ADVANCES IN PHOTOCATHODE TECHNOLOGY AT CORNELL UNIVERSITY*

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Abstract

Beam brightness from modern day photoinjectors is limited by the photocathode. A multifaceted photocathode development program has been undertaken at Cornell University with a goal to develop the ultimate photocathode which has high quantum efficiency, low mean transverse energy, quick response time and a long lifetime. Positive affinity cathodes like CsK_2Sb and Na_2KSb have been grown using different kinds of alkali metal sources (alkali-azide and pure metal), characterized and tested in the Cornell ERL photoinjector. Novel layered structures of various III-V semiconductors like GaAs and AlGaAs grown using Molecular Beam Epitaxy (MBE) and activated to negative electron affinity using Cs and NF_3 are also being investigated. Surface and photoemission diagnostics like Auger spectroscopy, LEED, RHEED and the 2D-electron energy analyzers have been connected in vacuum to the photocathode growth and preparation chambers to fully characterize the surface and emission properties of the materials grown. A Monte Carlo based simulation has also been developed to predict photoemission from layered semiconductor structures and help design novel structures to optimize the photoemission properties.

INTRODUCTION

Photocathodes used in photoinjectors that power modern and future 4^{th} generation light sources like the ERL's and FEL's have extremely stringent requirements. Moreover, the maximum achievable beam brightness from photoinjectors is limited by the photocathode [1]. For example, the photocathode in the Cornell ERL injector is required to have a high ($> 3\%$) QE (quantum efficiency) at 520nm laser wavelength, short ($<$ 2ps) response time, minimum possible MTE (mean transverse energy) with typical values being 150meV and a long lifetime during high current ($\sim$100mA) operation. Metallic cathodes are rugged and have a fast response time, but have very low ($< 0.1\%$) QE. Semiconductor cathodes provide a high QE in the visible and UV range. For this reason semiconductor cathodes are the choice for several photoinjectors around the world. However, they have very stringent vacuum conditions for longevity [2].

Several of the key emission properties required from semiconductor cathodes are conflicting. For example, at longer wavelengths, negative electron affinity (NEA) semiconductor cathodes give a small MTE ($\sim$25meV) but have a long ($>$100ps) response time [3]. Furthermore, the detailed physics of photoemission and the origin of the key photoemission properties like QE, response time and MTE are not well understood for semiconductor cathodes. This is largely due to lack of conclusive and self-consistent experimental data hampered by the demanding vacuum requirements and experimental difficulties associated with measuring key photoemission properties of MTE and response time from these cathode materials.

EXPERIMENTAL FACILITIES

A campus-wide photocathode investigation program has been initiated at Cornell University in order to address the need for experimental data. Both positive electron affinity (PEA) alkali-antimonide and NEA semiconductor photocathodes are under investigation. The alkali-antimonide photocathode growth chamber and GaAs activation chambers are connected in vacuum to surface analysis chamber with auger spectroscopy, RHEED and LEED capabilities. Abilities to measure spectral response, surface QE scan, activate NEA semiconductor cathodes using Cs and NF_3 while measuring QE at different wavelengths simultaneously have also been incorporated. Advanced photocathode diagnostics such as the electron energy analyzer [4] to measure simultaneously, transverse and longitudinal electron energy distributions have also been developed and added to the setup. Figure 1 shows the picture of the multipurpose vacuum system devoted to photocathode research. The entire assembly is under ultra high vacuum with a pressure of less than 10^{-10} Torr throughout and less than 10^{-11} Torr in the GaAs preparation chamber and the surface analysis chamber. Samples can be transferred from one part of the assembly to another in vacuum via use of magnetically coupled transfer arms.

