Micro/Nano-Machined Vacuum Photodetectors

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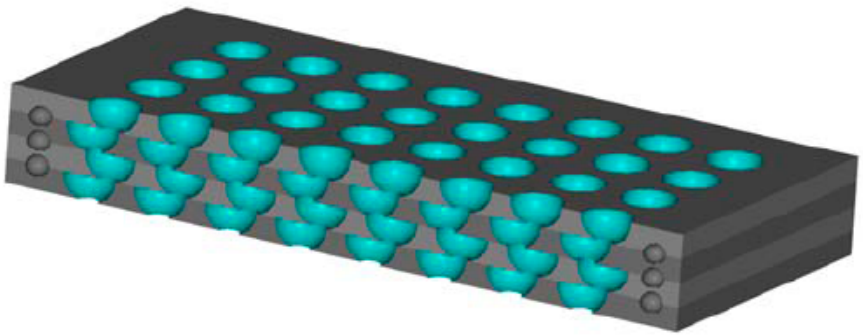
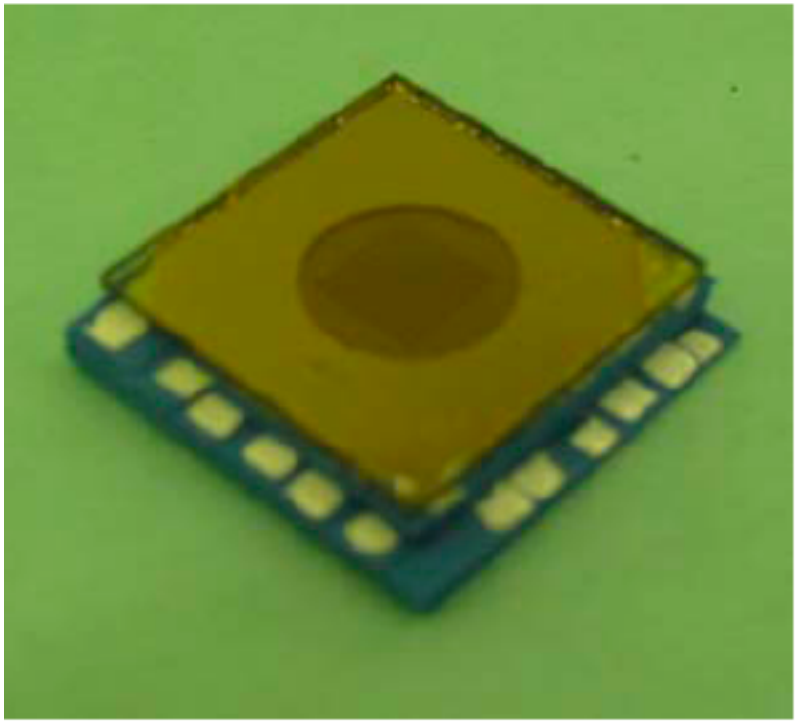
1. Also Fermilab 2. Also Erciyes University

Micro/NanoMachining/3D Print/ALD -> MicroDynodes->Unique PMT's



Self-aligned stack "teacup" Dynodes, 50 µm Si wafers



Form & Fit Prototype

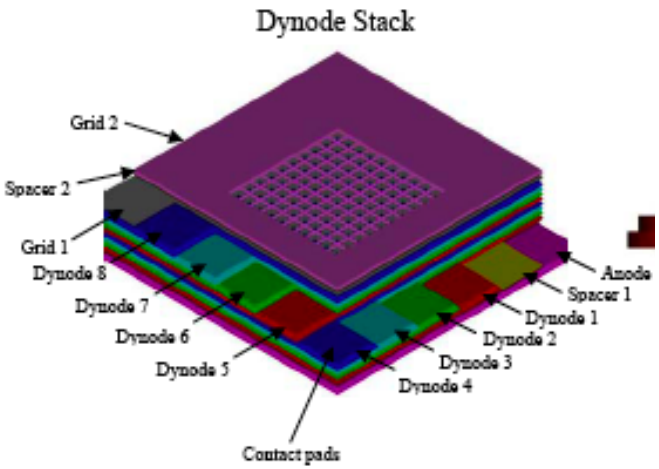
8 stage microdynode PMT prototype. ceramic body, 1x1 cm active area

Micromachined Compact μPMT->μPM

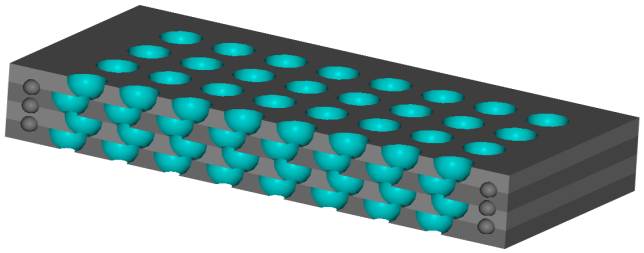
- MEMS techniques Si, SiO_2, glass, ceramic... yield MCP-like secondary electron(SE) channelized dynodes ->

-> μPM's suitable for use in:

- ➢ High Magnetic Fields (like MCP-PMT).
- ➢ Precision Timing (like MCP-PMT)
- ➢ High rates – UNLIKE MCP-PMT
- ➢ Linear Response – UNLIKE MCP-PMT
- ➢ Low Power – UNLIKE MCP-PMT
- ➢ Exceptional Compactness
- ➢ Large Areas/Arbitrary Shapes



- Dynode stages ~100-500 μm thick
- Self-Supporting, Self-Aligning
- No Separate Vacuum Envelope; Side Connectors
- Standard MEMS, Fab Tooling, Economics
- Thickness for 8-10 Stage "PMT"<3 mm
- *Channelized:* PC, p.e. gain, and Anode->
- **Essentially No Cross-Talk + High B-field operation**



MCP-PMT Compared with PMT

- **MCP-PMT Superior time resolution** – risetime, dwell time/transit time small
  – secondary electrons cannot diffuse sideways

- **MCP-PMT Magnetic field Operation:** **PMT very limited**
  MCP secondary electrons - laterally confined paths to the anode.

- **MCP Rate, Dynamic Range and Linearity:** ***deficits compared with PMT***
  - MCP resistance-dominated vs PMT with dynodes independently powered.
  - quiescent current/power ~x10-100 larger than signal current.
  - High rates/intensity – MCP resistive Ohmic heating causes thermal emission.
  - RC time constant: ~PMT w/resistive base: poor rate, linearity performance.

- PMT with individual dynode HV power (Cockcroft-Walton, transistor bases, other): **no quiescent current ->**
  - densely packed systems like calorimeters
  - remote applications like satellites.

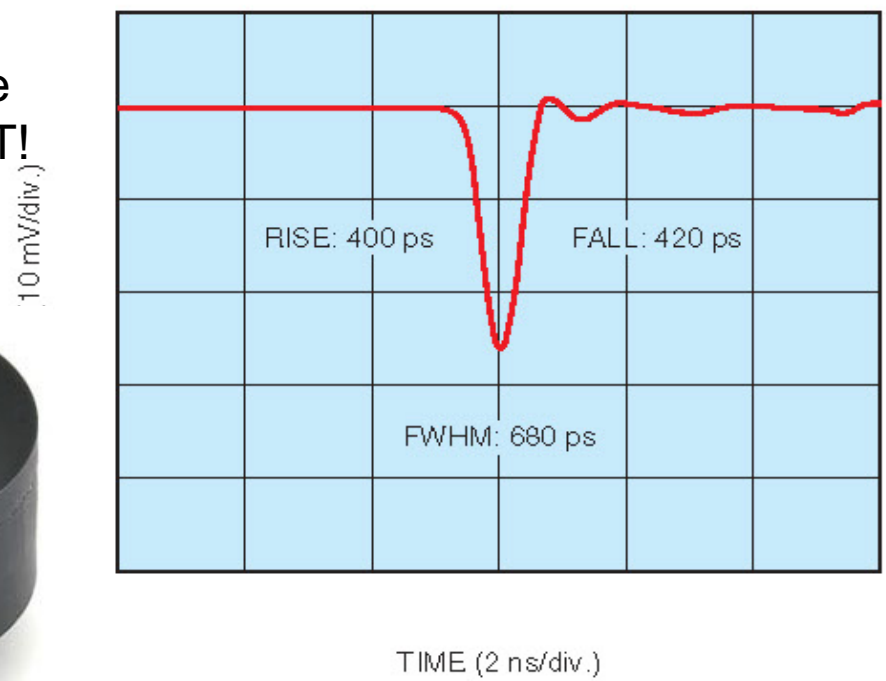
- Cosmic ray experiments used PMT powered by floating batteries in series.

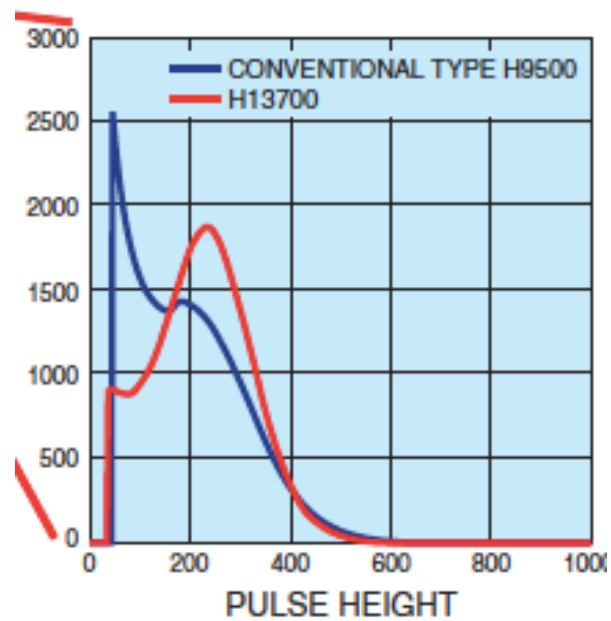
- MCP-PMT: most are costly; make relatively little use of microelectronic manufacturing technologies.

PMT Compared with SiPM

- SiPM Magnetic field Operation: Exceptional
- SiPM QE: Exceptional for many wavelengths; resolves p.e.
- SiPM Compactness: Exceptional
- SiPM Time Resolution: Excellent
- SiPM Cost: Low ……BUT
- SiPM Rate, Dynamic Range, Linearity,Noise, Afterpulse, X-talk->*deficits*
  - *RC time constant:* ~PMT w/resistive base: low rate, even with quenching.
- Many applications: needs cooling - adds complexity and size
- Linearity over large dynamic range compromised
- Afterpulsing & Cross-Talk affect usefulness in many applications
- Radiation Resistance limited: metal envelope PMT w/ quartz window-> GRads

Newer PMT Performance -> MCP-PMT!





-> Combine Best of PMT, SiPM, MCP-PMT by *Channelizing the Dynodes*

- **Adapt MEMS, 3D printed glass & metal technology**

- Thin sheet array of secondary emission "channels" serve as a dynode -> **the miniMCP**
- Channel aspect ratio length/diameter only ~1-4 – an MCP but thinner-> only 1 e-collision
  example: 20μm diameter "channel" is only 20-80 μm long
- single dynode stage: "miniMCP"
- the "miniMCP" are stacked/aligned forming continuous channelized dynodes.

- miniMCP Glass/SiO2: coated w/conducting secondary emission(SE) films -> PMT dynodes –
  - few nm thick oxide layer formed on thin (~1-2 μm) metal films (CuBe-O or Al_2O_3).
  - Metal oxides are stable and survive GigaRad electron bombardment in PMT
  - *No need for controlled conductivity channels*

- Dielectric Strength glass/silica ≥10V/μm. 10~30μm insulation miniMCP dynode sheets:
  - 100-300V applied between adjacent "miniMCP" dynodes

- Each dynode sheet has a side tab connection to a dynode voltage (see figures following)
  - No need for vacuum-air pins

- miniMCP sheet dynode stages stacked/aligned
  - confined channels from the top to the bottom of the dynode stack like an MCP
    - but without a significant resistive load.
  - electron cloud cannot diffuse sideways: B-field & timing like an MCP
    - A 10 "dynode" miniMCP stack ≤ 3mm thick.

