Can Nanotechnology revive Field Emission Display Technology?

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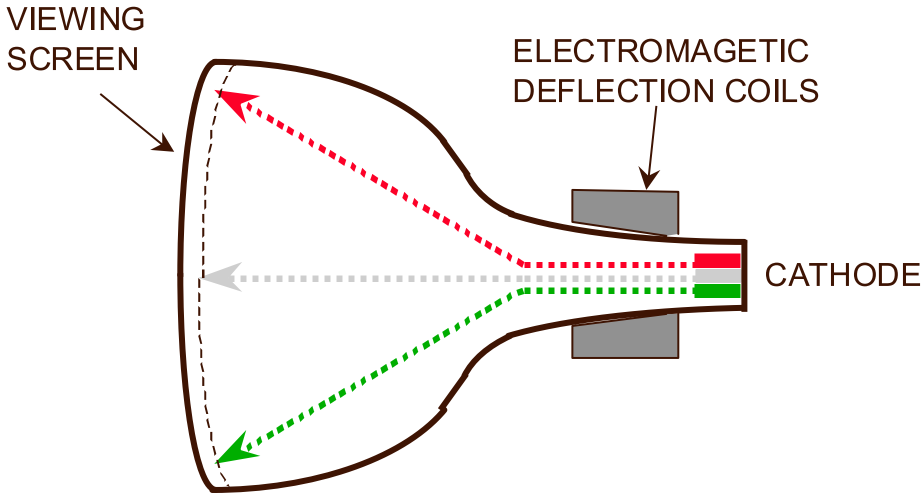
Outline

- Basic of Field Emission Display
- Key Issues and components for FED
- Nanotechnology for field emission technology
- Depletion mode operation
- Summary

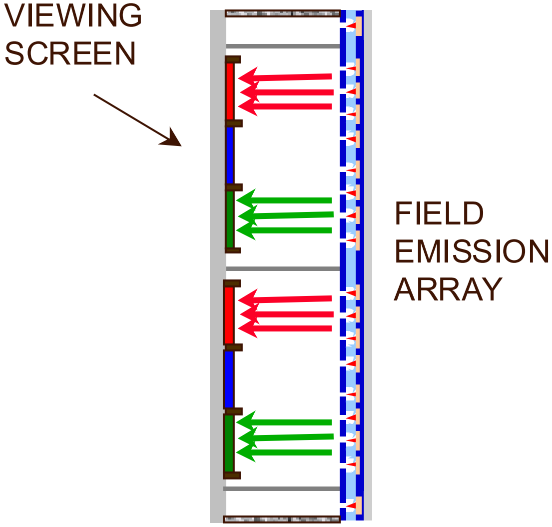
What is an FED?

Cathode Ray Tube



A CRT is a vacuum tube in which electrons from three hot cathodes are scanned across a multicolor viewing screen to create a picture.

Field Emission Display



An FED is a vacuum tube in which electrons from millions of tiny cathodes travel to a multicolor viewing screen to create a picture.

The Business Case for FEDs

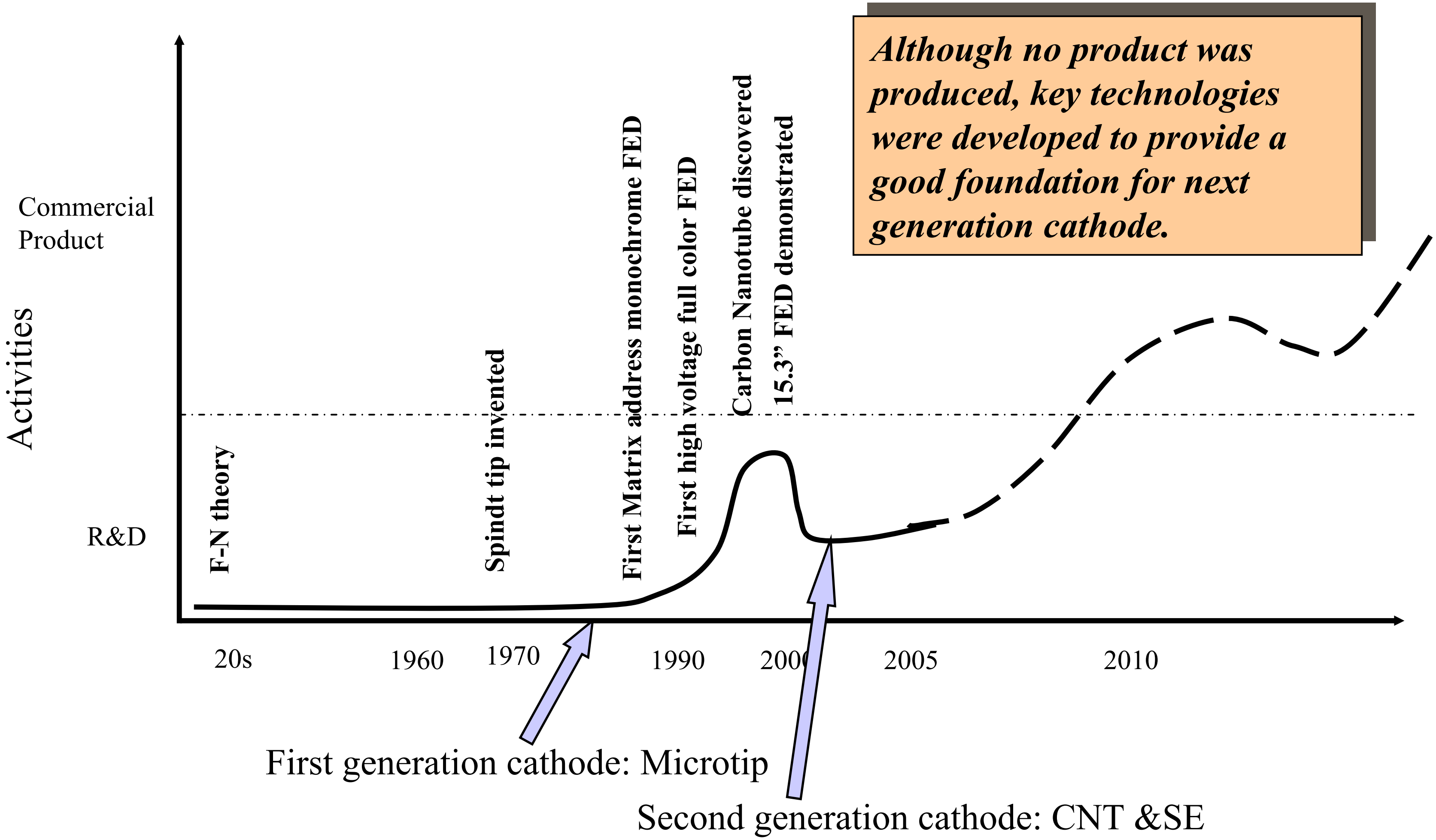
Superior performance:

- *Better than CRTs*
  - Less than 1/10th the thickness and weight
  - Lower power and more rugged
  - No non-linearities or color errors
- *Better than LCDs*
  - Viewable from any angle *with no change in brightness, contrast or color*
  - Usable from -40°C to 85 °C *with no change in performance!*
  - Potentially lower power consumption than LCDs
  - Wider operating temperature range
  - Larger viewing angle
  - Sunlight readability

Potentially lower manufacturing costs

- *Fewer processing steps than Active Matrix LCDs*

Milestones in development of Field Emission Display



FEDs - Industry Status

- At peak, TI, Motorola, Raytheon, Candescent, Micron, FED Corp., SIDT in the US; Pixtech in France, Samsung in Korea; Canon, Sony and Futaba in Japan investigated resources into the technology.
- The number of companies involved in FED development is down. Many companies keep low profile.
- Focus of cathode technology is switched from Microtip to carbon nanotube.
- Canon and Toshiba announced to invest $1.8 B in SED in DEC, 2004. Demonstrated 36 " SED at CES 2005

World Largest Field Emission Display

Prototype of a 15.3" full color FED capable of running video in real time

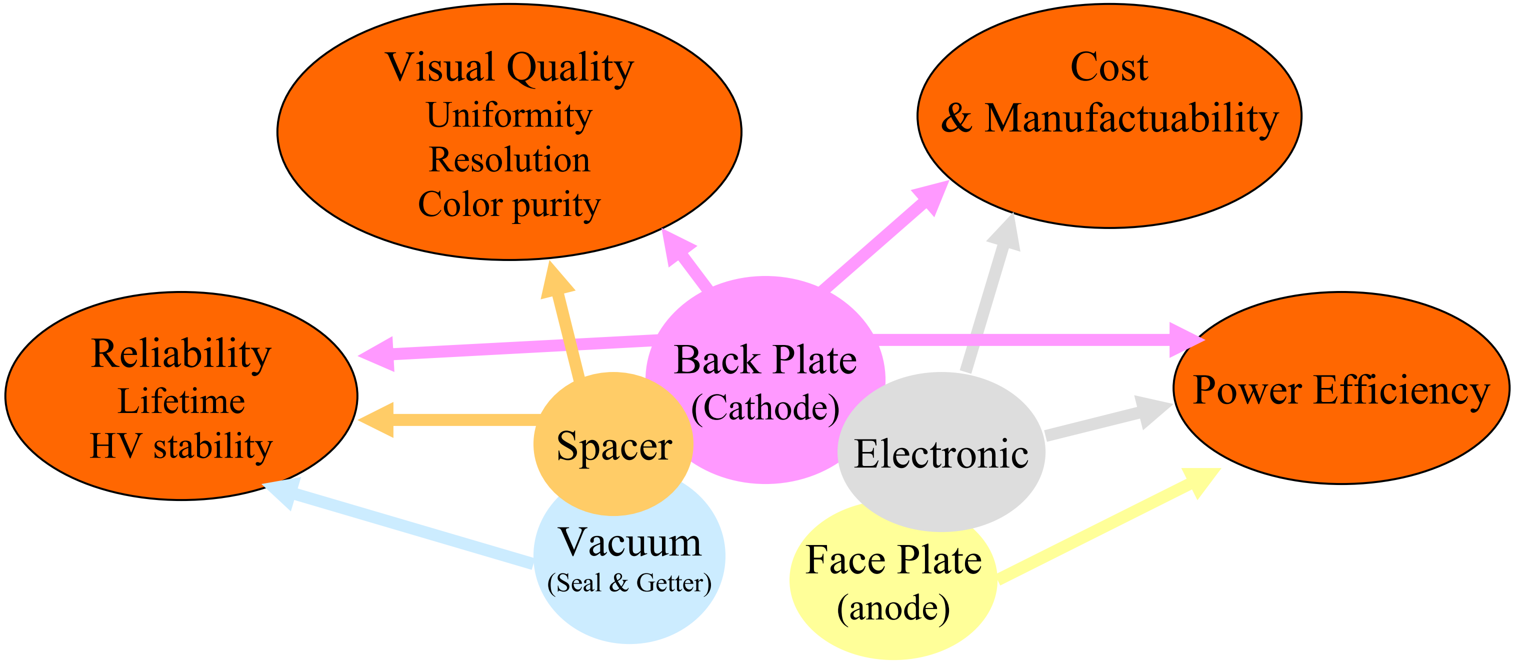
Display System Requirements

- Good color quality
- Wide operating temperature range
- Wide viewing angle
- Good viewability under bright ambient light conditions
- Lower power consumption
- Thin package profile and lower weight
- Competitive with AMLCDs and other FPD technologies

