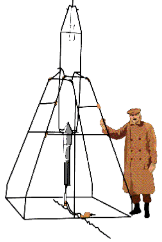
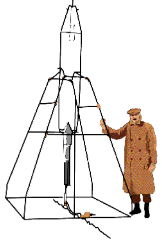


Quantum Efficiency and Noise III-V and II-VI Photocathodes for UV Astronomy

Timothy Norton, Bruce Woodgate, Joseph Stock, (NASA GSFC), Kris Bertness (NIST,CO) and R.D Vispute (U.MD)



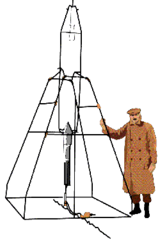
Overview

- Our photocathode application in UV space-based astrophysics
- Current NUV (100 - 320 nm) photocathodes and detectors - QE problem
- Gallium nitride (and alloys) a high QE III-V photocathode
- Our experience processing planar - opaque mode GaN and measuring GaN quantum efficiency
- Summary of the status of ours and others GaN work
- Nano-structuring GaN
- Noise
- ZnO a II-VI photocathode candidate
- Conclusions

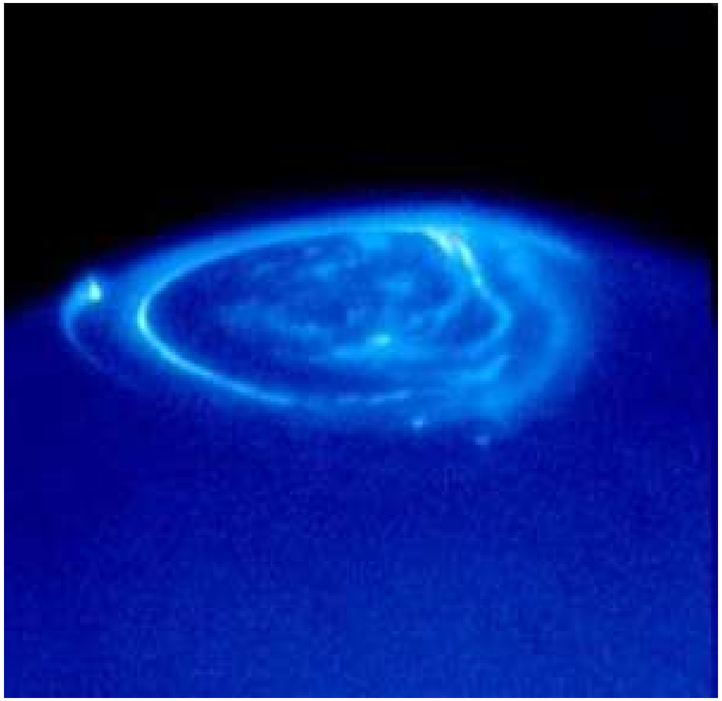
NUV photon-counting detector detector QE

MCP based UV photon-counting detectors are the workhorses of UV astronomy. (EBCCD/CMOS detectors can also serve as useful UV photon counting detector readout)

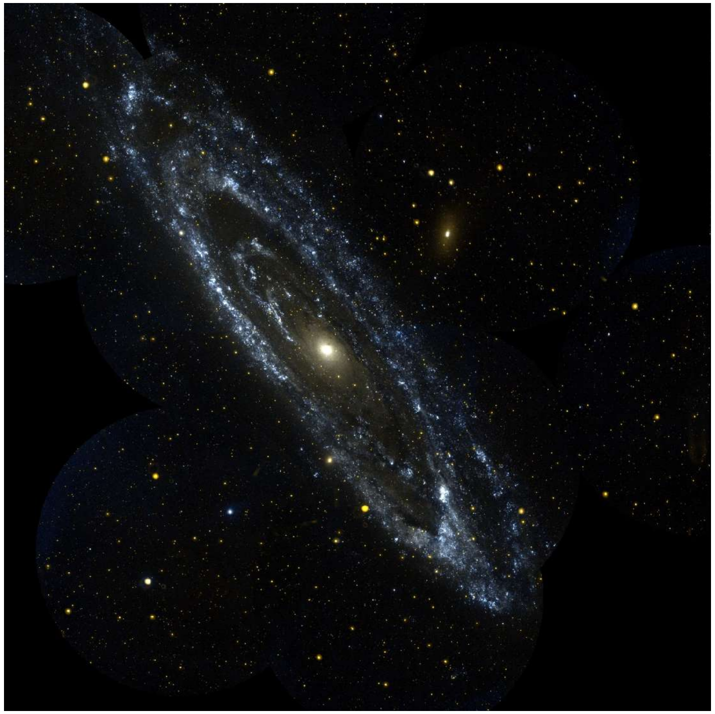
- They utilize a variety of photoemissive layers as the primary detection medium.
- For space-based astronomy missions QE and noise are paramount factors
- QE scales directly to required mirror size – payload size, weight and cost
- High QE enables new science discovery reach



State of the art - Photocathode based UV photon-counting detectors

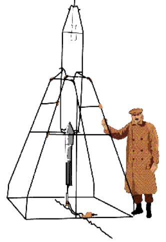


HST-STIS/ACS/COS MAMA



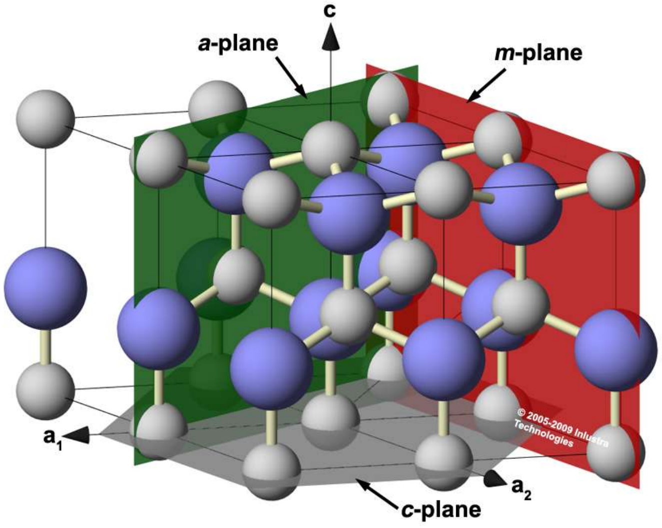
GALEX Delay line - UCB

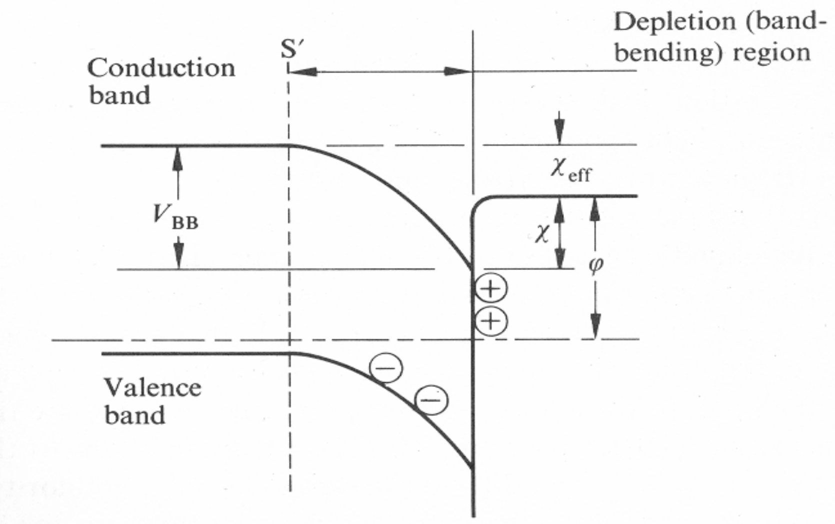
Excellent photon-counting detectors but they rely upon CsTe < 12% peak efficiency in the NUV. Their visible equivalents – CCDs – QE peak > 90 %



Gallium Nitride – a III-V photocathode

- GaN – Direct Band Gap material, 3.2eV
- Electron affinity 4.1 eV
- Can be cesiated to NEA
- Alloys – In for red response, Al for short wavelength cutoff
- Substrate match to sapphire
- Industry leverage – Blue LED – Bluray etc
- Photocathode development - active Groups : NASA GSFC, UCB, NWU, SVT Associates, POC/TDI and Hamamatsu.





After p-doping with Mg and cesiation - NEA

Spicer 3-step model

QE depends upon :-

1) Absorption of photon - Reflection
(angular dependence)

2) Electron- transit to the Surface
Random walk
e--e- scattering,
phonon - trap scattering
Transit through depletion layer

3) Escape surface probability
Overcome Work function
Reduction of Φ due to Cs dipole or applied field (Schottky Effect)

Spicer 3-step diffusion model

P – Escape probability – P-doping, Cs/CsO), surface cleanliness.

R – Reflectivity - Morphology

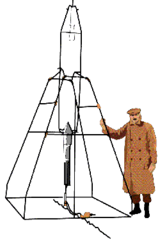
α – Absorption coeff – doping level.

