

Activation Studies of Negative Electron Affinity Gallium Arsenide Photocathodes

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Abstract

The Energy Recovery Linac (ERL) project at Cornell University and other future accelerator projects require high brightness electrons beams created by photocathodes that maintain a high quantum efficiency over a long operational lifetime. Gallium Arsenide (GaAs) photocathodes promise high quantum efficiency and high brightness electron beams and are currently under R&D to improve their operational lifetime. This paper presents the preparation and activation processes used at Cornell University to create negative electron affinity GaAs photocathodes for research. In addition, evidence is presented to prove that pure Nitrogen will not activate GaAs photocathodes to negative electron affinity.

1 Introduction and Background

III-V Semiconductors, such as Gallium Arsenide (GaAs) activated to negative electron affinity (NEA) are effective electron emitters used in modern energy recovery linac (ERL) projects such as the Accelerators and Lasers in Combined Experiments (ALICE) at Daresbury Laboratory, the proposed International Linear Collider (ILC) and the ERL project at Cornell University [1]. NEA photocathodes are not traditional electron emitters, such as thermionic emitters and field emitters, thus are currently under R&D to further understand their electron emission process and improve their quality. Thermionic emission occurs when a conduction material is heated such that the electrons in the material are given sufficient energy to overcome the work function barrier of the conductor and escape the material, whereas field emission, also known as Fowler-Nordheim tunneling, occurs when a sufficiently strong electric field applied to the material causes the electrons to tunnel through the surface barrier potential and escape the surface [2]. Two important qualities of electron emitters are their transverse energy spread, which determines the brightness of the electron beam, and their response time, directly affecting how well the electron emission of the

material can be modulated. ERL projects require high brightness electron beams that are easily modulated, whereas in general, thermionic emitters have high energy spreads and thus low brightness, and field emitters have high brightness but are difficult to modulate. Since traditional electron emitters do not fit the current needs of accelerators it is necessary to research different electron emitting materials.

Metallic and semiconductor photocathodes have both displayed high brightness as well as good response times, making them candidates for ERL R&D projects. Metallic photocathodes, such as Cu, Pb, and Mg have prompt response times and are robust under poor vacuum conditions. However, while they are easy to operate and have longer lifetimes in comparison to semiconductor photocathodes, their poor Quantum Efficiency (QE) of around 0.1% and requirement of UV lasers for photo-stimulation are not desirable in accelerator applications. While semiconductor photocathodes are more difficult to operate than metallic photocathodes their advantages lie in higher QE's of upwards of 20% and requiring lasers in the visible range for photoemission [3]. Two types of semiconductor photocathodes currently under R&D are positive electron affinity (PEA) photocathodes, such as K_2CsSb and Cs_3Sb , and negative electron affinity (NEA) photocathodes, such as GaAs which is studied in this paper.

After Einstein published his quantum theory of photoemission in 1905, researchers tended to believe that photoemission was a surface rather than bulk phenomenon, until W.G. Spicer published his approximate three step model in 1958, comprehensively describing photoemission as a bulk process [4]. Spicer described the photoemission process as the following, electrons bound in the bulk of the material are optically excited, after which the excited electrons diffuse towards the surface of the material, scattering with lattice phonons and other electrons along the way, where the electrons with sufficient energy escape from the surface of the material into the vacuum [2]. This process is depicted in Figure 1. The photoemission process can be described in further detail using the energy band diagram of a GaAs semiconductor in Figure 2. Before the electrons are optically excited their energy lies below that of the valence band, E_{vb} . However, if the incident laser light gives the electrons sufficient energy, that is energy equal to or greater than the band gap, E_{gap} , the electrons can enter the conduction band, which is the energy state between the conduction band minimum, E_{cbm} , and the surface of the material, located at E_{vac} , the energy level where the vacuum is located. In order for the electrons to escape from the surface they must overcome the work function barrier, ϕ , defined as the difference between the Fermi level, E_F , and E_{vac} , $|E_{vac} - E_F|$. The work function of an unactivated GaAs photocathode is large, however, the activation layer of Cs and a strong oxidizing agent creates a strong dipole field on the surface of the material which causes band bending, V_{bb} , effectively reducing the work function by lowering the energy level of the vacuum while E_F remains unchanged. The band bending also reduces the electron affinity, χ of the semiconductor, defined as $|E_{vac} - E_{cbm}|$, resulting in an effective negative electron affinity, χ_{eff} , which favors optically excited electrons escaping the crystal into the vacuum instead of remaining in the conduction band [5].

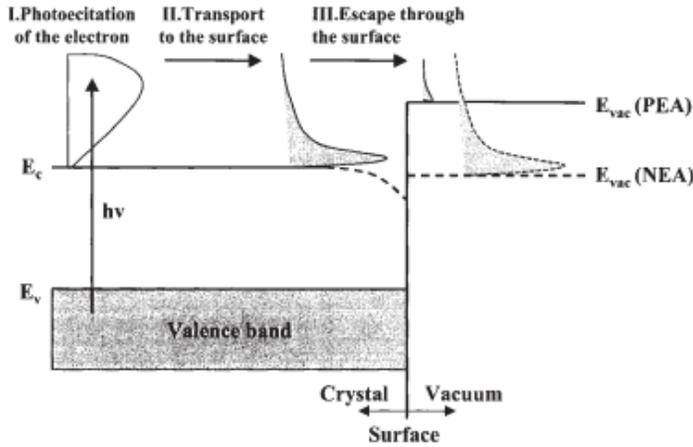


Figure 1: This drawing displays Spicer's Approximate Three Step Model of Photoemission. First, electrons are optically excited, second the excited electrons diffuse towards the surface of the material where third, the electrons with sufficient energy escape from the surface into the vacuum. The energy level of the vacuum, E_{vac} , is higher for PEA photocathodes than for NEA photocathodes [2].

