Scaling up total emission current from Field Emitter Arrays

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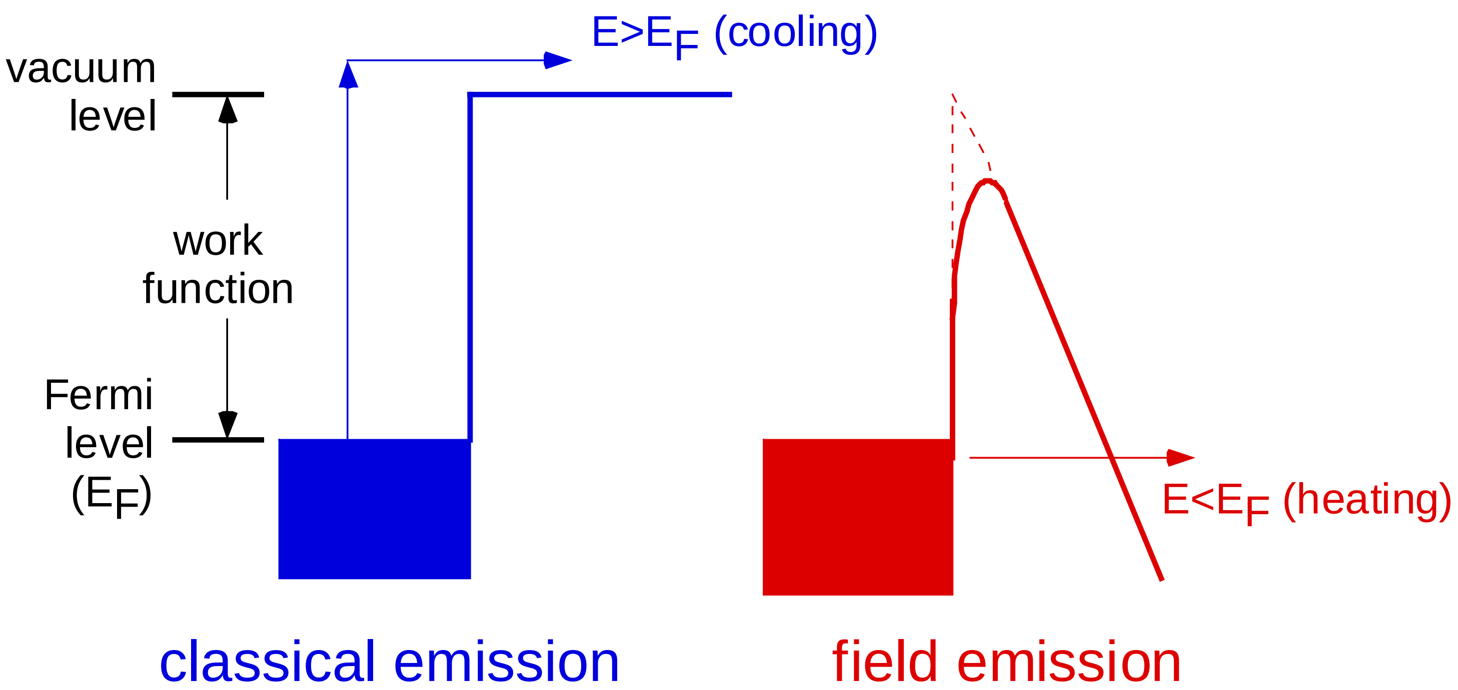
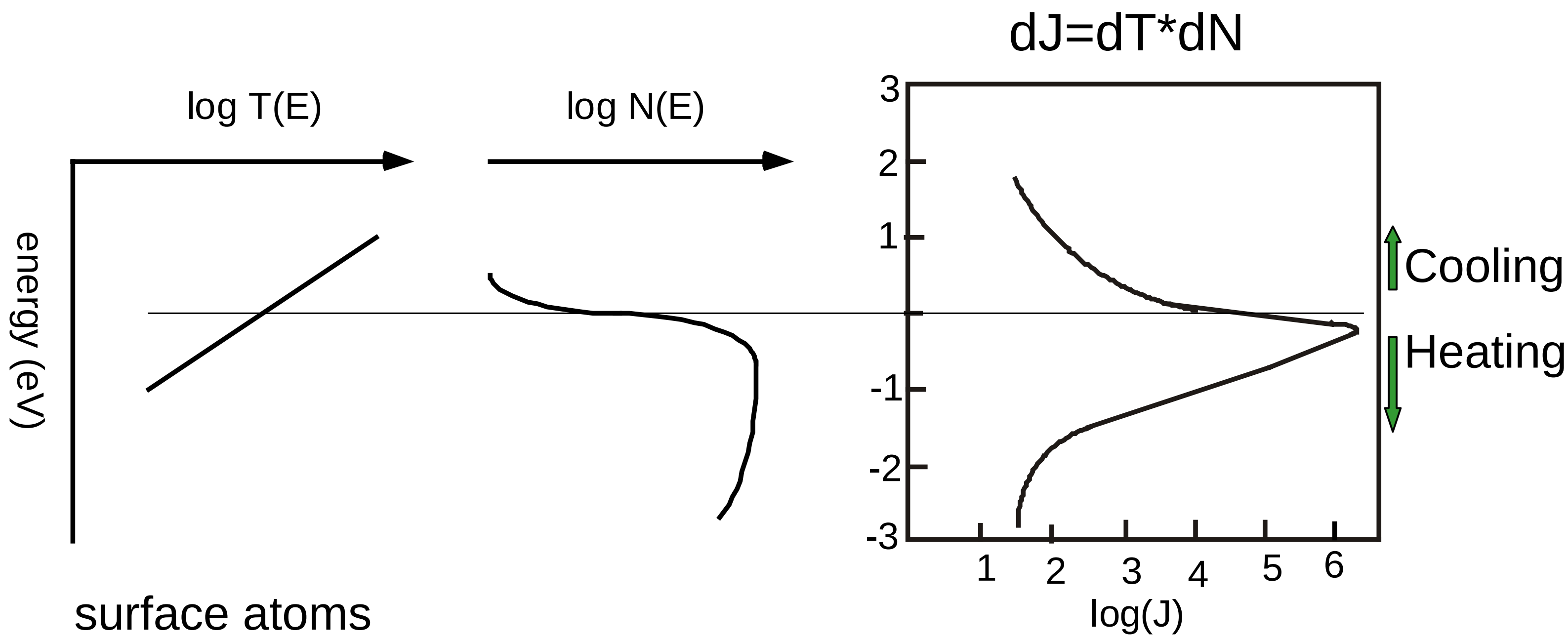
What is field emission?



electrons *tunnel* from solid to vacuum

they don't have to be excited (with heat or light)

Field Emission Physics



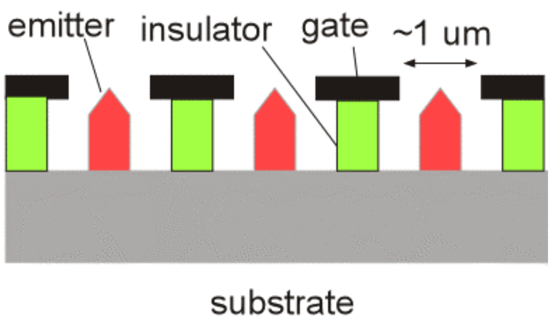
surface atoms can change T(E)

