Field-Emission Flat Panel Display Manufacturing

Daniel M. Dobkin
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Outline

- Introduction to Field Emission displays
  - terminology
  - design choices
  - performance specifications
- Overview of tube components
- Cathode fabrication
- Faceplate fabrication
- Tube assembly
Technology Driving Forces

- **Semiconductors:**
  - Feature size: smaller is better
  - Chip size: smaller is better
  - Cost: driven by feature/chip size and complexity

- **Displays:**
  - Feature size: doesn’t matter much (limited by human vision)
  - Display size: bigger is better
  - Cost: driven by number of display pixels
### Display Terminology

*(horizontal pixels x vertical pixels)*

<table>
<thead>
<tr>
<th>Display Type</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWS</td>
<td>2000x2000</td>
</tr>
<tr>
<td>UXGA</td>
<td>1600x1200</td>
</tr>
<tr>
<td>SXGA</td>
<td>1280x1024</td>
</tr>
<tr>
<td>XGA</td>
<td>1024x768</td>
</tr>
<tr>
<td>SVG A</td>
<td>800x600</td>
</tr>
<tr>
<td>VGA</td>
<td>640x480</td>
</tr>
<tr>
<td>QVGA</td>
<td>320x240</td>
</tr>
</tbody>
</table>

**Processed panel sizes:**

- **Generation 1:** 300 x 400 mm  late 80’s
- **Generation 2:** 400 x 500 mm  early 90’s
- **Generation 3:** 550 x 650 mm  late 90’s
- **Today:** Generation 7-8 (2 meters square)
Information Content of a Display

Number of Pixels

10,000,000

1,000,000

100,000

10,000

Display Diagonal (inch)

1

3

10

30

1280x800

640x480

COMPUTER MONITOR

Television

SOURCE: "Liquid Crystal Flat Panel Displays" W. O'Mara used by permission of the author
Start with a CRT and squeeze...

Elements of a CRT:
- emit electrons
- form and direct beam
- excite phosphor

CONVENTIONAL
- electron gun
- hot filament
- electron beam
- deflection yoke
- phosphor
- aluminiized phosphor
- glow

FIELD EMISSION FPD
- emitter
- column
- row
- focus structure
- electrons
- glow
Field Emission Flat Panel Display (matrix)

- Matched arrays of emitters and phosphors...

Simplified monochrome FED schematic
Emitter Detail: Spindt cathodes

- Cone cathodes formed by masked evaporation

CATHODE PLATE
カソードプレート

column
row

row metal

electron emission
gate
moly cone
insulator

抵抗

モリブデン円錐状放電電極

列電極

抵抗

電子放出

ゲート電極

絶縁体
**Faceplate Detail: Color phosphors**

- Screen-printed phosphor powders:
  - phosphor particles
  - aluminum reflector layer
  - polyimide (black matrix)
  - glass faceplate
  - color pixel
  - sub-pixels
  - R, G, B
Highly nonlinear emission-voltage relationship =>
- cathodes can be used as active devices
- active matrix not required
Design Choices

- **Faceplate voltage:**
  - high voltage = conventional phosphors, high brightness, low coulombic aging BUT high voltage supplies
  - low voltage = special phosphors, aging, but simple power supply

- **Cone-gate spacing:**
  - tight spacing = low control voltages, simple driver circuits, but hard to build
  - loose spacing = high control voltages but easy fabrication
**FED Approaches**

**High-voltage FED**
- Conventional long-life CRT phosphors can be used
- V ≈ 5 KV
- Tall, thin support walls needed
- Focus structures required to maintain color separation

**Low-voltage FED**
- Special phosphors needed for long life
- V < 1 KV
- Spacers are easy, focusing not necessary
- Small cathode-faceplate spacing

*Examples:
- Candescent ThinCRT Motorola
- Samsung Pixtech
- Roughly to scale
- Fabrication challenges:
  - spacer walls
  - focus structures
  - materials for faceplate / matrix
Display Characterization: Photometry

Displays have their own terminology...

