

Photocathodes for RF photoinjectors

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Abstract

Over the past ten years photocathodes have been extensively used as high-brightness electron sources in RF guns. In this paper, I present a general review of the alkali-based high quantum efficiency (QE) photoemitters (e.g. Cs₃Sb, K₂CsSb and Cs₂Te), together with a comparative analysis of the different preparation procedures and the results obtained, both in the preparation chambers and in RF guns.

The need to increase the photocathode reliability has provided the impetus to get an R&D activity to go over the alchemy of photocathode preparation procedure. In this paper, I will discuss the results so far obtained in different laboratories, both by using traditional investigation strategy (e.g. QE and RF behavior) and by means of surface science techniques as Auger Electron Spectroscopy (AES) and X-ray Photoelectron Spectroscopy (XPS).

Alkali antimonides have been used at first in the RF gun due to the high QE response to the green light of the Nd:YLF second-harmonic radiation. Measurements have confirmed the high reactivity of the alkali antimonide photocathodes to the residual gases: this fact makes their use in RF guns not practical, mainly for short lifetimes.

Further investigations have shown that the choice of the substratum preparation procedure and chemical composition plays a fundamental role in the photocathode performance, both from the point of view of the QE and the operative lifetime and ruggedness to gas exposition.

Cesium telluride (Cs₂Te) prepared on a molybdenum substratum seems to be, nowadays, the best compromise, in terms of preparation procedure reliability and ruggedness, that now the characteristics and drawbacks of this material are well understood (e.g. the need of an UV laser source).

Future possible developments will be discussed. In particular, the measurement and the control of the thermal emittance and the time response could be an important task.

1. Introduction

Radio Frequency (RF) photoinjectors are nowadays the most promising sources of high-brightness and low-emittance electron beams [1]. A photoinjector consists of a photoemissive material located in a high-gradient RF accelerating structure: a laser beam illuminates the photocathode and the photoemitted electrons are promptly accelerated. In this way it is possible to control the spatial (charge distribution, current density, etc.) and temporal (bunch length, phase with respect to RF, etc.) characteristics of the emitted electrons. The fast energy gain, due to the location of the electron source inside the accelerating structure, gives the possibility to produce high brightness, short electron bunches [2].

Since the electron source is the photocathode, photoinjector performances and operative characteristics

strongly depend on photoemitter characteristics. The general requirements for photocathode as RF gun electron sources are summarized here. A photocathode must have a fast response time, of the order of ps, in order to have a correct phase matching with the RF power in the injector. Moreover, to have a high-brightness beam, photocathode must be able to produce high current density (hundreds of amperes per square centimeter). Finally, the photocathode must have a reasonable quantum efficiency and a long lifetime.

Unfortunately, QE and lifetime requirements are in contrast and the choice of the photocathode is usually a compromise between high QE and a long lifetime.

2. Overview on photocathodes

Generally speaking, photocathodes can be divided in two different groups: metallic photoemitters and semiconductors. Metallic photoemitters are robust, both from the residual gases contamination point of view and the

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electric breakdown problems, but they have a low QE value (of the order of 10^{-4} in the UV range) due to their high reflectivity and electron–electron (e–e) scattering that reduce the escape depth [3]. The e–e scattering may also increase the emittance of the photoemitted electrons [4].

Among semiconductor photoemitters, Cs_3Sb and K_2CsSb [3,5] ($E_G + E_A$ about 2 eV, where E_G is the energy gap and E_A the electron affinity) can be operated with visible light but are very sensitive to contamination and must be operated only in XUV environments ($p < 10^{-10}$ mbar). Semiconductors with higher E_G value, such as CsI, are more robust but require the use of the radiation with λ shorter than 250 nm. Negative Electron Affinity (NEA) [6] photoemitters (as GaAs–Cs–O) can be used with visible light but they are still very sensitive to contamination. Moreover, they usually have a longer response time due to the tail in the electron emission [7].

The alkali-metal-based photoemitters fulfill the majority of the requirements previously discussed. Different laboratories have tested and used them, both in R&D apparatus (preparation chambers and HV DC electron extractors) and in RF injectors. Table 1 shows a summary of the alkali-based photocathodes used in the different laboratories, together with their characteristics and performances.

The main problem in using photoemissive semiconductor film in RF gun is the short lifetime due to high sensitivity of these compounds to contamination and the related poisoning effects caused by the residual gases. Moreover, an empirical approach to the preparation procedure optimization does not guarantee a good reliability of the film properties.

Therefore, the effort in the last years have concentrated on these limitations to understand and control the preparation procedure and the poisoning effects. Accordingly, new techniques have been applied, which are traditionally used in other fields, as Auger Electron Spectroscopy (AES) and X-ray Photoemission Spectroscopy (XPS). The use of these techniques is not effective due to the extreme sensitivity of these materials both to vacuum conditions (e.g. less than 1 Langmuir of oxygen can destroy a K_2CsSb film [21]) and to the possible alterations induced in the film structure and composition by the same investigating technique (e.g. electron beam during the characterization of a polluted film).

