

## PHOTOCATHODE R&D AT CORNELL UNIVERSITY\*

L. Cultrera<sup>#</sup>, I. Bazarov, J. Conway, B. Dunham, Y. Hwang, Y. Li, X. Liu, T. Moore, R. Merluzzi, K. Smolenski, S. Karkare, J. Maxson, W. Schaff, CLASSE, Cornell University, NY 14853, USA

### Abstract

A broad-range R&D program is pursued at Cornell University aimed at preparation and characterization of high quantum efficiency photocathodes for the Energy Recovery Linac photoinjector. The currently investigated photoemitters include both positive and negative electron affinity materials such as bi-alkali antimonides and III-V semiconductors activated with Cs and either O or F. Analysis techniques such as Scanning Auger Spectroscopy, Low Energy Electron Diffraction, Reflected High Energy Electron Diffraction and work function measurements are used to characterize the surfaces properties of the specimens. Spectral response, photoemission uniformity, electron energy distributions are used to characterize the quality of the photoelectron beam and to relate it to the measured surface properties.

### INTRODUCTION

Accelerator based light sources, either energy recovery linacs (ERLs) or free electron lasers (FELs), rely primarily on the photoemission process for generating high brightness electron beams required for this application [1,2].

While the physical processes involved in photoemission have been extensively studied in the past years, discrepancies between the existing theoretical models predictions and experimental results reveal that several aspects are not yet completely understood [3]. Moreover many of the fundamental properties of electron generated from photocathode materials used in modern photoinjector have not yet been experimentally determined [4].

The photoinjector prototype for the ERL project being developed at Cornell University is foreseen to provide an average current up to 100 mA [5]. The DC gun of the photoinjector requires photocathode materials having quantum efficiencies of at least a few per cent when illuminated by visible light, so as to reduce the laser power required to a reasonable level, e.g., a few watts of average power. Furthermore, a good photocathode candidate should have both small thermal emittance (or Mean Transverse Energy, MTE) and sub-picosecond response time to produce maximally bright beams. In addition, these photocathodes must be able to a certain extent to withstand operational damage, possibly due to either ion back-bombardment or high voltage breakdown events, which can cause both sputtering of the surface or disordering in the photocathode crystal [6].

\* Work supported by NSF DMR-0807731 and by DOE DE-SC0003965.  
# lc572@cornell.edu

Aiming at identifying a suitable and reliable photocathode for the injector, Cornell group has designed and constructed a unique integrated UHV system for the preparation of different photocathode materials and for investigating their properties. This UHV system allows the synthesis and activation of photocathodes based on bulk and Molecular Beam Epitaxy (MBE) grown GaAs and alkali antimonide, in-situ characterization of their photoemission and surface properties.

### EXPERIMENTAL SETUP

#### *Interconnecting UHV Chamber*

Both GaAs activated to Negative Electron Affinity (NEA), by alternated exposure to Cs and oxygen or  $\text{NF}_3$ , and alkali antimonite based photocathodes have extremely high surface sensitivity to oxidizing species present in the residual gases of UHV systems. Thus, in situ characterization of the photocathodes is essential, as exposure of the cathodes to air will significantly alter their photoemission and surface properties.

We have demonstrated in the past months that alkali antimonide based photocathodes grown under UHV condition could be moved from the deposition chamber to the ERL injector prototype by means of a suitable vacuum suitcase where the cathodes are kept in a vacuum level below  $10^{-9}$  Torr [7].

Over the past years, many stand-alone UHV systems have been designed and built at Cornell for preparing and characterizing photocathodes properties. These chambers are: (1) a growth chamber for the synthesis of alkali antimonide thin films; (2) a GaAs activation chamber and (3) a surface analyses chamber. In addition, we have been working on an UHV electron energy analyser that, using the adiabatic expansion of the electron beam in slowly varying longitudinal magnetic fields, allows mapping the longitudinal and transverse energy distribution of the photoelectrons as emitted from the cathode surface [8]. All these chambers share the same design for the cathode holder used in the DC gun of the photoinjector allowing for samples to be moved from one location to another without the need of mechanical adjustment.