"technical" surfaces usually *not* metallic

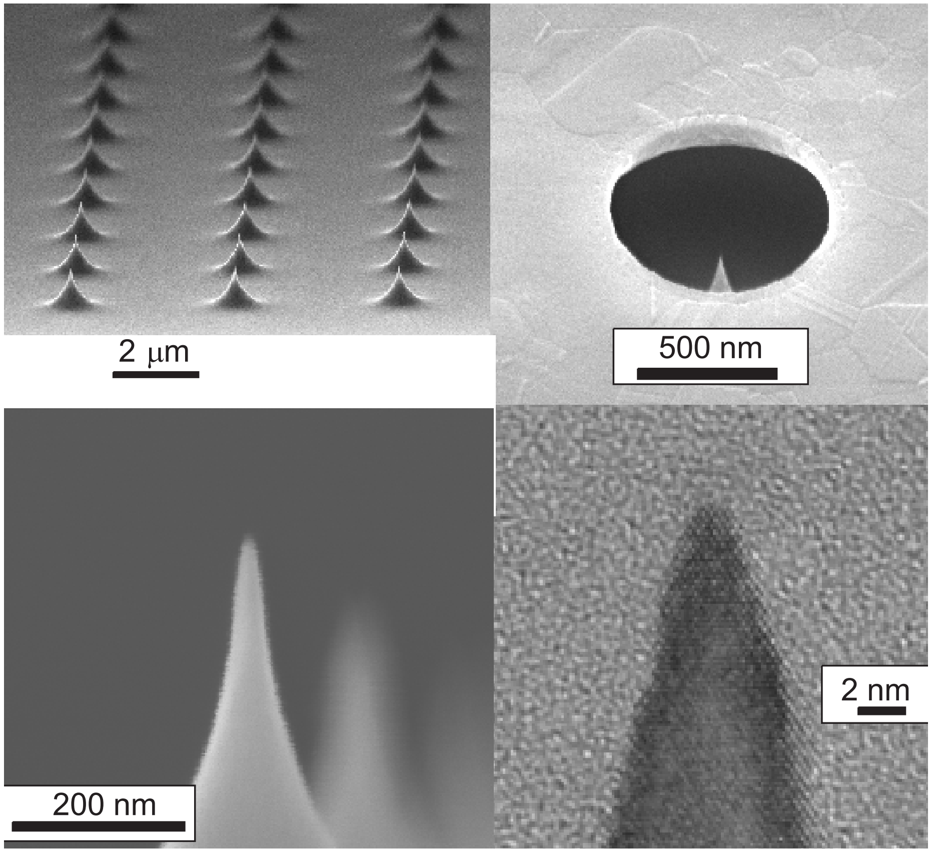
N(E) may change with emission current

What is a field emitter array?

many, tiny and sharp emitters (with gates) created with micro-fabrication methods

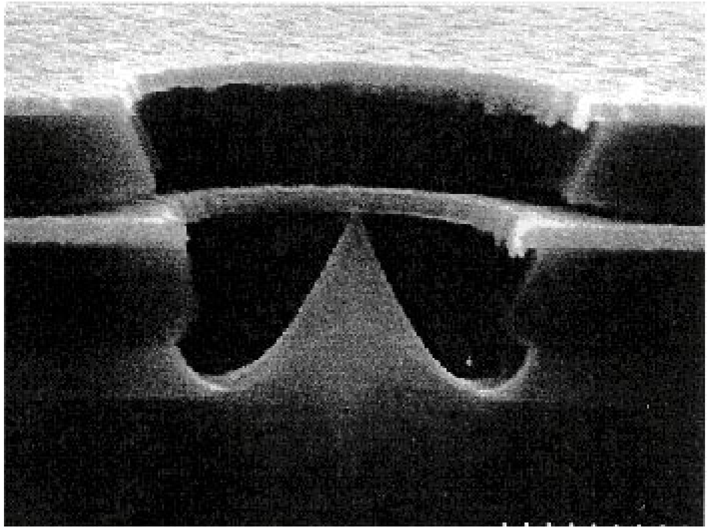


Silicon FEA



Photos courtesy of M. Ding and T. Akinwande, MIT

FEA Features



J. Itoh et al, proc. IVMC 1994, p25

very fast transit time (<1pS possible)

low gate current (<1%)

low gate voltage (<100V)

temperature insensitive

high current densities (up to 2000 A/cm^2)

low emittance possible (with focusing)

non-linear I-V curve (row-column addressing possible)

Potential FEA Applications

e-beam excitation
- x-ray tubes
- lasers
- phosphor lamps, displays

gas ionizers
- pressure, RGA
- micro-satellite thrusters

high voltage electronics (>5kV)
- switches
- diodes

13.2" field emission display
www.candescent.com

Why aren't FEAs more widely used ?

Not all the tips emit equally

Arcs can destroy elements, short gates

Local emission not stable in time

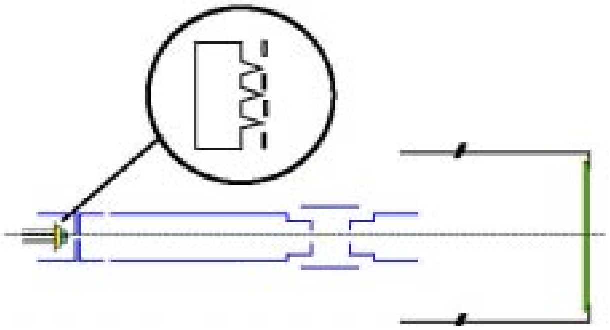
Sensitive to reactive gas (>10^{-8} torr)

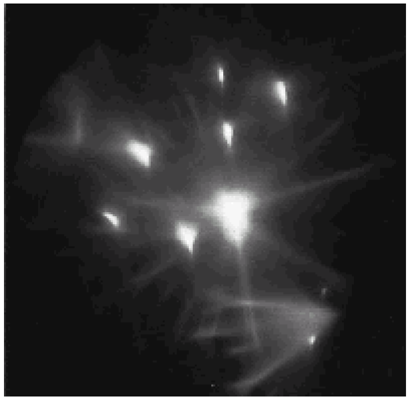
Sensitive to:

•nm-scale features at tip apex

•adsorbed molecules/reacted layers

•work function





FEA emission image showing emitting sites

J. Itoh et al, proc. IVMC 1994, p25

What causes changes in the emission current?

1. Adsorbed molecules :

    reduce the density of electrons near EF {change N(E)}
    may form dielectric layers that reduce transport to the surface

2. Emission and transport through dielectric layers

    removes adsorbed molecules
    breaks bonds dielectric layers

3. Resulting states increase transport and emission

4. Adsorption rate increases

    electron stimulated desorption generates additional gas
    higher surface electron density is more reactive
    e-beam cracks molecules like CO, N_2, O_2

5. States are removed by new adsorbed molecules

Dynamic balance between cleaning and adsorption

How to make an Arc

Initiation

Low current (<100uA):

Adsorbed layer bonds broken electronically by Auger-like processes

High current (>1mA):

Bonds in emitter broken thermally (evaporation) by Nottingham effect + bulk scattering

Positive Feedback

Desorbed material ionized by E-beam

ion bombardment removes additional material

Dissipate (Stored) Energy

gate-tip voltage and capacitance $E= CV^2$

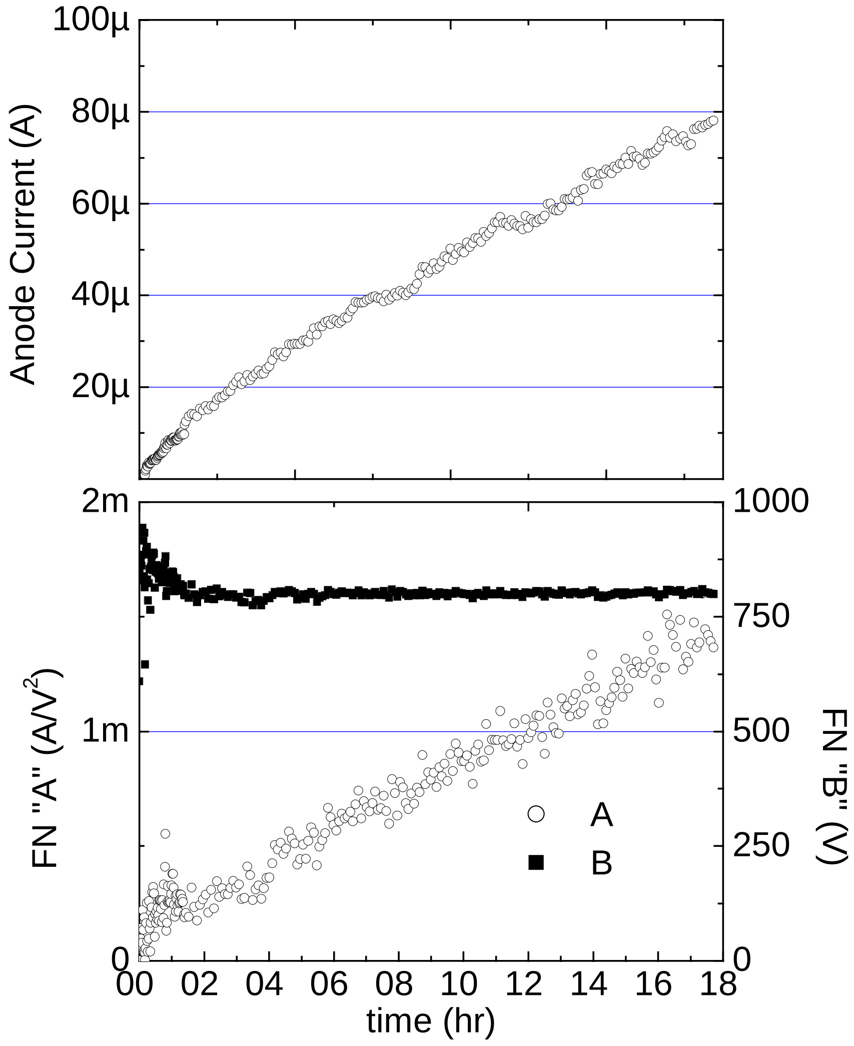
arcs may be reduced by blocking any step