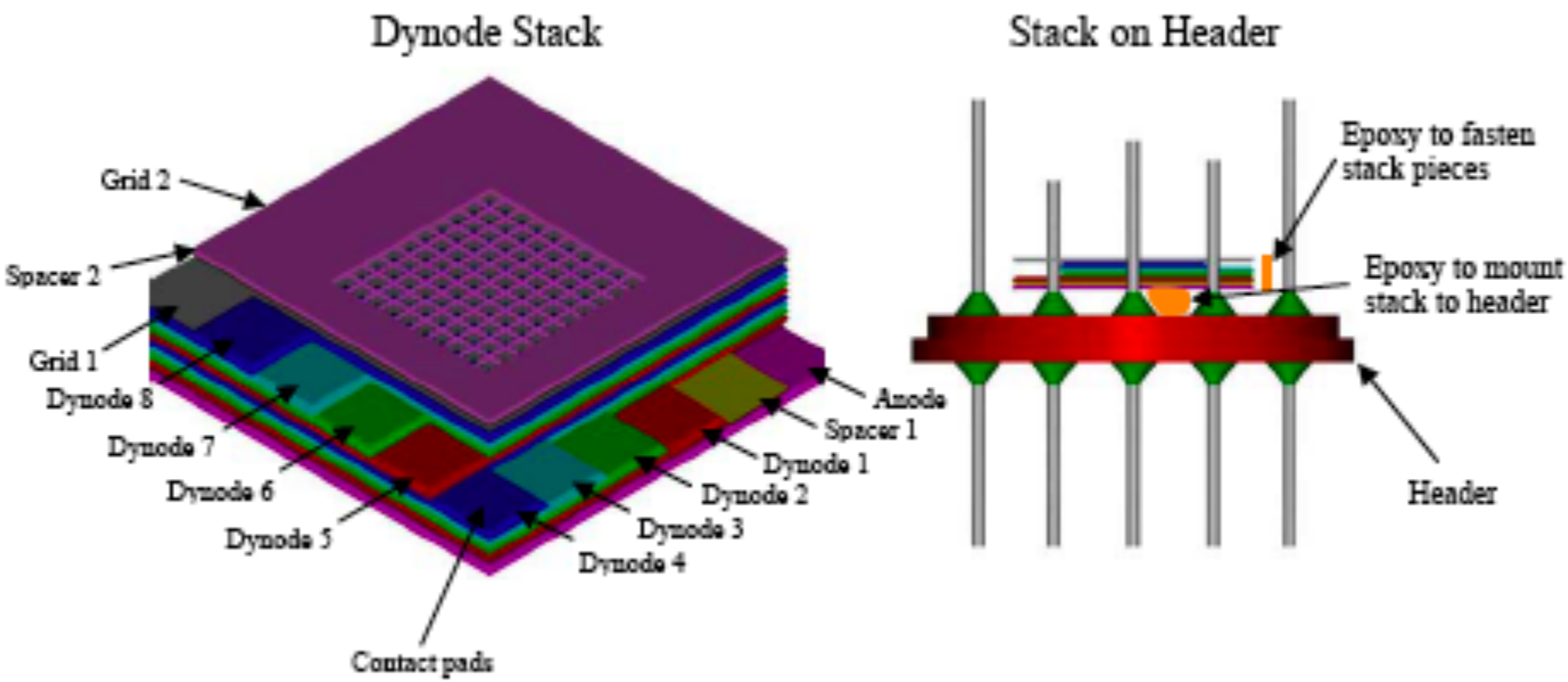
- The bonded stack is the vacuum "envelope"; no glass-metal vacuum pins needed (see figs)

We call this a μPM or more generally MCDM (MultiChannelDynodeMultipier).

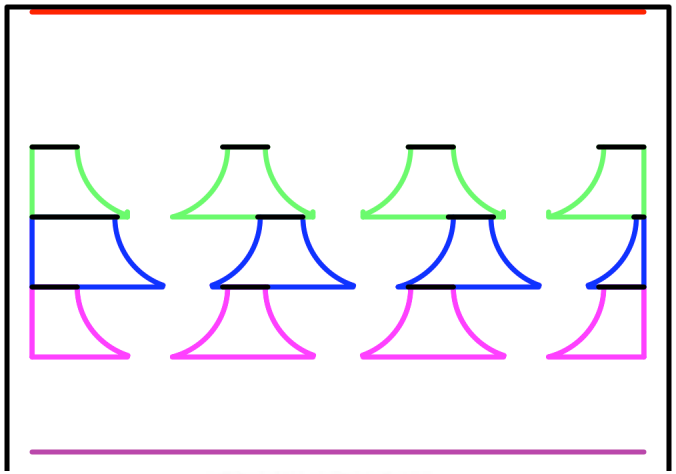
The μPM or MCDM:

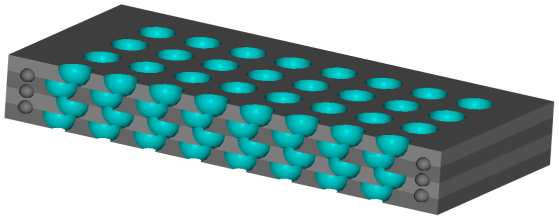
- B ~ 2T - like MCP-PMT
- individual dynode power -> **little cooling** ->
  - densely packed systems
  - particle flow and high η calorimeters
  - remote applications like satellites.
  - 300 MHz counting rate (η>3.5: ~10^8 p/cm2/s)

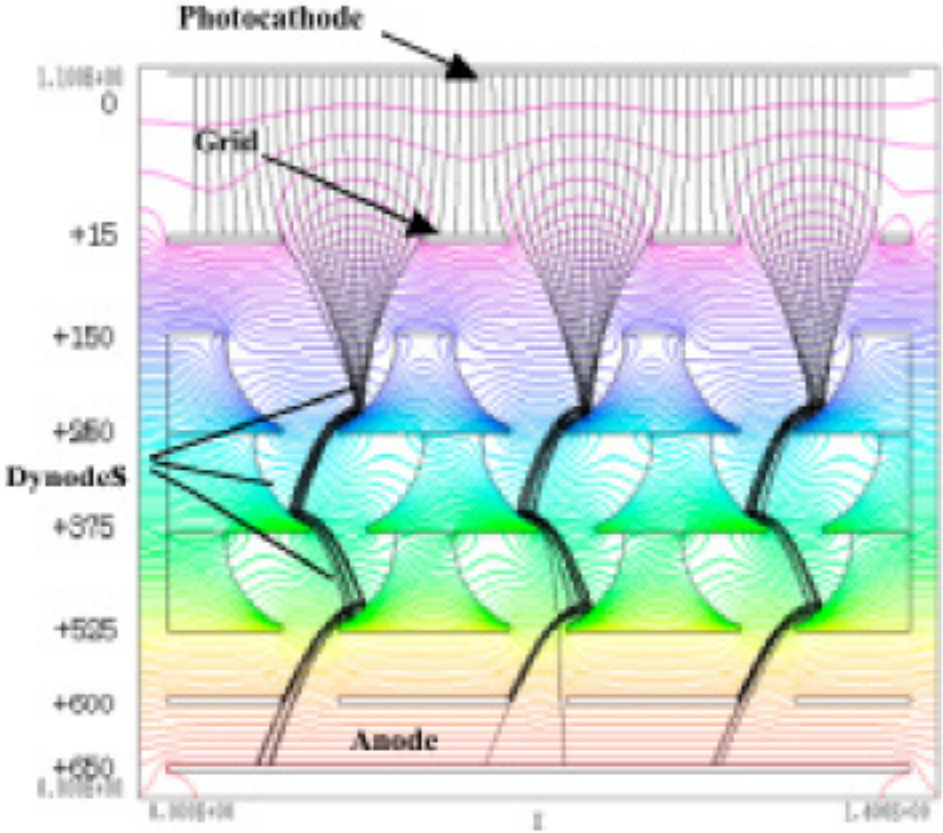
Micromachined μPM/MCDM Prototype



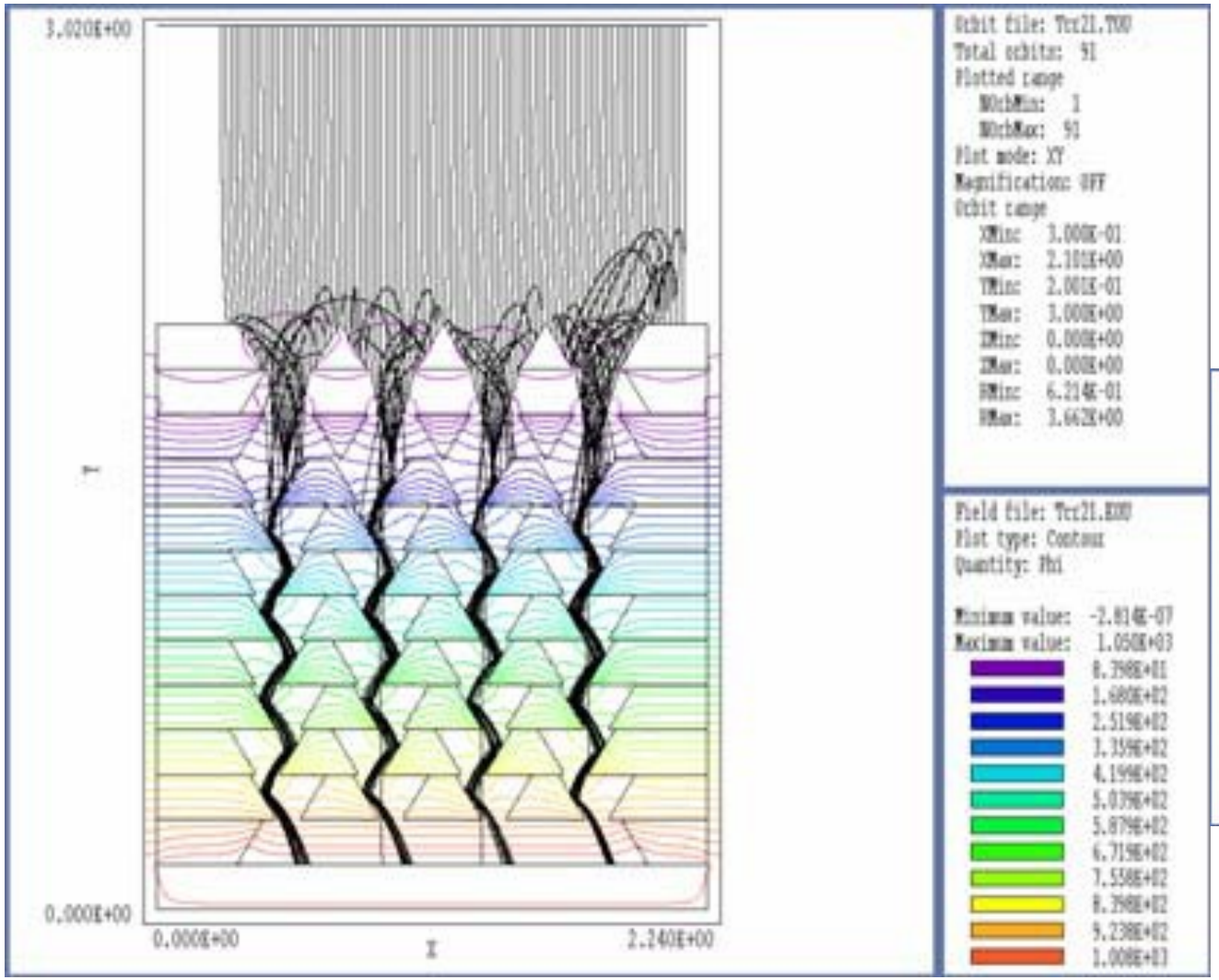
Electron trajectory
“teacup” dynode
miniMCP’s

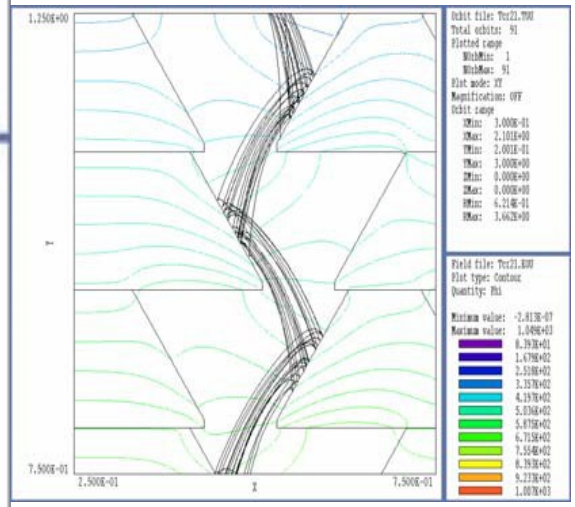




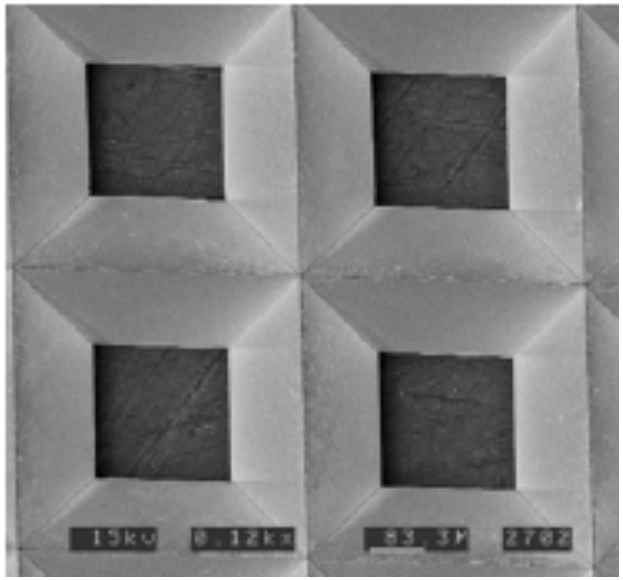


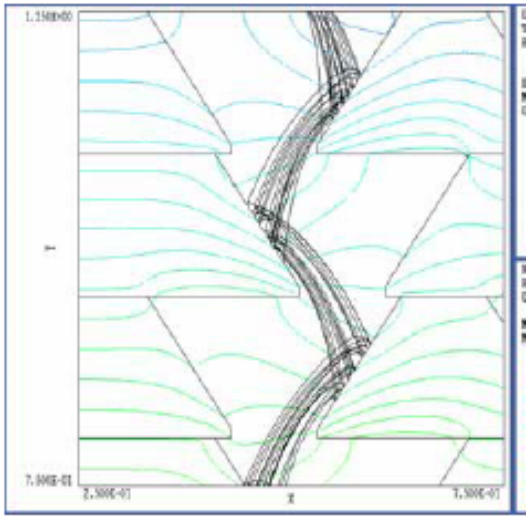
Electron trajectories for an inverted pyramidal dynode miniMCP structure with applied potentials as shown. The structure has 8 dynodes, 2 focusing grids and a planar common anode.

