InGaN Cathode Development

``Robust amorphous GaInN Cathodes''

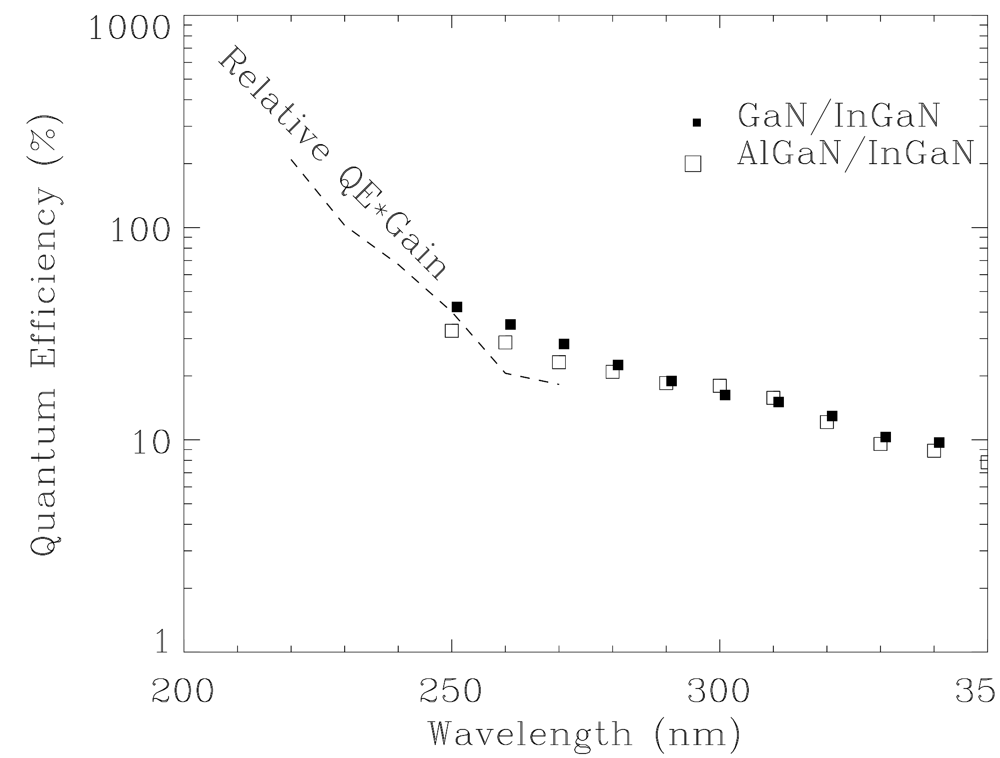
Jim Buckley and Dan Leopold

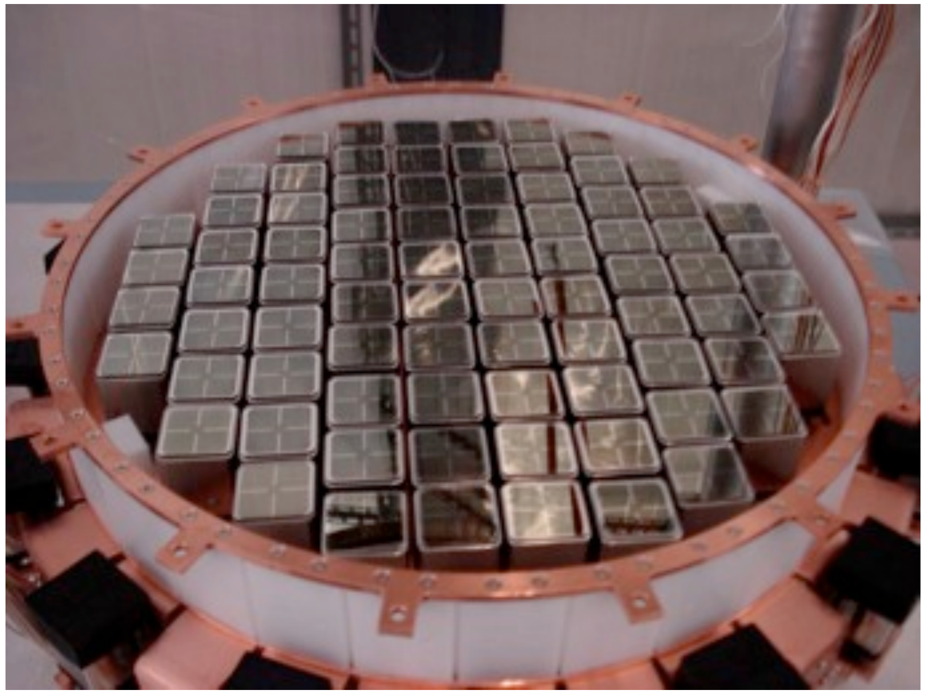
Washington University in St. Louis

Picosecond Timing Meeting, ANL, December 9, 2011

WU Photocathode Project Overview

- Nitride semiconductors are ideally suited for use in photocathode devices operating in the UV and blue spectral range
- Epitaxial crystalline structures have exhibited high quantum efficiency in this range
- Large-area lower-cost photocathodes with wavelength sensitivity extending throughout the blue range are needed for HEP and water Cherenkov detectors.
- Amorphous semiconductor nitride photocathodes have the potential to meet these requirements, allowing direct deposition at low-T on different substrates (e.g., Sapphire, MgF2, Scintillators, MCPs)
- High QE, low background photocathodes operating in the hard UV are also needed for noble gas detectors in HEP experiments (e.g., direct DM detection)





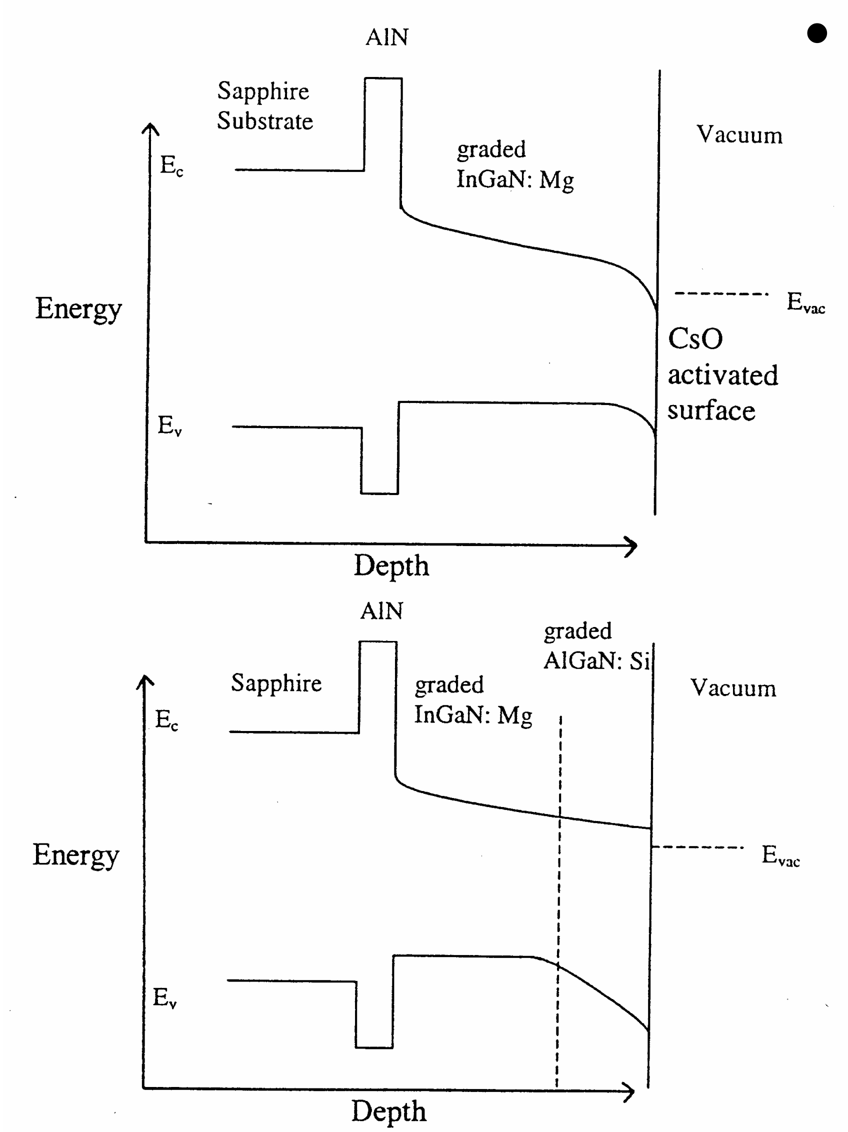
Xenon-100 PMT array. Liquid Xenon scintillation peaks at 175nm, Argon at 125nm

Materials Properties of GaN, InN, AlN and Alloys

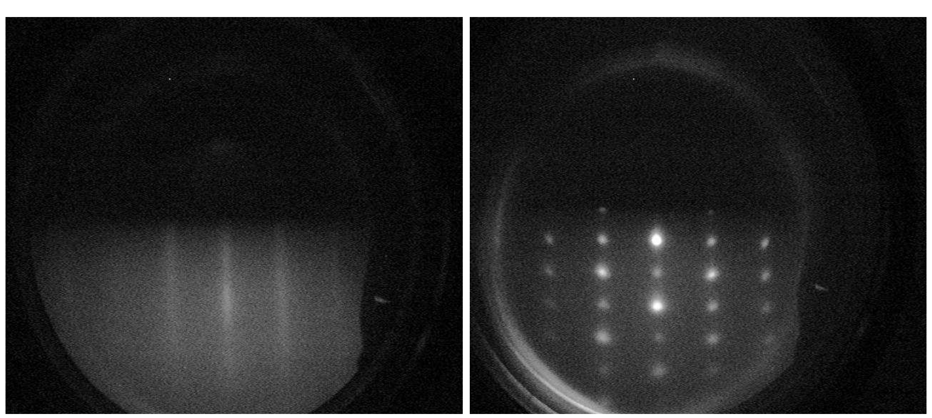
- **Crystal Phase**:
  - Hexagonal or cubic lattice
  - Band gap energy ranges from 0.8 to 6.2 eV
  - Epitaxial growth on sapphire window substrates (other substrates such as AlN, GaAs and Si also possible)
  - n-type doping with Si (intrinsically n-type)
  - p-type doping with Mg
  - Negative electron affinity surface (NEA) with Cs activation (intrinsic NEA possible with AlN)