Electron Devices - Common Issues

- Electron emission depends on the work function Φ of the emitter surface
- Electron transport is ballistic and requires a sealed vacuum package
- Uniformity of beam current density
- Cathode geometry, beam trajectories
- Electrode structures: diode, triode, tetrode, pentode, etc.
- Cathode contamination and emitter life degradation
- Effects of electron collectors like phosphors

Basic Components of FED



Key Accomplishments in 90s

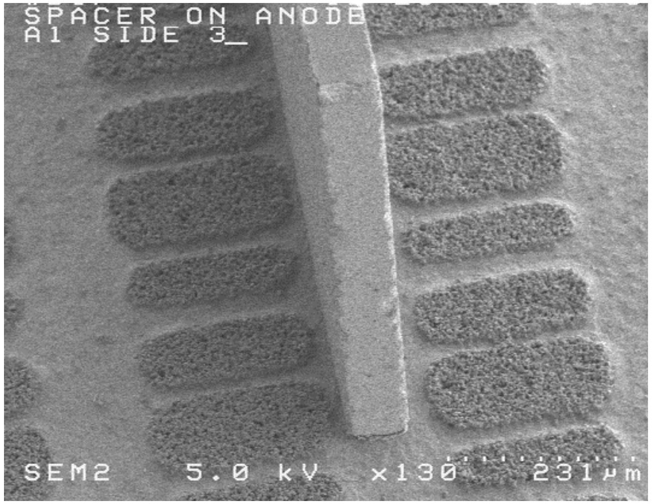
- Demonstrate invisible spacers in large display panel.
- Vacuum seal technique for thin glass panels.
- High voltage drivers and electronics.
- Knowledge of issues like cathode current degradation and phosphors degradation.
- Techniques to achieve high voltage operation stability.
- Device structure and pixel design.
- Understanding requirements of manufacturing for low cost and high yield product – 2D preferred and no precision fabrication
- Characterization techniques for FED.

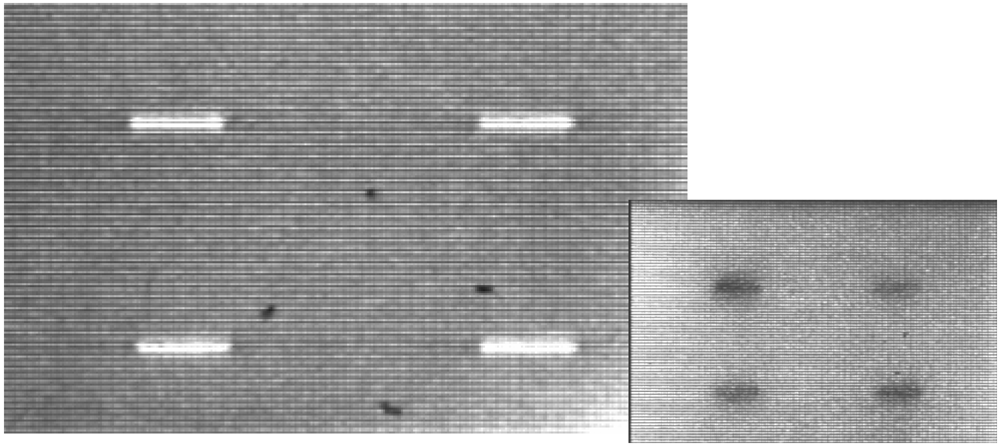
FED Spacer Technology

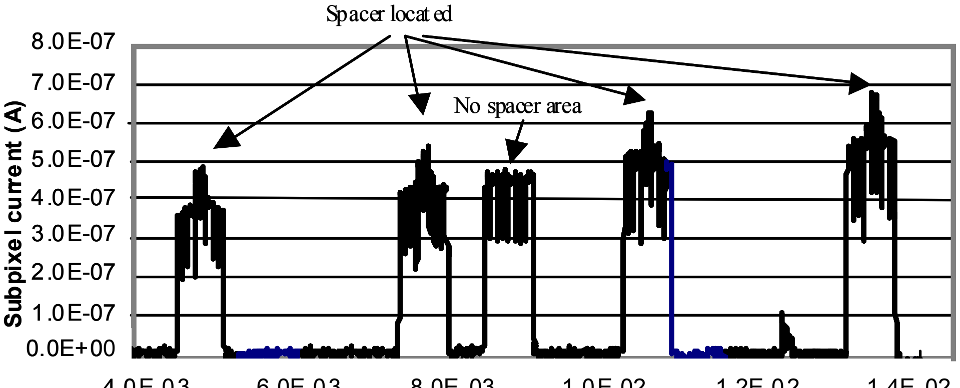
- Materials Requirements
  - Should withstand high voltages across small gaps
  - Low secondary electron emission coefficients
  - Capable of bleeding deposited charge
- Spacer Materials
  - Mainly engineered ceramics
  - Ceramics with special coatings
- Spacer Technology Issues
  - Better understanding of the surface properties
  - Electron-spacer materials interactions

Spacer- contamination

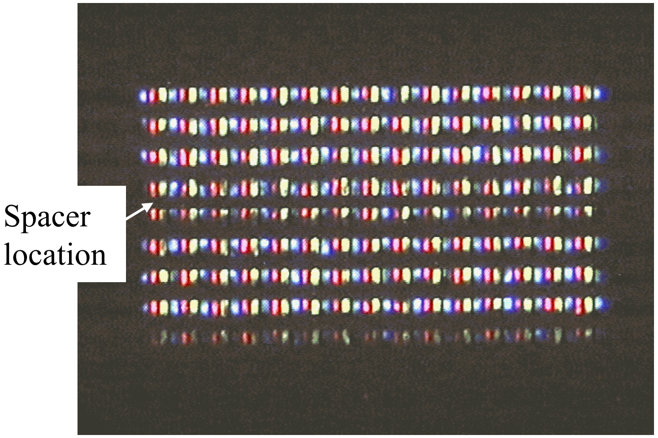
- White spacer is caused by Na contamination on spacer surface.

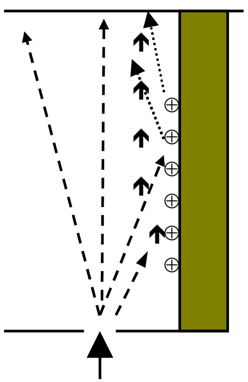




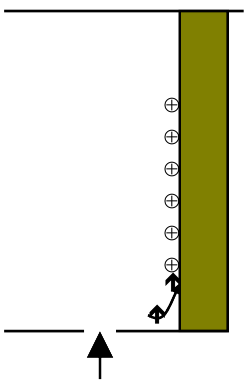


Spacer - Effect of Charging

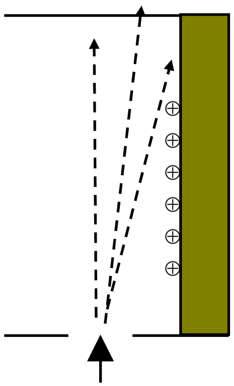




The spacer surface is bombarded by high energy electrons (1k-3k eV). Those electrons create positive charges on the surface due to 2nd electron emission yield of >1. Additional potential produced by those positive charges will change electron trajectory.
$\Delta V = \Gamma \rho I_p / \varepsilon$



Some positive charges may dissipate until next period. But most of them stay on surface because of rough surface, low conductivity.

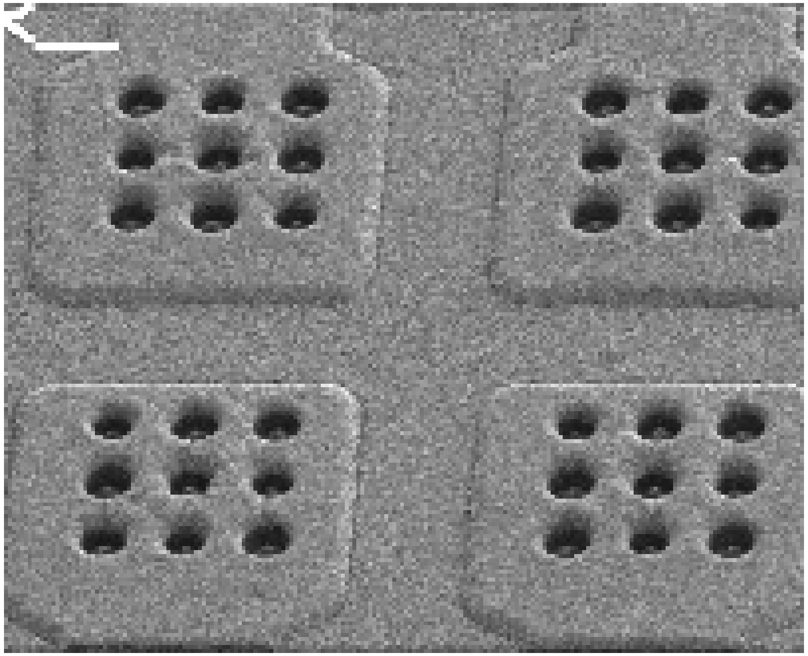


Positive charges on surface distort electron trajectory resulting in "dark" region

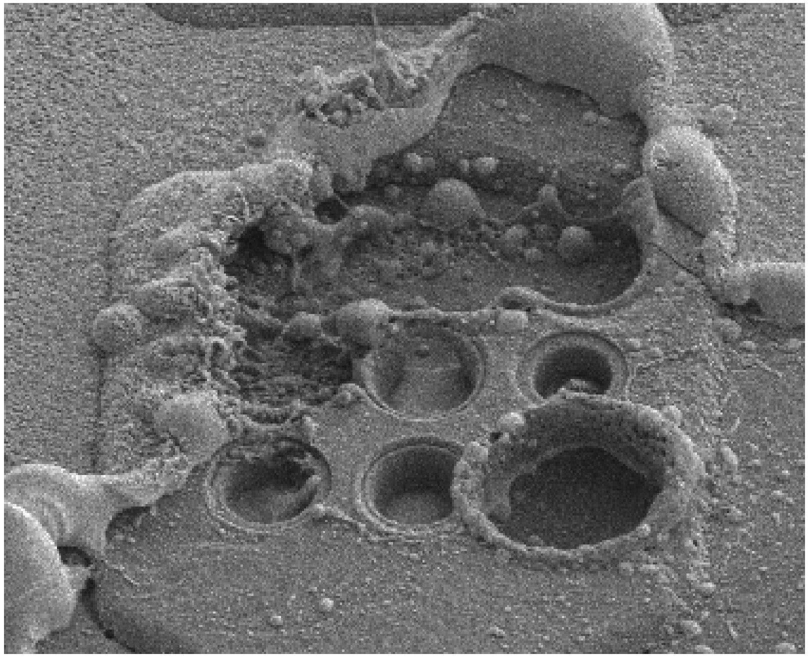
High Voltage Operation Stability

- Emitter damage due to uncontrolled emission current
- Undesirable vacuum levels: Electron impact ionization of the residual gases, followed by the ion bombardment damage of the emitters.
- Electron stimulated desorption from surfaces and device degradation resulting from the gas - emitter surface interactions.
- E-beam induced desorption of gas from phosphor and subsequent adsorption on tips.
- Emission from only few sites, leading to current run off
- Joule heating, melting of the emitter materials
- Dielectric breakdown between the cathode and anode
- Excessive leakage between cathode to anode electrical paths
- Particulate contamination and resulting damage