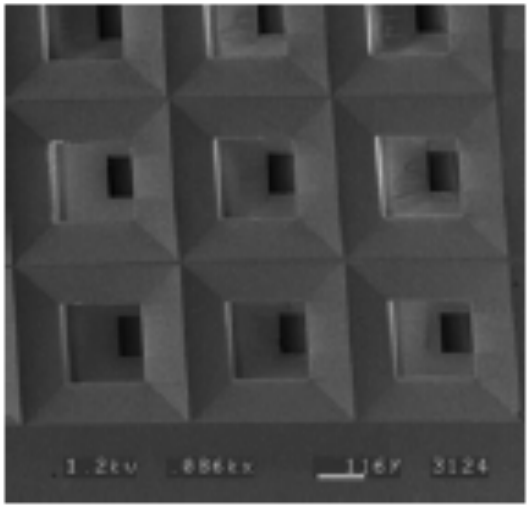


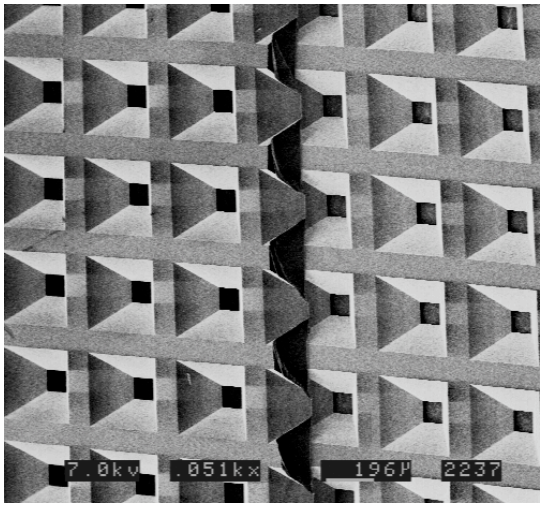


- Truncated Pyramidal dynode/miniMCP
- formed naturally by patterned simple KOH Etch Si(111)







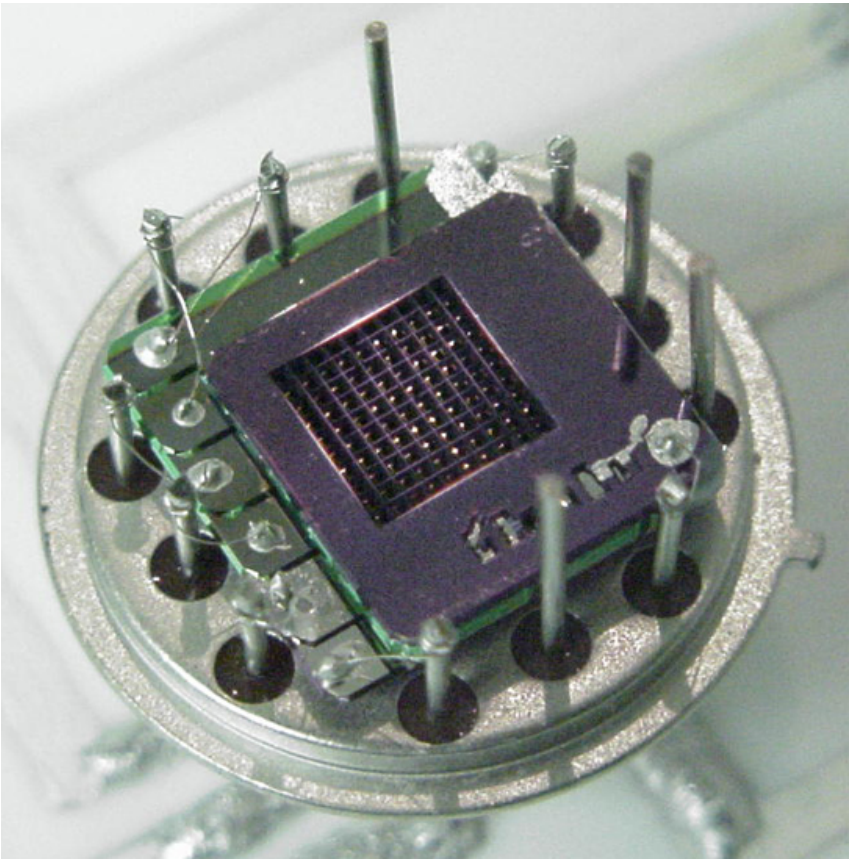


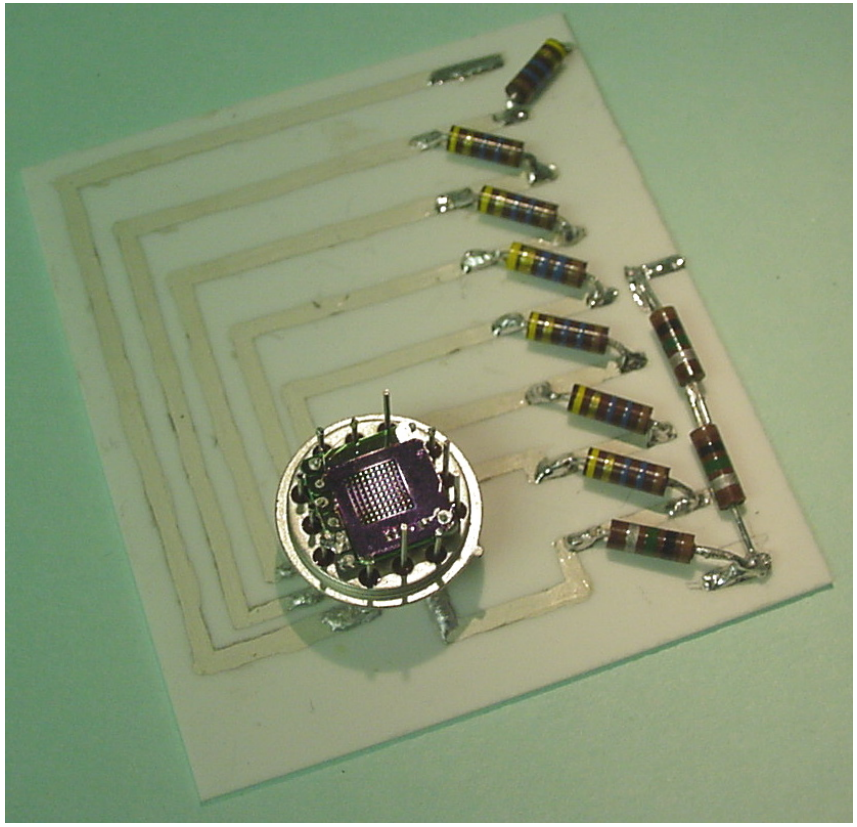
Form & Fit test MicroPMT

Pixels/Channels ~1 mm diameter

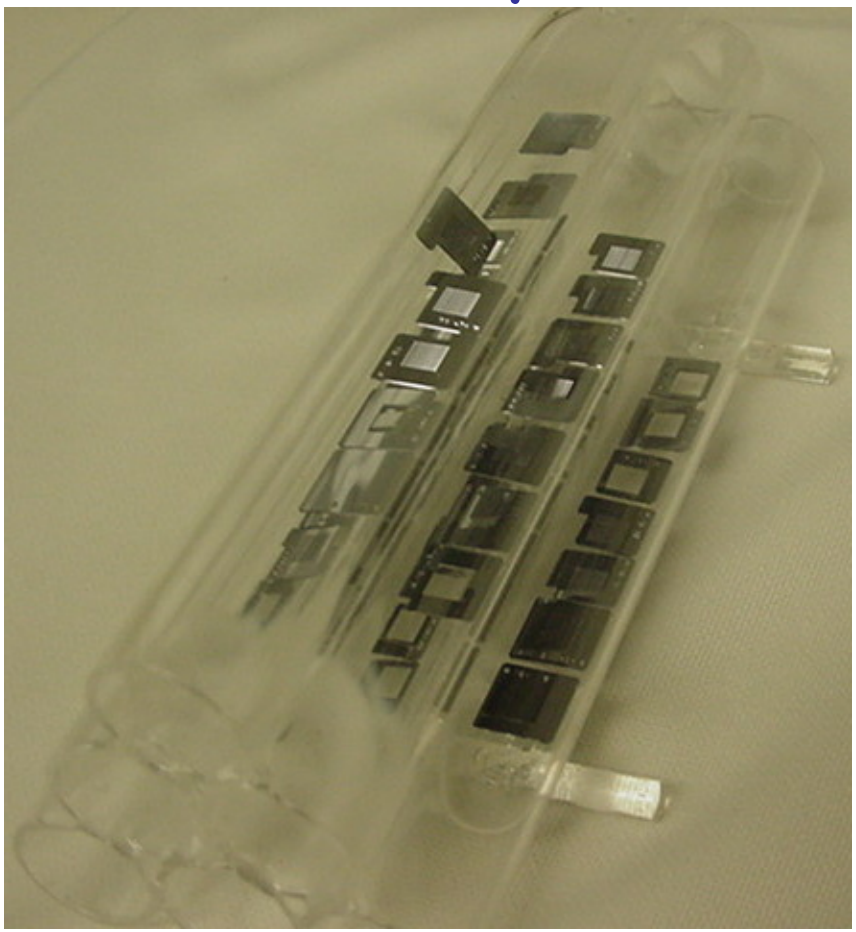
Gain: 2.5-4 per stage (at present: Au:Cs surfaces)

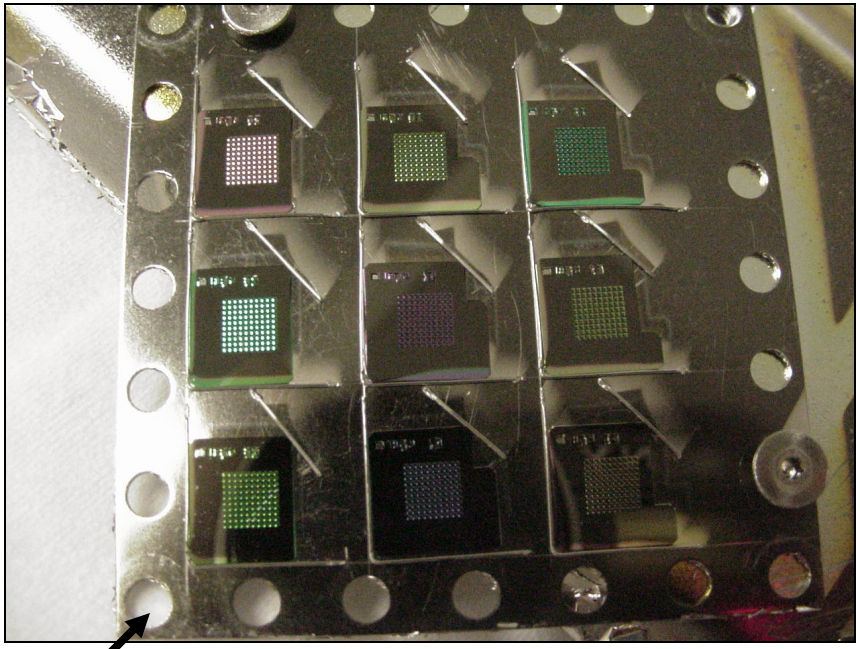
Future: 50 μm on centers easy – multi-anode would require bump-bond vacuum feedthrough.





μPMT Processing

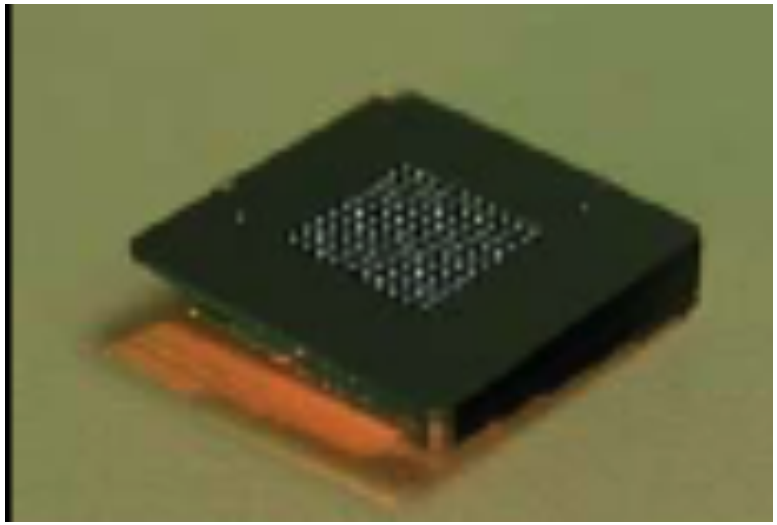




Metal Flux Direction; 50 μm penetration

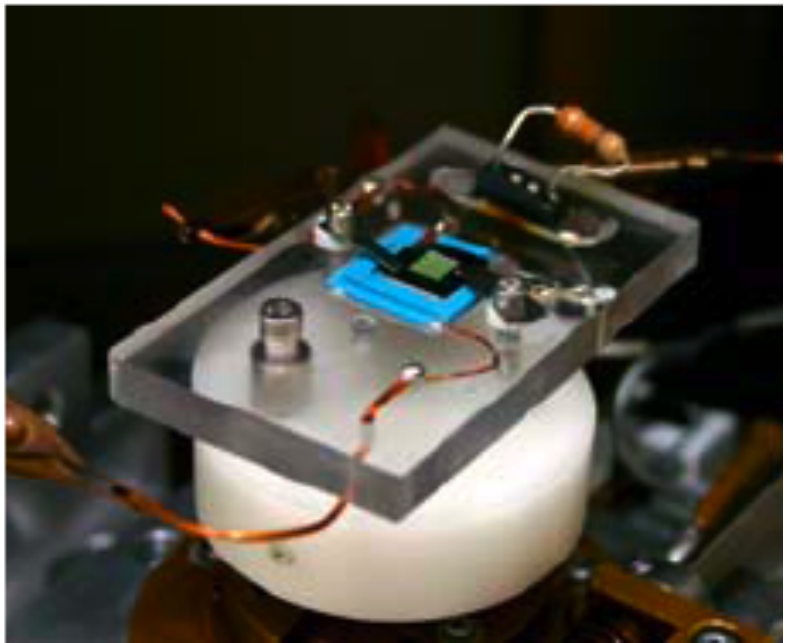
Dynode Metalization

Quartz boated loaded with multiple parts prior to oxidation and SEM activation.