In the past, we had to transfer samples among different chambers using the vacuum suitcase, which was very time consuming. The need to overcome this loss of time led to design a new vacuum system that interconnects all the cathode study chambers to allow moving a photocathode from one chamber to the other. A drawing of the whole assembly is shown in Figure 1, and a picture showing the UHV system assembled is shown in Figure 2. This includes also a load lock for the introduction and removal of samples and a vacuum chamber equipped with a

carousel holder with the up to eight samples stored for long term. The motion of the samples under vacuum is performed using magnetic arm linear translators. The vacuum level is kept below  $10^{-9}$  Torr level by a combination of ion, NEG and Ti sublimation pumps.

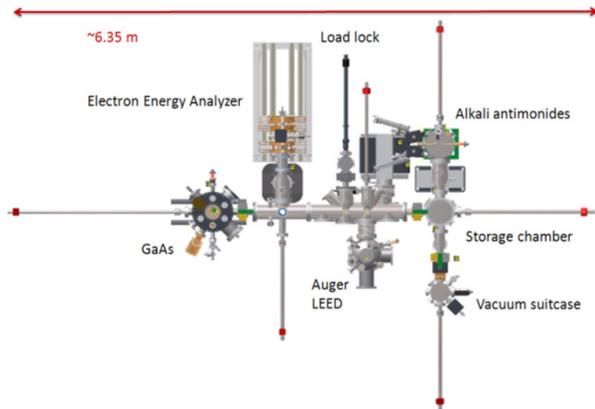


Figure 1: Top view of the drawing showing the photocathode laboratory integrated vacuum system.

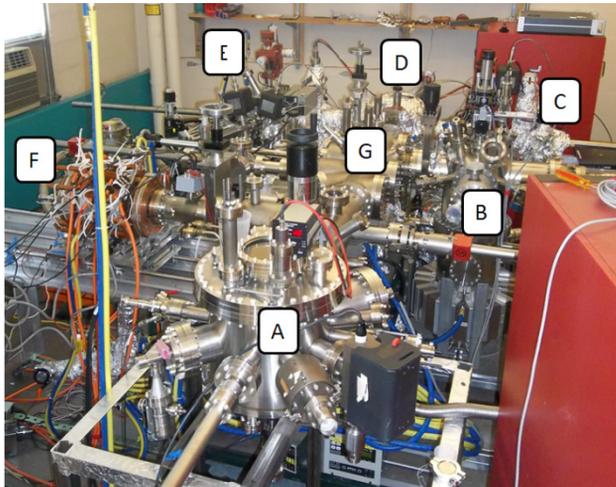


Figure 2: Photocathode laboratory integrated vacuum system showing: A) GaAs activation chamber; B) Surface analyses chamber; C) Vacuum suitcase; D) Storage chamber; E) Alkali antimonide growth chamber; F) Electron Energy Analyser; G) Interconnection Chamber.

In addition to the photocathode laboratory, we have access to a Molecular Beam Epitaxy reactor dedicated to the growth of homo-epitaxial GaAs film to investigate the effect of different dopants and different profiles on the doping density, through the Department of Electrical and Computer Engineering of Cornell University. The GaAs film grown with the MBE reactor are capped with protective As layer and transported in air to the injector or to the photocathode laboratory. The removal of the As cap is performed under UHV by heating the sample to a temperature slightly above  $400^{\circ}\text{C}$ . This temperature is way lower than the onset of incongruent evaporation of Ga and As preventing the roughening of the crystal surface [9].

