Effect of Water on Cryo-Cooled Bialkali Antimonide Photocathodes Grown on a Niobium Substrate

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ABSTRACT

The accelerator that will be used to implement electron cooling of the proton beam for the Jefferson Lab Electron Ion Collider requires continuous wave (CW) electron beam at high average current and high bunch charge. A superconducting radio frequency (SRF) photogun represents an ideal candidate electron source for this application, but only if the photocathode can provide high yield, or quantum efficiency (QE), when cooled to cryogenic temperatures. Furthermore, the photocathode QE must remain high for long periods of time while delivering beam, a metric referred to as Lifetime (LT). The focus of this project was to make bialkali-antimonide photocathodes using a niobium substrate and study photocathode QE and LT behavior at different temperatures under two different vacuum conditions (non-baked and baked apparatus). First, a mixture of potassium and cesium was co-deposited onto a thin antimony layer grown on a niobium substrate while controlling the temperature of the substrate and the partial pressure of the photocathode chemicals and the time of deposition. After this, we measured the photocathode QE induced by illuminating the photocathode with 532 nm laser light, for the photocathode at room temperature (RT) and at 77 K, for two vacuum conditions. For the non-baked system, the highest QE achieved was 11.1% and 7.4 days LT at room temperature; also, 4.8% QE and 20.8 days of LT at liquid nitrogen temperature 77 K. For the baked system the highest QE obtained was 12.89% at room temperature and 7.45% at 77 K. The highest LTs measured under these vacuum conditions were 29.3 and 1.0 days at RT and 77 K, respectively. Photocathode QE was expected to decrease at lower temperature due to the change in the bandgap energy of the semiconductor. The QE was also expected to decrease if chemicals adsorb onto the cold photocathode surface. These chemicals serve as contaminants that increase the surface work function. The results presented on this work suggest that one can expect a 74±9% reduction in QE when an alkali-animonide photocathode is cooled to 2 K, which is the operating temperature of an SRF gun. Our results also suggest that QE reduction due to contamination of the photocathode surface via adsorption can be minimized by reducing the amount of oxygen and water vapor within the gun chamber.

INTRODUCTION

The main reason to build a SRF photogun is to successfully produce high-average-current, high brightness electron beams at cryogenic temperatures for certain applications for which is necessary to develop a superconducting photocathode[1]. For this purpose, niobium photocathodes have been tested in order to study its behavior at low temperatures and attempt to fabricate a photocathode compatible with the SRF photogun.

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In this project, a semiconductor photocathode was fabricated over a niobium substrate aimed to its usage in SRF electron guns, which are ideal injectors for FEL light sources and ERLs[2]. Semiconducting photocathodes are known for having a good QE (~10%) at visible light (520 nm)[3]. The QE is the ratio of extracting electrons from a photosensitive compound by incident photons (photoelectric effect).

$$QE(\%) \quad \frac{\#e_{emitted}}{\#\gamma_{incident}} \quad 100 \quad\quad h\nu\frac{I}{P} \quad 100 \quad\quad \frac{124\, I(\mu A)}{P(mW)\lambda(nm)}$$

Equation 1: Expression for the QE percentage.

For this case, the last expression shown in equation 1 was used, where "I" is the induced photocurrent, "P" is the power of the light source and "λ" is its wavelength. This research focuses on the evaluation of QE and LT performance of photocathodes at two different temperatures, RT and 77 K. In order to calculate the LT of the photocathodes, it is necessary to find the value of the constants shown in Equation 2 which describes de natural decay of the QE. The LT is given by the inverse of the exponential coefficient.

$$QE(t) \quad QE0e^{\ t\ \tau}$$

Equation 2: Expression for the QE decay.QE0 ≡ initial QE, $1/\tau$ ≡exponentials coefficient, t ≡time (min).

The bandgap model for semiconductors predicts a decrease in QE when cooling the cathode. It is necessary to fabricate a photocathode with good QE at low temperatures in order to have a photocathode to be compatible with SRF photogun. The main challenge is to maintain optimal vacuum conditions to avoid water contamination on the photocathode's surface in order to preserve QE and LT at cryogenic temperatures.