Initial rise in current

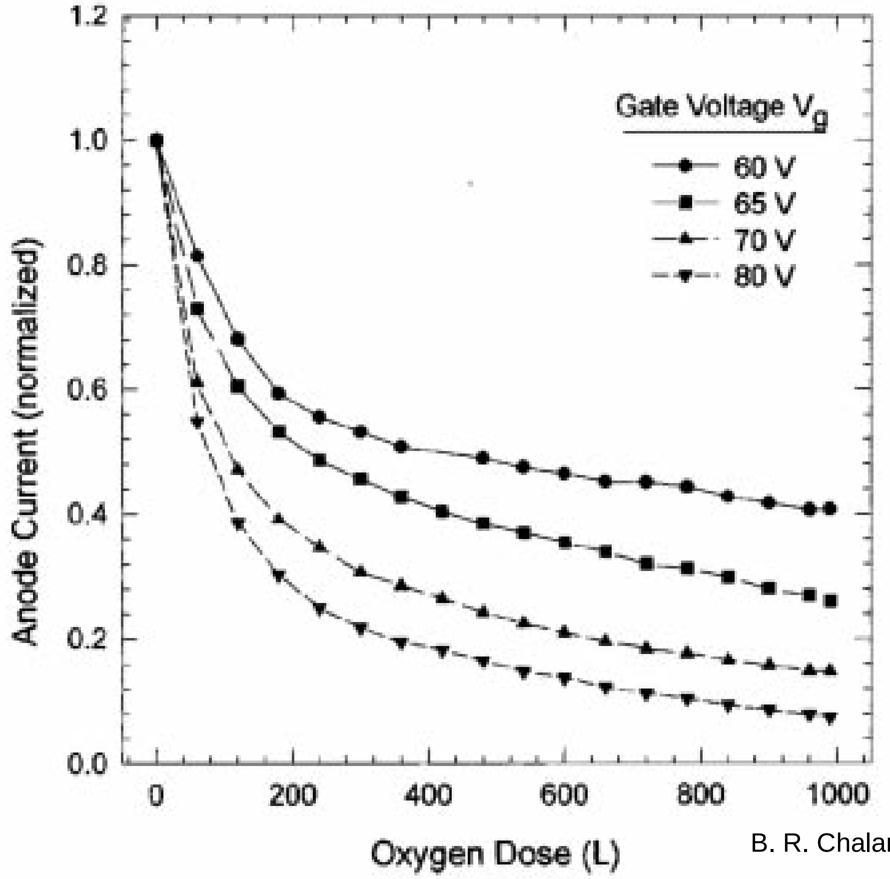
Increase in current due to increase in A, where