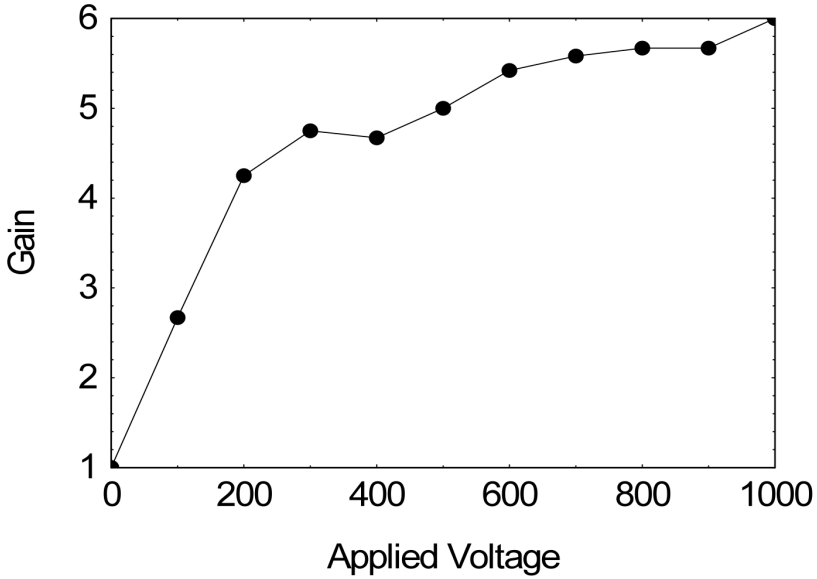


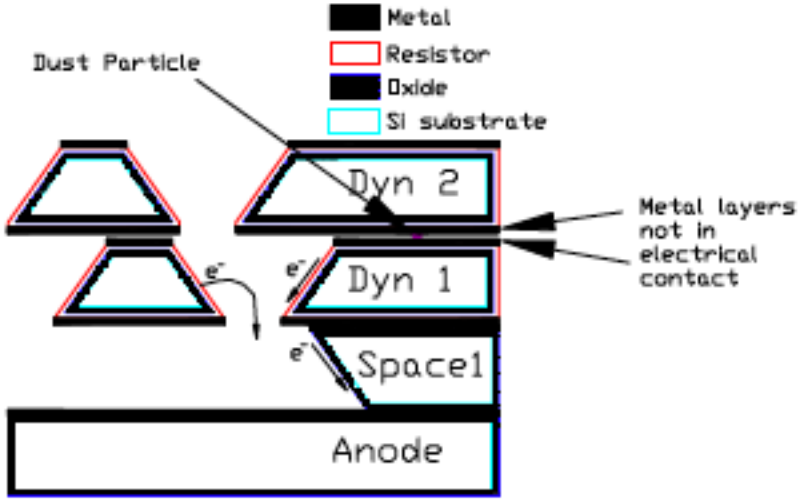
Ceramic μPMT body

μPMT stack ready
For e-beam tests
In SEM



Gain vs Voltage Measured on Two Stage Micro-PMT Dynode Chain





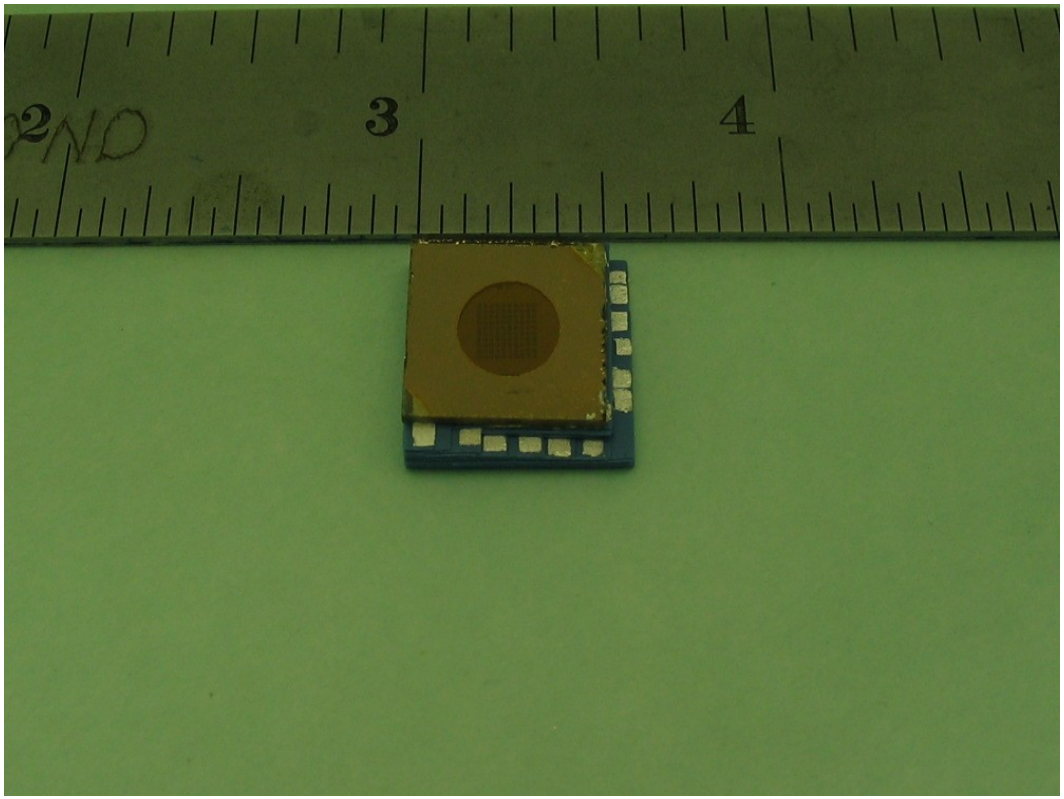
Si Dynodes(pyramidal):

SiOxNy (x <0.001, y < 0.01), P-doped at ~10^{15} to 10^{19} / cm^3 , ~10^8 - 10^2 ohm-cm resistive coating (N,P stochiometry), provided voltage gradients; strip current ~80μA x 100V ; δ ~2-3

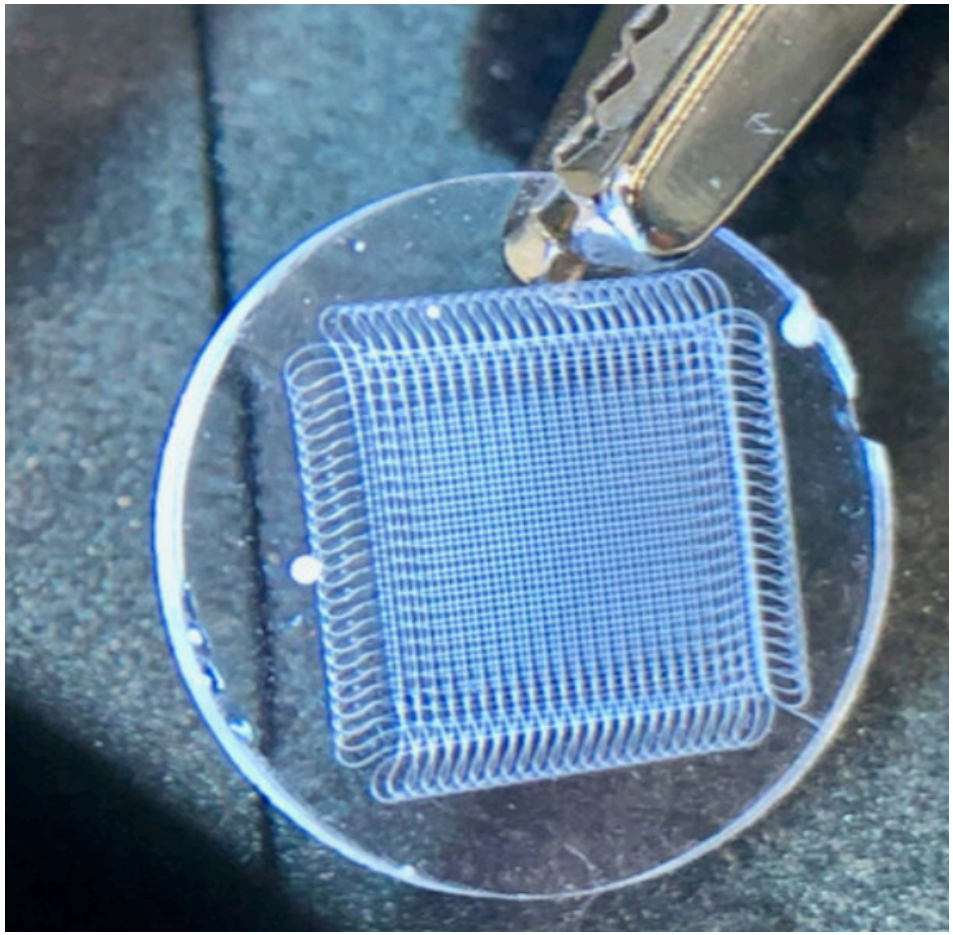
SiO2 Dynodes(teacup):

10-20 nm Al2O3 on 500 nm Al film; δ ~ 1.6-4.9

8-Stage Channelized Microdynode PMT Prototype



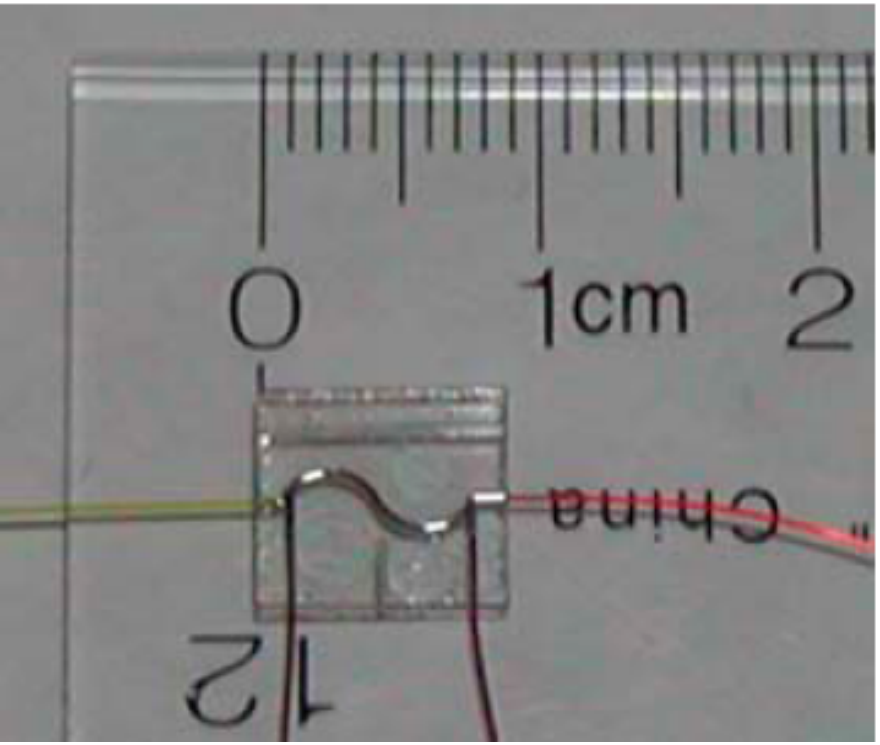
GLASS 3D Printing
A recent enabling breakthrough

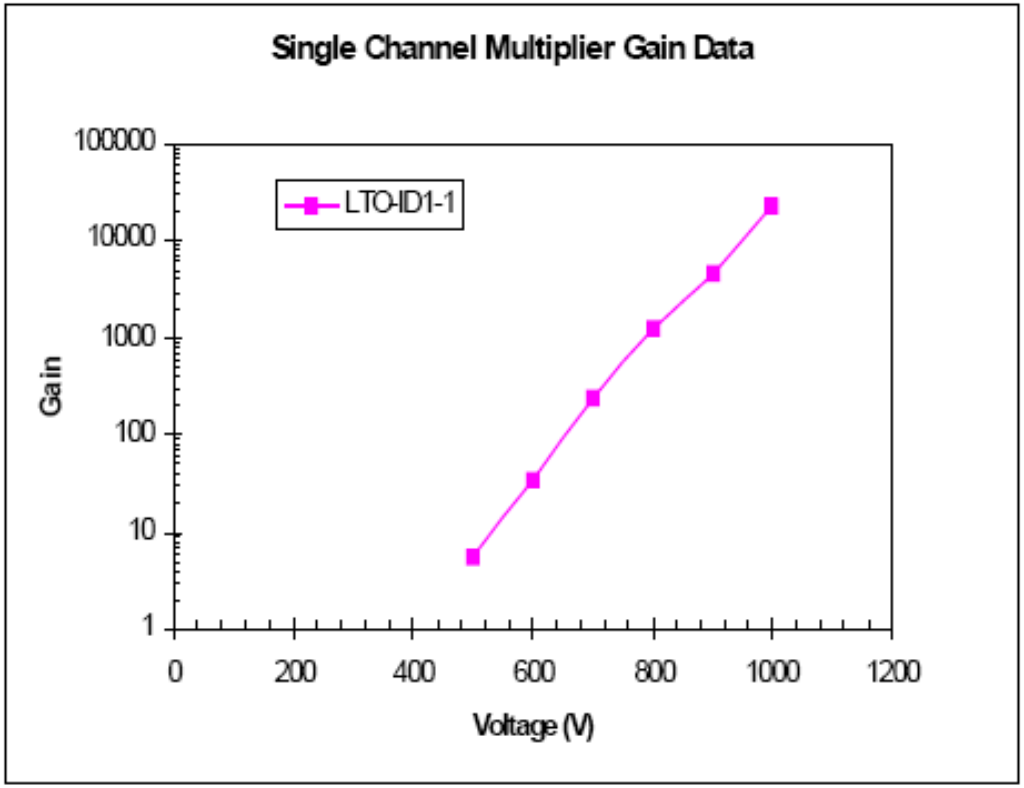


Novel PhotoDetector Geometries

- PMT Stripes–photocathode 3mmx300mm
  - Matched to scintillator, quartz sheets
- Pixel Arrays – no cross-talk/channelized
  - Direct connection to ribbons, bundles
- "Wafer" PMT
- Ultra-Compact
- High-B(?)