MATERIALS AND METHODS

A bialkali-antimonide photocathode was fabricated over a niobium (Nb) substrate, finely polished, using a recipe by M.A. Mamun[4,5], et al. The co-deposition of alkalis and antimonide over the Nb substrate was made inside a deposition vacuum chamber under UHV conditions equipped with the following components (Figure 1): substrate stalk - designed to hold the substrate inside the deposition chamber during the photocathode fabrication and evaluation; it consists of a manual movable stalk to control deposition distance, a computer controlled heater, a cavity for the storage of cryogenic materials and a holding surface for substrates - , antimonide source – designed for Sb deposition, consist of a mobile crucible heated through current power supply - , alkali source - manufactured for alkali co-deposition; it is composed by a computer controlled heater, effusion valve and nozzle, movable stalk and a cooper J-tube for alkali ampules storage - , Residual Gas Analyzer (RGA) – to monitor the partial pressure on compound of interest, such as water, potassium and cesium, during the deposition and measurement procedures - , Non-Evaporable Getter (NEG) - used to maintain water partial pressure below 10^{-11} Torr - , main viewport – to monitor the substrate appearance and illuminate the photocathodes surface with laser light - , optical mirrors arrangement - to guide the laser light towards the photocathodes surface - , bias system and anode ring (Figure 2), electrometer – to monitor the photocurrent induced by the laser light between the cathode and the anode ring - , optical power meter – to monitor the power of the laser light before passing though the viewport - , 532 nm green laser light – to illuminate the photocathode's surface, induce photocurrent and be able to calculate the QE and LT of it - , protection shutter – to block the laser light's path and protect the photocathode's surface -.

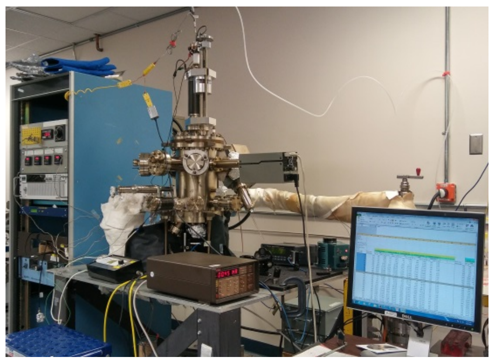


Figure 1: Experimental setup.

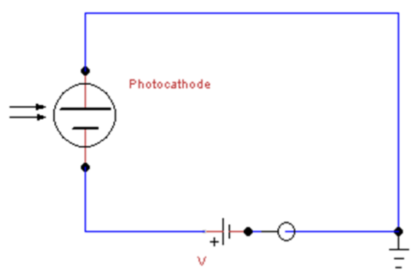


Figure 2: Bias system used, anode biased at ~1360 V.

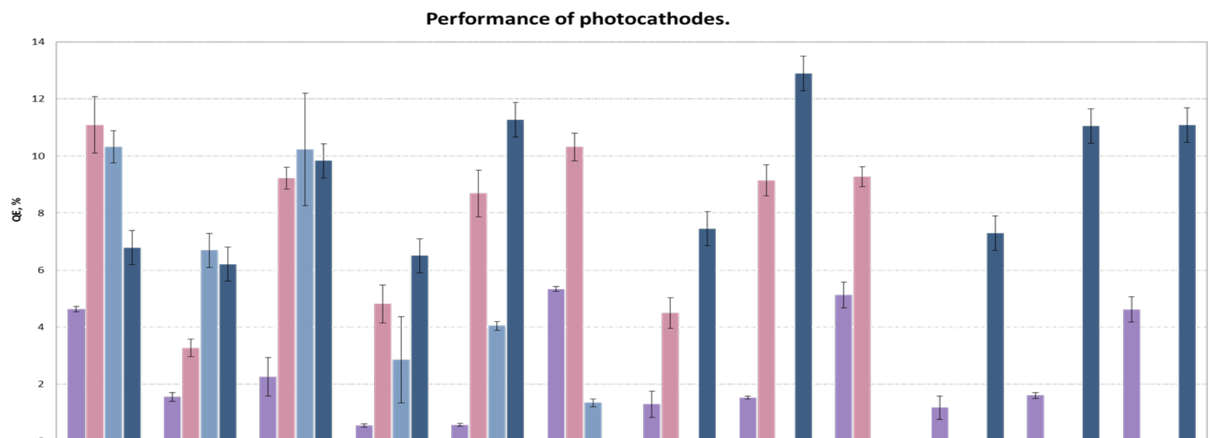
For the photocathodes growth and activation, the Nb substrate was heated at 400 °C for 4 hours in order to improve the vacuum conditions and the protection shutter was positioned to shield it from the 532 nm light source. With pressure $\sim 10^{-9}$ Torr inside the chamber, the substrate was cooled to 200 °C for Sb deposition. The current power supply feeding the Sb source was turned on and set to 32.7 A. The RGA spectrum was monitored at 122.6 amu and the power supply tuned until the Sb peak reached a partial pressure of $4.5(\pm 0.5)e^{-10}$ Torr. Then, the protection shutter was removed; the Sb's crucible set below the Nb substrate and the working distance adjusted depending on the vacuum condition (5 cm for non-baked system and 2.5 cm for the baked system). The time of deposition also depended on the vacuum, 25 min if working on non-baked system and 10 min if baked. After the deposition, the current power supply was turned off, the crucible was retracted and the protection shutter was placed. The substrate was cooled for alkali co-deposition; the alkali source was turned on and the RGA spectrum was monitored at 39 amu for K and at 132.7 amu for Cs maintaining the K peak partial pressure between 1.2-2.2(±0.02)e^{-10} Torr and the CS peak between 1.5-9.7(±0.05)e^{-10} Torr. The anode was biased at ~1360 V. The protection shutter was removed to illuminate the substrate's surface, the effusion nozzle set below the Nb substrate and the working distance adjusted depending on the working vacuum system. The photocurrent was monitored during the whole alkali co-deposition process. The co-deposition ended once the maximum amount of photocurrent was reached, the alkali source heater was turned off and the nozzle retracted. Once the alkali peaks disappeared from the RGA trace, the 532 nm light source illuminated the surface of the photocathode overnight in order to record the QE decay and to measure its lifetime.

