

## ALKALI ANTIMONIDE PHOTOCATHODES FOR EVERYONE

J. Smedley, K. Attenkofer, S. G. Schubert, BNL, Upton, NY 11973, USA

H. A. Padmore, J. Wong, LBNL, Berkeley, CA 94720, USA

J. Xie, ANL, Argonne, IL 60439, USA

M. Ruiz-Oses, I. Ben-Zvi, X. Liang, E. M. Muller, Stony Brook University, Stony Brook, NY 11794, USA

J. DeFazio, Photonis USA PA, Inc., Lancaster, PA, 17601, USA

### Abstract

The next generation of x-ray light sources will need reliable, high quantum efficiency photocathodes. These cathodes will likely be from the alkali antimonide family, which currently holds the record for highest average current achieved from a photoinjector. In this work, we explore a new option for delivering these cathodes to a machine which requires them: use of sealed commercial vacuum tubes. Two sealed tubes have been introduced into a vacuum system and separated from their housing, exposing the active photocathode on a transport arm suitable for insertion into an injector. The separation was achieved without loss of QE in one case. These cathodes are compared to those grown via traditional methods, both in terms of QE and in terms of crystalline structure, and found to be similar.

### INTRODUCTION

Alkali antimonide photocathodes have a long history in low-light photodetection, including image intensifiers. These needs have been met by commercial production; principally by RCA and its successors. The accelerator community also has great interest in alkali antimonide photocathodes – they are a prime candidate for use in high-brightness photoinjectors of free electron lasers and 4th generation light sources [1-3]. However, within the accelerator community, cathodes have traditionally been grown in dedicated vacuum systems tied to specific injectors. In some cases cathodes have been transferred from one system to multiple injectors, typically on a limited basis [2,4].

We have developed tools to understand the formation of these materials, both structurally and chemically, with the goal of altering the growth to produce cathodes with less roughness, better stoichiometry, and larger crystal grains. The *in situ* techniques being used are x-ray diffraction (XRD), grazing incidence small angle x-ray scattering (GISAXS) and x-ray reflection (XRR). These tools enable determination of the crystal form of the cathode at each phase of growth, the film thickness and roughness, the texture and grain size of the film, and the presence of “imperfectly reacted” material. This work has been carried out at the National Synchrotron Light Source (NSLS) using beamline X21 and at the Cornell High Energy Synchrotron Source (CHESS) using beamline G3.

The goal of this work is to enable the large scale production of identical photocathodes, using recipes developed in the *in situ* analysis chamber, which will provide high QE while minimizing the surface roughness which can dominate the intrinsic emittance [5,6]. One

aspect of this effort is collaboration with an industrial partner to produce photocathodes in sealed tubes which can be separated in vacuum.

Figure 1 shows a prototype photocathode in a sealed vacuum capsule. The substrate for growth is polycrystalline Molybdenum, which is brazed to the copper plug shown in the picture to the left. The capsule is sealed with a low temperature solder visible around the copper. A window on the isolated top electrode enables the QE of the device to be measured while the capsule is still sealed. The photocathode is visible as the blue area in the picture on the right, through this window.

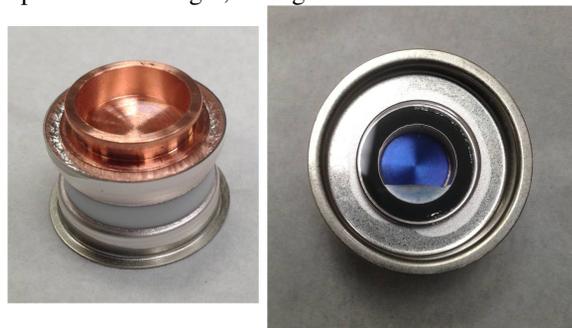


Figure 1: Sealed photocathode.

### EXPERIMENT

In the interest of space, the growth chamber with *in situ* x-ray analysis is described elsewhere [7]. This chamber has been used to measure both the capsule photocathodes, and to grow cathodes for comparison. The comparison cathodes are grown in a UHV chamber, with a typical operating pressure of 0.2 nTorr. Residual gas analysis confirms that the partial pressures of reactive gases ( $H_2O$ ,  $CO$ ) are better than 0.05 nTorr. Silicon [100] wafers  $1 \times 2 \text{ cm}^2$  are used as substrates; these are exposed to HF prior to installation, and baked to 500 C for an hour prior to growth. Once the substrate has cooled to 160 C, a further cleaning of the substrate is achieved by an initial potassium evaporation – XRR measurements confirm that this K does not remain resident on the surface, however the QE of cathodes grown is significantly improved by this initial step. Antimony is evaporated from PtSb beads; alkali-Bi sources from Alvatech are used to supply Potassium and Cesium. Deposition is sequential, with Sb evaporated, then K, then Cs, all at  $\sim 0.2 \text{ \AA/s}$ . The QE is observed during K and Cs evaporation, and the deposition is halted when the QE reaches a plateau. The “traditional” cathode is a multi-layer growth on a single substrate, with the first cathode “baked off” (substrate raised to 500 C for 10 min) prior to the growth of a second (recipe in Table 1).

