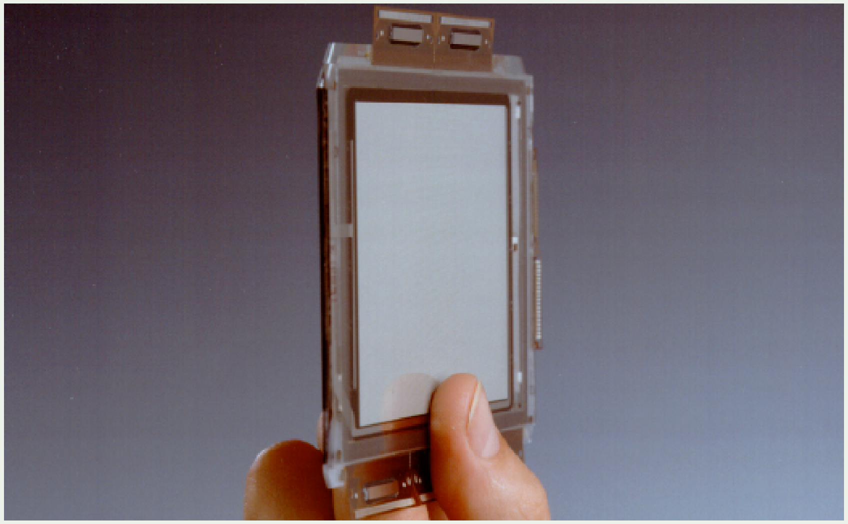
Field-Emission Flat Panel Display Manufacturing



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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

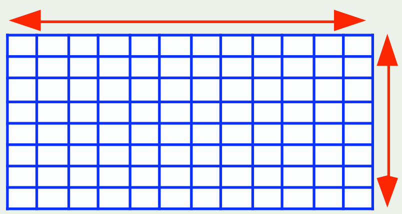
Technology Driving Forces

- 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)

EWS	2000x2000
UXGA	1600x1200
SXGA	1280x1024
XGA	1024x768
SVGA	800x600
VGA	640x480
QVGA	320x240



12 x 8 display

Processed panel sizes:

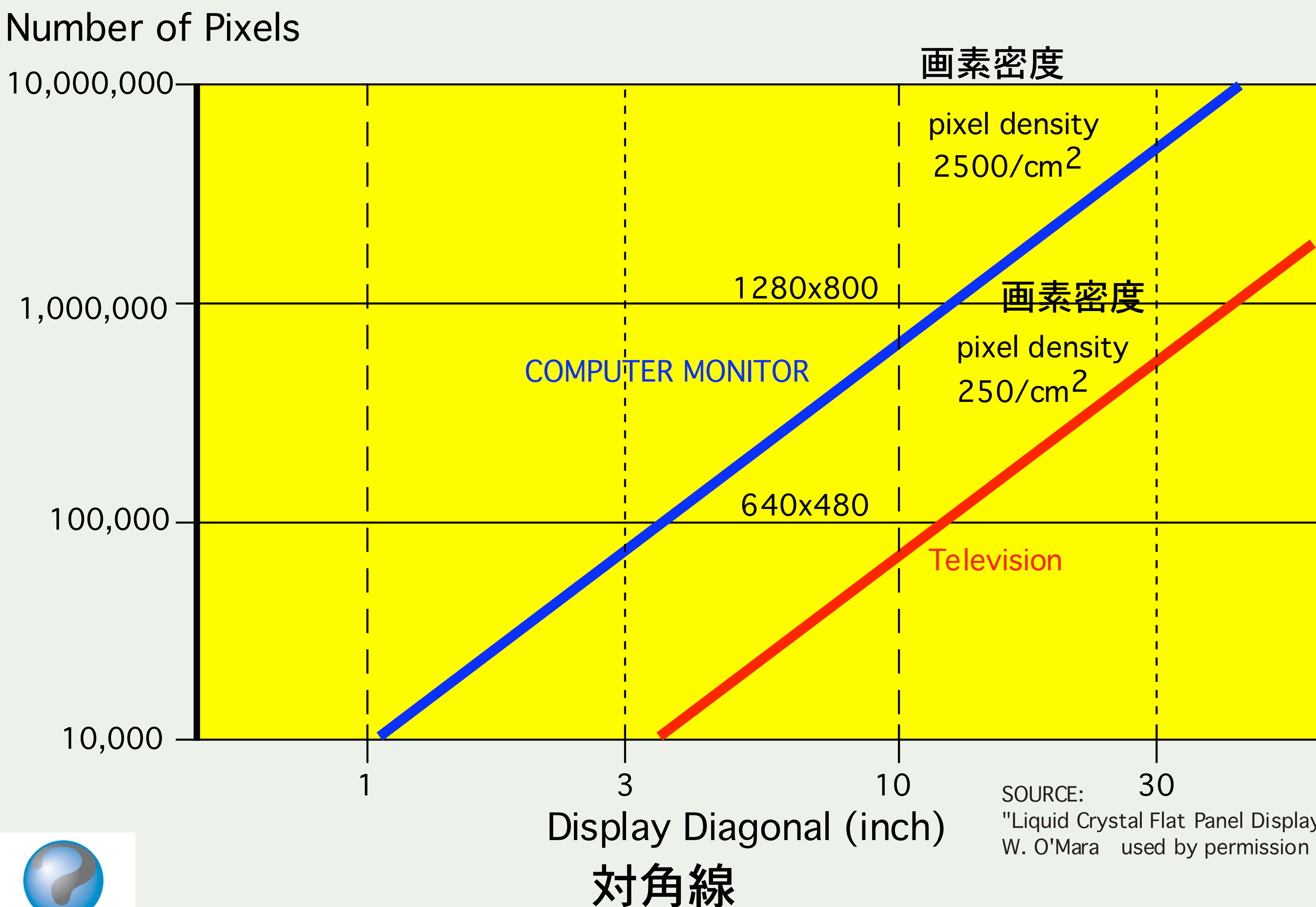
Generation 1: 300 x 400 mm late 80's

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



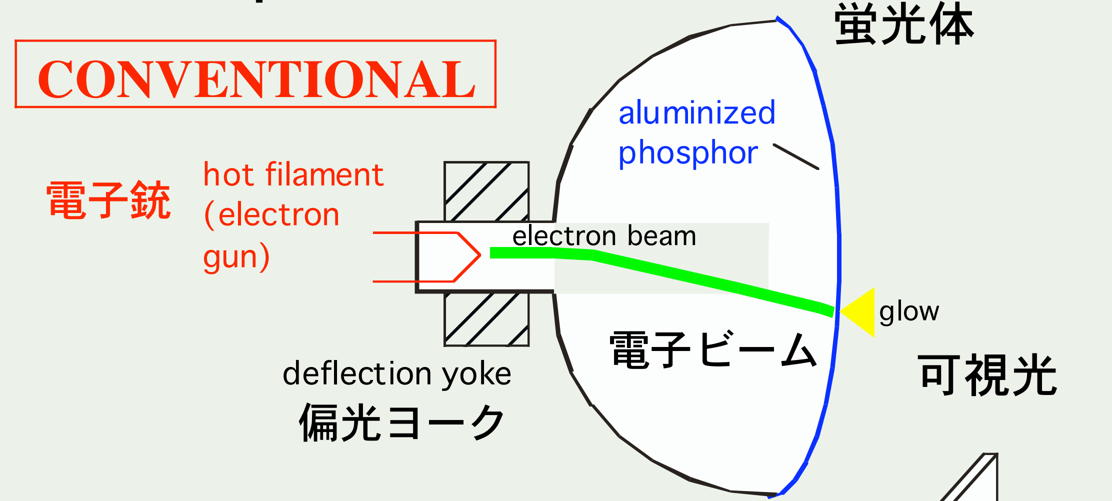
SOURCE:
"Liquid Crystal Flat Panel Displays"
W. O'Mara used by permission of the author

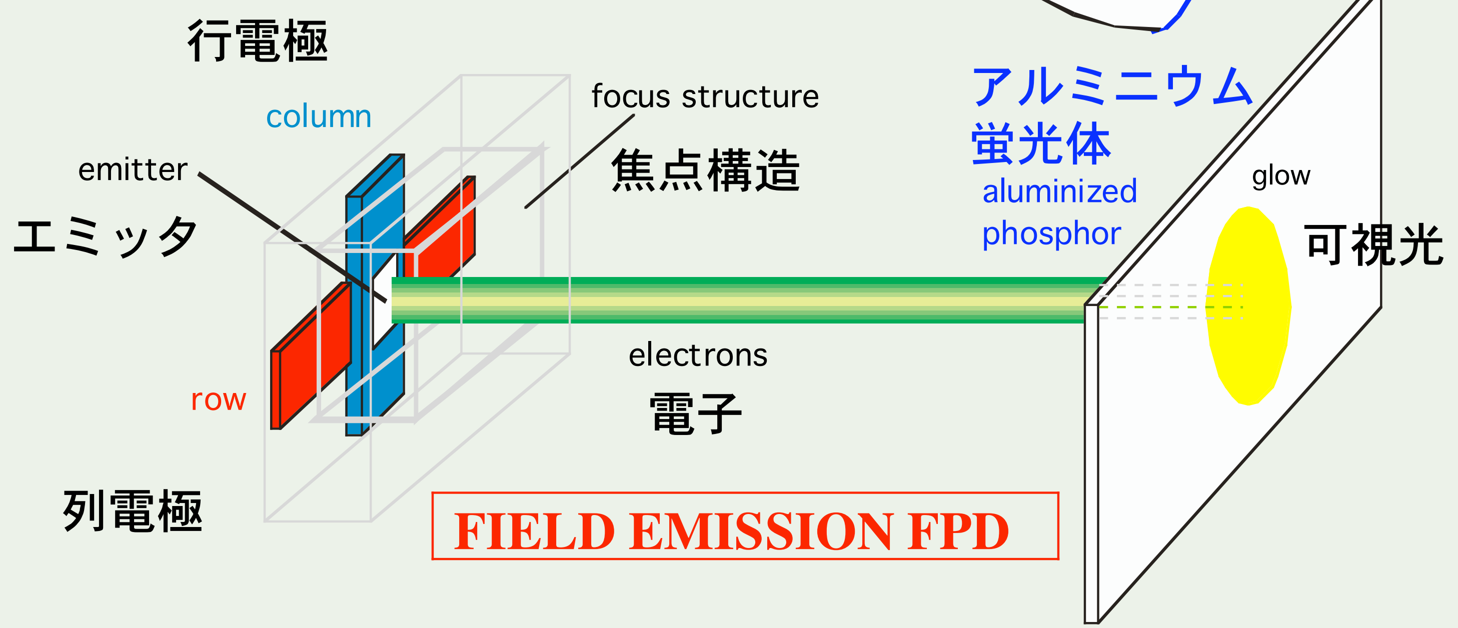
Field Emission Flat Panel Display (pixel)

- Start with a CRT and squeeze...

Elements of a CRT:

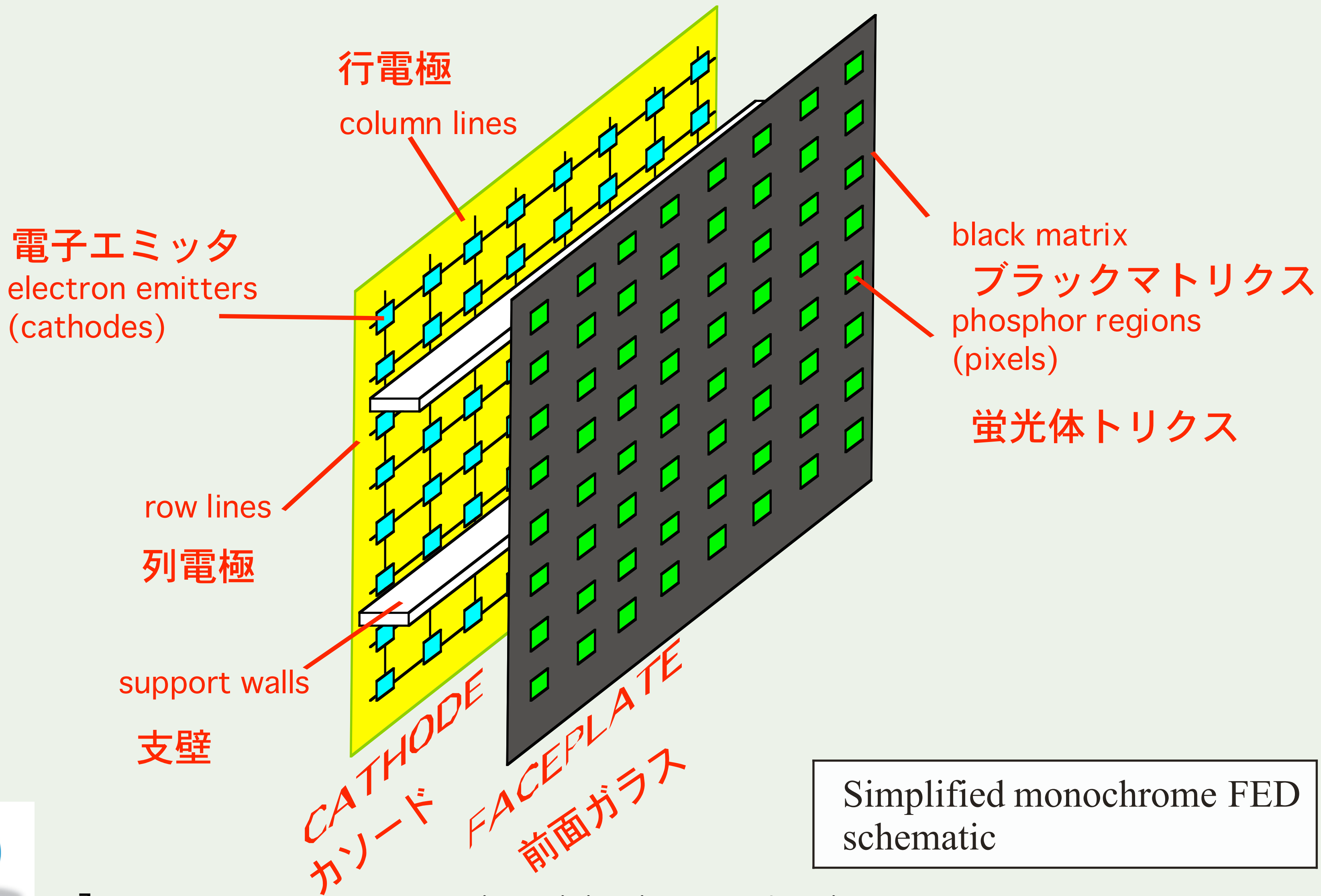
- emit electrons
- form and direct beam
- excite phosphor





Field Emission Flat Panel Display (matrix)