Quartz MicroMachining



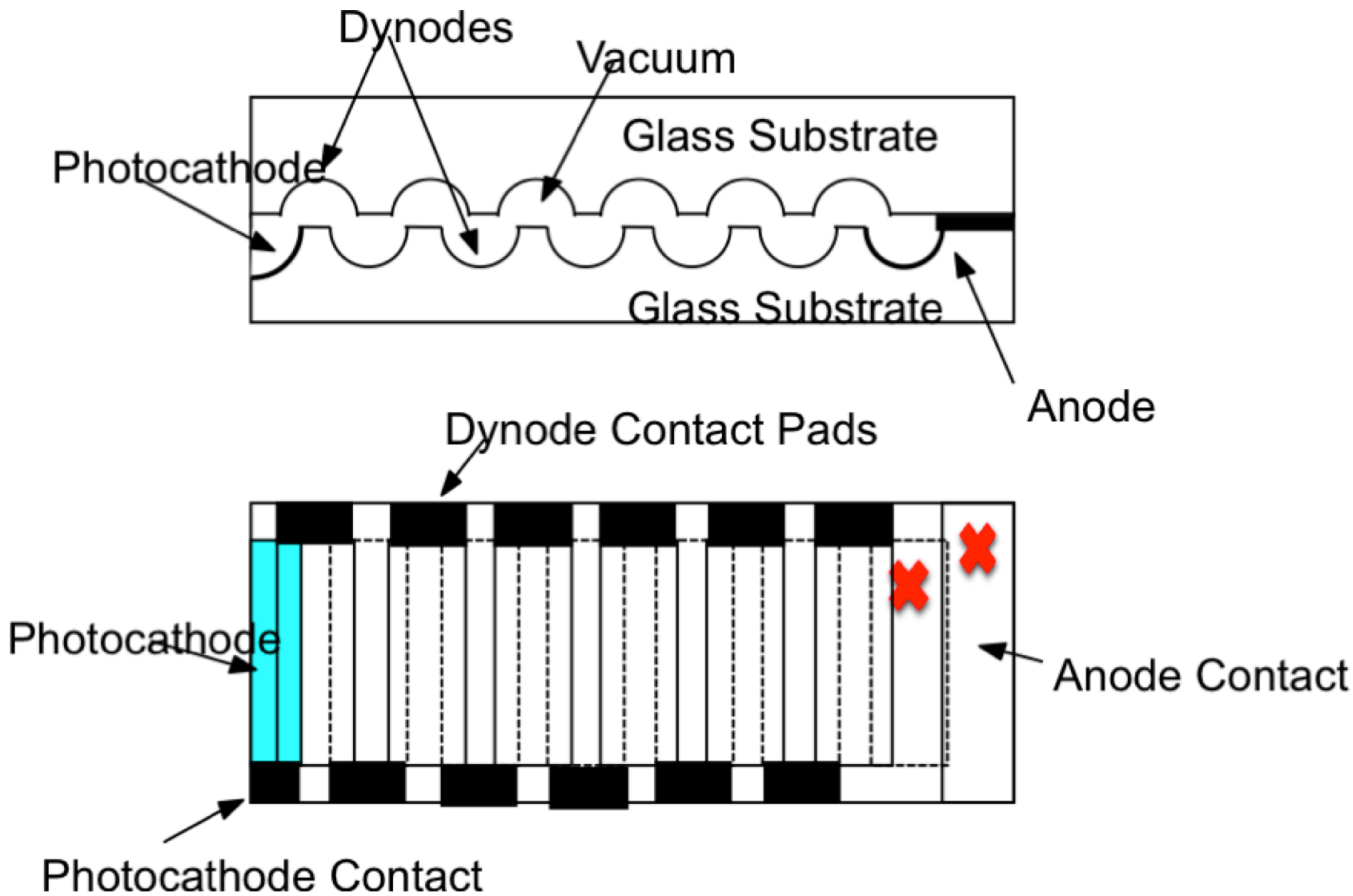


Low Noise Single Fiber Optic Receiver

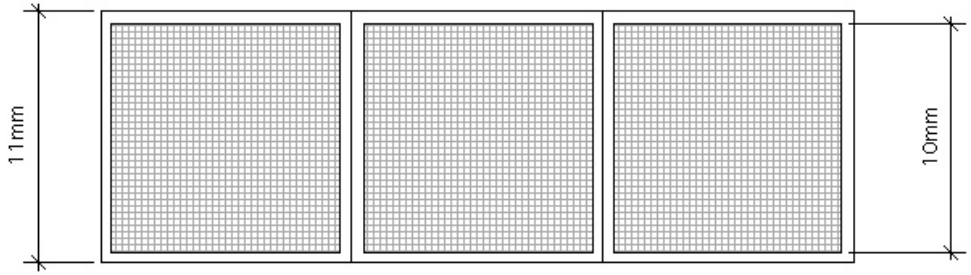
-Continuous S-dynode, 200 μm fiber input

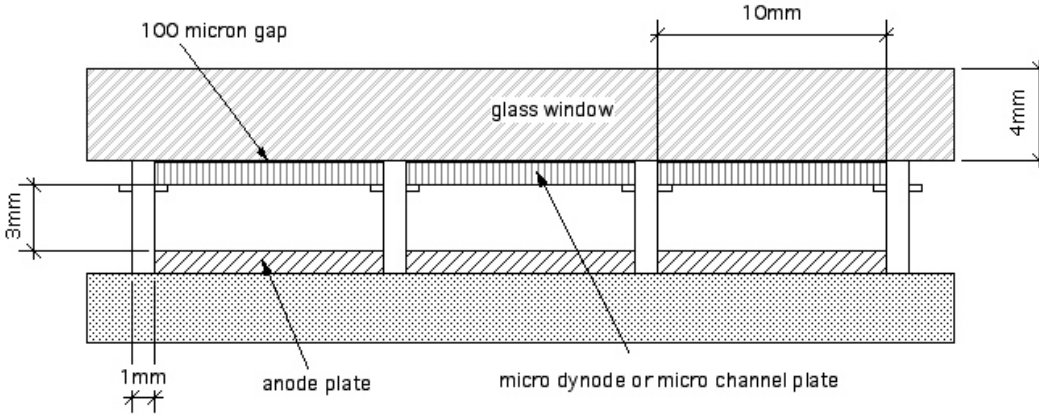
- *Gain ~22,000 at ~1KV*

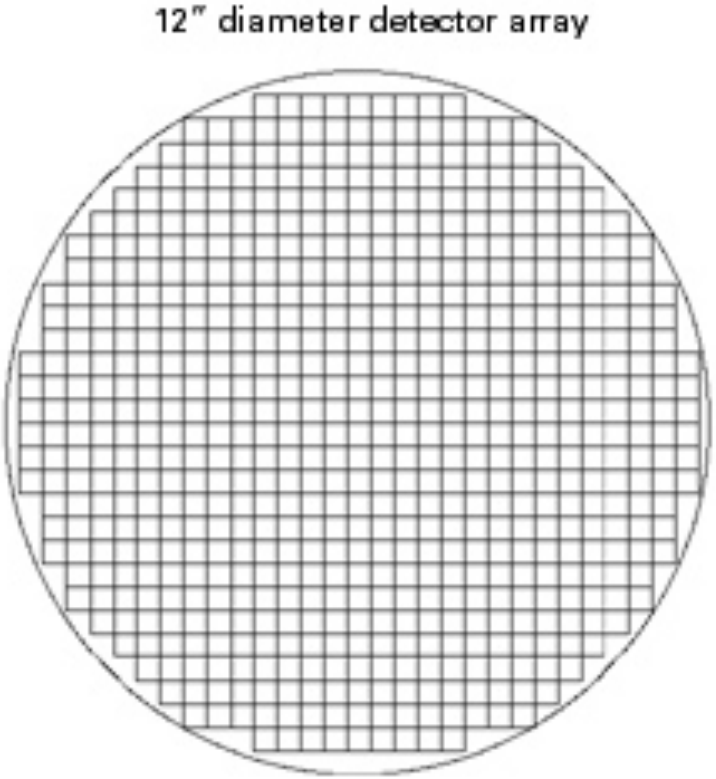
Rate capability relatively modest


Dynodes
Vacuum
Glass Substrate
Photocathode
Glass Substrate
Anode
Dynode Contact Pads
Photocathode
Anode Contact
Photocathode Contact

Tiled Arrays – mMachined Dynodes for Large PMT



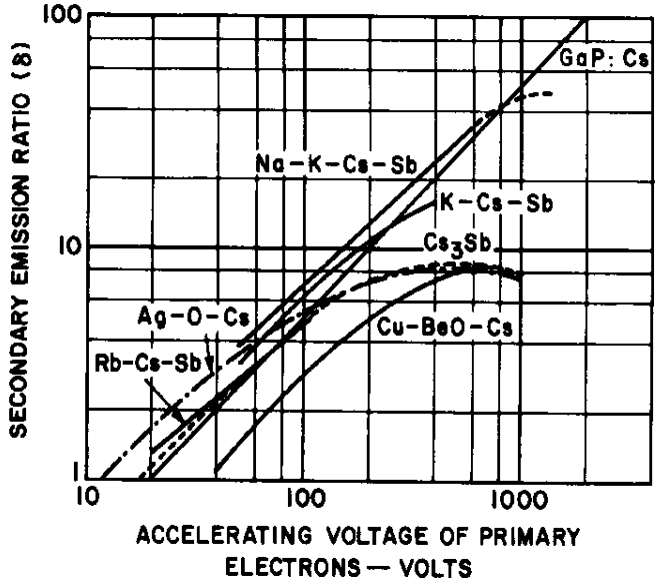


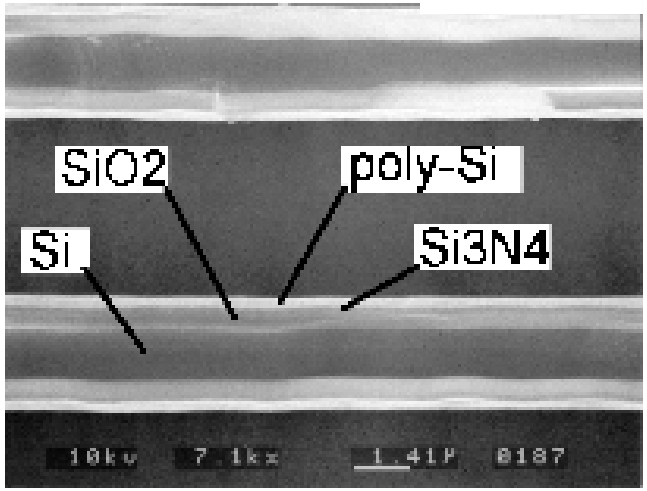


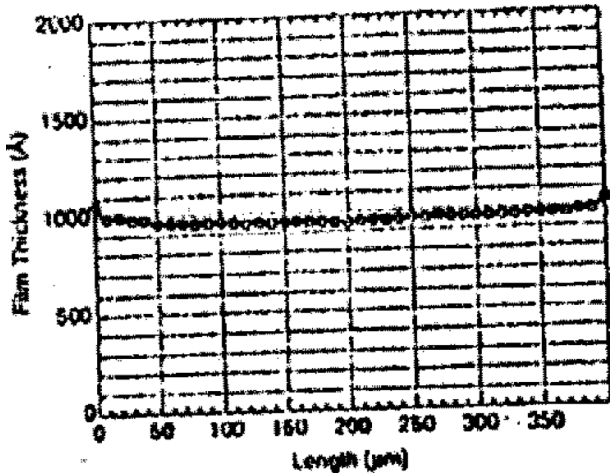
Extra Slides Follow:

