Tasks and Responsibilities

Washington University (James Buckley and Daniel Leopold)

High Quantum Efficiency Amorphous Nitride Semiconductor Photocathodes

- Explore the potential for using amorphous nitride materials as high quantum efficiency photocathode layers
- Extend wavelength response further into the blue range using higher concentrations of Indium
- Evaluate alternative substrates for fabrication of thin film amorphous nitride photocathodes
- Examine methods to restore cathode surfaces exposed to air, and the use of protective coatings for transporting cathodes to other laboratories
- Implement tube sealing capabilities within our UHV growth/testing chamber

High Quantum Efficiency Amorphous Nitride Semiconductor Photocathodes

Jim Buckley and Daniel Leopold
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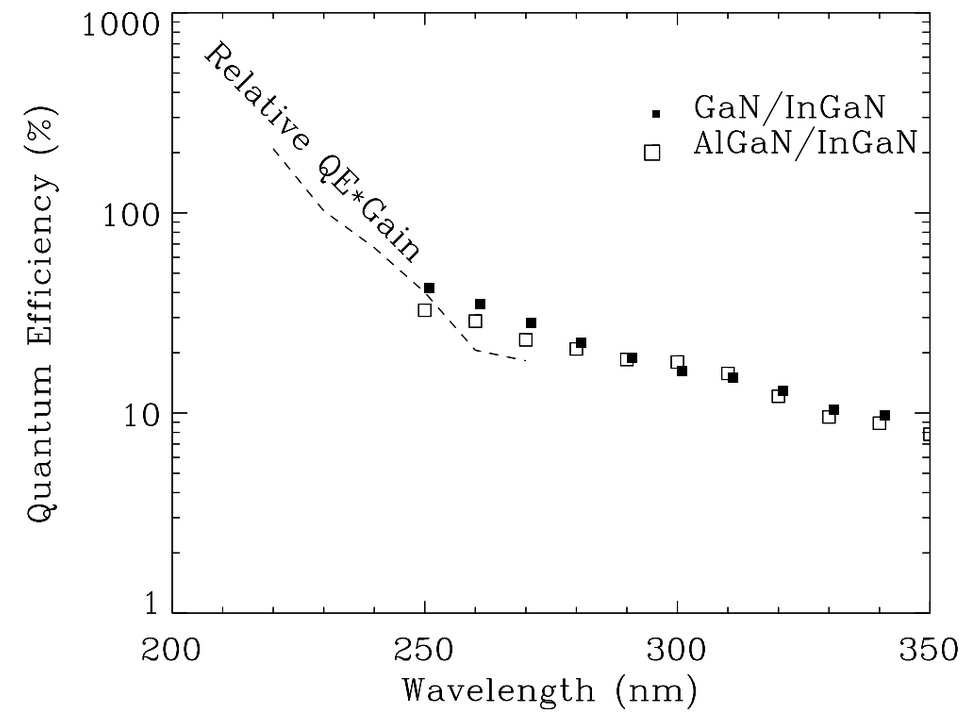
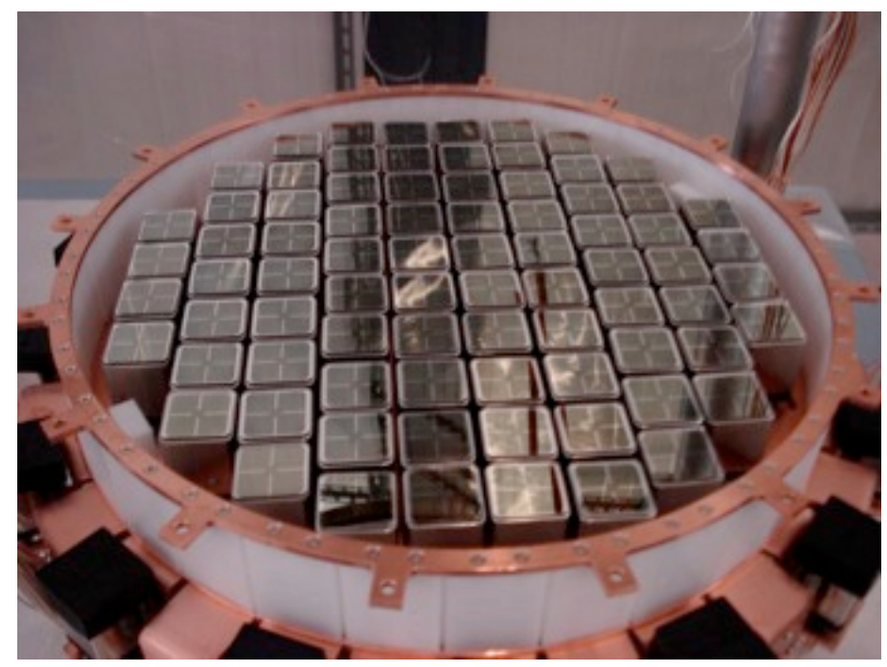
Outline

- Photocathode Project Overview
- Objectives
- Strategy and Approach
- Results
- Future Plans

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
- High QE, low background photocathodes operating in the hard UV are also needed for noble gas detectors in HEP experiments





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

Objectives

- Optimize amorphous nitride photocathode materials for high quantum efficiency
- Extend wavelength response further into the blue range using higher concentrations of indium
- 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
- Implement tube sealing capabilities within our UHV growth/testing chamber

Strategy and Approach

- Make use of our existing epitaxial growth/Cs activation/QE measurement system to fabricate and examine amorphous nitride cathodes
- Optimize the procedures for fabricating amorphous nitride photocathodes for good QE in the blue wavelength range
  - Increased Indium
  - Optimized Mg doping
  - Thermal annealing
  - Cs activation
- Explore use of atomic nitrogen plasma source for cleaning cathode surfaces after exposure to air
- Develop procedure to cap cathode layers with Indium and evaluate the efficacy of thermal removal of In after exposure to air
- Seal cathodes inside vacuum chamber using Indium bonding techniques

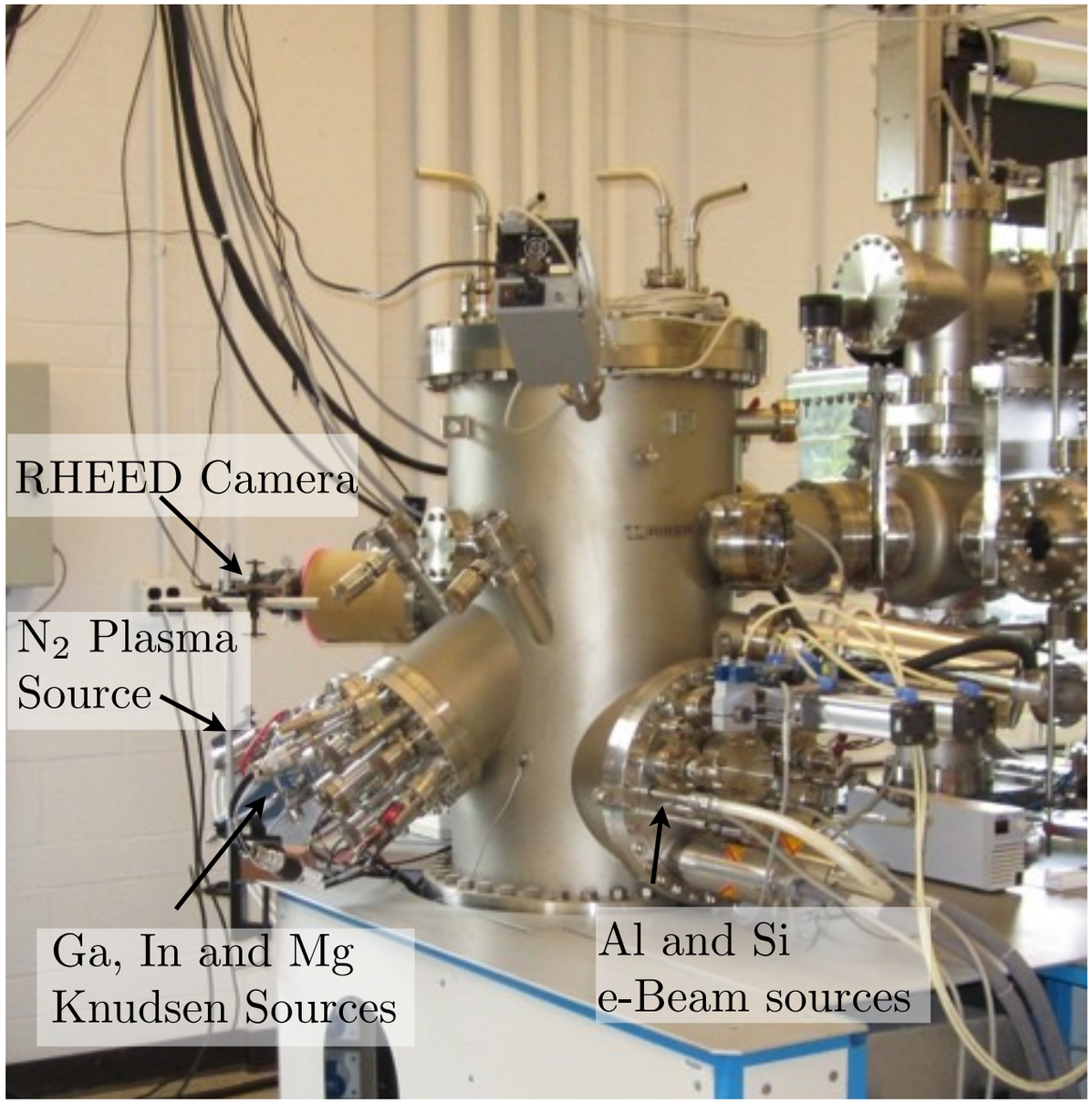
Materials Properties of GaN, InN, AlN and Alloys