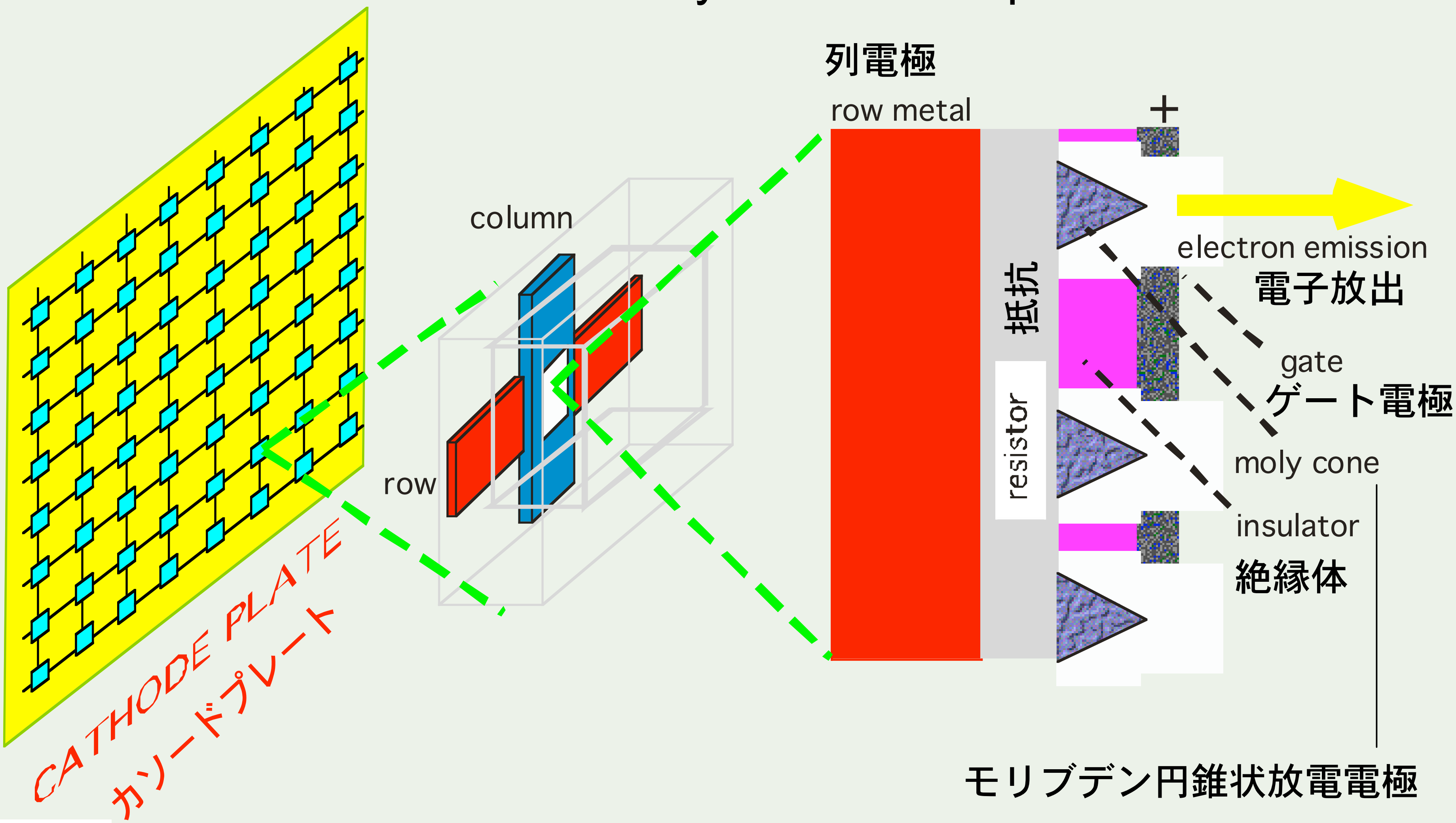
- Matched arrays of emitters and phosphors...



Simplified monochrome FED schematic

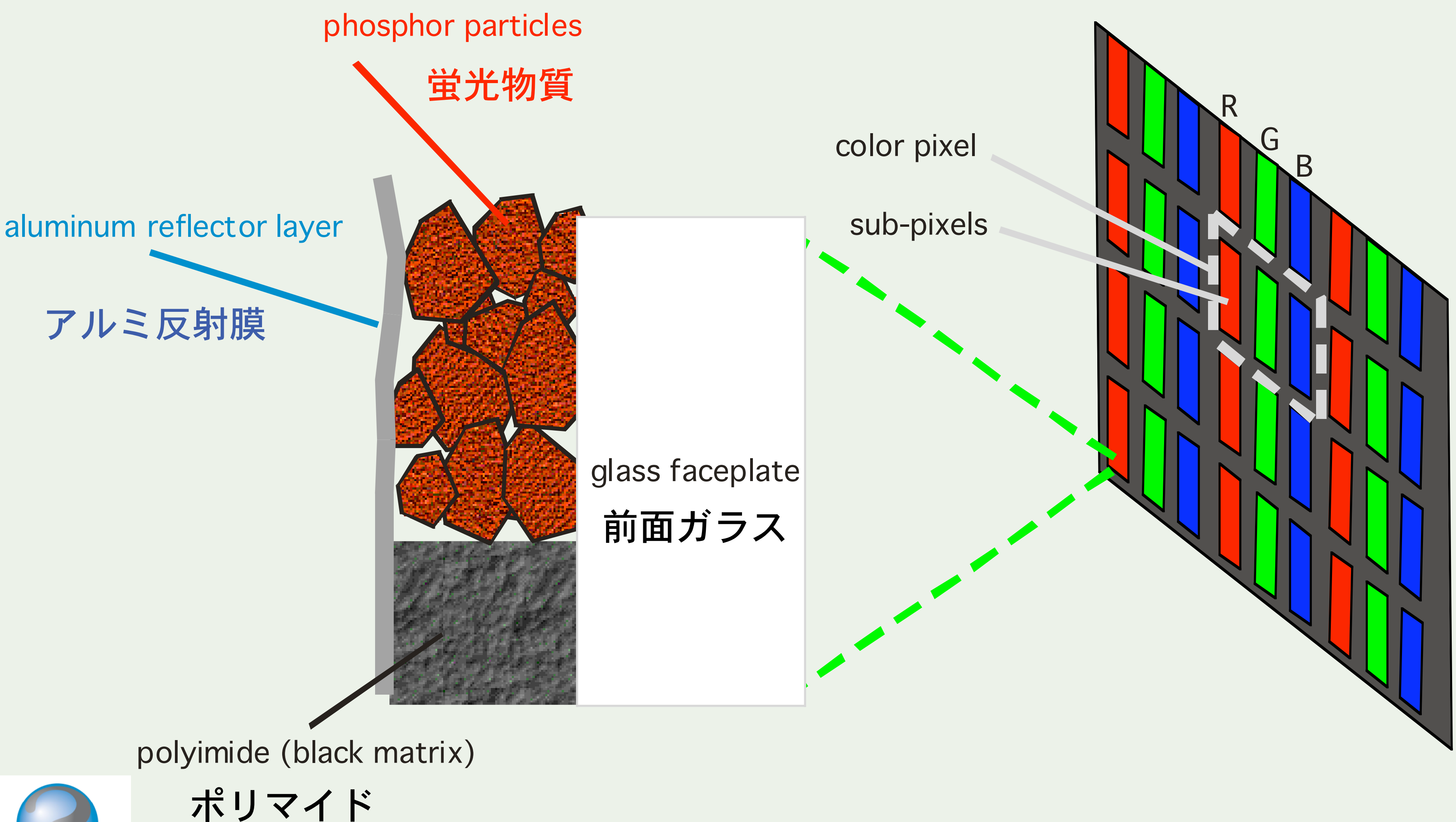
Emitter Detail: Spindt cathodes

- Cone cathodes formed by masked evaporation



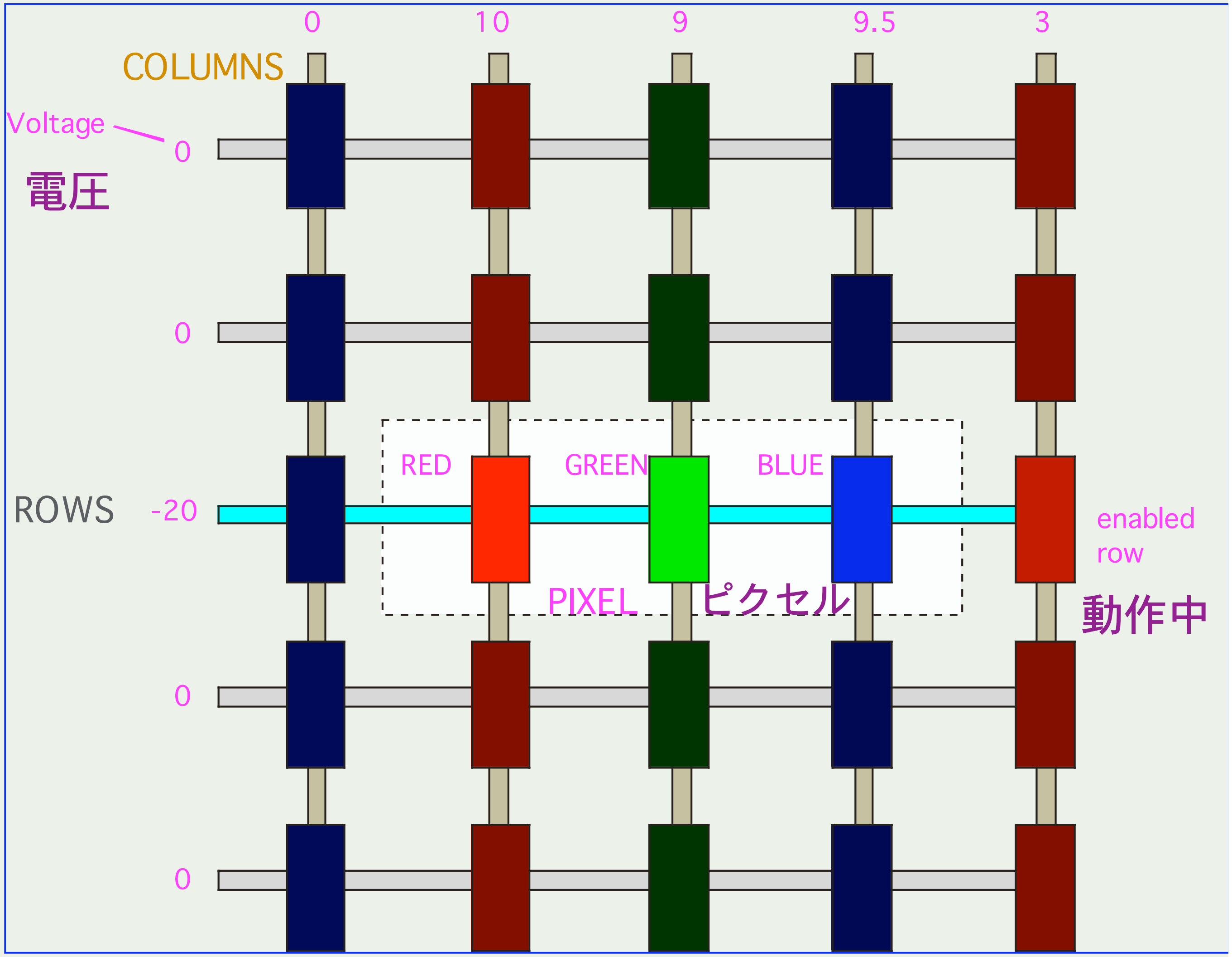
Faceplate Detail: Color phosphors

- Screen-printed phosphor powders:



Sub-pixel Addressing

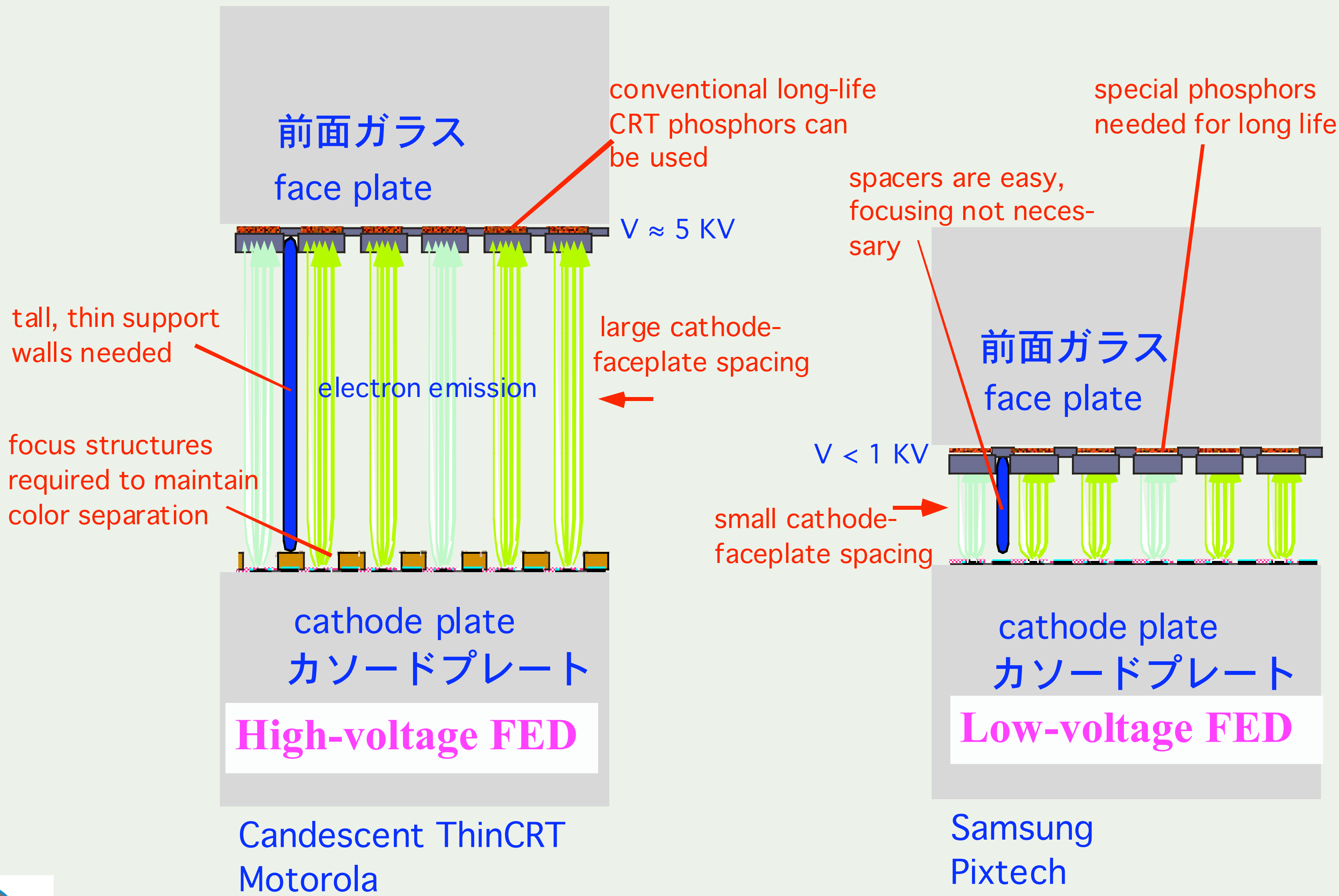
- Highly nonlinear emission-voltage relationship =>
  - cathodes can be used as active devices
  - active matrix not required



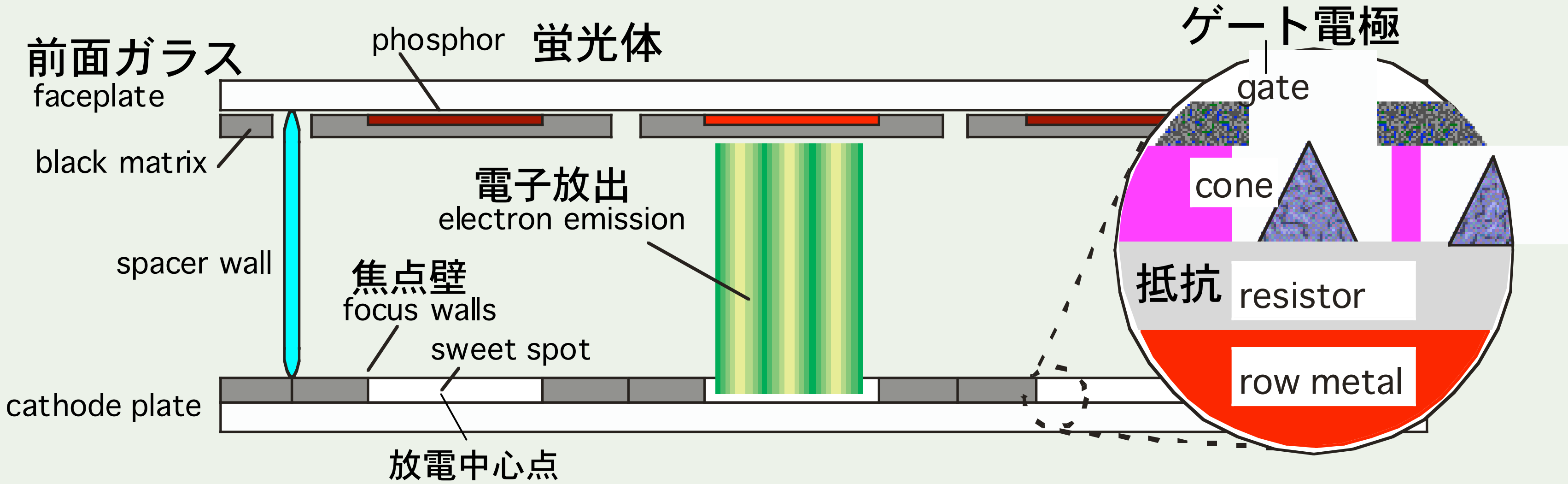
Design Choices

- 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



FED Cross-Section



- Roughly to scale
- Fabrication challenges:
  - spacer walls
  - focus structures
  - materials for faceplate / matrix

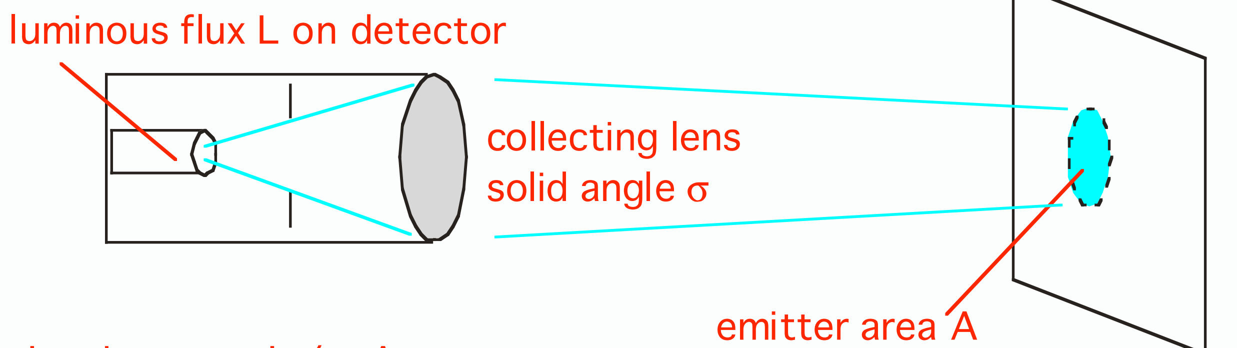
Display Characterization: Photometry

- Displays have their own terminology...