3. Alkali antimonide

Alkali antimonide, and in particular, Cs_3Sb and K_2CsSb , extensively used in photodiodes and photomul-

Table 1
Summary of the photocathode produced and used in different laboratories

Laboratory	QE % @ λ	Substrata	Operational lifetime ^a	Pressure (mbar)	Resp. time (ps)	QE measurement technique	E _{max} (MV/m)	Ref.
CEA								
Cs_3Sb	1.3 (@ 532 nm) ^a	Mo	–	10^{-10}	–	Low voltage	25	[8]
K_2CsSb	3 (@ 532 nm) ^a	Mo	$T_{1/e} > 1$ h	10^{-10}	–	Low voltage	25	[9,10]
Cs_2Te	10 (@ 265 nm) ^b	Mo	–	10^{-10}	–	Low voltage	25	[11]
CERN								
Cs_3Sb	0.4 (@ 532 nm) ^b	–	–	10^{-9}	–	High voltage	8 ^c	[12]
Cs_2Te	6 (@ 266 nm) ^a	Cu/Cu + Mo	$T_{1/e} > 100$	10^{-9}	~ ps	High voltage	100	[13]
LANL								
Cs_3Sb	4 (@ 527 nm) ^a	Mo	$T_{1/2} < 4$ h	10^{-10} – 10^{-9}	~ ps	Low voltage	> 20	[14]
K_2CsSb	8 (@ 527 nm) ^a	Mo	$T_{1/2} < 4$ h	10^{-10} – 10^{-9}	~ ps	Low voltage	> 20	[14]
Cs_2Te	13 (@ 263 nm) ^a	Mo	$T_{1/e} > 100$ h	10^{-10} – 10^{-9}	< 3 ps	Low voltage	> 20	[14]
Milano								
Cs_3Sb	9 (@ 543 nm) ^b	Cu	–	10^{-10} – 10^{-9} ^b	–	Low voltage	–	[15]
K_2CsSb	6 (@ 543 nm) ^b	S. Steel	–	10^{-11} – 10^{-10} ^b	–	Low voltage	–	[16,17]
Cs_2Te	13 (@ 254 nm) ^b	Mo	–	10^{-10} – 10^{-9} ^b	–	Low voltage	–	[18]
Twente								
K_2CsSb	4 (@ 534 nm) ^a	Mo	$T_{1/2} < 2$ h	10^{-9}	–	Low voltage	28	[19]
Cs_2Te	20 (@ 254 nm) ^b	Mo	$T_{1/2} > 10$ h	10^{-9}	–	Low voltage	28	[20]

^a RF gun

^b Test system

^c HV DC test gun

tipliers tubes, have been the first photocathodes used in RF guns. In particular, Cs₃Sb was the photocathode employed inside the first RF gun at LANL in 1988 [22]; in consequence of the high dark current in the gun this material was replaced by K₂CsSb [23].

As shown in Table 1 these photocathodes have been investigated in many laboratories but only CEA, LANL and Twente have successfully operated them in an RF gun.

Even though these photoemitters are largely used, the recipe for the fabrication is not well standardized and the formation process is unknown. For instance, Twente [19] and CEA produced this film starting from a thin layer of K₃Sb. Furthermore, Milano has developed a recipe for K₂CsSb starting from Cs₃Sb [21]. The Milano recipe was studied and optimized using AES and a step-by-step analysis during the cathode growth. A comparison between cathode prepared by CEA and Milano is discussed in Ref. [17]. As a matter of fact, the spectral responses of the cathodes used in different laboratories are not equal and this shows that the compounds produced are not the same.

Investigation about poisoning effect on cesium antimonide and potassium cesium antimonide compound has been done by LANL [24], by CEA [10] and Milano [16], using traditional approach: cathodes are polluted by exposing them to oxygen, carbon dioxide, water, etc. While methane and hydrogen have no effect on the cathode performance, carbon dioxide and oxygen produce a high degradation of the QE characteristic of the cathode. Also in these investigations, the use of AES allows to have important information. It is possible, for example, to investigate the influence of the substratum cleanliness on the properties of the cathode that is to be prepared. In particular, it has been shown that it is not possible to remove completely a cathode from the substrate only by a heating process (after 1 h at 600°C, Cs, K and Sb are still present at the surface). Moreover, a heavily poisoned cathode (e.g. with oxygen) is harder to be cleaned. These results show that the properties of a cathode depend on the history of its substratum. An effective way to clean-up the surface is by Ar ion bombardment [25].

4. Cesium iodide

This material has an energy gap of 6.3 eV, forcing the use of VUV radiation such as the fifth harmonic of Nd lasers in order to have a reasonable QE. Notwithstanding this, CsI is easily prepared film (can be evaporated directly from CsI crystals). It was used at CERN (evaporated on a copper substrate) as a possible photocathode for the CTF gun. Unfortunately, it is affected by some kind of charge saturation effects when is used inside a RF gun [12].