Cathode Destruction due to Uncontrolled Emission

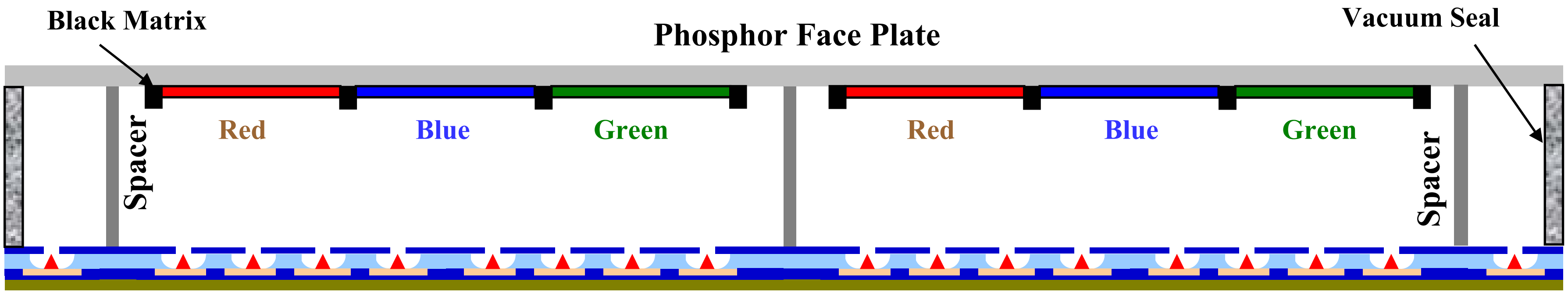


Before Arc Damage



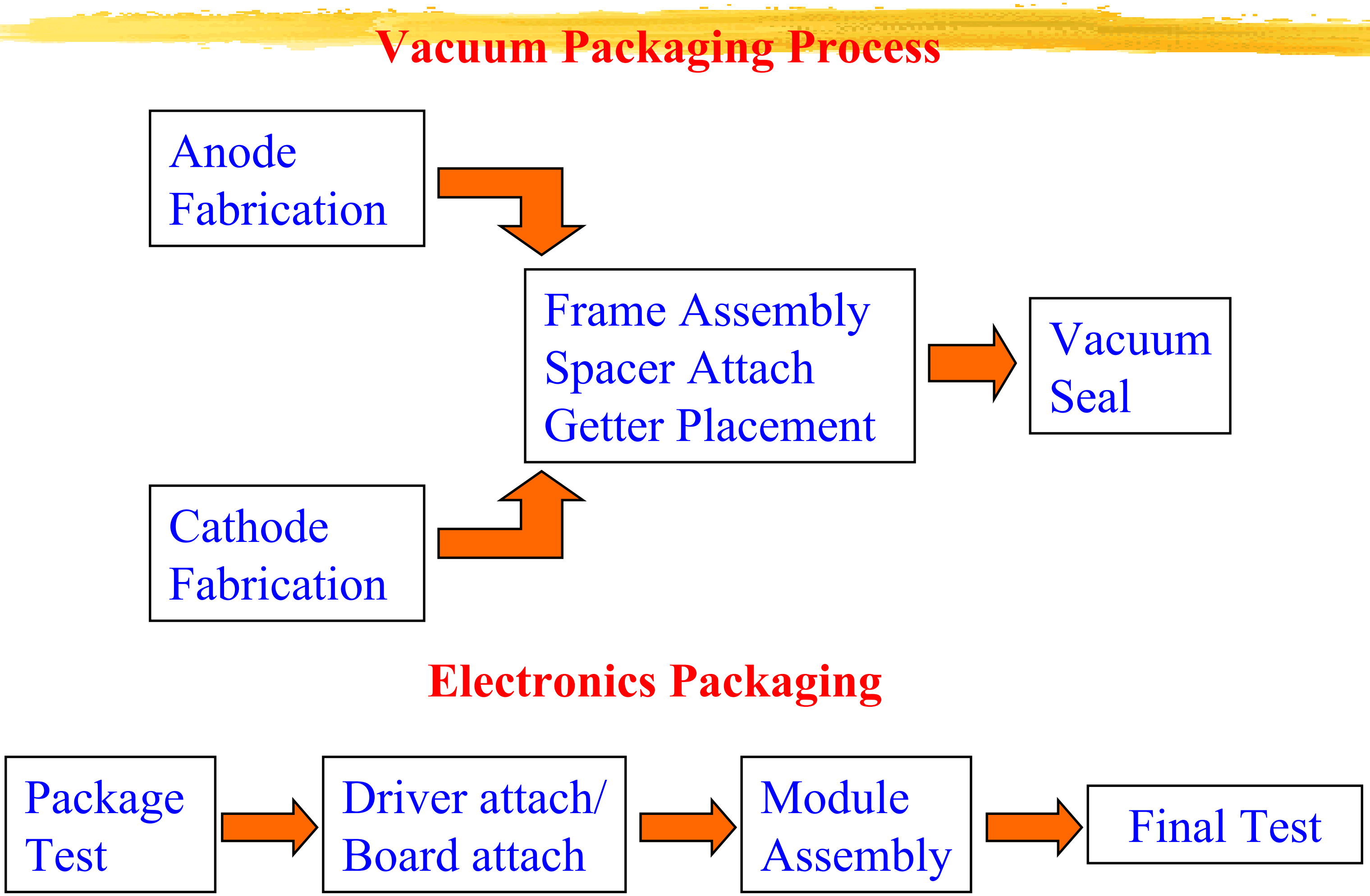
After Arc Damage

Field Emission Display Package Outline

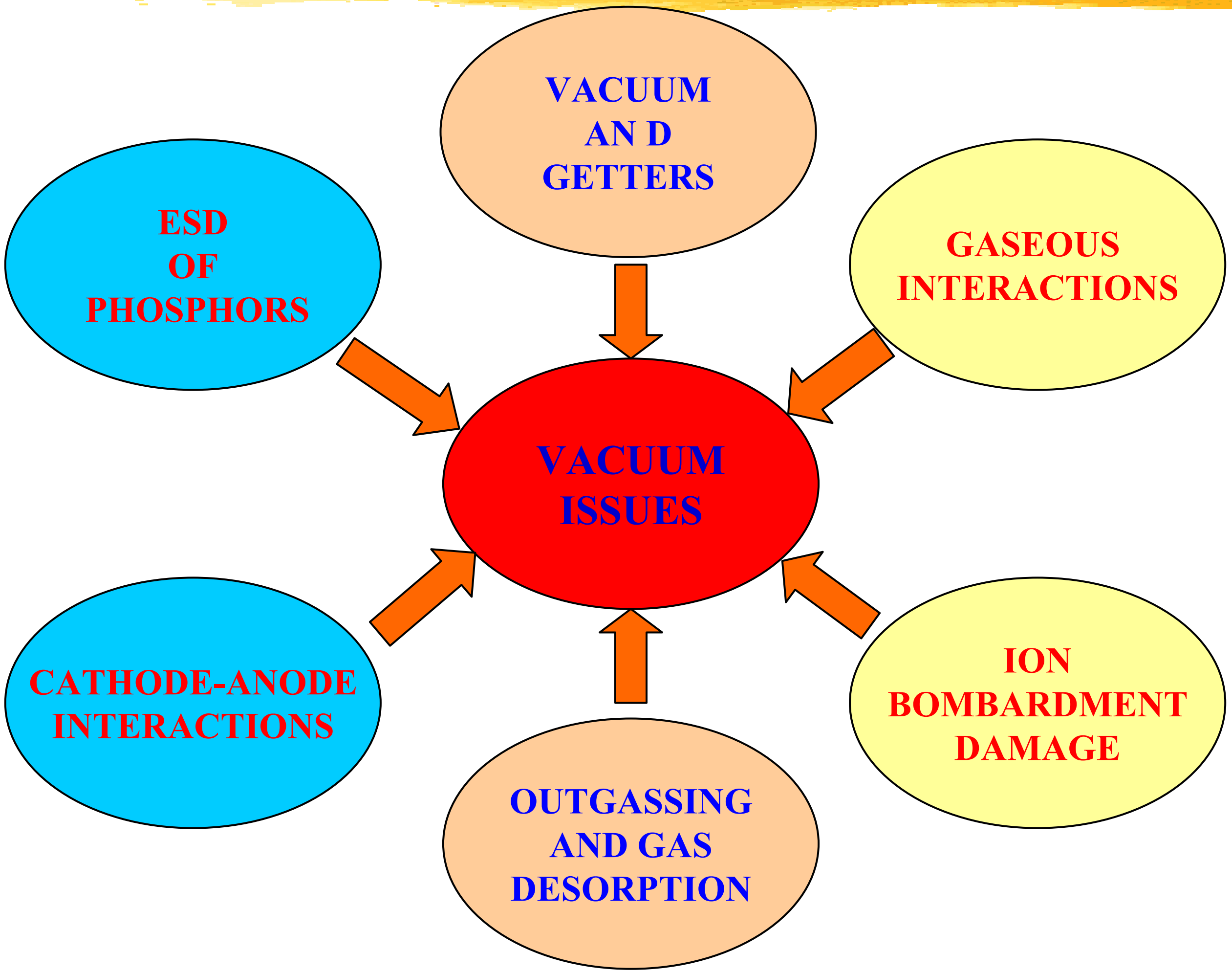


- Requires a hermetically sealed vacuum package
- Maintenance of high vacuum during the package life
- Spacers to reduce glass bowing