- High SE Dynode Materials for MCDM/μPM
- Novel micromachined APD & SiPM

Towards a high performance MEMS PMT

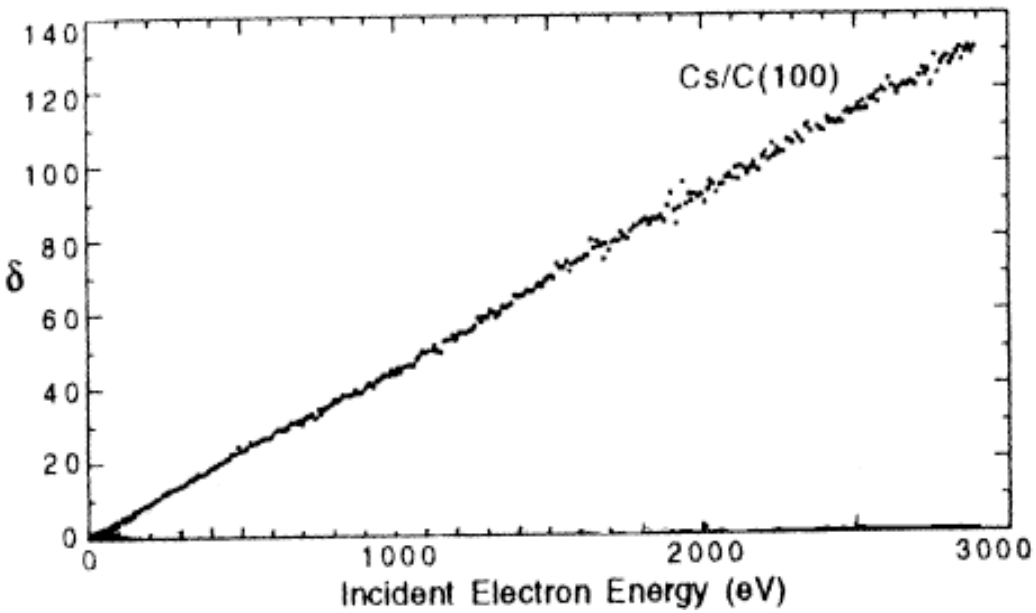


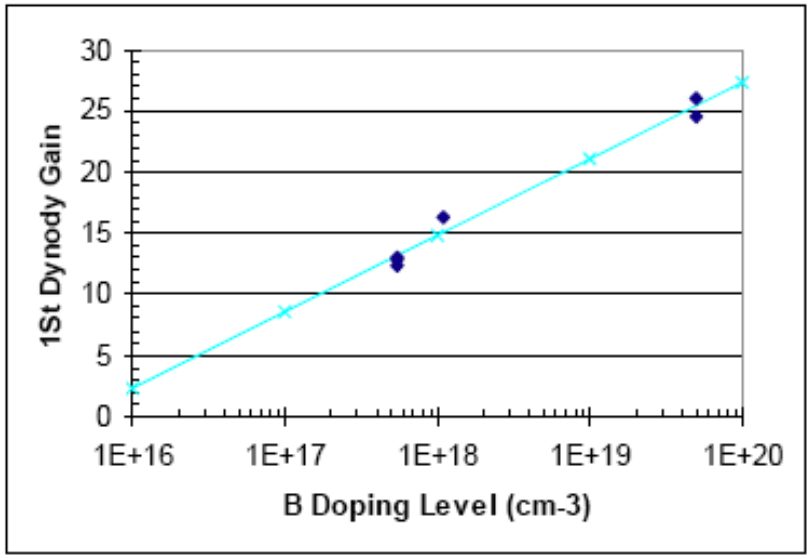




Flow through CVD SE coatings remarkably uniform – ALD preferred

Diamond Secondary Yields

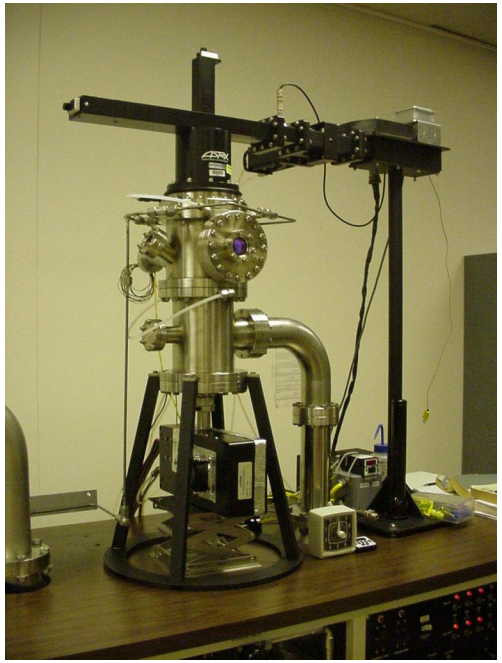


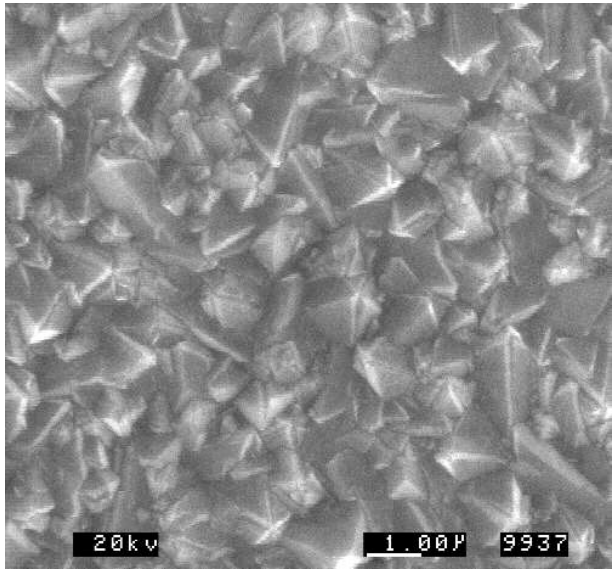


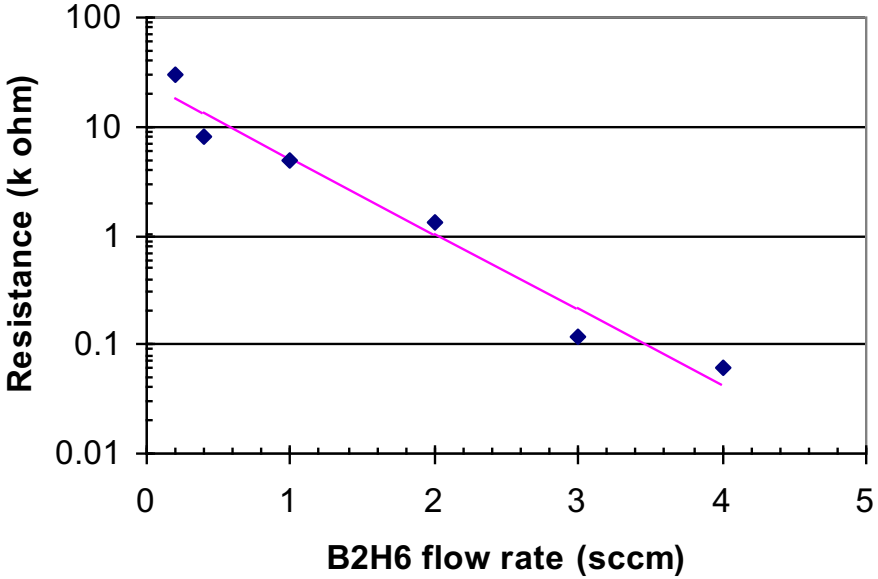
1st Dynode Gain vs B-doping
400 Volts K-D1

High secondary yields -> 10% single p.e. resolution

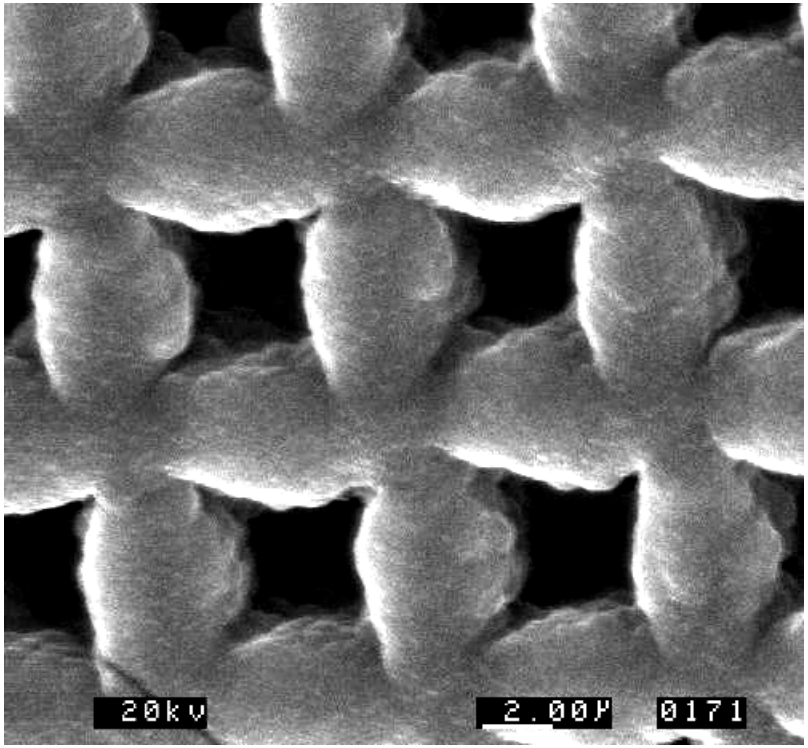
Diamond-Si pseudolattice match

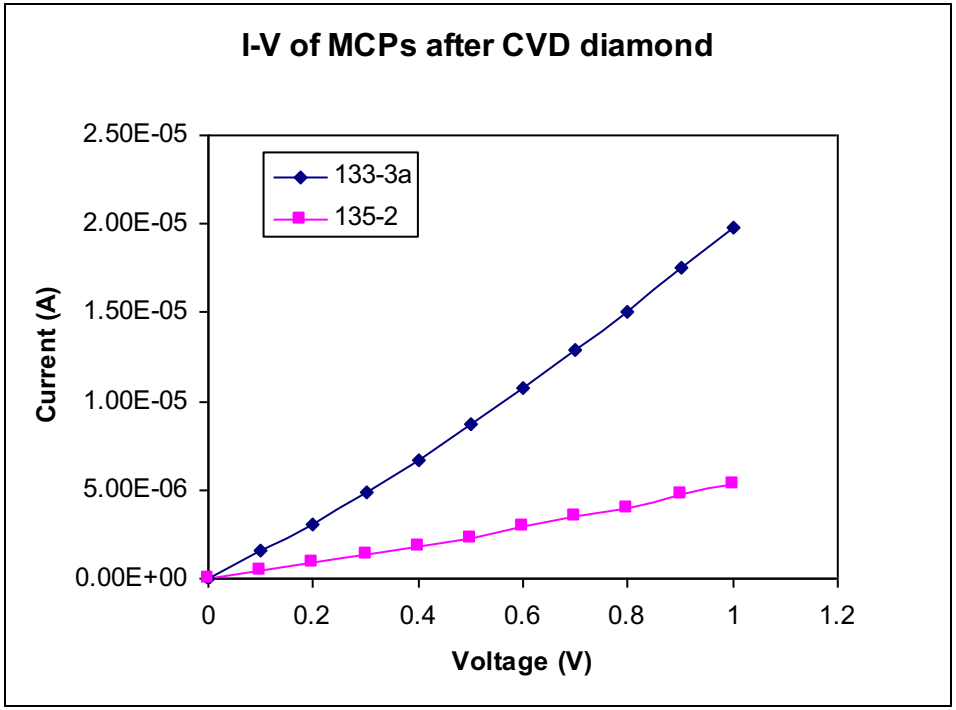






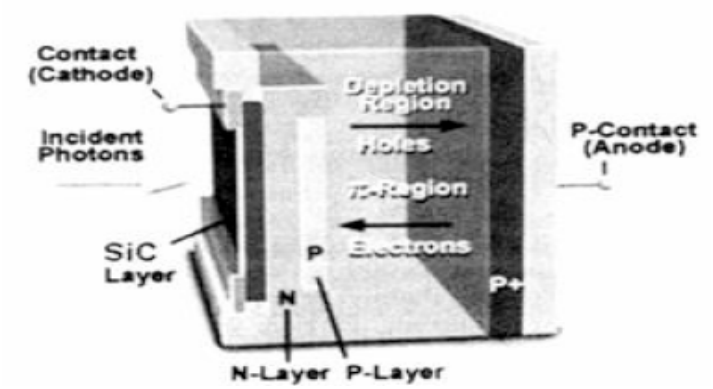
MCP/PMT Diamond SE Films

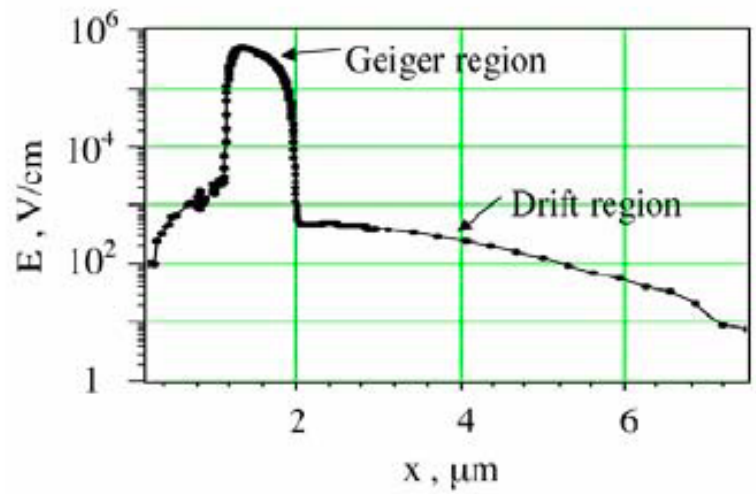




- CVD Polycrystalline Diamond–resistivity $0.1<\rho< 10^{18}$ Ω-cm
- Pseudo-Lattice Match to Si
- Deposited by CH_4/H_2 decomposition 10 Torr