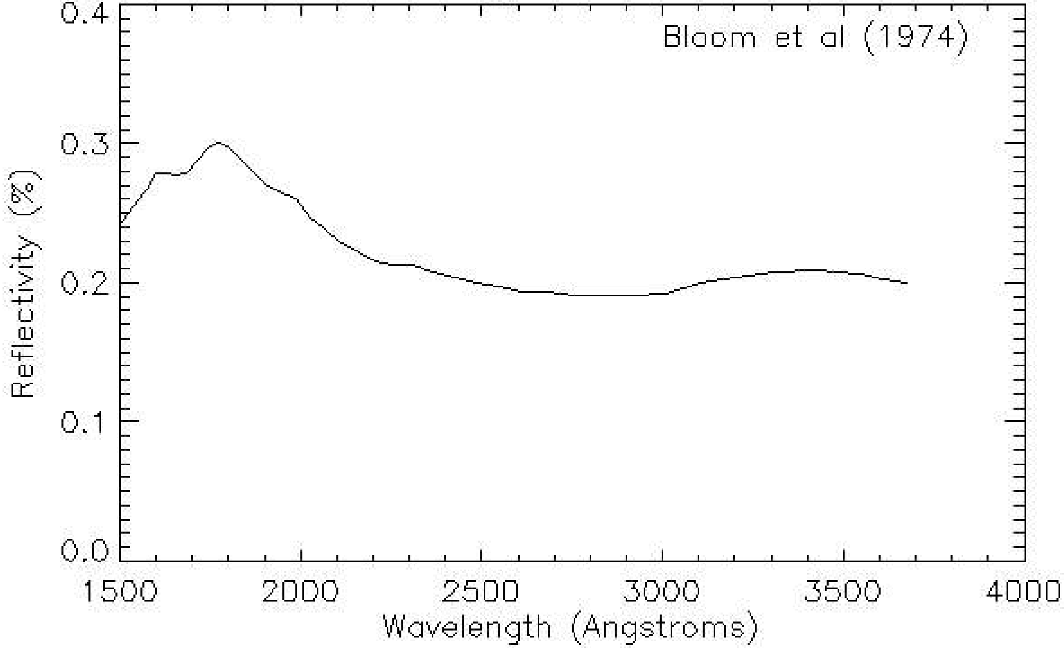
L – Diffusion length – (doping level,traps,quality)

$$QE = \frac{P\,(1 - R(\lambda))\,\alpha(\lambda) L}{1 + \alpha(\lambda)\, L}$$

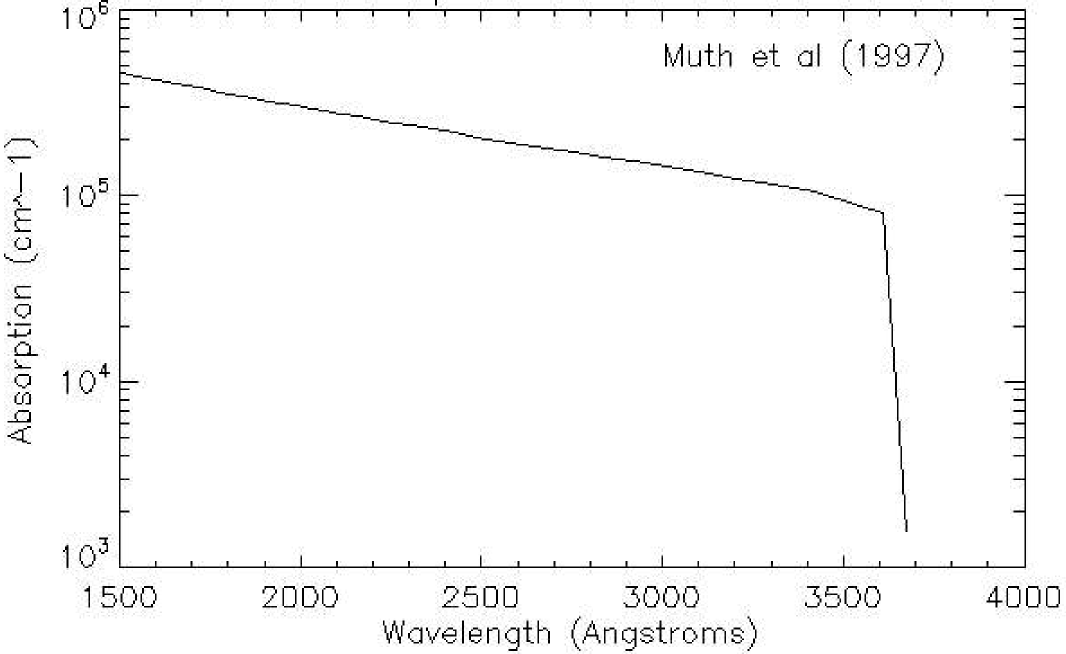
For NEA cathodes : $\alpha(\lambda)\, L >> 1$