Package Integration - Typical Process Flow



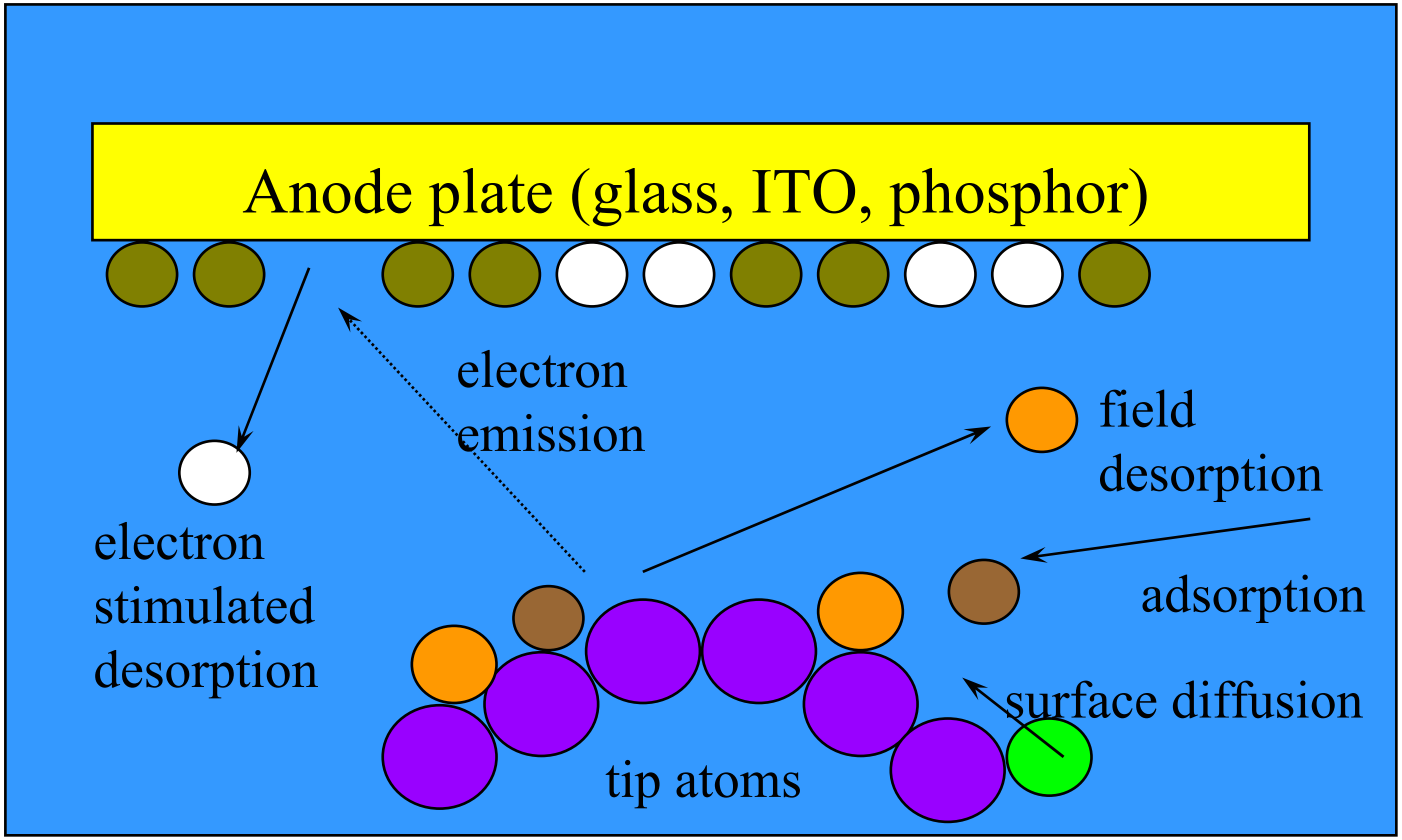
Vacuum Technology Issues



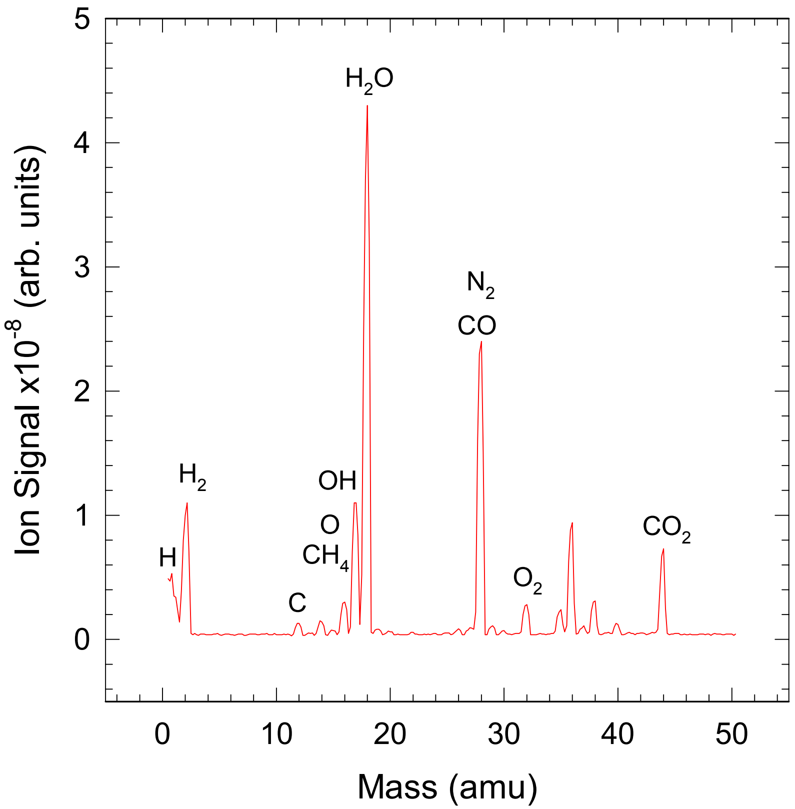
Maintaining a Good Vacuum

- Getters are used to maintain a good vacuum in the package
- Major issues:
  - Better understanding of the outgassing characteristics of FED materials
  - Reduction of desorption from phosphors
  - With increasing display size, gas flow through the narrow spacing between the anode and cathode becomes a major problem
  - Distributed gettering will become important
- Vacuum levels in the 10^{-6} to 10^{-7} Torr range are required for long life
- Nanoparticles can significantly improve pumping rate of the getter

Vacuum Technology Issues



Typical Gases inside FED Panels



Residual gas contents of a typical FED package

- Most of the residual gases are typically H_2O, O_2, CO_2, CO, H_2, hydrocarbons like CH_4, process residues, gases trapped inside sputtered layers
- With the metal and silicon emitters, it is the oxygenic gases we need to be concerned with.

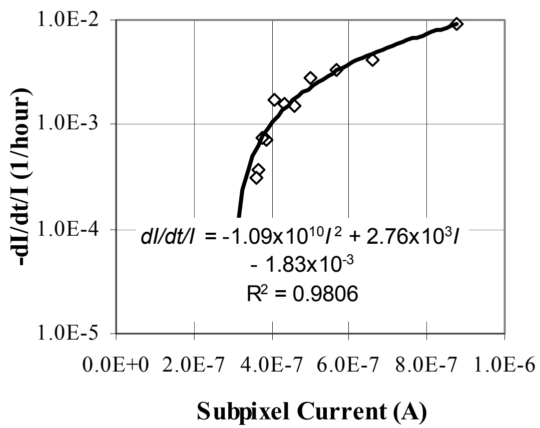
Cathode Degradation and lifetime model

- Interaction of gases with the cathode resulting in modified tip surface work function Φ
- Ion impact and sputter induced tip shape modification
- High field effects such as field desorption and dissociation
- Detail description of the model was published in IEEE Trans on Electron Device.

Life model

Basic Assumption
Partial coverage;Ionized species more reactive; Self-clean capability

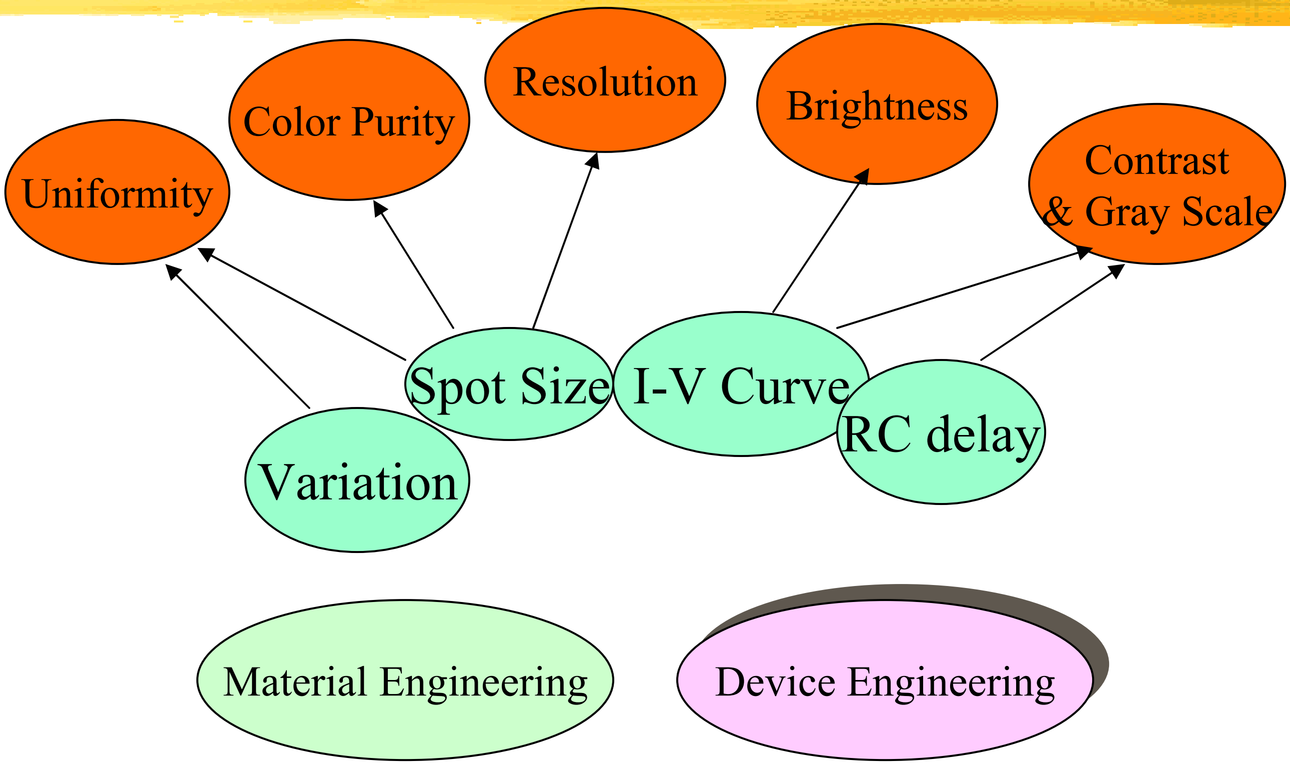
$$\frac{dI}{Idt} = a - bI - cV_a I^2$$



FED Reliability - Fundamental Issues

- Vacuum Technology Issues
  - Outgassing of surfaces
  - Electron stimulated desorption
  - Vacuum seal integrity; Getter pumping
- Materials
  - Cathode degradation, Phosphor degradation, Cathode-Phosphor interaction
  - Charging of dielectrics and spacers
  - Dielectric breakdown
- Design and Systems Engineering
  - Electron beam spot size issues
  - Beam focussing issues

Display Visual Quality & Cathode Characteristics

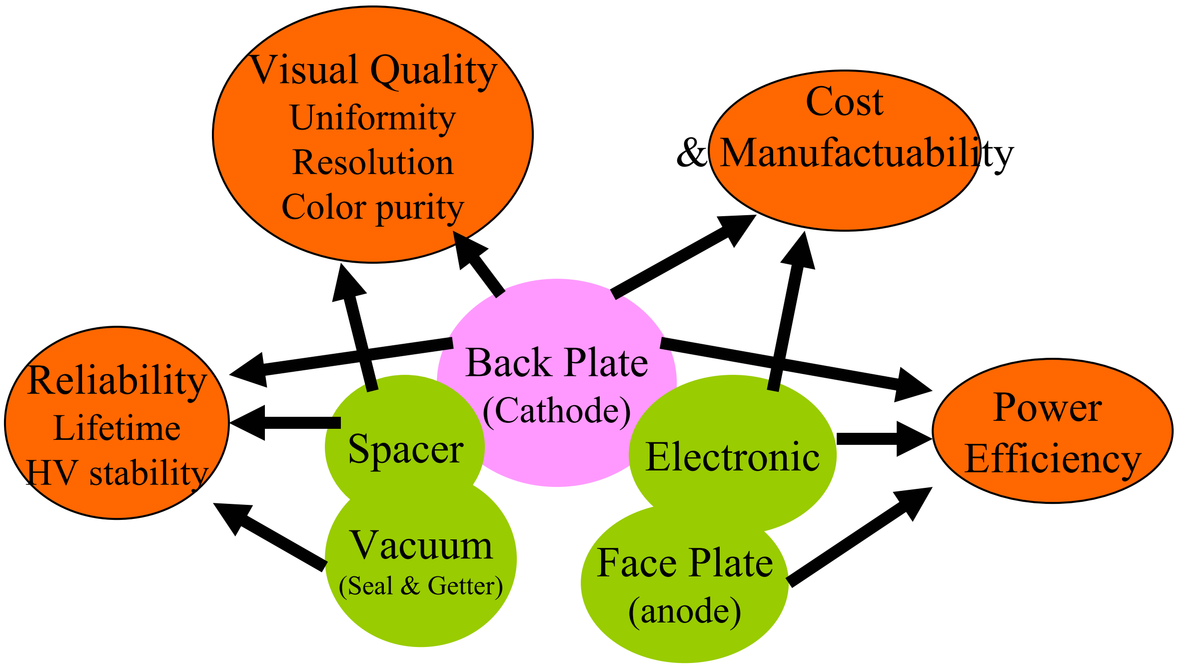


Understand the Issues: Spot Size, Spatial Distribution, RC delay and Current sensitivity

How Can Nanotech help?