$$I = AV^2 \exp(-B/V)$$

A~ N(E), area



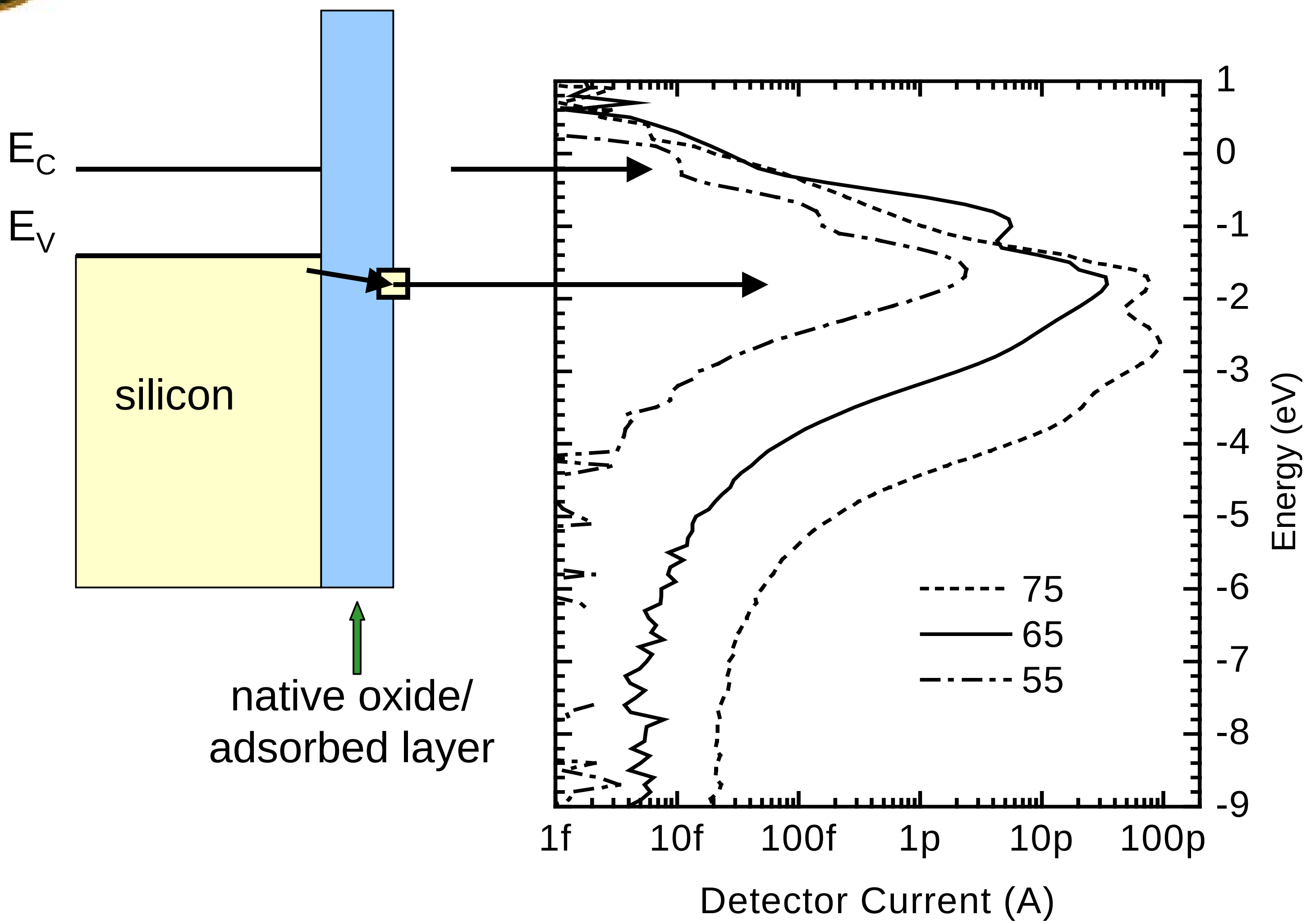
Emission Reduced by Gas Exposure



B. R. Chalamala et al, JVST B 16 2859 (1998)

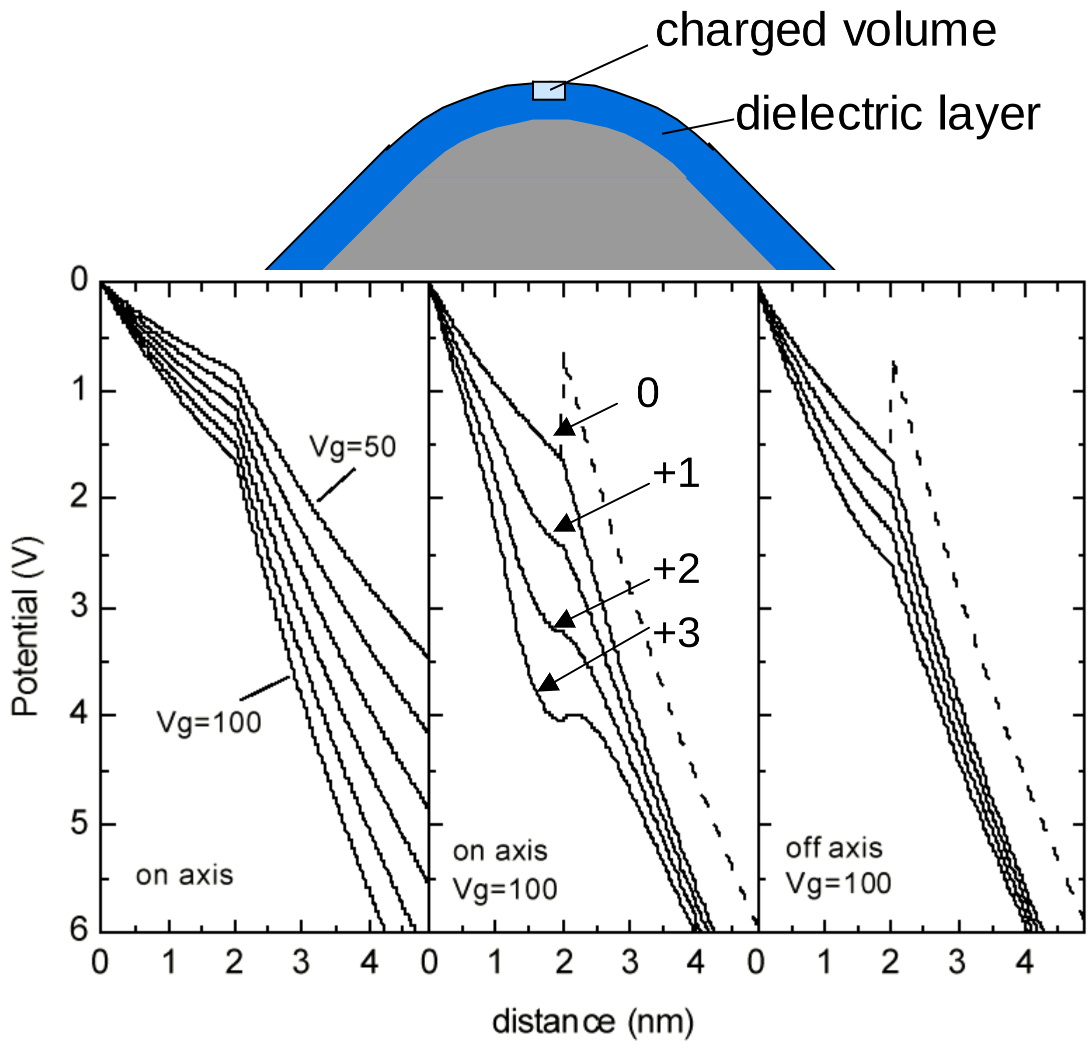
Degradation Rate Increases with Emission Current

Oxide states mediate emission



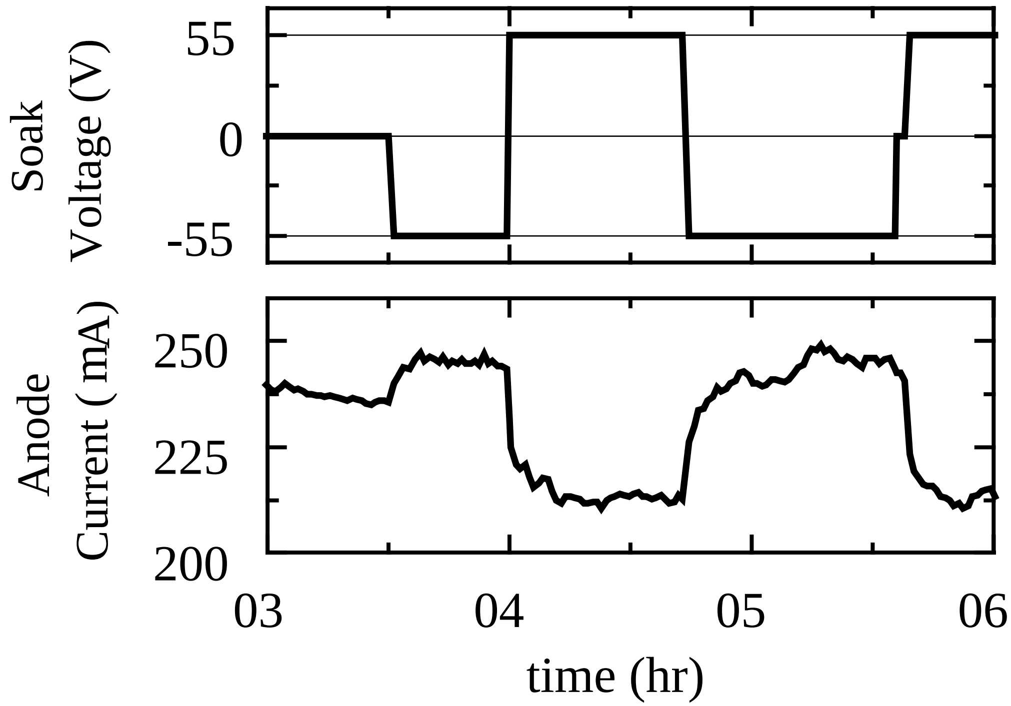
J. Shaw, JVST B18, 1817 (2000)

Local potentials from single charges



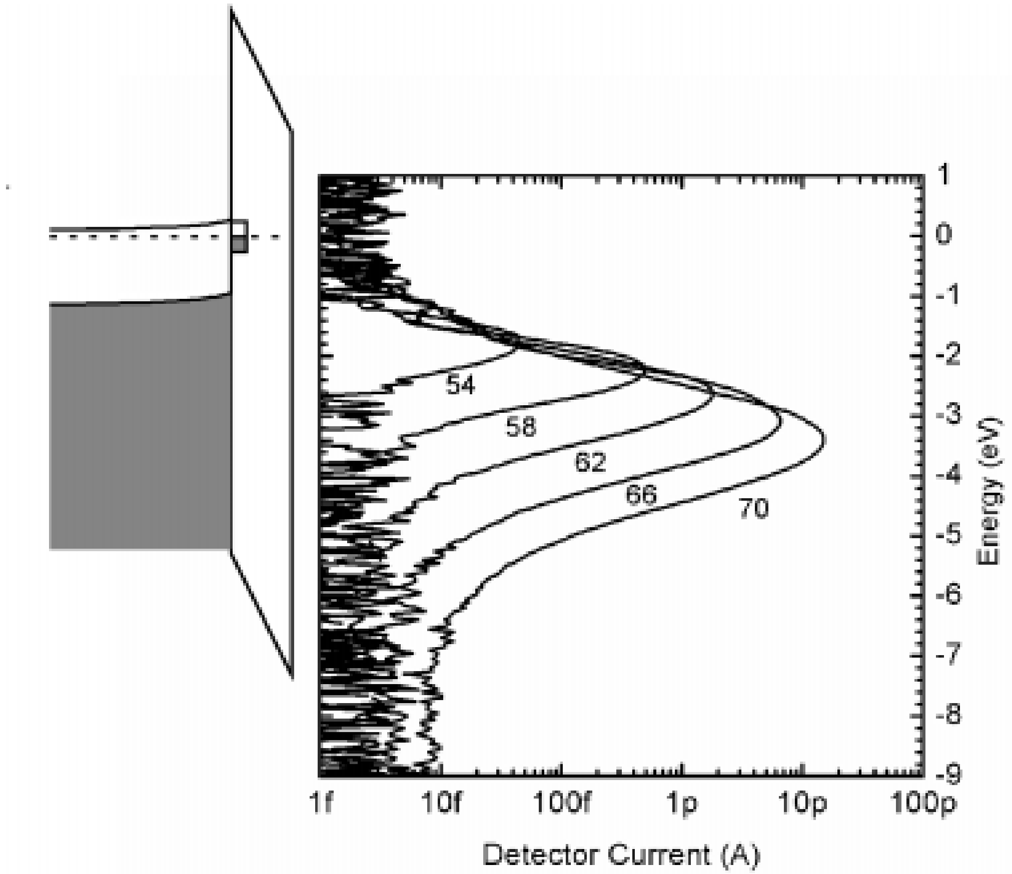
Hysteresis (gate voltage memory) effects