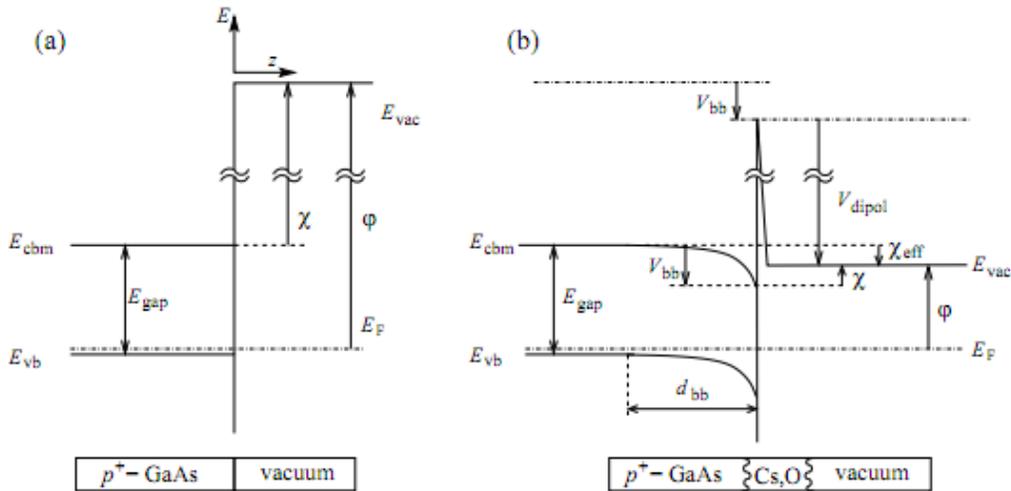


Figure 2: This diagram shows the energy band structure of a p-doped GaAs semiconductor before activation (a) and after activation with Cesium and a strong oxidizing agent (b) [5].

While a cathode’s quality depends on its transverse energy spread and response time, as mentioned earlier, it is also determined by its quantum efficiency as well as its lifetime. The quantum efficiency, QE, sometimes referred to as quantum yield, QY, of a cathode measures how efficiently the cathode emits electrons. QE is defined as the ratio of emitted electrons, N_{el} , to the number of photons, N_{hw} , incident upon the cathode. The number of emitted electrons is determined by the current of the electrons leaving the surface, also called photocurrent, I_p , while the number of emitted photons is determined by the laser power incident upon the cathode, P_l , and the wavelength of the laser light, λ . QE is quantitatively defined as,

$$QE = \left| \frac{hcI_p}{P_l\lambda e} \right| * 100\% = \left| \frac{N_{el}}{N_{hw}} \right| * 100\%[1]$$

where h is Plank’s constant, c is the speed of light, and e is the value of the elementary charge. The span of time over which a photocathode produces a satisfactory QE is called its lifetime and is customarily measured using two different methods. The operational lifetime of the cathode is measured under high current production, or constant illumination by laser light, whereas its dark lifetime is measured under lower laser power by intermittently providing illumination over a longer period of time. Both lifetimes of the cathode are quantitatively measured by the time it takes the QE to reduce to 1/e of its original value. It is assumed that the QE decays exponentially, however, the lifetime curves of a cathode are better fit using multiple exponential curves, as the decay process is most rapid immediately after activation but slows with time.

The first purpose of this paper is to detail the experimental set up and procedures of studying the activation process and lifetime of semiconductor photocathodes. Second, activation of GaAs photocathodes using Nitrogen as the oxidizing agent is studied, concluding that Nitrogen does not activate GaAs photocathodes since the rate of activation was dependent upon the level of Oxygen impurity in the Nitrogen.

2 Experimental Set-Up

2.1 The QE Chamber

Activated GaAs photocathodes are extremely sensitive to contamination thus their preparation, handling and activation must be performed under ultra-high vacuum (UHV) of at least 10^{-10} Torr, although vacuum levels of 10^{-11} Torr result in better quality photocathodes. Figure 3 shows a schematic of the vacuum chamber used in the studies presented in this paper. The chamber is made of stainless steel and uses conflat knife edges in combination with copper gaskets to create a tight seal between the chamber and all attached parts. When accessories are removed from or added to the chamber those performing the swap wear gloves to protect the inside of the chamber from oils on their hands. It is important to have an oil free environment inside the chamber as any contamination deters the goal

of UHV and oils cannot be removed from the chamber unless it is baked to very high temperatures.