RESULTS

The QE of the photocathodes made was measured in two different vacuum conditions: non-baked and baked system. To achieve this, two photocathodes were made having H_2O partial pressure ~10^{-11}. The QE and LT of both photocathodes was measured at two different temperatures, RT and 77 K, following the next sequence: RT →77 K → RT → 77K → RT → RT after a brief heating (at 440-470 K) → 77 K → RT → RT post brief heating→ […].

Once the measurements were done, we baked the chamber at 455.15 K for 30 hours in order to improve vacuum and decrease the partial pressure of H_2O (~10^{-12}). The same procedure of measure was followed in order to be able of compare the performance of QE between the two systems.

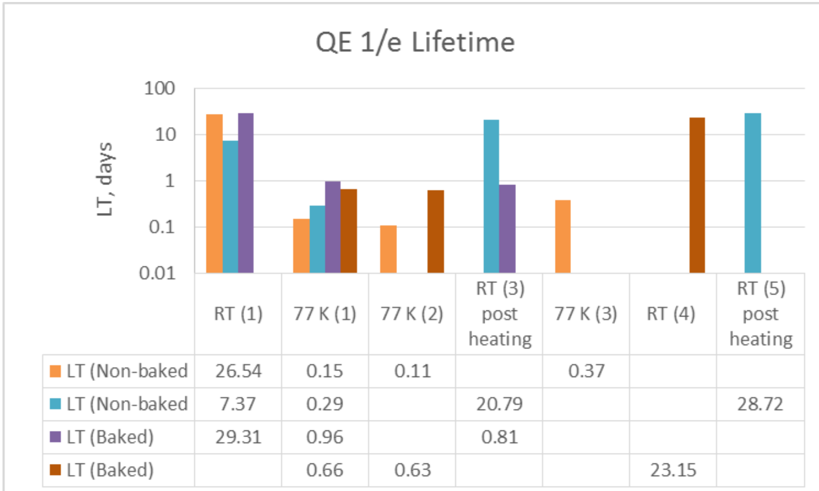
In Figure 3, the obtained QEs of the photocathodes made during this research at the different conditions mentioned are presented.



	RT (1)	77 K (1)	RT (2) post 77 K (1)	77 K (2)	RT (3) post 77 K (2)	RT (4) post heating	77 K (3)	RT (5) post 77 K (3)	RT (6) post heating	77 K (4)	RT (7)	RT (8) post heating
QE (non-baked)	4.63	1.55	2.25	0.55	0.56	5.33	1.29	1.52	5.12	1.17	1.60	4.61
QE (non-baked)	11.09	3.26	9.22	4.81	8.69	10.32	4.49	9.14	9.27			
QE (Baked)	10.31	6.69	10.22	2.84	4.04	1.34						
QE (Baked)	6.78	6.20	9.83	6.50	11.27		7.45	12.89		7.29	11.05	11.08

Figure 3: Photocathodes QE performance at different temperatures in two different vacuum systems.

The laser light illuminated the surface overnight and by using a LabView program, the natural decay of photocurrent was recorded. An exponential fitting was made to the date to have the equation that describes the behavior and be able to calculate QE's LT. In Figure 4, the LT measured for the photocathodes is summarized.



