MULTI-ALKALI PHOTOCATHODE DEVELOPMENT AT BROOKHAVEN NATIONAL LAB FOR APPLICATION IN SUPERCONDUCTING PHOTOINJECTORS

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Abstract

The development of a suitable photocathode for use in a high average current photoinjector at temperatures ranging from 273 K down to 2 K is a subject of considerable interest, and active research. The choice of photocathode material is often a trade-off made based on the quantum efficiency of the cathode material, the tolerance to adverse vacuum conditions, and the laser wavelength needed to produce photoelectrons. In this paper an overview of the BNL work to date on CsK_2Sb photocathodes on a variety of substrates, irradiated at multiple wavelengths, and at temperatures down to 170 K will be discussed. The application of this photocathode material into a SRF photoinjector will also be discussed.

INTRODUCTION

The choice of photocathode material for use in a high average current SRF photoinjector is limited to a few candidates by the demands placed upon them by the parameters of the injector. The photocathode must possess a high quantum efficiency, preferably at least a few %, as well as have a work function at a convenient laser wavelength. This here is defined as the second or third harmonic of a Nd:Vanadate system, 532 or 355 nm. Finally, one would like a photocathode that is robust with regards to the vacuum conditions into which it is placed. While this has traditionally been the Achilles heel of photocathodes in normal conducting guns, the nature of the SRF photoinjector may alleviate this concern. This relief is not provided because the photocathode is any less susceptible to damage, but because the photoinjector does not warm up when operated as a normal conducting photoinjector does. Thus the outgassing of material from the photoinjector surface is negated, thereby resolving the issue of poisonous gas contamination of the photocathode.

The list of possible photocathodes offers up only a few photocathode candidates, namely multi-alkali photocathodes such as Cs_3Sb or CsK_2Sb, both with work functions below 2.23eV or 532 nm, or other semi-conductors such as GaAs, irradiated at 800 nm.

The photocathode of choice at BNL is CsK_2Sb due to the fact that in order to obtain currents on the order of 0.5A at 352 MHz there are additional conditions that must be satisfied.[1]

Table 1: The photocathodes considered as candidates for use in the 352 MHz, and 0.5A ERL are listed below.

Photocathode	CsK_2Sb	Cs_2Te*	GaAs[1]	Mg*
Laser wavelength	532nm/ 355nm	266 nm	800 nm	266 nm
QE	3-10%	3%	5-10%	.1%
Laser power to achieve .5A	38W/ 17W	77 W	15 W	2300 W
Prompt emission	Yes	Yes	No	Yes

*Not obvious candidates, merely shown for comparison sake.

[1]While GaAs has worked quite well in a DC gun it has never been used in an RF gun.

Table 1 presents a comparison of these different cathodes and the relevant laser parameters that are required to generate 0.5A average current. It is easy to see that there is really only one option, as unfortunately GaAs operating at these high currents would have a short lifetime due to its total electron charge delivery prior to needing re-cesiation as well as the fact that it is not a prompt emitter in the form that is needed here. The Cs_2Te photocathode which has been well demonstrated by FZ Rossendorf at 1 mA levels[2] requires a laser to deliver nearly 80 watts in the UV, a power level that is not presently possible, and without a significant breakthrough in laser technology will not be for quite some time.

Figure 1: The photocathode deposition system used for CVD of cesium potassium antimonide photocathodes.

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EXPERIMENTAL APPARATUS

The CVD system that is presently being used at BNL was built based on the deposition recipe and technique originally pioneered at Boeing[3] and was designed with the assistance of David Dowell. The general layout of the apparatus is shown in figure 1 with a schematic of the deposition process given in figure 2. As seen in figure 1, it is a UHV system, made up of three chambers separated by manual gate valves. The three chambers from left to right are the test chamber, the storage chamber, and the deposition chamber. Cathodes are fabricated in the deposition chamber and then placed in the storage chamber where there is a 5 substrate storage unit. This storage unit allows us to place a fresh cathode into storage for months at a time for periodic lifetime studies, as well as acts as a handoff location for substrate exchange. The test chamber has been designed for multiple photocathode studies, specifically the low temperature work through a cryogenically cooled manipulator arm, the oxygen QE enhancement and the high charge extraction using a fine wire mesh grid capable of being biased to 10s of kV and 100s of mA.

