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PHOTOEMISSION PROPERTIES OF LEAD*

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Abstract

In this paper we present a study of the photoemission properties of lead at several UV wavelengths, including a study of the damage threshold of electroplated lead under laser cleaning. A quantum efficiency in excess of 0.1% has been achieved for a laser cleaned, electroplated lead sample with a laser wavelength of 193 nm. Niobium cathodes have been measured for comparison, and lead is found to be a superior photoemitter for all measured wavelengths.

INTRODUCTION

There is significant interest in the possibility of building a superconducting injector for moderately high average current accelerator applications [1]. Such an injector would be made considerably simpler if it could be designed to use a superconductor as the photocathode, eliminating the need for Cesiated materials in the injector. Unfortunately, although niobium has proven to be a good superconductor, it is a comparatively poor photoemitter. For this reason, we investigate lead as a candidate for a superconducting cathode material.

PREPARATION OF LEAD CATHODES

The cathodes used in this work were lead films electroplated on copper substrates. The surface of the copper substrates was mechanically polished with Beuler diamond polishing compounds. Nine, six and one micron polishing compounds were used, resulting in a mirror finish with scratches on the order of one micron wide. This process and the resulting surface finish are described in detail elsewhere [2,3].

The polished cathodes were electroplated with lead by a procedure developed for use on superconducting cavities for heavy ion accelerators [4]. The plating solutions are based on methane-sulfonic acid chemistry and are created from commercially available products [5]. Each cathode was immersed in plating solution and flashed four times for several seconds with 10 mA/cm^2 plating current to prepare the surface. The current was then lowered to 2 mA/cm^2, corresponding to a plating rate of 10 μm/hour, and plated with 8 μm of lead. The cathodes are then rinsed with de-ionized water and dried with a stream of nitrogen gas.

To even more closely mimic real world conditions, a second class of cathodes was initially plated, chemically stripped, then re-plated. The stripping solution was 10% Solderon Acid to 90% de-ionized water by volume. The QE was measured for both cathodes, and found to be similar. For the purpose of identifying the cathodes, the cathode which was plated but not stripped will be designated cathode 1, and the cathode that was plated, then striped, then plated will be designated cathode 2.

DAMAGE THRESHOLD

The damage threshold of the lead plating was established by irradiating a lead coated sample with 248 nm light. Different cathode locations were irradiated for 40 minutes by laser energy densities ranging from 0.11 to 1.8 mJ/mm^2. In all cases, the laser spot on the cathode was 1 mm in diameter, controlled by an aperture. The laser used for this measurement was a KrF Excimer with a pulse duration of ~20ns and a repetition rate of 10 Hz. After irradiation, the cathode was removed from the vacuum and observed with an optical microscope and a scanning electron microscope (SEM). The SEM was used to perform an analysis of the surface composition as well as the surface structure. SEM pictures at each energy density are shown in figure 1.

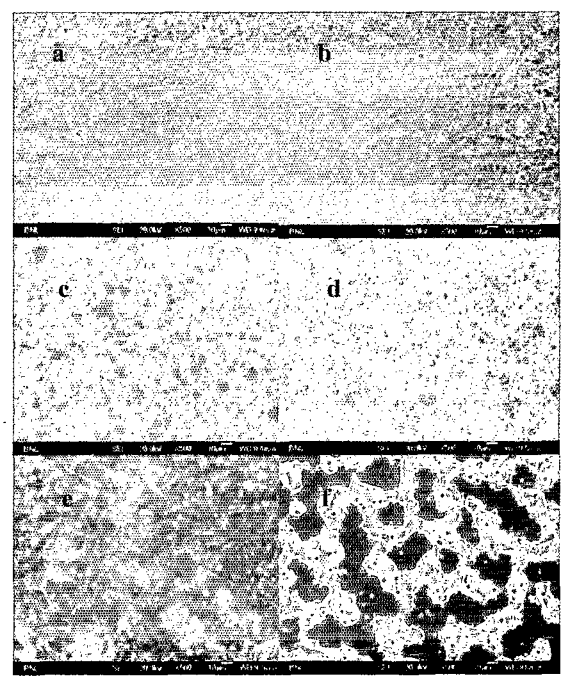

Figure 1: Surface structure of lead coated cathode after laser irradiation: **(a)** no laser **(b)** 0.11 **(c)** 0.26 **(d)** 0.52 **(e)** 1.1 (f) 1.8 mJ/mm^2.