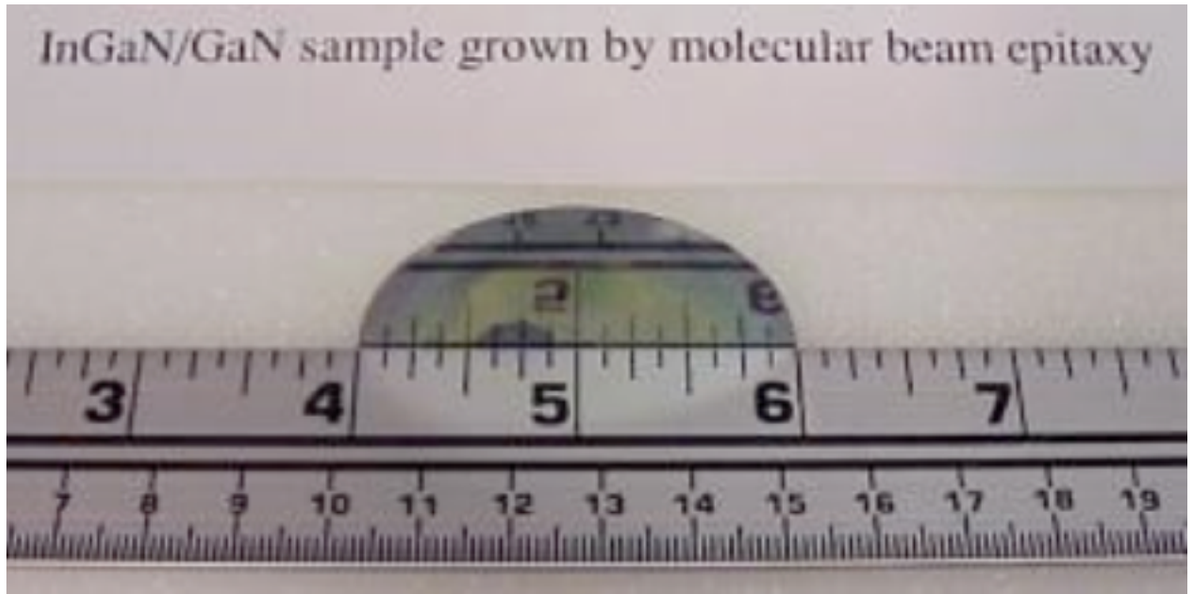
- **Crystal Phase**:
  - Hexagonal or cubic lattice
  - Band gap energy ranges from 0.8 to 6.2 eV
  - Epitaxial growth on sapphire window substrates (other substrates such as AlN, GaAs and Si also possible)
  - n-type doping with Si (intrinsically n-type)
  - p-type doping with Mg
  - Negative electron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

MBE Growth System

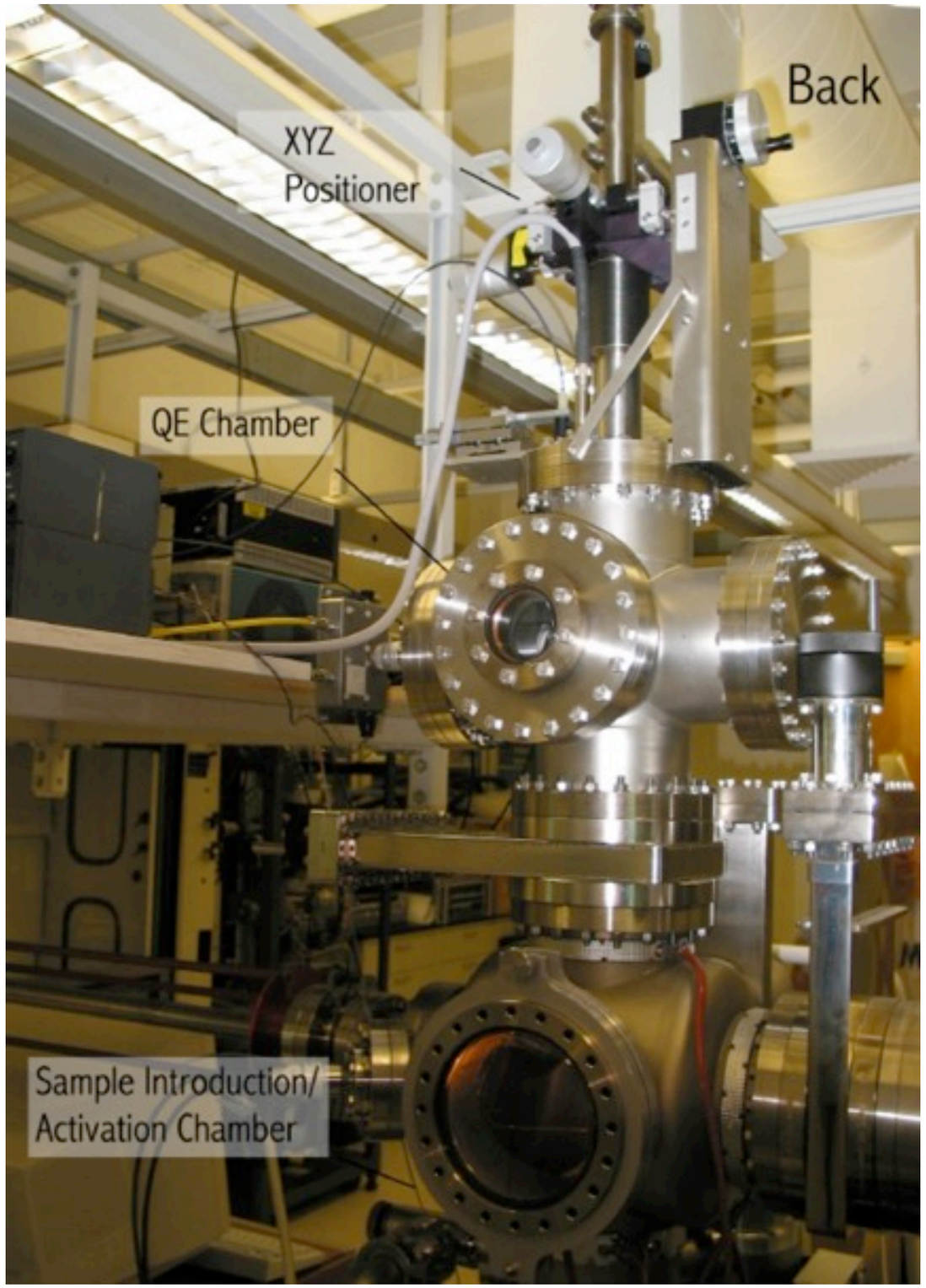
- MBE utilizes a UHV growth chamber with a rotating, heated substrate and shuttered beams from the different sources. Our Nitride system also includes a Nitrogen plasma source





