 SRB Meeting
Taiwan
Polarizers by Coating

Optiva

Polarizer

(not to scale)

Next move?
- Improve orientation
- Improve environmental stability (w/o protective films)
- In-cell coating

<table>
<thead>
<tr>
<th>Uniformity of Transmittance (T ≥ 39%)</th>
<th>Mayer Rod Coating</th>
<th>Slot Die Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR&gt;25</td>
<td>&lt; +/- 3%</td>
<td>&lt; +/- 1%</td>
</tr>
<tr>
<td>Contrast Ratio (T ≥ 39%)</td>
<td>CR&gt;25</td>
<td>CR&gt;34</td>
</tr>
<tr>
<td>Polarizing Efficiency (T≥39%)</td>
<td>E≥96%</td>
<td>E≥97.5%</td>
</tr>
<tr>
<td>Uniformity of Polarization</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Off-angle coating</td>
<td>Done</td>
<td>Need Additional development</td>
</tr>
<tr>
<td>Cost of equipment</td>
<td>Cheaper (Simple coating mechanism)</td>
<td>Expensive (High precision required)</td>
</tr>
<tr>
<td>Target product</td>
<td>TN/STN LCDs</td>
<td>C-STN/TFT LCDs</td>
</tr>
</tbody>
</table>
3M DBEF Stacks

Structure of a brightness-enhancing film
Source: 3M's DBEF-D document

Approximately 440 μm

DBEF Layer

Diffusion sheets
Alternative Brightness Enhancement Films

Nitto, Philips, Reveo, BASF, ROLIC, Charmica
Polaroid, Honeywell, Brown Univ.

1. Stretching

Paliocolor LC242

2. UV curing

Figure 7. The SEM picture of elliptical cured liquid crystal particles obtained from stretched POC films.

Next move? Direct integration/coating on the back light unit.
Compensation Films

For MVA mode

Next Move??
1. Coated compensation films on polarizer
2. Coated compensation films in LCD cell
Active Matrix TFT Choices for Flexible Substrates

1. Transfer high performance silicon devices onto plastic substrates
   • Very low temperature processing
   • Not compatible with low-cost objectives

2. Amorphous Silicon (a-Si) TFT:
   • Work horse of the well established AM LCD Industry
   • Low Mobility ~ 1 cm²/V.Sec
   • Typical deposition temperature ~ 300°C
   • Low temperature (~ 150°C) a-Si TFT process feasible

3. Low-Temperature Poly-Silicon (LTPS) TFT:
   • High TFT Mobility ~ 100 Cm²/V.Sec.
   • Both NMOS and PMOS TFTs available
   • Typical process temperature ~ 450 to 600°C
   • Ultra low temperature (~ 100°C) Poly-Si (ULTPS) process is being developed

4. Organic TFTs
   • Mobility ~ 3 cm²/V.Sec
   • Very low temperature processing (~ 100°C)
   • Technology is being developed
ECD Roll-to-Roll Flexible Solar Cell

Akzo Nobel Roll-to-Roll Flexible Solar Cell

Temporary Al foil

Plastic film
Flexible Display/Electronic Paper Technologies

1. Light Emitting Diode technologies:
   - OLED/PLED/PHOLED, CCM, ECL, and their hybrids

2. Reflective, Bistable Display technologies
   - cholesteric LC, electrophoretic, gyroelectric, electrochromic, electrodeposition, conducting particles, and liquid powder.
Recent Flexible PM OLEDs/PLEDs

Pioneer in SID’03.
3”, 8 bits grey scale 160xRGBx120
SiON passivation layers

Pioneer in IDW’03.

NHK in IDW’03.
3.6”, 64xRGBx64

R.C. Liang for 08/05 SRB Meeting,
Taiwan
PHOLED (Universal Display)

Thin Film Encapsulated Display on Plastic

Display under compression  Display under tension

In action:

- 64x64 passive matrix
- small molecule phosphorescent
- 80 dpi resolution
- video rate
- 178 µm barrier coated PET
- 5-7 µm thick encapsulant

In collaboration with Vitex Systems

R.C. Liang for 08/05 SRB Meeting,
Taiwan
Printed PLED by DNP

OLEDs in Point of Purchase Displays

R.C. Liang for 08/05 SRB Meeting, Taiwan
CCM by Univ. of Cinn.

- Single Inorganic Material High Efficiency LED - (Al,Ga,In)N
- Organic Material - "Passive" layer:
  - Very high luminescence efficiency
  - No current flow ⇐ No contacts ⇐ Simple process
  - No current-related degradation
- Single organic layer/LED
- 3-color integration
  - Vacuum evaporation - shadow mask in single pumpdown
  - Ink jet printing, Screen printing

Flexible Display - Key Ingredients

Flexible Plastic Waveguide
Light Wave Optical Coupling (LWC)

Optical Pump (Inorganic LED)
Organic Color Conversion Material (CCM)

Microfluidics
Electrowetting (EW) Switch

R.C. Liang for 08/05 SRB Meeting,
Taiwan
Electrowetting (by Philips, Cornell Univ, RPI)

Fig. 5: Shown is a possible subpixel layout for reflective or transmissive CMY ELs. One subpixel consisting of two differently colored oil layers can produce several colors. The center subpixel, for example, which has cyan and magenta oil layers and a solid-yellow filter, can produce black, green, red, and yellow, depending upon which of the two oil films is displaced.
Reflective Displays
1. Cholesteric LC

Planar (Bragg Reflecting)
Homeotropic (transparent)
Focal Conic Weakly Scattering

Flexible Full-Color VGA 6.3 inch Cholesteric Reflective Display on Plastic Substrates

Source: Bill Doane (Kent Displays)
2. Rotating Balls (Gyricon Media)

3. ElectroChromic Displays
   (N’Tera Ltd., Ireland and Uppsala Univ, Sweden)
4. Iridigm Digital Paper
   (A MEMS Based Display)

5. Conducting Particles (Citala)
6. Electrodeposition Displays (Sony)

7. BridgeStone Liquid Powder
8. E-ink EPDs

Cross-Section of Electronic-Ink Microcapsules

Top Transparent Electrode

Positively charged white pigment chips

Clear Fluid

Negatively charged black pigment chips

Subcapsule addressing enables high-resolution display capability

Bottom Electrode

Light State

Dark State

NOTE: Copyright E Ink Corporation, 2002. Image not drawn to scale - for illustration purposes only.

R.C. Liang for 08/05 SRB Meeting, Taiwan
SiPix Microcup® EPDs

The world’s first roll-to-roll line in production
Each step must be accomplished within seconds

R.C. Liang for 08/05 SRB Meeting, Taiwan
SiPix Microcup® Electronic Paper
Rollable Active Matrix EPD

Back plane supplied by Philips

Thickness: ~ 125 µm
Bending radius < 1cm !!!!
Rollable Microcup® EPDs

Integrated by Polymer Vision, Philip

R.C. Liang for 08/05 SRB Meeting, Taiwan
Conclusions

- Technical challenges exist in barrier, substrate, cell gap control, flexure resistance of electrodes, viewing angle, light and thickness management, and manufacturing processes.

- As of today, Electrophoretic (EPD) is one of the most encouraging for Rollable Displays/Electronic Paper applications for their
  - Reflective, wide viewing angle
  - Bistability
  - Low operation voltage & negligible current demand
  - Ultra thin, ultra light weight
  - Compatibility with roll-to-roll manufacturing & converting processes
  - Format flexibility
  - Both PM and AM driving
  - Full color with high color saturation (to be demonstrated)
  - Physicomechanical & environmental durability (Microcup® EPDs)