### Alkali Antimonide Photocathodes

In the last year we have been working mainly on optimizing the parameters for growing high quantum efficiency CsK<sub>2</sub>Sb photocathodes we have demonstrated the capability to routinely obtain thin film with QE around 10% at 520 nm (the operating wavelength of the drive laser of the photoinjector). With respect to our experimental recipe, reported elsewhere [10], the sequential growth is now performed with higher temperatures (Sb at  $175^{\circ}\text{C}$ , K at  $150^{\circ}\text{C}$  and Cs at  $120^{\circ}\text{C}$ ). Typical spectral response of a CsK<sub>2</sub>Sb photocathode and the QE distribution over the grown area are reported in Figure 3 and 4 respectively. Experimental values obtained for MTE are reported in Table 1. We also implemented a new movable mask to select the area where the alkali antimonide film will be grown allowing off-center deposition.

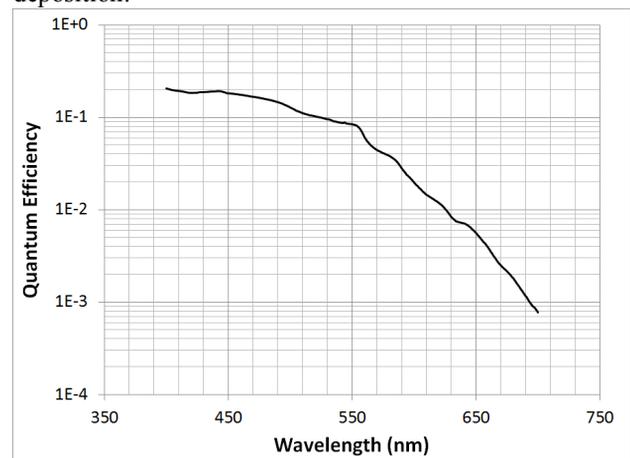


Figure 3: Typical spectral response of a CsK<sub>2</sub>Sb photocathode grown at Cornell University.

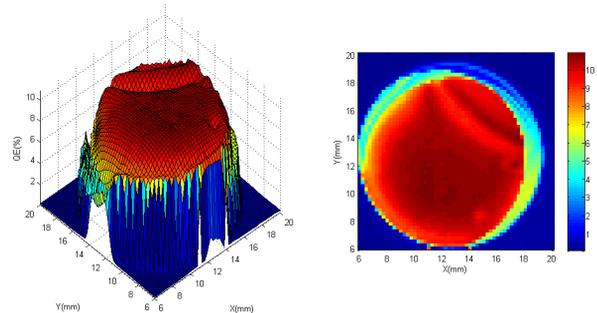


Figure 4: QE uniformity over the surface of a typical CsK<sub>2</sub>Sb photocathode grown at Cornell University.

Table 1: Typical MTE Values for CsK<sub>2</sub>Sb Photocathodes

Wavelength	MTE
532 nm	160 meV
475 nm	240 meV
405 nm	390 meV

### GaAs Photocathode Grown by MBE

Disagreement between the theory prediction and experimental results related to thermal emittance measurement of NEA photocathodes based on highly p-doped GaAs [3] led us to investigate different approaches for their preparation. Based on simple emission model we have partially attributed the larger emittance values measured in our DC gun to surface roughening of the GaAs wafer induced by incongruent evaporation of the two elements when a sample is heat cleaned above 580°C for the purpose of removal of oxides before performing activation to NEA [11]. In order to avoid heat cleaning to such high temperature we homo-epitaxially grown thin films (40-100nm) of intrinsic and carbon doped ( $5 \times 10^{19} \text{ cm}^{-3}$ ) GaAs film over the surface of a heated GaAs p-type wafer. RHEED pattern showed that the surface was atomically flat after the growth (see Figure 5). The wafer was capped with As inside the MBE reactor before being exposed to air and then installed in the load lock of the photoinjector gun. Before the activation samples were heated to about 450 C to remove the As cap. Activation to NEA was performed in both single cycle (one Cs and one  $\text{NF}_3$  exposure) and full cycle (alternating the exposure until maximum QE was achieved). Thermal emittance and QE were then measured at different wavelength to characterize the quality of the electron beam. The results obtained at the wavelength of 532 nm are summarized in Table 2. So far the lowest MTE value we ever measured (about 80 meV) was obtained with a 100 nm thin film of intrinsic GaAs activated with only one cycle of Cs and  $\text{NF}_3$  exposure.