Name	Description	Unit
Luminous Flux	Light energy (corrected for response of the eye)	lumen
Intensity	Luminous flux per unit solid angle	candela = lumen/steradian
Luminance	Intensity per unit area of emitter	candela/m^2 (NIT)
Illuminance	Luminous flux per unit area of receiver	lux = lumen/m^2

1 watt @ 550 nm = 680 lumens

Luminance photometer



Luminance = L / σ A

Display characterization: typical specs

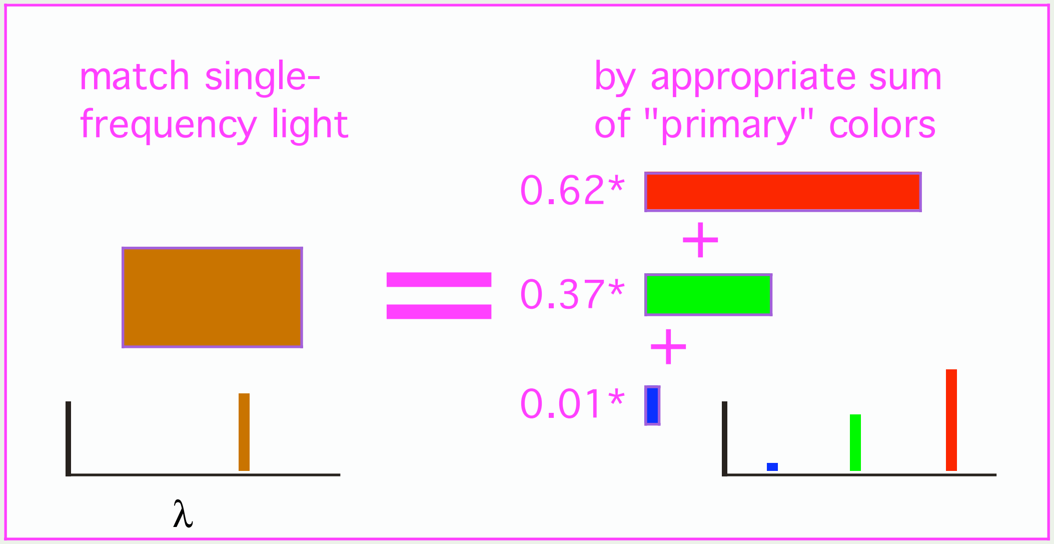
Name	*Description*	*Typical value*
power consumption	Voltage * current for image with 67% of full-white	0.7 W @ 70 cd/m^2 0.8 W @ 100 cd/m^2
brightness (luminance)	light/area emitted per steradian of solid angle	100 cd/m^2
brightness uniformity	variation in brightness at various length scales	1% for .3 to 30 mm 3% for 100 mm
video response	time to turn off; determined by phoshor choice	< 5 msec to 10% brightness
viewing angle	measure any parameter (e.g. brightness) vs. angle in plane	170 degrees for emission display
contrast ratio	brightness will all pixels 'on' vs. 'off'	300:1 in dark ambient; >9:1 in brightly lit ambient
defects	missing or dark sub-pixels, rows, or columns	none for usable display (difficult!)
lifetime	on-time to 50% luminance degradation	20,000 hours (target)

Chromaticity and Color

- 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

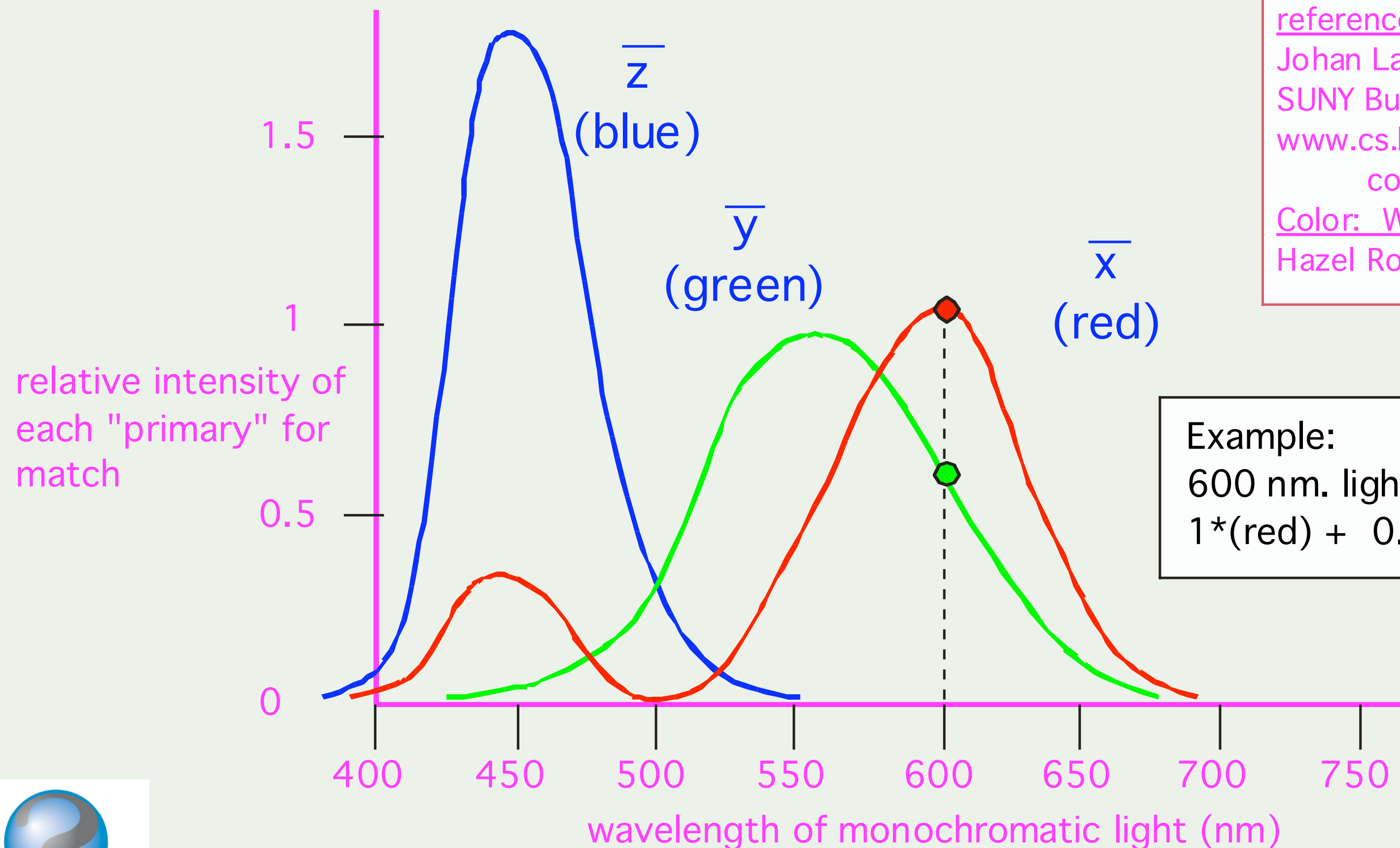
Step 1: Find matching functions

- Define "primaries"
  - e.g. Red = 700 nm Green = 546 nm Blue = 436 nm (CIE 1931)
- For monochromatic light, each λ from ≈ 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



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.



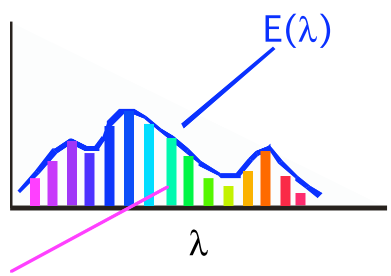
references:
Johan Lamnens Ph.D. Thesis
SUNY Buffalo, 1994
www.cs.buffalo.edu/pub/colornaming/diss
Color: Why the World Isn't Grey,
Hazel Rossotti, Princeton 1983

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

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)

$$X = \int E(\lambda)\ \bar{x}(\lambda)\, d\lambda$$

$$Y = \int E(\lambda)\ \bar{y}(\lambda)\, d\lambda$$

$$Z = \int E(\lambda)\ \bar{z}(\lambda)\, d\lambda$$

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

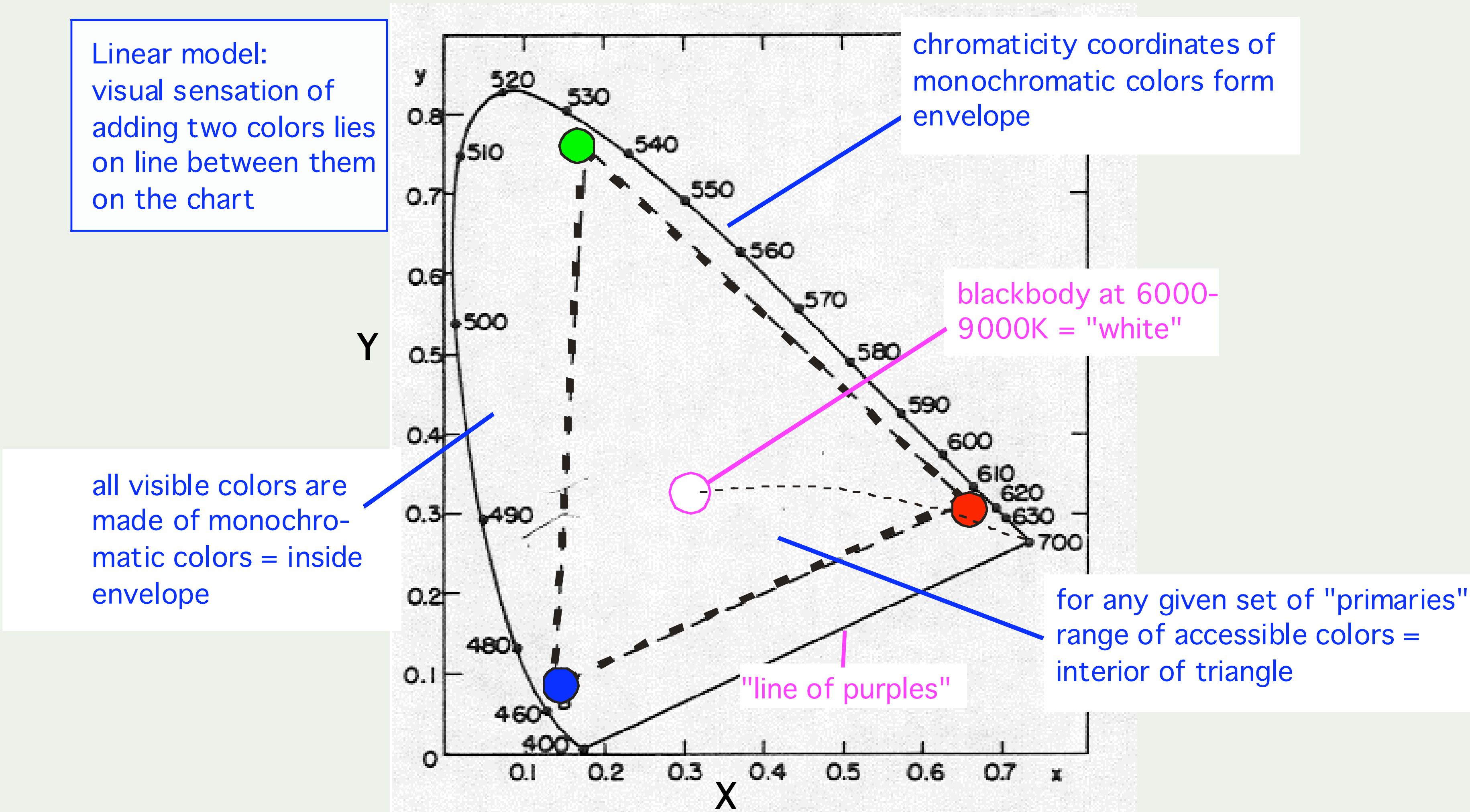
$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