- **Amorphous Phase**:
  - Predicted to have a ``clean'' energy band gap (absence of electronic defect states)
  - Growth at room temperature
  - Large area deposition possible on almost any substrate
  - Electron and X-ray diffraction confirm films are amorphous
  - NMR studies show local-disorder-mode "motion" typical of glassy materials

WU Photocathode Work

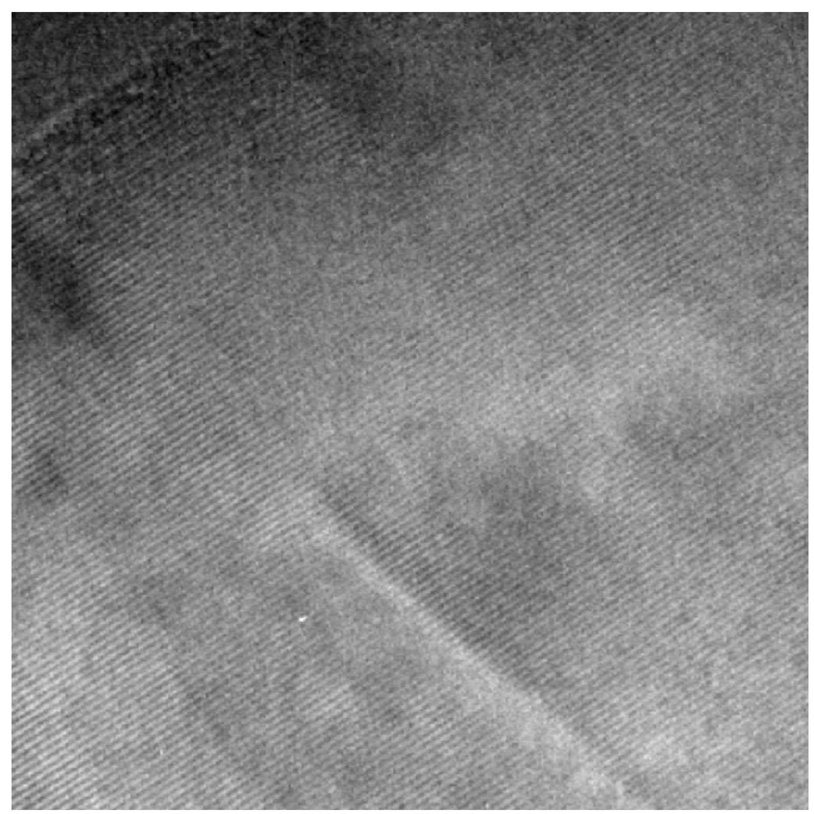


Band structure concept for 1998 Proposal

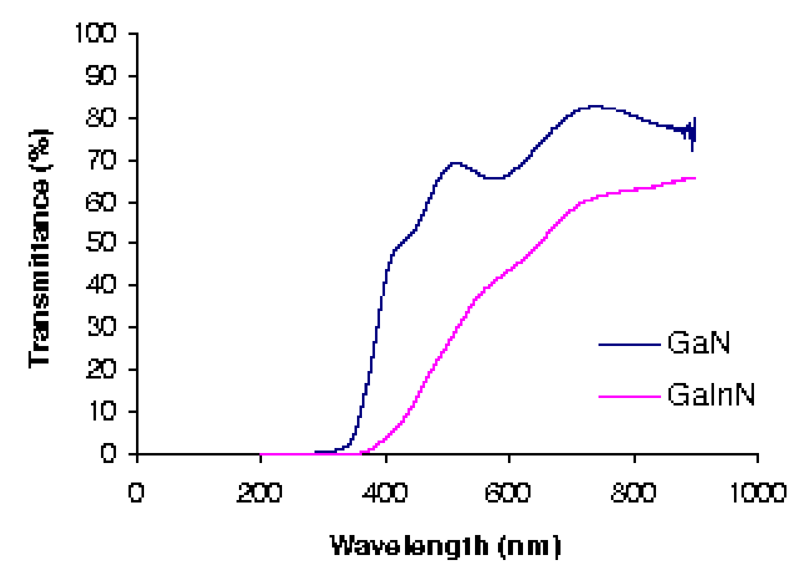


RHEED images from growth optimization

- 1999-2000 NASA funding (Technology Development for Explorer missions) → Added QE stage, Nitrogen plasma source. Produced first GaN cathodes. Came up with concept of (1) epitaxial growth on a UV-transparent window substrate (no etch-stop and transfer as for GaAsP), (2) use of an *AlN buffer layer* for lattice matching, refractive index matching and a *reflection barrier for electrons* keeping them from defects at the wall (3) *graded composition for an internal field* to aid mobility, (4) Cesation or Si doping to achieve and NEA surface, (5) *Indium to reduce bandgap*



TEM image of WU GaN/InGaN structure grown on c-plane sapphire



Demonstration of shift in band structure by alloying with In

History of WU Cathode Work

- In 2001 submitted proposal with SSL to combine his cross-strip MCPs with our AlGaN/InGaN photocathodes (NASA Space Astrophysics Research and Analysis, NRA 01-OSS-01)
- Comprehensive paper published in 2005 (see below if you want to reference it!)
- 2007 - David Schuster Ph.D. Thesis including NMR studies of amorphous GaN
- DOE ADR support, but lapses in funding, moved MBE system (support from the WU MCSS)
- Proposals on development of low background UV-PMTs for Liquid-Xe not funded.
- LAPPD project and concentrated work on aInGaN development. Supplement from DOE supporting about 40% of Leopold.

JOURNAL OF APPLIED PHYSICS **98**, 043525 (2005)

High quantum efficiency ultraviolet/blue AlGaN/InGaN photocathodes grown by molecular-beam epitaxy

D. J. Leopold
Department of Physics, Washington University, St. Louis, Missouri 63130 and Center for Molecular Electronics, University of Missouri-St. Louis, St. Louis, Missouri 63121

J. H. Buckley[a)]
Department of Physics, Washington University, St. Louis, Missouri 63130

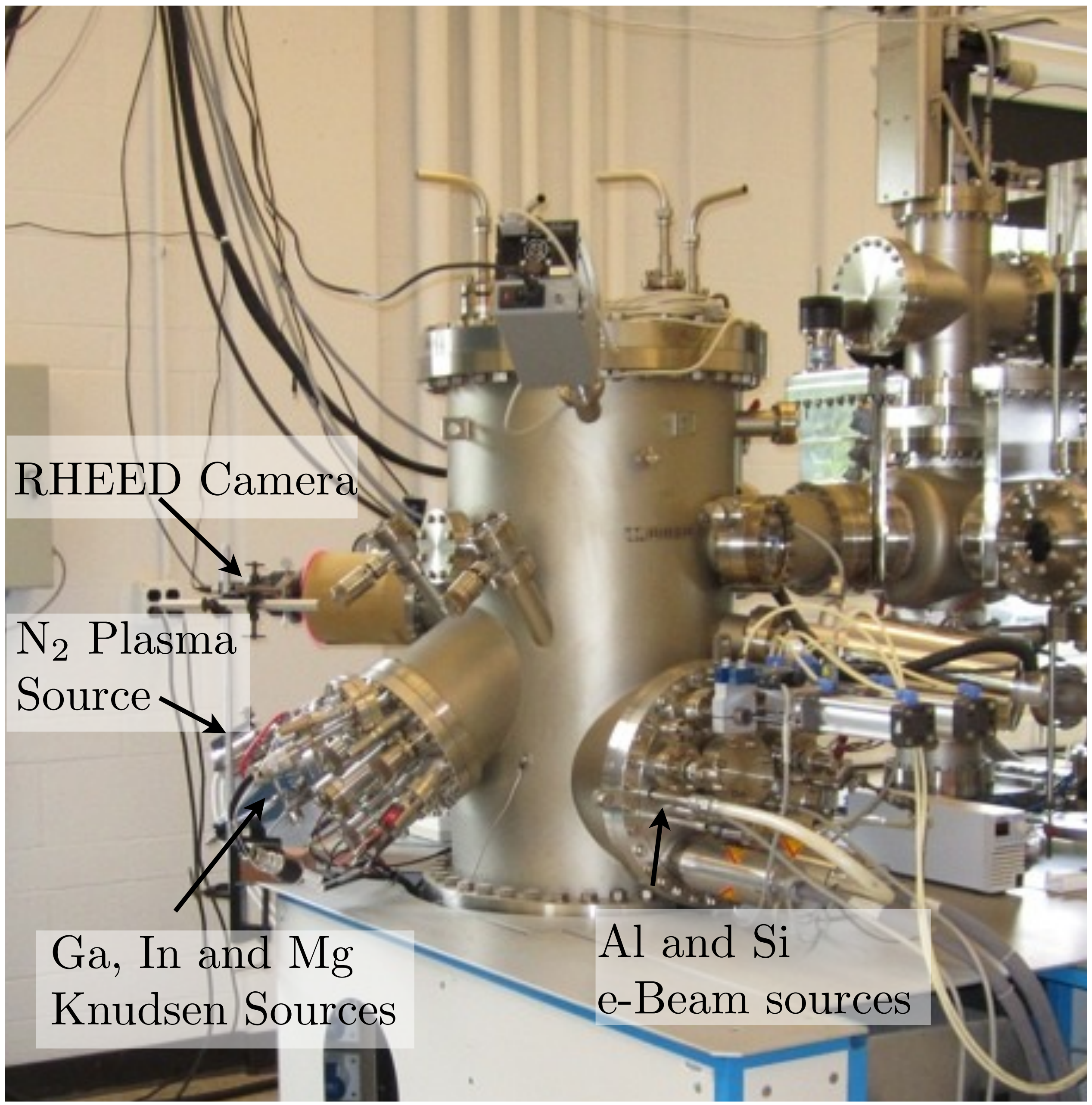
P. Rebillot
Department of Physics, Washington University, St. Louis, Missouri 63130