Two energy-density thresholds were observed. The first corresponds to a visible structural change to the surface at an energy density of 0.26 mJ/mm^2. The characteristic size of the surface structures increases with increasing laser energy density. The second threshold was the density at which the laser removed a portion of the few-micron lead coating and exposed the copper substrate. This was identified by looking at the X-ray fluorescence spectrum in the SEM and observing copper peaks. No copper spectrum was observed for energy densities up to 1.1 mJ/mm^2. For 1.8 mJ/mm^2, the surface was noticeably modulated (figure 1f). A clear copper fluorescence peak is observed when the SEM electron beam is focused on the valleys in this surface (the dark areas in the figure), indicating that energy density between 1.1 and 1.8 mJ/mm^2 is sufficient to remove the lead plating.

PHOTOEMISSION

Photoemission measurements were performed in a vacuum cell with parallel electrode geometry. Charge leaving the cathode was measured with a charge-sensitive preamplifier. The anode consisted of a copper mesh to allow laser irradiation to the cathode at normal incidence. The anode mesh was biased to extract the photoemitted electrons. This bias was also used to investigate the dependence of the QE of lead on the applied field (in the range of 1 to 10 MV/m). The vacuum cell was mounted on a motorized stage, enabling the cathode position to be adjusted to maximize overlap between the cleaned area and the measurement lasers. This apparatus is described in detail elsewhere [2,3].

Three lasers were used to measure the QE, to investigate the dependence of the QE of lead on wavelength (λ). A frequency-quadrupled Nd: YAG laser provided 266 nm light with 10 ns pulse duration. A KrF excimer was used for 248 nm light, and an ArF excimer was used for 193 nm light, both with 20 ns pulse duration. The KrF laser was used to laser clean the surface between photoemission measurements. During this process, a rectangular area of the cathode (1.8x2.2 mm^2) was exposed to a specified energy density at 20 Hz for 10 minutes. The cleaning and photoemission measurements are made at normal incidence to the cathode, through the anode grid. The anode grid occludes 10% of the incident light; this factor is accounted for in the stated QE values. During laser cleaning, no bias was applied to the anode.

The QE of the cathodes are shown in tables 1 & 2. The QE measurements were made for all three λ* under variable bias from 1 to 10 kV; results for 1 kV and 5 kV are shown. The laser energy used to extract the charge was controlled to keep the charge at less than 2 pC for all wavelengths. At this value of charge the charge scales linearly with the laser energy, indicating that the process observed is linear photoemission with no significant space charge retardation of the emission. The small observed variation of the QE with field is explained by the Schottky reduction of the workfunction in the presence of an applied field [2,3]. The QE was observed to increase by a few percent over the course of the measurement (at a constant bias). This effect is attributed to a minute laser cleaning process occurring due to the measurement laser. This interpretation is supported by the fact that the increase was most pronounced for the cathodes prior to laser cleaning, where the low QE required a measurement laser energy of ~2μJ, as compared to <30 nJ for the cleaned surfaces. The measurement spot was roughly 1 mm in diameter. The values for 1 kV and 5 kV shown in the table were taken after the cathode QE had stabilized.

Table 1 Quantum efficiency for cathode 1.