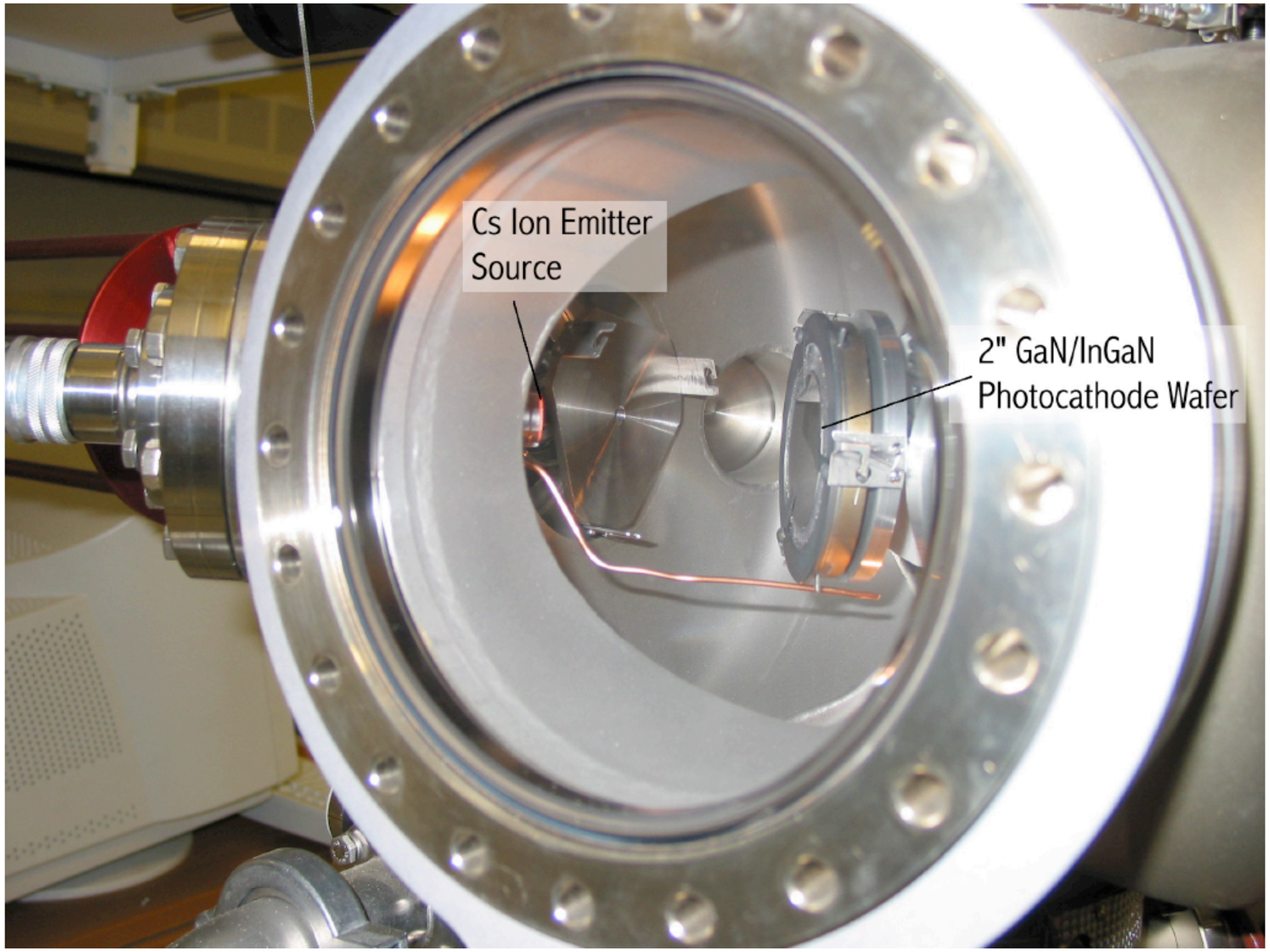
Our system currently has the capability of growing wafers up to 3 inch in diameter

Activation and QE Measurement System



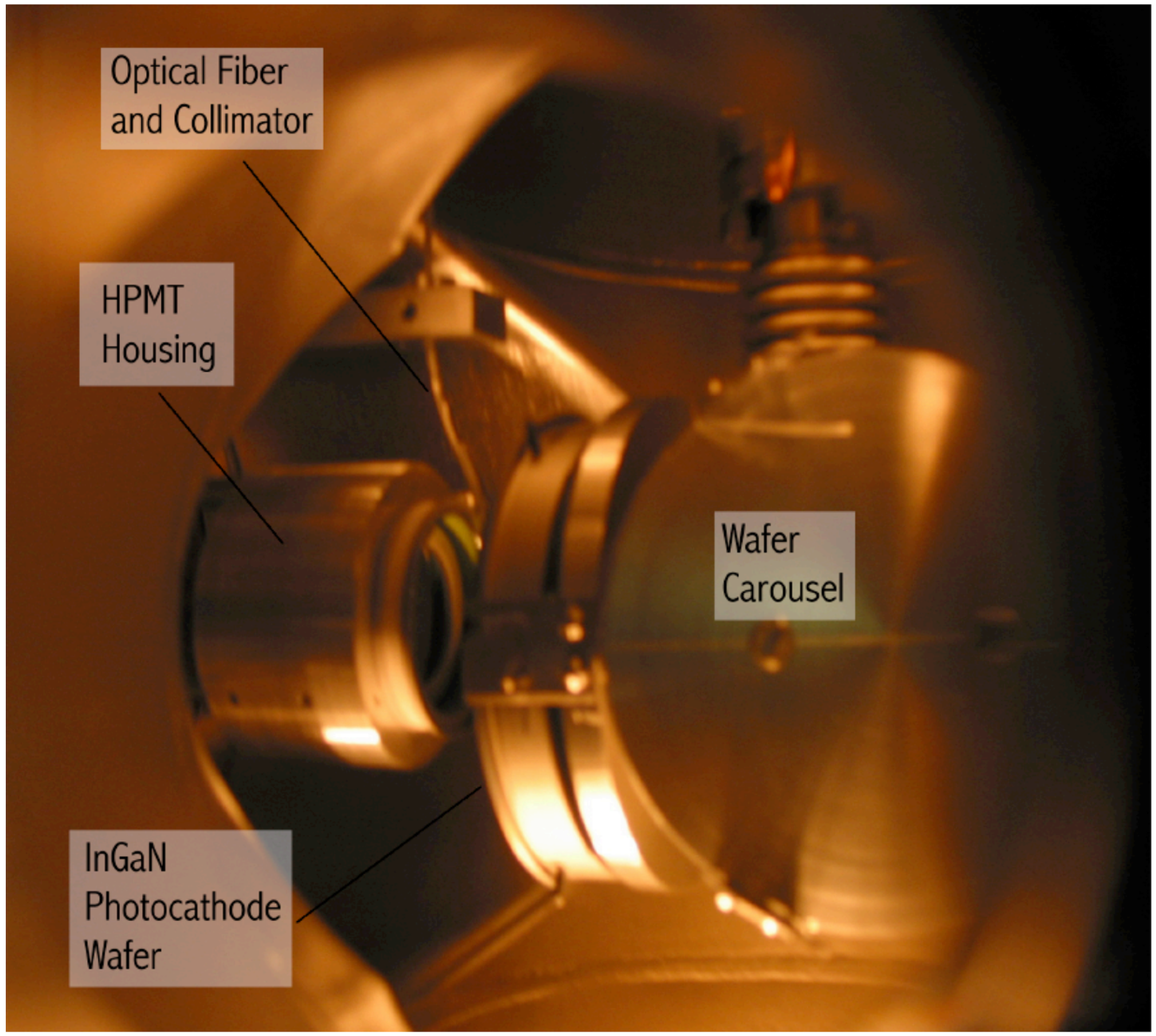
- Our system includes a number of vacuum transfer stages for in-situ Cs activation, docking with electron multipliers and readout electronics as well as in-situ QE measurements