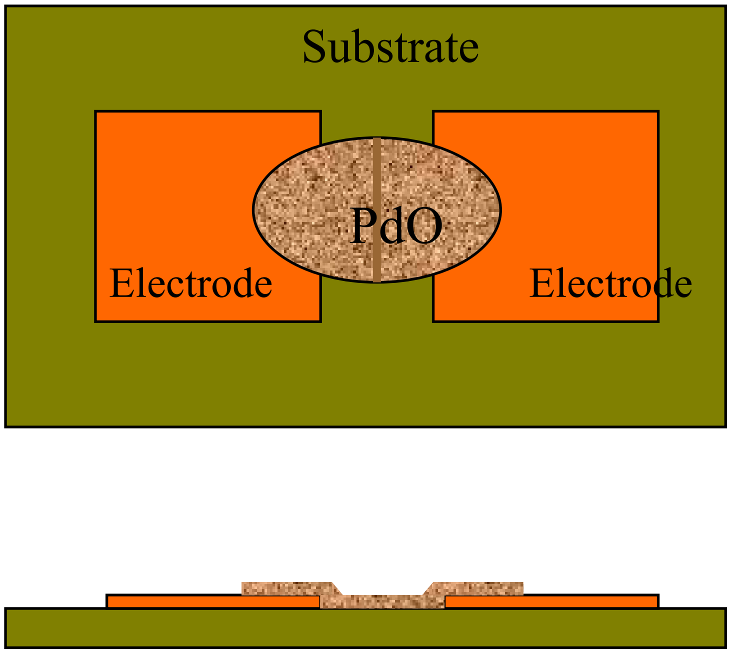
- Nano material may be a good material for gettering material.
- Nanoparticle phosphor can improve the efficiency.
- Nano material is a new generation of field emission cathode.

Basic Component of FED



Surface Conduction Cathode - Nanoparticle

- Surface emission display from Canon is based on surface conduction emission from nanoparticle films.
- Ink-jet deposit a droplet of PdO to form a 10 nm thick, 100 μm size film
- Create ~ 10 nm rupture on the PdO film
- Field emission occurs when a voltage is applied across the gap
- Advantages
- Simple device structure - Low manufacturing costs
- Screen printing - suitable for large panel fabrication

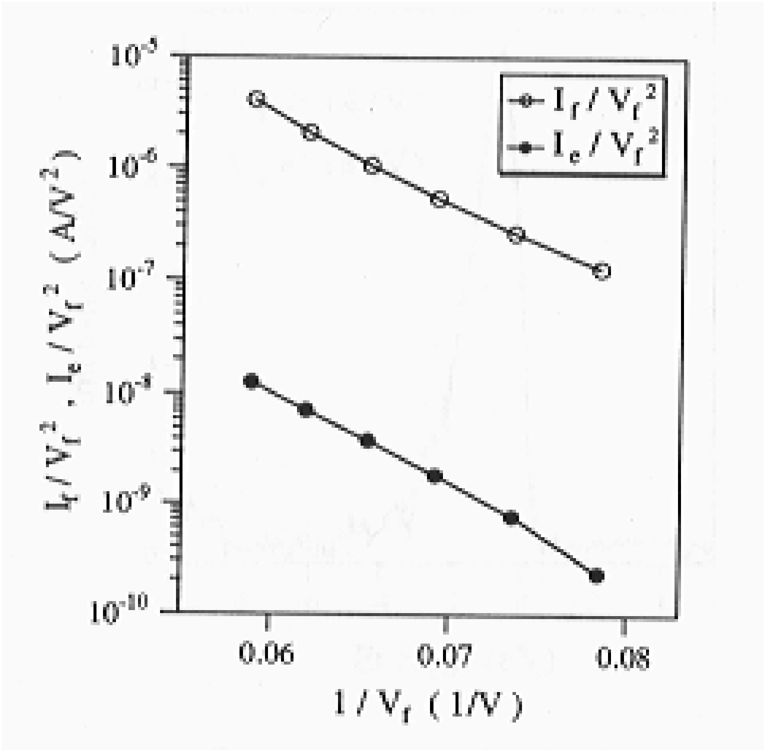


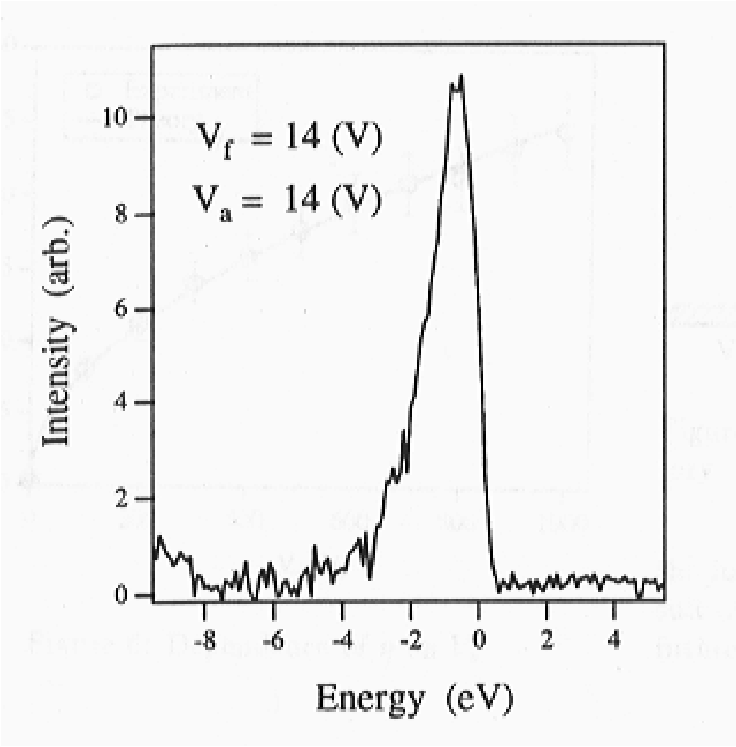
Canon's Surface Conduction Emitter

E. Yamaguchi, et al, SID Digest, p. 52, (1997)

Canon SCE - Emission Characteristics

- Anode current is about 0.2-0.5% of the total emitted current.
- Low emission efficiency, comparable to Spindt FEAs.





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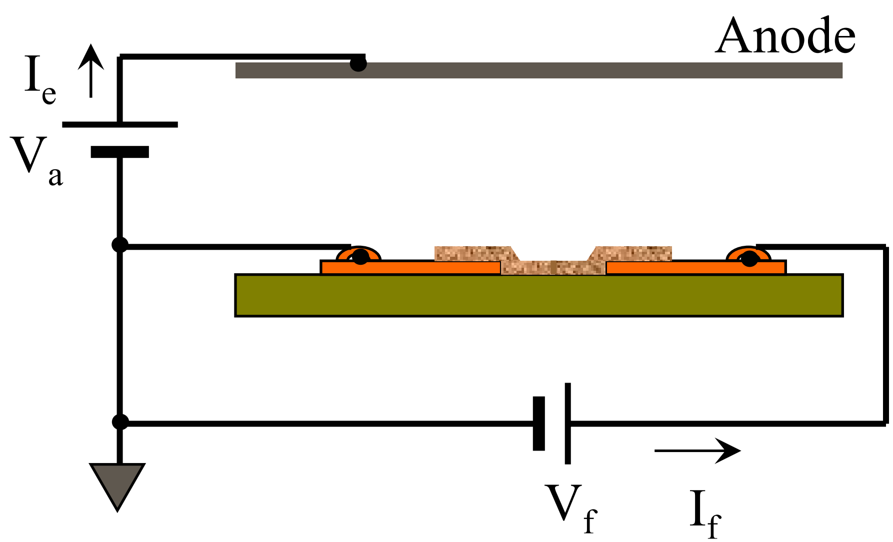
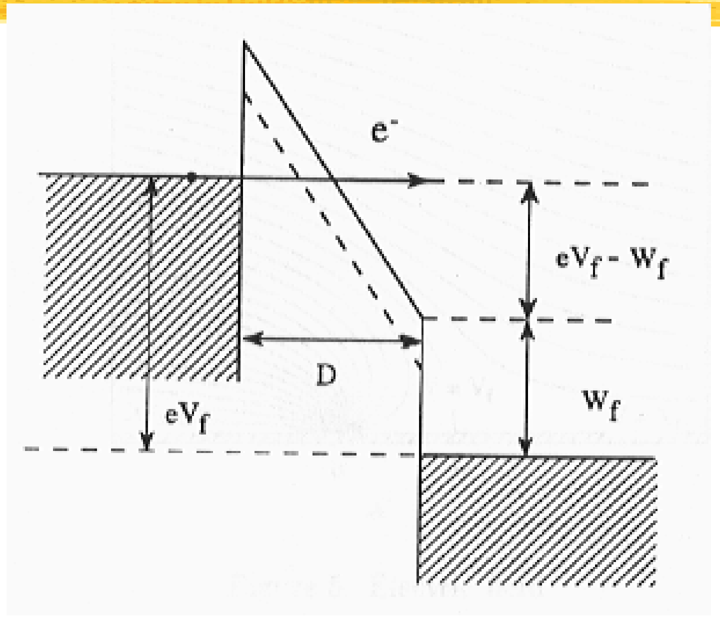
Canon SCE - Emission Physics





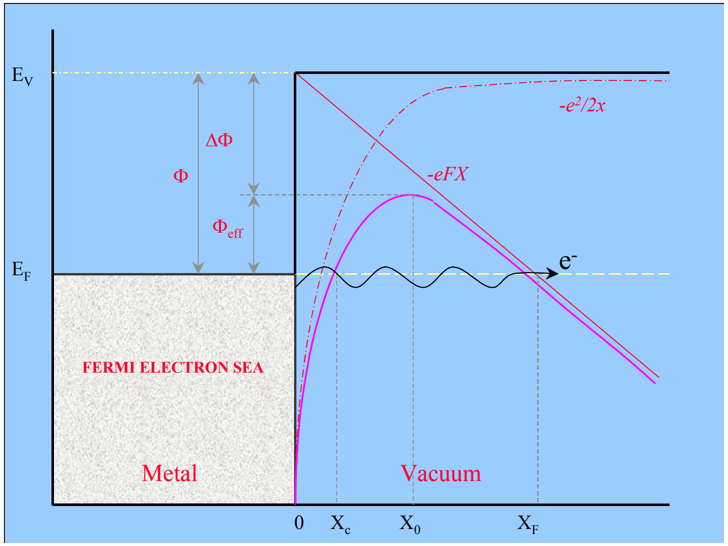
- Electron tunneling through a barrier (like a double quantum well structure)
- Electron scattering on the right edge
- Some of these scattered electrons get towards the anode

E. Yamaguchi, et al, SID Digest, p. 52, (1997)

Why is Carbon Nanotube a promising candidate for FED?

- They are very sharp! 2 um long and 10 Å wide!   2000:1 Aspect ratio. The electric field at the tip which pulls out electrons is ~ 2000 times greater than the parallel plate field!
- Basic material: Carbon. Unlimited resource.
- Key Issues
  - a traditional field emitter; follows FN plot.
    - Sensitive to surface conduction, geometry and environment.
    - Spotty emission
  - Uncontrolled growth.
  - No device structure yet.
  - Lifetime?
  - Low voltage operation, <5-10 volts.