Voltage applied *before* current measurement



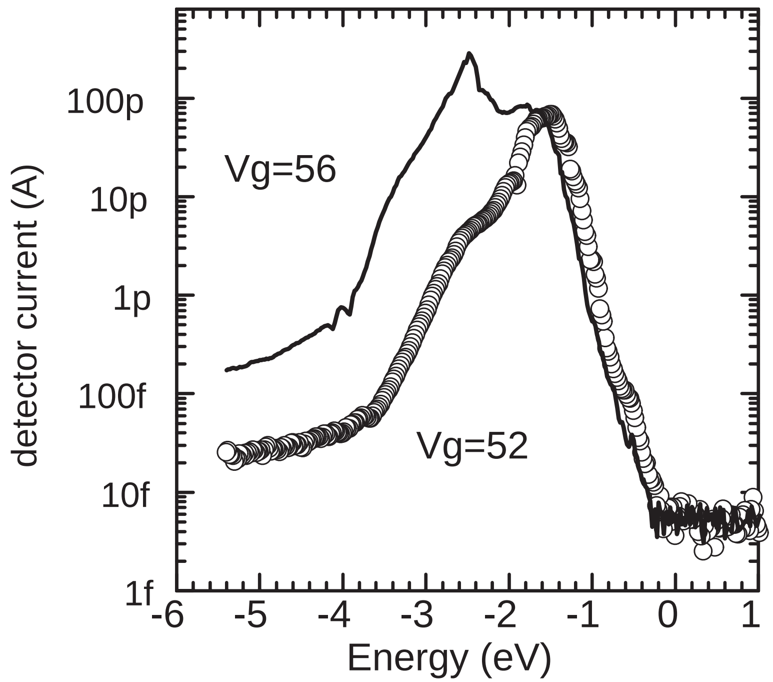
Larger emission when prior Vg is negative

