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PHOTOCATHODE EPITAXY AND BEAM EXPERIMENTS (PHOEBE) LABORATORY AT CORNELL: CURRENT STATUS AND FUTURE WORK*

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Abstract

High-efficiency alkali antimonide photocathodes degrade with little oxidation, making them hard to characterize and test outside their growth chamber. In this proceeding, we report on the design and performance of the PHOtocathode Epitaxy and Beam Experiments (PHOEBE) laboratory at Cornell University, where the growth, characterization, and testing of alkali photocathodes in vacuum has been successfully integrated. The growth of photocathodes is characterized in-situ by measuring the quantum efficiency (QE) and by looking at the photocathode's reflection high energy electron diffraction (RHEED) pattern. Once the desired photocathode is obtained, it is moved to a storage chamber to collect spectral response data, after which it is moved to the cryogenic emittance diagnostic beamline via a vacuum suitcase. A rapid cathode exchange system in the diagnostic beam can efficiently transfer alkali-antimonide photocathodes to beamline operation with little QE loss. Using this beamline, the mean transverse energy of the photocathode can be measured at various photoexcitation wavelengths in the visible spectrum and sample temperatures within 20-300 K.

INTRODUCTION

Electron beams are widely used in science and technology, therefore the search for high-brightness electron sources is an important topic for the accelerator community [1]. Figures of merit such as Quantum Efficiency (QE) and Mean Transverse Energy (MTE) are key for evaluating the performance of the investigated material. Currently, alkali antimonide photocathodes are particularly promising because they have been shown to have high QEs and low MTEs [1–5].

However, these photocathodes are hard to characterize and test outside the growth chamber, limiting fundamental understanding. In this direction, the PHOtocathode Epitaxy and Beam Experiments (PHOEBE) Laboratory at Cornell University uses an integrated system that allows the study, characterization, and testing of these materials with minimal degradation due to transfer or chemical poisoning.

This work presents an overview of the PHOEBE laboratory and some of its capabilities, starting from the sample/sources preparation to the final MTE measurements. Figure 1 shows a panoramic picture of the laboratory. It contains a clean hood, sources preparation area, photocathode Molecular Beam Epitaxy (MBE) system, cryogenic emittance diagnostic beamline, and a vacuum suitcase. The clean hood and sources preparation areas are used to clean substrates and holders to be loaded into the system. Each alkali source (Cs, K, Na) is mixed with 80 at % of indium. This alloy undergoes a melting process followed by solidification within a glove box. Subsequently, it can be exposed to air for loading into the MBE.

This laboratory takes the standard flag-style plate holder as shown in Fig. 2a with some modifications (Figs. 2b-d) depending on the holder's use, as will be discussed later in the paper. Wobble sticks are used to put the holders into transfer arms that allow sample transfer within the system.

PHOTOCATHODE MBE

Figure 3 shows a schematic of the photocathode MBE system which consists mainly of a load lock, a growth module, and a storage chamber. Photocathodes are grown and characterized here before going to the vacuum suitcase for the emittance diagnostic beamline.

Growth Module

The growth module is equipped with 8 source ports each one containing an effusion cell for thermal evaporation of the corresponding source, an SRS Residual Gas Analyzer (RGA) 200, and a kSA 400 analytical Reflection High Energy Electron Diffraction (RHEED) system. The photocurrent of the sample is collected by measuring the drain current from the electrically floated sample holder, which is biased at -40 V. The photocurrent is registered with an SRS 8340 lock-in amplifier. A single wavelength from a laser diode is used to measure QE.

The rate deposition for all the sources is characterized by a Quartz Crystal Microbalance (QCM). All temperatures of the sources and substrates can be controlled using a customized LabView program. The system is set up such that sources can be evaporated individually or simultaneously, and pneumatic valves are used to have better control of the opening/closing of the shutters.

A typical system for growing photocathodes is QE oriented, i.e., it is based on monitoring the photocurrent of the grown film *in situ*. Then, a post-analysis of the film is performed. At PHOEBE, an *in operando* RHEED equipment has been added to account for the structural component of the film. This technique has been widely used in the

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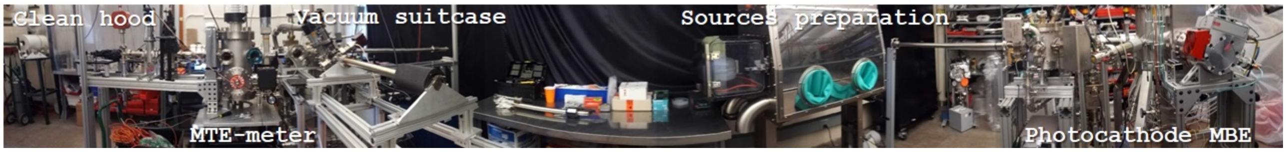

Figure 1: Panoramic view of the PHOtocathode Epitaxy and Beam Experiments (PHOEBE) Laboratory at Cornell.