Cesium Activation



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

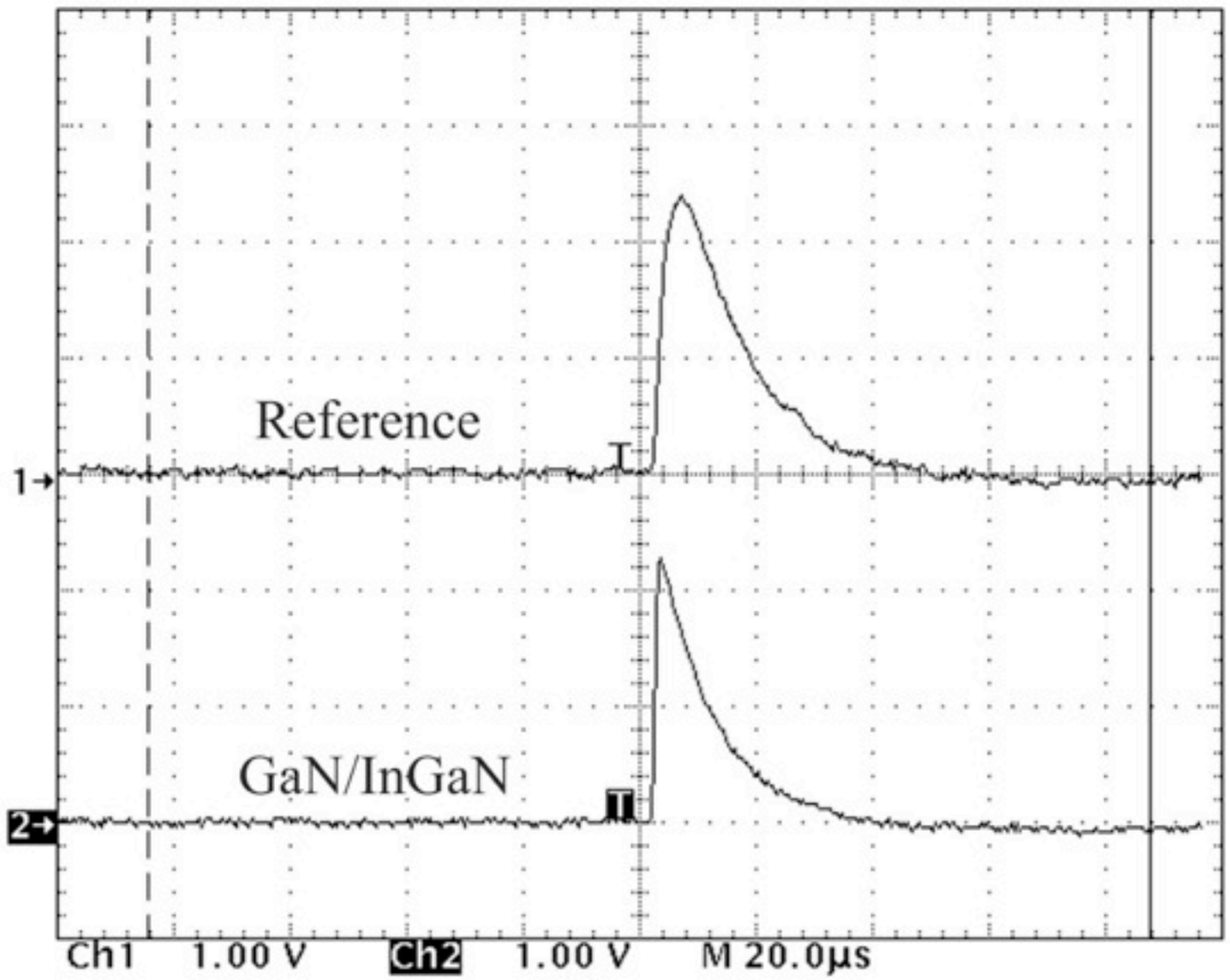
QE Measurement System



- 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

HPMT output signals

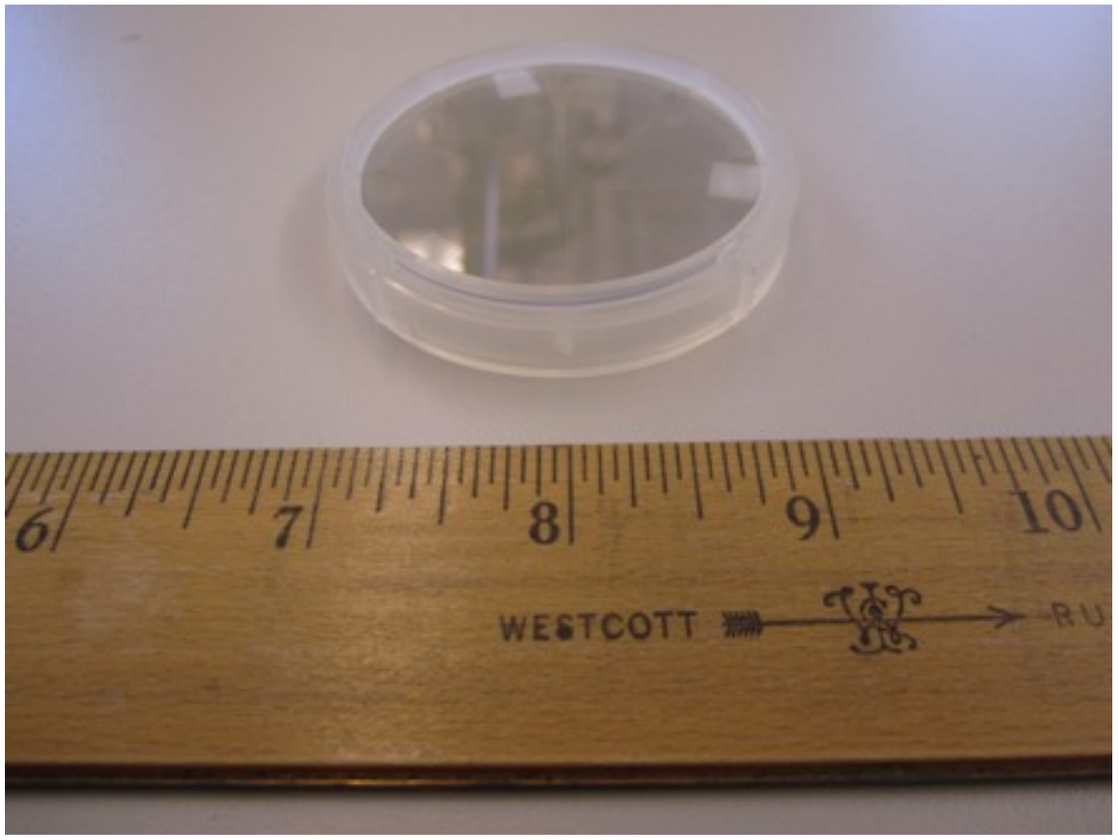


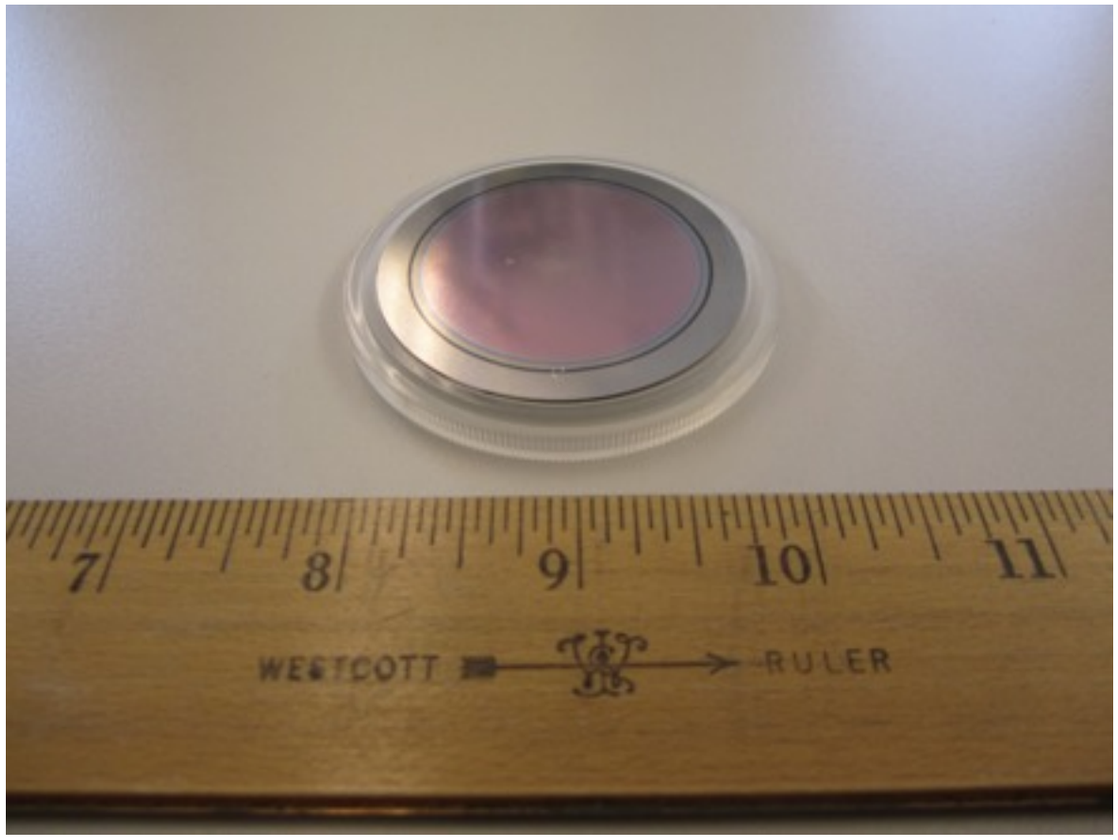
- Electronic pulses from HPMT pin diode and reference photodiode registered by low-noise amplifier electronics.

Results

- Fabricated amorphous GaInN photocathodes on sapphire and stainless steel substrates (ready for ITO coated glass window substrate!)