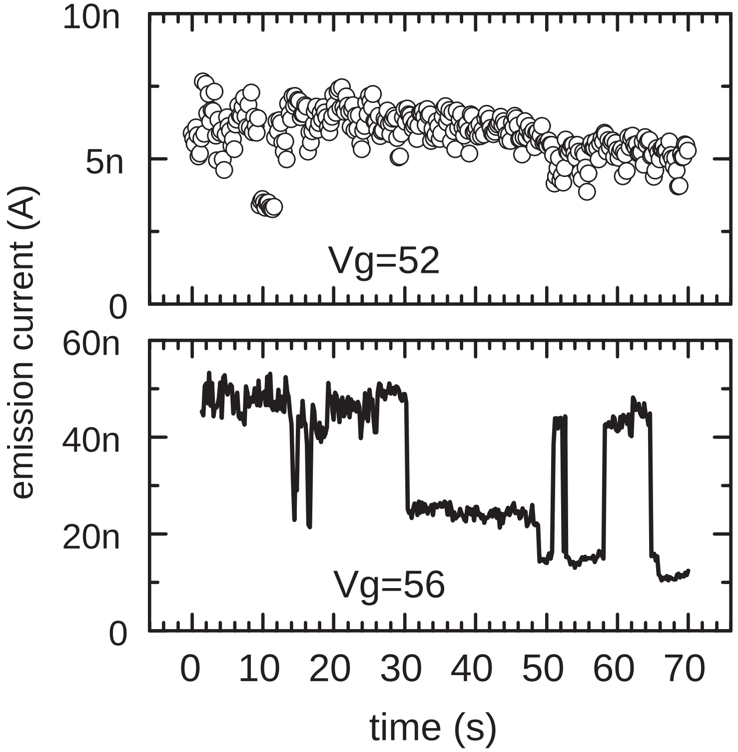
Emission limited by oxide transport



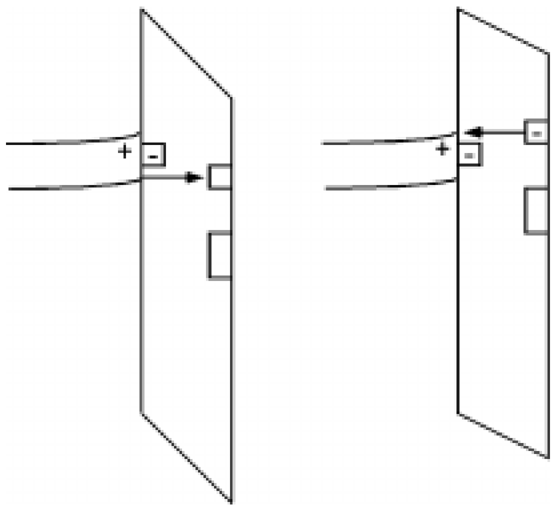
Emission near E_F does not increase

Fluctuating emission from oxide states



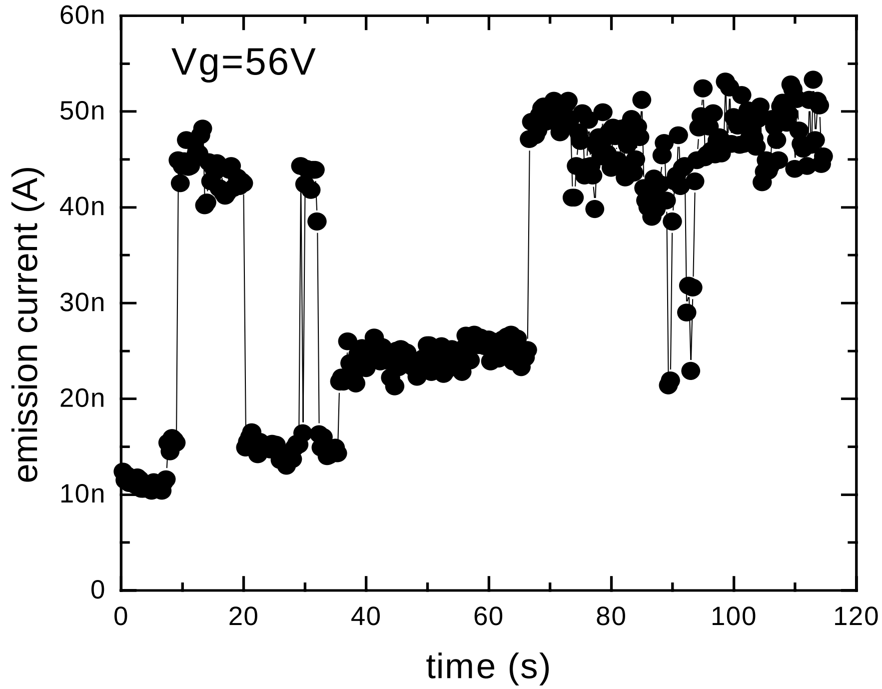


Hysteresis & fluctuations from trapped charge

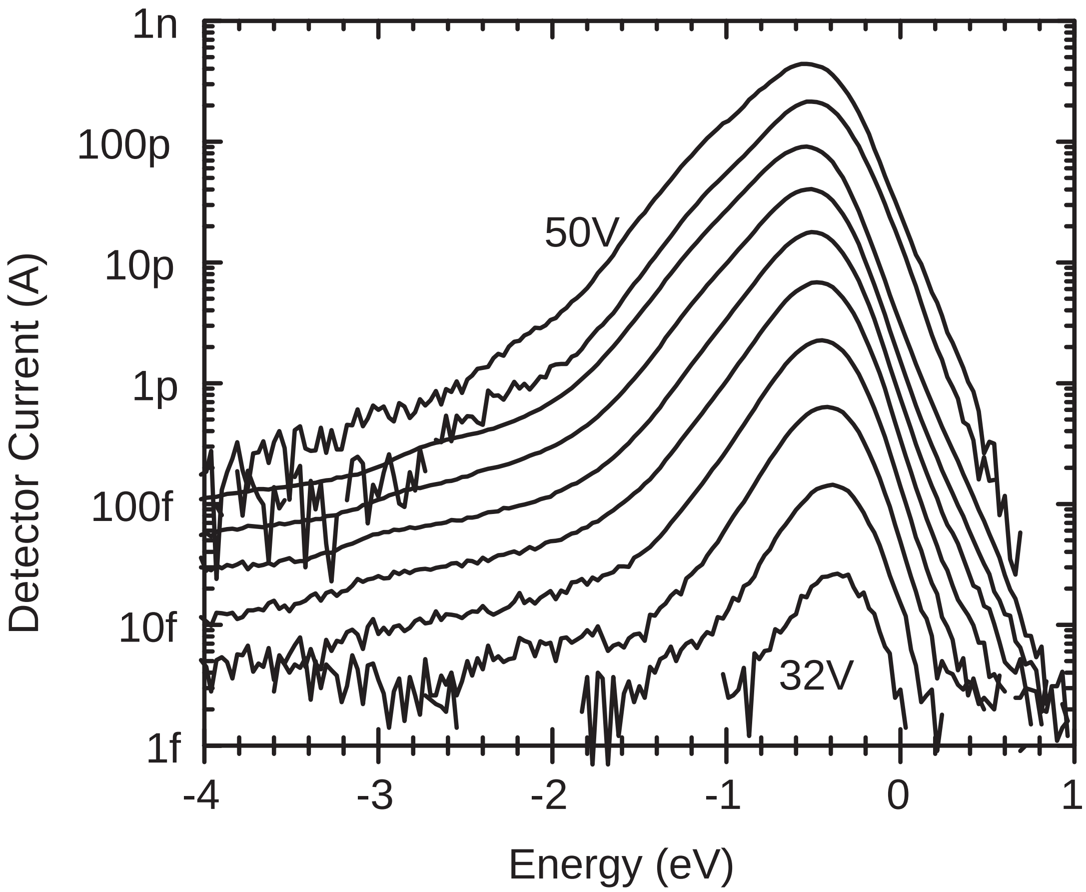


high E:
trap e^-

low E:
de-trap



Oxide removed by emission



What can be done to improve performance?

Use emitter materials that:

- do not form dielectric layers
- have high field enhancement
  - low gate voltage
  - low stored energy
  - gas will not ionize

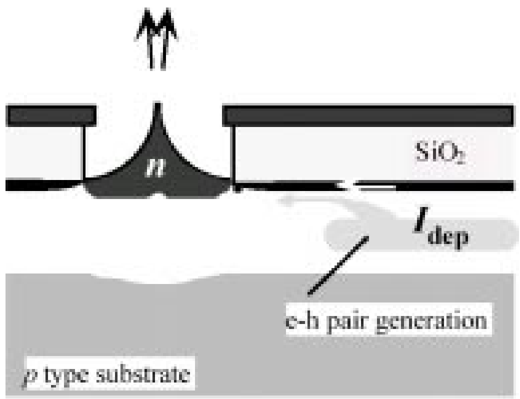
Remove adsorbates

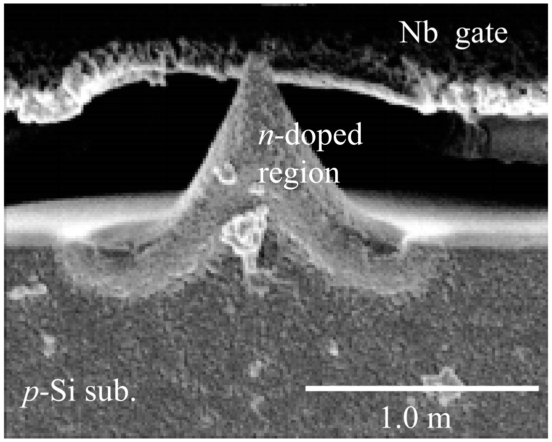
- heat, e-beam, ions
- ramp the emission current

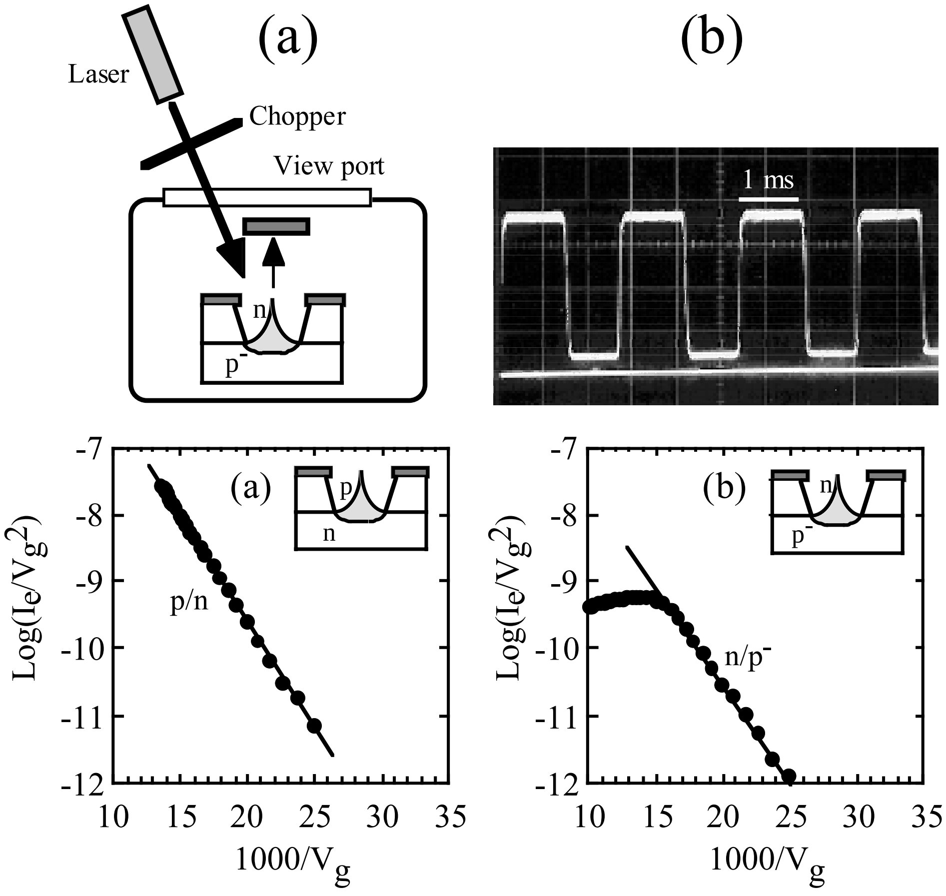
Limit the emission current to prevent runaway