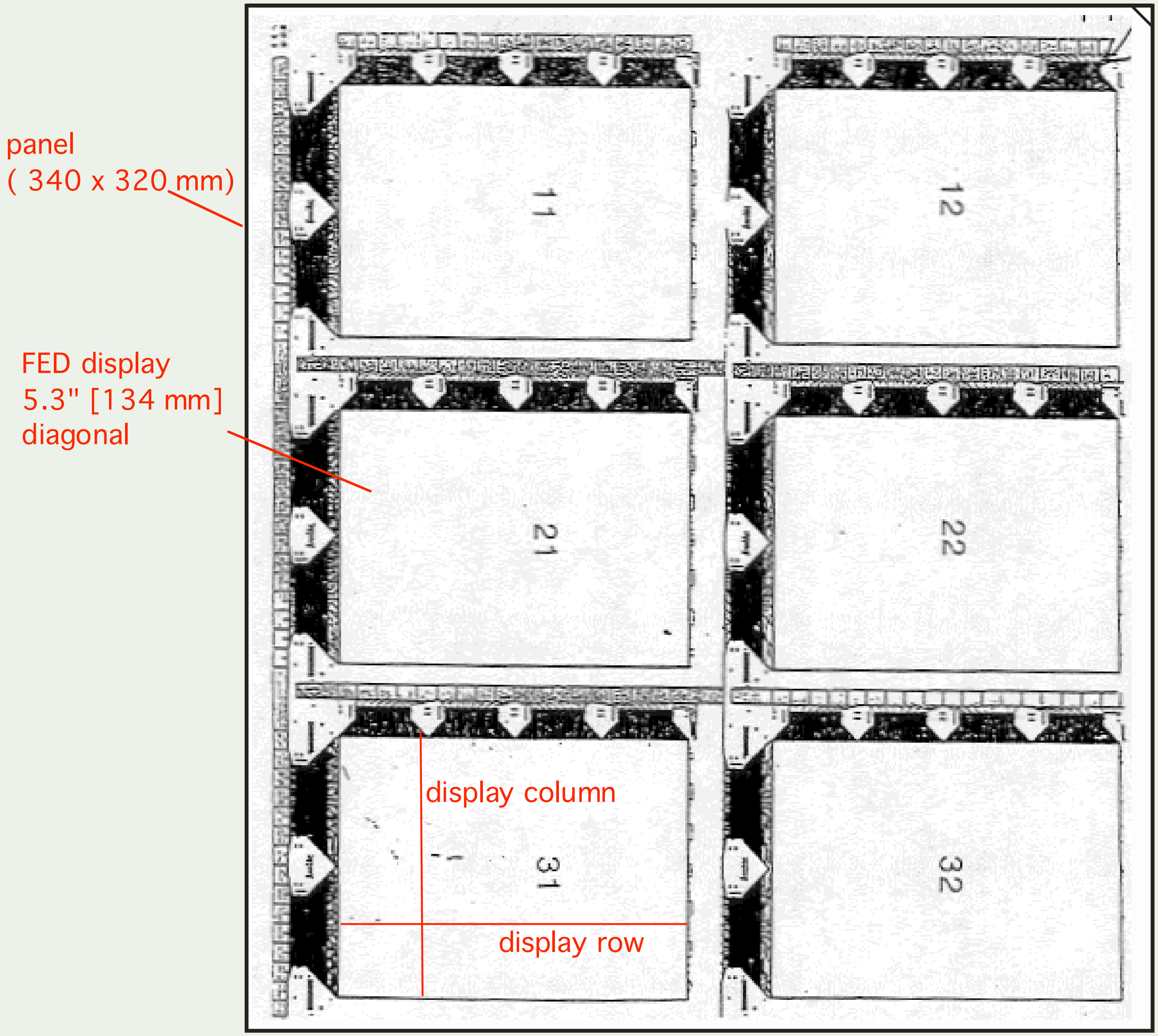
Result: Chromaticity Diagram

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

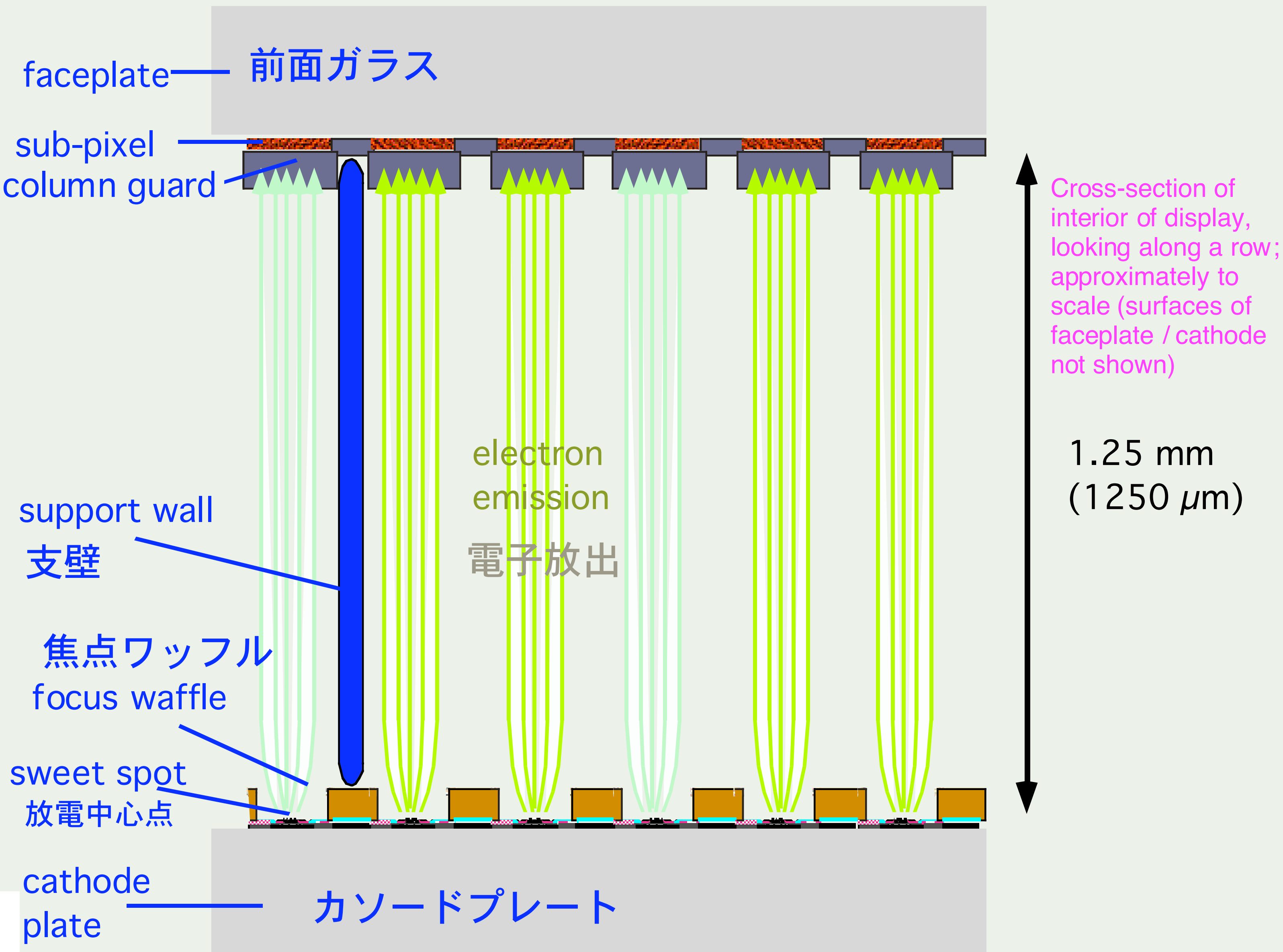


since x + y + z = 1 only need
2 axes (=brightness arbitrary)

FED Fabrication: Panels and Displays



Cross-Section of Display



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

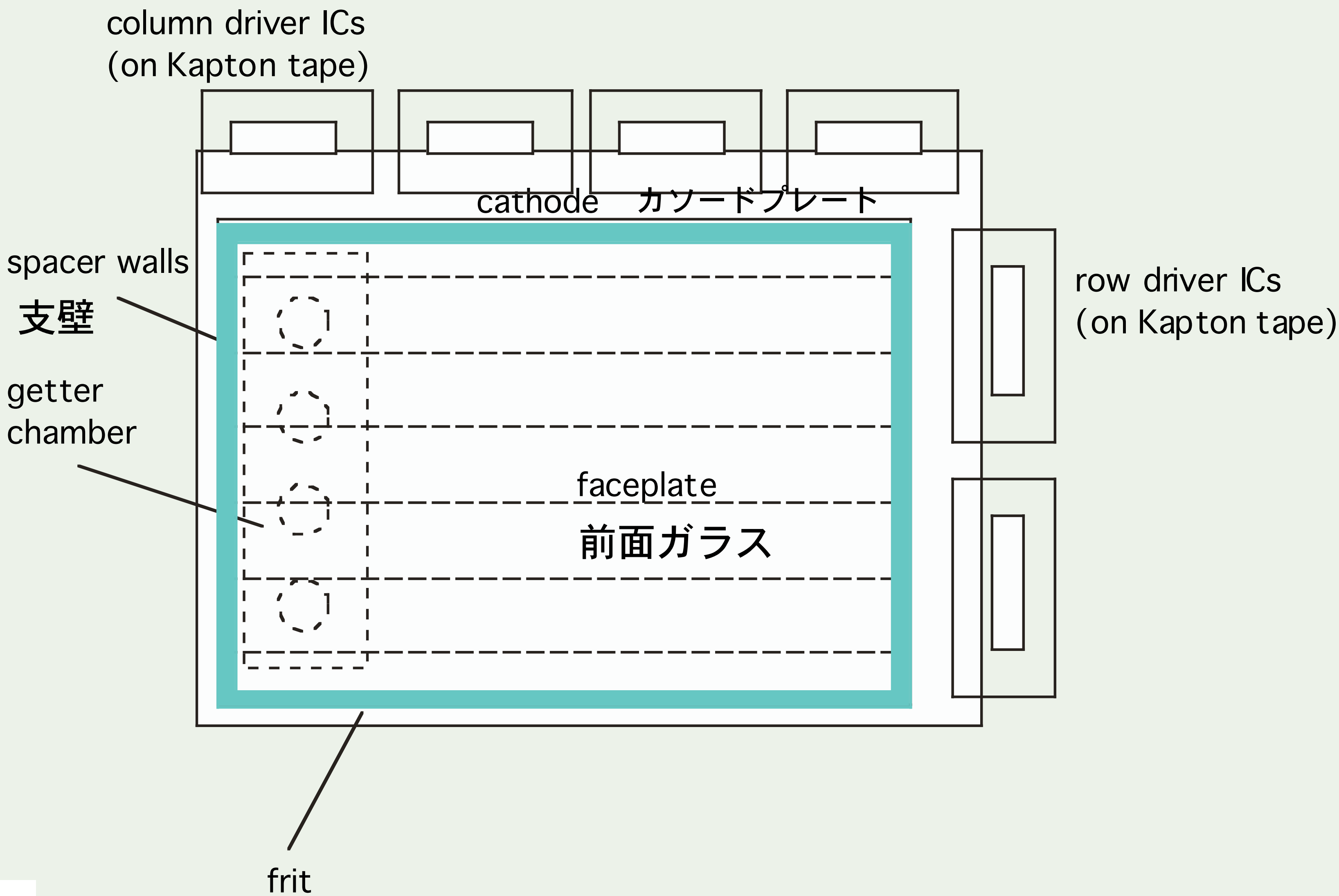
Faceplate overview

- 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

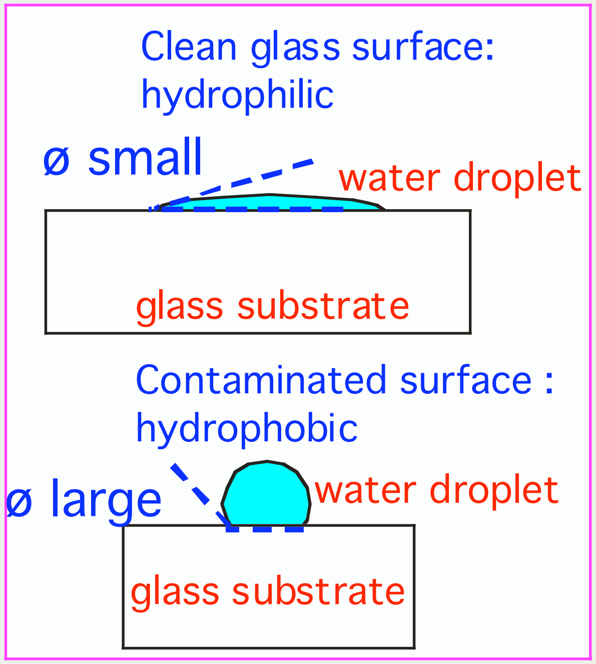
- Alignment:
  - assemble cathode and faceplate together so that each emission spot aligns with sub-pixel
- Spacer walls:
  - ceramic, 1.2 mm high, 50 microns wide (!)
- Frit:
  - fusible Pb-based glass bonds cathode to faceplate
- Getter:
  - attached smaller chamber with flash getter to improve vacuum
- Driver electronics:
  - attached to periphery
- Pump down:
  - 10^{-7} Torr (10^{-5} Pa) needed for reasonable lifetime

Assembled Display



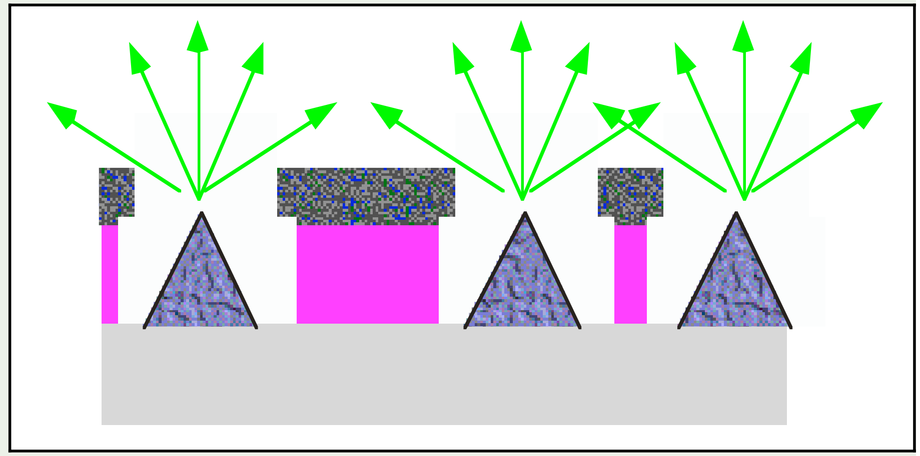
Cathode Parts: Substrate

- 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 °C ; support panel to avoid sagging
    - after densification, expect < 7 µm shrinkage across panel (vs. emission spot size of about 35 µm)
  - monitor wetting angle to check for contamination before / after densification
  - particle control critical to prevent row/column shorts

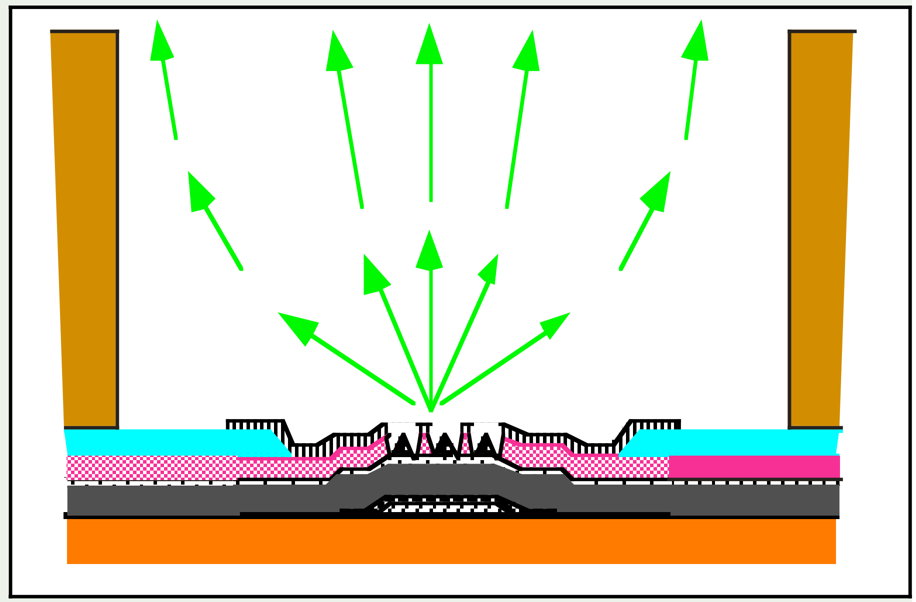


Cathode: Emitters and Focussing

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

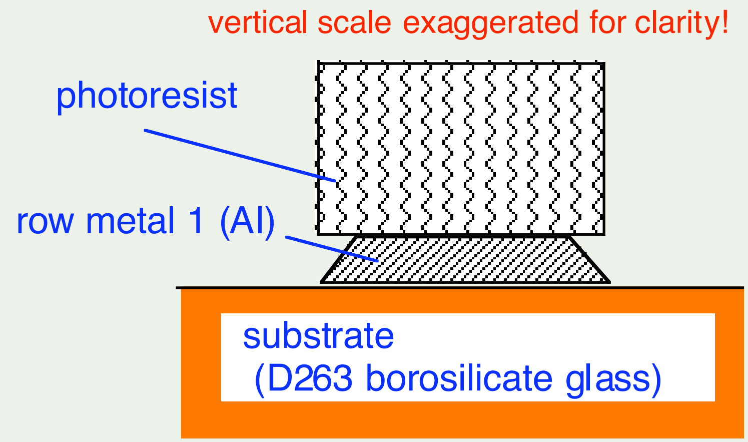


- Solution: provide focus structure for emission spot
  - thick polyimide + metallization

