ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOPLM15

DESIGN OF THE ASU PHOTOCATHODE LAB

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Abstract

Recent investigations have shown that it is possible to obtain an order of magnitude smaller intrinsic emittance from photocathodes by precise atomic scale control of the surface, using an appropriate electronic band structure of single crystal cathodes and cryogenically cooling the cathode. Investigating the performance of such cathodes requires atomic scale surface diagnostic techniques connected in ultra-high vacuum (UHV) to the epitaxial thin film growth and surface preparation systems and photo-emission and photocathode diagnostic techniques. Here we report the capabilities and design of the laboratory being built at the Arizona State University for this purpose. The lab houses a 200 kV DC gun with a cryogenically cooled cathode along with a beam diagnostics and ultra fast electron diffraction beamline. The cathode of the gun can be transported in UHV to a suite of UHV growth chambers and surface and photoemission diagnostic techniques.

INTRODUCTION

Increasing electron beam brightness is central to many accelerator applications like Free Electron Lasers (FEL) [1], Ultrafast Electron Diffraction (UED) setups [2], and Energy Recovery Linacs (ERL) [3]. Beam brightness is inversely proportional to the square of the intrinsic emittance of the photocathode producing the electron beam. The intrinsic emittance is described by the equation $\epsilon_n = \sigma_x\sqrt{\frac{\mathrm{MTE}}{mc^2}}$, where MTE is the mean transverse energy of the photoemitted electrons, σ_x is the rms laser spot size on the cathode, m is the rest mass of an electron, and c is the speed of light in vacuum [4]. Thus, the development of low MTE (or low intrinsic emittance) cathodes is crucial to increasing beam brightness.

Various theoretical and experimental investigations performed over the last decade show that the MTE of electrons obtained from the cathode depends on the excess energy (i.e the difference between the photon energy and the work function) [5], the lattice temperature [4, 6], the surface non-uniformities of physical roughness and work function variations [7, 8], the band structure [9] and non-linear photoemission effects of electron heating and multiphoton emission [10]. Recently, by minimizing contributions from all of the above an MTE as low as 5 meV was demonstrated from the atomically ordered Cu(100) surface cooled to 30 K when photon energies close to the photoemission threshold were used. However, due to the low quantum efficiency (QE), it is not possible to extract large charge densities at 5 meV MTE from this surface and higher QE materials that can minimize the MTE are essential [11].

In general reducing the excess energy and the lattice temperature reduces the MTE [4, 6]. Hence it is essential to investigate the cathode performance at cryogenic temperature with a photon energy that can be tuned very close to the photoemission threshold. Minimizing the effects of surface non-uniformities requires the use of atomically flat, ordered, single crystalline surfaces as cathodes [7, 8]. This necessitates the cathode surfaces to be grown/prepared and characterized in UHV and requires atomic scale surface diagnostics connected to photoemission diagnostics in UHV. Achieving the smallest MTE also requires that the emission does not occur from electronic states with a large transverse momentum, and hence choosing single crystal cathodes with the right band structure is essential [10]. Finally, demonstration of low MTE performance at large charge extraction densities is essential. This requires testing at cryogenic temperatures in a relatively high field electron gun.

Identifying cathode surfaces that satisfy all criteria to achieve low MTE will require testing a wide variety of cathode materials requiring a relatively quick transfer of the cathode between the various growth and characterization chambers.

To enable such complete characterization and to identify low MTE cathode materials, we are developing an advanced photocathode lab at the Arizona State University. The lab will house 200 kV DC gun with a cryogenically cooled cathode along with a beam diagnostics and ultra fast electron diffraction beamline. The cathode of the gun can be transported in UHV to a suite of UHV growth chambers and surface and photoemission diagnostic techniques. In this paper we highlight the design and the various capabilities of this lab.

LAB DESIGN

Figure 1 shows the 3-D model of the ASU photocathode laboratory. The laboratory will house two growth chambers, an atomic scale surface diagnostics chamber, an electron energy analyzer, and a DC electron gun all connected in UHV using a trolley based sample transfer mechanism. The details of the various experimental capabilities in the lab are outlined below:

Sample Transfer

The various UHV chambers will be connected in UHV by a single long transfer line that is designed to have vacuum pressures of 10^{-10} torr or lower. This will prevent the possibility of contamination of the cathode that could arise when transporting it between the different UHV chambers.

