CORNELL LABORATORY FOR HIGH INTENSITY, ULTRA-BRIGHT AND POLARIZED ELECTRON BEAMS*

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Abstract

We report on the current activities pursued at Cornell University for the production of electron beams tailored to a wide range of applications. We have developed the expertise to grow many different type of high quantum efficiency photocathodes belonging to the alkali antimonide family. Those materials are ideal candidates to produce high intensity beam with average currents in the mA range. When operated near threshold at cryogenic temperature in transmission mode they can also generate the electron beams needed to perform ultrafast electron diffraction of bio molecules. We have recently expanded our facility with a Mott polarimeter to include the capability to measure polarization of the electron beam. The photocathode lab is being complemented by a dedicated photo-gun laboratory to test the photocathode properties in a real environment and to perform measurements of the beam properties under new and yet unexplored operating conditions.

INTRODUCTION

Semiconductor materials belonging to the alkali antimonide have been demonstrating their capability of generating electron beam with record high average current, extremely low intrinsic emittance and high Quantum Efficiency (QE). Their extreme high QE in the visible range has made them also one of the materials of choice for the photomultiplier (PMT) industry and further optimization of the growth process to produce multi-alkali photocathodes with maximal QE in the visible range of the spectrum over relatively large areas has big implication on future developments of large detectors dedicated to neutrino physics [1]. A recent demonstration of the possibility to operate these materials in transmission mode in a photoinjector has opened new perspective to the realization of ultra-bright electron beams capable of performing ultrafast diffraction of biological samples [2].

State-of-the-art electron sources delivering high polarization electron beams currently operate with average currents on the level of hundreds of microamps. Attempts aimed at demonstring that an average current of few mA can be produced using strained-superlattice multi-layer GaAs/GaAsP photocathodes resulted in lifetimes limited to few hours [3]. Inclusion of distributed Bragg reflectors has boosted the efficiency of these superlattice photocathode up by about a factor 6 [4] but the main limitation for generating high average current levels mostly resides in the extreme vacuum sensitivity of the surface dipole layers used to achieve Negative Electron Affinity condition (NEA). One of the three schemes proposed for the realization of an Electron-Ion Collider in the US design (the so called Linac-Ring option) would make use of the existing RHIC infrastructure already exisiting at BNL for the ion beam and but will required to operate with the electron beam characteristics well beyond the current state-of-the-art needing a polarized electron source capable of delivering an average current of 50 mA [5].

EXPERIMENTAL RESULTS

Rb-based Multialkali Photocathode

Inspired by the original work of Dvorak [6] who demonstrated peak QE of about 40% using Rb based multi-alklai antimonides photocathodes we experimented on the realization of these materials. We performed several preliminary growths using sequential evaporation of K and Rb only over a thin layer of Sb. Initial growth of either 10 or 20 nm Sb base layer and exposure of it to K vapors was performed with a roughly constant substrate temperature of about 140 C. The cooling down to room temperature of the substrate, obtained only by radiative losses, was initiated only once photocurrent first peaked and during exposure to Rb vapors by turning off the substrate heater. The growth of the Cs-Rb-K-Sb photocathode was completed with exposure of the photocathode to Cs vapors once the photocurrent extracted during Rb exposure no longer increased.

While we cannot provide any information on the chemical composition and crystal structure of the Rb-K-Sb and Cs-Rb-K-Sb photocathodes, recent state-of-the-art density functional theory calculations indicate that a bi-alkali antimonide compound K_2RbSb has a direct band gap with strong absorption coefficient in the visible and ultraviolet region of the spectrum [7]. Multiple growth experiments have been performed resulting in production of these bi alklai photocathodes with QEs as large as 20% at 400 nm. The growth chamber produces photocathodes with a high degree of uniformity and it was not difficult to reproducibly obtain cathodes that operated in reflection mode with QEs of a few percent at 532 nm. The growth of the Cs-Rb-K-Sb was performed on Borofloat 33 glass substrates with an initial Sb base layer thickness set to be 10 nm aim at producing thinner photocathodes better suited for transmission mode operation.

The spectral response of one of these Cs-Rb-K-Sb photocathode is reported in Fig. 1 along with the curves obtained for other cathodes of the alkali antimonides family grown in our laboratory. The spectral response obtained from this multi-alkali antimonides photocathode show a clear advan-

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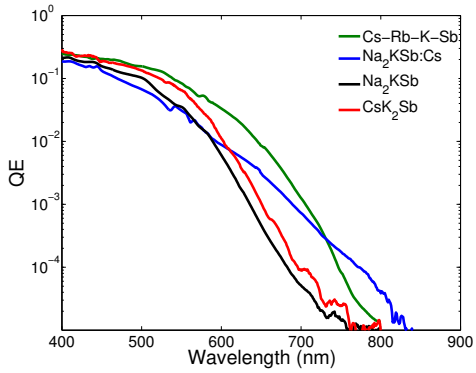

Figure 1: Spectral response of a multi-alkali Cs-Rb-K-Sb photocathode is compared with typical spectral responses of other alkali antimonides grown in our laboratory.