APD: Compensated Doping -> Geometry





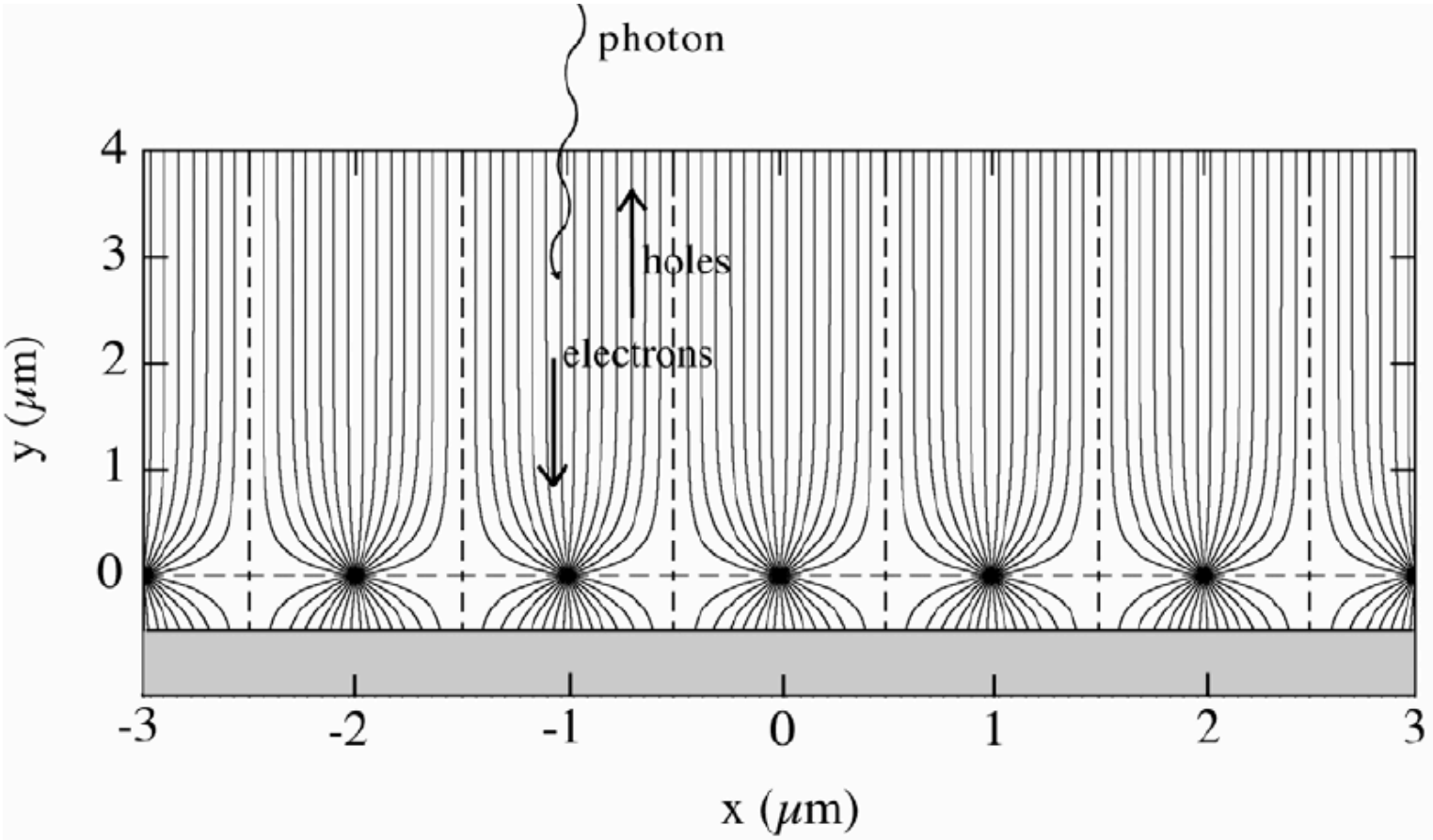
R= R1+R2+R3; R2 >> R1, R3

1. *High E-field Region,10^3-10^4 times higher than Drift Region; and*
2. *sufficiently long for many ionizing collisions*

High E-Field by higher resistance – via compensated doping.
The doping also results in lower energy interbands that generate more thermal noise.

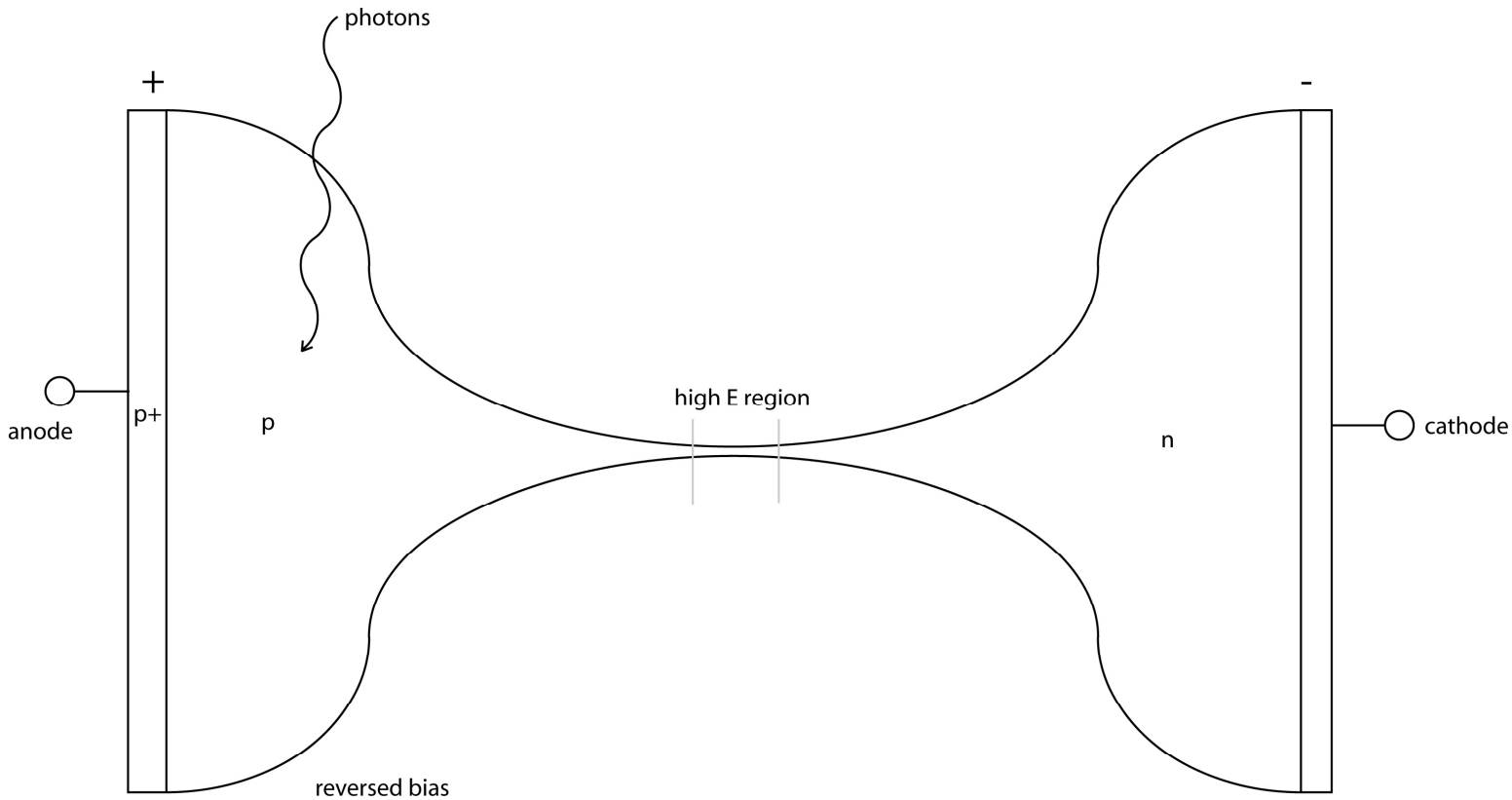
Toy Model: APD high field by Geometry!

- *Analogy to Drift Chamber or GEM!*



- works well in insulator gas…But Semiconductor?

Nanomachined Geometric APD



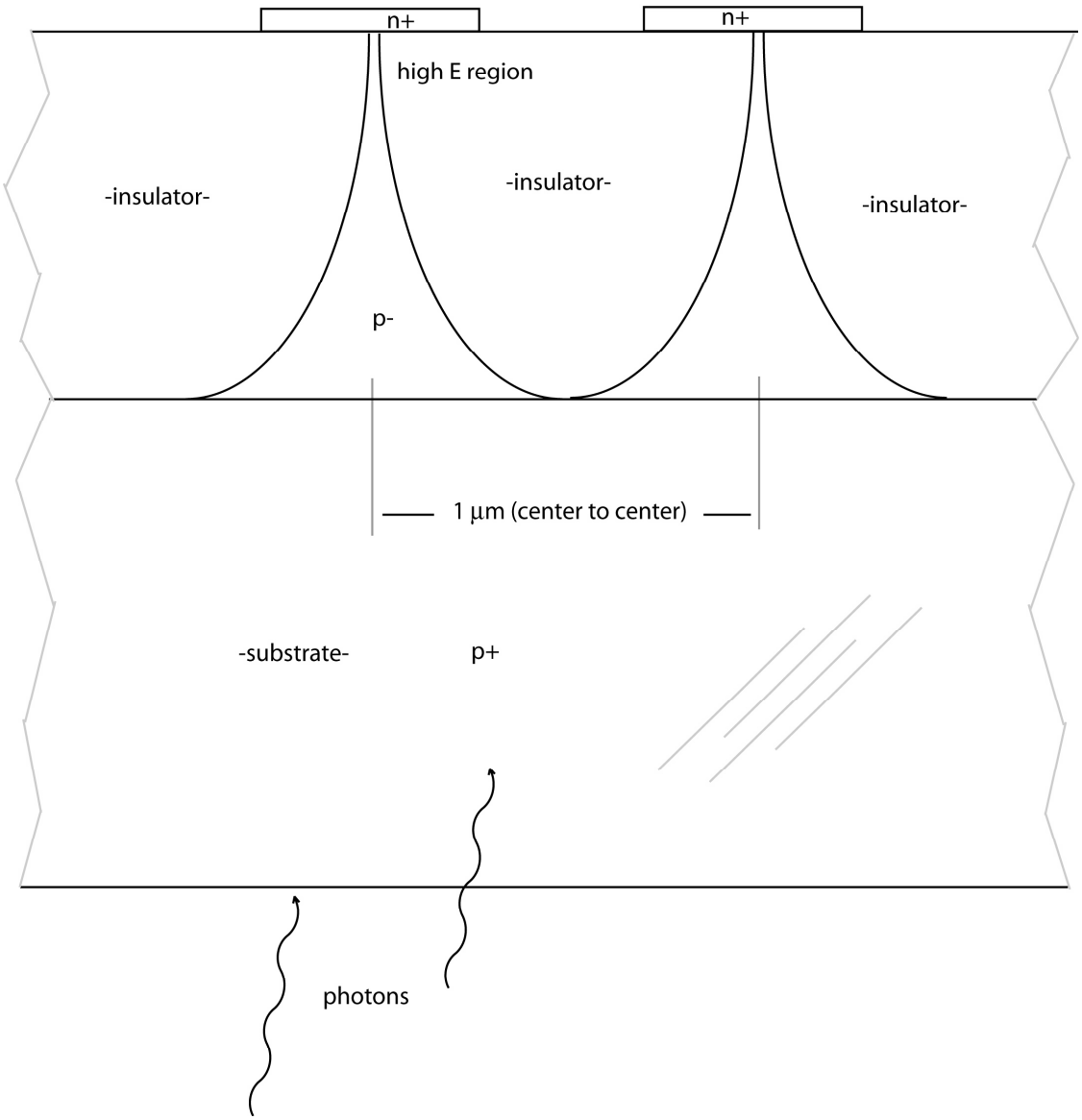
3D-Electric Field Enhancement ~ Ratio of Areas Electrode/Neck

example: 1 micron wide pixel requires neck < 30 nm diameter

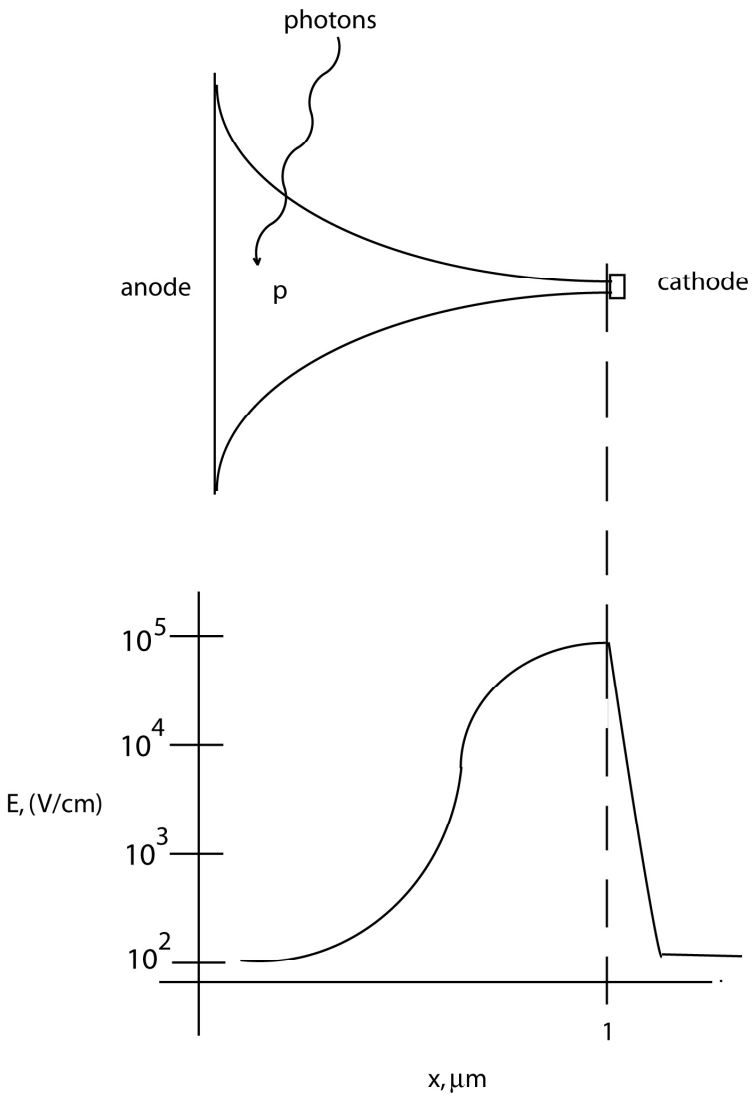
Control: Length, Size, Shape of high E field by geometry(+ Doping?)