Basics of Field Emission



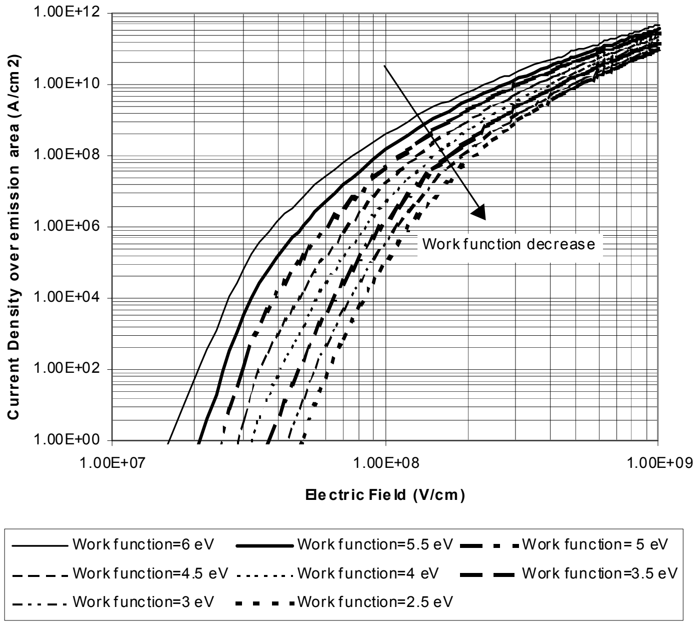
Key obstacle

Emission current is very sensitive to work function and electric field

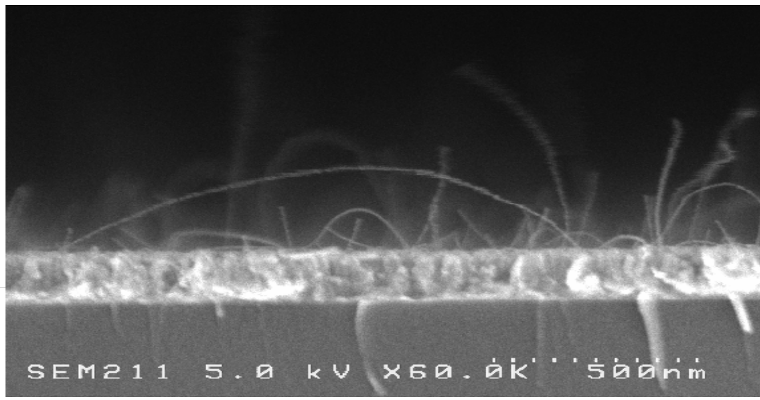
$$J = \frac{\alpha E^2}{\Phi t^2(y)} \exp\left(\left(-B \frac{\Phi^{\frac{3}{2}}}{E} v(y) \right) \right) [A/cm^2]$$

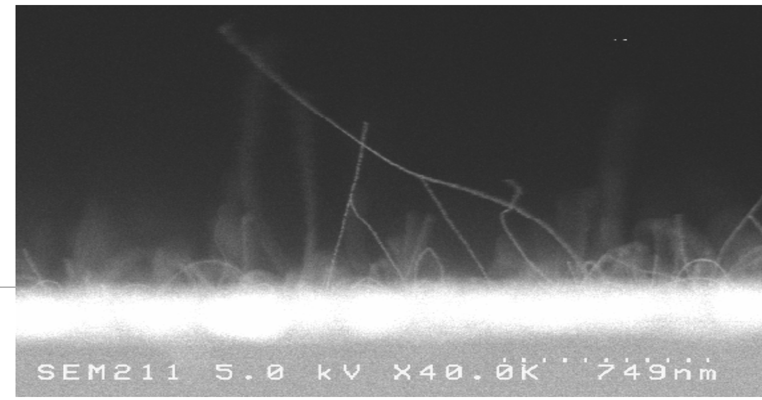
$$E = electric\ field\ at\ surface; \Phi = work\ function$$

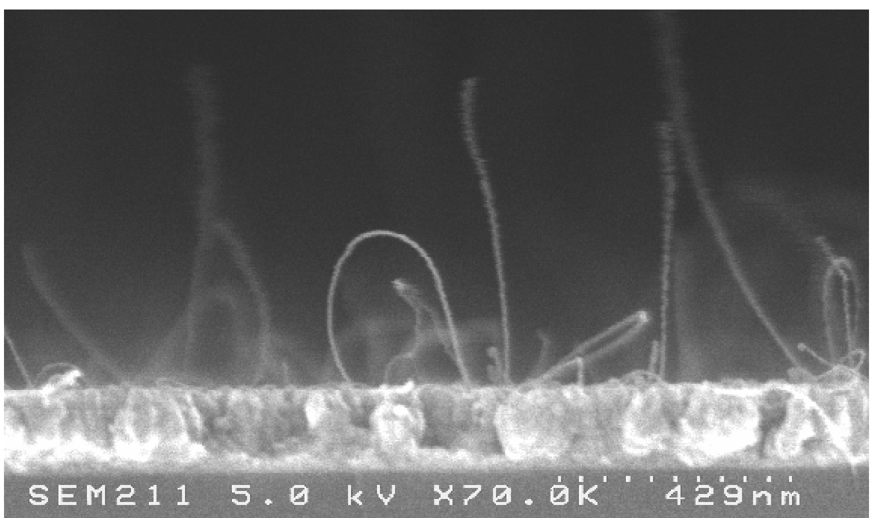
$$\alpha, B = const.; y = 3.79x10^{-4}\frac{\sqrt{E}}{\Phi} : image\ correction$$

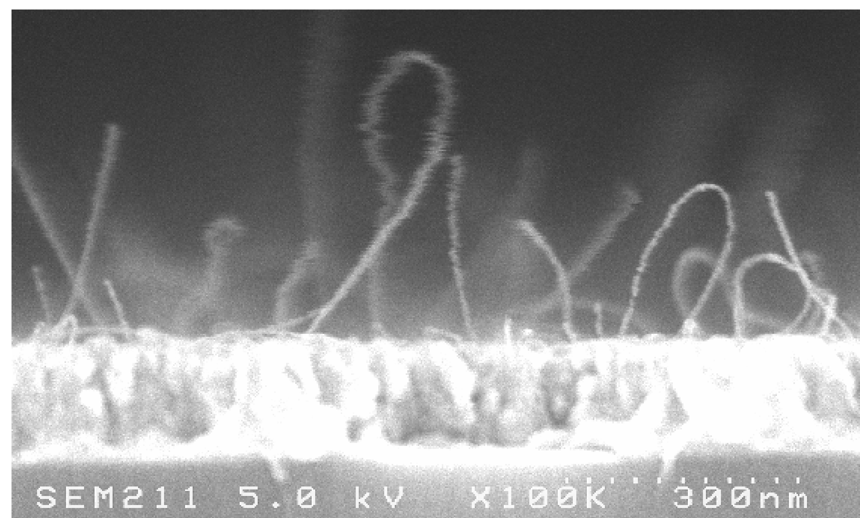


Cross-section of nanotube device





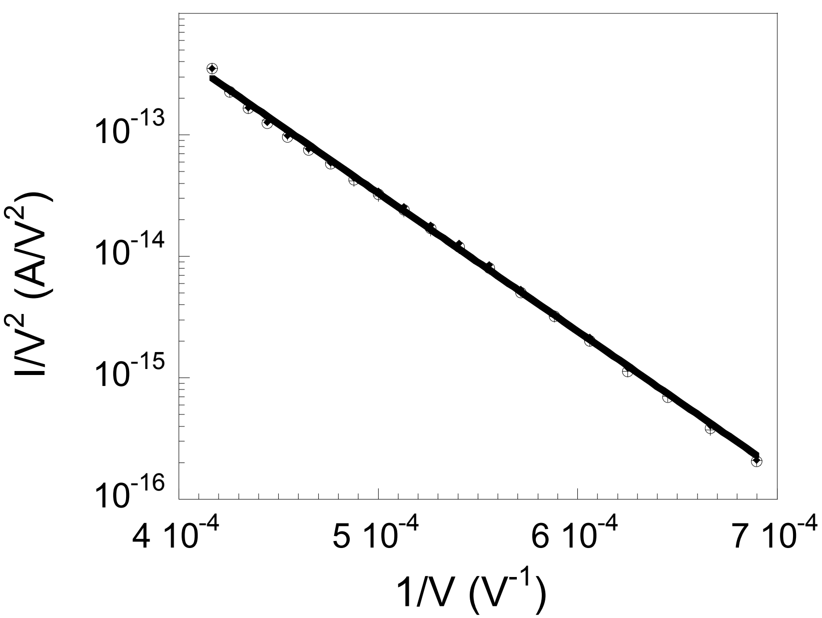




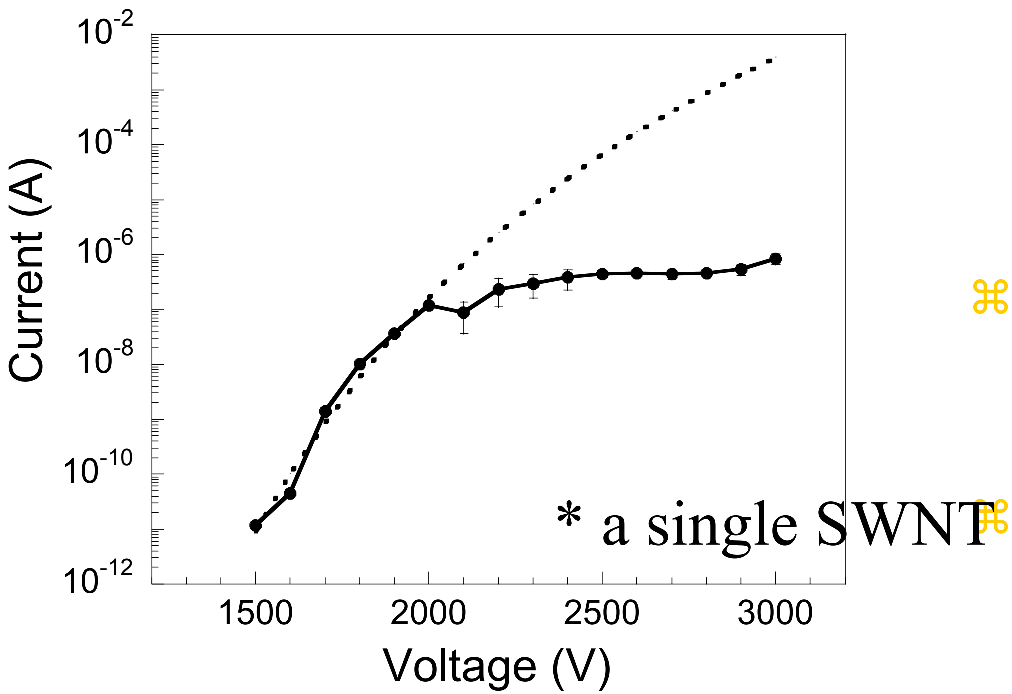
Emission Uniformity - Major Issue

- The I-V curve is consistent with electron tunneling. The curve produces a straight line on a Fowler-Nordheim plot.
- CNTs face the same challenges of other traditional FE like microtips.
  - Uniformity
  - Stability
- Approach to achieve uniform emission
  - ballast structure
  - More emission sites to make each pixel the same statistically.
  - New device structure.
  - New driving scheme.