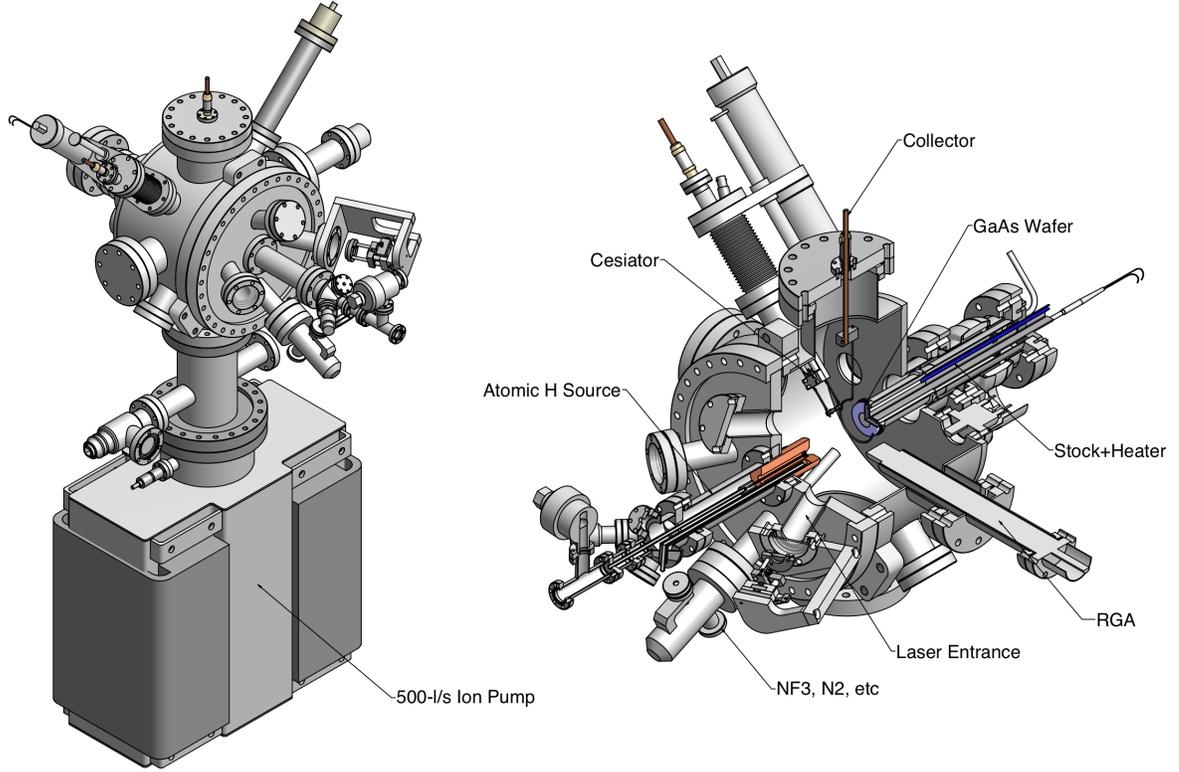


Figure 3: The above drawing depicts the QE chamber where all experiments described in this paper were performed. The ion getter pump at the base operates at pressures of 10^{-6} Torr or better and preserves the vacuum throughout the experiments. The collector ring can be used to collect electrons emitted from the activated cathode, however, the stock is electrically isolated from the rest of the chamber so the photocurrent was measured with direct connection to the exterior of the stock. The cesiator is retractable by the knob adjacent to the bellows at the top of the chamber and is further depicted in Figure 4a. A laser is affixed to the viewport of the chamber while the exit laser power is measured by a detector affixed to the viewport to the left of the atomic H Source, which was not used in the experiments presented in this paper. The leak valve at the bottom of the chamber where the NF_3 and N_2 used in the activation process are stored is attached to the gas manifold.

Once the chamber is completely assembled a turbo pump is used to bring the chamber

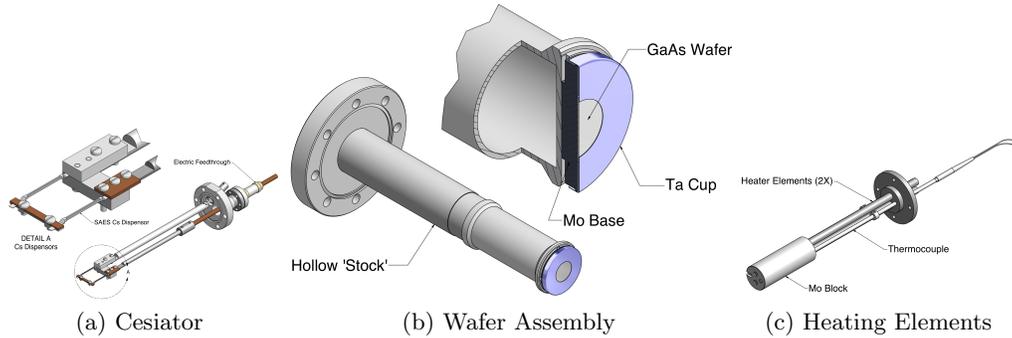


Figure 4: Parts of the QE Chamber: a.)The cesiator is used to deposit Cesium on the cathode during the activation process and it is retractable so as to be moved away from the cathode upon completion of the activation process. Cesium is dispensed when a current of at least $I = 4.0\text{A}$ is applied to the electronic feedthrough. b.) The wafer assembly consists of a hollow stock which contains the heating elements used to heat clean the cathode and perform Thermal Desorption Spectroscopy experiments. At the end of the stock is the Molybdenum base which is covered by a protective Tantalum cup. The GaAs wafer is then attached to the Molybdenum base using Indium soldering. c.) The heating elements are connected to the Molybdenum base which they heat in order to heat the cathode. The temperature of the base is then read by the thermocouple. The heater is plugged into an external temperature controller which powers the heater and runs the heating program.

pressure to 10^{-6} Torr, after which point the ion getter pump attached to the base of the chamber brings the total chamber pressure down to the 10^{-9} Torr or 10^{-10} Torr range. The vacuum is not sufficient for activation studies at this pressure, thus the chamber is baked out. It is necessary to bake out the chamber after it has been exposed to air since air contains water vapor which the ion pump cannot remove from the chamber. However, water vapor desorbs from the chamber walls at $120\text{ }^\circ\text{C}$, thus the chamber is baked to $150\text{ }^\circ\text{C}$ to remove the water vapor. The bake out is set up by first covering the chamber in a layer of aluminum foil which protects the outside of the chamber from staining, then the exterior of the chamber is covered with heat tapes. These tapes are then plugged into heaters run by omega temperature controllers. Thermocouples are then affixed to the chamber's surface near their corresponding heat tapes thus the temperature controllers are able to track the temperature they are providing to the heat tape. Once all of the heat tapes and thermocouples have been attached to the chamber two layers of aluminum foil are added over the heat tapes to evenly disperse the heat over the chamber. Finally, once the bake is completely assembled, each omega temperature controllers is programmed in the ramp/soak (r-s) mode. A typical ramp/soak program used to achieve UHV for these experiments raised the temperature of the chamber to $150\text{ }^\circ\text{C}$ over 6 hours, held the

chamber at that temperature for between 32 and 48 hours, then slowly cooled the chamber back down to room temperature over 6 more hours. After the bake out process is finished the pressure in the chamber was typically around 1.5×10^{-10} Torr or 2.0×10^{-10} Torr.