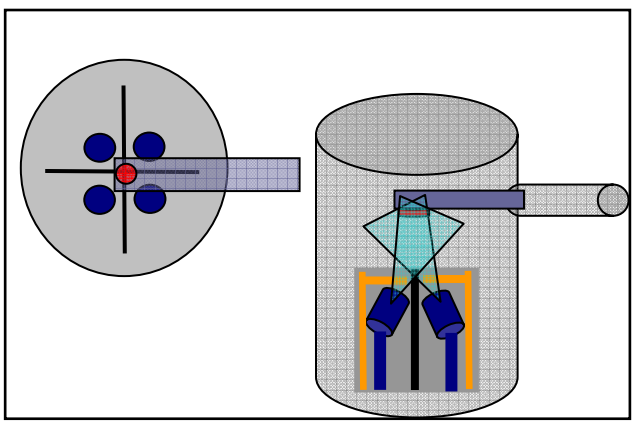

Figure 2: The Cesium Potassium Antimonide cathodes are made using a CVD technique from three independent furnaces. These furnaces are aimed at the cathode and covered by shutters to precisely meter out the chemical being heated. The deposition rate is monitored by a crystal balance.

Figure 2 shows a schematic of the operation of the deposition chamber during the CVD process. Briefly, a 1" circular substrate of molybdenum, copper, or stainless steel is heated to ~130°C at which point antimony is deposited to a thickness of 200 Å at a rate of ~1Å/sec. This is followed by deposition of potassium to a thickness of 130 Å, again at ~1Å/sec, after which cesium is deposited while illuminating the cathode with a 2 mW green HeNe at 542nm. The photocurrent is monitored as a function of the cesium deposition and the deposition is stopped when a maximum in current is reached. This deposition system has been used to prepare in excess of 40 photocathodes working to optimize the deposition technique. To date 2% QE is routinely obtained at 542 nm, while 10% QE was observed at 355 nm. The significance of studying the photoemission at 355 nm lies in the fact that commercial laser systems are quickly becoming available at MHz repetition rate and ps pulse length delivering sufficient laser power to produce >200mA average current. (Coherent Paladin 355, 8W, 81.25 MHz, 15ps) As such it is becoming cost effective, both in terms of dollars and wall plug efficiency, to seriously consider operating at 355 nm.

RESULTS

The key topics to be addressed with regards to the use of CsK_2Sb photocathodes in a high average current SRF photoinjector are the lifetime of the photocathode during irradiation, the emission uniformity, the ability to increase the QE through exposure to O_2 or H_2O, and the QE as a function of temperature. All of these items have been successfully addressed at BNL and will be discussed here.

The lifetime of the photocathode under constant irradiation is shown in figure 3. The photocathode was irradiated continually for 2 months using our 2mW HeNe and no degradation in performance was noted. The laser was also focused to a sub 100 μm spot size in order to simulate the current density that will be required for the ERL use. This focused laser study was carried out for 1 week with no notable decrease in performance.

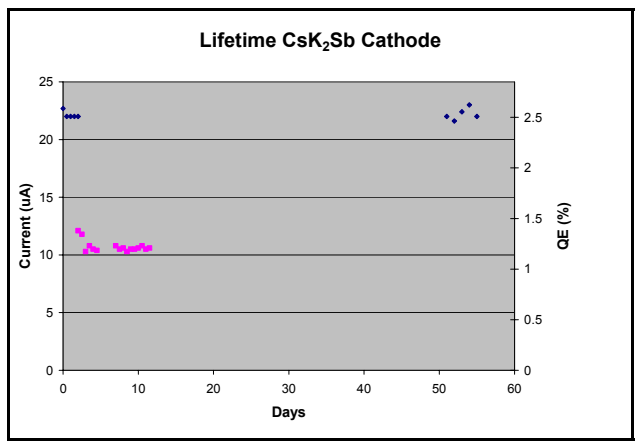

Figure 3: The photocathode lifetime studies in the deposition system under continual irradiation for 2 months. Data in blue is the normal laser beam while the magenta is the focused laser beam.

The uniformity of electron emission from the photocathode is another key parameter in designing a good photocathode. The electron beam emittance is directly related to the surface uniformity, so the more uniform the emission, the better the emittance. With that said, the emission uniformity is better at 355 nm than at 542 nm, and due to the fact that the QE is also higher this has led to the interest in operating at 355 nm. The superb uniformity may be due to the fact that the irradiation at 542 nm is very close to the work function of the material, and having a photon energy significantly greater than the work function helps ensure that the electrons are able to

escape out of the surface and are not recaptured by the bulk during escape collision de-excitation.

