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Mg based photocathodes for high brightness RF photoinjectors

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Abstract

Advanced high brightness radio frequency (RF) gun injectors require photocathodes with a fast response, high quantum efficiency (QE) and good surface uniformity. Metal films deposited by various techniques on the gun back wall could satisfy these requirements. A new deposition technique has been recently proposed, i.e. pulsed laser ablation. Several Mg samples have been deposited by this technique: the emission performance and morphological changes induced on the cathode surface during laser activation are compared and discussed.

Keywords: Magnesium; Pulsed laser deposition; Quantum efficiency; Photocathode

1. Introduction

The main trend in electron sources of ultra-bright electron beams is the use of a radio frequency (RF) gun photoinjector. The most common version of an RF gun is a cylindrical RF cavity made of a half cell plus a full cell (1.5 cells gun). The electromagnetic fields in the cavity oscillate in such a mode that the electric field amplitude is maximum at the middle of the back plane of the half cell. In this zone is inserted the photocathode [1]. The requirements for photocathodes are prompt response, low thermal emittance [2], long lifetime and high quantum efficiency (QE), defined as the number of emitted electrons per incident photon, at wavelengths affordable by existing lasers. Metallic cathodes are fast (tens of femtoseconds range) but their QE is low compared to alkali semiconductors. Drawbacks of alkalis are slower response and short lifetime. In addition, they are delicate and require UHV both during transport and in operation. Metals are rugged and a few of them, such as Cu, Mg, Pb and Y have reasonable QEs at near UV wavelength (266 nm). Bulk Cu and Mg cathodes are already in use in several photoinjectors. The Cu back plate of 1.5 cells RF guns has been used directly as photocathode. With accurate cleaning procedures Cu can attain a QE in the order of 10^{-4} and good emission uniformity [3]; however, Mg disks inserted by press fitting in the Cu back plate of the RF gun cavity have shown problems with RF breakdown at the Mg–Cu interface [4]. Moreover, the QE distribution over the irradiated area can be extremely non-uniform [5]. High quality metal films deposited directly on the gun plate could circumvent such problems. Sputtered Mg films have already been tested. They are rugged and the oxide layer that forms when the film is exposed to ambient air can be easily removed by laser cleaning [6]. However, when tested in the very high electric fields of a RF gun, the sputtered Mg films have been damaged by discharges during RF conditioning [7]. This is due to poor quality of the film, especially regarding uniformity and adhesion. A key parameter determining the quality of a deposited film is the kinetic energy of the particles impinging on the substrate. Therefore it is worthwhile to study alternative deposition processes with higher inherent particle energies, such as pulsed laser deposition (PLD) [8]. Previous results on Mg films grown by PLD gave promising results in terms of achievable QE and uniformity of emission [9,10].

2. Experiment

The PLD deposition apparatus is made up of an UHV chamber containing the Mg target to be ablated and the

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substrate to be coated. A pulsed laser beam from a XeCl excimer laser ($\lambda = 308$ nm, $\tau = 30$ ns), enters through a quartz window, impinges on the target with a 45° angle of incidence and forms a plume of Mg vapor. The substrate is placed in the plume cone at few cm distance from the target. The PLD technique makes multi-layer deposition of different materials viable within the same session by using composite targets. By this means one can cover the main film with a thin protective layer to avoid pollution by ambient atmosphere, or create additional layers of special materials to enhance emission yield. A graphite protective layer has been tested. In that case, the target was Mg–C, with a Mg belt surrounding a graphite core. The laser beam was translated in succession from one zone to the other.

Thus, we produced films 0.2 μm thick and covered with 20–60 nm protective layers of graphite, deposited in UHV at pressures on the order of 10^{-6} Pa. Additionally, other deposition experiments were carried out in He background atmosphere (5 Pa). This allowed the growth of thicker films, making use of the ''plume confinement'' effect [11]. The deposition parameters of the grown samples are listed in Table 1.

The QE measurement and laser cleaning apparatus consisted of a test UHV chamber, at 10^{-7} Pa background pressure. Two electrodes are arranged in the middle of the cell. One of them, holding the film to be measured, constitutes the cathode. DC voltages up to 5 kV can be applied to the anode. An UV 266 nm laser pulse, 30 ps duration, from a mode-locked Q-switch frequency quadrupled Nd:YAG laser, entered through a quartz window to excite the cathode. The laser beam crossed the anode through a fine copper wire mesh and illuminated the cathode at normal incidence.

