PROGRESS ON LEAD PHOTOCATHODES FOR SUPERCONDUCTING INJECTORS

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Abstract

We present the results of our investigation of bulk lead, along with various types of lead films, as suitable photocathode materials for superconducting RF injectors. The quantum efficiency of each sample is presented as a function of the photon energy of the incident light, from 3.9 eV to 6.5 eV. Quantum efficiencies of 0.5% have been obtained. Production of a niobium cavity with a lead-plated cathode is underway.

INTRODUCTION

An all-niobium superconducting RF gun has been proposed as an injector for a moderate average current (~1 mA) energy recovery Xray FEL [1]. Although niobium has proven to be a good superconductor, it is a comparatively poor photoemitter, with a typical Quantum Efficiency (QE) of $\sim10^{-5}$ for 266 nm light [2]. For this reason, we investigate lead as a candidate for a superconducting cathode material, with the eventual goal of constructing a hybrid lead-niobium cavity. The QE of several types of lead cathode was measured, including bulk, vacuum deposited, sputtered, electroplated and arc deposited. For all but the bulk lead and vacuum deposited cathodes, niobium was used as a substrate. The optimal laser cleaning energy density has been established, and the cathode surfaces have been studied via SEM.

PREPARATION OF LEAD CATHODES

Five distinct cathodes were studied in this work. The electroplated sample was prepared at Stony Brook University. The process for copper substrates has been described previously [2]. The procedure for plating niobium was identical to that for copper, except that the coating thickness is 2 µm.

The bulk lead cathode was prepared from cylindrical stock obtained from Goodfellow (99.95% purity). The surface was mechanically polished with Beuler diamond polishing compounds. This process and the resulting surface finish are described in detail elsewhere [3]. SEM images taken after the photoemission measurements revealed diamond inclusions covering roughly 5% of the cathode surface, likely imbedded during polishing.

The vacuum deposited sample was prepared at SBU in a vacuum evaporator, with a background pressure of 5 µTorr and a deposition time of 9 minutes. The coating thickness is 6 µm. A polished copper cathode was used as a substrate.

A sample was covered by means of the magnetron sputtering technique at the Soltan Institute. Deposition of lead was performed by using a cylindrical cathode and in the presence of argon under pressure of 3 mtorr. The Nb substrate was placed at the distance of 3 cm from the sputtered cathode. The current discharge was set at value of 100 mA. Such conditions ensure stable discharge without any surface melting of the cathode. The obtained film was smooth and macrodroplet-free. Total deposition time was 60 minutes and estimated thickness of the layer was 4 µm.

The arc deposited sample was prepared, at the Soltan Institute, by means of arc discharge with planar cathode in UHV conditions. This process is characterized by a high ionization ratio of metallic plasma, higher energy of ions in comparison with the magnetron sputtering technique and also a higher purity of the deposition process due to the absence of a working gas. A discharge current of 25 A allowed stable arc operation (typical value for niobium is 100 A). The deposition process was performed with an Aksenov-type magnetic filter connected to the plasma source in order to eliminate macrodroplets. The coating thickness is 1 µm on a niobium substrate.

LASER CLEANING

Laser cleaning with 248 nm light was used to improve the QE of all of the samples measured. The 248 nm light was provided by a KrF excimer (GAM Laser EX5), with a pulse duration of 10 ns. The damage threshold and surface structure after cleaning for electroplated lead has been determined previously [2]. Based on these results, an energy density of 0.2 mJ/mm^2 was chosen as the starting point for the cleaning. The surfaces were each irradiated for ~10 minutes, with the laser operating at 20 Hz. To avoid alignment difficulties, the region of the cathode exposed to the cleaning beam was significantly larger than the measurement area.

For the solid lead and electroplated samples, the cathode was cleaned a second time at an energy density of 0.4 mJ/mm^2. In both cases, little improvement was observed in the QE due to this increase. The samples were analyzed with an SEM after removal from the measurement system. The total air exposure between the measurement and SEM vacuum systems was kept under 10 minutes. Figure 1 shows the surface structure for four of the cathodes after cleaning. In all four cases, the X-ray fluorescence spectrum in the SEM showed only lead (no niobium), indicating that the coating was intact.

