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ADVANCED GROWTH AND CHARACTERIZATION OF ALKALI ANTIMONIDE PHOTOCATHODES FOR BRIGHT BEAM APPLICATIONS

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Abstract

The properties of photoemitting electron sources are key determinants of performance in advanced electron accelerator applications, such as particle colliders, X-ray free electron lasers, ultra-fast electron diffraction and microscopy experiments. Therefore, low mean transverse energy (MTE), high quantum efficiency (QE) along with long operational lifetime and robustness under high electric fields and laser fluences must be demonstrated by the photocathode for these bright beam applications. Recent investigations have revealed that the epitaxial growth of single crystal cesium antimonides can be achieved by photocathode growth on lattice matched substrates. In this work, the experimental setup for highly promising alkali antimonide photocathode growth by molecular beam epitaxy on lattice matched substrates and *in-situ* characterization with reflection high-energy electron diffraction (RHEED) has been considered. To adapt the L-band RF gun of Argonne Cathode Test-stand (ACT) for extensive testing of alkali antimonides in real accelerator conditions, compatible cathode plug design and smooth transportation process have been developed and also described in this paper.

INTRODUCTION

Due to their low positive electron affinity, alkali antimonide photocathodes (e.g., Cs_3Sb, K_2CsSb, Na_2KSb, etc.) are great candidates for electron sources with high quantum efficiency (QE) in the visible light range. Moreover, these materials demonstrate reduced physical roughness and crystalline structure if grown on lattice-matched singe-crystal substrates [1–3]; thus, low mean transverse energy (MTE) can be achieved by these photocathodes. Therefore, these electron sources are highly promising for bright beam applications such as particle colliders, x-ray free electron lasers (XFELs), ultrafast electron diffraction (UED) and microscopy (UEM). One of the key challenges for bright electron sources is achieving long lifetimes and robustness under high electric field gradients and intense laser fluences. Although cesium antimonide (Cs_3Sb) photocathodes are sensitive to vacuum conditions and require more sophisticated experimental setup as compared to metal cathodes, they still can be robust enough to be used in photoinjectors with high gradients. These photocathodes have been studied in DC guns previously; however, no experiment has been carried away to test their performance in the RF or SRF environment.

The goal of this work is to grow high quality alkali antimonide photocathodes at Northern Illinois University (NIU) with advanced *in-situ* characterization techniques and test them at Argonne Cathode Test-stand (ACT) of Argonne Wakefield Accelerator (AWA) Facility.

ALKALI ANTIMONIDE PRODUCTION

The NIU alkali antimonide growth system is based on the growth chamber received from Fermi National Accelerator Laboratory (FermiLab), which was previously used to grow cesium telluride photocathodes. It is built around a 10″-diameter vacuum chamber (Fig. 1) and uses an INFN-style plug (Fig. 2). One turbo pump, one sublimation pump, and two ion pumps are used to achieve UHV conditions.

The system is operated by 5 different manipulators. Manipulator A exerts its action by means of permanent magnet and can move a storing carriage along the chamber. The carriage, shown in the inset of Fig. 1, can hold up to 5 cathode plugs. Manipulator B is also operated by a permanent magnet that can grab one plug at a time to move it along the beamline. Manipulators C, D and E are operated via bellows. A rigid pincer in the top of manipulator D can grab the cathode from the carriage and place it to the growth position and vice versa. Manipulator C rides inside manipulator D where a halogen bulb is inserted inside the hollow and can be moved up to the bottom surface of the cathode surface to heat it up. The temperature of the cathode can be measured by a thermocouple inserted through a hole in the cathode plug. Manipulator E moves a thickness monitor in and out to the growth path for calibration of the deposition rates. A mask attached to the SAES source control makes sure that the particles are only deposited on desired surface of the plug. The transfer cross (or "vacuum suitcase" shown in Fig. 1) separated by a gate valve ensures the photocathode transportation from a growth facility to the testing facility in UHV environment.

Some system upgrades are underway to improve alkali antimonide photocathode growth and *in situ* characterization. More efficient and long-lasting effusion cells in combination with gate valves will be used for the film deposition instead of SAES dispensers. This will allow us to avoid frequent source replacements and vacuum interruptions. The epitaxial growth of Cs_3Sb films can be achieved through the codeposition of Cs and Sb on a lattice-matched substrate such as STO (100), 3C-SiC (100), Al2O3 (1010) and TiO2 (001) [2]. To ensure *in situ* monitoring of the epitaxial growth of Cs_3Sb throughout film deposition, the Reflective High Energy Electron Diffraction (RHEED) system has arrived

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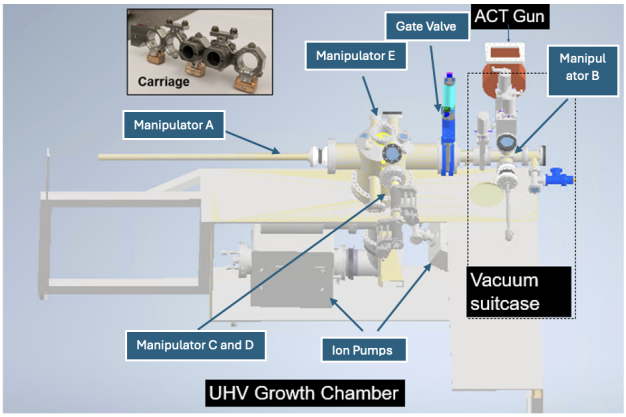

Figure 1: NIU alkali antimonide growth system.

in the laboratory and will be incorporated into the growth system in a short period of time.