For the purpose of laser cleaning the laser beam was focused on the cathode surface. The laser spot had a diameter of about 300 μm. The laser pulse energy density was about 300 μJ/mm^2. The cleaning operation was performed in steps. In each cleaning step the laser beam was scanned over an area of approximately 2.4 mm × 2.4 mm by executing a double raster. After the activation process, the laser beam diameter was enlarged up to about 1 mm to cover the emitting spot and the laser energy was decreased to perform QE measurements far from space charge saturation limit. Accelerating electric fields up to 2 MV/m can be applied to the diode. The emitted charge is sent via a coaxial cable to the input of a high-speed oscilloscope or to a high sensitivity charge amplifier.

The morphology and the composition of the samples were studied by scanning electron microscopy and energy dispersive X-ray spectrometry (SEM and EDS, JEOL-JSM-6468LV) both before and after the QE measurements.

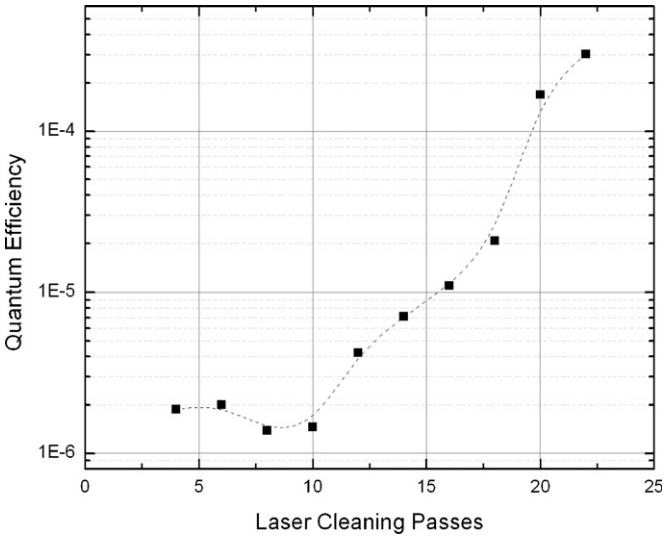

Fig. 1. The graph reports the QE as a function of the laser cleaning passes used to remove the protective graphite layers from sample labeled Mg003.

3. Results and discussion

Fig. 1 reports the QE values for the sample labeled Mg003 after several cleaning cycles. This sample, as shown in Table 1, is a Mg film (thickness about 200 nm) covered by a thin graphite layer (about 60 nm). There is an evident increase of the emission yield by two orders of magnitude (from 10^{-6} to 10^{-4} range). This result suggest that the graphite covering layers effectively protect the Mg layer from oxidation and that with the removal of this coating the quantum efficiency of the photocathode may be restored to high values.

In Fig. 2 the maximum values of QE achieved with an electric field of 1 MV/m for different samples are reported and the relative emission curves, plotted as collected charge versus laser energy, are shown. It can be observed that the highest QE values have been obtained from the Mg samples without the graphite protective layer. It is noticeable that the maxima QE value measured for such samples (1.7×10^{-3}) is the highest ever reported in literature for Mg.

SEM and EDS characterization of the irradiated surface of a graphite covered Mg film are reported in Fig. 3. The SEM micrographs reveal that the surface of the area irradiated to remove the protective graphite layer presents a periodic patterning. The main dark lines represent the shadows of the

Table 1
Experimental parameters used for deposition of Mg and Mg covered with graphite samples

Sample	Target	Substrate	T–S distance (cm)	Laser spot size (mm^2)	Deposition pressure (Pa)	Laser pulses	Laser fluence (J/cm^2)
Mg002	Mg + C	Cu	4.5	1.1	5×10^{-6}	30000 + 2000	10
Mg003						30000 + 9000	
Mg007	Mg		3.5	0.9	5 He	50000	14
Mg009							10