After the chamber has been baked out the vacuum in the chamber is nearly ready to begin activation studies on photocathodes, but first it must be conditioned to any devices that will outgas when in use, which includes the cesiator and the RGA. The RGA is simple to outgas, as it involves turning the device and filament on and letting them outgas until the vacuum has recovered its initial pressure. Initially the total pressure in the chamber will increase as the filament releases various ions and gases, but the ion pump will remove them. The cesiator takes a few more steps to outgas than the RGA as it could raise the pressure in the chamber too high too quickly and ruin the vacuum. First the cesiator should be outgassed while it is retracted so as to not deposit Cs on the cathode before it is activated. Initially the current through the cesiator was turned up to $I = 2.5$ A, which raised the pressure in the chamber to 10^{-6} Torr, the limit of the ion pump. When the pressure in the chamber dropped down to the low 10^{-8} or high 10^{-9} range, the current through the cesiator was increased 0.5 Amperes until $I = 5.0$ A, the maximum amount of current that would be used for the activation studies, was reached. The outgassing process ensured that when these devices were used later in experiments they would not raise the pressure in the chamber and ruin the vacuum.

2.2 Reading and Interpreting Data

In addition to the QE chamber it is also necessary to prepare the computer program to read in data from, interpret the data, and communicate with the various devices used in activation studies measurements. These devices include the laser shutter controller, the laser power meter, the picometer, the omega temperature controller, the SRS RGA, and the cold cathode gauge. Various methods were used for communication between the devices and the computer including USB, RS232, and Opto22 network connections. All the devices used for the activation studies measurement run through the GrandUnifiedProgram.vi, henceforth abbreviated as GUP.

The laser shutter controller used in these experiments is made by ThorLabs and is an SC10 model, which communicates with the computer via RS232 connection. Through the labVIEW program it is possible to manually open and close the shutter, using the manual mode, accessed by the drop down menu, and pressing the *Open / Close Shutter* button in the *Laser Power & Laser Shutter Controller* tab. However, for dark lifetime measurements it is possible to program the shutter to intermittently open and close. First access auto mode from the drop down menu, then program the *Time Open* and *Time Shut* by typing in the desired time in milliseconds you would like the shutter to be opened and closed and begin the program by pressing the *Open / Close Shutter* button.

The laser power meter is a Nova II Ophir model and communicates with the computer via USB connection. The labVIEW program for the laser power meter was made by the

company itself and the controls and graphs of the data in real time are located in the *Laser Power & Laser Shutter Controller* tab. Since QE, Equation 1, is dependent not upon the exit laser power as the power meter measures, rather the entrance laser power, it is necessary to calculate the entrance laser power using the numeric control *alpha* located in the *Laser Power & Laser Shutter Controller* tab. Alpha is a constant that linearly relates the entrance laser power, $P_{l,entrance}$ and the exit laser power, $P_{l,exit}$, by $P_{l,entrance} = \alpha P_{l,exit}$.

A Keithly 6485 picoammeter was used to measure the photocurrent of the electrons emitted from the photocathode. The data from the picometer is read in via RS232 connection and can be accessed from the *PAmeter Controls & Graph* tab. To see the data graphed in real time press the *Start Photocurrent Plot* and always be sure that the button, *6485 id query* is switched on to ensure communication with the device.

During TDS experiments and heat cleaning the cathode, the omega temperature controller, model CN8202, is used to read the approximate temperature of the cathode and to write the ramp/soak program to the controller. The temperature is indicated by the thermometer, numeric indicator and the graph in the *Cathode Temperature & Chamber Pressure* tab. It is then possible to create a ramp/soak program by writing ramping up and down times in minutes, soak levels in °C, and soak time in minutes, then uploading the program with the *Upload Ramp/Soak Parameters* button and beginning the program with the *Run/Resume Recipe* button. It is also possible to simply assign the set point temperature with the numeric indicator called *Setpoint (deg C)* and the button, *Assign Setpoint*.

To read in the gas composition of the chamber an SRS Residual Gas Analyzer (RGA) is used. It can scan over any desired ranges of masses, controlled by the numeric indicators, *Initial Mass* and *Final Mass* in the *RGA Mass Spec.* tab. It is also possible to watch the partial pressures of select masses over time with the *Partial Pressures* graph located on the *TDS & Partial Pressure* tab. The desired masses can be selected using the numeric indicators located below the *Partial Pressures* graph.

Finally, the total chamber pressure is read in via a cold cathode gauge using the network connections through an Opto22. The controls to change the remote IP Address of the Opto22 as well as the real time graphed data are located on the *Cathode Temperature & Chamber Pressure* tab. The Opto22 reads in the pressure data as an analogue signal that is converted to the pressure reading by, $10^{(S_A-10)} = P_{chamber}$, where S_A is the analogue signal from the Opto22 and $P_{chamber}$ is the total chamber pressure.