Limit the gate or emitter current to limit arc damage

p-n junction limits emission

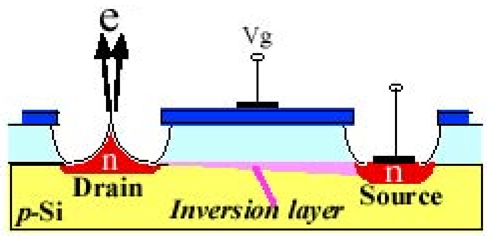




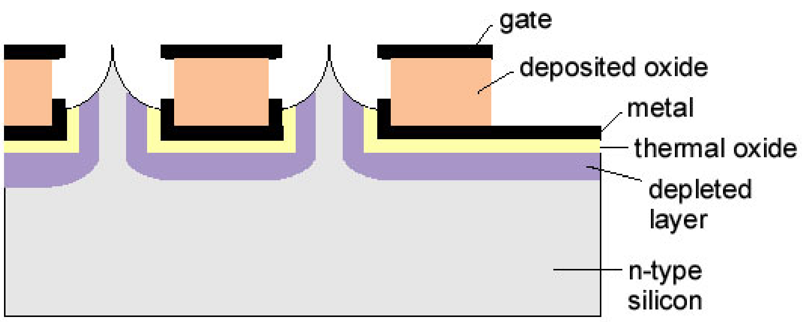


figures courtesy of J. Itoh

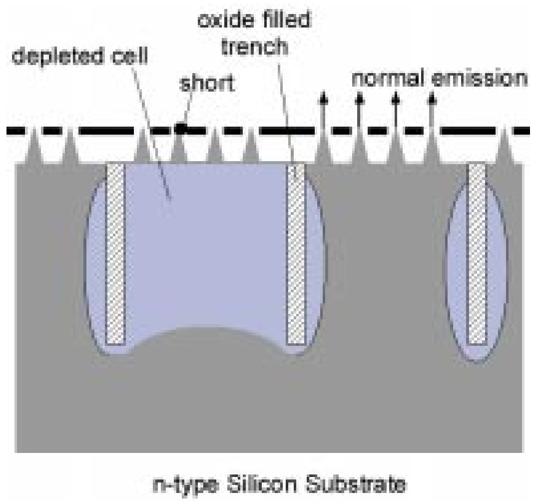
transistors limit emission



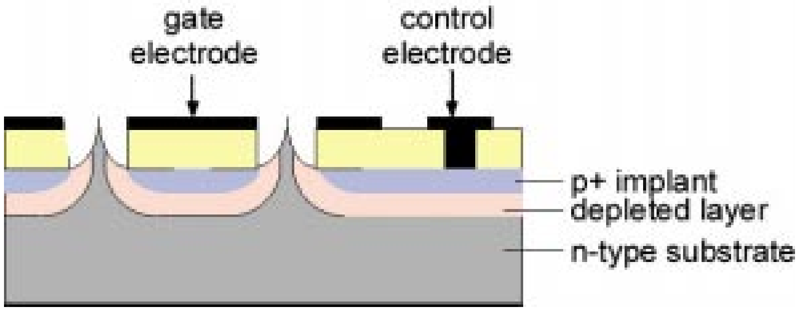
horizontal MOSFET



vertical MOSFET



Vertical Emission CurrenT Limiter



vertical JFET

Emission-limiting techniques

Upside

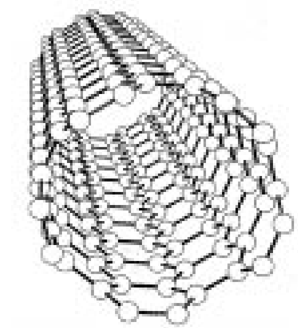
- improve uniformity
- reduce or eliminate arcing
- allow total current scale-up
- provide alternative modulation gate

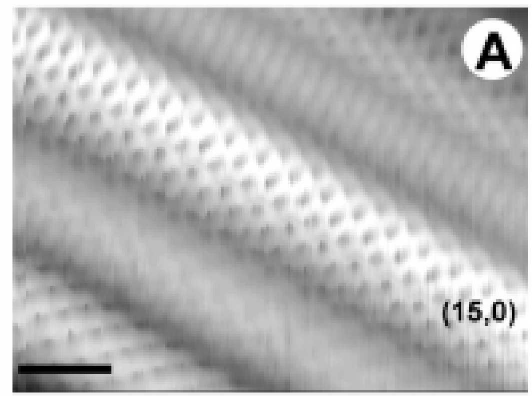
Downside

- increase electron energy dispersion
- reduce or eliminate ability to focus
- increase gate voltage
- create temperature sensitivity
- increase fabrication cost

Emission limits could be used only for initial conditioning

Self-assembled emitters: Carbon Nanotubes





chemically stable (high work function!)

volatile oxide

long scattering length (>1um)

high mechanical strength

high thermal conductivity

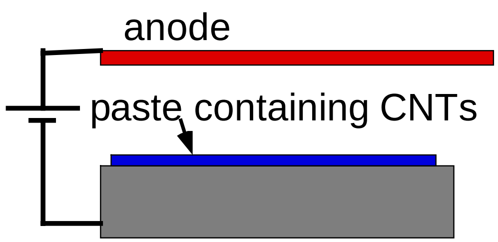
high field enhancement (~1000)

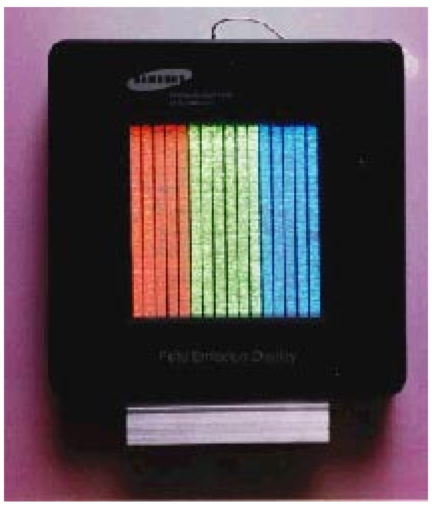
low density of states near E_F
(may limit emission current)