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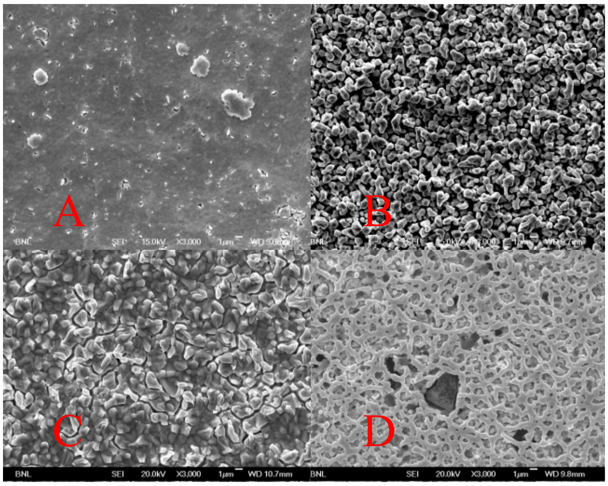

Figure 1: Surface structure of lead cathodes after laser irradiation with 0.2 mJ/mm^2: (**A**) Arc deposited (**B**) Sputtered (**C**) Vacuum deposited (**D**) Solid lead.

PHOTOEMISSION

A schematic of the photoemission measurement system is shown in figure 2. A deuterium light source (Ocean Optics DH-2000-S-DUV) is fiber-coupled to a monochromator with a 300 micron exit slit. The desired wavelength is selected by the dial on the monochromator (Edmund DCM1-01). The output bandwidth is 2 nm, measured with an Ocean Optics HR2000 spectrometer. A fused silica lens is used to focus the light on the cathode through a vacuum window and the anode mesh. The output of the monochromator is measured for each wavelength, at a point after the lens but prior to the vacuum window, using a power meter (Newport 918-UV). For the QE measurement, the anode is held at a positive voltage, and the current is measured leaving the cathode by a picoammeter (Keithley 487). The optical transmission of the vacuum window and the mesh are calibrated separately for each wavelength.

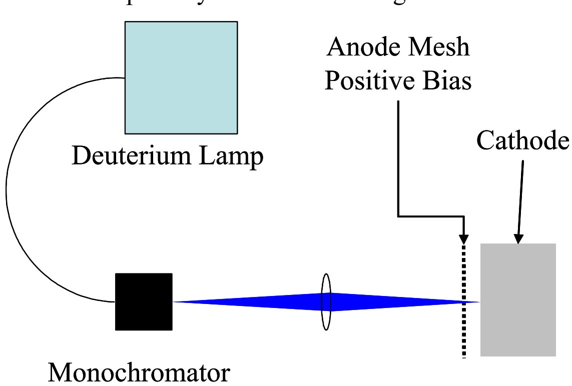

Figure 2: Apparatus for photoemission measurements.

Figure 3 shows the photoemission results for each cathode, at a field of 1 MV/m. Niobium [2] points are included for reference. While all of the lead cathodes are significantly superior to niobium, arc deposition results in the surface with the best QE.

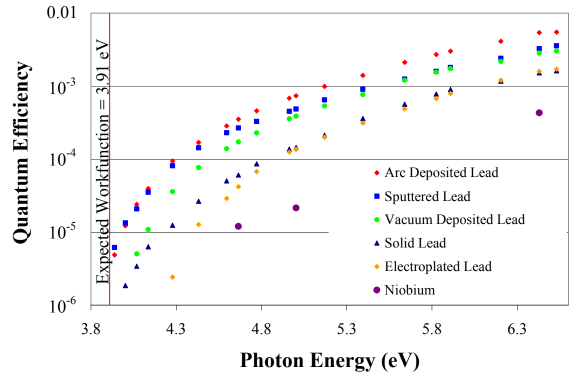

Figure 3: QE of lead cathodes at 1 MV/m applied field, after laser cleaning (0.2 mJ/mm^2).