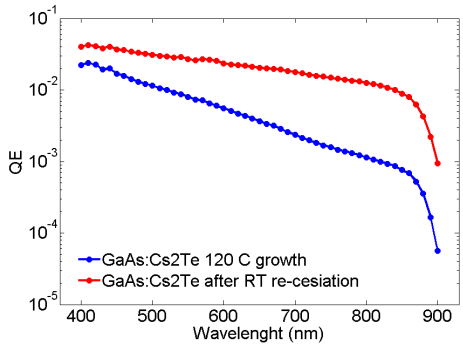

Figure 2: Spectral response of GaAs activated to NEA using a very thin layer of Cs_2Te: (blue) just after the move from the growth chamber and (red) after the exposure to Cs vapors at room temperature.

tage in terms of QE with respect to other bi-alkali photocathodes. At 400 nm (the shortest wavelength we can operate which is imposed by limitation of our optical setup) we measured QE of about 25% thus comparable with other high efficiency bi-alkali antimonides photocathodes. On the other hand in the spectral region between 650 and 750 nm, where most of our bi-alkali antimonides shows their photoemission threshold, the efficiency of the multi-alkali Cs-Rb-K-Sb is more than a factor 10 larger then our convention bi-alkali antimonides. The spectral response in the case of Cs-Rb-K-Sb photocathodes extends further towards the infrared part of the spectrum (as compared to other bi-alkali cathodes) up to roughly 800 nm, but for wavelengths longer than 750 nm the Na_2KSb:Cs photocathode still shows the larger sensitivity.

Cesium Telluride over GaAs

New recent successful result demonstrated that the Negative Electron Affinity formation on GaAs photocathodes can be achieved with an alternative to the Cs-O/F dipole-layer formation approach, which is instead based on the growth of an ultra-thin layer of Cs_2Te [8]. An immediate consequence of having an ultra-thin Cs_2Te activation film in place of the sensitive Cs-O/F is that it should significantly improve the GaAs photocathode resistance against chemical poisoning as seen from the experience of using Cs_2Te photocathodes in several photoinjectors that operates with the much relaxed vacuum levels typical of RF guns. This can potentially allow operation of Cs_2Te-protected GaAs in RF (or SRF) guns, which is also expected to reduce the effect of ion back bombardment because of the time dependent fields that the ions will be seeing in RF cavities and due to their mass-to-charge ratio being much larger than that of an electron. In addition to the effect on the polarization state of the electrons photoemitted from Cs_2Te NEA activated GaAs also mean transverse energies (MTE) deserve to be investigated for possible application of these photocathode in the generation of high brightness electron beam for X-FEL application. To answer these question the UHV installation of the Cornell Univeristy Photocathode Laboratory is being upgraded with a Mott polarimeter [9] and new experiments have been carried out in order to achieve the realization of NEA on GaAs by thin layer of Cs_2Te. Our initial results indicate indeed that a very thin layer of Cs_2Te is capable of producing the NEA on the GaAs wafers. The growth of Cs_2Te was performed by sequential and co-deposition of elemental Te and Cs evaporated using effusion cells under UHV conditions in our growth chamber. The growth was performed with the substrate cooling down to room temperature from about 120 C. At the end of the Cs_2Te growth the photocurrent generated with light at 532 nm wavelength corresponded to a QE of about 1.5%. QE remained stable in the growth chamber but it was found to have decreased by a roughly factor 2 once moved into another UHV chamber to measure spectral response. In the attempt to restore and further improve the sensitivity of the photocathode we exposed its surface to a very small flux of Cs evaporated using alkali chromate based source until the photocurrent was seen to increase. A new spectral response was taken just after the photocurrent peaked and. Both spectral response curves are reported in Fig. 2 showing that the onset of photoemission is observed for photon energies of about 1.4 eV indicating the formation of NEA surface. The photocurrent was measured in the activation Auger chamber while the photocathode was held in a vacuum lever better than $1x10^{-10}$ Torr. We observed QE decaying rather quickly and we were able to fit the experimental data using the sum of two exponential decay as reported in Fig. 3. The Auger spectrum (Fig. 3), collected at the end of the lifetime measurement, shows clear signatures of Cs and Te as well as Ga indicating the Cs_2Te layer to be few nm thin. We are now in the process of recommissioning the Mott polarimenter that was part of the SLAC photocathode test stand to perform polarization measurements on this and other promising photocathode materials.