Laser Cleaning Energy Density (mJ/ mm^2)	λ (nm)	Quantum Efficiency x10^{-4} 1kV bias	5kV bias
Prior to Cleaning	193	25	26
0.24	193	30	31
0.51	193	30	31
0.24	248	2.9	3.0
0.51	248	2.3	2.4
Prior to Cleaning	266	0.0025	0.0027
0.24	266	1.3	1.4
0.51	266	1.2	1.3

Table 2 Quantum efficiency for cathode 2

Laser Cleaning Energy Density (mJ/ mm^2)	λ (nm)	Quantum Efficiency x10^{-4} 1kV bias	5kV bias
Prior to Cleaning	248	0.27	0.30
0.82	248	2.8	3.0
Prior to Cleaning	193	3.5	3.7
0.82	193	16	17

The process of laser cleaning burns the shadow of the anode grid into the cathode surface, as shown in figure 2. It is interesting to note that the cleaned area of the cathode appears brighter than the area occluded by the grid in the SEM image. This implies that the cleaned area of the cathode has an improve secondary emission yield, suggesting that laser cleaning improves the QE of the cathode for electron, as well as photon, stimulated emission.

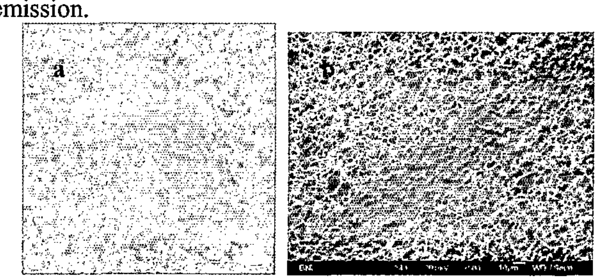

Figure 2 SEM images of cleaned area of cathode 1 (**a**) and 2 (**b**), including the shadow of a line from the anode grid.

For the purpose of comparison, two bulk RRR 250 niobium samples were measured in a manner identical to that used for lead. The niobium samples were prepared with Buffered Chemical Polishing, a standard cleaning method for niobium cavities. One sample was measured as delivered, while the second was mechanically polished

* 248 nm light was not used for QE measurements prior to laser cleaning.

using the same diamond polishing technique used on the copper substrates for the lead. The results of this measurement are shown in tables 3 & 4. Other niobium samples have yielded a QE of $6x10^{-5}$ for 266 nm and $1x10^{-4}$ for 248 nm using different laser cleaning [2,3].

Table 3 QE of polished niobium cathode at 1 kV bias

Laser Cleaning Energy Density (mJ/ mm^2)	Wavelength (nm) 193	248	266
	QE (x10-4)		
Before Cleaning	1.0	0.036	0.009
0.76	2.4	0.087	0.037
1.45	2.5	0.078	0.042
2.52	2.2	0.067	0.035

Table 4 QE of etched niobium cathode at 1 kV bias

Laser Cleaning Energy Density (mJ/ mm^2)	Wavelength (nm) 193	248	266
	QE (x10-4)		
Before Cleaning	1.0	0.02	0.005
0.76	4.9	0.15	0.075
1.45	5.7	0.22	0.12
2.52	5.3	0.18	0.11

Note that the values obtained for niobium are significantly lower than the theoretically achievable values [4]. This observation is common to nearly all niobium cathodes that have been measured in accelerator literature, suggesting that achieving the optimal QE from niobium that has been prepared as a superconducting cathode is quite challenging.

CONCLUSIONS

The quantum efficiencies of lead and niobium have been measured for three UV wavelengths (266 nm, 248 nm, 193 nm). Prior to laser cleaning, the QE at 193 mn was $\sim 2x10^{-3}$ for electroplated lead. With very modest cleaning energy density, the QE was found to be $\sim 3x10^{-4}$ for 248 nm and $\sim 1.3x10^{-4}$ for 266nm, consistent with values for pure lead [6].

The relatively high QE of lead, coupled with the availability of harmonic crystals capable of phase-matching to 193 nm† and high-average power Ti: Sapphire laser systems‡, open the possibility of constructing a 1 mA injector based on all-superconducting technology. A niobium injector with a lead coating on the cathode region may be able to maintain the high Q and surface fields that can be obtained in a superconducting cavity, while supplying a moderate average current.

† See for example: Cesium Lithium Borate (CLBO)

‡ 1 mA would require a laser power of <3W @ 193 nm, requiring perhaps 15-20 W from the fundamental (772 nm).

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