$L >$ 1 micron



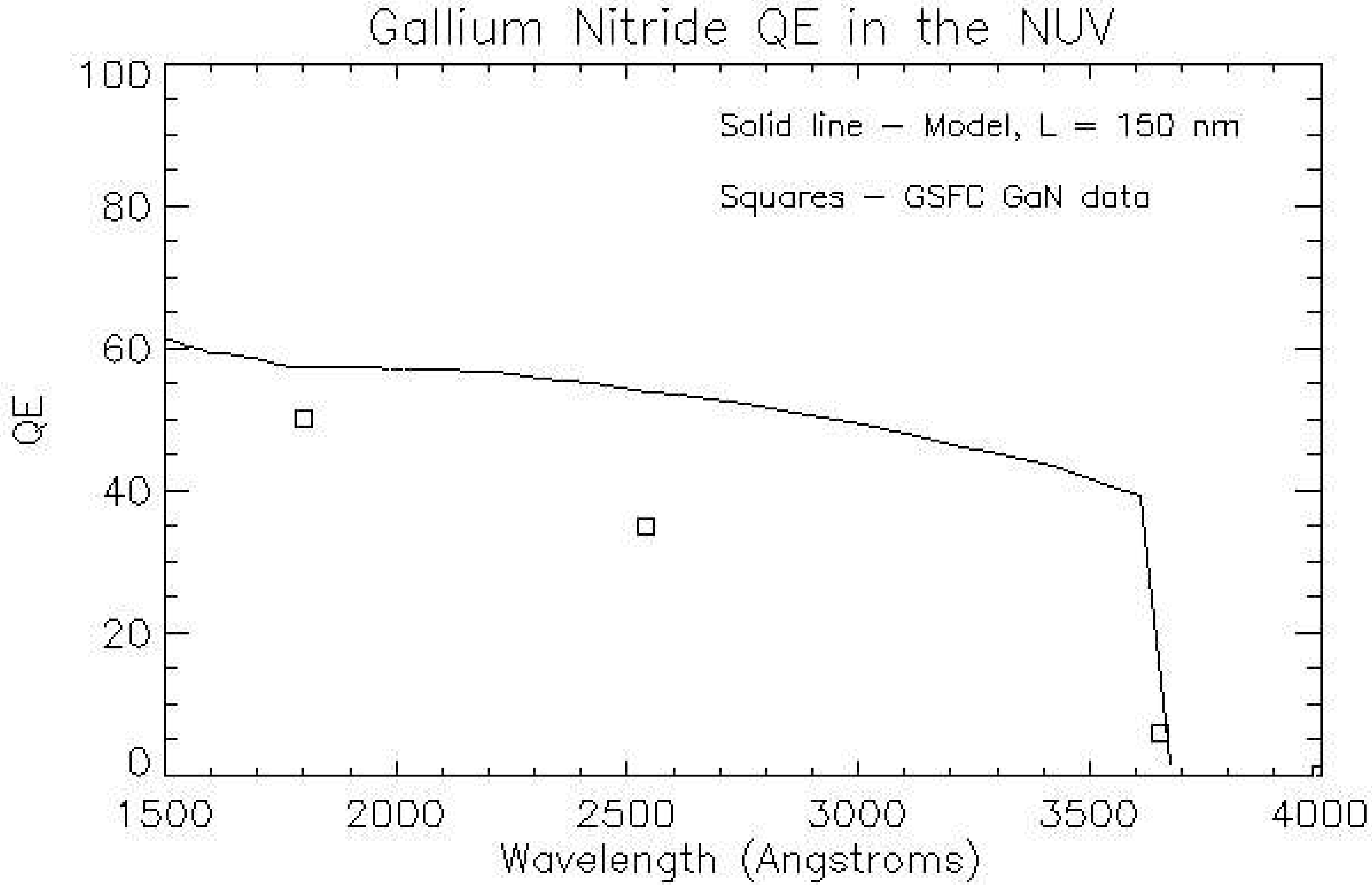


UV reflectivity of Gallium Nitride



UV absorption of Gallium Nitride

GaN QE – Model and data



GaN sample mounting

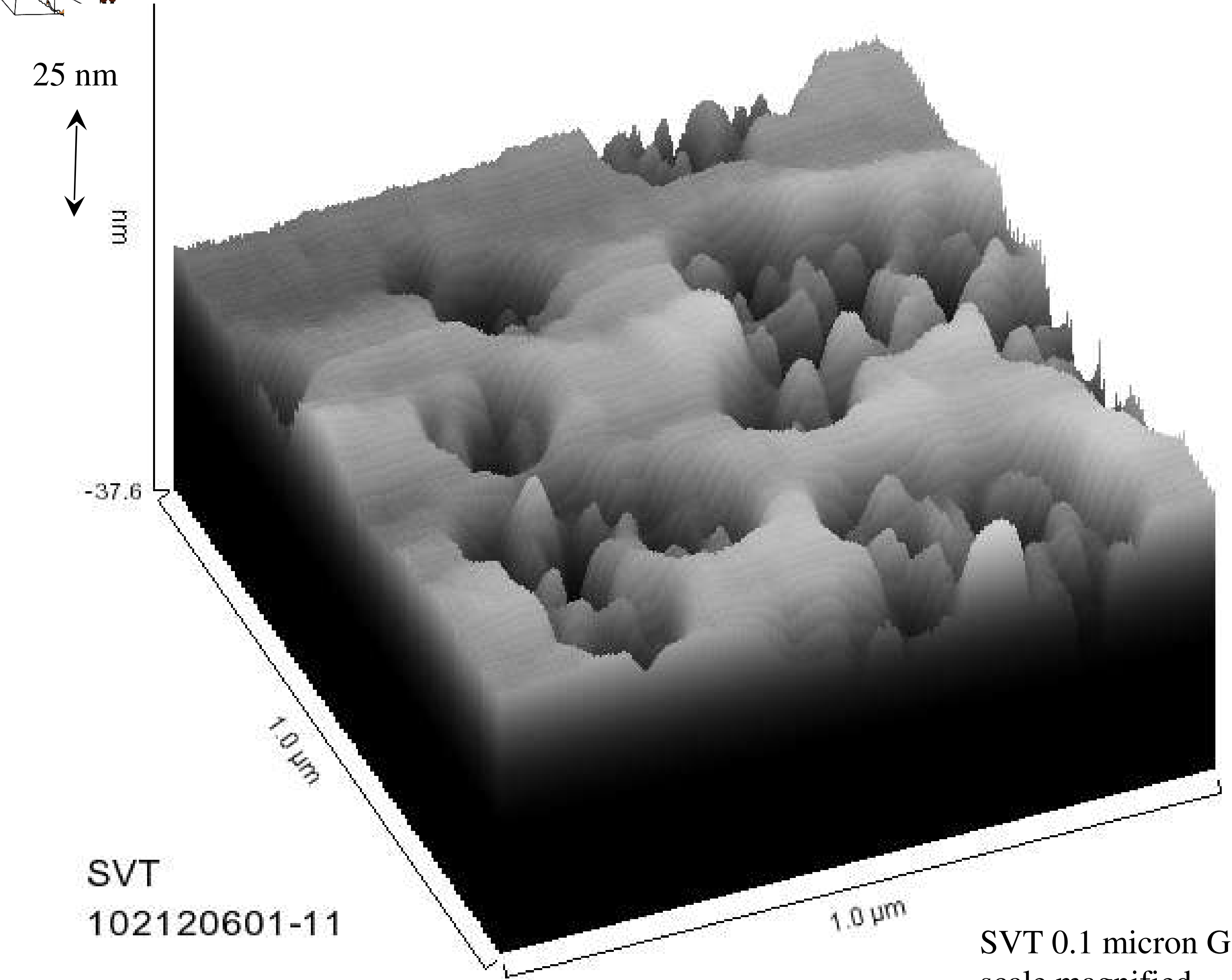
GaN suppliers :-

SVT Associates

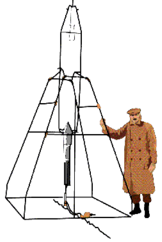
NWU

TDI/Oxford Instruments

NIST, CO



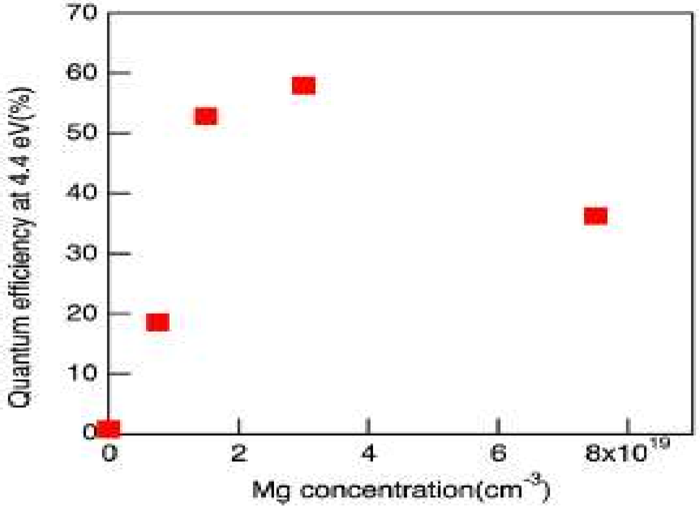
SVT 0.1 micron GaN, planar. Vertical scale magnified.



P-Doping – Band bending and escape probability

- Optimum acceptor (Mg) doping required for high QE.
- Too low results in minimal band bending – low escape probability.
- Too high increases minority carrier scattering and trapping.
- We (GSFC have too limited data set to verify optimum level)

- Hamamatsu Inc (Uchimaya) show 3 x 10^19 cm^-3) optimum level.



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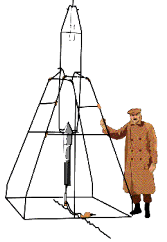
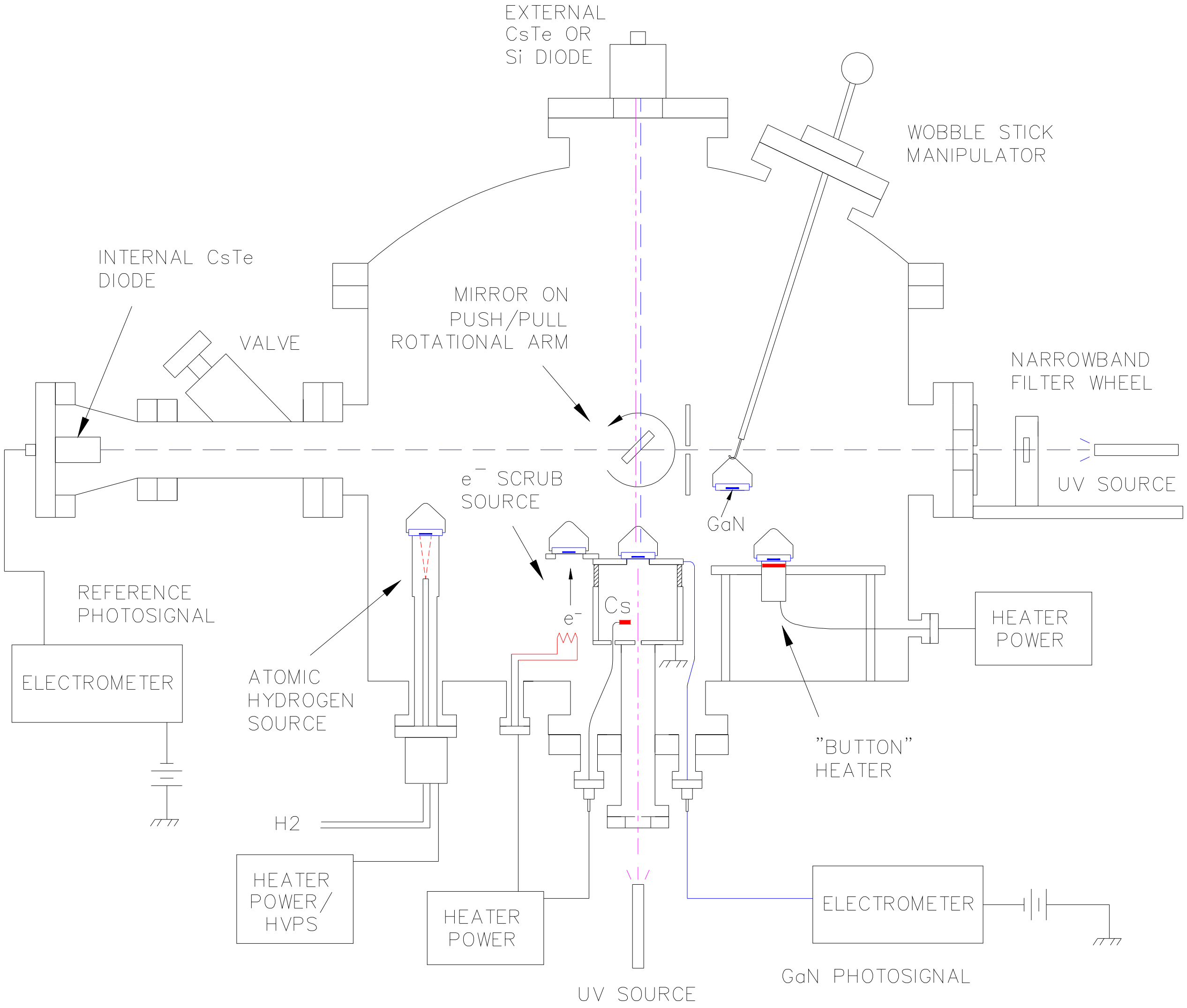
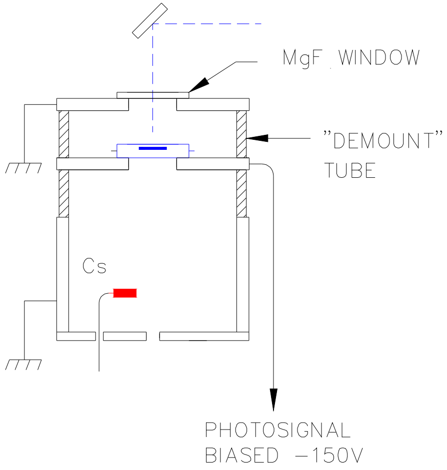
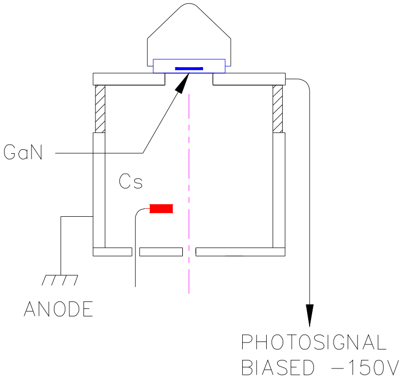