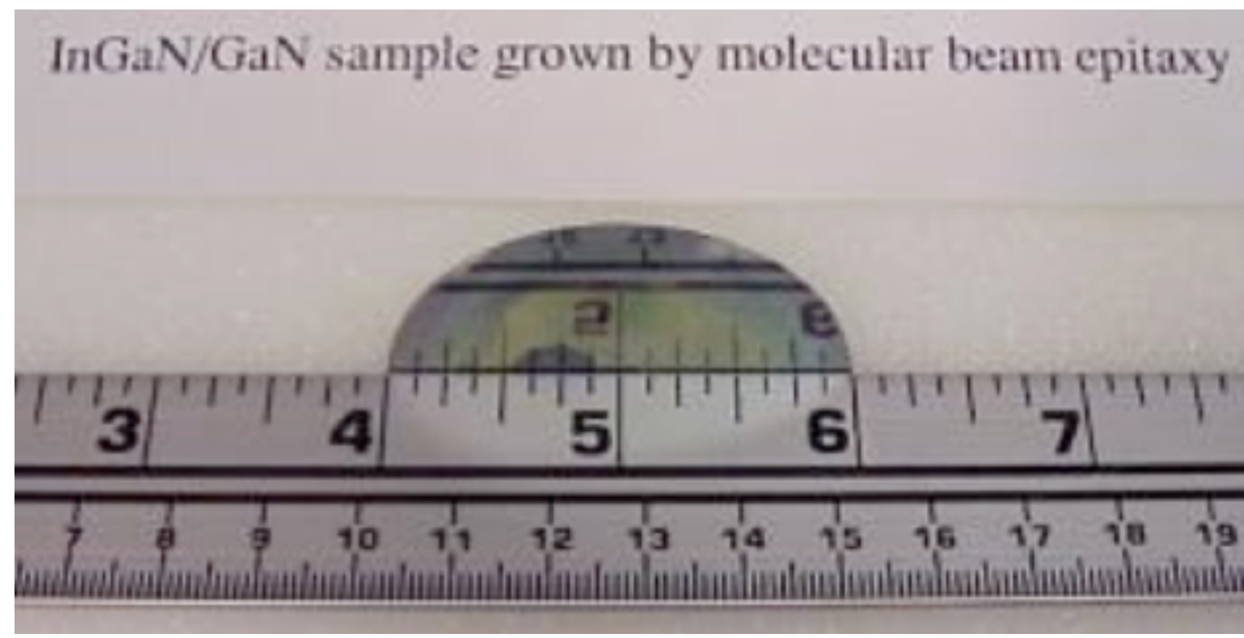
(Received 11 March 2005; accepted 21 June 2005; published online 26 August 2005)

Enormous technological breakthroughs have been made in optoelectronic devices through the use of advanced heteroepitaxial-semiconductor crystal-growth techniques. This technology is being extended toward enhanced ultraviolet/blue single-photon detection through the design and

MBE Growth System

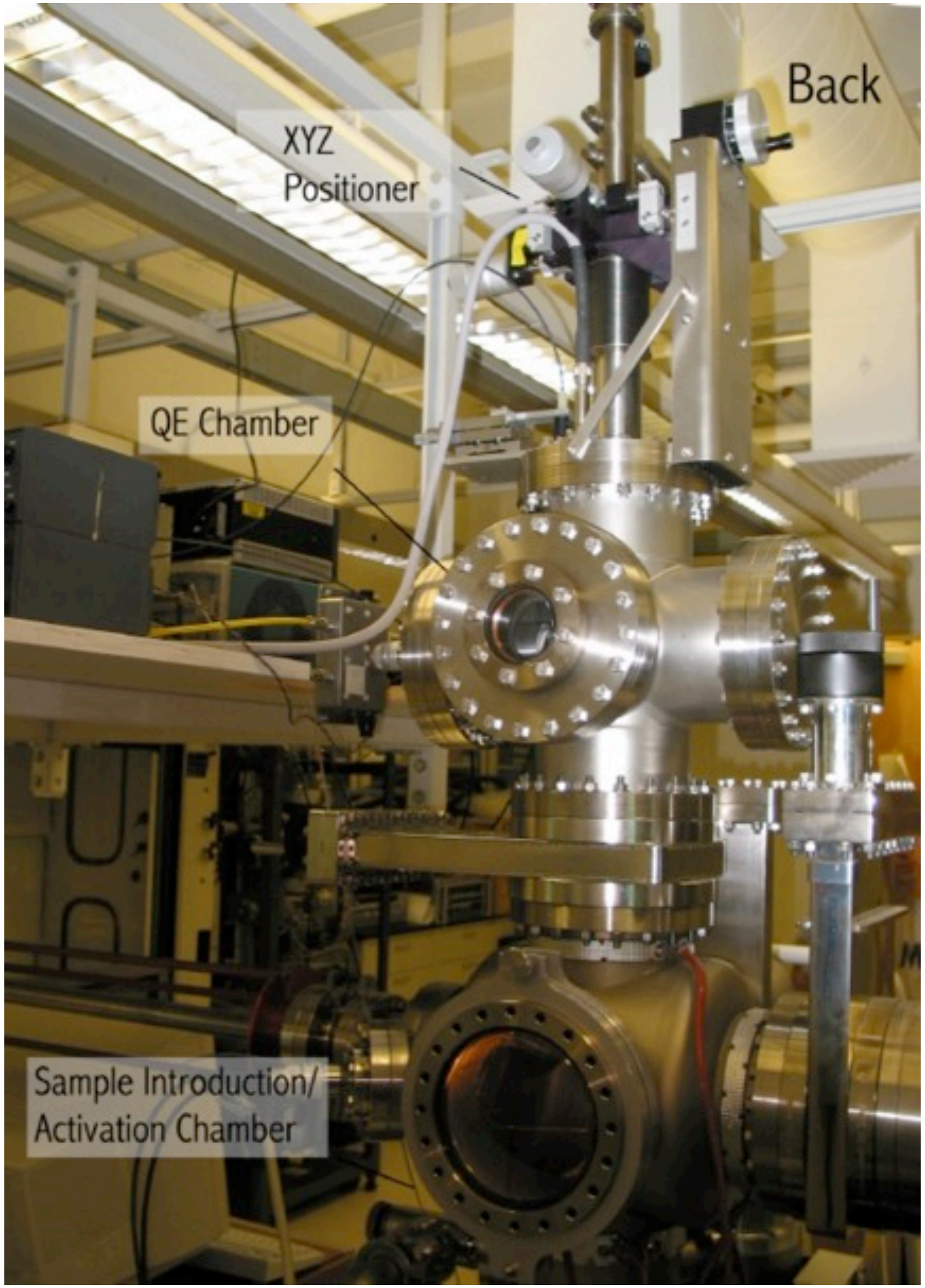
- MBE utilizes a UHV growth chamber with a rotating, heated substrate and shuttered beams from the different sources.   Our Nitride system also includes a Nitrogen plasma source





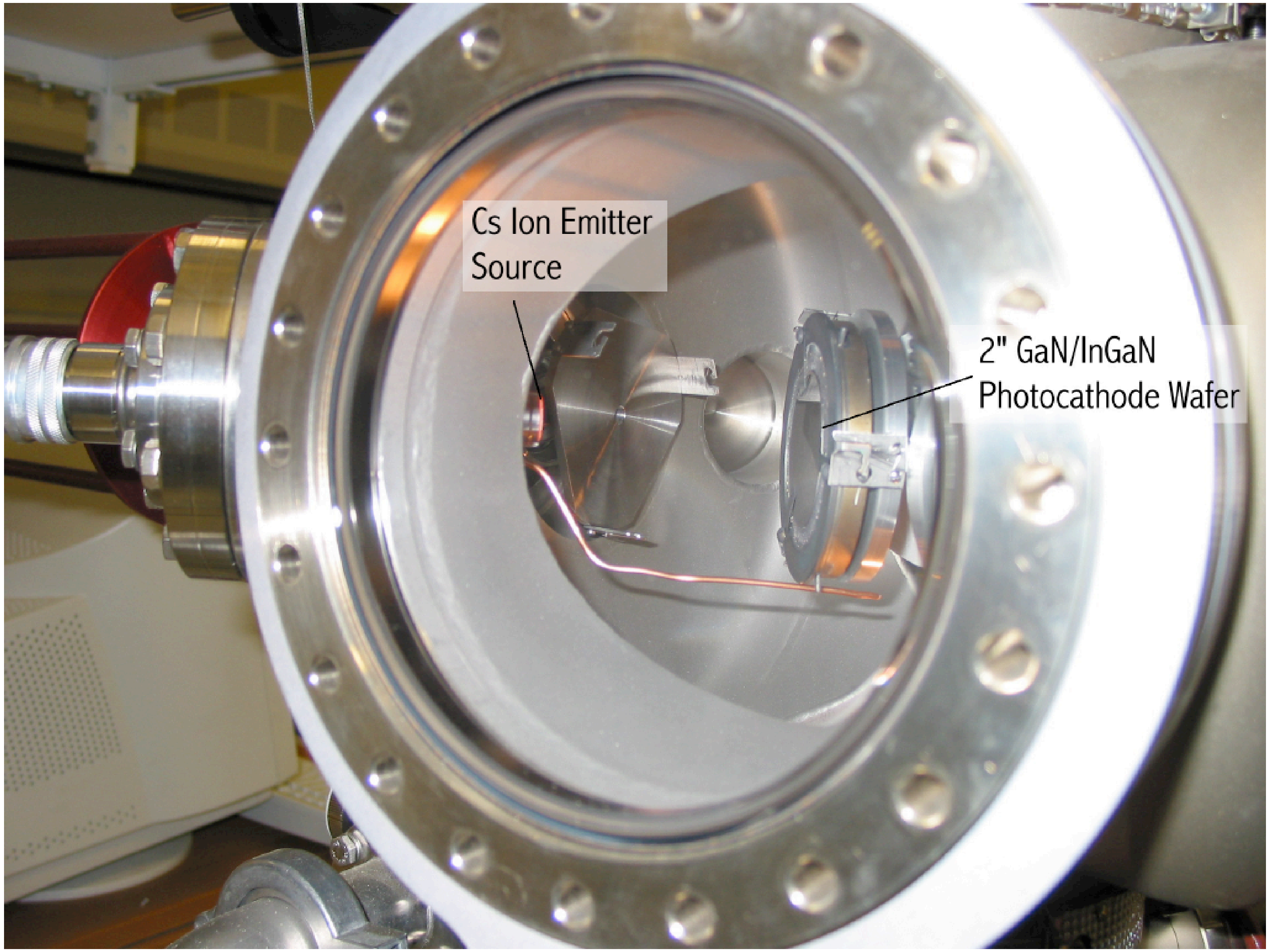
Our system currently has the capability of growing wafers up to 3 inch in diameter