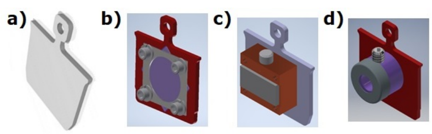

Figure 2: Sample holders used in PHOEBE. a) Standard Flag-Style Plate, b) Standard Flag Style Plate with pocket, c) Crossplatform Holder, and d) Holder for the beamline.

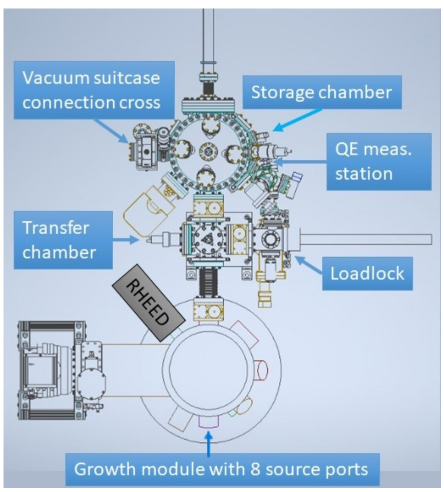

Figure 3: Schematic of the photocathode MBE system.

Molecular Beam Epitaxy (MBE) growth of traditional semiconductors but is rarely used during photocathode growth. Incorporating this technique as a structural diagnostic of the photocathode growth and using lattice-matched substrates allows us to tune the growth parameters to synthesize single-crystal alkali antimonides photocathodes [6]. The growth of epitaxial alkali antimonides as potassium-based (See [7]) and sodium-based antimonides have also been observed at PHOEBE and will be presented elsewhere.

The system is also equipped with a leak valve connected to a compressed oxygen tank with 99.999 % purity, which enables oxygen dosing experiments, where the partial pressure of oxygen is monitored with the RGA while the QE at a single wavelength is measured. This has allowed us to discover that a new phase of cesium antimonide ($CsSb$) is very robust to oxygen degradation as opposed to Cs_3Sb, extending the usages of alkali antimonide cathodes to higher pressure environments [2].

Storage

The storage chamber is equipped with a disk platform storage unit that allows for storage of up to 10 samples at a time. One of the window ports of the storage is used to collect the spectral response of the grown film (See Fig. 3). For that, an Oriel Apex Monochromator light source, a Newport optical power meter (model 843-R), and an SRS 8340 lock-in amplifier are used. A metallic coil placed 5 cm from the sample is biased at +120 V and used to collect the film's photocurrent when illuminated with monochromatic light. The base pressure achieved in the storage chamber is 2×10^{-10} Torr.

Inter-System Transportation

The storage chamber can be connected to a suitcase via a cross section as shown in Fig. 3. Pumping in the suitcase is performed by a NEXTorr D100-5 non-evaporative getter and ion combination pump with 100 l/s (H2) pumping speed. Base pressure achieved in the suitcase and cross are below 1×10^{-10} Torr. The sample's photocurrent can be acquired in the suitcase by a biased metallic coil, the same as how it is measured in the storage chamber. This allows lifetime measurements during transport and monitors the sample's degradation if any. The suitcase is then disconnected from the MBE system and connected to the cross on the beamline exchange section. A complete transfer of photocathodes from the MBE storage to the photogun in the emittance diagnostic beamline takes a couple of days, mainly waiting for the pressure in the cross sections of both systems to be low enough to avoid sample oxidation during transfer.

The suitcase is also used to move samples from the MBE system to other systems that allow additional characterization, such as X-ray Photoemission Spectroscopy (XPS) and Scanning Tunneling Microscopy (STM) measurements. In this case, a cross-platform holder as shown in Fig. 2c is used. In this design, a block is attached and secured to the flag-style plate holder. The substrate is glued to the block using a PELCO High-Performance silver paste that allows high-temperature annealing and is suitable for high vacuum. This approach decreases noise or additional signals coming from the mask or clips used to hold the substrate as in Fig. 2b. Additionally, the block has a threaded rod that permits the transfer to systems that do not have flag-style holders.