	RT (1)	77 K (1)	77 K (2)	RT (3) post heating	77 K (3)	RT (4)	RT (5) post heating
LT (Non-baked	26.54	0.15	0.11		0.37		
LT (Non-baked	7.37	0.29		20.79			28.72
LT (Baked)	29.31	0.96		0.81			
LT (Baked)		0.66	0.63			23.15	

Figure 4: Lifetime of photocathodes at different temperatures in two vacuum conditions.

In order to get a deeper evaluation of the performance of QE at different temperatures, a spectral response analysis was made. It consisted of replaced the 532 nm laser light for a monochromatic light source and measure the photocurrent at RT and 77 K changing the light's wavelength (Figure 5).

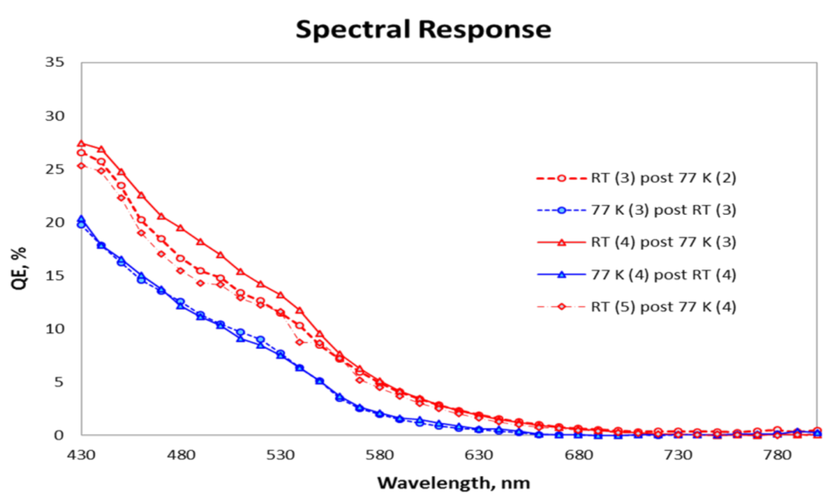


Figure 5: Spectral Responce of QE at different temperatures.

After obtaining the behavior of QE under these conditions, an attempt to overlay the curves shown in Figure 5 was made. In figure 6, it's shown that 35.6 nm wavelength shift fixed the gap between the RT and 77 K spectral response curves.

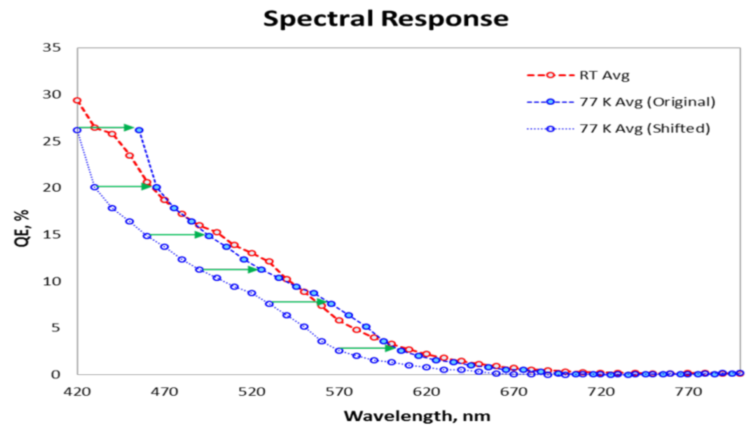


Figure 6: Wavelength shift equivalent to 35.6 nm when cooling the photocathode to 77K.

CONCLUSIONS

Niobium is a viable substrate for the production of bialkali-antimonide photocathodes, which exhibit high QE and long lifetime. We made the following observations for the Non-baked system: the highest QE was measured as 11.1% at RT and 4.8% at 77 K, the highest QE lifetime was measured as 26.5 and 0.4 days at RT and 77 K, respectively, QE drops by 74±9 % each time when cryo-cooled, QE can be fully recovered only by desorbing water via brief heating at 440-470 K, Lifetime improves when QE is recovered by heating. For the baked system we observed that: the highest QE was measured as 12.9% and 7.5% at RT and 77 K, he highest QE lifetime was measured as 29.3 days at RT and 1.0 days at 77 K, QE at 77 K was stable and did not decrease over the repeated cooling cycles, the initial QE at RT was observed to be fully recovered by itself when photocathode temperature returned from 77 K to RT. The QE lifetime was observed to improve from cooling the cathode and leaving it to reach RT by itself.

In summary, an improvement in vacuum by a simple bake helps to preserve the QE and enhance the QE lifetime of the cryo-cooled photocathodes by minimizing the extent of water contamination. The spectral response results indicate that a decrease in QE from cryo-cooling is likely a temperature dependent bandgap shift phenomenon of the photocathode material.

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