Fowler-Nordheim plot

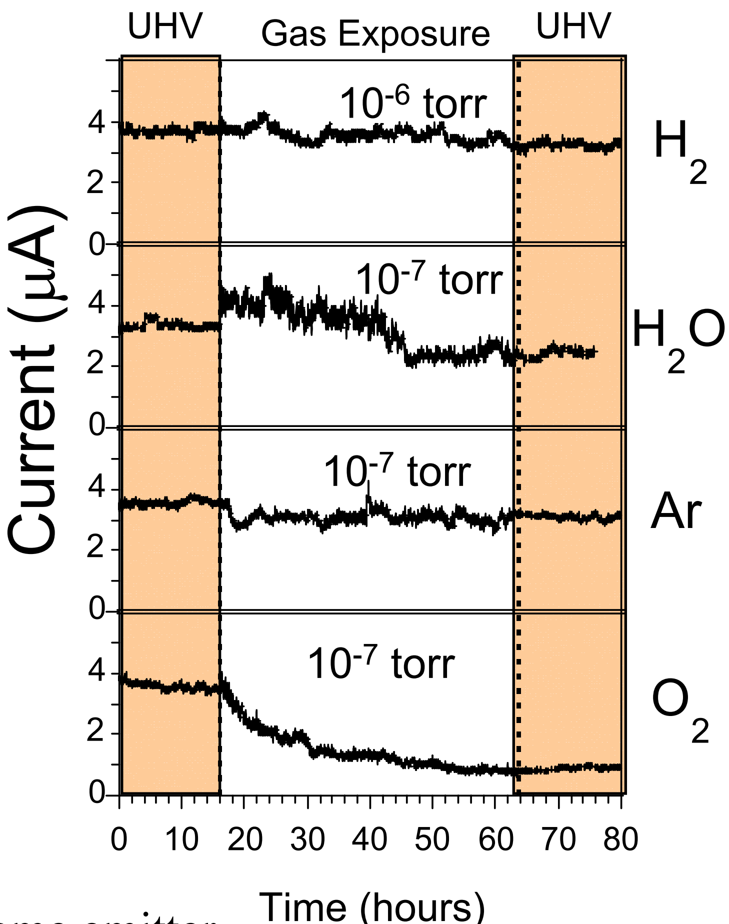


Current Saturation- may help



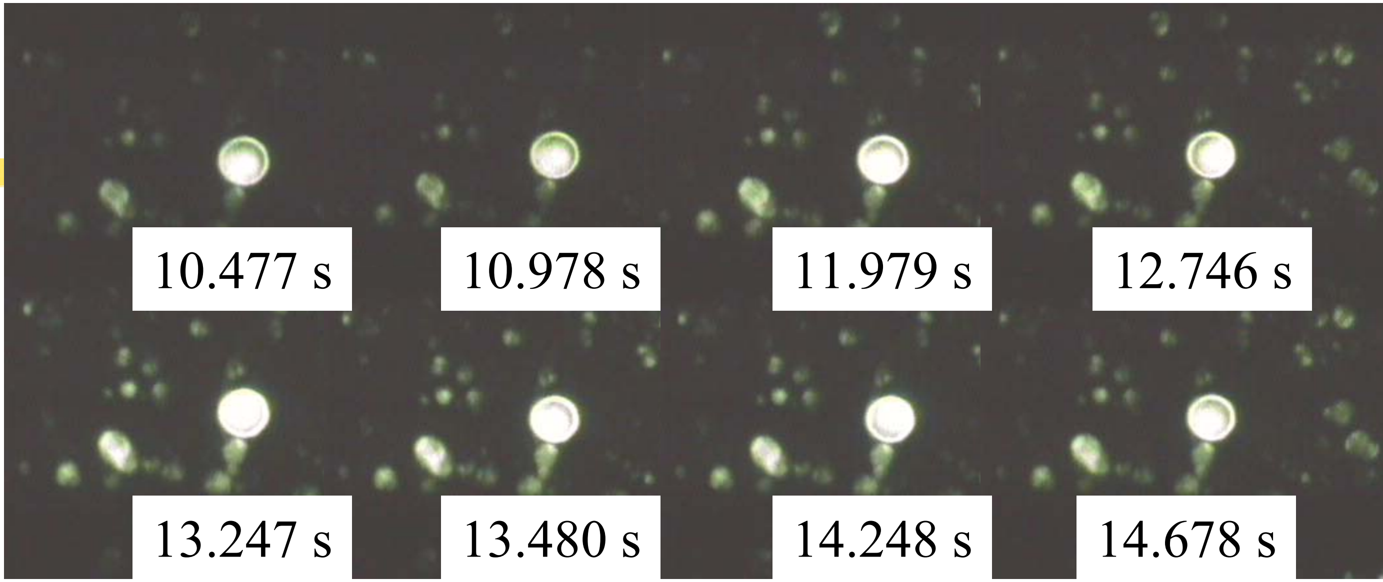
- Current saturation is observed:
  - In MWNTs by Saito et al.; Collins and Zettl; Bonard et al., Xu and Brandes
  - IN MWNTs and SWNTs, and individual SWNTs.
- Saturation could be the greatest thing for FED. May help fix uniformity problem if we know how to implement it.
- Some kind of current limiting function is needed to compensate for non-uniform emission from CNT

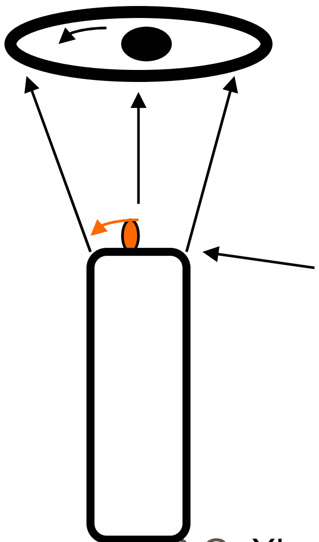
Stability of SWNT field emission in Gas Ambients



Curves on same emitter

- Ok with H2 and Ar.
- Some degradation under H2O.
- Serious degradation under O2.
- More study under display environment is needed.



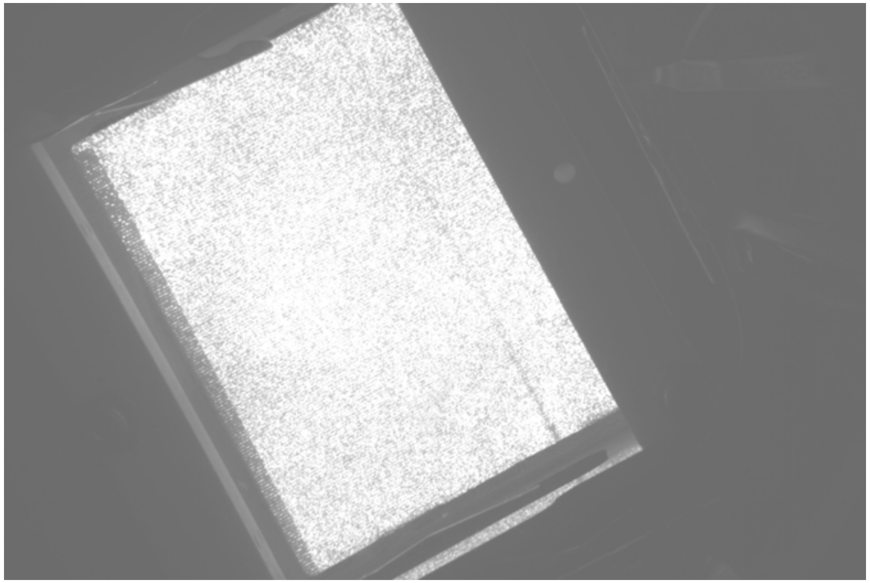


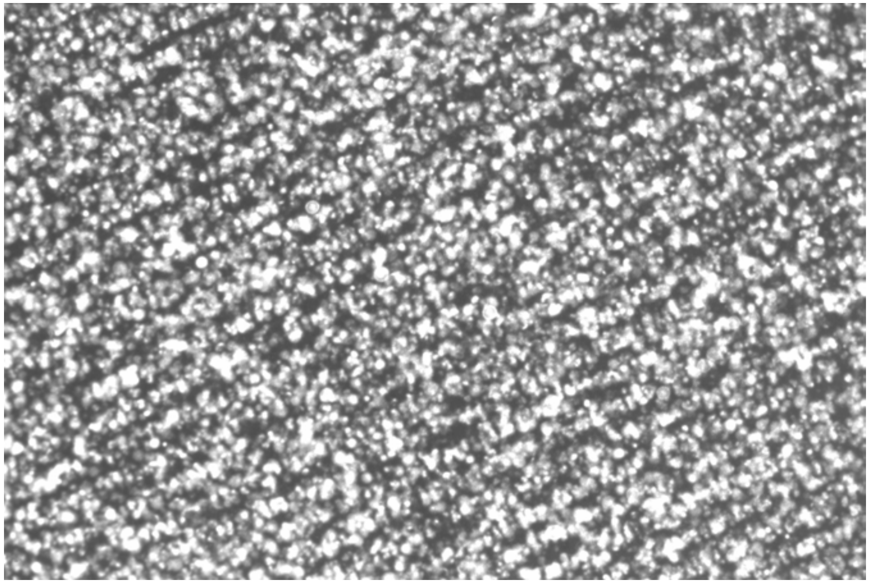
field emission from adsorbate on top

Thermionic emission from wall

Nanotube Deposition Techniques

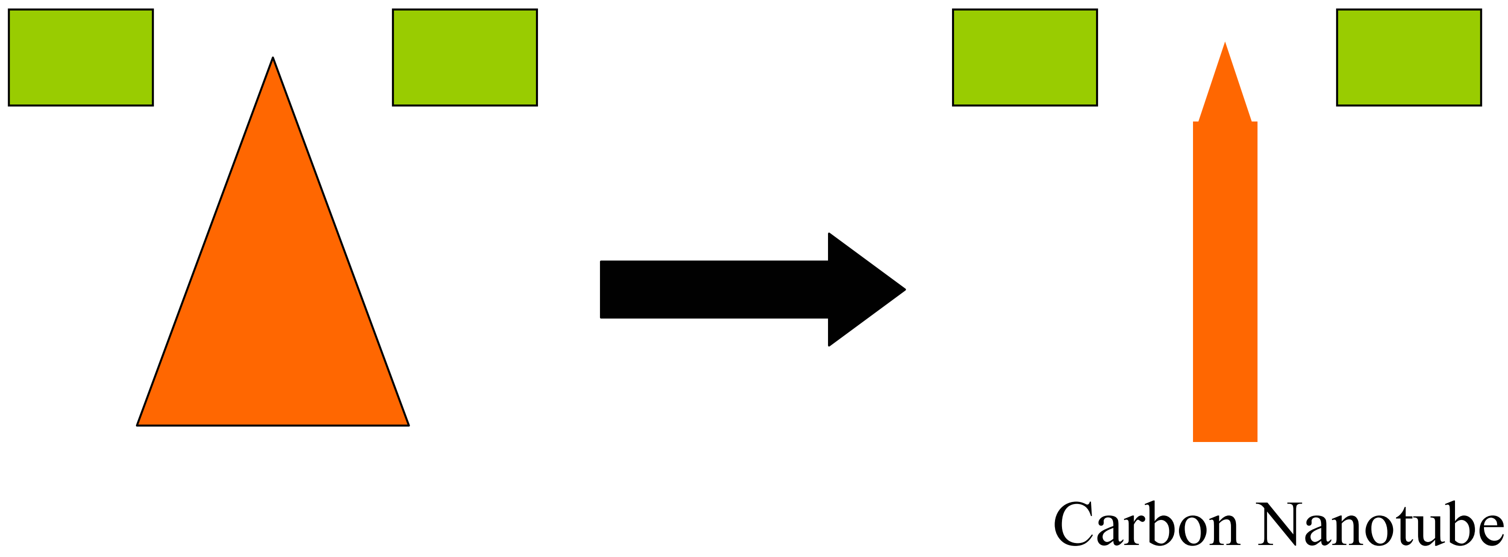
- Key Issues:
  - nanotubes must be "sticking up"!!
  - Nanotubes have high surface energy and they like to stick to the substrate
  - Nanotubes must be bound down strongly and reliably
    - just one loose nanotube can cause arcing
- Sparsely distributed to avoid field screening
  - as far apart as they are tall
- Low Temperature Deposition