- Longer wavelength QE response (out to 400nm) improved with increased In incorporation, and after repeated Cs exposures
- Evidence for improved QE response after thermal annealing
- Evidence that amorphous cathodes have good long-term stability
- Cathode surface restored after exposure to atomic nitrogen beam from plasma source
- Investigation of protective capping layer on cathode surface underway

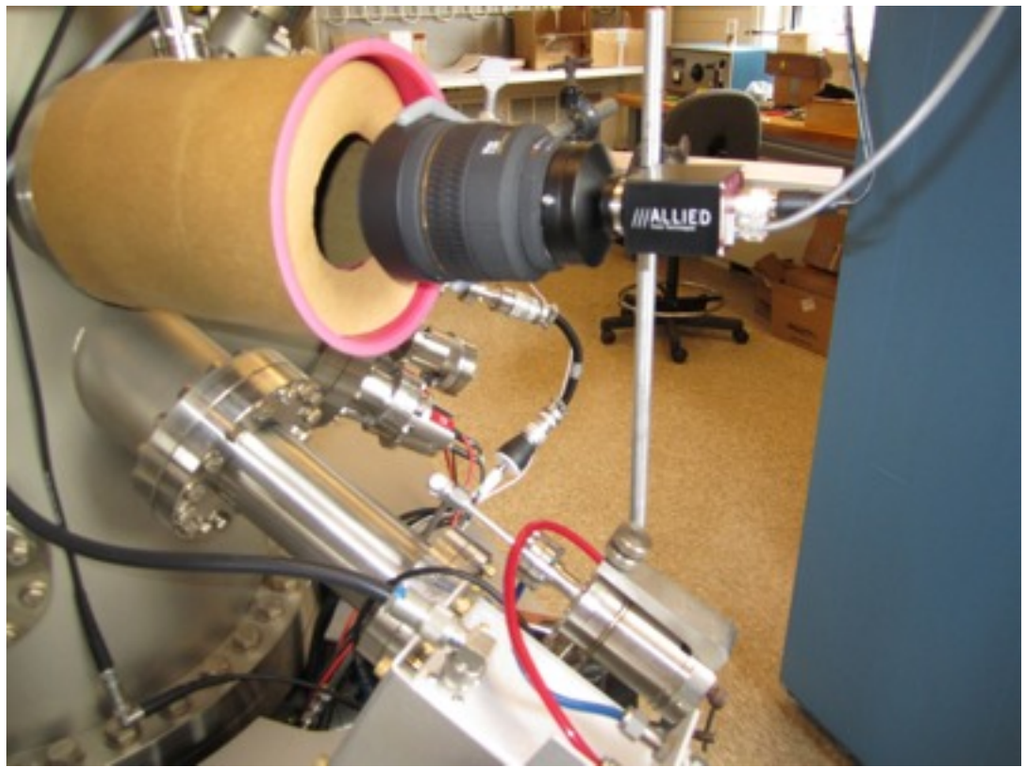
Amorphous InGaN Cathodes





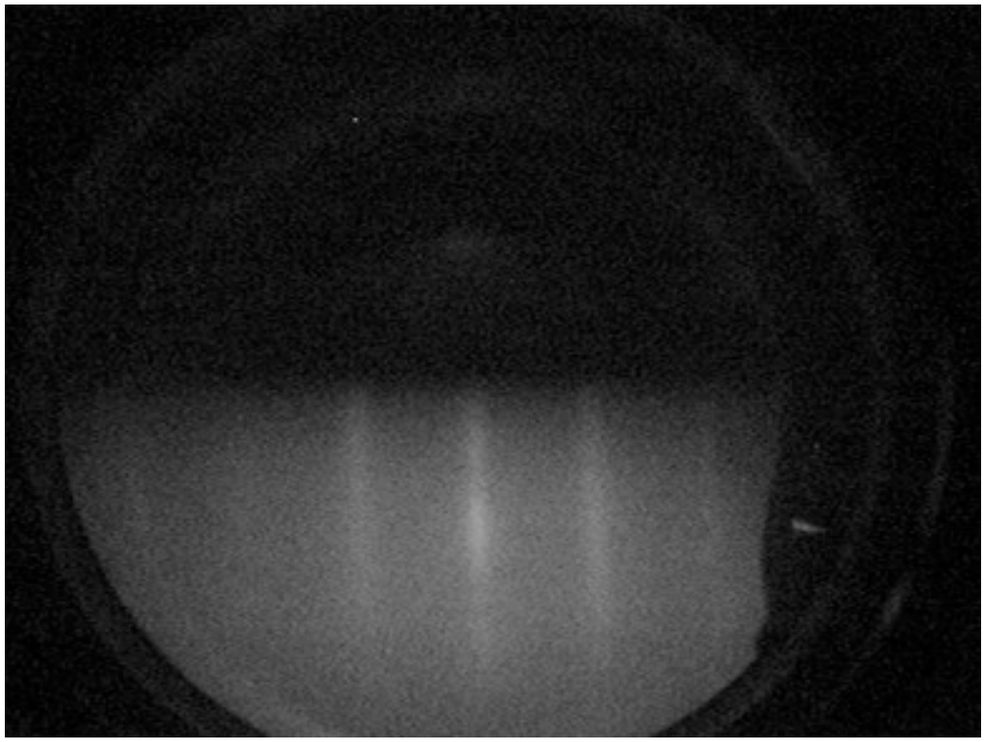
- Have grown amorphous InGaN on sapphire (left) and on stainless steel (right)