Multialkali photocathodes developed and characterized here can be transferred to the Cornell ERL injector for studying their performance in a DC photoemission gun under high voltage (350kV) and high beam currents ($>$ 70mA) [5] via a vacuum suitcase capable of maintaining a pressure of a few 10^{-10} Torr during the transfer. Another facility is a semiconductor MBE reactor used to grow and activate III-V semiconductor photocathode structures. New layered structures of GaAs/AlGaAs can be grown with graded doping levels in order to optimize photoemission characteristics. These structures, once grown in the MBE reactor can be capped with a thick As layer and be transported in air to either the multipurpose photocathode

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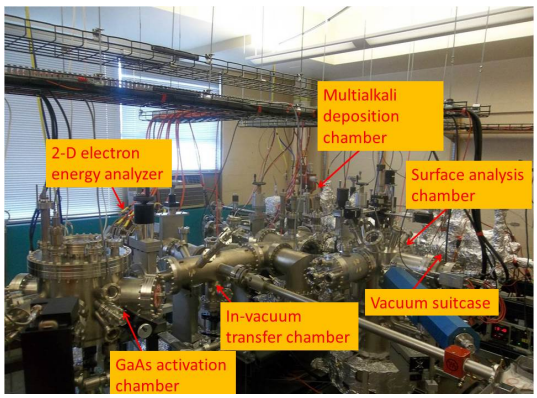

Figure 1: Photocathode growth and analysis chamber.

research chamber or to the DC photoemission gun, without contaminating the surface. The As layer can then be removed by heating the surface to about 350°C for one hour prior to the NEA activation.

ALKALI-ANTIMONIDE CATHODES

Characterization and High Current Operation

Various multialkali cathodes are routinely grown for use in the Cornell ERL injector using ALVATEC [6] alkali metal sources. Cs_3Sb, K_2CsSb and Na_2KSb have been successfully grown and characterized w.r.t their spectral response, MTE and response time in the photoinjector [7, 8, 9]. The results obtained have been summarized in Table 1. It can be seen that Na_2KSb gives a noticeably lower MTE than the Cs cathodes. Further Na_2KSb is also known to withstand higher temperatures making it more suitable for high current operation. Successful high current operation has been demonstrated by extracting 65mA of beam current from Na_2KSb cathode in the Cornell photoinjector for a period greater than 8hrs. The QE degradation during this operation had a 1/e lifetime constant of 66hrs [9].

Table 1: QE, MTE and Response Time Characterization of Multialkali Cathodes

Cathode	QE @ 532nm	MTE @ 532nm	Response time
Cs_3Sb	4-5%	160meV	< 2ps
K_2CsSb	7-10%	160meV	< 2ps
Na_2KSb	4-7%	120meV	< 2ps

Investigating Alkali Metal Sources

Although multialkali cathodes have been successfully and reliably grown with the ALVATEC alkali metal sources, it has been found that the exact reproducibility of the growth process is difficult. The alkali metal flux changing over time and between individual dispensers is the main reason causing this lack of reproducibility. This makes it difficult to automate the cathode growth process. With this goal in mind various alkali metal sources are being investigated.

Along with ALVATEC sources, alkali antimonide cathode growth has been successfully demonstrated at Cornell using SAES dispensers [10], alkali azides and pure metal alkali sources. SAES dispensers are easy to handle and very reliable but have some drawbacks. They have to be heated to a temperature exceeding 600°C for alkali metal evaporation. Furthermore, the alkali metal flux from these sources is very small and hence they need to be placed very close to the substrate, increasing the substrate temperature due to radiative heating from the substrate and hindering cathode growth.

Alkali azides are stable compounds in air and decompose to release alkali metal vapor and nitrogen only when heated close to the melting point at about 300°C. This makes them easy to handle outside vacuum. They are cheap and the flux of alkali metal released is large. However, during the alkali metal evaporation the nitrogen released can cause the pressure to rise above 10^{-5} Torr. Very fine temperature control (to a fraction of a degree) of the furnaces is required to avoid excess pressure in the chamber. Such tight temperature control is one of the challenges to a successful use of these sources.

Pure metal alkali sources have been tested to some extent and have been found to be easy to operate for photocathode growth. But, pure alkali metals are strongly reactive and hazardous to handle in open air. A proper facility to insert these sources into the vacuum chamber through an inert gas atmosphere needs to be developed to avoid handling difficulty. Considering the stability and reliability of the sources, the pure metal alkali sources appear to be optimal. The above results are summarized in Table 2.

