

PERFORMANCE CHARACTERISATION AT DARESURY LABORATORY OF Cs-Te PHOTOCATHODES GROWN AT CERN

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Abstract

The search for high-performance photocathodes is a priority in the field of particle accelerators. The surface characteristics of a photocathode affect many important factors of the photoemission process including the photoemission threshold, the intrinsic emittance and the quantum efficiency. These factors in turn define the electron beam quality, which is measurable using figures of merit like beam emittance, brightness and energy spread.

We present characterisation measurements for four caesium telluride photocathodes synthesized at CERN. The photocathodes were transported under ultra-high vacuum (UHV) and analysed at STFC Daresbury Laboratory, using ASTeC's Multiprobe [1] for surface characterisation via XPS and STM, and Transverse Energy Spread Spectrometer (TESS) [2] for Mean Transverse Energy (MTE) measurements. The transverse energy distribution curves were measured at both cryogenic and room temperatures and the respective MTE values extracted at each illumination wavelength. We discuss correlations found between the chemical composition and MTE values.

INTRODUCTION

The intrinsic emittance of a photocathode is governed by multiple physical factors such as surface roughness, crystallographic face, cleanliness, work function and the QE. As the intrinsic emittance defines the achievable lower limit for the electron beam emittance within a linear accelerator, it is important to understand the effects that changing a photocathode surface has on these characteristics [3]. Minimising the mean transverse energy (MTE) of an electron beam is crucial, as total emittance cannot be reduced by using electrostatic or magnetic lenses as described by the Liouville theorem, thus motivating photocathode R&D to minimise MTE at the cathode surface to achieve low-emittance electron beams [4].

Caesium telluride (Cs-Te) has been used in accelerators as a photocathode for high bunch charge, high repetition rate superconducting radiofrequency photoinjectors, which are an essential technology for the current state of the art energy recovery linacs and high-power free electron lasers [5, 6]. The value of Cs-Te, as a photocathode source, stems from its balanced properties of high quantum efficiency (QE), its robustness to chemical contamination (in comparison to other semiconductor photocathodes such as GaAs

[7]) and hence long operational lifetime. The main challenges of Cs-Te photocathodes, however, lie in the growth of the photoemissive layer as small variations in the growth conditions can significantly affect the composition and performance of the cathode, highlighting the complexity in the mechanism behind the chemical reaction between caesium and tellurium [8, 9].

In a collaboration between the STFC Daresbury Laboratory and CERN, caesium tellurium (Cs-Te) photocathodes were manufactured at the CERN photoemission laboratory [10] using the co-deposition method, and then transported overland in a UHV suitcase to the STFC Daresbury Laboratory. The photocathode surfaces were first performance characterised using the TESS to obtain their transverse energy distribution curves (TEDC) [11, 12], before being transferred to the Multiprobe system for surface characterisation. In this paper we present the results of MTE measurements for three of the four Cs-Te photocathodes, their atomic composition, and a discussion on the effect of surface composition on photoemissive performance.

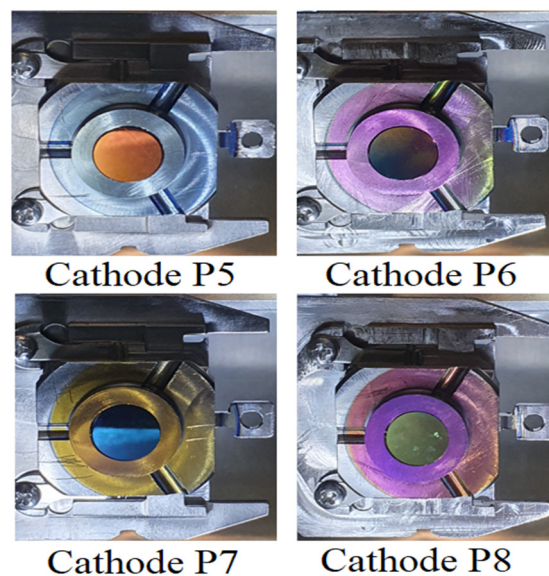


Figure 1: Photographs of the 4 Cs-Te photocathodes taken with the same lighting conditions and camera settings during transfer from the vacuum suitcase into the Photocathode Preparation Facility.