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

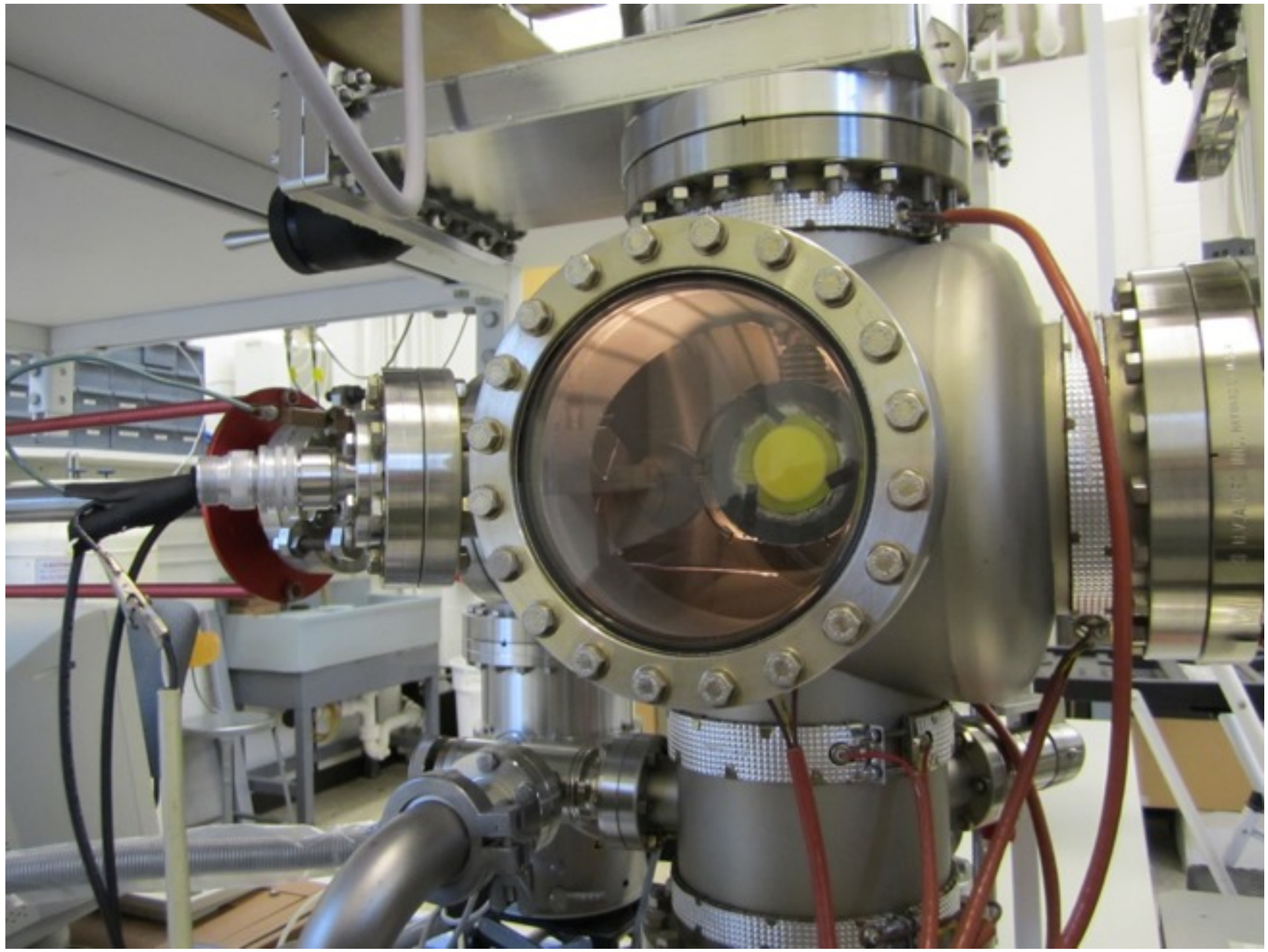
epitaxial InGaN



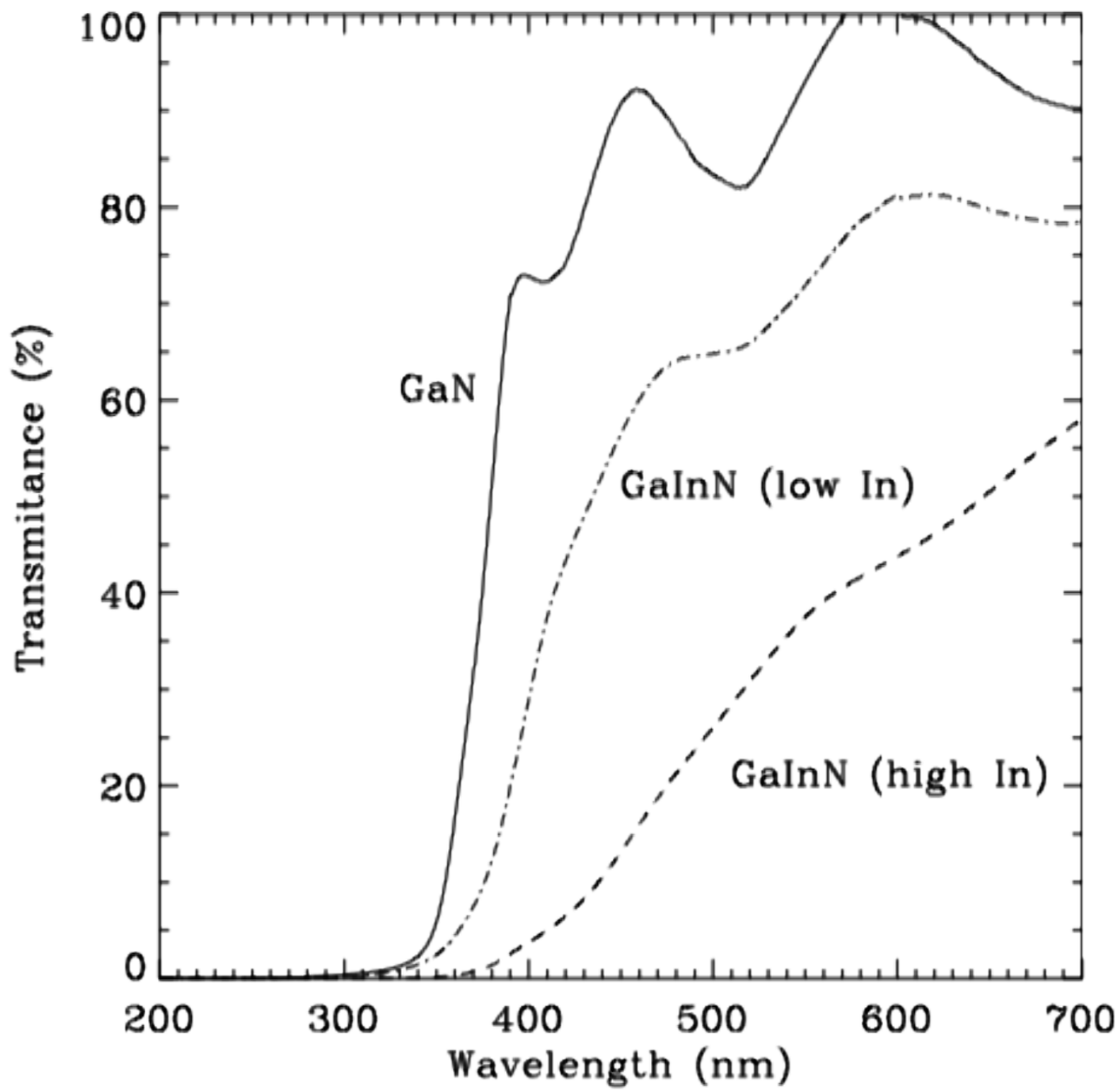
amorphous InGaN

Increased In

- Amorphous cathode grown on SS substrate shown through window of Cs activation chamber.