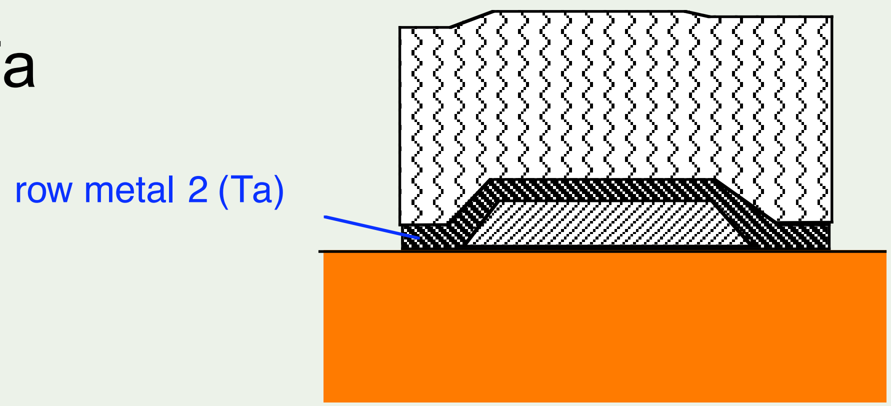


Cathode Processing: Row metal

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

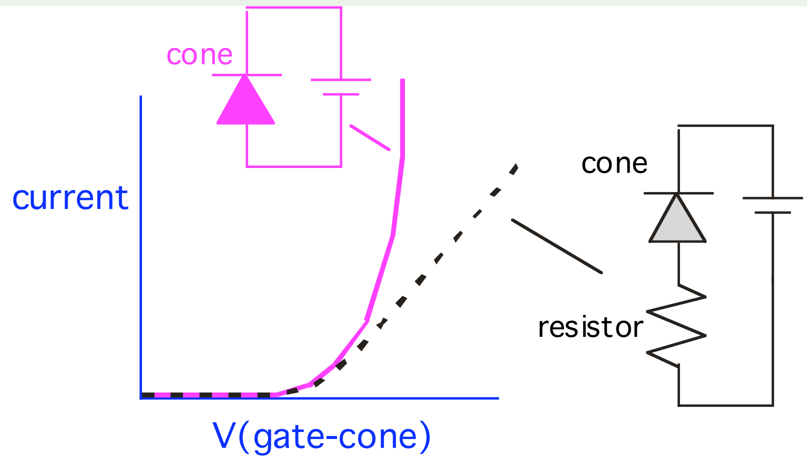


- Row metal 2:
  - sputter & pattern 120 nm Ta
    - hillock prevention, protects Al from corrosive chemicals

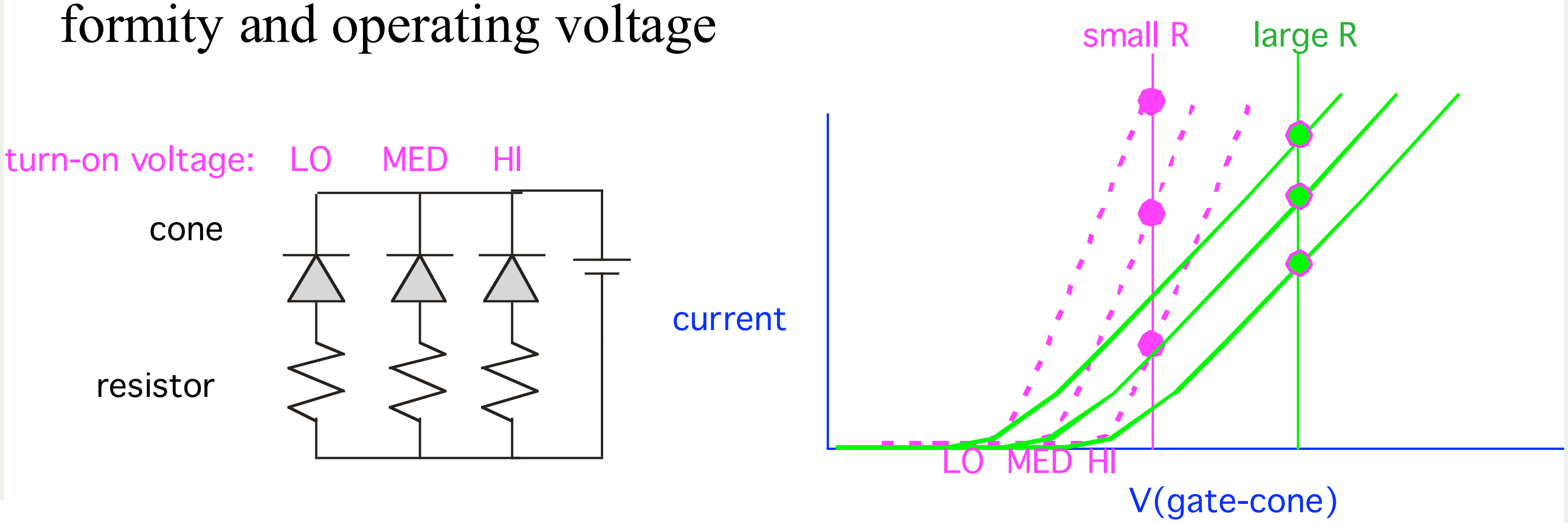


Cathode processing: Resistor Layer

Resistor limits rapid turnon of cones

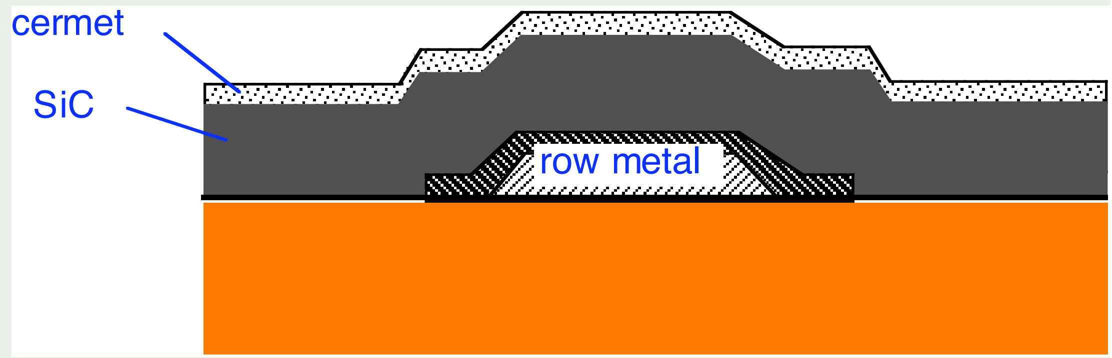


Choice of resistor value is a tradeoff between current uniformity and operating voltage

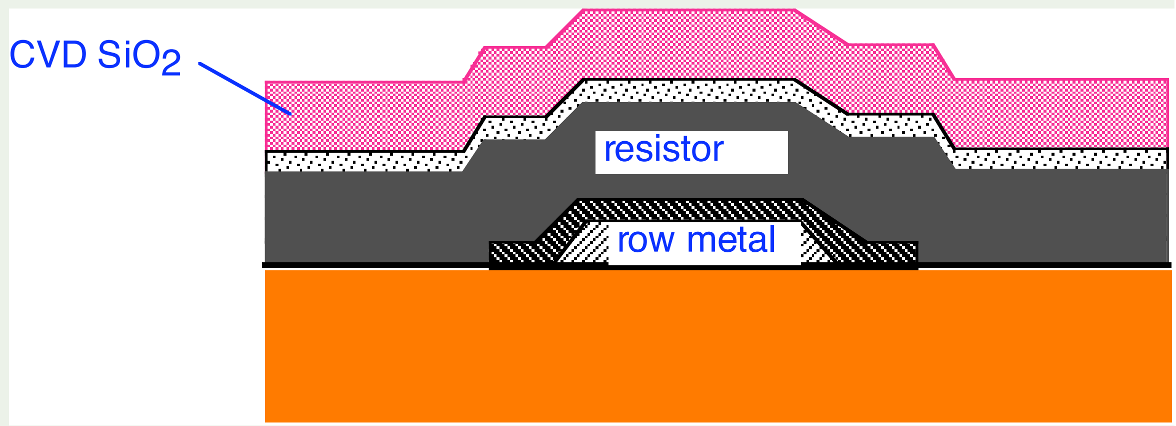


Cathode processing: Resistor layer fab

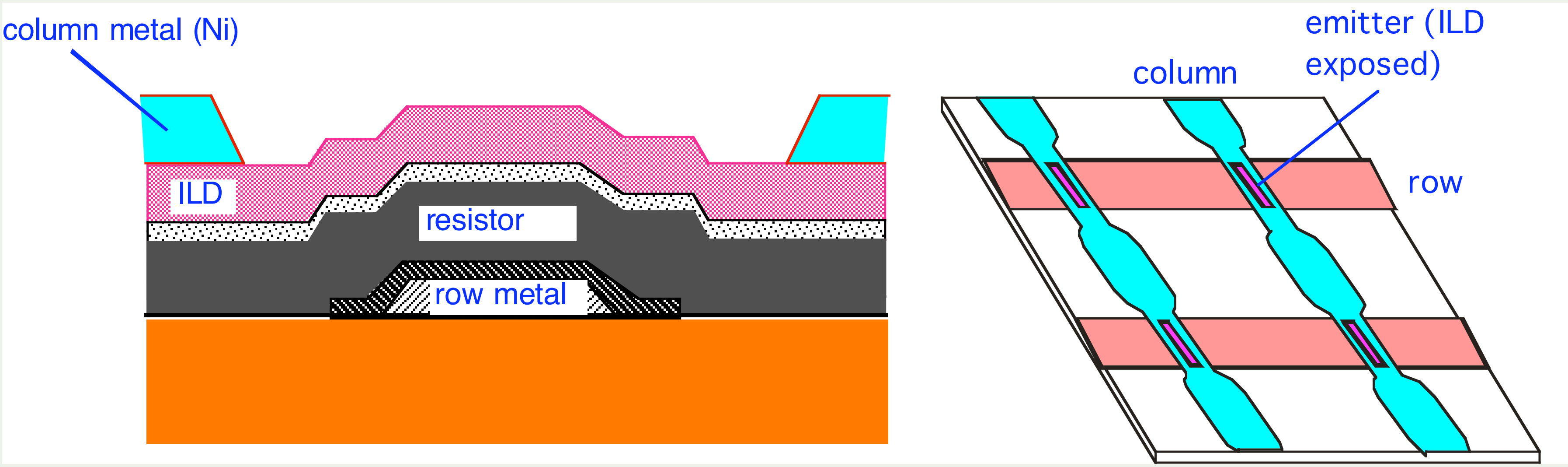
- 300 nm SiC layer has well-controlled resistivity of about 300,000 Ω-cm
  - series resistance of several GΩ per emitter => about 2 V drop
  - Fused SiC target by CVD, very expensive
  - Material spalls from shields, high particle count
- CVD insulator layer
  - row-column metal insulator
  - gate - emitter insulator
  - 150 nm APCVD (conveyorized belt furnace)
  - shorts represent important yield limiter



- 50 nm 'cermet' (40% Cr in SiO_2)
  - used as selective etch mask later



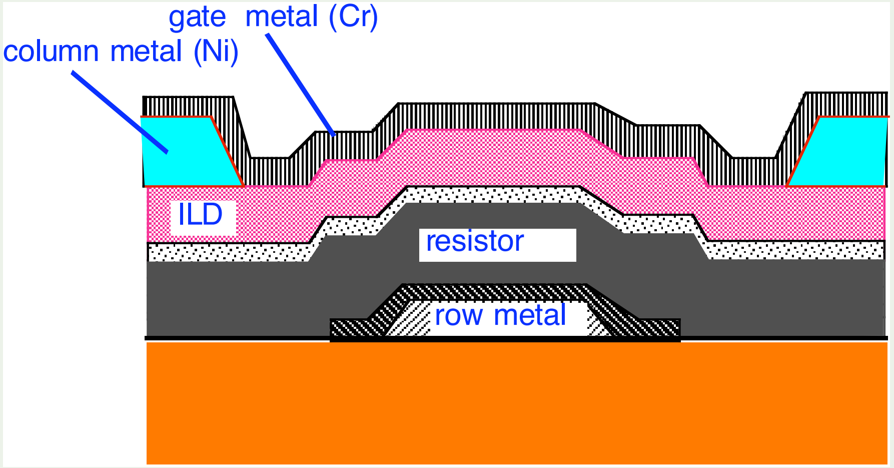
Cathode Processing: Column metal



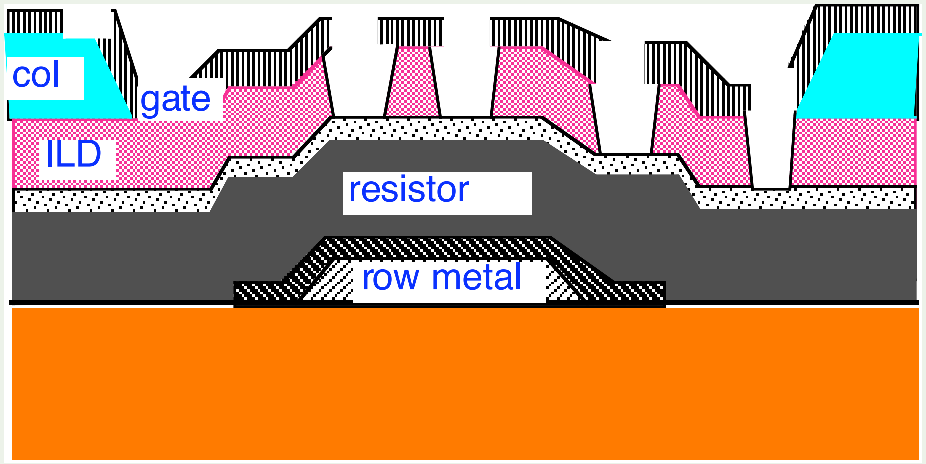
- 150 nm sputtered Ni; wet pattern, sloped edges for contact to gate metal
- Hole in row metal defines emitter region

Cathode Processing: Gate metal

- 40 nm Cr masks cavities for discrete emitters

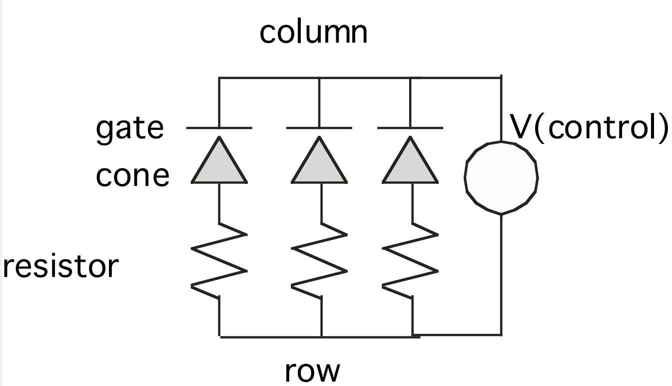


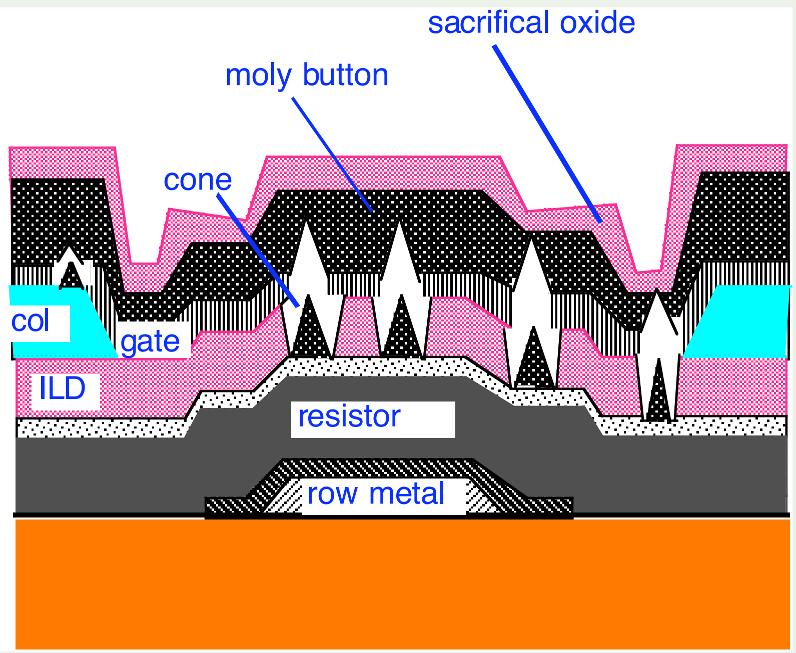
- Pattern and etch



Cathode processing: emitter formation

- Spindt cathode (evaporated Mo)
- cover with APCVD SiO_2 afterwards to protect tips during processing