Activation and QE Measurement System



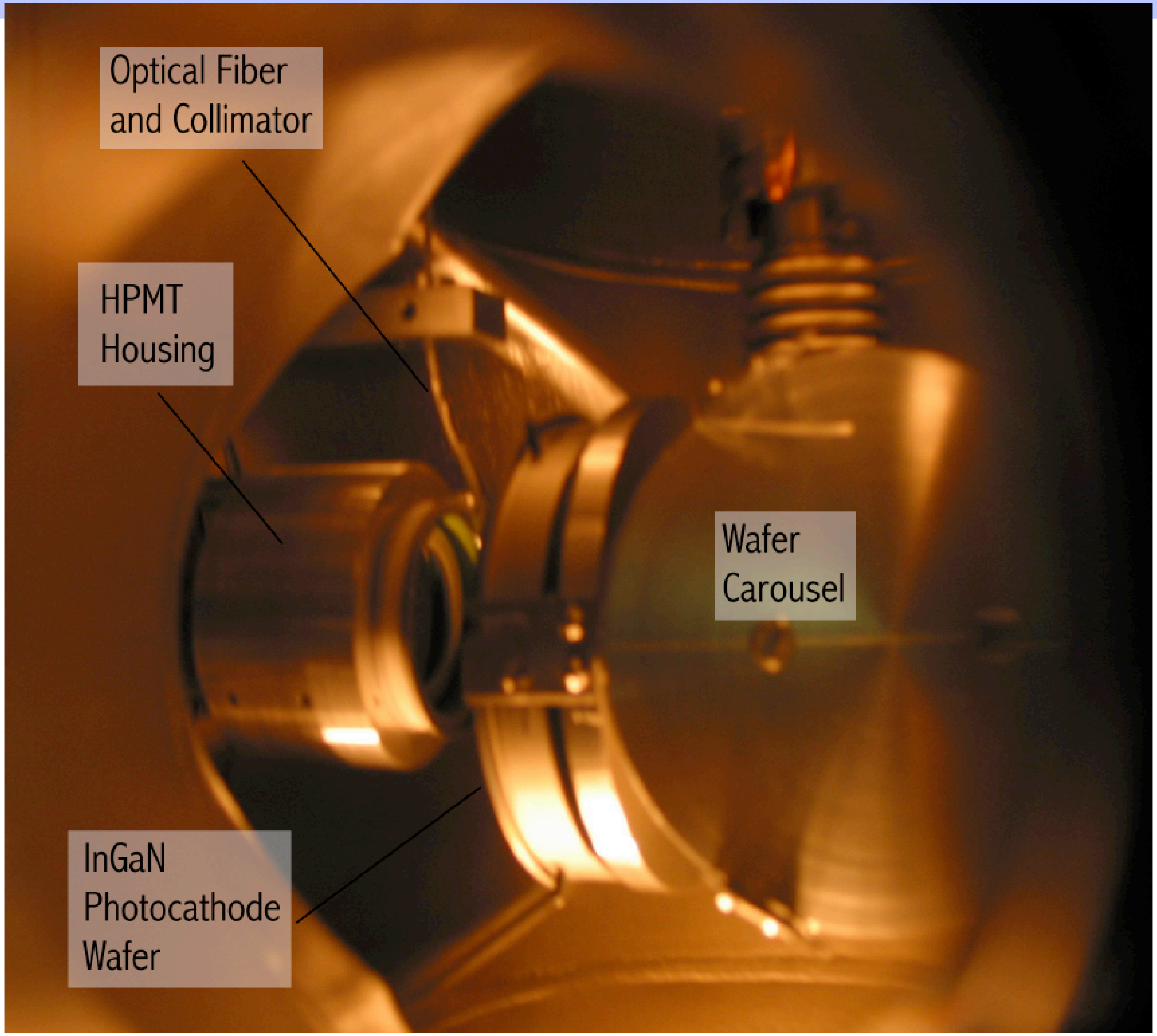
- WU system includes a number of vacuum transfer stages for in-situ Cs activation, docking with electron multipliers and readout electronics as well as in-situ QE measurements.
- *Unique UHV transfer capability for cathode growth, device integration and testing without removing from vacuum*

Cesium Activation



- Ion-beam source for Cs activation. Cs exposure monitored by Ion current

QE Measurement System



- Hybrid phototube with 7-pin photodiode array, and two independent HVs for gain and cathode bias. External low-noise preamplifier and data acquisition system connected by vacuum feedthroughs
- UV-fiber coupled signal from monochromatic pulsed light source