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminous Flux</td>
<td>Light energy (corrected for response of the eye)</td>
<td>lumen</td>
</tr>
<tr>
<td>Intensity</td>
<td>Luminous flux per unit solid angle</td>
<td>candela = lumen/steradian</td>
</tr>
<tr>
<td>Luminance</td>
<td>Intensity per unit area of emitter</td>
<td>candela/m² (NIT)</td>
</tr>
<tr>
<td>Illuminance</td>
<td>Luminous flux per unit area of receiver</td>
<td>lux = lumen/m²</td>
</tr>
</tbody>
</table>

![Luminance photometer diagram](image)

Luminance = \( \frac{L}{\sigma A} \)

1 watt @ 550 nm = 680 lumens
### Display characterization: typical specs

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>power consumption</td>
<td>Voltage * current for image with 67% of full-white</td>
<td>0.7 W @ 70 cd/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8 W @ 100 cd/m²</td>
</tr>
<tr>
<td>brightness (luminance)</td>
<td>light/area emitted per steradian of solid angle</td>
<td>100 cd/m²</td>
</tr>
<tr>
<td>brightness uniformity</td>
<td>variation in brightness at various length scales</td>
<td>1% for .3 to 30 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3% for 100 mm</td>
</tr>
<tr>
<td>video response</td>
<td>time to turn off; determined by phosphor choice</td>
<td>&lt; 5 msec to 10% brightness</td>
</tr>
<tr>
<td>viewing angle</td>
<td>measure any parameter (e.g. brightness) vs. angle in plane</td>
<td>170 degrees for emission display</td>
</tr>
<tr>
<td>contrast ratio</td>
<td>brightness will all pixels ‘on’ vs. ‘off’</td>
<td>300:1 in dark ambient; &gt;9:1 in brightly lit ambient</td>
</tr>
<tr>
<td>defects</td>
<td>missing or dark sub-pixels, rows, or columns</td>
<td>none for usable display (difficult!)</td>
</tr>
<tr>
<td>lifetime</td>
<td>on-time to 50% luminance degradation</td>
<td>20,000 hours (target)</td>
</tr>
</tbody>
</table>
Human eye does NOT measure spectra directly
- retina contains three types of cone cells, peak sensitivity at 450, 550, 600 nm
- brain senses color by relative excitation
- any visible ‘color’ (power spectral distribution) can be reduced to 3 ‘color coordinates’

To quantify:
- define matching functions
- decompose spectrum into sum of matching functions
- obtain chromaticity coordinates
**Step 1: Find matching functions**

- Define “primaries”
  - e.g. Red = 700 nm  Green = 546 nm  Blue = 436 nm (CIE 1931)
- For monochromatic light, each $\lambda$ from $\approx$ 400-700 nm
  - Vary proportions of R/G/B until visual sensation IDENTICAL for monochromatic light and mixture of primaries
  - Record intensity of each primary vs. wavelength

![Diagram showing match single-frequency light by appropriate sum of "primary" colors](chart.png)
Result: color matching functions

- Amount of each primary needed to match any given monochromatic illumination
  
  - Note: model is imperfect; "virtual" primaries required to give positive matching function for all wavelengths as shown here.

Example:
600 nm. light ≈ 1*(red) + 0.6*(green) + 0*(blue)

References:
Johan Lamnens Ph.D. Thesis
SUNY Buffalo, 1994
www.cs.buffalo.edu/pub/
colornaming/diss
Color: Why the World Isn't Grey,
Hazel Rossotti, Princeton 1983
**Step 2: Decompose arbitrary spectrum**

- Treat arbitrary light as sum of monochromatic segments
- Emulate each monochromatic segment by appropriate combination of primaries

match arbitrary color by decomposing into spectral lines, building each one from R/G/B primaries

0.3(R)+1.3(G) + 0.1(B)

\[
\begin{align*}
X &= \int E(\lambda) \ \bar{x}(\lambda) \ d\lambda \\
Y &= \int E(\lambda) \ \bar{y}(\lambda) \ d\lambda \\
Z &= \int E(\lambda) \ \bar{z}(\lambda) \ d\lambda
\end{align*}
\]

Weighted sum of primaries for all colors = "Tristimulus value" : brightness of primaries to emulate original spectrum

- Normalize to unit brightness (i.e. capture only color information): "Chromaticity coordinates"
  - Note requirement of unit brightness implies x+y+z = 1: only two coordinates actually required, can display on 2D graph

\[
\begin{align*}
x &= \frac{X}{X + Y + Z} \\
y &= \frac{Y}{X + Y + Z} \\
z &= \frac{Z}{X + Y + Z}
\end{align*}
\]
Result: Chromaticity Diagram