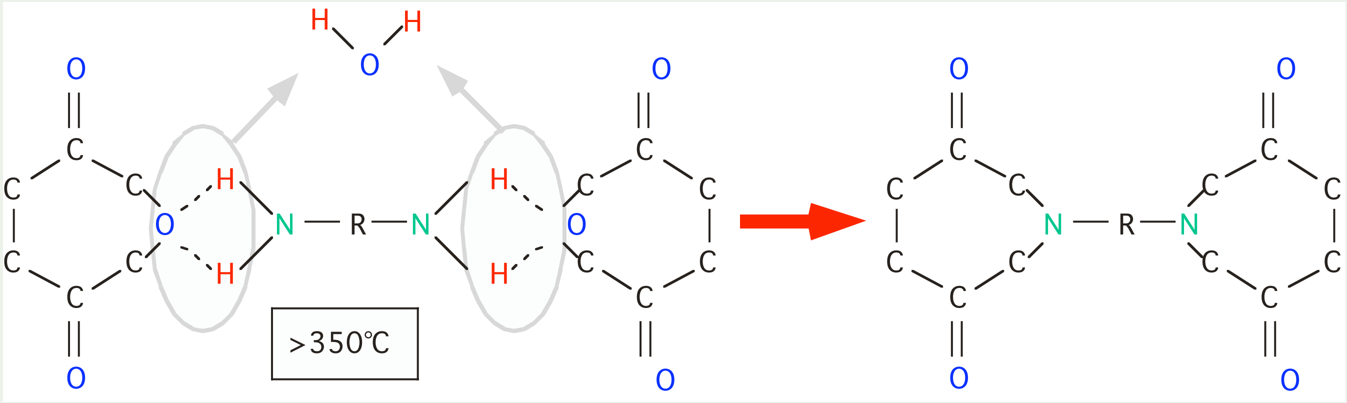


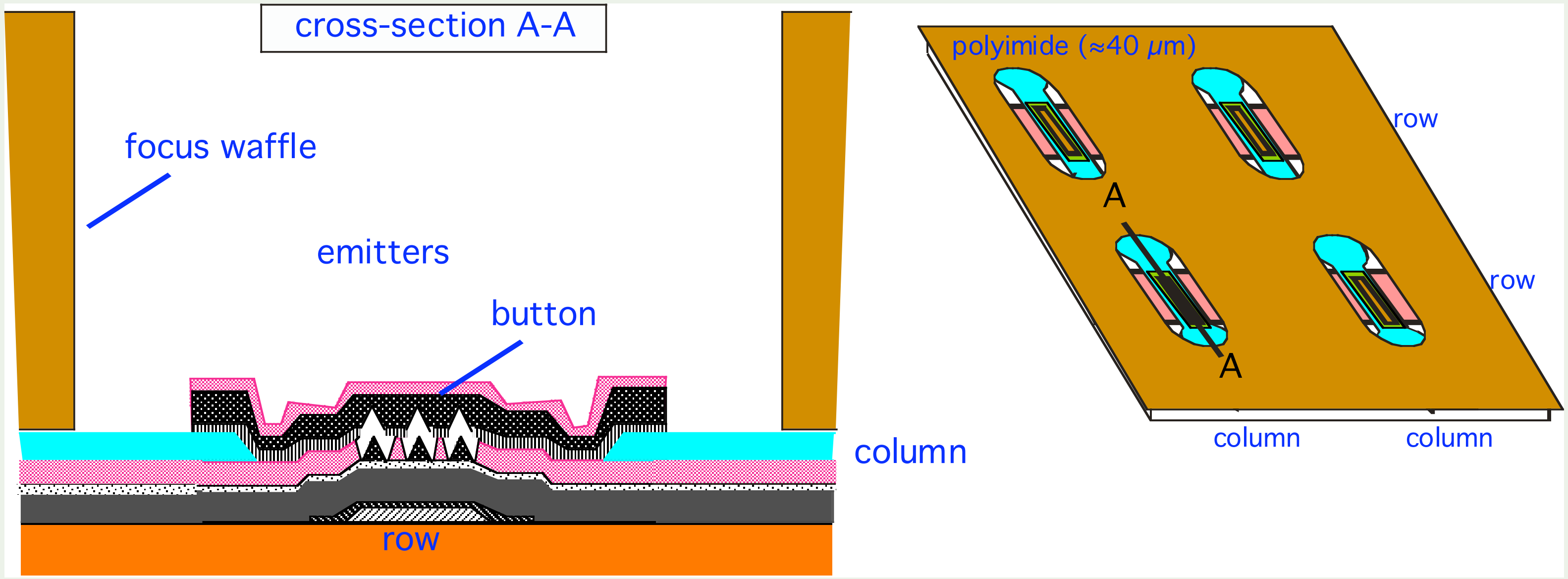


- etch Mo and Cr away except in emitter regions
- etch dielectric to expose row metal

Cathode processing: focus waffle

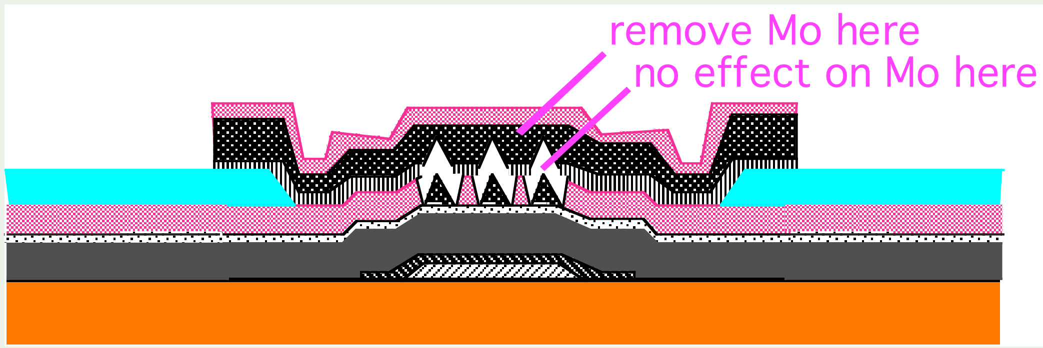
- Thick (70 μm) photosensitive polyimide, applied while Cr/Mo remains over emitter tips
- Cure 400º C 8 hours in nitrogen after develop



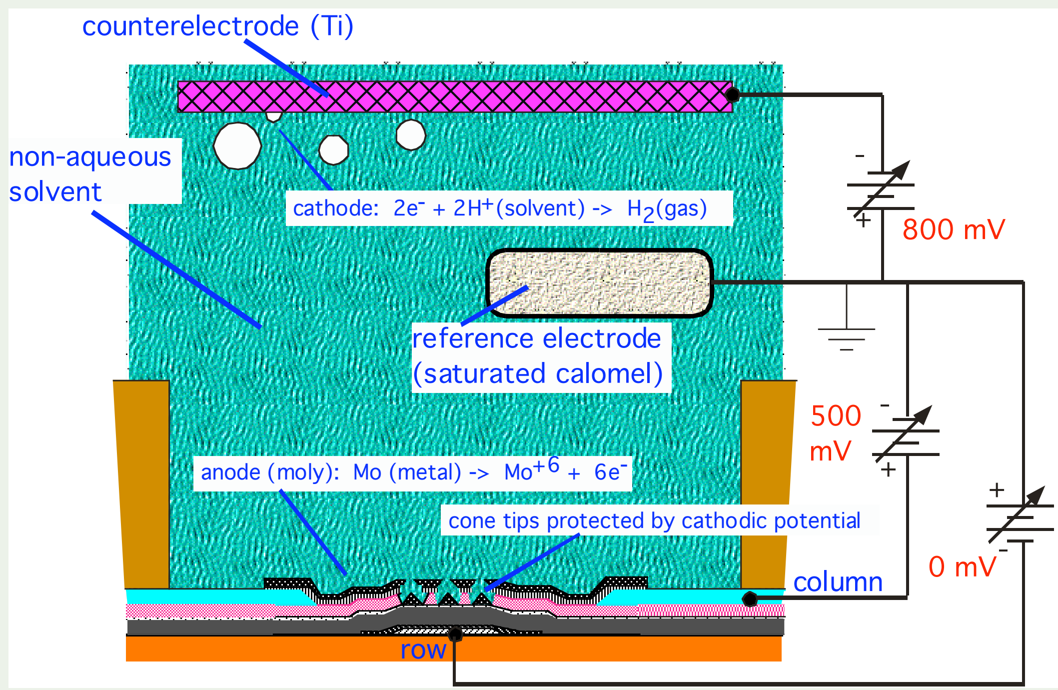


Cathode processing: selective Mo etch

- Challenge: remove Mo 'button' protecting emitters without attacking emitters

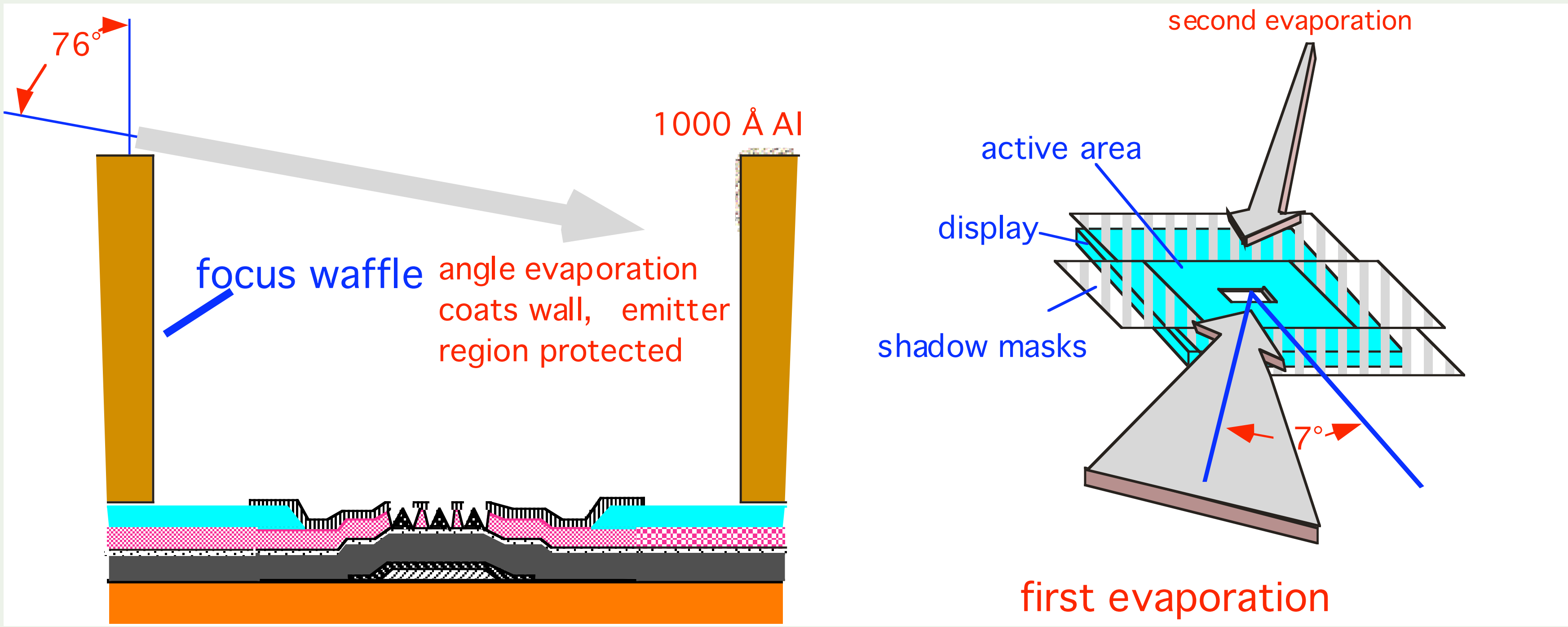


- Approach: use electrochemical etch since 'button' is electrically isolated from emitters



Cathode Process: Focus Waffle Metal

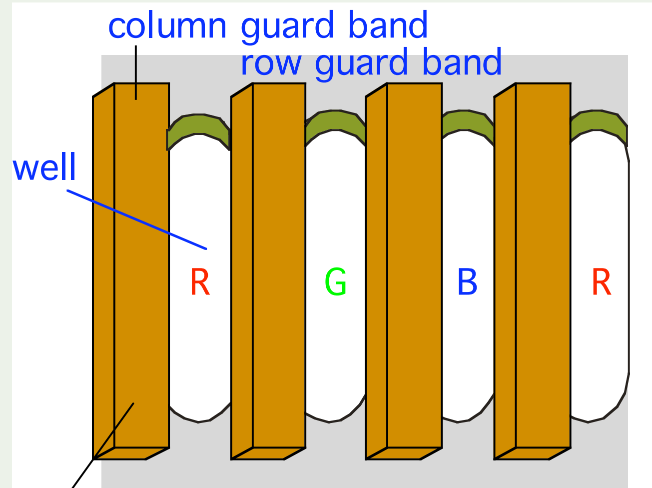
- Use angle evaporation to deposit metal on walls without contaminating emitter region

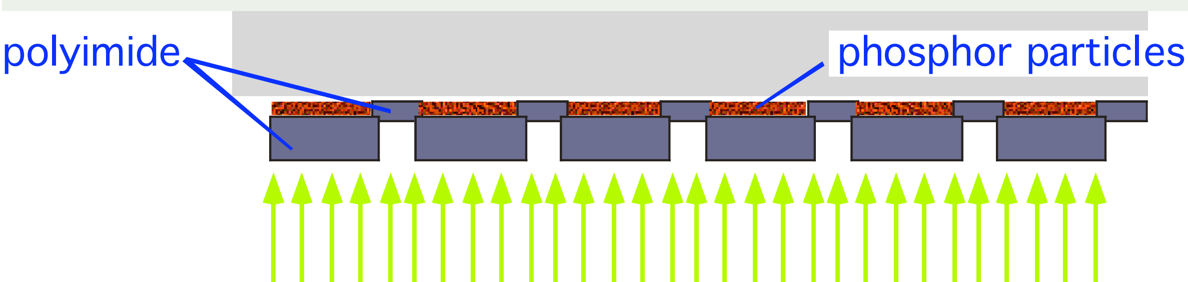


- Ready for bakeout, electrical test, emission uniformity test

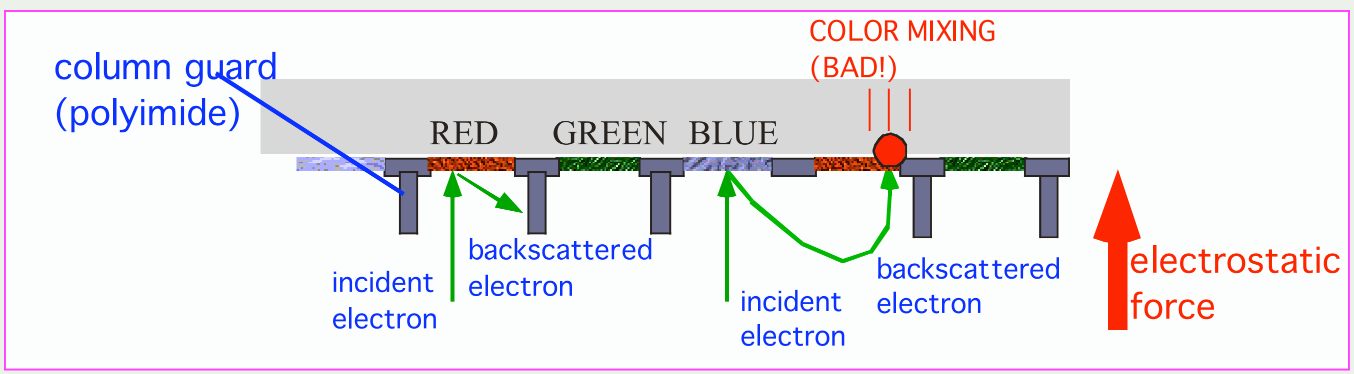
Faceplate

- 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



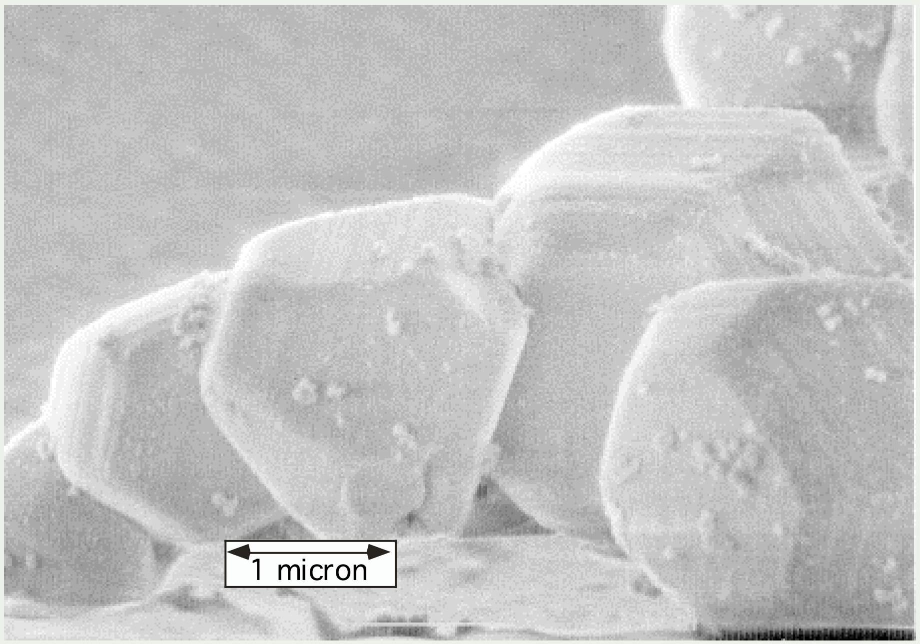


- High-T cure + supercritical extraction to control polyimide outgassing under electron bombardment