III-V SEMICONDUCTOR CATHODES

Monte-Carlo Simulation of Photoemission

A Monte-Carlo based simulation has been developed to explain the process of photoemission from GaAs [11]. This simulation is based on Spicer's 3-step photoemission model. Electrons are excited by photons from the valence band to the conduction band. The electrons are then transported within the GaAs bulk. During this transport they undergo scattering with phonons and holes and lose energy. The ones that reach the surface can get emitted into vacuum via tunneling through a surface potential barrier. This simulation successfully describes the spectral response and response time of GaAs cathodes without the use of any ad hoc parameters. Upon assumption of an elastic surface scattering that causes electrons to be emitted in a cosine angular distribution w.r.t. the surface normal, the Monte-Carlo code gives MTE values very close to the measured ones [12]. The exact value of NEA is extremely sensitive to the vacuum conditions and surface cleanliness. It can differ from activation to activation and hence is the only free parameter allowed in the simulations. The code has now been extended to layered structures with graded doping.

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Table 2: Comparison of Alkali Metal Sources

Source	Capacity	Stability	Thermal load on substrate	Effect on vacuum	Handling outside vacuum
SAES	Poor	Good	Significant	Negligible	Stable in air
ALVATEC	Good	Poor	Not measurable	Negligible	Stable when unused
Azides	Good	Poor	Not measurable	Rises to 10^{-5} Torr	Stable in air
Pure metal	Good	Good	Not measurable	Negligible	Needs inert gas environment

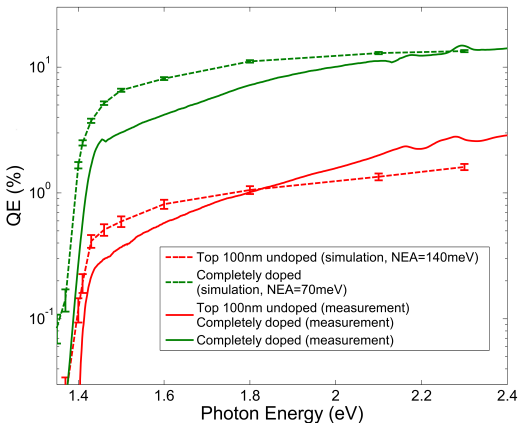

Figure 2: Measured and simulated spectral response of layered and non-layered GaAs cathode.

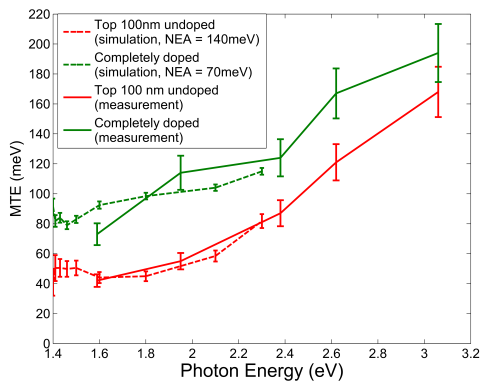

Figure 3: Measured and simulated MTE of layered and non-layered GaAs cathode.

Layered Structures

Novel layered structures of GaAs/AlGaAs with graded doping can be grown to optimize photoemission properties. So far layered structures have been grown to maximize QE [13]. The Monte-Carlo modeling predicted a simple structure consisting of 100nm undoped GaAs layer over a substrate doped to 5×10^{18}cm^{-3} using carbon would have a smaller MTE and a smaller QE as compared to completely p-doped GaAs. Such a structure was grown using MBE and activated to NEA. The MTE and spectral response were found to be in reasonable agreement with the values obtained from the Monte-Carlo simulation [14]. Figs. 2 and 3 show the comparison of the spectral response and MTE, respectively, of the layered and non-layered structures.

FUTURE WORK

We have concluded that pure metal sources are optimal for growing alkali-antimonide cathodes reproducibly. Developing an automated growth procedure using pure metal sources and growing advanced alkali-antimonide cathodes like the S-20 photocathode and characterizing it are among the next natural steps. The Monte-Carlo simulation has already allowed us to predict and realize new low emittance cathodes.This opens a way to systematic theory-driven investigations of more complicated layered structures optimizing certain photoemission properties. Simulations are continually being improved by including new relevant physics especially pertaining to the surface. Capability of activating and characterizing NEA cathodes within the MBE growth chamber is being implemented to skip the step of As capping and to ensure a clean and atomically flat surface.

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