Linear model: visual sensation of adding two colors lies on line between them on the chart

all visible colors are made of monochromatic colors = inside envelope

chromaticity coordinates of monochromatic colors form envelope

blackbody at 6000-9000K = "white"

for any given set of "primaries", range of accessible colors = interior of triangle

"line of purples"

since $x + y + z = 1$ only need 2 axes (=brightness arbitrary)
FED Fabrication: Panels and Displays

- Panel: (340 x 320 mm)
- FED display: 5.3" [134 mm] diagonal
- Display column
- Display row
Cross-Section of Display

- faceplate
- sub-pixel column guard
- support wall
- focus waffle
- sweet spot
- cathode plate

Cross-section of interior of display, looking along a row; approximately to scale (surfaces of faceplate/cathode not shown)

1.25 mm (1250 µm)
Cathode Overview

- **Function**: supply controlled electron packets to sub-pixels on the faceplate
- **Emission spot**: several thousand individual emitters per sub-pixel
- **Focus waffle**: prevent mixing between neighboring sub-pixels
- **Resistive ballasting for emitters**: improves uniformity of emission current over the emitters in an emission spot
**Faceplate overview**

- **Function:** glow in response to electron impact
- **Phosphor:** aluminized to control charging, reduce ambient reflection
- **Pixel:** columns of red/green/blue sub-pixels form rows of square pixels
- **Column / row guard bands form ‘black matrix’, about 50 μm high**
  - separates pixels
  - suppresses reflection of ambient light
Assembly Overview

- **Alignment:**
  - assemble cathode and faceplate together so that each emission spot aligns with sub-pixel

- **Spacer walls:**
  - ceramic, 1.2 mm high, 50 microns wide (!)

- **Frit:**
  - fusible Pb-based glass bonds cathode to faceplate

- **Getter:**
  - attached smaller chamber with flash getter to improve vacuum

- **Driver electronics:**
  - attached to periphery

- **Pump down:**
  - $10^{-7}$ Torr ($10^{-5}$ Pa) needed for reasonable lifetime
Assembled Display

column driver ICs (on Kapton tape)

cathode  カソードプレート

spacer walls

getter chamber

faceplate

前面ガラス

frit

row driver ICs (on Kapton tape)
Cathode Parts: Substrate

- Borosilicate glass, e.g. Schott D263
  - identical for cathode and faceplate
  - coefficient of thermal expansion (7 ppm/K) matches that of frit material
  - edges of panel rounded to avoid chips; one corner notched for orientation
  - density at 548°C prior to processing to avoid shrinkage
    - note $T_g=557 \, ^\circ C$; support panel to avoid sagging
    - after densification, expect < 7 $\mu$m shrinkage across panel (vs. emission spot size of about 35 $\mu$m)
  - monitor wetting angle to check for contamination before / after densification
  - particle control critical to prevent row/column shorts

Clean glass surface: hydrophilic

$\Phi$ small

water droplet

glass substrate

Contaminated surface: hydrophobic

$\Phi$ large

water droplet

glass substrate
**Cathode: Emitter and Focussing**

- Individual emitters emit electrons over wide angle
  - color mixing will result for high-voltage FED due to large cathode-faceplate spacing

- Solution: provide focus structure for emission spot
  - thick polyimide + metallization
Cathode Processing: Row metal

Row metal 1:
- sputter & pattern 150 nm Al
  - ensure sloped edge to allow crossovers by column metal

Row metal 2:
- sputter & pattern 120 nm Ta
  - hillock prevention, protects Al from corrosive chemicals
Cathode processing: Resistor Layer

Resistor limits rapid turn-on of cones

Choice of resistor value is a tradeoff between current uniformity and operating voltage
**Cathode processing: Resistor layer fab**

- 300 nm SiC layer has well-controlled resistivity of about 300,000 Ω-cm
  - series resistance of several GΩ per emitter => about 2 V drop
  - Fused SiC target by CVD, very expensive
  - Material spalls from shields, high particle count

- CVD insulator layer
  - row-column metal insulator
  - gate - emitter insulator
  - 150 nm APCVD (conveyorized belt furnace)
  - shorts represent important yield limiter

- 50 nm ‘cermet’ (40% Cr in SiO<sub>2</sub>)
  - used as selective etch mask later
Cathode Processing: Column metal

- 150 nm sputtered Ni; wet pattern, sloped edges for contact to gate metal
- Hole in row metal defines emitter region
Cathode Processing: Gate metal