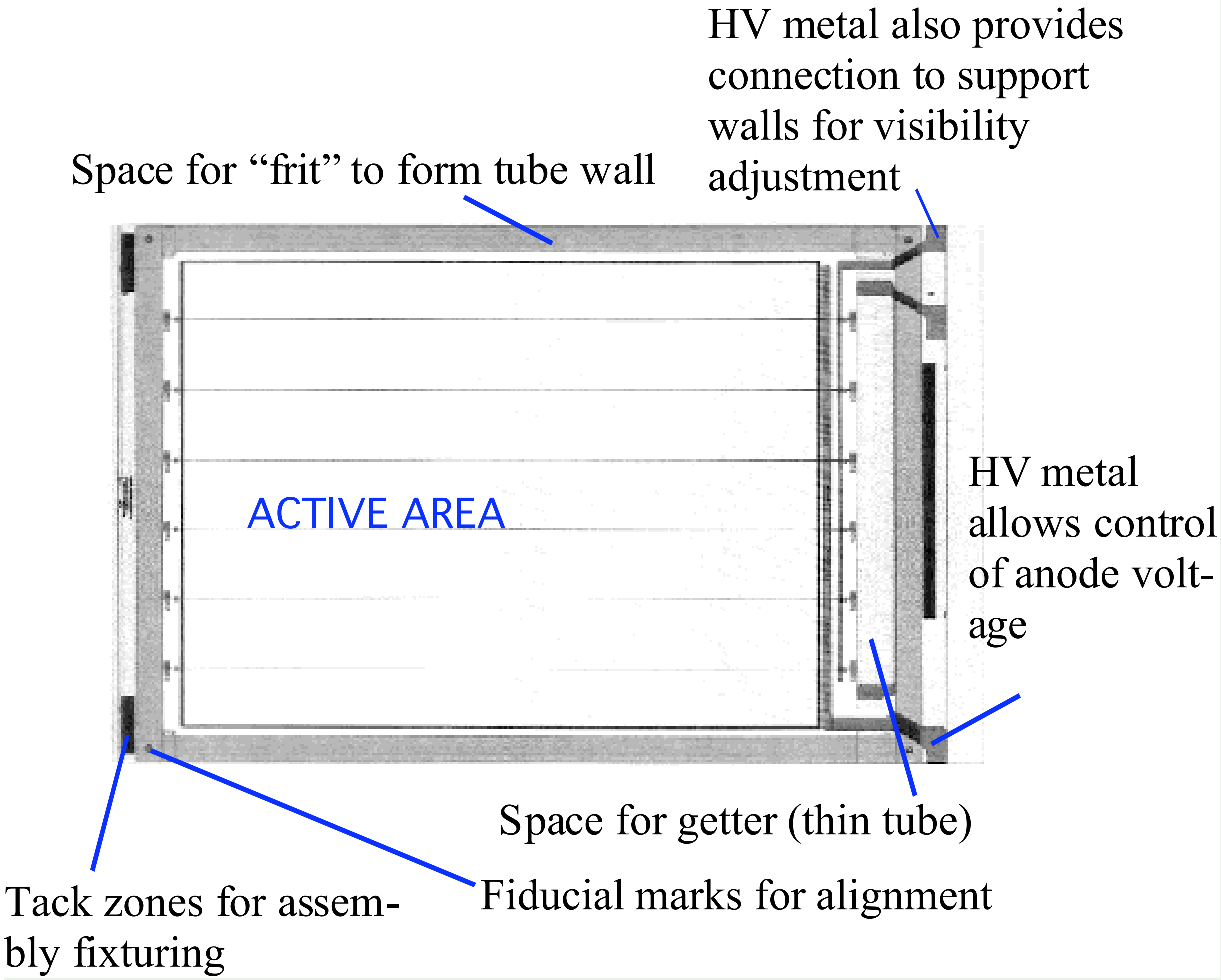


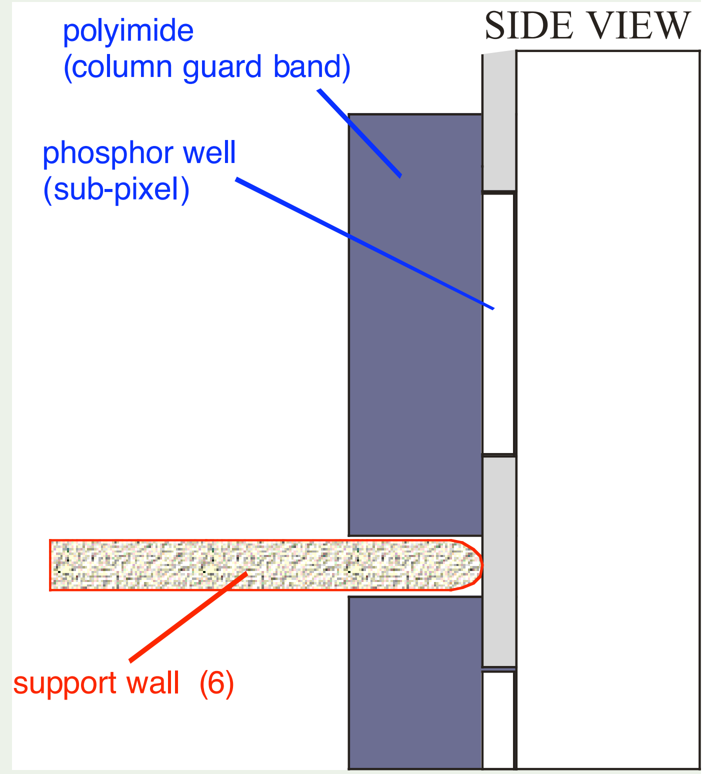
Phosphors

- 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



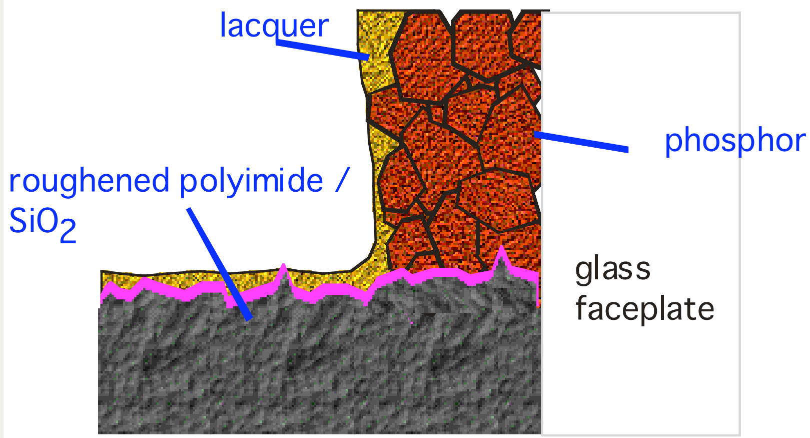
Faceplate Assembly Provisions



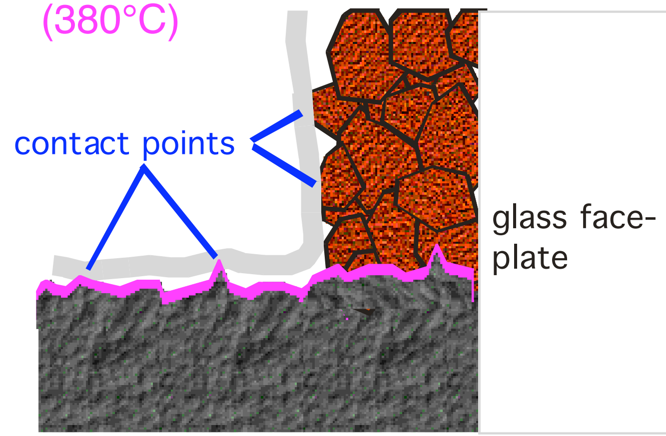


Faceplate: Aluminize

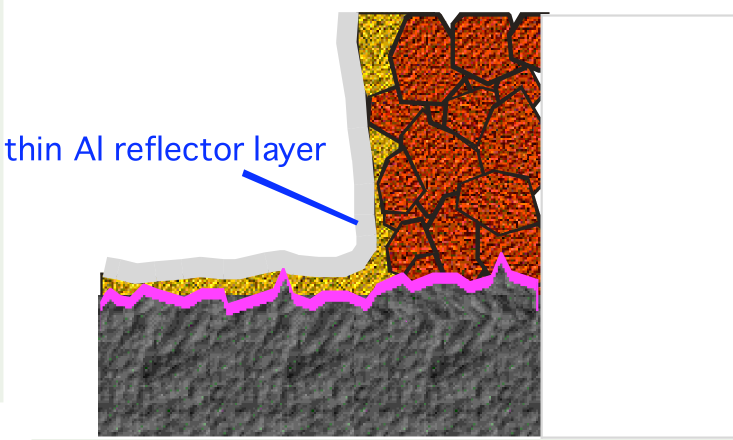
1: Apply lacquer



3: Decompose and remove lacquer (380°C)

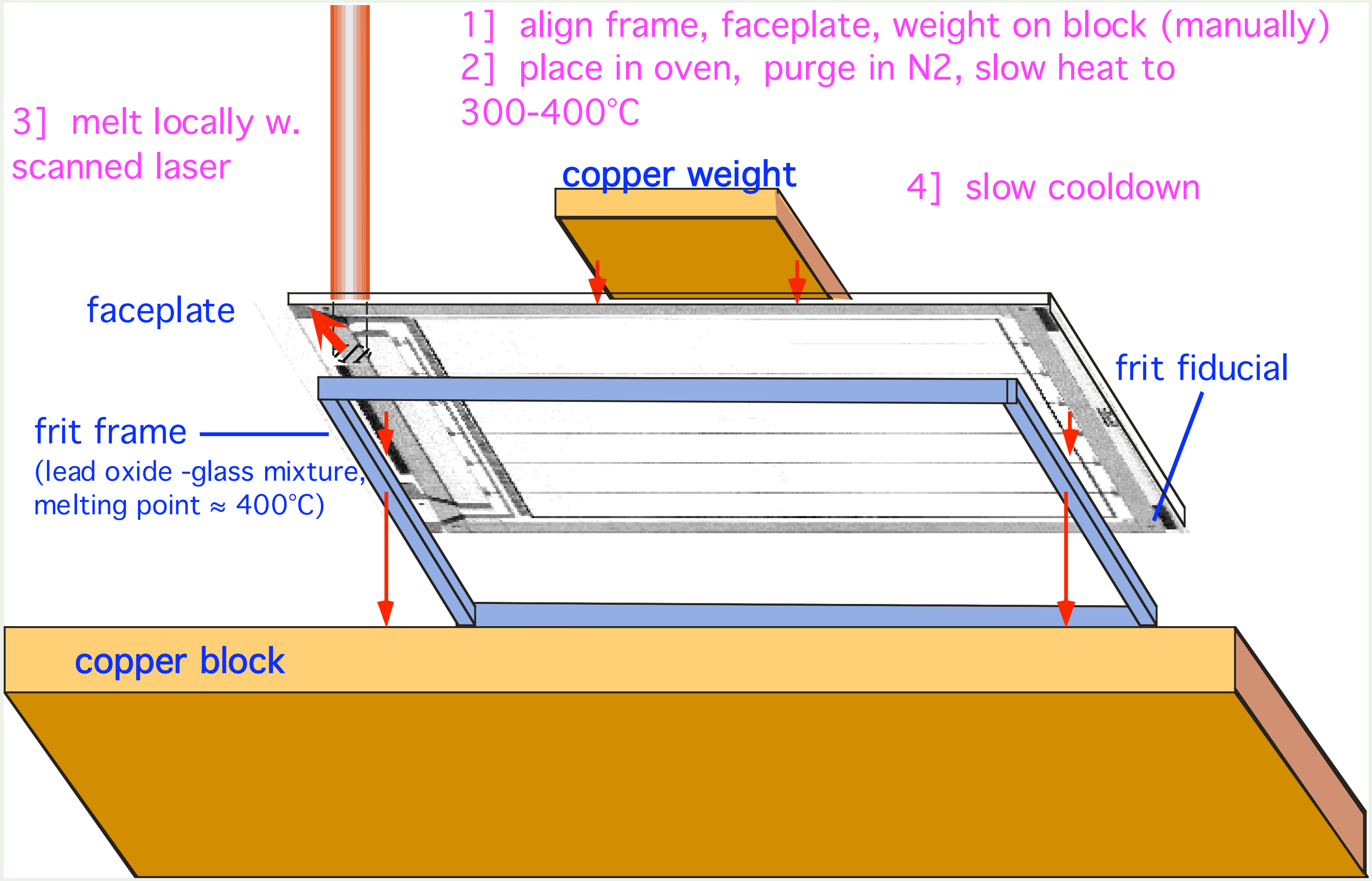


2: Deposit reflector aluminum



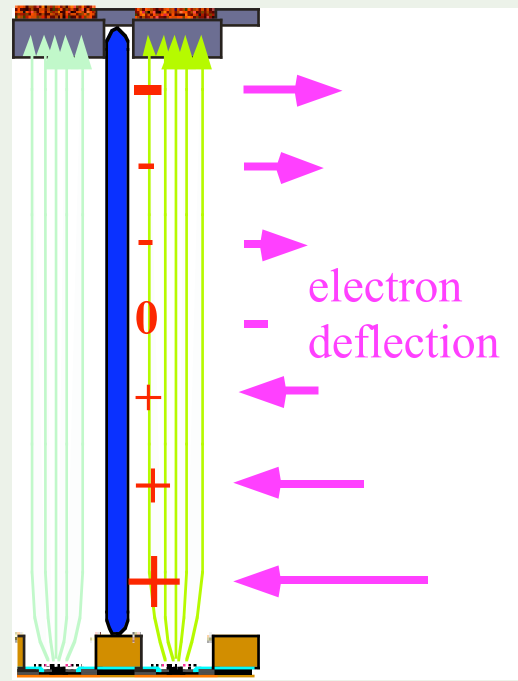
- Minimize emission into tube (lost light)
- Sacrificial lacquer process dates back to 1939