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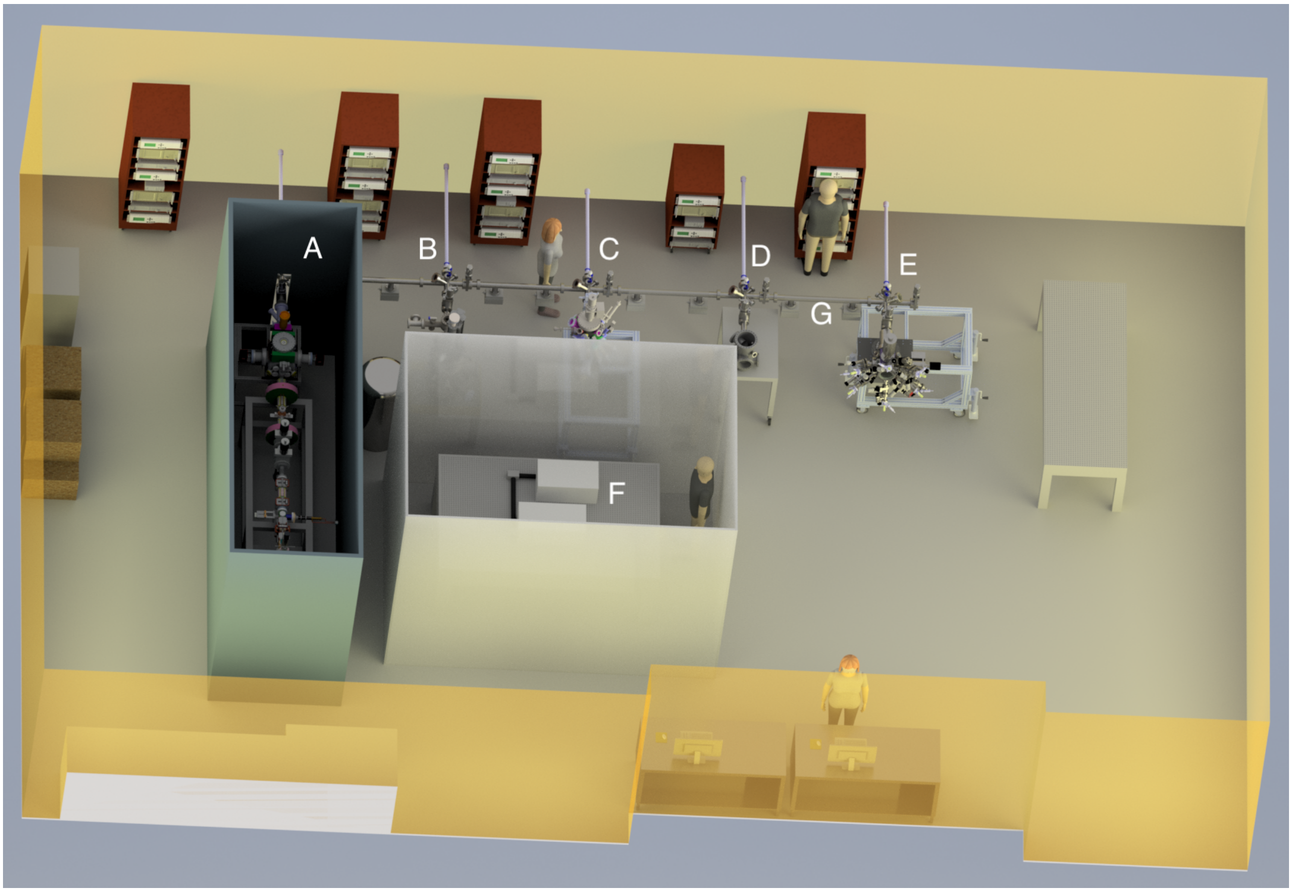

Figure 1: 3-D model of the ASU Photocathode lab (currently under development). The letter labels correspond to the following (A) 200 kV DC Electron Gun with diagnostics/UED beamline; (B) Electron Energy Analyzer; (C) Alkali-Antimonide Growth Chamber; (D) Surface Diagnostic Chamber; (E) Single-Crystal Growth Chamber; (F) Tunable wavelength laser (G) UHV transfer line.

Various photocathode samples will prepared on an omicron flag-style sample holders. The substrates used for sample preparation will be mounted onto the flag-style holders using tantalum strips spot welded to the holder as shown in Fig. 2a. They will then be transported along the transfer line using a magnetically driven cart on a track. The cart will contain a sample garage capable of storing multiple omicron sample holders (Fig. 2b). At each junction between the transfer line and a chamber there will be a section where the sample will be removed from the cart with a vertically aligned wobble stick, then handed off to a horizontally aligned linear transfer arm for placement inside of the chambers (Fig. 2c). The sample transport system has been designed by Xelera Research LLC.

Growth Chambers

The growth chambers can utilize both thermal and electron-beam evaporators to grow thin films on the omicron sample holders and perform molecular beam epitaxy. They are designed to allow deposition of up to 6 elements simultaneously. They will also equipped with the Reflective High Energy Electron Diffraction (RHEED) to allow for single atomic layer growth characterization. They also have the ports for installing an ellipsometer for measuring the optical constants of the cathode films grown, and a port for measuring the photoluminesence and other optical characterization techniques. Measuring such optical properties is crucial for investigating the photoemission process. Alkali-antimonides are the brightest sources of photoemitted electrons and an order of magnitude higher brightness has been predicted from single crystalline films of such materials. Hence one of the growth chamber will be dedicated to alkali-antimonide growth. The other growth chamber will be used for growth of novel materials like Dirac semi-metals and topological insulators which may produce very low intrinsic emittance owing to their band structure. Two separate growth chambers helps avoid the possibility of chemical cross-contamination of species with low vapor pressure.