- 40 nm Cr masks cavities for discrete emitters

- Pattern and etch
Cathode processing: emitter formation

- Spindt cathode (evaporated Mo)
- cover with APCVD SiO$_2$ afterwards to protect tips during processing

- etch Mo and Cr away except in emitter regions
- etch dielectric to expose row metal
Cathode processing: focus waffle

- Thick (70 µm) photosensitive polyimide, applied while Cr/Mo remains over emitter tips
- Cure 400º C 8 hours in nitrogen after develop

Cross-section A-A

Focus waffle
Emitters
Button
Column
Row
Cathode processing: selective Mo etch

- Challenge: remove Mo ‘button’ protecting emitters without attacking emitters

- Approach: use electrochemical etch since ‘button’ is electrically isolated from emitters
Cathode Process: Focus Waffle Metal

- Use angle evaporation to deposit metal on walls without contaminating emitter region.

- Ready for bakeout, electrical test, emission uniformity test.
**Faceplate**

- Convert electrons into proper colors
  - thick continuous phosphor films for good color saturation
- Minimize reflection of ambient light
- Minimize scattering of electrons
- Anchor support walls
- Form front of tube

High-T cure + supercritical extraction to control polyimide outgassing under electron bombardment

![Diagram of Faceplate](image)
Phosphors

- Typically powders doped with heavy elements
- Typically 2 layers (about 5 μm) thick
- Applied by screen printing from slurry
  - photosensitive slurry + masking to place in correct wells
- Example: ‘P22’ set:
  - RED: yttrium oxysulfide:Eu, medium efficiency
  - GREEN: ZnS:Cu/Au/Al, good efficiency
  - BLUE: ZnS:Ag/Cl, poor efficiency
**Faceplate Assembly Provisions**

- Space for “frit” to form tube wall
- HV metal also provides connection to support walls for visibility adjustment
- Fiducial marks for alignment
- Tack zones for assembly fixturing
- Space for getter (thin tube)
- HV metal allows control of anode voltage
- Support wall (6)
- Phosphor well (sub-pixel)
- Polymide (column guard band)

**ACTIVE AREA**
**Faceplate: Aluminize**

1: Apply lacquer

- Roughened polyimide / SiO₂
- Lacquer
- Glass faceplate
- Phosphor

2: Deposit reflector aluminum

- Thin Al reflector layer

3: Decompose and remove lacquer (380°C)

- Contact points
- Glass faceplate

- Minimize emission into tube (lost light)
- Sacrificial lacquer process dates back to 1939
1] align frame, faceplate, weight on block (manually)
2] place in oven, purge in N2, slow heat to 300-400°C
3] melt locally with scanned laser
4] slow cooldown

frit frame
(lead oxide -glass mixture, melting point ≈ 400°C)
Support Walls

- Charging of support walls due to secondary electron emission deflects electrons, must be controlled
  - coatings, resistivity control
- Mixture of alumina (strength), titania (conductivity), chrome oxide (secondary emission control)
Assembly: Support Walls

- Wall electrode held by vacuum
- End effector support wall
- Polyimide adhesive
- Column guard bands hold walls straight
- Faceplate
- Laser cure adhesive $\approx 300^\circ C$

- Also add ‘tack posts’ to hold cathode in place
Wall crushes wirebond upon assembly to ensure contact between wall electrode and "common" line.
Assembly: Cathode Mount

- part of frit left unsealed to allow pumpout

melt frit locally with laser beam
Assembly: Driver IC’s

Kapton tape with driver IC

anisotropic conductive adhesive

faceplate

- and to final test (!)
Conclusions

- Complex display process of which electron emitter is only the first step
- Emitter tolerance of contamination is a critical issue (but not the only one):
  - contamination and damage in processing
  - outgassing during life of display
  - degradation in emission may limit display life
  - Carbon nanotubes should help
- Other problems are catastrophic failure (arching?) and internal charging:
  - “Nearly all panel failures were of the catastrophic variety, even with...careful derating of the accelerating voltage. I consider the high voltage holdoff, combined with the need for structures that remain absolutely neutrally charged despite variable electron flux, to be the killer problem(s) for this technology.” --Stephanie Oberg, formerly with Candescent
  - These problems are not addressed by substitution of carbon nanotubes for Spindt cathodes
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