EMITTANCE DIAGNOSTIC BEAMLINE

The emittance diagnostic beamline, referred to as the Cryo-MTE-Meter, consists of an exchange section, photogun, and beam transport section. Within the exchange section, photocathodes are removed from the vacuum suitcase attached at the cross and inserted into the photogun via a specially designed carrier. The photogun accelerates electrons emitted by the photocathode up to 60 keV into the

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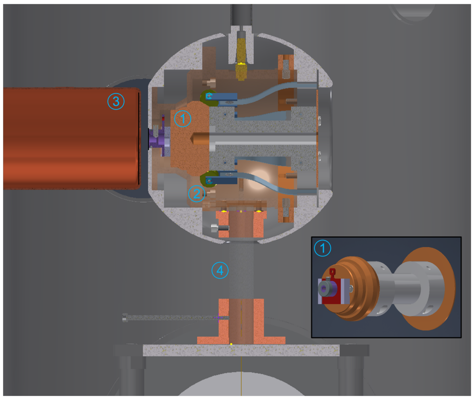

Figure 4: Cross-section side view of cathode ball in the photogun (beam propagates towards left of image). 1: sample carrier, 2: leaf springs, 3: anode, 4: sapphire rod attached to cryocooler stage. Inset: sample carrier.

beam transport section, where the MTE of the photocathode is measured via a variety of methods, including direct 4D phase space imaging and solenoid scans. To reduce noise from mechanical vibration, the entire beamline is supported by a low-vibration table.

Cathode Transfer

The photocathode is moved from the vacuum suitcase to a sample carrier, shown in Fig. 4, which is attached to a bayonet-style arm. The sample carrier is inserted into the cathode ball structure in the photogun, where the leaf springs automatically engage with the sample carrier to hold it in place once fully inserted, with minimal variation between cathode transfers. A simple twist of the transfer arm releases the sample carrier and the arm can be fully retracted, leaving the photocathode in the photogun.

Cathode transfer times typically range between 15 to 30 min, even when performed by new trainees with minimal experience. Thanks to the small size of the photocathode holder, operating the transfer arms to manipulate the sample carrier can be easily done by a single person. To aid with cathode transfer, a camera is aimed at the front and back of the cathode ball to avoid collisions and ensure proper alignment. The base pressure ranges between 2×10^{-10} to 3×10^{-10} Torr within the exchange section and 1×10^{-10} to 2×10^{-10} Torr within the photogun. The maximum pressure spikes are in the 10^{-9} Torr range while moving the photocathode.

Photogun

The DC photogun has been commissioned for energies around 60 keV, but typically operates at 15 keV. A Glassman Series FC power supply supplies high voltage to the polished stainless steel cathode ball in Fig. 4 and the copper tube anode is grounded. The tube anode shields the beam from stray fields past the accelerating section, preventing undesirable emittance growth in the beam [8]. Additionally, the photocathode sample holder shown in Fig. 2d differs from the other sample holders in that it features a circular cap holding the photocathode substrate in place. The circular cap is designed with smooth edges and does not expose screws or substrate, unlike the holder in Fig. 2b, thereby avoiding features that may field emit during photogun operation.

The cathode ball is attached to a cryocooler stage via a sapphire rod as part of the ARS UHV Closed Cycle Cryostat (Model CS-215-SB-1200). With the radiation shield installed, a base temperature of 18 K at the photocathode has been measured.

Laser Optics

The photocathode is driven by a CW diode laser (typically 405 or 532 nm) or an optical parametric amplifier (OPA) that outputs visible light of variable wavelength between 620 to 900 nm. The OPA itself is driven by a 20 W, 2 mJ Light Conversion Pharos at 1030 nm. The laser is passed through a pinhole, which is imaged onto the cathode, resulting in a round flat-top profile with variable diameter depending on the choice of pinhole diameter. Immediately before entering the photogun, a beamsplitter picks off roughly 2 % of the laser power and sends it to an Allied Vision Manta CCD camera that functions as a virtual cathode. Motorized mirror stages allow scanning of the laser spot across the cathode for various characterization such as QE maps of the photocathode and pincushion scans of the beamline.

Beam Transport Section

The MTE-Meter mainly operates in two modes, 4D phase space imaging and solenoid scans. Upon exiting the gun into the beam transport section, the beam travels through a solenoid and forms a waist at either the detector when performing solenoid scans or an upstream aperture with varying diameters (30, 50, 70 μm) when performing 4D phase space imaging. Dipole corrector magnets steer the beam onto the detector when performing solenoid scans or scan it across the aperture when performing 4D phase space imaging. The detector consists of a microchannel plate followed by a scintillator screen, which is imaged by a scientific CMOS camera. The point spread function of the microchannel plate limits the resolution of the detector, which is measured to be roughly 80 μm rms or an angular resolution of 0.16 mrad in phase space. Using the 30 μm aperture, General Particle Tracer simulations reveal that the smallest emittance measurable by 4D phase space imaging is roughly 1.6 nm or an MTE of 0.5 meV.

SUMMARY

We describe the design and capabilities of the MBE system and Cryo-MTE-Meter beamline that makes up the PHOEBE laboratory. PHOEBE thus provides a robust environment for reliable and efficient production, transportation, and testing of sensitive alkali-antimonide photocathode sources for high-brightness beams. Refer to [7] and [9] to see the results of the MBE and Cryo-MTE-Meter operation.

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