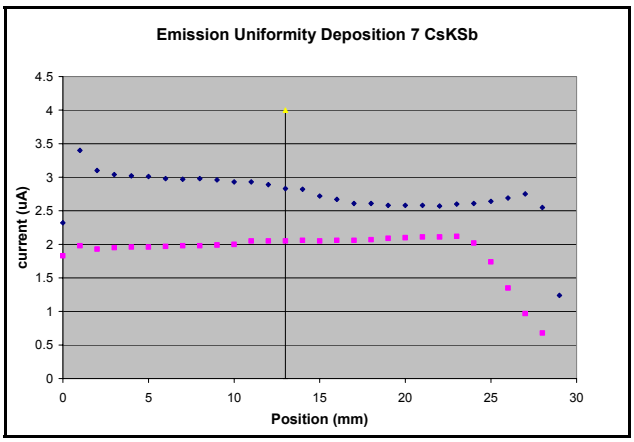

Figure 4: The surface emission uniformity was studied as a function of position and wavelength. The manipulator arm was moved in 1 mm increments and the photocurrent measured at each position. The blue markers are from irradiation at 542 nm, while the magenta are from irradiation at 355 nm.

Another approach to improving the QE of the photocathodes is to expose them to small quantities of O_2 or H_2O vapor. While this technique has been demonstrated before for different multi-alkali photocathodes[4] our study of the effect of O_2 exposure on a variety of substrates is given here. Table 2 lists the QE obtained on three different substrates and the effect of exposure to small quantities of O_2 on 2 substrates. The initial results are very encouraging, and in the future more detailed work and experimentation with the cycling of O_2 and Cs exposure will be carried out.

Table 2: A list of QE obtained on three substrates and the effect of exposure to O_2.

Substrate	QE w/o O_2	QE w/ O_2
Cu	1.95%	3.6%
Mo	2%	4%
SS	2.1%	

The final piece of data collected from the photocathode study is perhaps the most important for operation in a SRF photoinjector, namely the photocathode performance at reduced temperatures. This was studied on multiple substrates, Mo, Cu, SS, and the general effect can be seen in figure 5. From studying multiple samples in our test chamber attached to a LN_2 dewar it was possible to reduce the temperature at the substrate to -100 °C or 173 K. At these reduced temperatures the photocathode performance was only slightly below that at room temperature.

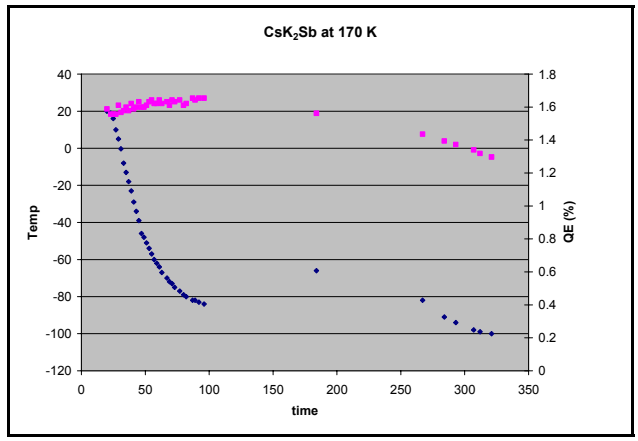

Figure 5: The CsK_2Sb QE measured as a function of temperature and time while being cooled to 170 K. The magenta symbols are the QE while the blue is the temperature.

From analysis of the data in figure 5 one can see that there is actually a slight rise in QE upon initial cooling of the sample. This is attributed to the fact that there is still a small partial pressure of water, $1x10^{-10}$ torr, in the vacuum system and as it is well established that exposure to small amounts of water increases the performance of the cathode. The subsequent decline in QE is likely due to the fact that the substrate is now cryo-pumping the residual gases in the chamber, effectively poisoning itself.

This data is very encouraging and demonstrates that these photocathodes can be used in an SRF environment. The cryo-pumping effect of the photocathode is not likely to be an issue as the photocathode will be inserted into the SRF photoinjector after the injector is cooled, and the photocathode will also be maintained above the temperature of the surrounding gun. The reason that past experiments with these photocathodes at reduced temperature showed a marked decrease in QE is attributed to the fact that in previous studies the photocathode was usually part of a photomultiplier tube and as such the substrate was glass. This resulted in the electron replenishment to the photocathode coming through the semi-conductor photocathode material itself. In our case the substrate is metal and is not subject to reductions in electrical conductivity as seen in semi-conductors.

REFERENCES

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[2] D. Janssen et al. Nucl. Instr & Meth., A507, (2003) 314.
[3] D. H. Dowell, S. Z. Bethel, K. D. Friddell, Nucl. Instr & Meth., A356, (1995) 167.
[4] B. Erjave. Appl. Surf Sci., 103 (1996) 343.