MonteCarlo Simulation of Photoemission

For application in X-FELs and in Ultrafast Electron Diffractions where the required average current is very small or negligible the high QEs typical of alkali antimonides can be traded by operating these materials near the emis-

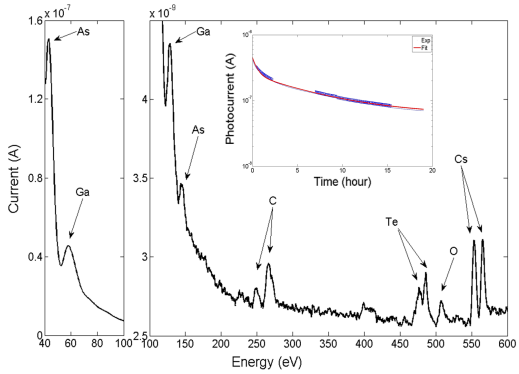

Figure 3: Auger spectra shows clear signal of Cs and Te, also the Ga and As lines are visible indicating that the thickness of coating is below few nm.

sion threshold taking advantage of the lower intrinsic emittances achievable in these regimes. When photocathodes are operated at near photoemission threshold electrons mean transverse energies limited by the lattice temperature can in principle be obtained. Based on these results we recently commissioned a cryogenic high voltage DC photogun that is capable of cooling the photocathode to about 40 K [10] allowing in principle to generate electron beam with MTEs of about 4 meV (corresponding to intrinsic emittances of about 0.09 mm mrad per mm rms of the laser spot size). Such extremely low intrinsic emittances are about one order of magnitude lower than the typical ones measured on commonly used photocathode materials like Cu and Cs_2Te. In order to study the onset of the photoemission to such low temperature we have developed a semiclassical Monte Carlo simulation for cesium antimonide (Cs_3Sb) with an emphasis on near-threshold photoemission properties. Interfacial effects, impurities and electron-phonon coupling are central features of our Monte Carlo model. We have used these simulations to predict photoemission properties at cryogenic temperatures as low as 20 K, and identified some of the critical material parameters that need to be properly measured experimentally for reproducing the electron photoemission properties of Cs_3Sb and other materials more accurately. One of the relevant result of the simulations relates the electronic structure of the material to the achievable electron beam MTEs. While is somewhat accepted that the emission near threshold for the alkali antimonide is originated from electrons belonging to impurity levels localized in the band gap, two different descriptions of how these levels are localized have been proposed in literature: The rst route, suggested by Spicer [11], claims acceptor levels being close to the valence band maximum and contributing an eective tail to the valence band density of states; the second route, suggested by Sakata [12], posits a sharply dened, isolated acceptor level well into the band gap (see Fig. 4). This last scenario carries with it the prediction of a freeze out of electrons leading to lack of electrical conductivity at extremely low temperatures. Near the photoemission threshold measurements of electron beams MTEs should reveal, as shown in Fig. 4, where these levels are located.

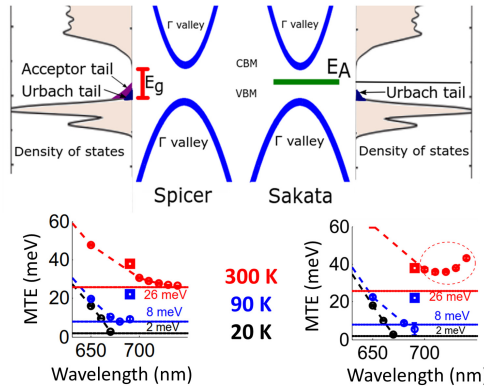

Figure 4: Schematics of the electronic structure of Cs_3Sb as proposed by Spicer and Sakata and simulation results for MTEs in both cases for different temperatures.

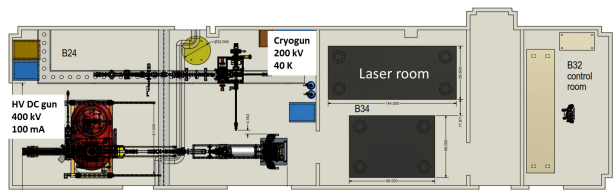

Figure 5: Layout of the photo gun laboratory being assembled at Cornell University.

CONCLUSIONS

A wide range of activities are being pursued at Cornell University to further develop the performance of photocathodes for photon detectors, for the production of electron beams having the required brightness for next generation light sources and to enable UED experiments on biological samples, and to explore new materials for the production of highly polarized electron beams. The photocathode laboratory is being complemented by a new photogun laboratory (Fig. 5) which will host two high voltage DC guns. One of these gun will have the capability to cryo-cool the photocathodes to 40 K.

REFERENCES

[1] B.W Adams *et al.*, arXiv:1603.01843v1.
[2] H.Lee *et al.*, Appl. Phys. Lett. 108, 2016, 124105.
[3] R. Suleiman *et al.*, Proc. of PAC11, paper WEODS3.
[4] S. Zhang *et al.*, Proc. of IPAC2015, paper TUPMA038.
[5] NP Community Panel Report on Electron Ion Collider (EIC) Accelerator R&D, February, 2017.
[6] M. Dvorak, Adv. Electronics Electron Phys. 28A, 61, 1969.
[7] G. Murtaza *et al.*, Bull. Mater. Sci. 39, 1581, 2016.
[8] M. Kuriki *et al.*, Proc. of IPAC2015, paper TUPWA062
[9] T. Maruyama *et al.*, Nucl. Instrum. Methods Phys. Res. A492, 199, 2002.
[10] H. Lee, this proceeding paper TUPAB127.
[11] W. Spicer, Phys. Rev. 112, 114, 1958.
[12] T. Sakata, J. Phys. Soc. Jpn. 9, 1031, 1954.

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