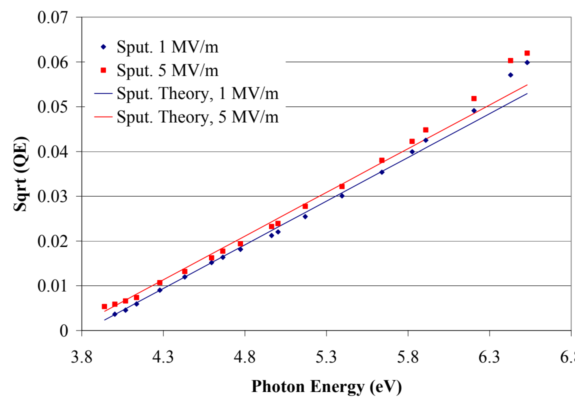

Figure 4: Sqrt QE vs photon energy for sputtered lead

For the vacuum deposited cathode and the sputtered cathode, measurements were made at 5MV/m gradient (in addition to those at 1 MV/m). Figure 4 shows the plot of (QE)^{½} as a function of photon energy for the sputtered lead. The horizontal intercept of this plot provides the workfunction (Φ) of the material. This value is expected to change with applied field due to the Schottkey effect. Table 1 gives the best fit Φ for each sample, along with the QE obtained at 213 nm (5.8 eV) and 193 nm (6.4 eV). The fitting for the workfunction was performed using a simple model, in which the QE is assumed to be proportional to (hν-Φ)^2. Minimization of the sum of the squares of the percent deviation between the theory and data was used to obtain Φ for each data set. This method emphasizes photon energies closest to Φ in determining Φ. No attempt was made to account for the 2 nm bandwidth of the lamp light. This introduces an uncertainty of ±0.04 eV on the values for Φ.

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Table 1: Workfunction and QE @ 213 nm & 193 nm

Material	Field	Φ	QE 213nm	QE 193nm
	MV/m	eV	x 10^{-3}	x 10^{-3}
Arc	1	3.86	2.7	5.4
Sputtered	1	3.82	1.6	3.3
Sputtered	5	3.72	1.8	3.6
Solid	1	3.91	0.8	1.5
Vac. Dep.	1	3.96	1.6	2.8
Vac. Dep.	5	3.88	1.4	2.8
Electroplated	1	4.18	0.7	1.6

The workfunction of lead is 3.95 eV [4] at zero applied field. Neglecting surface enhancement, the field is expected to reduce this to 3.91 eV for 1 MV/m, and 3.87 eV for 5 MV/m. The workfunction values largely match expectations, with the exception of the electroplated surface. Further investigation of the electroplated sample is planned to determine the source of this higher value for Φ.

PRELIMINARY RF GUN TESTS

A preliminary investigation of the effect of introducing lead into a niobium cavity has been performed at Jefferson Lab. A 1.42 GHz cavity has been constructed. The results of these tests are presented in another paper in this conference [5]. Neither the Q- values of the cavity nor the obtainable surface fields were found to be significantly lowered by the introduction of lead in the cathode region.

CONCLUSIONS AND FUTURE PLANS

The quantum efficiencies of five distinct lead cathodes have been measured for a broad range of UV wavelengths (190 nm-315 nm), corresponding to a range of photon energies from the work function of lead (3.9 eV) to 6.5 eV. Of the cathode deposition methods investigated, arc deposition has the best QE and surface quality after laser cleaning. The QE of the arc-deposited sample was 0.27% at 213 nm. With this QE, 2.1W of laser power would produce 1 mA average current. Laser cleaning with an energy density of 0.2 mJ/mm^2 of 248 nm light is sufficient to achieve the maximum QE from each surface.

An important question is raised by recent work on an all-niobium injector at BNL [6]. The QE of the niobium cathode was observed to be significantly worse at 4 K than at room temperature. For this reason, our next step will be to investigate the effect of cryogenic temperatures on photoemission from lead. The vacuum system has been modified with a cold finger that will allow QE measurements to be made with the cathode at ~80 K. Additionally, a second electroplated sample (lead on niobium) will be measured to see if the higher-than-expected value for Φ is characteristic of this process.

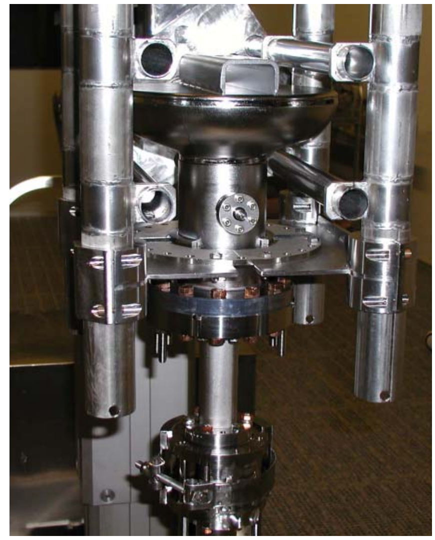

Figure 5: Niobium cavity at DESY

A 1.3 GHz niobium SRF cavity has been constructed at DESY (Figure 5). The cavity is currently undergoing cold tests. The cathode region of this cavity will be plated with lead. The emission properties will be characterized using an arrangement similar to that used for the all-niobium cavity at BNL [6].

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