Table 1: Traditional Cathode Recipe

1 <sup>st</sup> Layer	Temp	QE	2 <sup>nd</sup> Layer	Temp	QE
15 nm Sb	100		15 nm Sb	125	
62 nm K	125	0.14	60 nm K	125	0.37
118 nm Cs	125	4.1	120 nm Cs	125	7.5

The Photonis photocathodes are also grown via sequential depositions, but on a Molybdenum substrate. The recipe used is similar to that used by the company for its transmission-mode cathodes (traditionally grown on glass substrates), and has yet to be optimized for this application. The spectral response of this cathode as delivered is shown in Figure 2.

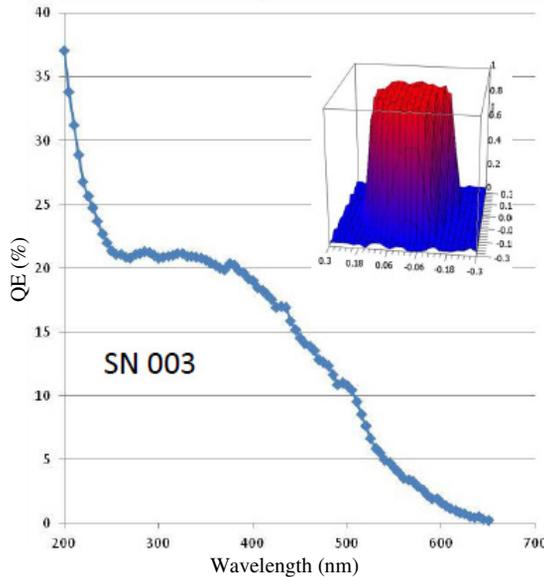


Figure 2: Spectral response of Photonis photocathode within the sealed tube. Inset shows spatial uniformity.

## RESULTS

### Transfer and Separation

The initial and final stages of the capsule loading and separation are shown in Figure 3. On the left is a capsule loaded onto the platen. On the right is the cathode ready to be transferred off the platen and into an injector. This design is compatible with the transfer system for the BNL 112 MHz Gun [8], and future iterations of this design will be tested in this gun (some design modifications are required to mask the solder joint from the gun).

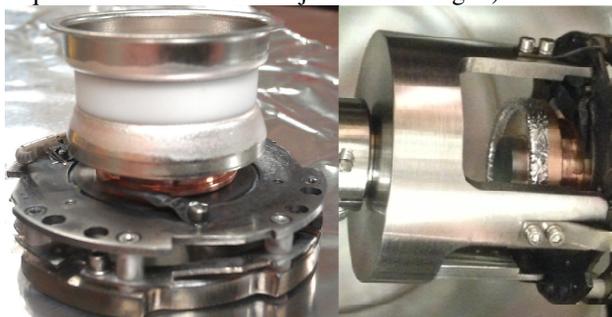


Figure 3: Left – sealed cathode mounted on platen. Right – Cathode after cap is removed, still attached to platen.

The sequence of cap removal is shown in figure 4. First the platen with capsule is loaded onto the heater. Second, the platen temperature is increased slowly to ~100 C (the solder eutectic temperature is 72 C; thermal conduction from the platen to the solder joint as well as alloying of the solder with the base materials likely explains this difference). A manipulator is used to gently pry at the cap (bottom left), eventually resulting in the cap tipping away from the cathode (bottom right). The QE of the cathode is measured using a green (532 nm) laser immediately after the removal process (figure 5). The QE of the cathode initially decreases due to the rise in temperature (to 3.1% for cathode 1 and 1.8% for cathode 2); the first cathode recovered fully (actually slightly higher) once it cooled to room temperature. The second attempt resulted in a permanent degradation with a final QE of 3%, thought to be due to excessive overheating of the photocathode during the cap separation process.

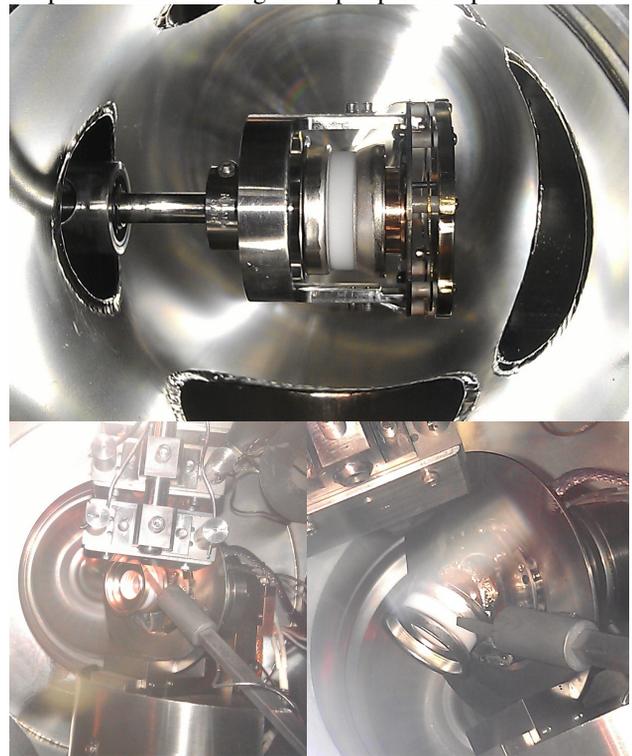


Figure 4: Top: Capsule loaded onto platen and mounted for insertion. Bottom Left: Finger positioned to remove cap. Bottom Right: Cap partially off.