3 Activation Studies

3.1 Cleaning the Cathode

The same Zn doped, p-type Gallium Arsenide wafer purchased from American Crystal Technologies was used throughout the experiments presented in this paper. Originating as a 4 inch diameter, mirror finished wafer, it was cut in house using home made cutting tools

with diamond suspension. To protect the wafer during the cutting process it is sandwiched between two glass slides with wax protecting the surface of the wafer, the wax bought from Southbay Technology, Inc. Then to extract the freshly cut wafer the wax is melted away on a hot plate, then the wafer goes through a solvent cleaning process of two boiling acetone baths for ten minutes each, followed by an acetone ultrasonic procedure for ten minutes and finally a ten minute bath in boiling trichloroethylene. Although it is not true of all GaAs photocathodes studied at Cornell, the wafer used in these experiments was acid etched in a $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2$ (20:1:1) solution for 15 seconds at 40°C . Previous experiments at Cornell University have not shown a difference in QE and dark lifetime of cathodes that have or have not been acid etched, however, many other research groups have found a more intensive acid etching process involving a second etch in an HCl solution further removes oxide contaminants on the surface of the cathode as well as creates a protective elemental Arsenic layer on the surface of the cathode that anneals at relatively low temperatures, leaving the surface smooth rather than rough. It is also worth while to mention that these same groups also perform all their cleaning processes inside of either Argon [2] or Nitrogen [6] purged glove boxes attached to their QE chambers. As the cathodes at Cornell are exposed to air after they are acid etched this leaves them vulnerable to further oxide contamination before the thermal annealing process.

Due to oxide contaminants on the surface of the cathode, such as Gallium Oxides and Arsenic Oxides, it is necessary to heat clean the cathode to a high enough temperature such that the oxide contaminants desorb and leave an atomically clean cathode surface. Due to the cathode's exposure to air at Cornell, it is necessary to heat the cathode to 650°C for two hours in order to achieve an atomically clean surface. Though, other research groups achieve atomically clean surfaces by heating their cathodes to either 400°C or 550°C for shorter amounts of time [2, 6].

3.2 Activation Process

The GaAs wafer must be activated in order to achieve negative electron affinity, which at Cornell is done using the yo-yo method. First the chamber is set up by unplugging the heater and thermocouple so as to electrically isolate the cathode holder and the picometer wire is affixed to the outside of the puck holder. In addition, the RGA is never turned on during the activation process so as to avoid accidental activation due to outgassed molecules from the filament of the RGA. Further the cesiator is positioned such that it will deposit cesium on the surface of the cathode and the laser is turned on and shone upon the center of the cathode. The yo-yo method begins by initially depositing Cesium on the surface of the cathode, which increases the photocurrent and thus the QE of the cathode to a peak when there is approximately a monolayer of Cesium on the surface of the cathode. Once the monolayer of Cesium is surpassed the surface of the cathode is overdosed with Cesium, consequently reducing the photocurrent. Once the photocurrent reaches one half of the original peak due to Cesium, the Cesium is turned off and the cathode is exposed to the

oxidizing gas via the leak valve connected to the oxidizing channel on the QE chamber. The photocurrent recovers once the overdosing of Cesium is finished and continues to climb due to exposure to the oxidizing gas. However, eventually this gain also peaks, at which point the leak valve is closed and the cesiator is once again turned on. This causes another overdose of Cesium on the surface of the cathode from which the photocurrent sharply declines, but once the photocurrent has reached half of the previous peak, once again the Cesium is turned off and the leak valve of the oxidizing agent is opened. The peak in photocurrent rises with each exposure to the oxidizing gas yet this gain in QE plateaus after a number of alternating depositions of Cesium and the oxidizing gas, called yo-yo's. Once the QE of the cathode has plateaued by as few as 7-10 yo-yo's or as many as 12-17 yo-yo's [7] the activation process is complete and the leak valve is closed and the cesiator is retracted. A typical yo-yo activation is displayed in Figure 5.

While the yo-yo method has proved to achieve the highest QE in activation experiments at Cornell University, another method of activation called co-deposition has resulted in higher quality photocathodes for some research groups [2]. The co-deposition method also begins by depositing Cesium on the surface of the cathode until it reaches a peak photocurrent emission. However the co-depositon method differs from the yo-yo method in that once the peak photocurrent drops between 20% and 30% instead of turing off the cesiator, cesiation continues at the same time as deposition of the oxidizing agent until the QE once again peaks and the leak valve of the oxidizing gas is closed and the cesiator is shut off and retracted. A typical co-deposition curve is shown below in Figure 6.

3.3 Activation with N_2

In researching which agents activate and which agents harm photocathodes, there is much debate over the role Nitrogen plays. Some research projects have shown that Nitrogen will not activate photocathodes [2] whereas some research projects, including previous work at Cornell University [7], found Nitrogen to activate GaAs photocathodes. In search of a more definitive answer to this debate I performed a yo-yo method activation using ultra high purity Nitrogen. I pumped down the gas manifold with a turbo pump and then filled the gas manifold with Nitrogen. The activation proceeded at a rate significantly slower then a typical yo-yo method activation using NF_3 or O_2 , nevertheless the photocathode was activated to a QE of 3.8% during the first trial and 4% in the second trial. The activation curves of these two trials are presented in Figure 7a, displaying the same activation process for both trials.