Volume of Si reduced by more than x10 – less thermal noise….

Towards a GAPD Pixel Array



G-APD



CONTROL:

-Length of High field region

-E-field size/shape/taper

-Size of E

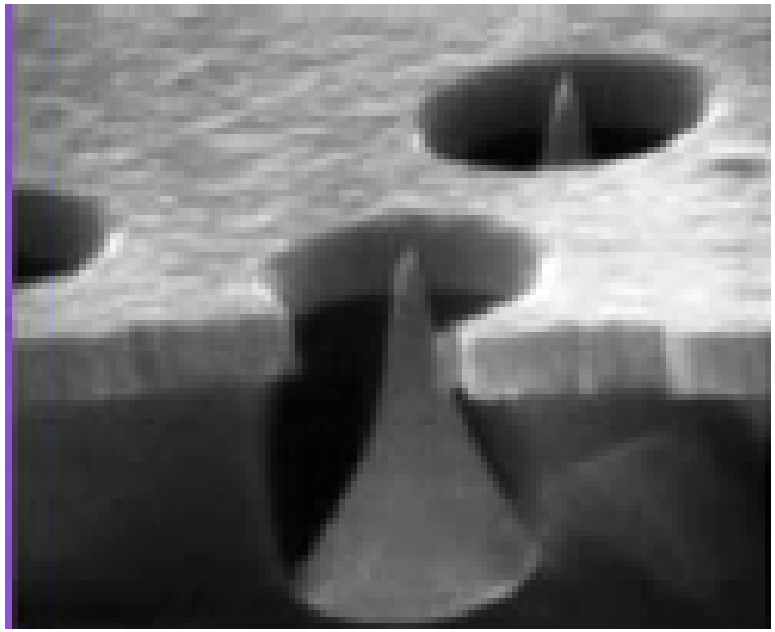
Benefits:

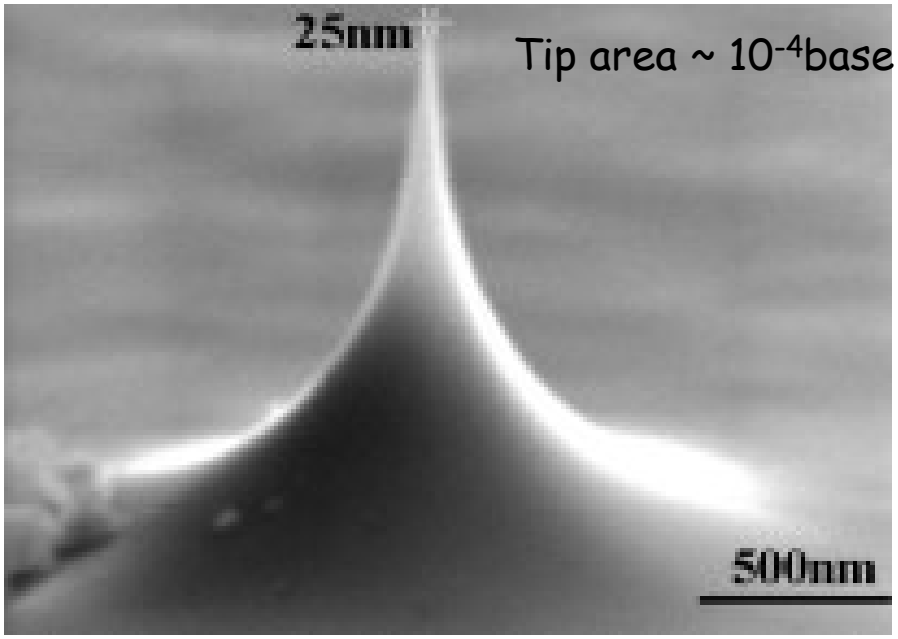
a) Less Noise:

- Lower interband Doping
- Less high field Si volume (x 100-1000 less)

b) Proportional Gain

Towards a Geometric APD
leverage field emitter tips



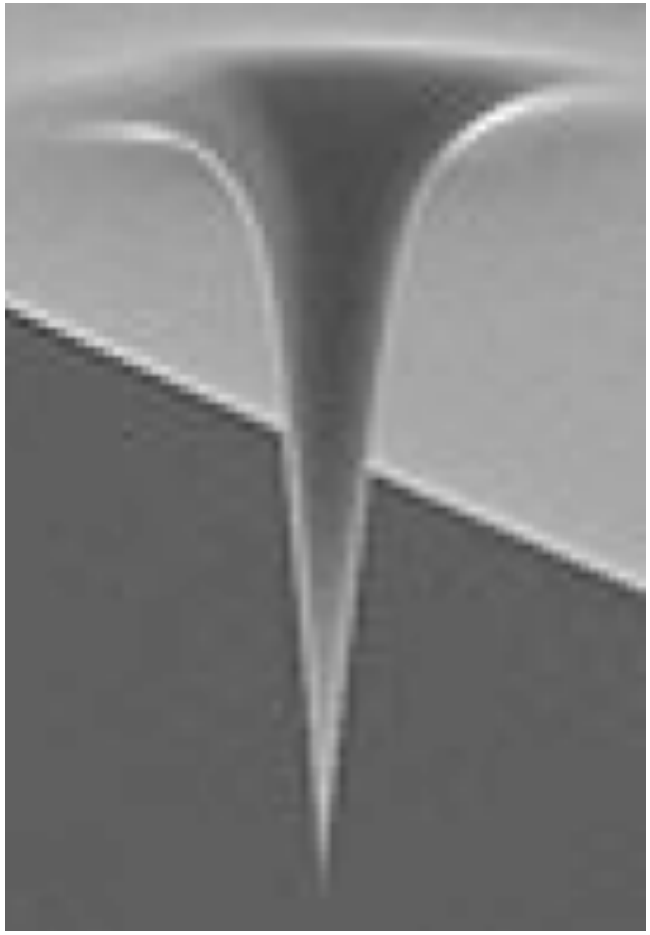


Standard Monotonous Patterned Nanomachining:

- Controlled isotropic chemical etch
- Anisotropic electrochemical etch
- Photoelectrochemical etch
- Others……

~Analogous to "Field Emitting" back into silicon

Single Pixel Tests



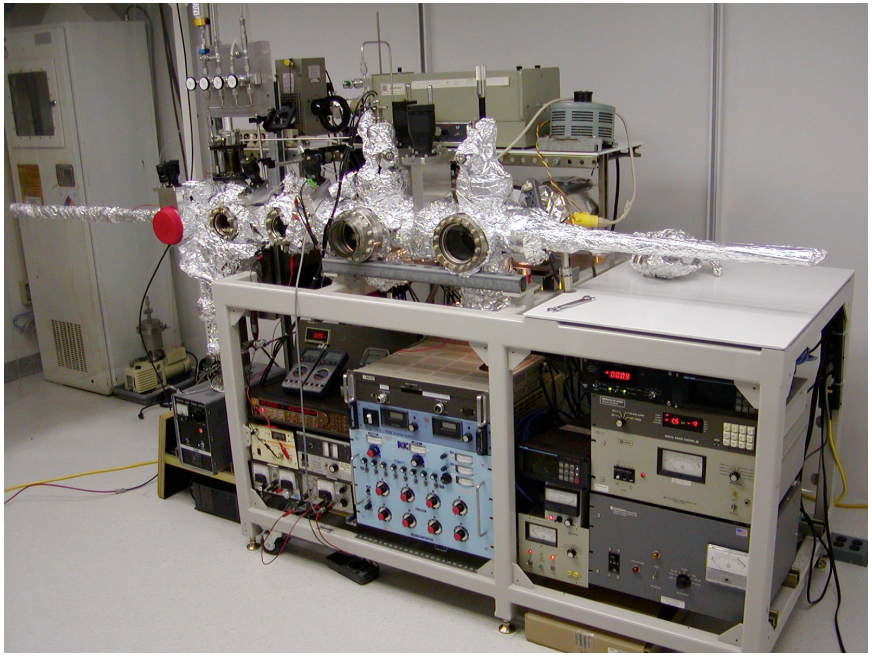
- Tips from STM/AFM manufacturers!
- Modify tips (and lever) to suit (thin top Si)
- Insulate or strip-off insulation, deposit transparent electrode/s
- Use AFM/STM to assemble to the opposite doped Si

Single Pixel Tests

- p-Type AFM tip, ~50 micron base x ~250 μm long, insulated ~20 nm Si3N4 except tip, metal annulus contact
- Tip placed by AFM to the surface of polished thin n-type Si wafer, metal ohmic back connector.
- Direct/Anodic bond - few μs HV voltage pulse.
- Reverse Bias, intensity I~400,000+/-10% green photons/s 40 micron core optical fiber on back annulus.

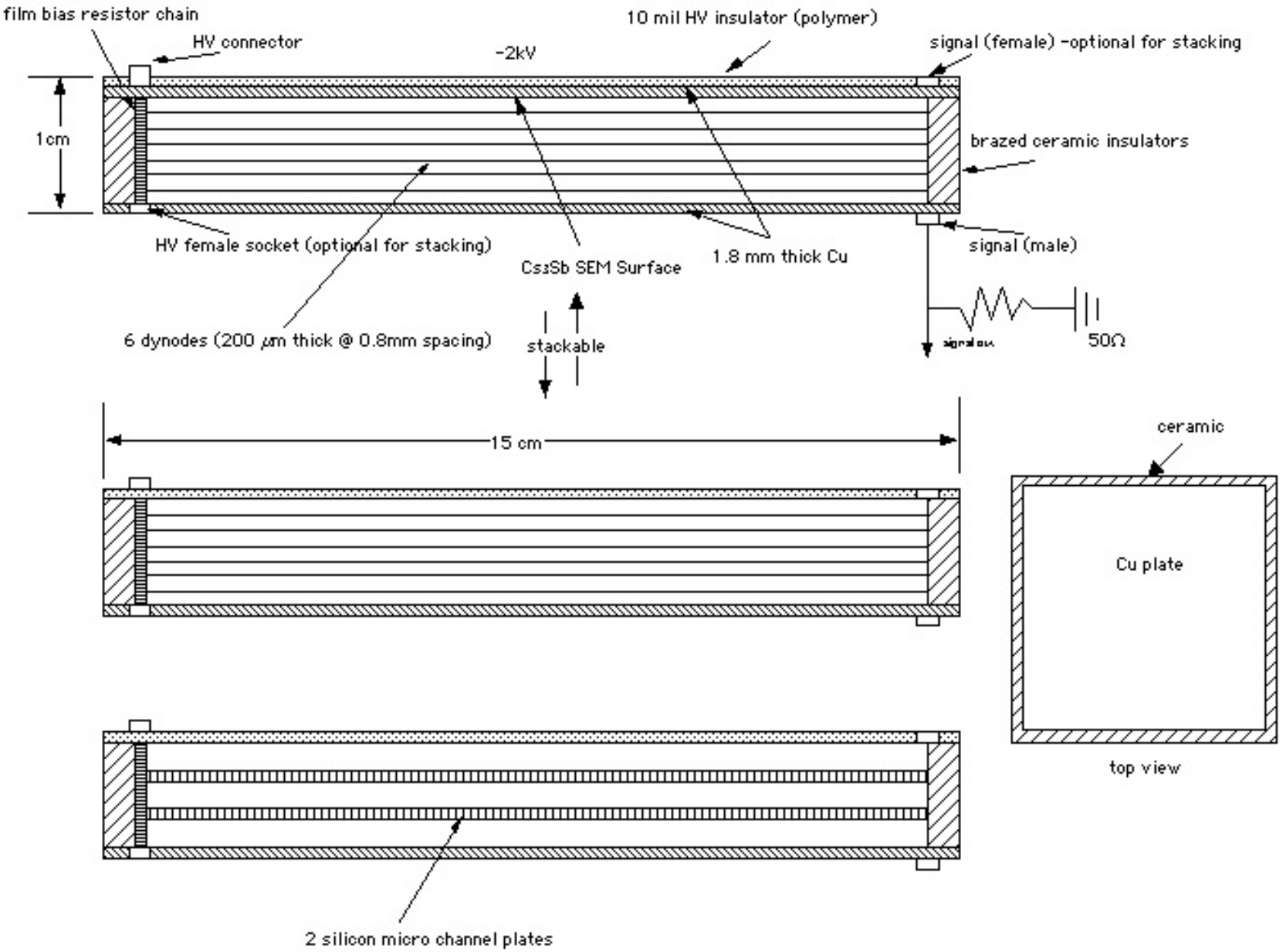
- **40 V, G>200, assuming QE~50%.**
- **30-80 V & I->3I: Gain ~ linear within 20%**
- **90~110 V, draws large current, Geigering.**
- **>110 V failed (Heating? Electromigration?)**

Tube & PC Processing



From left: monochrometer, Kelvin probe, photoemission, sample introduction, sealing, and photocathode transfer.

Schematic of SE Emission Calorimeter Module



Box ~ Size of Lab-Note Book with HV, Ground & Signal