Material and Surface Diagnostics

In order to ensure that the cathode is a good candidate for low emittance, it is important to characterize the surface of the cathode. We will have a chamber containing an RHK UHV atomic force microscope (AFM) and a Kelvin Probe Force Microscope (KPFM). This instrument can also be used in the scanning tunnelling microscopy (STM) mode.

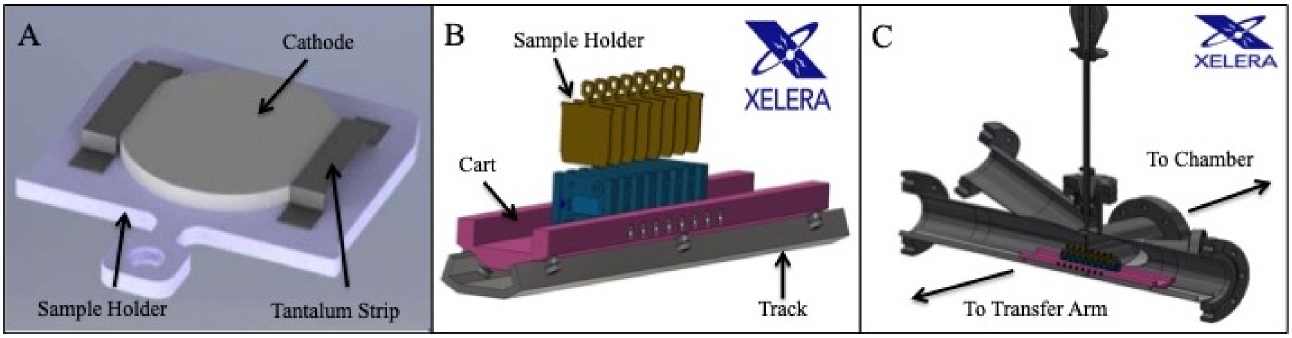

Figure 2: (a) Omicron flag-style sample holder for cathodes; (b) Cart on track for transporting samples; (c) Section of transfer line for placing the sample into the chambers.

Along with the AFM/KPFM, the growth chamber will have ports for reflective high energy electron diffraction (RHEED), photoluminescence, and spectroscopic ellipsometry. The UHV chamber containing the electron energy analyzer has low-energy electron diffraction (LEED) and Auger electron spectroscopy (AES) capabilities. This collection of UHV atomic scale surface diagnostic and materials characterization capabilities is critical for developing a detailed understanding of the dependence of photocathode performance on the surface and material properties.

Electron Energy Analyzer

The electron energy analyzer is a device that measures the 3-D energy and momentum distribution of photoemitted electrons from a cathode using the time-of-flight technique [12]. It measures meV-scale energy electron distributions with sub-meV energy resolution. During experimentation, the cathode can be cooled with liquid helium to 30 K, which allows us to test the effects of the lattice temperature on the 3-D energy and momentum distribution of the photoemitted electrons. This makes it an ideal device for studying photoemission right near the photoemission threshold. For an ordered surface sample of Cu(100) cooled to 30 K, an MTE of 5 meV has been measured with this device [11].

DC Electron Gun

The final chamber in the transfer line is a 200 kV DC electron gun attached to a lab sized characterization and UED beamline [13]. The gun will be uniquely designed to use a cathode mounted on an omicron sample holder. This will allow a wide flexibility in terms of the cathode size and shape that can be used in the gun and also allow cathode transfer under UHV between the gun and various diagnostics and preparation chambers mentioned above. The cathode will be cryogenically cooled with liquid helium to temperatures around 20 K, which provides us with the possibility of reaching the minimum intrinsic emittance of the cathode. The electric field at the cathode in the gun can go up to 10 MV/m allowing investigation of cathode performance at relatively large electric fields. The beamline consists of two solenoid lenses, one 3 GHz buncher cavity and one 3 GHz deflection cavity synchronized to the output of the laser with a sub-100 fs jitter. This will allow measurement of the emittance (and thus the MTE) using the solenoid scan techniques and the measurement of the response time to about 100 fs time scales [14].

Laser

The lab houses a 20W, femtosecond solid state laser with a repetition rate up to 500 kHz (LightConversion PHAROS). The laser output will be fed to an optical parametric amplifier (LightConversion ORPHEUS) to provide tunable wavelengths from 220 nm to 2000 nm. This will allow us to test cathodes right near the photoemission threshold resulting in a reduced MTE.

CONCLUSION

In this paper we have reported on the design of a laboratory capable of investigating the growth, characterization, and testing of photocathodes all in an UHV environment. The cathodes can be tested under a range of wavelengths (220 nm to 2000 nm) and a variety of temperatures (20 K to room temperature) allowing a complete characterization of the cathode for accelerator applications. Such complete cathode characterization will be essential for increasing the brightness of electron beams through the reduction of the cathode's intrinsic emittance.

ACKNOWLEDGEMENTS

This work was supported by the U.S. National Science Foundation under Award No. PHY-1549132, the Center for Bright Beams.

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