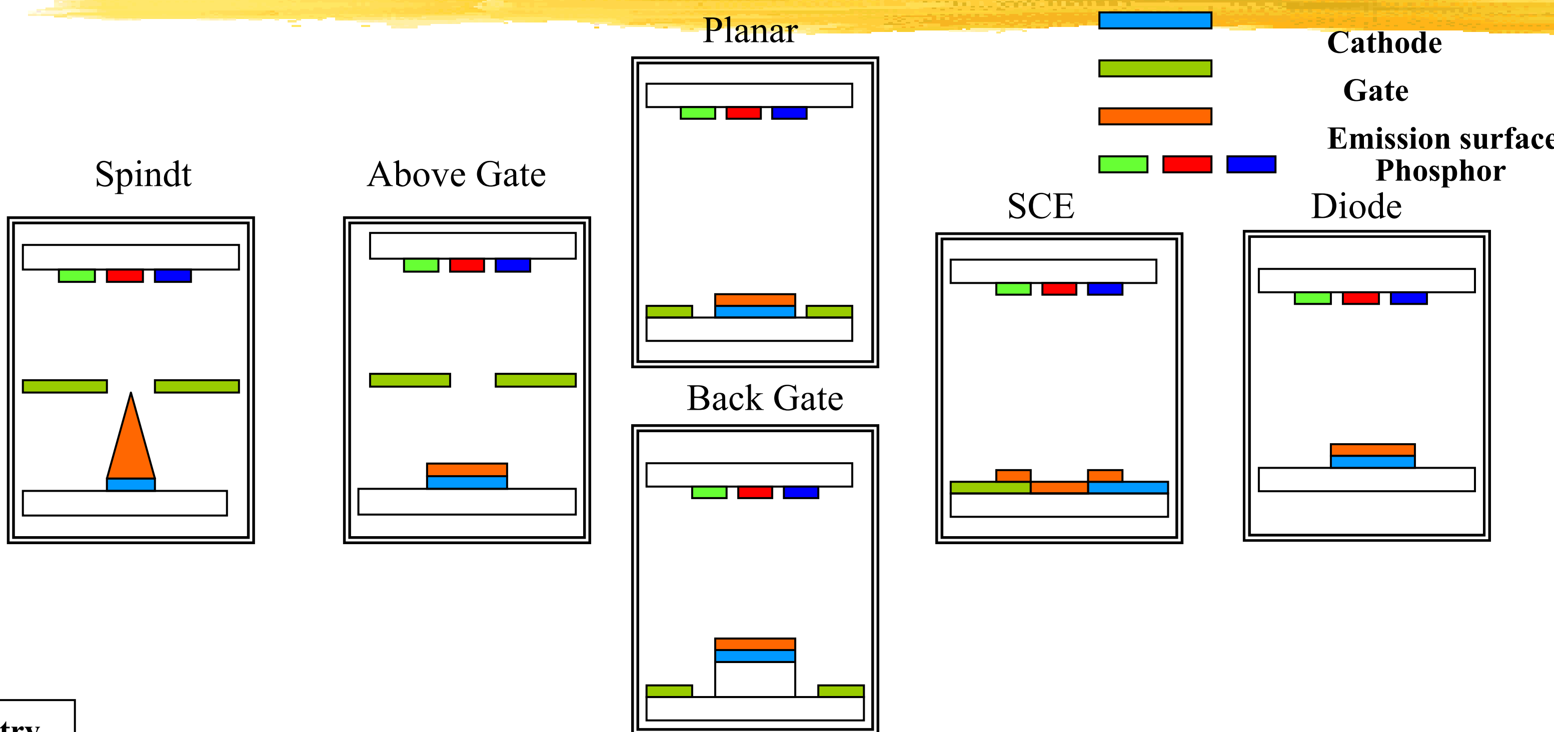


Ideal gated field emitter

- Ideal but not practical



What is the device structure best suited for CNT?



Geometry	**3D** →	**2.5D** →	**2D** →	**"1D"**
Precision fabrication	**Critical** →	**Less critical** →	**Not critical**	
Pixel Cap	**High** →			**Low**
Emissive efficiency	**99%** →		**Less than 1%**	

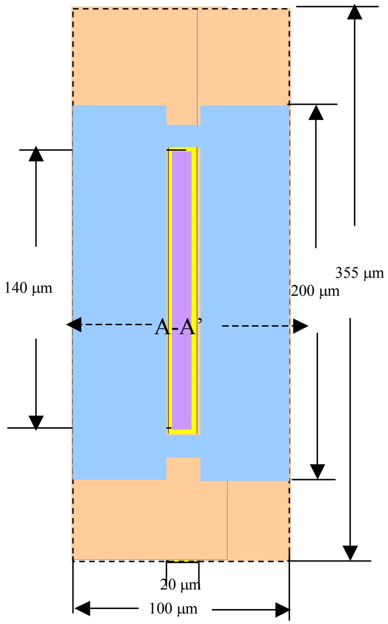
Basic Device Requirement

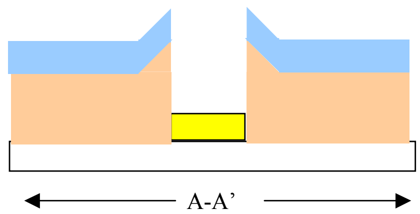
- Diode is the simplest but switching voltage is too high.
- Basic Requirements
  - No needs for alignment between gate and cathode
    - self-aligned structure
    - Gate and cathode on the same layer.
  - Low pixel capacitance-a must for large display
    - no overlap between gate and cathode
  - Low switching voltage
  - Emission Controllability
- New Driving Scheme - depletion mode operation

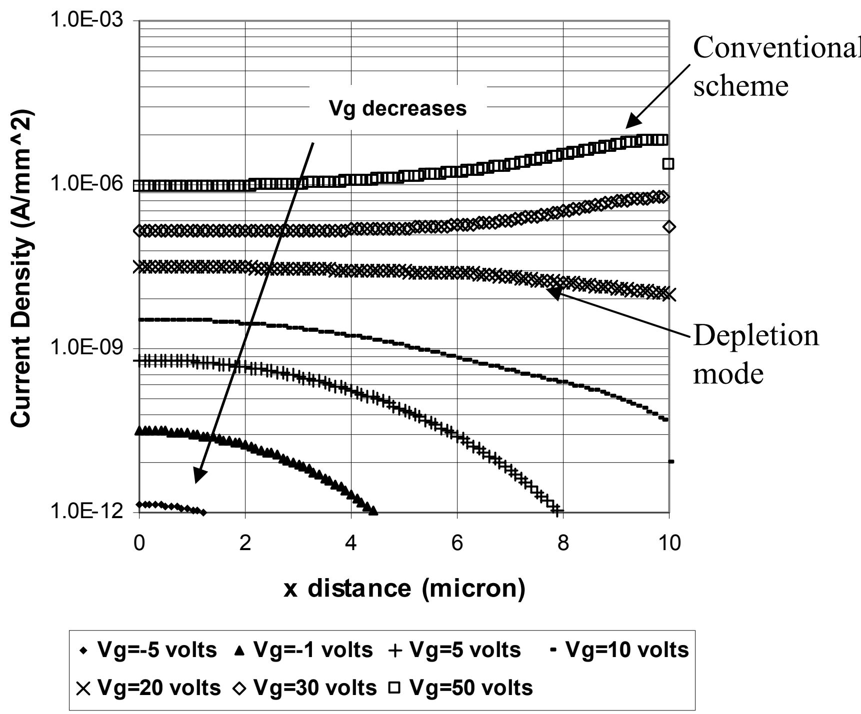
Depletion Mode Operation

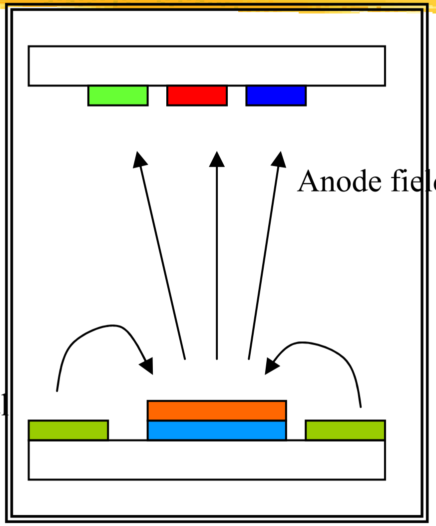
- Detail discussion was published in IEEE Trans on Nanotechnology, vol.3 no.3, Sept. 2004, pp404
- Contrary to the conventional driving scheme, in depletion mode, the gate is used to turn off emission not to turn on emission.
  - Electrons emit under anode field – require low field emission material
  - More stable, avoid edge emission.
  - Better uniformity
  - Work with planar structure
  - Small beam spread
  - Less critical requirement for emission layer alignment to the gate.
- Disadvantages
  - Need highly selective deposition of emissive material
  - New Concept in field emission display.

Anode voltage produce

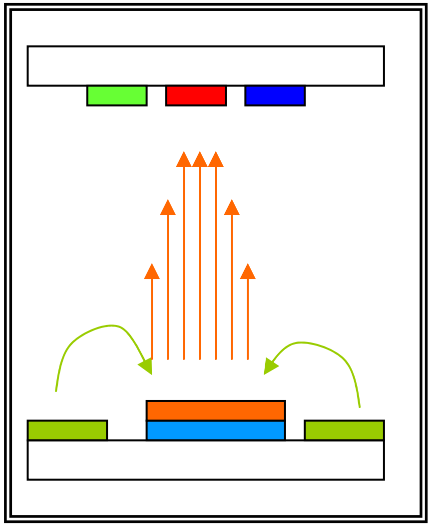








- The electric field on emission surface generated by applied anode voltage must be strong enough to extract electrons.
  - Anode voltage=3-6kV, gap=1mm; required operating electric field=3-6V/um.
  - Carbon nanotube performance matches the requirement.
- High electric field at center and low at edge. Avoid edge emission and achieve stable high voltage operation.
- Since lateral field is very small under emission conditions, beam spread is small, similar to that from diode.



Summary

- Investment in 90s established valuable infrastructure for next generation field emission display technology.
- Many challenging issues, such as spacer visibility, high voltage operation stability, vacuum sealing, pixel layout and drivers, which was little known to us in 90s, now are better understood.
- Know more about manufacturing issue of field emission display and requirements of field emission cathode.
- Nanotechnology can have great impact on phosphor material, gettering material and specially emission material.
- Carbon nanotube has great potential to revive field emission display technology but difficult engineering challenges are still ahead.
  - New device structure
  - Process to produce uniform emissive material.