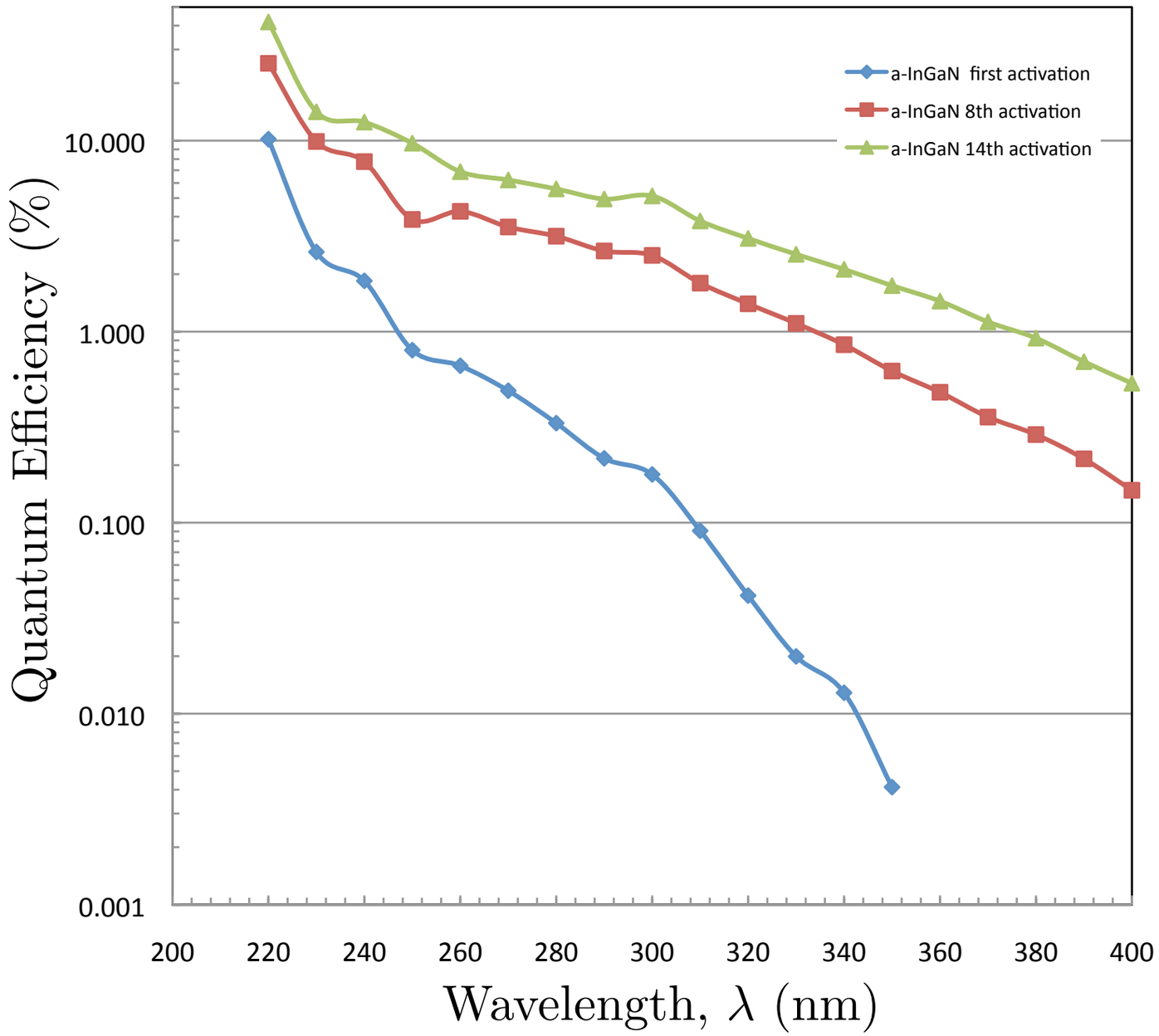


Optical Transmission



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

Improvements with Repeated Cs Activation



- Results continue to improve with higher In, higher Mg doping
- Efficiency continues to improve with repeated Cs activation

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

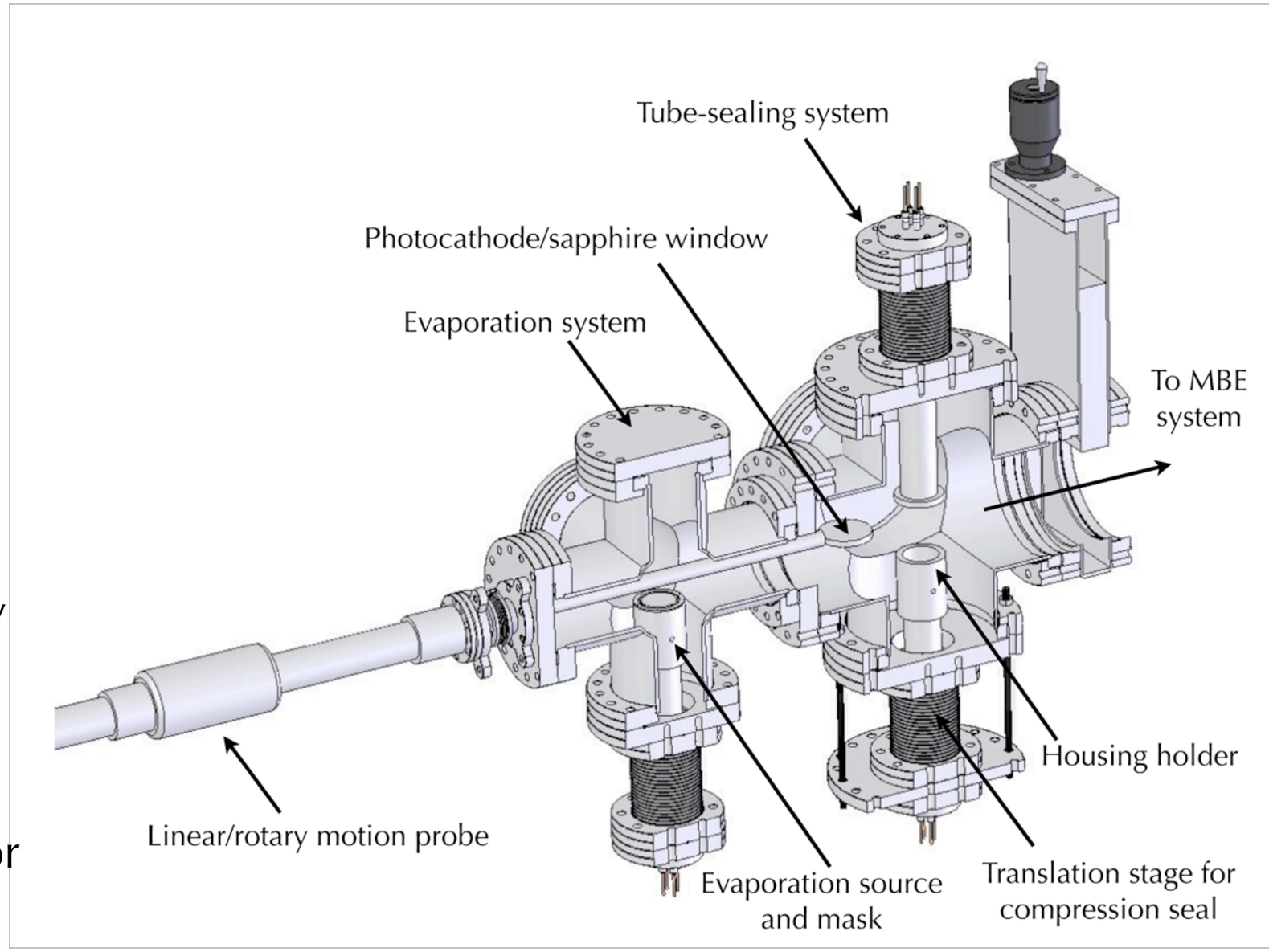
- Very little aging effect (QE stays the same one day later!) - early exposures actually show increase with time after activation (diffusion?)
- Continued improvement with repeated Cs activation, larger improvements in long wavelengths.
- Indicates that QE is still limited by surface, not bulk properties.