Photocathode processing chamber

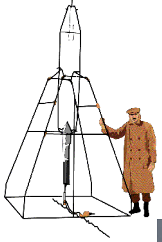




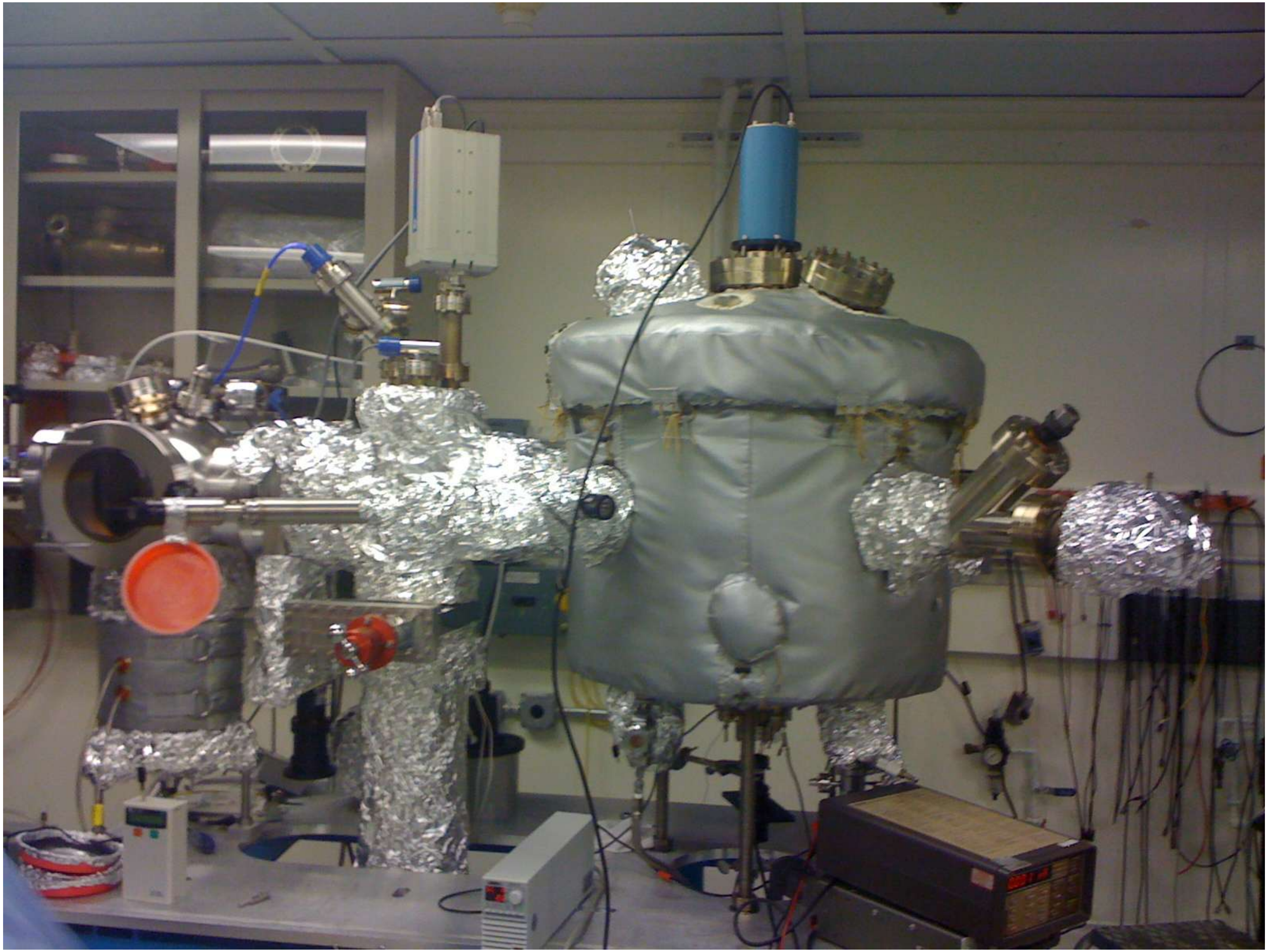
CALIBRATION POSITION



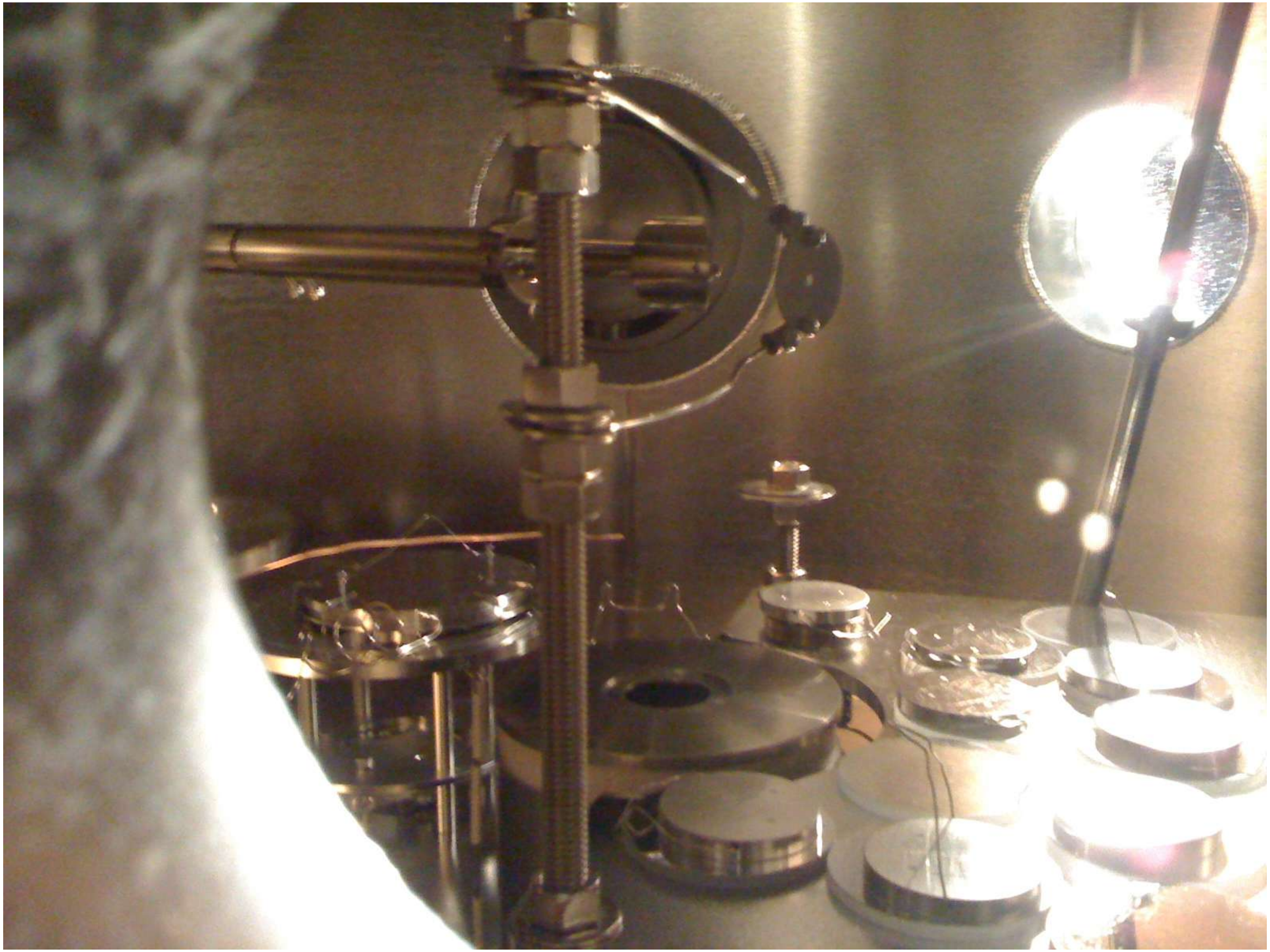
CESIATION POSITION



Photocathode processing and transfer chamber



GaN annealing, cesiation and calibration



Basic GaN photocathode process

- Acquire p-GaN – Vendors, SVT, TDI, NWU, NIST.
- Cut into 1 cm squares – mount into sample holders.
- Wet etch – Pirahna + HF, DI rinse – N2 bagging.
- Button heater anneal > 2 hrs at 600C.
- Electron scrub – 300 eV electrons, 1600 microamp/hrs.
- Cesiation – SAES sources – 15 minute process – over cesiate.
- Calibrate at 121, 150, 180, 254 nm vs CsTe – NST calibrated diode.
- Decision to seal into device.