Knowing that the rate of activation is dependent upon the amount of oxidizing agent the cathode is exposed to, the slow rate of activation observed during the Nitrogen activation prompted the question - was the activation due to a contaminant in the gas? To find if the activation was in fact due to a contaminant in the N_2 gas we completely pumped out the gas manifold by attaching a turbo pump to the manifold and purifying the N_2 , taking care to avoid contamination due to exposure to air. RGA scans of the N_2 gas leaked into

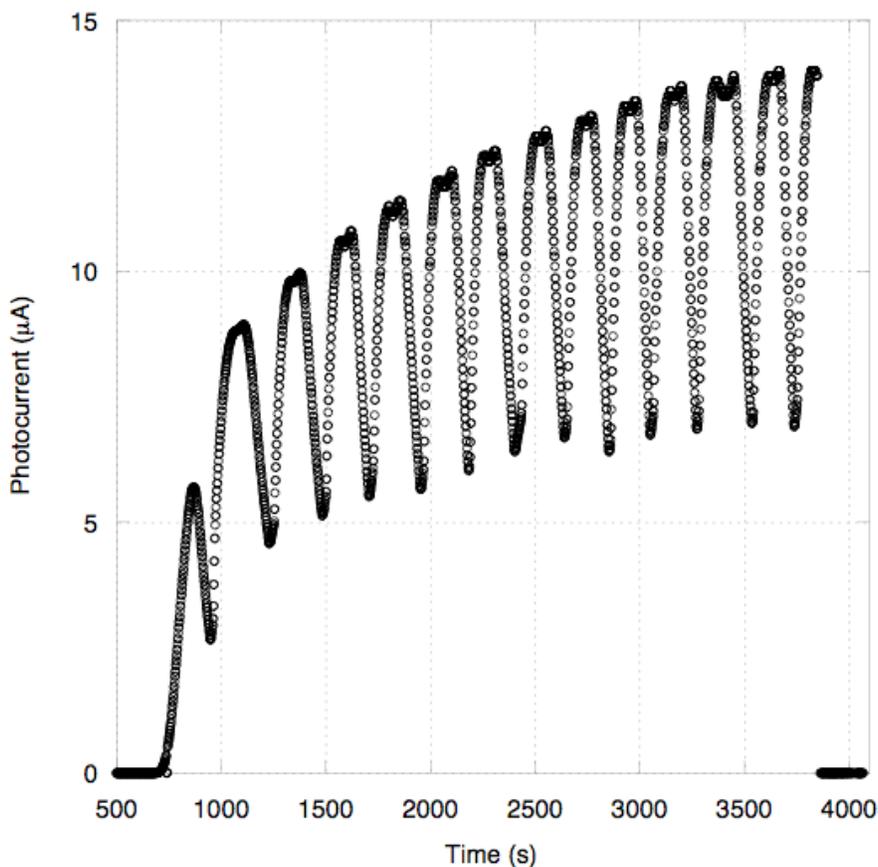


Figure 5: This graph displays the typical format of a cathode activated using the Yo-Yo method. Specifically this curve is the activation performed on 7/28/11 using NF_3 as the activating gas. Time = 800s indicates the initial peak in photocurrent due to Cesium deposition and time = 1100s indicates the initial opening of the leak valve to deposit the NF_3 on the surface of the cathode.

the chamber before and after the purification process showed a significant reduction of O_2 contamination, as the average partial pressure of mass 32 in the gas before the purification was 6.64×10^{-11} Torr while after the purification, the average partial pressure reduced to 6.88×10^{-12} Torr, a reduction of nearly an order of magnitude. Then to deduce if the previously believed N_2 activations were due to O_2 contamination instead of N_2 , the yo-yo activation was repeated with the purified N_2 gas. The initial cesium peak, unaffected by the activating gas, proceeded similarly to the previous two activation trials, however, the rate of activation once the purified N_2 gas was exposed to the cathode was reduced significantly as in the same time it took to finish the entire activation process in the first two trials I

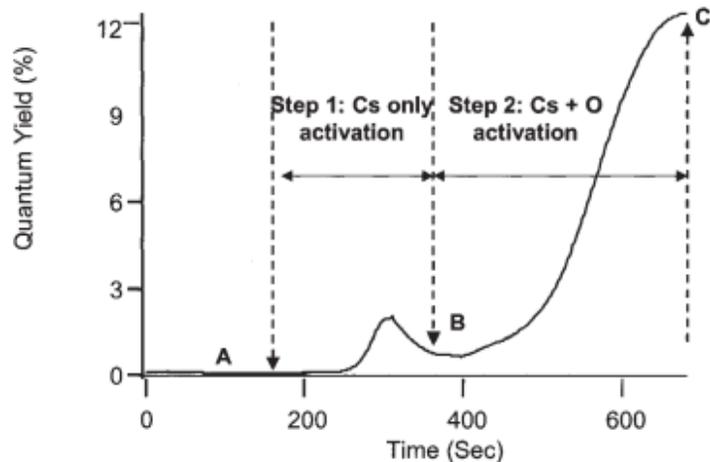
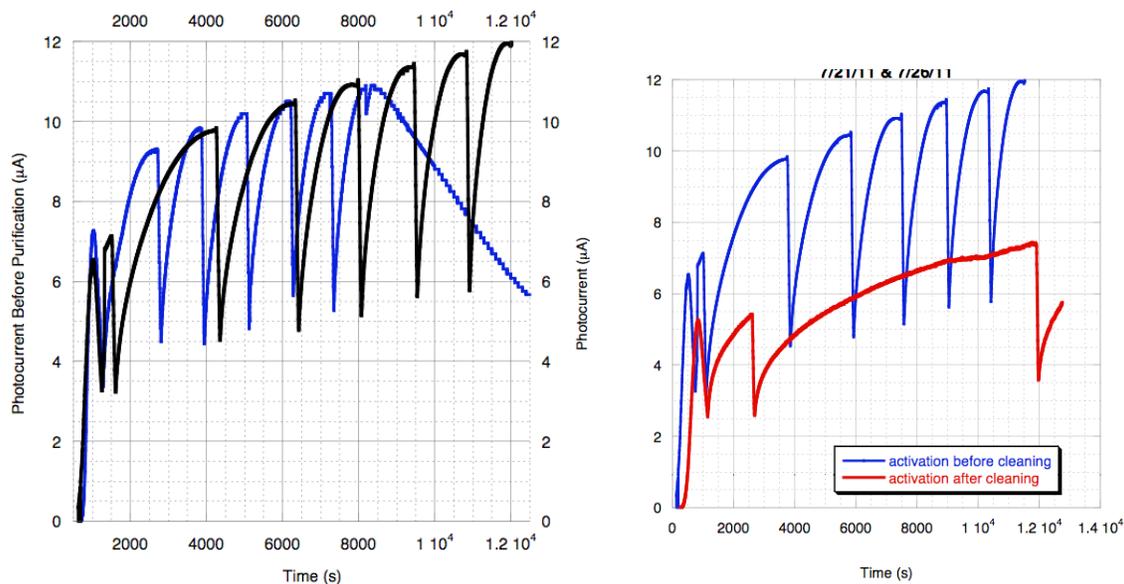