Future Plans

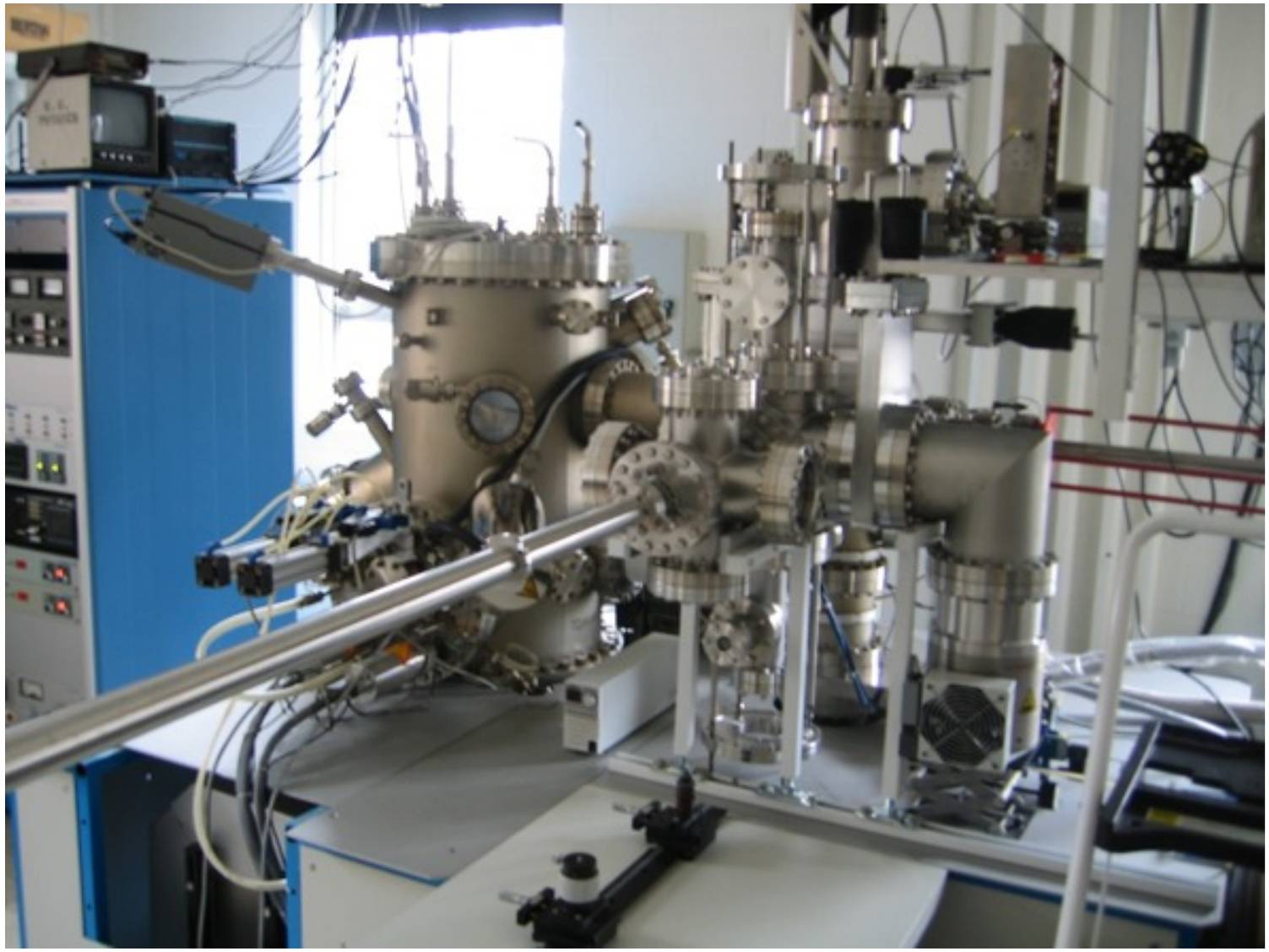
- Continue to optimize amorphous GaInN photocathodes for blue spectral range
- Fabricate amorphous nitride cathodes on other substrates (ITO-coated glass, thick sapphire, etc.)
- Upgrade measurement system for deep UV (175nm LiXe and 125nm LiAr) measurements. *Equipment needed: windowless, NIST-calibrated UV photodiode, vacuum monochromator.*
- Investigate capping and other techniques for transfer of cathodes
- Study field enhancement at nanostructured surfaces. *Equipment needed: in-situ optical microscopy or STM*
- Develop a system design for large-area amorphous cathode growth
- Work with LAPPD group on development of complete devices for Liquid-Noble experiments?

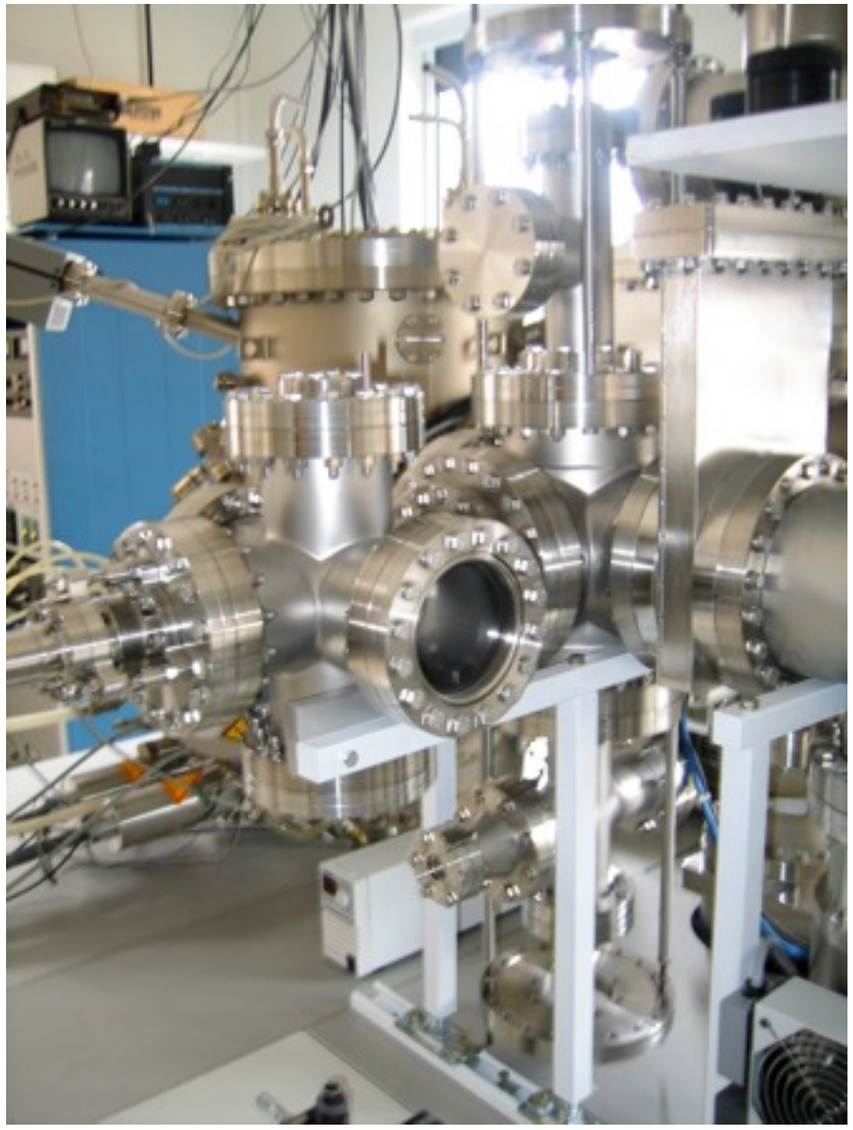
Tube Testing and Sealing

- Develop tube sealing/transfer/testing system
- Transmission-mode QE measurements for comparison with reflection-mode measurements
- Hot or Cold Indium seals
- Evaporator for preparing window and housing for seal
- Mechanical press for compression, radiative heaters for hot seals
- Incorporate SAES getter into housing



Tube Sealing System





- Construction of vacuum transfer system largely complete
- Need to finish design of vacuum press
- Need to acquire components for transmission-mode QE and VUV measurement system.