Surface preparation is crucial !

Piranha wet etch :-

$H_2S0_4 + H_20_2$ (3:1) 10 min.- 90C; DI H_20 rinse 5 min.; H_2O + HF (10:1) 10 sec dip; DI H_2O rinse 10 min.; Blow dry with N_2. Package in clean, sealed N_2-purged bag.

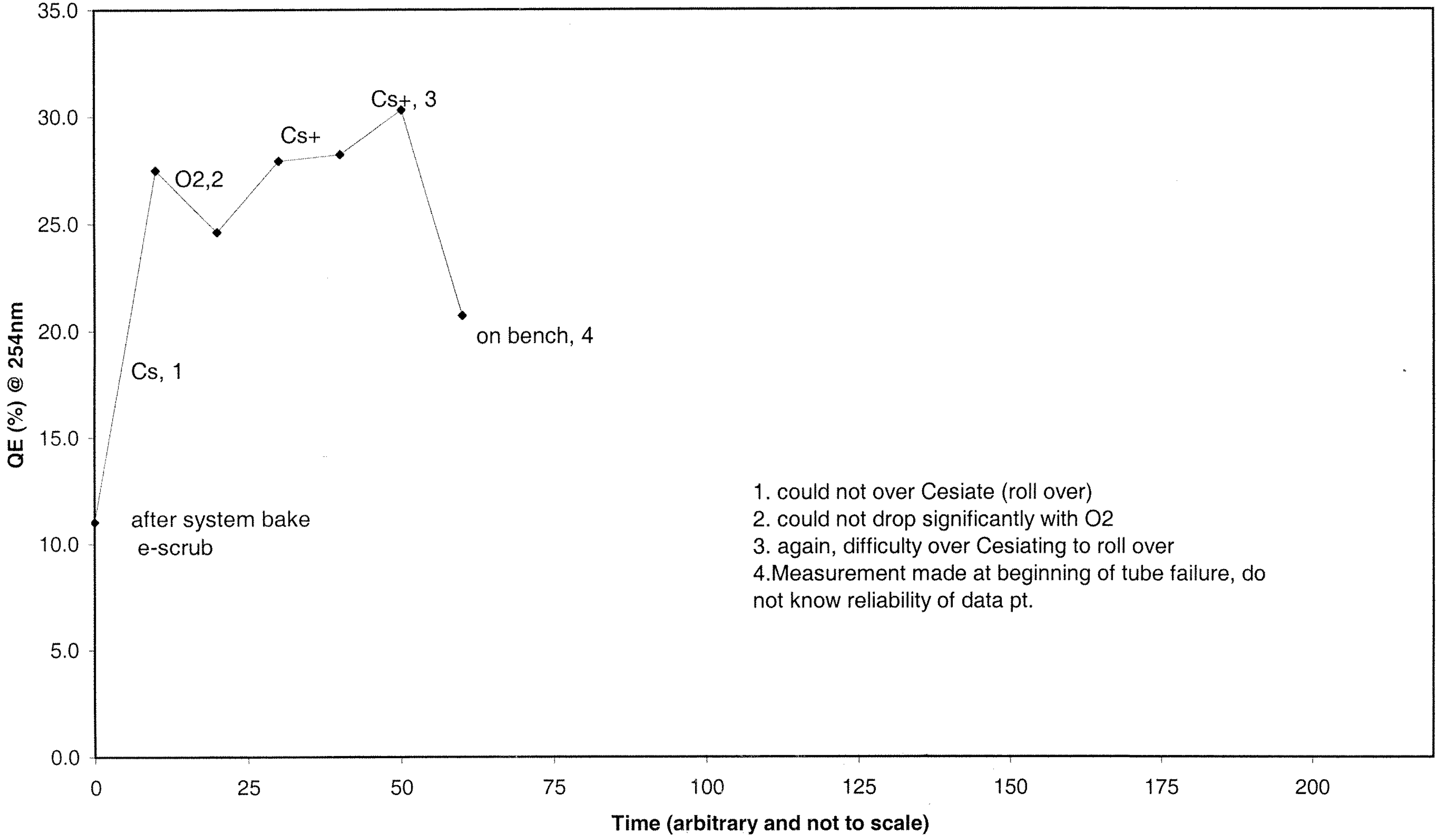
Vacuum bake – UHV chamber – 350 C – 24 hrs

Button heater - 600 C for 2 hrs

Electron scrub – 300 eV electrons – 160 μ/hr dose

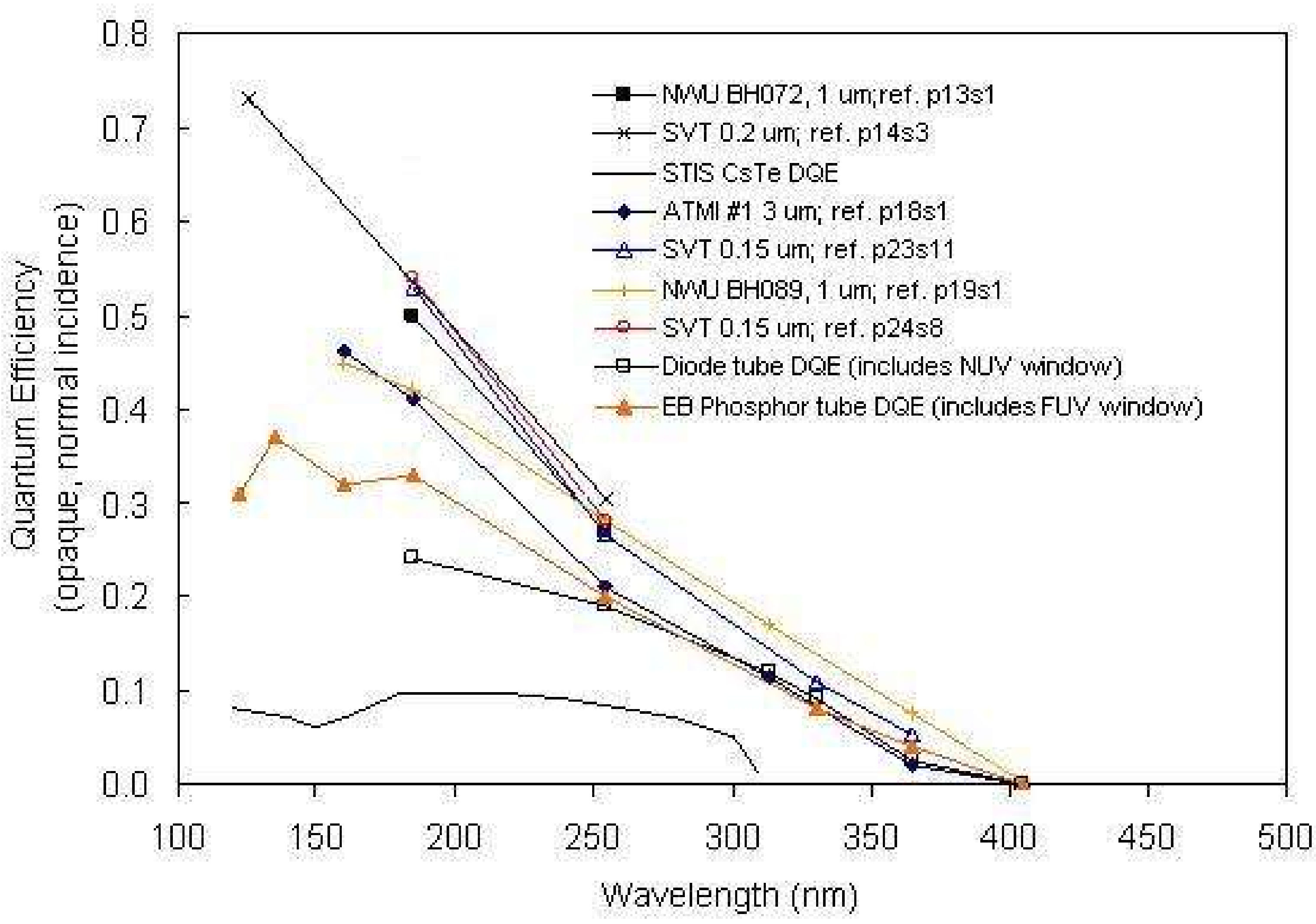
Cannot overstate importance of these process steps in improving QE.