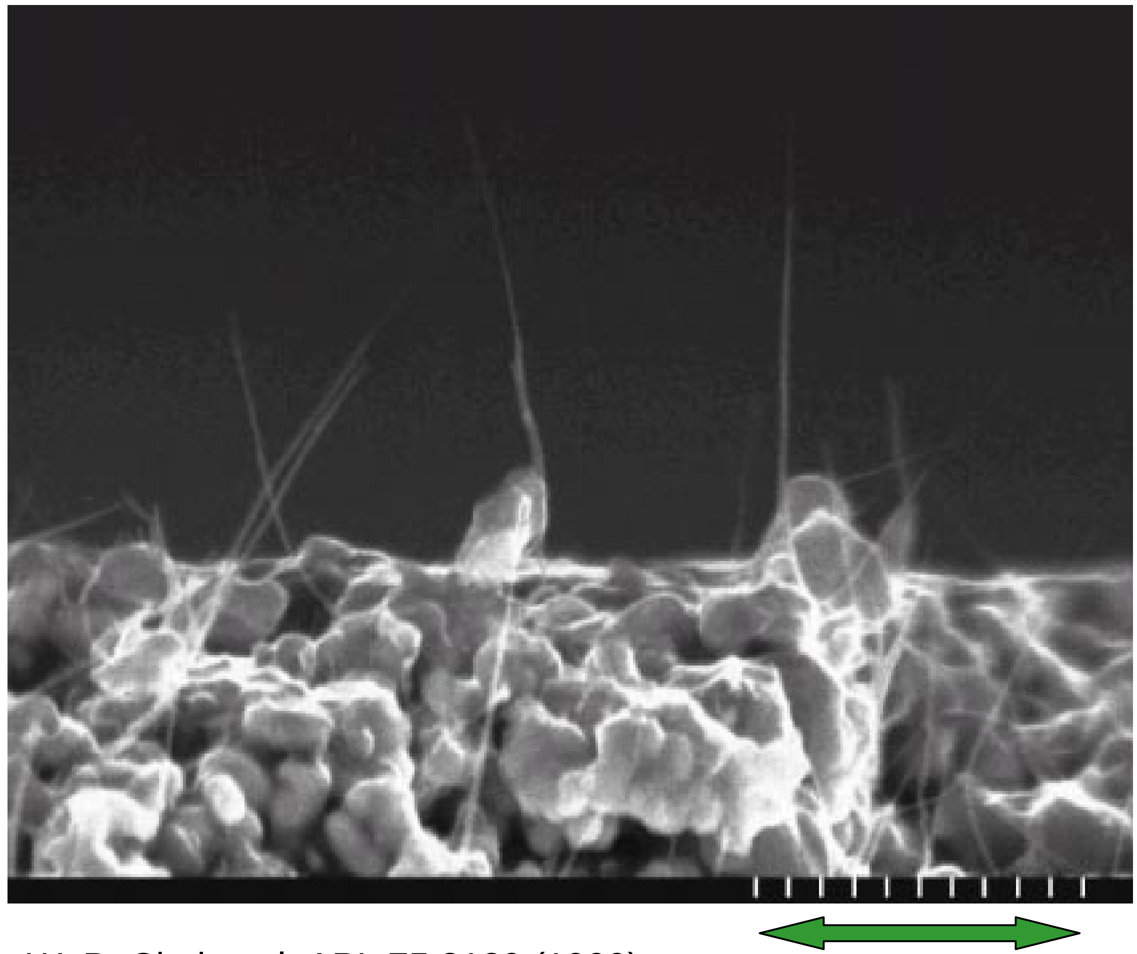
no shorts due to tube burn-out

water adsorption *increases* emission, *negative* feedback

Ungated CNTs grown ex-situ

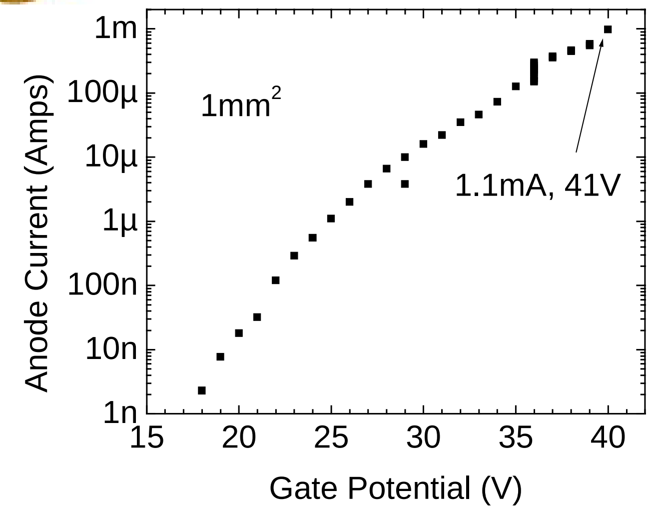


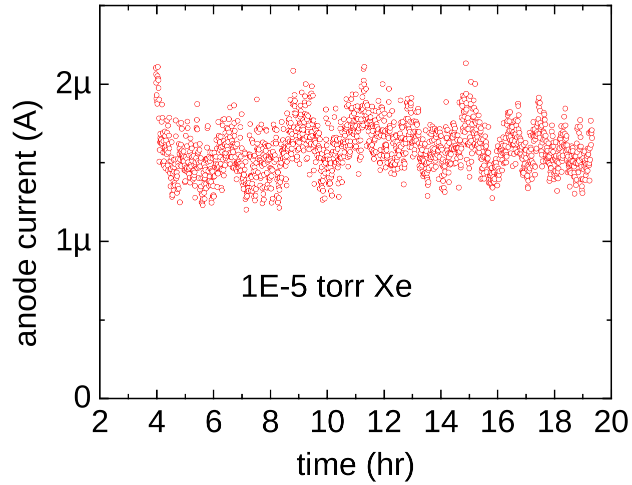


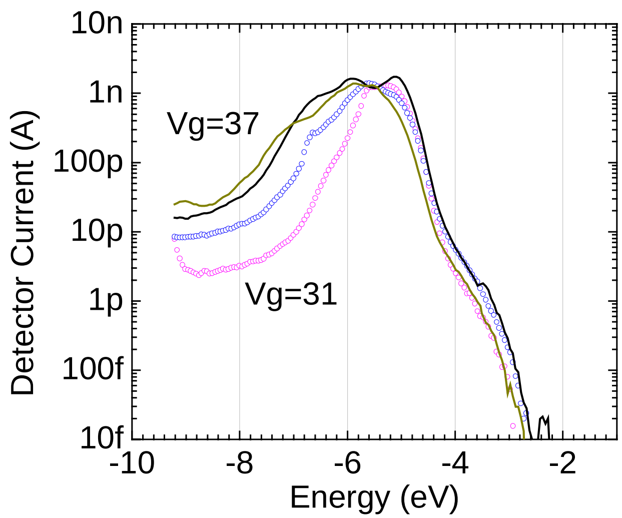


W. B. Choi et al, APL 75 3129 (1999)

Emission from gated carbon nanotubes







Low voltage

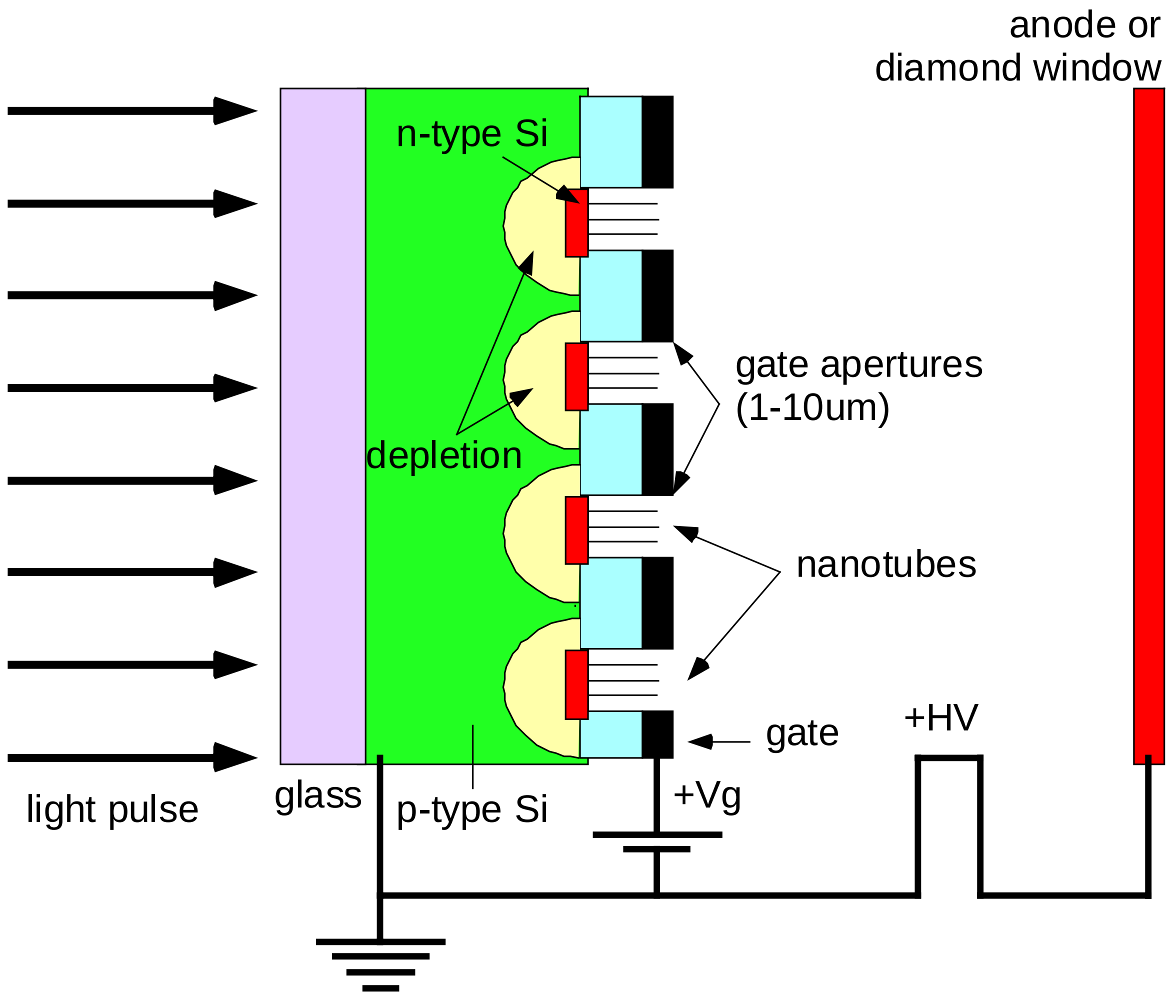
T< 600C

10^{-5} torr Xe, H_2O

emission saturates

D. S. Y. Hsu and J. L. Shaw

junction-limited CNT FEA



Take-home messages

Current-limiting or negative feedback needed for uniform emission

Clean (dielectric free) surfaces required for high emission current w/o plasmas

Carbon seems to provide a clean surface without external treatment or emission ramp-up

CNTs provide high field enhancement features over large areas at low-cost