Objectives

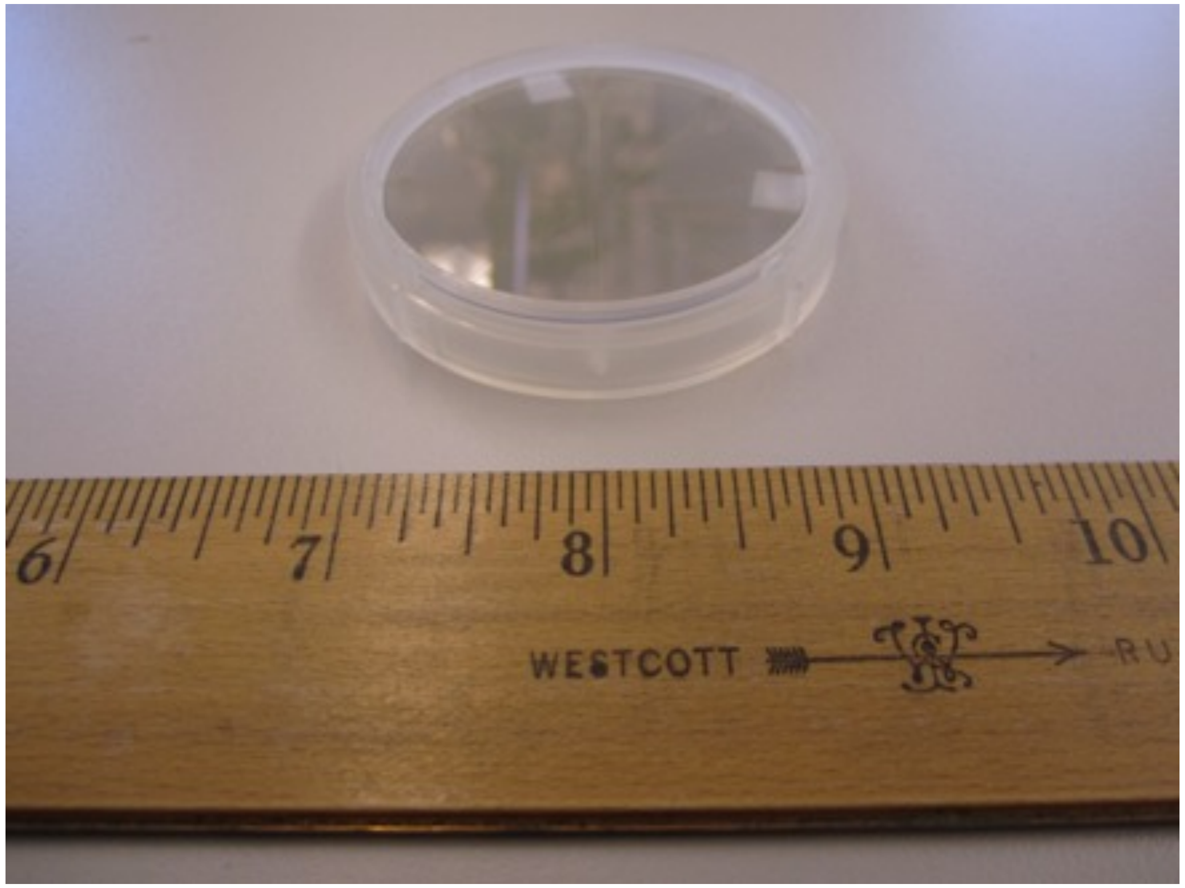
From April 11 LAPPD Presentation

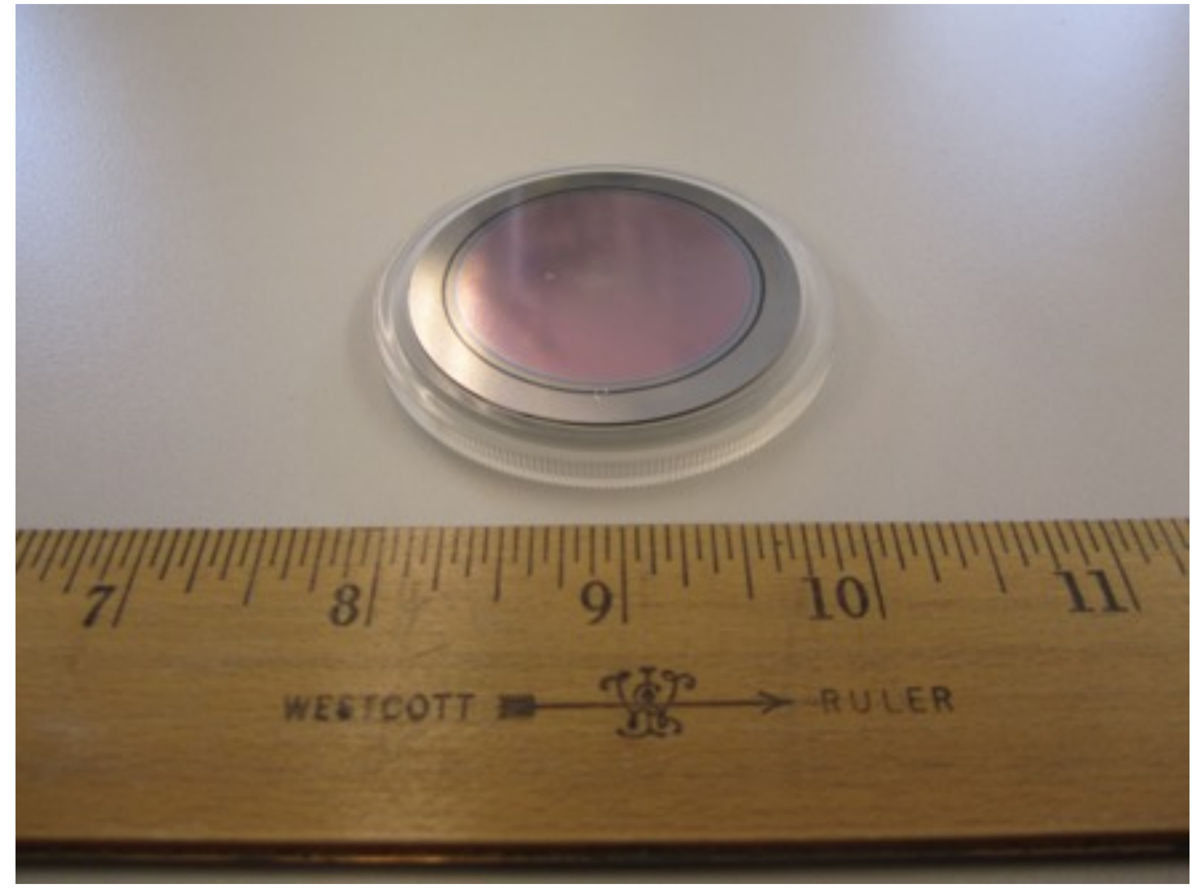
- ½ Optimize amorphous nitride photocathode materials for high quantum efficiency
- ✔ Extend wavelength response further into the blue using higher [In]
- ✔ Explore alternative substrates for fabrication of thin film amorphous nitride photocathodes
- ✔ Examine methods to restore cathode surfaces exposed to air, or the use of protective coatings for transporting cathodes to other laboratories
- ½ Implement tube sealing capabilities within our UHV growth/testing chamber

From October11 LAPPD Presentation

- ✔ Modify QE vacuum stage for MCP measurements.
- Bench top optical reflection/transmission measurements.
- ½ Direct cathode deposition on MCP and in-situ measurements.
- ½ MCP for transfer to ANL or SSL.
- New substrate preparations for Cathode growth and further optimization of growth parameters.

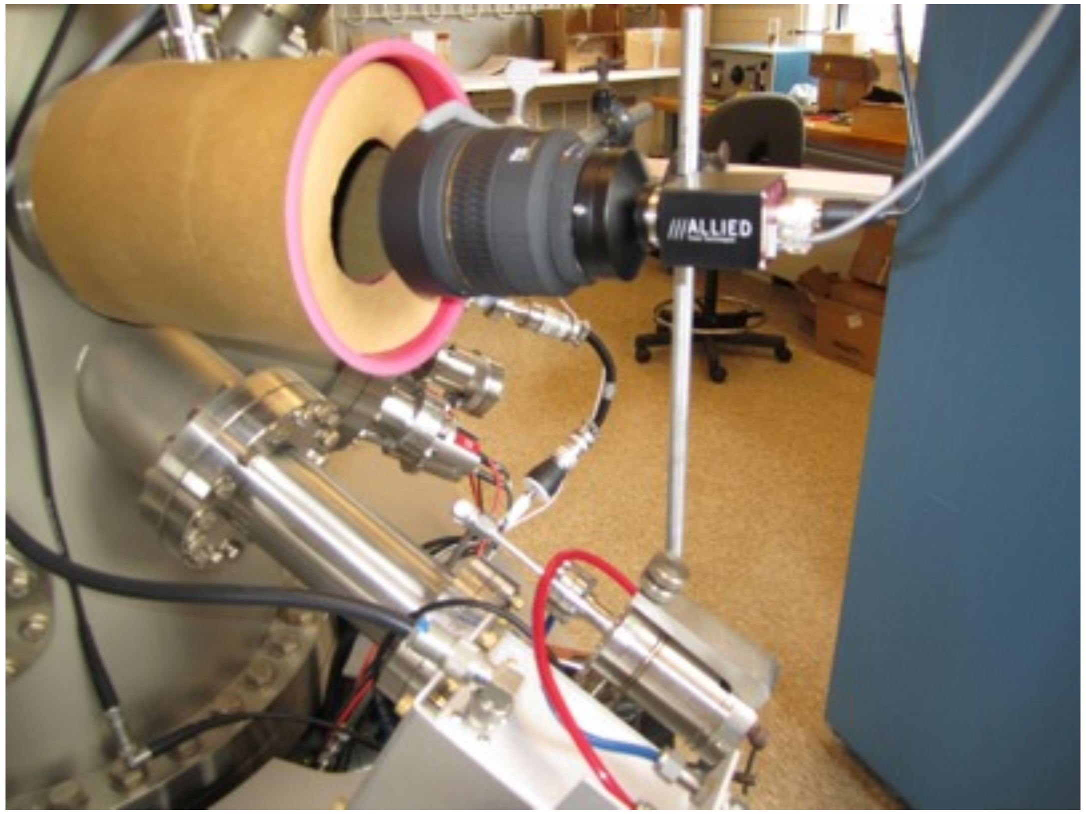
Amorphous InGaN Cathodes





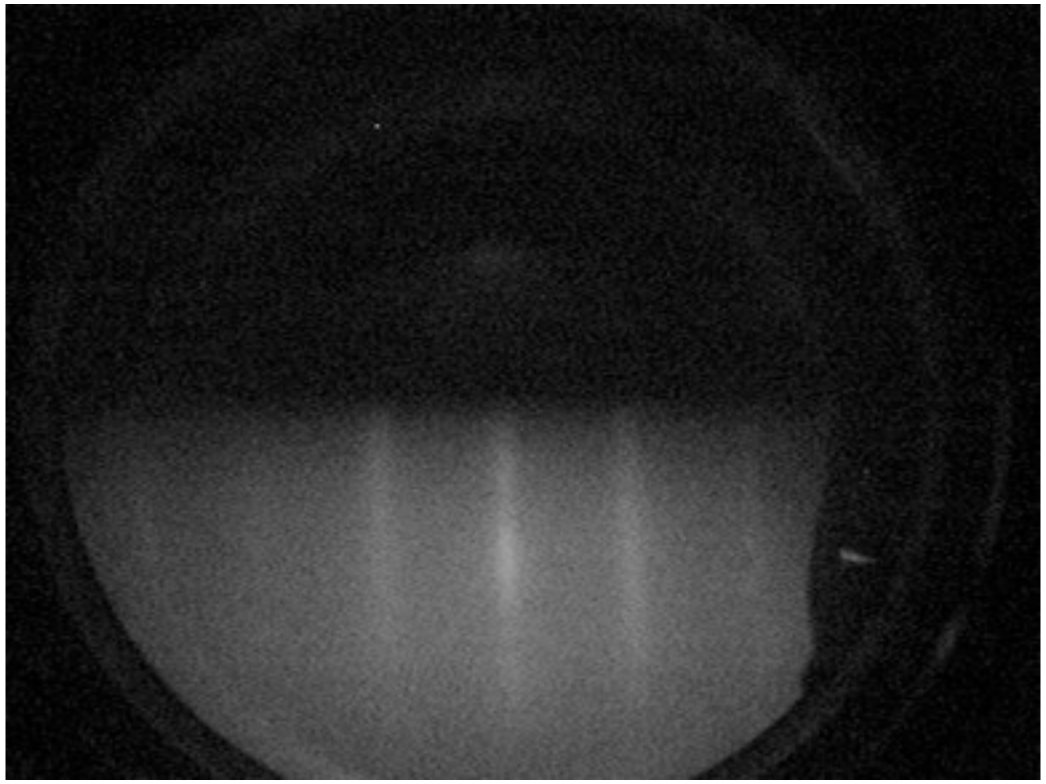
- We have grown amorphous InGaN on sapphire (left) and on stainless steel (right)
- Consistent with the theoretical prediction that a-GaN should have a clean gap, we have achieved similar QEs to epitaxial (single-crystal) structures.
- Now have the capability to grow efficient cathodes at low temperature on a variety of substrates.