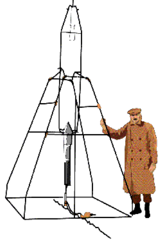
Process 20, Tube01, SVT 0.15um
QE vs. Processing



1. could not over Cesiate (roll over)
2. could not drop significantly with O2
3. again, difficulty over Cesiating to roll over
4. Measurement made at beginning of tube failure, do not know reliability of data pt.

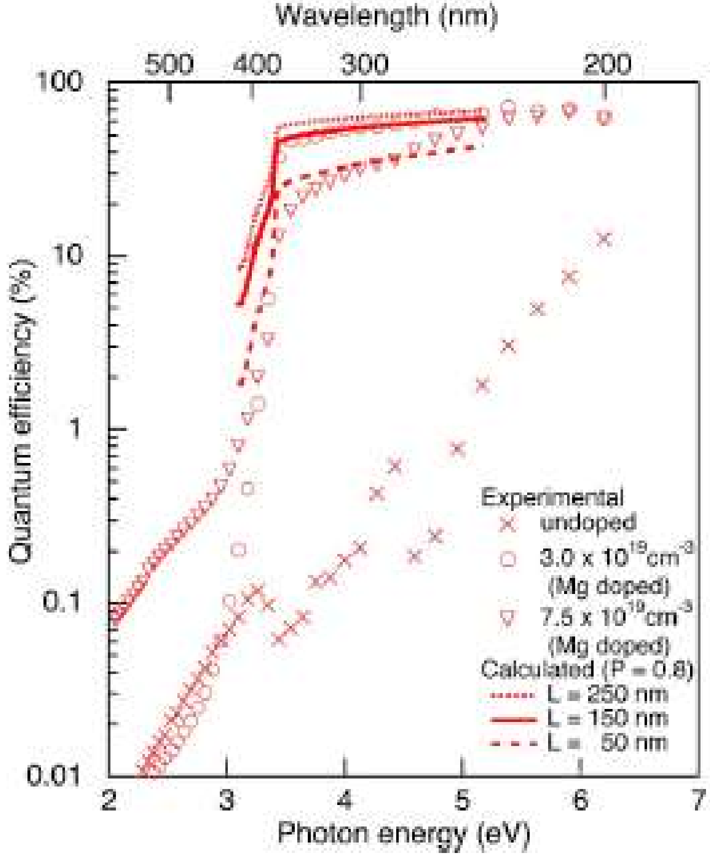
GSFC GaN processing - QE results

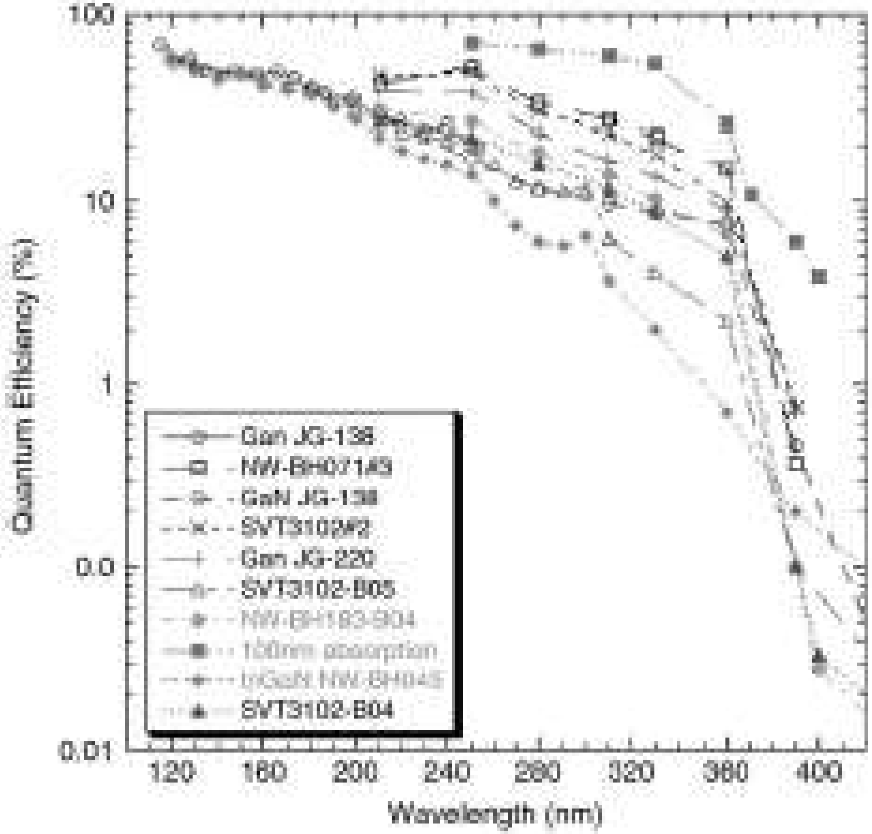


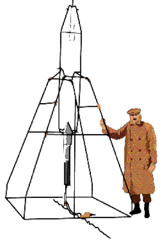


Opaque Gan QE - Progress

103511-2 Uchiyama *et al.*







Secondary effects

- **Electron mirror induced field due to higher band gap substrate heterostructure AlN/GaN – we see thinner GaN < 0.2 micron shows higher QE than > 1 micron thicker samples.**

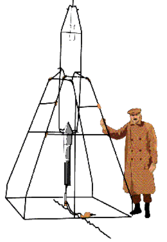
- **Piezio strain field in GaN due to substrate mismatch – not confirmed**

GaN thermionic noise

- The noise of a wide band gap emitter without high internal fields (eg. a TE photocathode) such as GaN will be dominated by the electron diffusion current in the bulk absorber region multiplied by the thermalized electron escape probability.

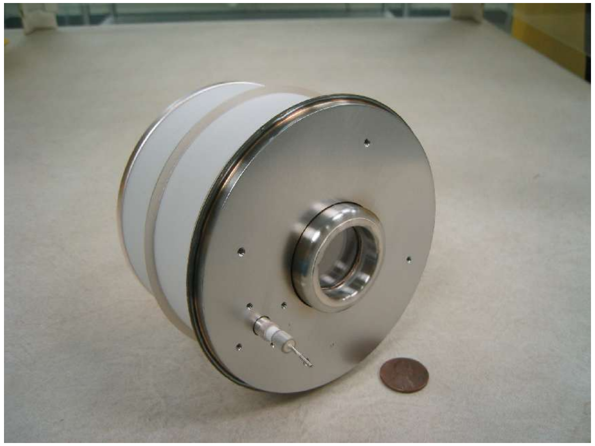
- We are setting up a MCP based system to measure

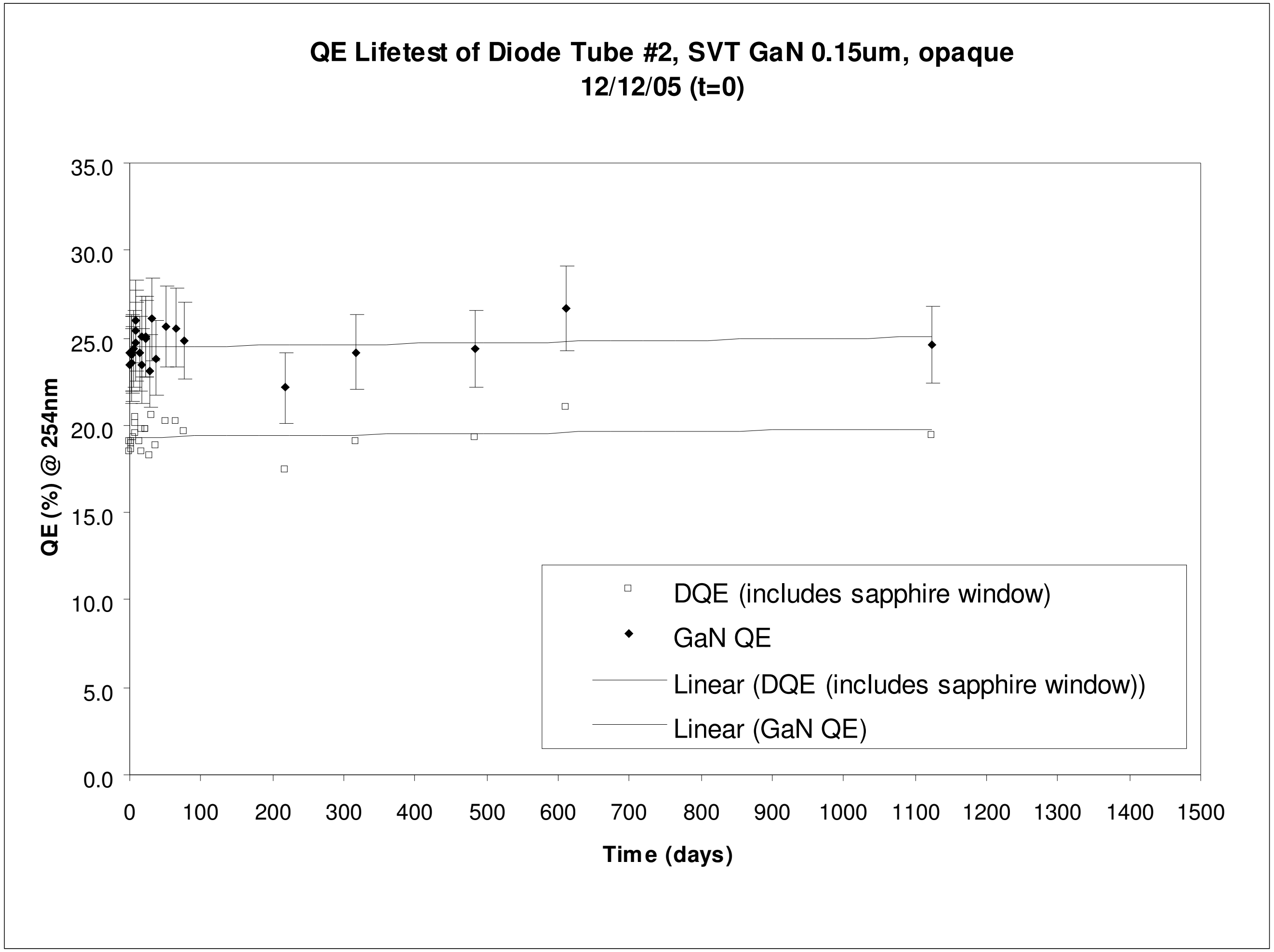
- UCB – already measured few counts/cm/s.