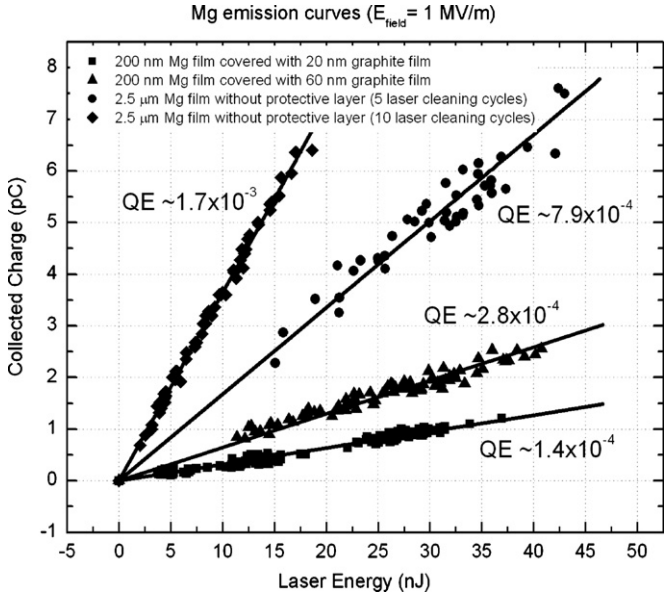

Fig. 2. Emission curves at the highest achieved QE values for PLD Mg grown samples.

anodic grid crossed by the laser beam. The finer structure of lines are Fresnel fringes generated by the anodic grid, as checked by numerical simulation. Looking at the EDS maps it is evident that the pattern observed with SEM has several correspondences with compositional maps. Therefore, from the EDS maps it can be deduced that the graphite protective layer had not been completely removed and, moreover, that the laser cleaning was not uniform over the irradiated area. Our tests had shown that the removal of the graphite layer requires a stronger laser cleaning than to remove the thin layer of oxide that forms naturally on the unprotected surface. Therefore, it can be argued that the lower measured QE of Mg films that had been protected with a graphite layer with respect to that of the unprotected ones is due to the non-uniform and non-complete removal of the protective coating.

The surface morphology of the Mg films deposited in He is reported in Fig. 4. While low magnification SEM pictures do not show macroscopic differences between the film surfaces before and after the laser cleaning cycles (Fig. 4a and c), high magnification micrographs reveal interesting details about the surfaces of the deposited films. Indeed, the Mg films deposited in He atmosphere are comprised of an agglomerate of droplets with diameters ranging from a few hundreds of nanometers up to a few microns (Fig. 4a and b). High magnification SEM pictures of the irradiated areas show that during the laser cleaning cycles the material undergoes also some kind of laser annealing. In fact, during the laser cleaning process with pico-second laser pulses, due to thermal effects, surface layers may be ablated and then removed from the laser exposed areas, while the deepest layers may suffer heating just below the vaporization temperature. In this case the liquid material can fill the voids that characterize the original film morphology shown in Fig. 4b, giving rise to the surface morphology observed in Fig. 4d. Evidences of sub-micron sized explosions probably due to residual gases trapped inside cavities are also present.