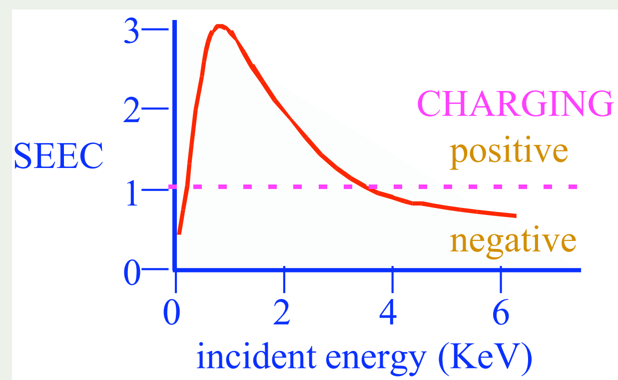
Assembly: Frit Frame Attachment



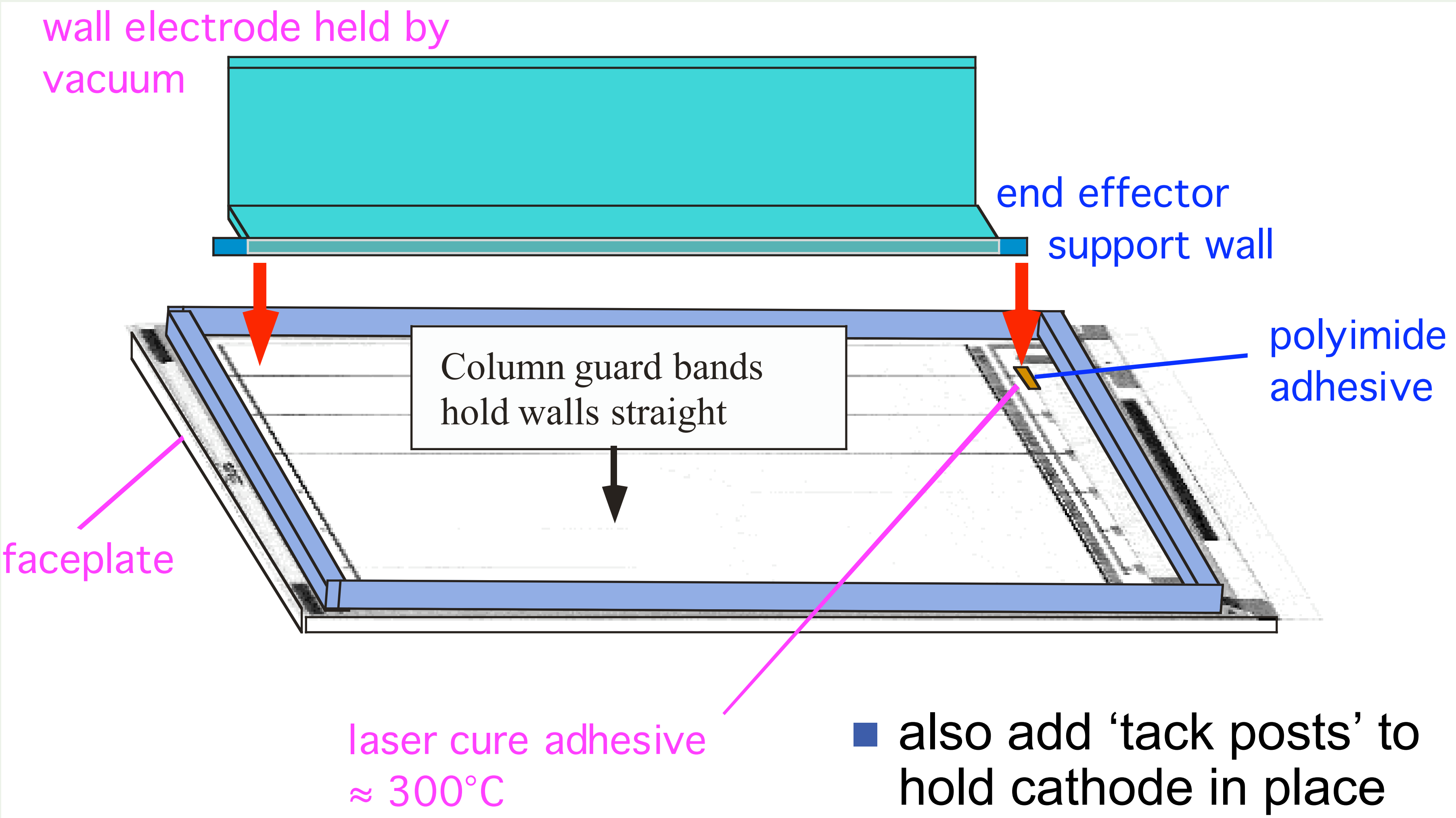
Support Walls

- 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)



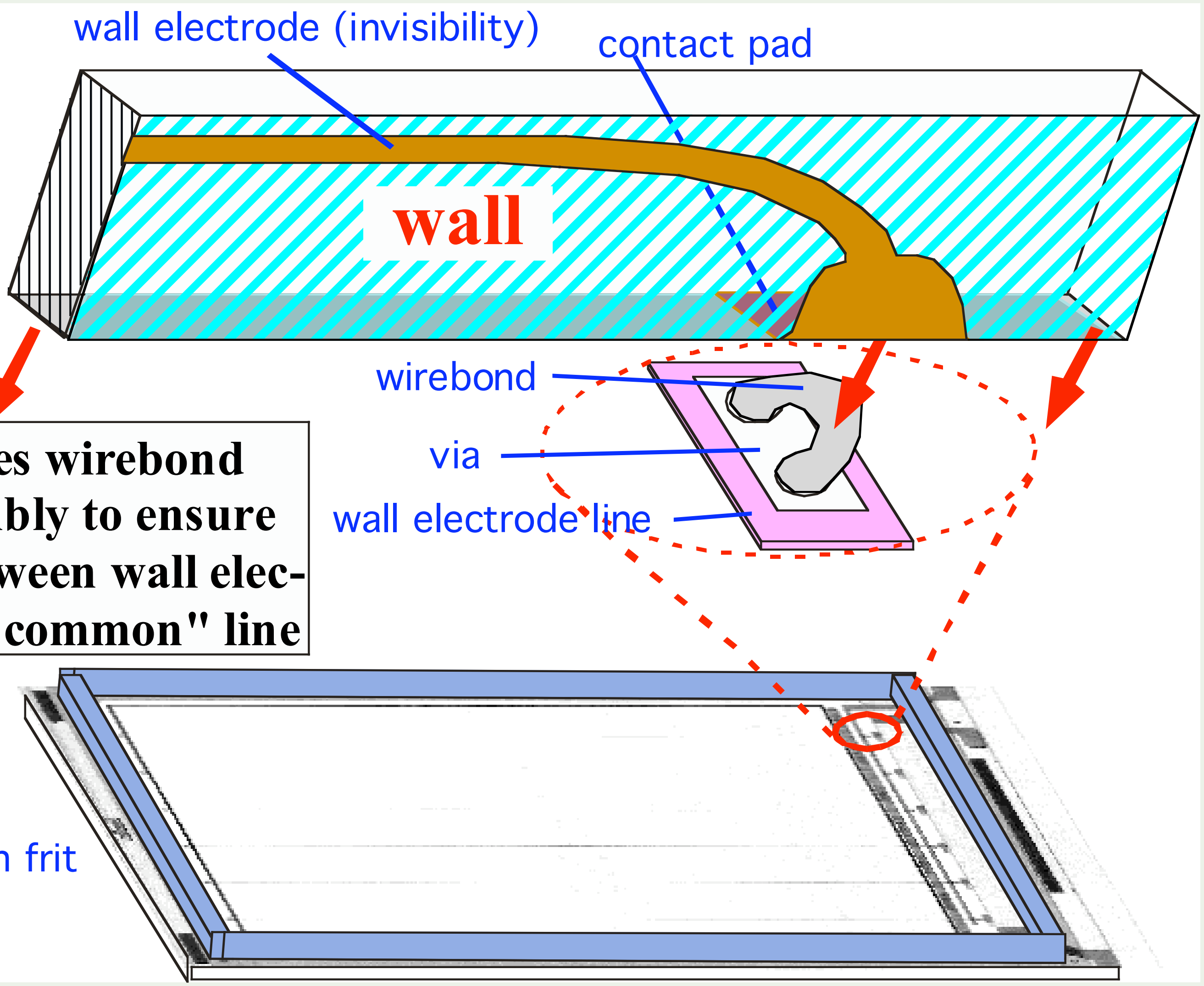


Assembly: Support Walls



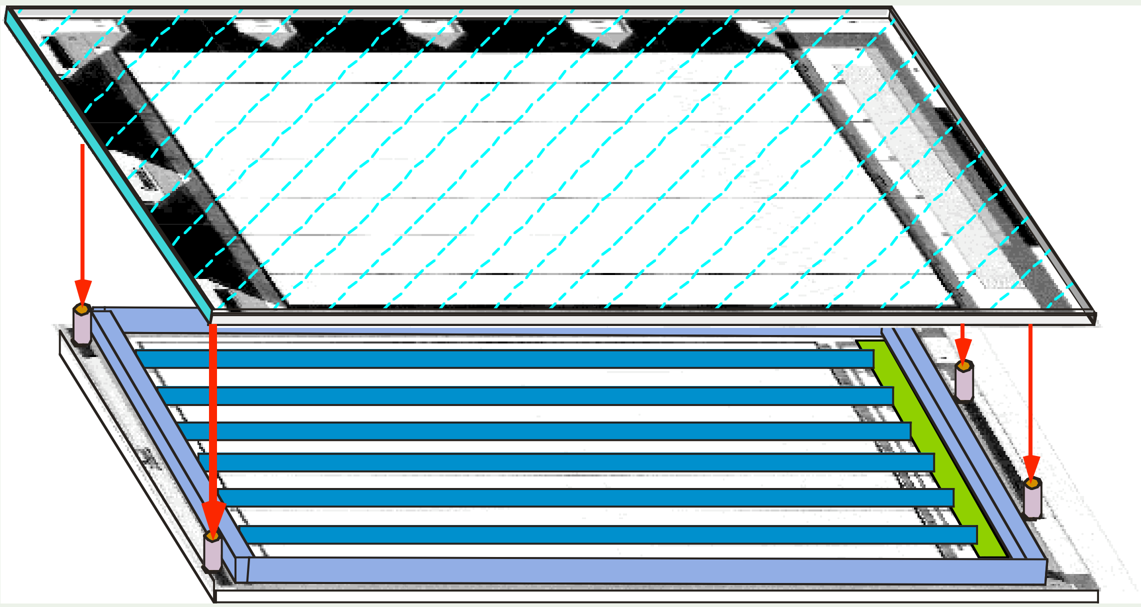
- also add 'tack posts' to hold cathode in place

Assembly: Wall Electrode Connections

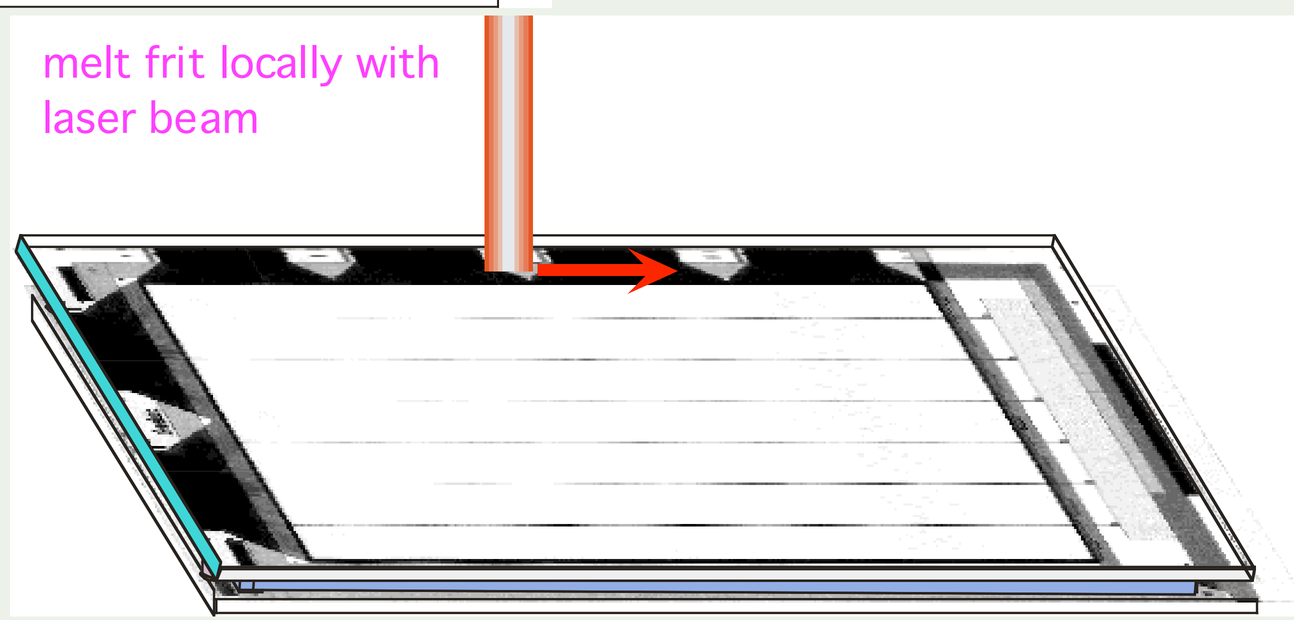


Wall crushes wirebond upon assembly to ensure contact between wall electrode and "common" line

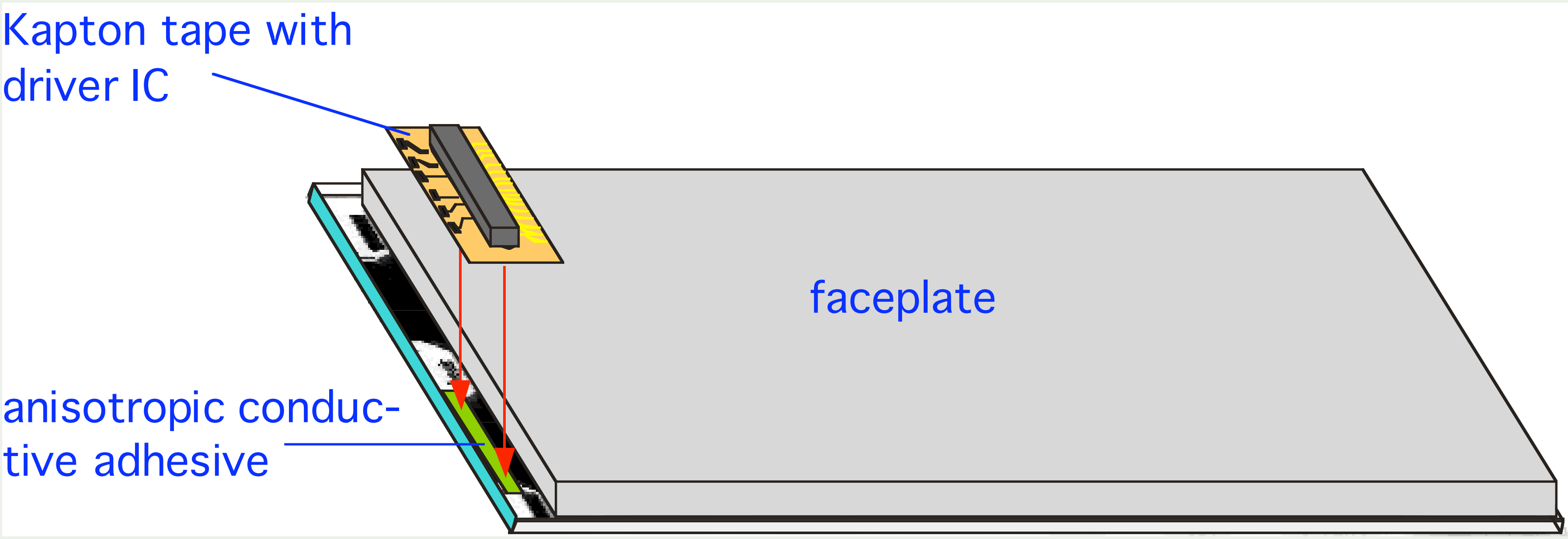
Assembly: Cathode Mount



- part of frit left unsealed to allow pumpout



Assembly: Driver IC's



- 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 (arcing?) 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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