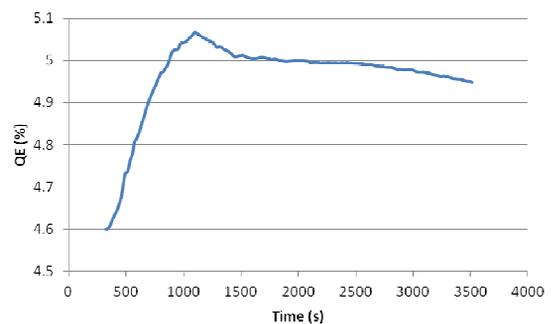


Figure 5: QE of cathode after cap removal. The QE rises due to the post-separation cooling of the substrate.

## X-ray Diffraction

Figure 6 shows the crystalline structure of both capsule cathodes, along with the “traditional” recipe cathode described above. For the traditional recipe, the cathode is cubic phase  $K_2CsSb$  with a mixed 222 and 220 surface textures. The grain size estimated from Scherrer analysis is  $49.3\pm 2.0$  nm. No unreacted  $K_3Sb$  is observed in this cathode. The capsule cathodes are similar, except that they have a more pronounced 222 texture. The broader peak widths likely imply smaller grains ( $38.9\pm 0.5$  nm for cathode 1,  $36.8\pm 0.2$  nm for cathode 2). The strong peak at 32.4 degrees is from the Molybdenum substrate.

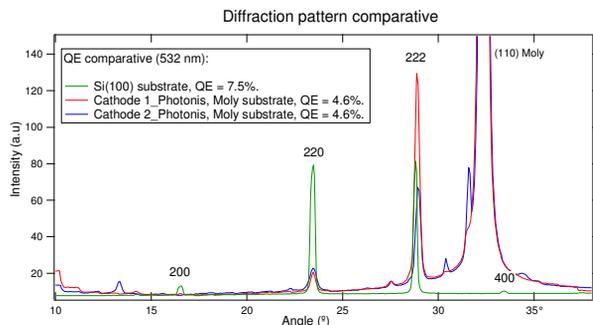


Figure 6: XRD results of two capsule cathodes after cap removal, along with a “traditional” recipe photocathode for comparison.

## CONCLUSIONS

Sealed “Phototube like” photocathodes have been prepared to be separated in vacuum, allowing the photocathodes to emit electrons into a test system. The removal process can preserve the QE of the cathodes; 4.6% QE in the green was observed both before and after opening. While this QE is somewhat inferior to purpose-grown cathodes, the process has not yet been optimized and is expected to improve significantly. This technique has the potential to allow injector projects to purchase photocathodes that are produced commercially in batches,

providing quality control and reproducibility, and dramatically reducing costs.

Further, the ability of these cathodes to be studied and compared to existing recipes using *in situ* materials diagnostic techniques will allow the evaluation and optimization of the cathode properties relevant to accelerator applications. These are somewhat different than traditional phototube attributes – in particular, the eventual ability to use GISAXS to evaluate surface roughness will provide insight into the expected intrinsic emittance of these cathodes. This was not possible on the current samples, as the growth substrate was “rough” polycrystalline Molybdenum. Samples grown on single crystal Molybdenum are already in production, and roughness measurements are part of the near-term future plan. In addition, other materials, such as  $Cs_3Sb$  and  $K_2NaSb$ , will soon be grown and evaluated in sealed-tube form. In the somewhat longer term, these cathodes will be tested in the BNL 112 MHz SRF injector.

This work was supported by the US DOE, under Contracts DE-AC02-05CH11231, DE-AC02-98CH10886, KC0407-ALSJNT-I0013, DE-FG02-12ER41837 and DE-SC0005713. Use of CHES is supported by NSF award DMR-0936384.

## REFERENCES

- [1] L. Cultrera et al., Appl. Phys. Lett. 103 (2013) 103504.
- [2] R. R. Mammei et al., Phys. Rev. ST - Accel. Beams 16 (2013) 033401.
- [3] T. Vecchione et al., Appl. Phys. Lett. 99 (2011) 034103.
- [4] <http://www.lasa.mi.infn.it/ttfcathodes/>
- [5] T. Vecchione et al., Proc. of IPAC2012, New Orleans, Louisiana, p. 655 (2012).
- [6] S. G. Shubert et al., APL Mater. 1 (2013) 032119.
- [7] J. Smedley et al., Proc. of IPAC2013, Shanghai, China, 464 (2013).
- [8] T. Rao et al., Proc. of IPAC2013, Shanghai, China, 461 (2013).