Figure 6: A typical activation curve using the co-deposition method. Between points A and B only Cesium was deposited on the cathode, followed by the co-deposition of Cesium and Oxygen between points B and C, where at point C deposition of both Cesium and Oxygen are ceased and the activation is complete [2]

performed only two yo-yo's achieving half of the maximum QE as in the activation before the N_2 purification as shown in Figure 7b. The differing activation rates are more clearly displayed in Figure 8, where the time axis of the activation curve after the purification of the activating gas is scaled to reflect the amount of O_2 contamination in the gas. I found the scaling factor by calculating the ratio, α , of the O_2 contamination before and after the purification, as reported above, obtaining a scaling factor of $\alpha = 0.103$. While I scaled the time axis, I did not scale the initial cesium peak as it was unaffected by the O_2 contamination.

As the scaled time axes in Figure 8 shows, the activation of the photocathode was completely dependent upon the amount of O_2 contamination since the activation rate is the same when the activation with the purified N_2 is scaled to have the same amount of O_2 contamination as the first activations. Since the first two activations were not due to the N_2 gas we found that N_2 does not activate GaAs photocathodes, suggesting that exposure to N_2 will not harm the QE of GaAs photocathodes and it would be possible to transport activated GaAs photocathodes in a pure Nitrogen environment. The activation due to contamination also indicates how sensitive GaAs photocathodes are to contamination since a reduction of one activating contaminant since a small reduction of an oxidizing contamination reduced the activation rate considerably.



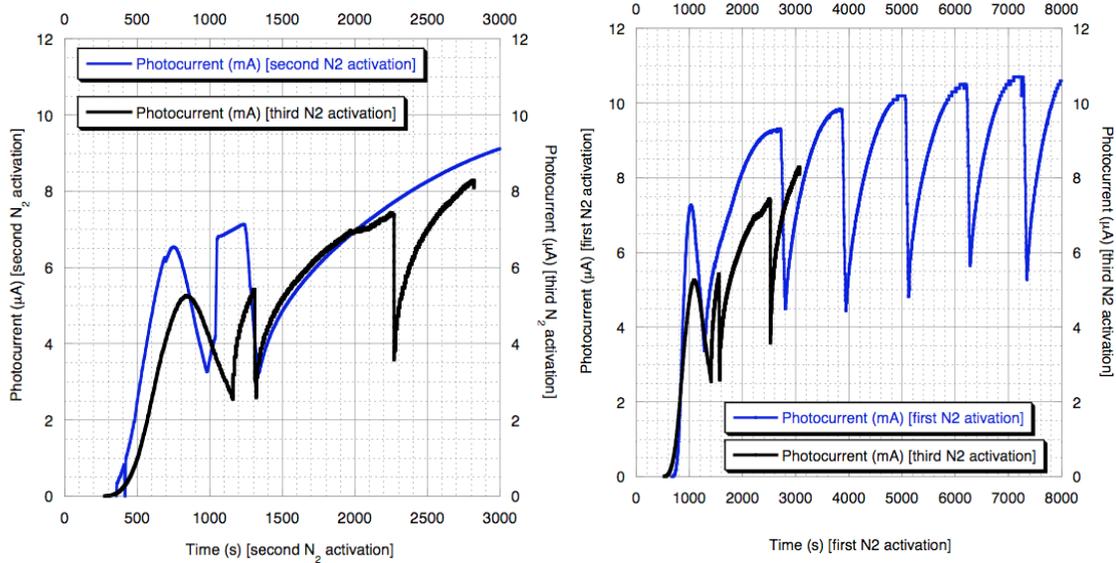
(a) Experiments performed 7/8/11 and 7/21/11. (b) Experiments performed 7/21/11 (before purification) and 7/25/11 (after purification).

Figure 7: Activations with Nitrogen. a.) This graph compares the first two activations with Nitrogen. Even though the yo-yo’s do not perfectly match their similar activation rates show that the results of the two activations are consistent. b.) This graph compares the second activation performed with Nitrogen, which was performed before the cleaning of the gas manifold, and the third activation with Nitrogen, which was performed after the purification of the Nitrogen. Set to the same time scale it is evident that the activation rate after the purification of the activating gas is much slower than the activation using the contaminated Nitrogen.

3.4 Activation with NF_3

Following the conclusion that N_2 does not activate GaAs photocathodes, activation using NF_3 as the oxidizing agent was investigated. The activation curve using the yo-yo method by alternating deposition of Cs and NF_3 is shown in Figure 5. A similar QE was achieved as with the contaminated N_2 gas, however the activation was much quicker, averaging 250 seconds for each yo-yo as opposed to 1500 seconds for each yo-yo with the N_2 gas before purification.