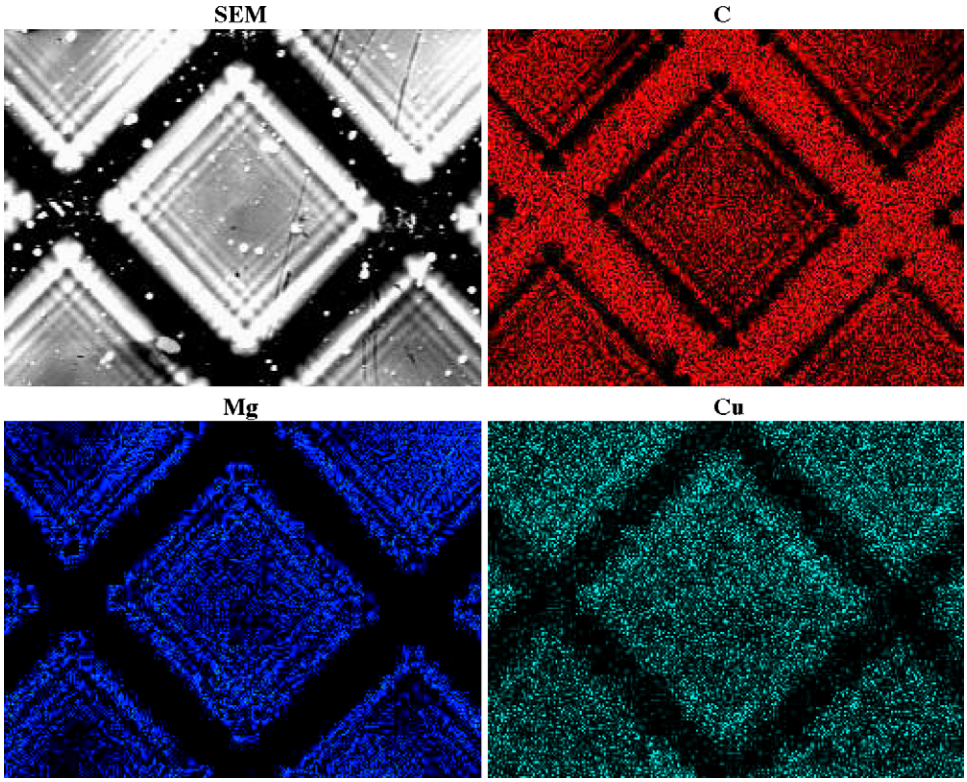

Fig. 3. SEM and EDS maps of the areas interested by the laser cleaning on Mg covered by graphite (sample Mg003) film show that not all the graphite protective layer has been removed. The reason for this non-uniform cleaning lies on the diffraction pattern generated by the anodic mesh.

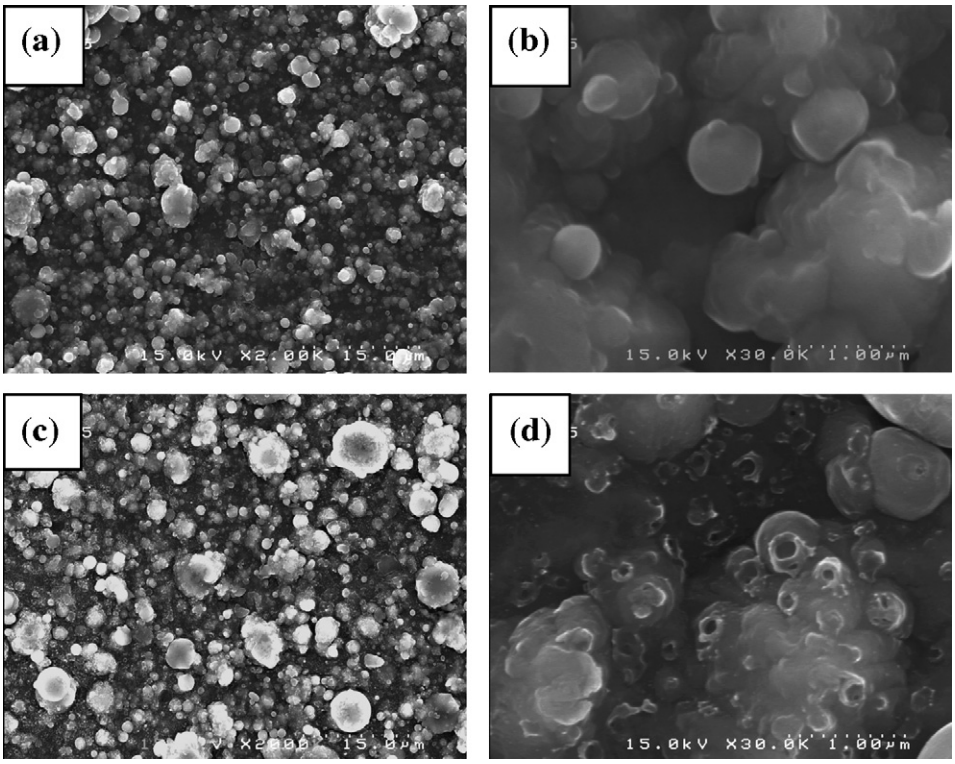

Fig. 4. (a–d) SEM micrographs at different magnification showing the surface of an Mg film before and after the laser cleaning. In particular, pictures are relative to sample Mg009 after five laser cleaning cycles.

A droplets-rich structure of the film may give rise to intolerable levels of the background current due to field emission under the very high electric fields (on the order of 100 MV/m) experienced in RF guns. This has to be verified by power tests. In this respect it is anyway interesting to notice that the annealing process taking place during laser cleaning may render the surface smoother and therefore alleviate the field emission phenomena.

4. Conclusions

Mg films produced using PLD are promising candidates for the photocathodes required for high brightness electron sources. The deposition parameters needed to obtain uniform and high QE films have been determined. A thin protective layer of graphite or oxide allows easy handling and conservation of the cathodes before installation in the RF gun. The post-annealing of the film surface can be useful in decreasing its roughness in order to reduce the dark current emitted in high RF electric fields. This can be verified only by power tests in an RF gun.

The film cathode usable in a 1.5 cells RF gun is simply obtainable by depositing the film in the middle zone of the back plate of the cavity. The challenge posed to the PLD technique is to deposit a well adherent and uniform 10 mm diameter film in the middle of a 10 cm diameter plate. The construction of such a cathode is in course and successive power tests are foreseen.

Acknowledgements

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