Quantum efficiency stability

Sealed tube – GaN quantum efficiency lifetime

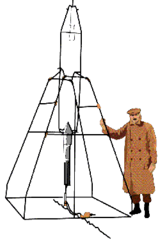




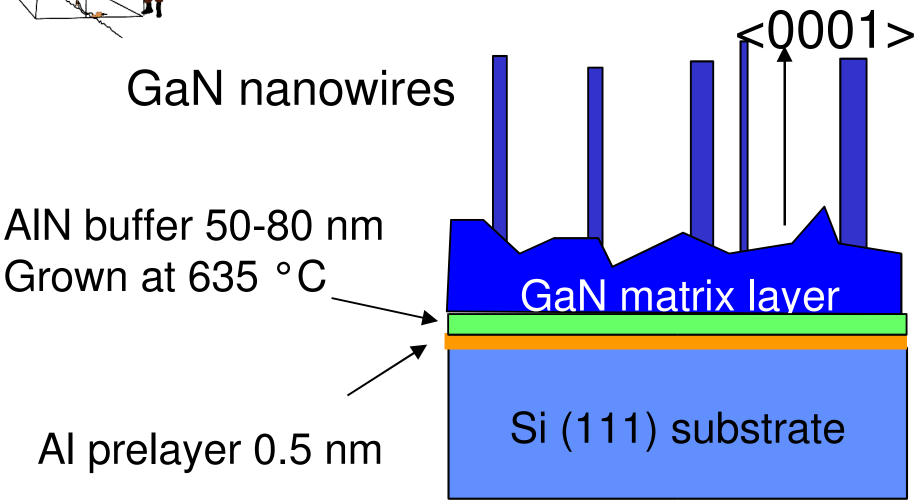
Can be assumed long term quiescent stability demonstrated

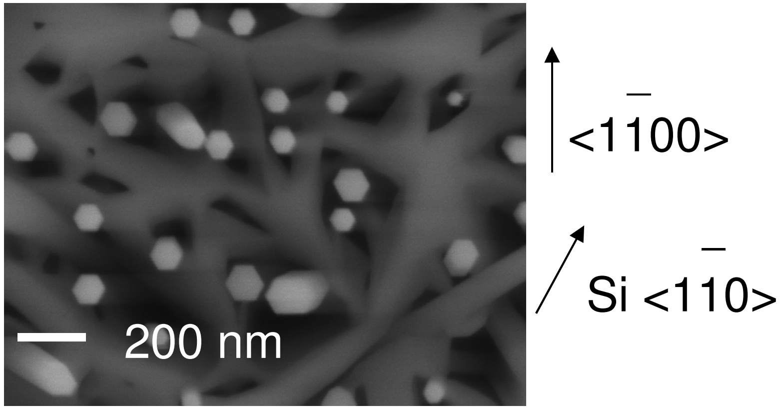
Nanowire structuring

- Nanowires may lead to higher QE due to :-
- Higher absorption – analogous to “Black Silicon”
- Much higher crystal purity – longer diffusion length and QE
- Can match a variety of layers eg Silicon MCP substrates.

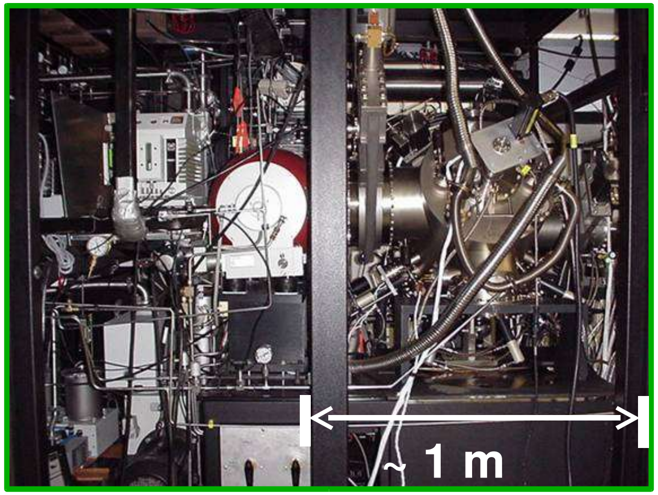


GaN nanowire (p-doped) at NIST, CO

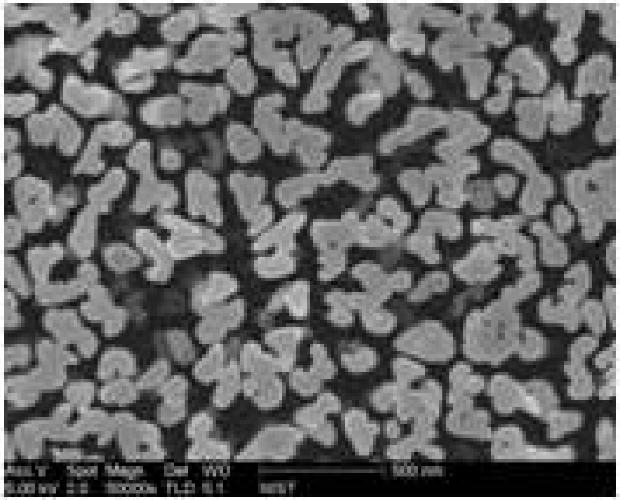


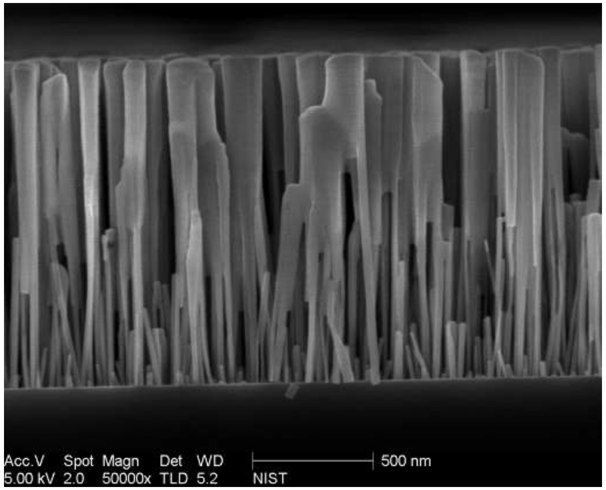


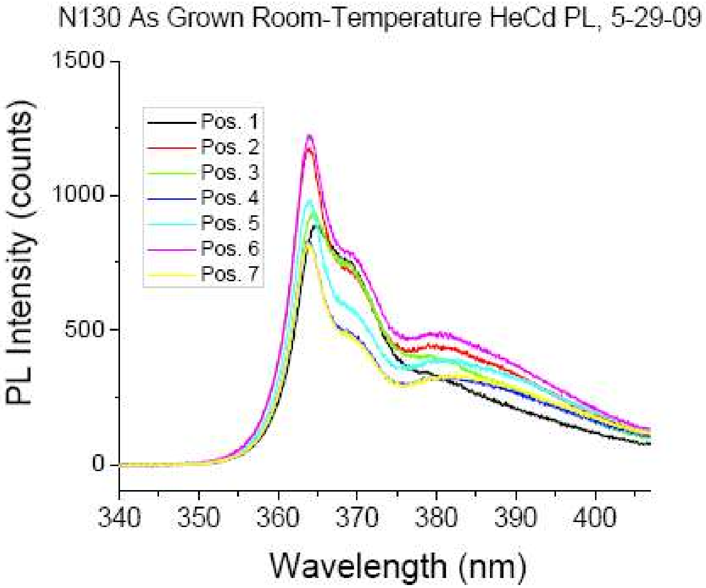
No catalyst
Wire growth in range 810 to 830 °C
MBE with plasma-assisted N2 source
Low Ga flux and high nitrogen flux
Smaller wires have perfect hexagonal cross-section, aligned to substrate and therefore to each other
Both wire tips and matrix are Ga-face as determined by CBED and etching