Activation of GaAs photocathodes using NF_3 could not be further compared to activations with O_2 by using pure O_2 as the oxidizing agent due to the unexpected death of and inability to recover the QE of the cathode. The leak valve was opened too far resulting in a rapid increase of chamber pressure that killed the QE of the cathode and prevented the recovery of the cathode. While the cathode could not be activated to a photoemitting



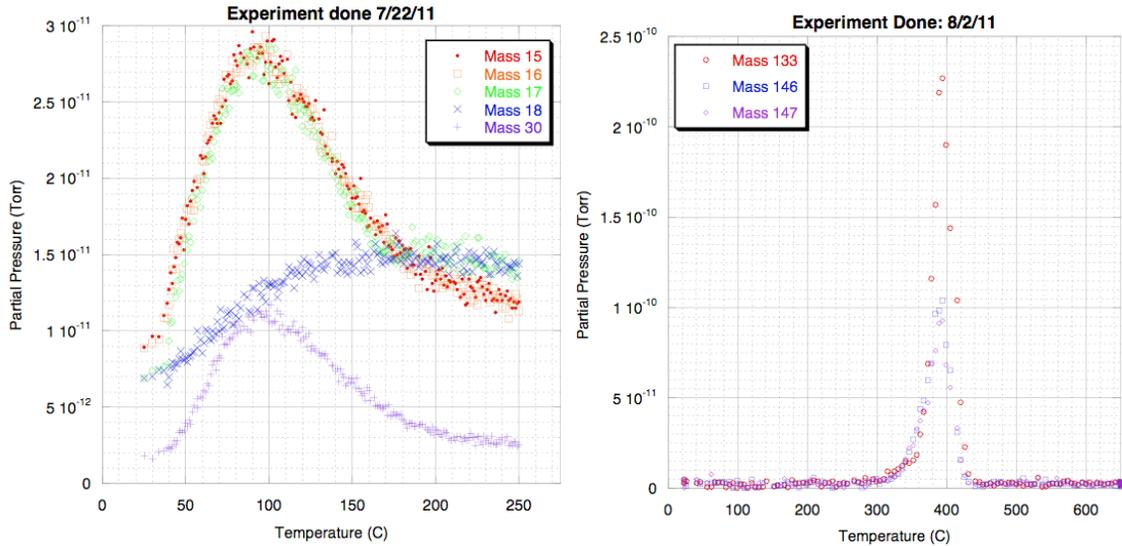
(a) Experiments performed 7/21/11 and 7/25/11. (b) Experiments performed 7/8/11 and 7/21/11.

Figure 8: Comparison of activation with Nitrogen before and after purification. The time axis of the activation after purification is scaled after the initial Cesium deposition to have the same amount of Oxygen contamination as the activations before the purification of the Nitrogen. Even though the curves do not match perfectly it is easy to see that the scaling factor gave the activation after the purification the same activation rate as the activations before the purification, displaying that the activation was due to the Oxygen contamination in the gas and not the Nitrogen itself.

state a blank activation was performed on the cathode so as to study the surface chemistry of the activation layer. The blank activation was conducted by alternating deposition of Cesium and NF_3 following the yo-yo method, however, the points at which to switch the depositions were guessed as there was no measurable photocurrent to track peaks or troughs in photocurrent.

3.5 Thermal Desorption Spectroscopy

Following the activation of each cathode and preceding the next activation a Thermal Desorption Spectroscopy (TDS), also known as Temperature Programed Desorption (TPD), experiment was performed. The TDS experiment involves heating the cathode at a relatively quick rate, $5.25\text{ }^\circ\text{C}/\text{min}$ was used for the following experiments, in order to desorb adsorbed molecules on the surface of the cathode, at the same time cleaning the cathode of any contaminants that could impair the QE of the cathode. By recording RGA scan



(a) TDS curve of notable masses desorbed from the cathode activated with Nitrogen on 7/21/11, TDS ex-table masses from the cathode activated with NF_3 on 7/22/11. (b) TDS curve of Cesium desorption and other non-cathode activated with Nitrogen on 7/28/11, experiment done 8/2/11.

Figure 9: Sample thermal desorption spectroscopy plots.

data over the duration of the experiment it is possible to track the partial pressures of specific masses as a function of temperature, as shown in Figure 9. The temperature at which a mass desorbs and the rate of desorption gives insight to the surface chemistry of the molecule represented by each mass peak, such as the low desorption temperature and slow rate of desorption of mass 18 in Figure 9a suggests that there is not a strong interaction between it and the cathode, whereas the high temperature of desorption and rapid rate of desorption for mass 133, which is the Cesium peak, in Figure 9b, suggests a strong bond between the GaAs surface and the deposited Cesium. It would be desirable to find the binding energy of Cesium on the surface of the cathode, however, too few trials were conducted to find a consistent temperature of desorption for Cesium. On the properly activated cathode Cesium desorption peaked at 394°C whereas on the blankly activated cathode Cesium was found to desorb at 354°C . The discrepancy between the two desorption temperatures is most likely due to inconsistencies in the activation processes. Even though both were performed with the yo-yo method and using the same materials, the exact same process could not be followed as the blank activation could not measure photocurrent thus could not accurately determine when it was appropriate to switch Cesium and NF_3 deposition. The corresponding peak of mass 147 also pictures in Figure 9b is most likely due to the formation of a Cs-N molecule on the surface of the cathode, previously reported by other research groups as a potential species in the activation layer of GaAs

photocathodes activated with NF_3 .

3.6 Future Work

Future work will look for an ideal activation method by comparing various activation processes. By comparing the yo-yo method and the co-deposition method as well as NF_3 activation to O_2 activation the best activation process should be found. Once the best activation process is determined, it will be possible to begin lifetime studies on the cathode and more TDS experiments to understand how the activation layer is formed and how it degrades to decrease the QE of the cathode. Once the process by which the cathodes' QE degrades is understood it could be possible to create cathodes with longer dark and operational lifetime.

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