CHARACTERIZATION AT ACT

Following the completion of the system and the successful growth of alkali antimonide photocathodes, the next step is to characterize and evaluate the performance of these sources under real photoinjector operating conditions. ACT is one of the most convenient testing sites due to its proximity to NIU along with its availability and testing capacity. This is an L-band normal-conducting high gradient single-cell RF gun with a unique imaging system to precisely locate the emitters on cathode surface with a resolution of 20 µm [4]. The ACT has the experimental capability to measure a wide range of cathode properties, including emission current, current density, uniformity, emittance, and lifetime, using well-developed diagnostics. Since the ACT was only suitable for testing air-stable cathodes, some upgrades to the gun are ongoing in order to enable testing Cs_3Sb photocathodes under UHV environment. In particular, the pumping capability of ACT will be improved to reach the base pressure of 10^{-10} Torr and the load-lock system will be added.

CATHODE-PLUG AND LOAD-LOCK DEVELOPMENT

Since the standard INFN cathode plug at NIU is not compatible with the ACT beamline, a new plug model has been developed that can be used for photocathode production at NIU and characterization at ACT. The updated cathode will enable film deposition on the semiconducting substrates, which is a key factor towards achieving atomically smooth surfaces and thus ultra-low MTE. The prototype of such photocathode plug is shown in Fig. 2. Highly ordered epitaxial films with atomically smooth surfaces are predicted to result in ultra-low MTE even in high electric fields [1].

Since Cs_3Sb and other alkali antimonides are very susceptible to chemical poisoning and vacuum contamination, monitored UHV conditions must be maintained throughout the entire photocathode growth, transportation, and characterization phase. Therefore, a load-lock system and a vacuum suitcase (shown in Fig. 3) has been developed to enable the

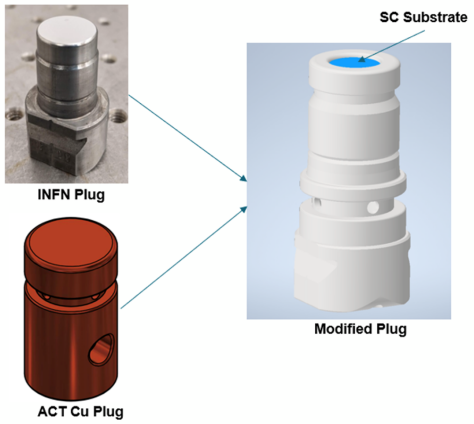

Figure 2: Modified INFN plug designed for photoemitting film growth on semiconductor substrates and fully compatible with the ACT.

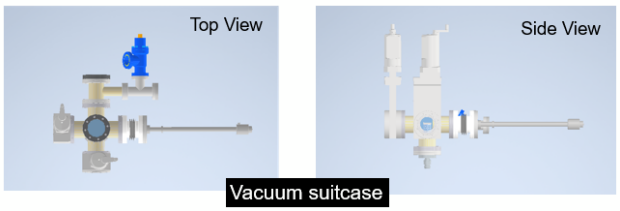

Figure 3: Vacuum suitcase for transferring NIU-grown photocathodes to ACT.

transportation of NIU-grown photocathodes to the ACT for testing their performance under realistic photoinjector conditions.

RF FIELD SIMULATION AND BEAM SIMULATION FOR NEWLY DEVELOPED CATHODE

To predict the cathode response once inserted into the 1.3 GHz RF gun cavity, electric and magnetic field maps have been studied through CST simulation in eigenmode, as shown in Fig. 4. Several simulation runs have demonstrated satisfactory results with 1.310 87 GHz resonant frequency for the cavity. A well-equipped tuner with the cavity will be used to further adjust the resonant frequency to as close to 1.3 GHz as possible. There is also ongoing work on beam simulation by ASTRA (particle tracking algorithm) to predict various beam parameters contributing to beam emittance, such asspace charge, laser spot size, bunching factors, etc.

CONCLUSION AND FUTURE FORK

Ultra-smooth, low-MTE cesium antimonide photocathodes can be obtained by the co-deposition process on lattice-matched semiconductor substrates. As a first step of growing high-quality alkali antimonide photocathodes for bright beam applications, a prototype of the photocathode plug containing a semiconductor substrate has been developed. The equipment required to upgrade the NIU growth system

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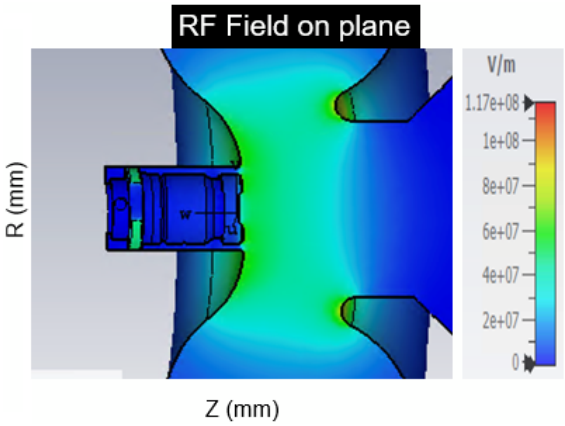

Figure 4: RF field map on plane from CST.

has been ordered. Characterization of the photocathode will be done at ACT gun shortly after successful growth of cesium antimonide photocathode at NIU. It is expected that we will be able to demonstrate a photocathode that can operate for longer than 1 week with MTE < 35 meV at $50\,\mu J \cdot cm^{-2}$ laser fluence and high field (> 50 MV/m) for high-peak-current applications such as compact XFELs.

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