RHEED Measurements

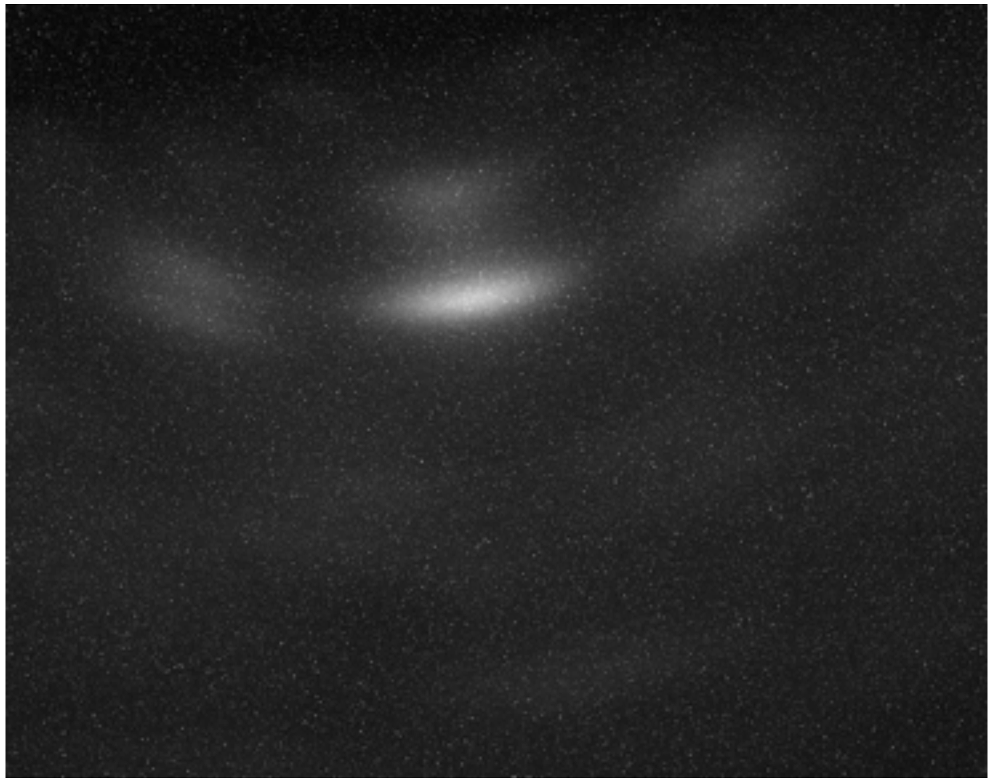


Upgraded RHEED system using a wide-field lens, and high-speed low-light interline digital camera and new LINUX CPU and DACQ software