NIST, CO GaN Nanowires

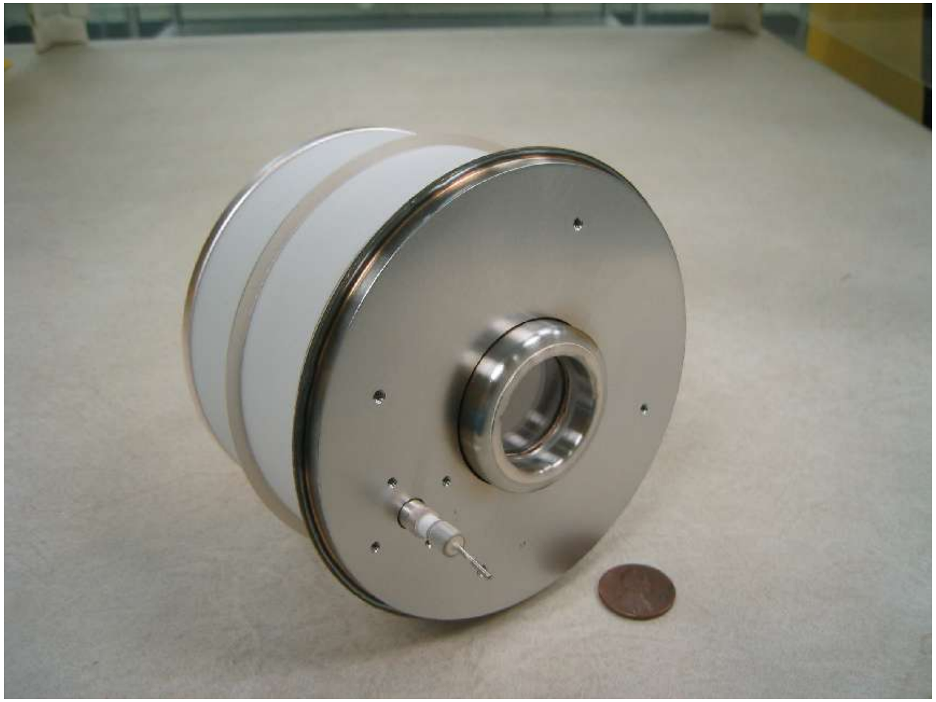






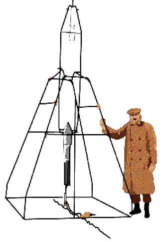
Recent sample shows un-cesiated QE > 30 % at 121nm

Detectors with GaN processed and sealed at GSFC

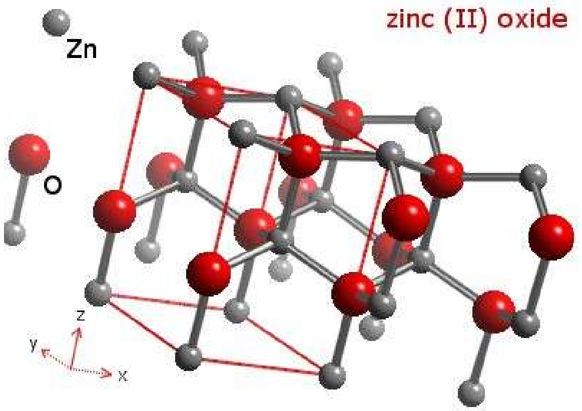


Diode tube

EBCCD tube – Photek
resealed by GSFC

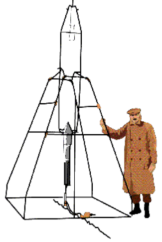


ZnO



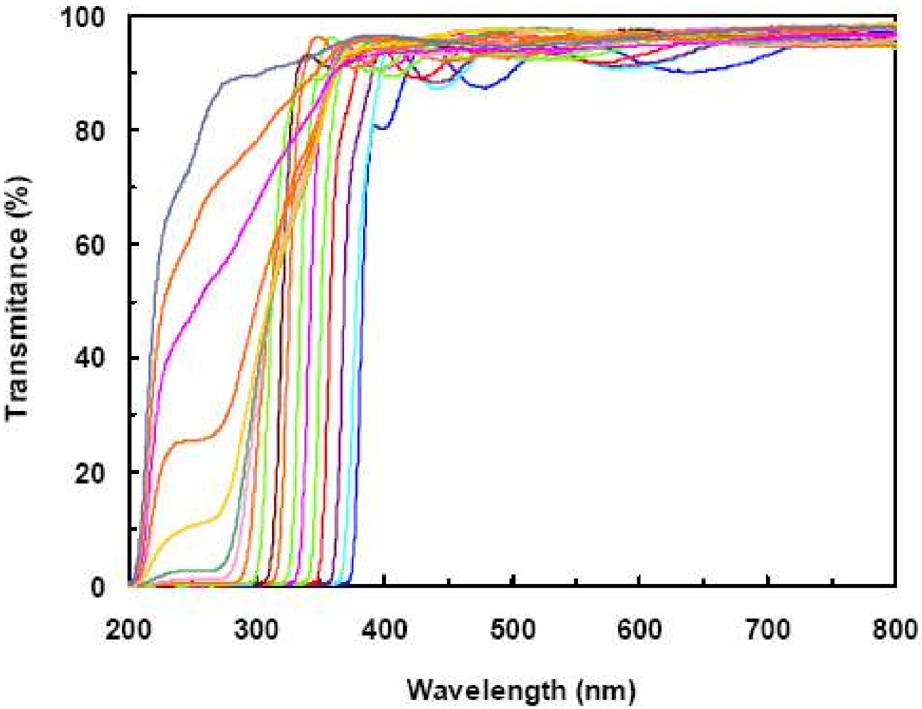
- **Potential advantages – much lower intrinsic defect levels than GaN, can be matched to a large variety of substrates, can be readily grown in nanowire configurations.**

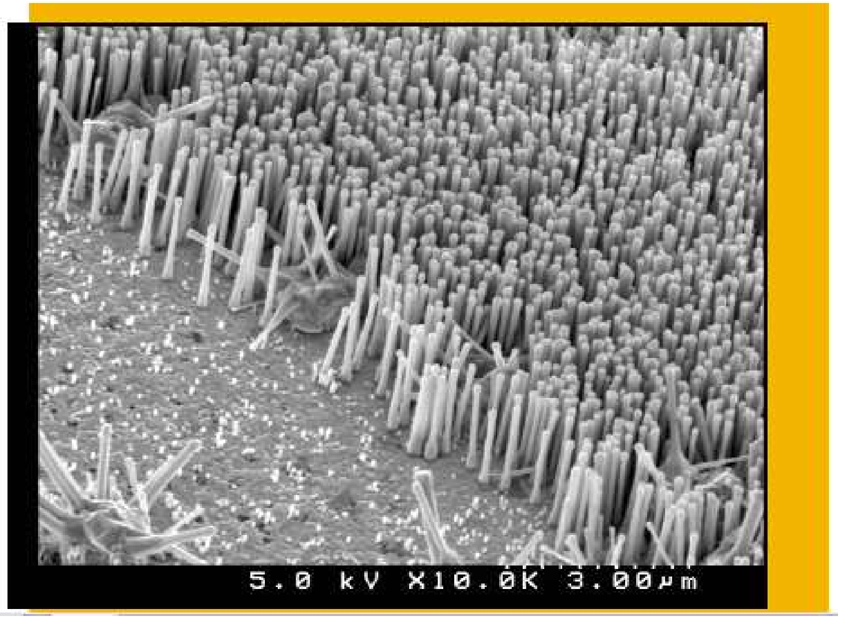
- **Problems – intrinsically n-type difficulty in p-doping,– same solubility issues as GaN**
- **Phosphorous p-doping has recently been demonstrated by UMD.**



University of Maryland ZnO research

Wide band gap thin film Zn(1-x) MgxO system is capable of tuning a band gap from 3.3 eV to 7.9 eV for visible blind UV detection. Selective area growth of nanowires can be facilitated using diamond-like carbon film as a pattern and nucleation layer.





Conclusions

- State of the art III-V opaque mode photocathodes eg GaN can attain very high QE in the NUV > 72 %, (as demonstrated by GSFC,UCB,Hamamatsu).
- p-Doping level is crucial in optimizing yield.
- Surface preparation also very important.
- Alloying with In or Al can extend wavelength response.
- Nanowire structuring may yield higher QE via improved diffusion length and reduced reflectivity and optimized absorption.
- Main challenge - matching to usable detector substrates including Silicon and Ceramic MCPS to be demonstrated.