5. Cesium telluride

As mentioned before, one of the major drawbacks in the use of alkali antimonides is their sensitivity to gas exposure. In the last two years, CERN and LANL have partially overcome this limitation by moving towards the use of cesium telluride (Cs₂Te).

Cs₂Te is a semiconductor with an $E_G + E_A$ of about 3.5 eV and is used as photocathode in solar blind UV detectors. A detailed investigation on Cs₂Te photoelectron energy distribution can be found in the Ph.D. thesis of Powell [26,27] and Taft and Apker [28]. Unfortunately, there is a lack of information about its formation process and its reactivity to gas exposure.

Due to the high E_G , Cs₂Te has a high resistivity [3]. Nevertheless, CERN and LANL have demonstrated that it produces high current density, high-brightness electron bunches when used on a metallic substrate. The dark current measurements on the Los Alamos AFEL injector have shown values lower than those obtained with K₂CsSb [29]. Furthermore, LANL has measured the ratio of an emittance figure of merit between K₂CsSb and Cs₂Te: they have not found any significant difference [29]. For these reasons, Cs₂Te is, at this time, the best compromise in terms of robustness, quantum efficiency and lifetime.

In the following, I will illustrate some results about the formation process, the reactivity with gases and the rejuvenation effect. The last-mentioned effect may be interesting both for the use of Cs₂Te in RF guns (it could increase the cathode lifetime) and for the physics of the phenomenon itself.

5.1. Cs₂Te production

Cesium telluride production goes through the formation of some compounds with different Cs to Te stoichiometric ratio. The formation of a new compound during the photocathode growth is highlighted by a change in the photocurrent behavior, moving from an increasing slope to a “plateau” [30]. The principal parameters that influence the cathode growth are the substratum material and its temperature during the cathode formation.

Using XPS and AES, Cs₂Te formation has been investigated, by a step-by-step analysis of the cathode during its growth, stopping the preparation procedure at each “plateau” and performing an analysis of the new compound. This kind of approach has been done on cathode prepared at room temperature on copper (CERN-like) and on molybdenum substratum, both at room temperature and at 120°C (cathode similar to the one in use at LANL). While a cathode grown on molybdenum substrate allows the formation of a “thick” (few tens of nm) Cs₂Te film with the right stoichiometric ratio along all its depth, in the copper case the tellurium diffuses in the

substrate and so a more complicated structure is obtained. In particular, in the latter case, Cs₂Te film is present only in a very thin layer at the surface [18]. The substratum affects not only the structure of the photocathode but also its QE value: a cathode grown on Mo has higher QE. In spite of this fact, the different photocathodes have about the same operative lifetime.

5.2. Cs₂Te poisoning and rejuvenation

As previously discussed, Cs₂Te cathodes are more robust than the alkali antimonide ones. Information about Cs₂Te robustness and poisoning can be had in Ref. [18,31]. These investigations have confirmed that Cs₂Te is at least 2–3 orders of magnitude less sensitive to O₂ exposition [32] in comparison to K₂CsSb and is barely sensitive to CO₂ and not affected by CO and methane [18].

LANL, was the first to mention the possibility to rejuvenate Cs₂Te polluted films [31]. Investigations on this phenomenon have highlighted that by contemporaneously heating (at about 220°C) and illuminating with UV radiation ($\lambda = 254$ nm) a Cs₂Te poisoned cathode is capable of rejuvenating it: heating and UV radiation (few tens of μ W) must be present at the same time, otherwise this effect does not take place. XPS measurements of Cs₂Te polluted films has highlighted that oxygen is bound to cesium and that during the rejuvenation process we can partially go back to unpolluted Cs₂Te films [18]. A detailed discussion on these themes is also presented at this conference [33]. This process could balance poisoning effects and extend the operative lifetime of the cathode in the RF guns.

6. Future developments

The results so far obtained on the photocathode properties must be applied and developed in order to fulfill the requirements of the new sources for linac based XUV FEL and those from the new acceleration techniques (plasma accelerators). In particular,

- the request for very low emittance beams (i.e. few π mm mrad) forces some investigation on the thermal emittance of the photoemitted electrons. The Milano collaboration has planned to perform an angular resolved photoelectron spectroscopy in order to measure the thermal emittance [32]; the use of oriented crystals could eventually help in having a lower emittance value from the cathode.
- The photocathode response time is another critical parameter. Requirements on time response in the femtosecond regime are mandatory to apply photoinjector as electron sources in a plasma accelerator. In this case, the electron bunch must be inside the plasma bucket and this requires very short electron bunches.
- Finally, for TeV colliders, fast sources of polarized electrons are very welcome. Nowadays, the only photocathode that delivers spin-polarized electron bunches is the strained GaAs. Unfortunately, these photocathodes have some drawbacks such as long response time, low QE value and the charge limit effect [34].

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