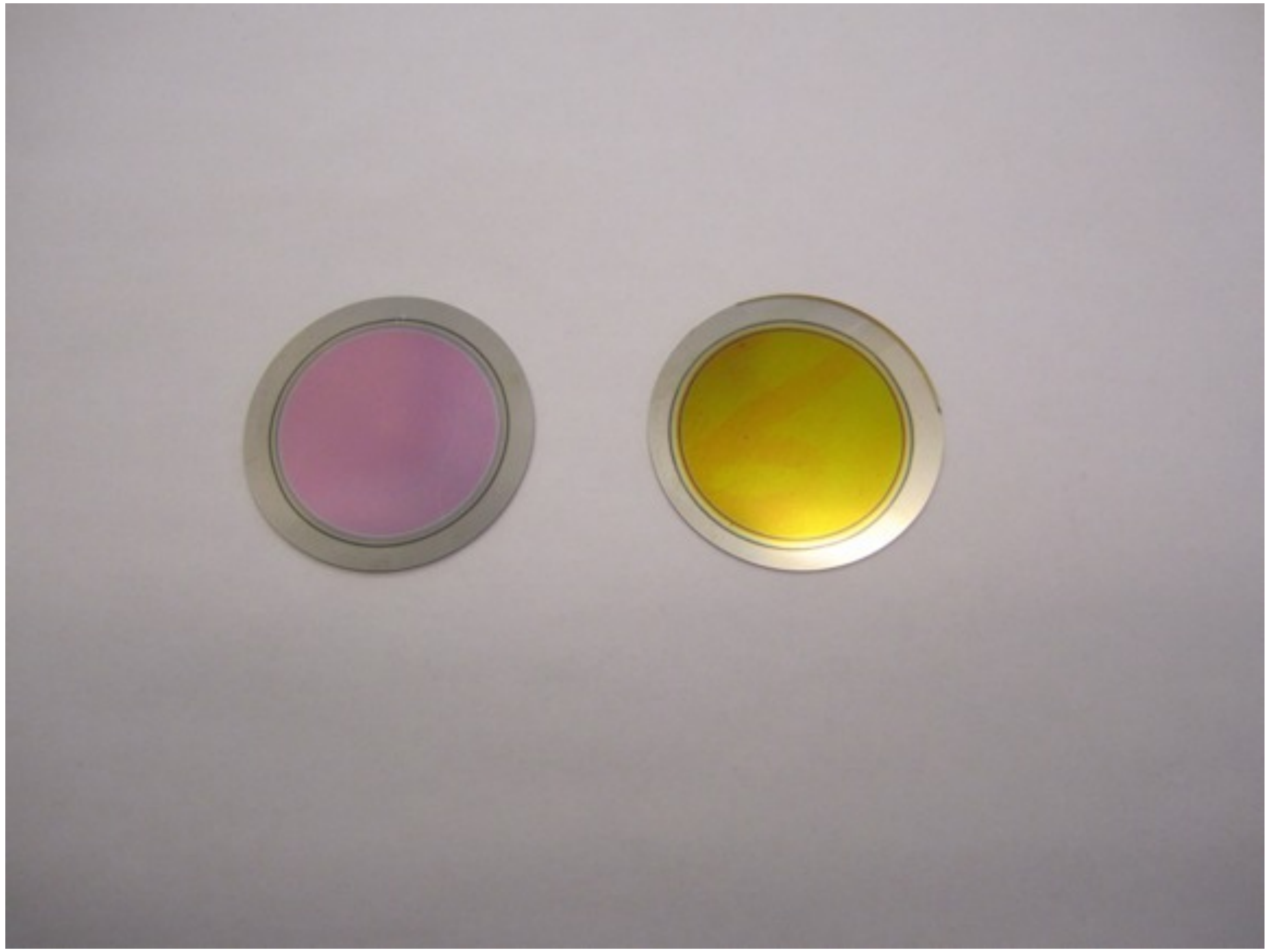
epitaxial InGaN



amorphous InGaN

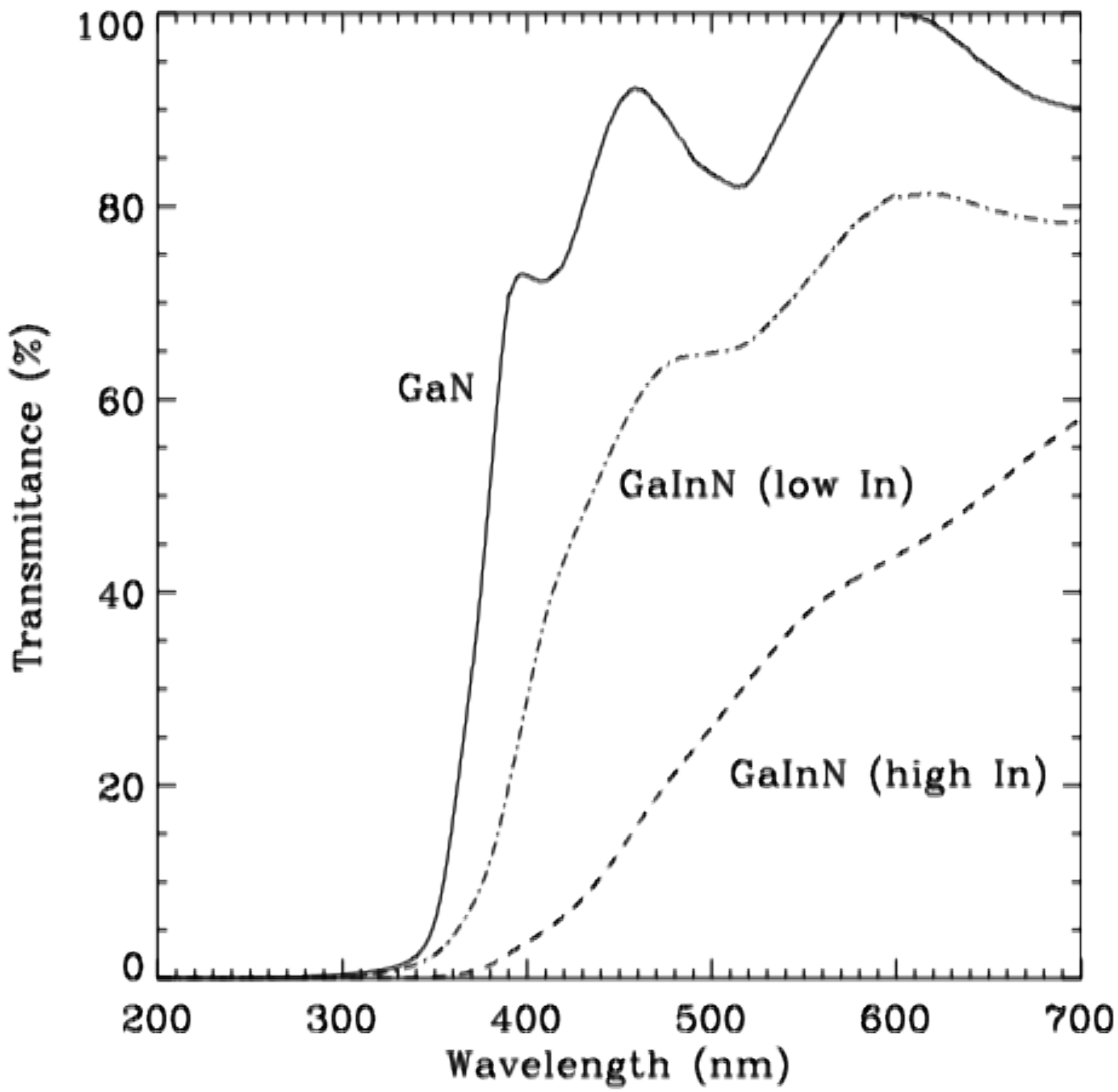


Increased In Concentration



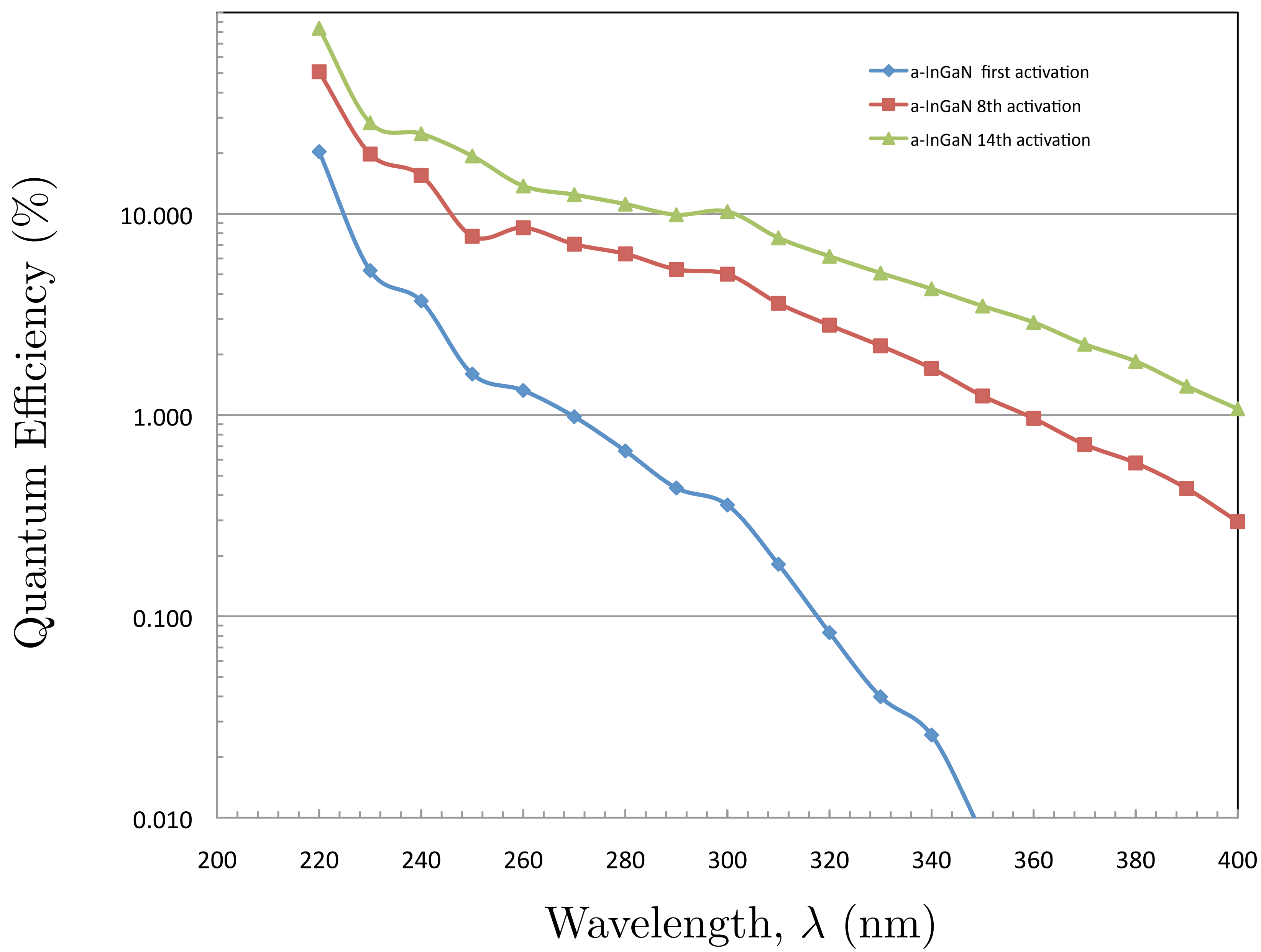
- Cathodes were fabricated with increased In (25% and 50%)
- Absorption edge shift apparent in reflected light (high In on right)

Optical Transmission



- Alloying with In shows a shift to longer wavelengths (smaller bandgap)

QE for a-In$_{0.5}$Ga$_{0.5}$N



Cs Activation

Amorphous GaInN Photocathode Quantum Efficiency Ratios
after activation with Cs

Wavelength	2nd/1st Cs	3rd/2nd Cs	4th/3rd Cs	5th/4th Cs	6th/5th Cs	7th/6th Cs	8th/7th Cs
220 nm	1.34	1.22	1.1	1.23	1.19	1.11	1.1
270 nm	1.47	1.44	1.32	1.26	1.35	1.14	1.19
310 nm	1.92	1.75	1.61	1.43	1.43	1.26	1.18
320 nm	2.44	1.75	1.64	1.61	1.4	1.28	1.19
330 nm	3.06	2.2	1.9	1.55	1.52	1.31	1.19
350 nm				1.74	1.59	1.43	1.27
370 nm				2.15	1.76	1.54	1.33

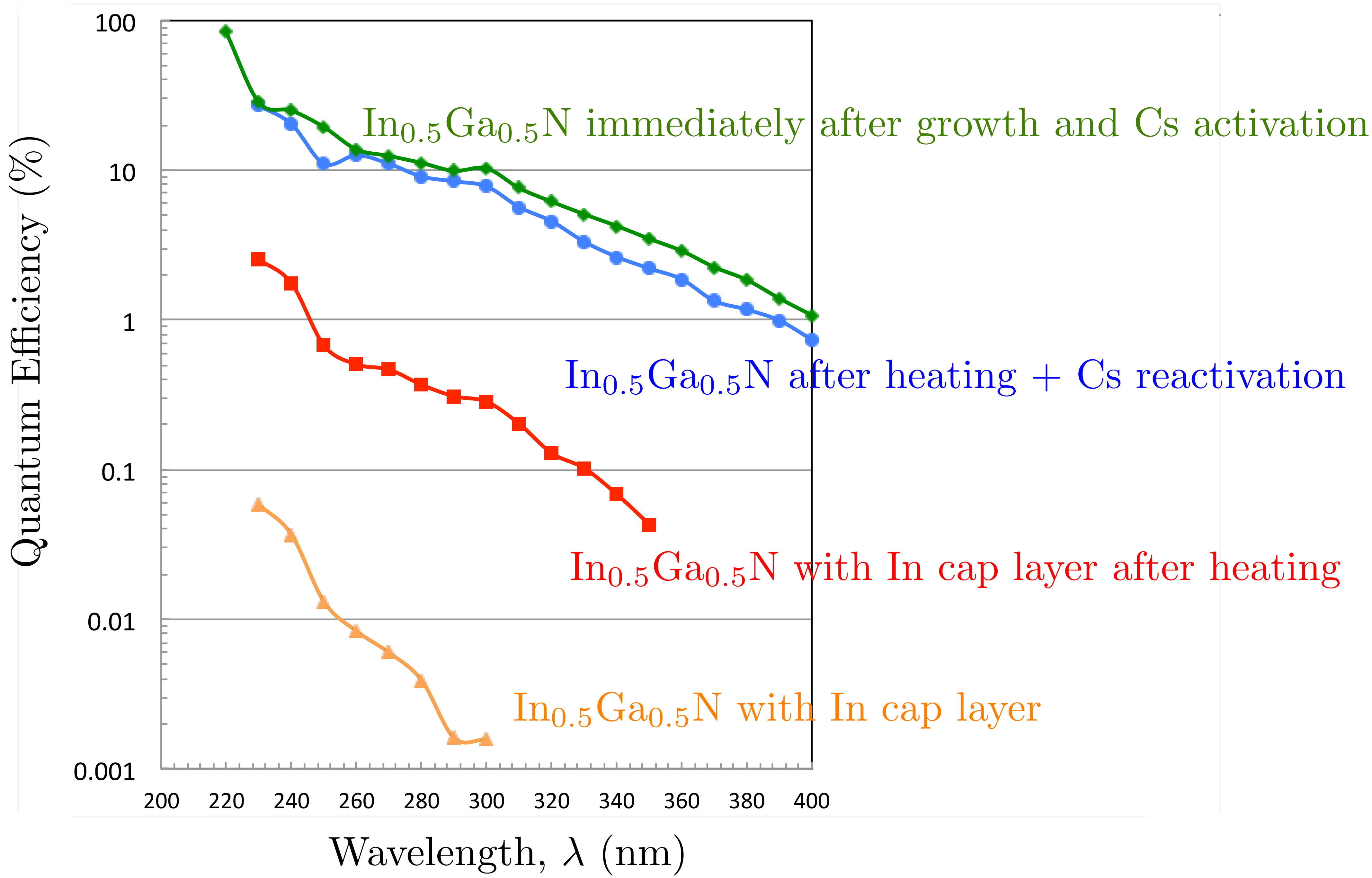
- Very little aging effect (QE stays the same one day later!) - early exposures actually show increase with time after activation (diffusion?)
- Continued improvement with repeated Cs activation, larger improvements in long wavelengths.
- Indicates that QE is still limited by surface, not bulk properties.

Cathode Transfer

- We previously demonstrated restoration of cathode using Nitrogen plasma and Cs
- Recently explored a new method using an Indium cap layer, then using heat alone (or heat and Cs re-activation) to restore cathode (*and they said it couldn't be done!*)
- Now have two potential methods for transfer to a remote site for integration with MCP PMTs.

Results of In Capping of a-$In_{0.5}Ga_{0.5}N$ Cathode

- Capped cathode was exposed to air (no bag or hermetic container) for several months, then capping stripped off with heat. Changes in QE through process are shown below:



Other Progress

- Increased doping from 25% to 50% Indium. Slight improvement in long wavelength response, big difference in visible light absorption.