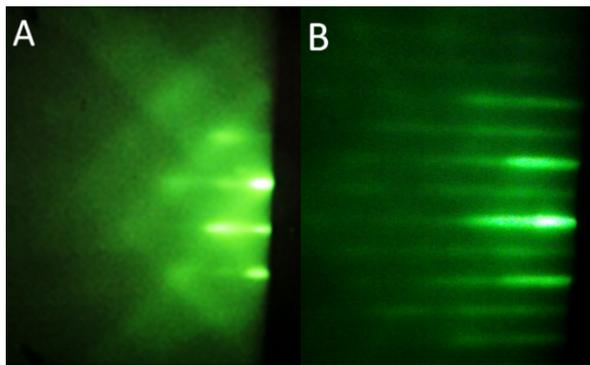


Figure 5: RHEED pattern of GaAs surface roughened by heat cleaning performed above 580 C (A) and after the MBE growth of thin GaAs over the same surface (B).

Table 2: Quantum efficiency and MTE values obtained at 532 nm wavelength for MBE grown GaAs thin films after full (f.a.) and 1 cycle activation (1 c.)

Photocathode	QE	MTE
c-doped (f. a.)	9%	150 meV
c-doped (1 c.)	3%	120 meV
Intrinsic (f. a.)	5%	107 meV
Intrinsic (1 c.)	1%	80 meV

The thermal emittance measurements showed that the doping profile on the sample and activation process can strongly affect the transverse energy distribution of the extracted electrons from GaAs. This suggests that band bending near the surface, the thickness and structure of the active layers, play an important role in achieving higher brightness electron beam.

In order to increase the understanding of the those results and to suitably tailoring the photocathode properties we are developing a numerical code based on Monte Carlo technique to simulate the photoemission process in III-V semiconductors, as well as to study the role of and the structure of the active layers through work function measurements, LEED and photoluminescence techniques.

### CONCLUSIONS

We presented the activities of Cornell ERL group related to our R&D program on photocathodes detailing the realization and commissioning of a unique modular UHV system now hosted in a dedicated laboratory. New results showing our capabilities in growing and characterizing high QE photocathodes based either on alkali antimonide and on GaAs have been discussed. Those new insights are leading us on defining the path to pursue for a better understanding of the photocathode physics.

### REFERENCES

- [1] T. Shintake, "Review of the worldwide SASE FEL Development", PAC07, Albuquerque, June 2007, MOZBAB01, p. 89 (2007); <http://www.JACoW.org>
- [2] G.R. Neil, "Worldwide ERL R&D overview including JLAMP, BNL, and Cornell ERLS", LINAC10, Tsukuba, September 2010, TU103, p. 347 (2010); <http://www.JACoW.org>
- [3] I. Bazarov et al., J. of Appl. Phys., 103 (2008) 054901.
- [4] D.H. Dowell et al., Nucl. Instr. Meth. A 622 (2010) 685.
- [5] D. H. Bilderback, "Energy Recovery Linac experimental challenges", FLS06, Hamburg, May 2006, PTL03, p. 7 (2007); <http://www.JACoW.org>
- [6] L. Cultrera et al., Phys. Rev. ST-AB 14(12), (2011) 120101.
- [7] L. Cultrera et al., "Growth and Characterization of Bialkali Photocathodes for Cornell ERL Injector", PAC2011, New York, October 2011, WEP244, p. 1942 (2011); <http://www.JACoW.org>
- [8] D.A. Orlov et al., Appl. Phys. Lett. 78 (2001) 2721.
- [9] S. Karkare et al., "Effect of Surface Roughness on the Emittance from GaAs Photocathode", PAC2011, New York, October 2011, THP192, p. 2480 (2011); <http://www.JACoW.org>
- [10] I. Bazarov et al., Appl. Phys. Lett. 98 (2011) 224101.
- [11] S. Karkare and I.V. Bazarov, Appl. Phys. Lett. 98 (2011) 094104.