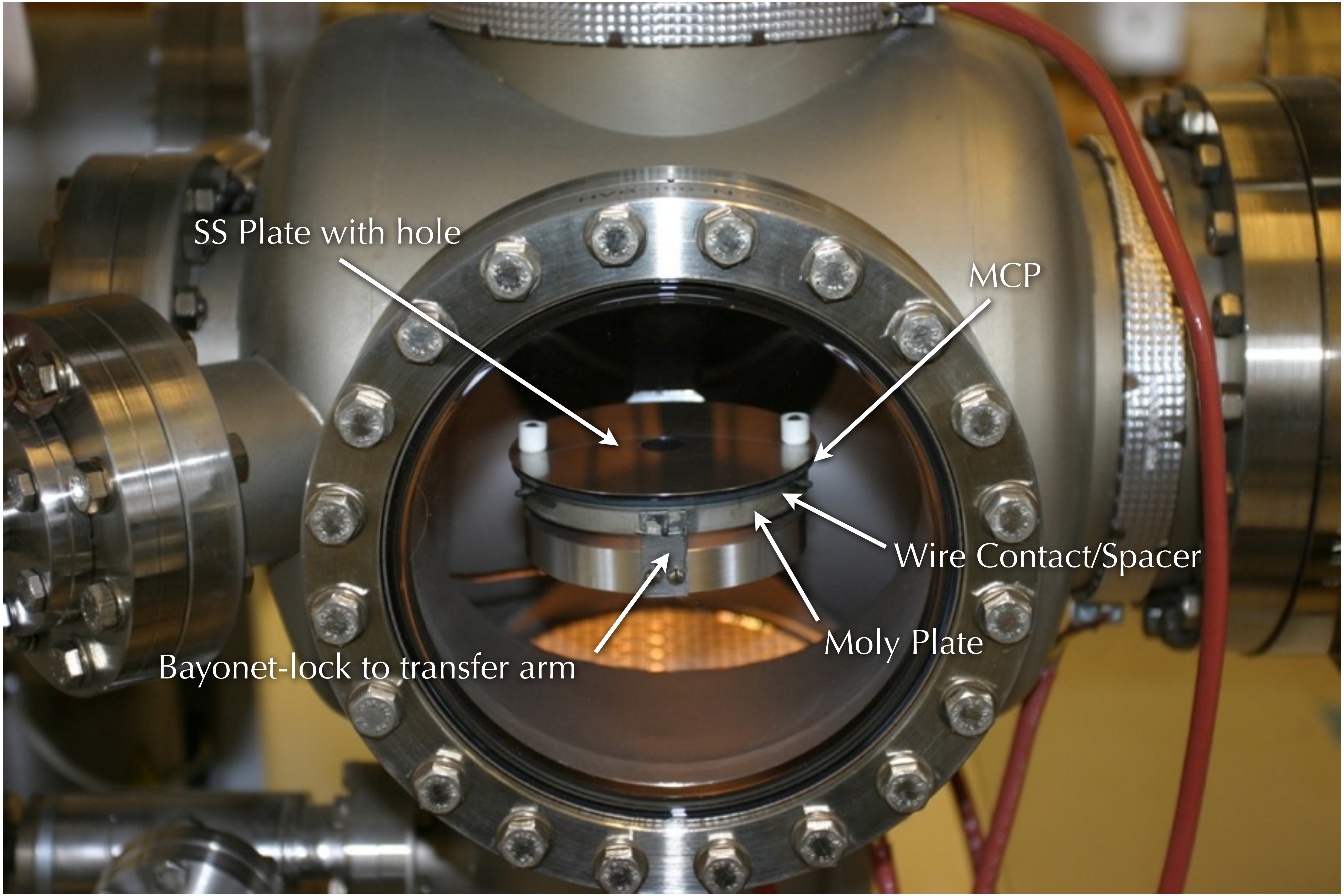
- A second cathode with 50% Indium and much higher Mg doping level resulted in somewhat reduced QE - indicates diminishing returns.

- Verified that annealing after repeated Cs activation yields an *additional* improvement

- Received two 33mm ALD-coated MCPs. Made modifications to system to allow biasing and signal feed through for in-situ QE and resistance measurements.

- First MCP assembly installed in vacuum system, resistance (at 200V) measured. HV bias before and after activation coming in next couple of weeks.

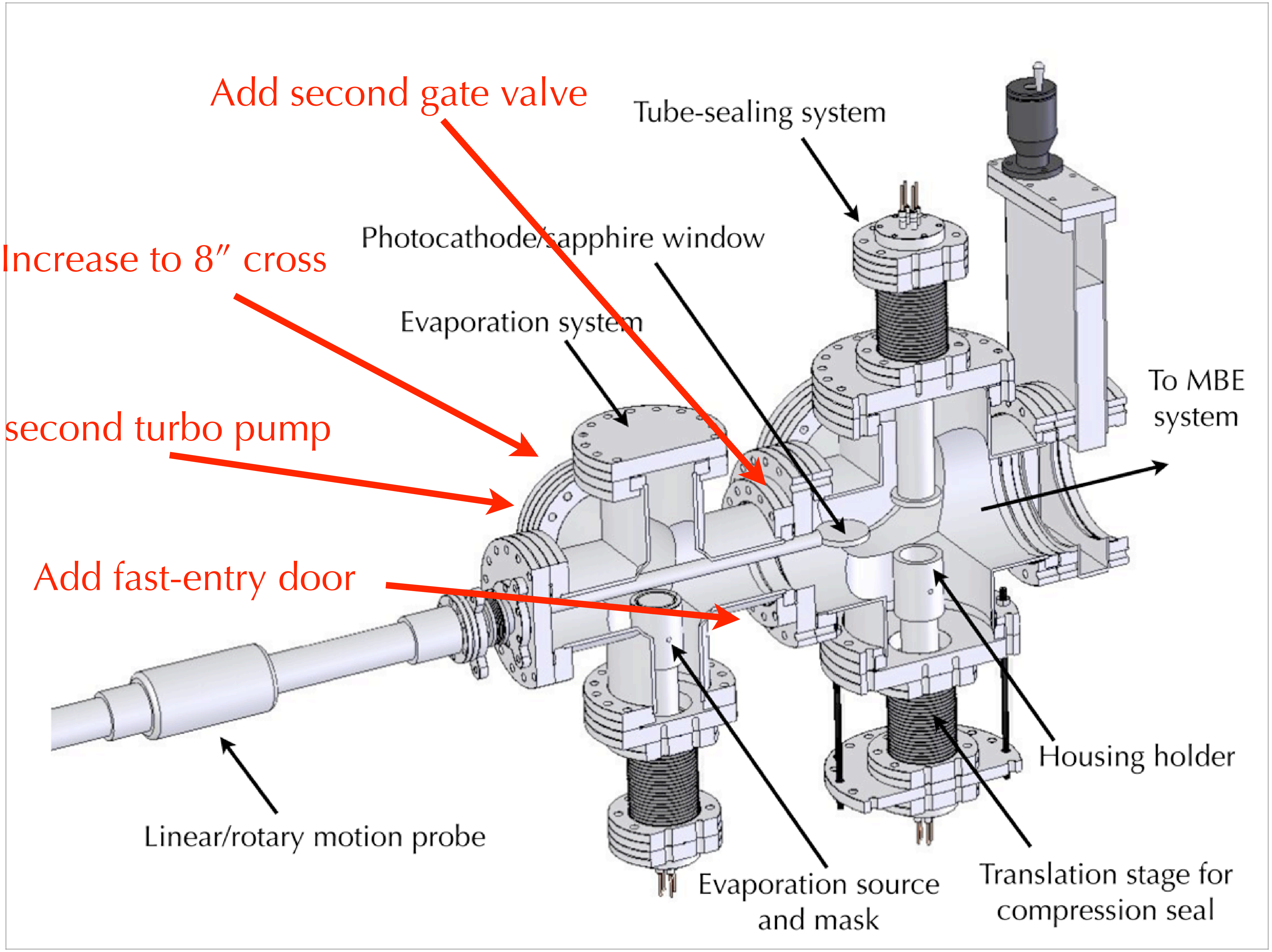
MCP Loaded in Vacuum Chamber



Objectives

- Demonstrate ability to measure MCP response with system
- Deposit amorphous cathodes on MCPs and measure response (without removing from UHV)
- Add a capability for more precise in-situ measurements of resistance
- Simplify our load-lock system and increase the size of our evaporator stage to improve throughput for testing more substrates, MCP structures.
- Experiment with different substrate preparations, polycrystalline growth.
- Improve our UV measurement capabilities by adding a vacuum monochrometer and windowless NIST-calibrated photodiode.
- Indium-cap cathodes for transfer to ANL.
- Continue development of hot-In tube sealing system.

Proposed Load-lock/Evaporator Upgrade



Load-lock / Evaporation Upgrade

- Oil-free Diaphragm Vacuum Pump, DA-241S - $1,890
- 8″ CF Fast-Entry Door, DS-LL00800VP - $1,095.00
- 8″ 6-Way Cross, C6-0800S - $2,150.00
- CF Copper Gasket Gate Valve SG00MCCF - $2,760
- Turbo Pump
  - Edwards EXT 225H 6″ CF, oil-free (ceramic bearing) turbopump - $7260+$2780 (225 L/sec) OR
  - Pfeiffer Turbo-Drag with mag/ceramic bearings - 6″ CF 270 L/sec $10,275.

Conclusions / Future

- Making good progress on demonstrating robust, large area amorphous cathodes with extended long-wavelength response
- Developed viable methods for cathode transfer
- Close to putting first cathodes on ANL ALD-coated MCPs!
- For a future proposal, I suggest expanding into development of low-background PMTs with UV-response for liquid noble detectors (175 nm for Xenon, 125 nm for Argon). May need to develop new electron-multipliers since glass typically has high radioactive backgrounds - silicon MCPs?