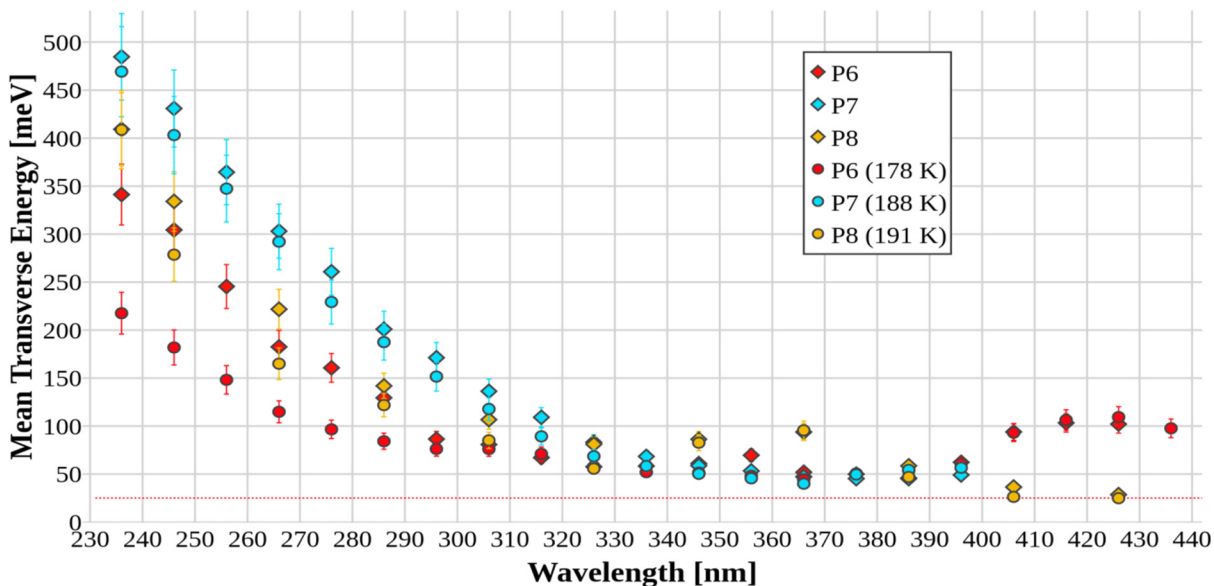


Figure 2: Measured MTE values for the P6, P7 and P8 Cs-Te cathodes at room temperature (diamonds) and cryogenic temperatures (circles) under illumination wavelengths between 236 nm and 436 nm

EXPERIMENTAL DETAILS

Four copper substrates were prepared at Daresbury Laboratory and shipped to CERN in a vacuum suitcase. CERN synthesized four Cs-Te samples designated P5 to P8, which were then transported back to Daresbury inside the vacuum suitcase maintaining a pressure of less than 1.0×10^{-10} mbar for the majority of the journey. These cathodes shown in Fig. 1 were then transferred into the PPF for storage in XHV conditions (5.0×10^{-12} mbar). The photocathodes experienced pressures of 1.0×10^{-9} mbar during this vacuum transfer. Each photocathode was subsequently transferred into the TESS where the TEDCs were obtained as described previously by Jones *et al.* [2].

Measurements were typically taken at illumination wavelengths between 236 nm and 436 nm in 10 nm steps. The TEDCs obtained were then fitted with an exponential curve as described in [12] and the MTE determined at each illumination wavelength. An experimental error of $\pm 10\%$ is ascribed to all MTE data points presented in this proceeding. The cathodes were then transferred in-vacuum to the Multiprobe system to perform XPS analysis.

EXPERIMENTAL RESULTS

The data in Fig. 2 shows the MTE measurements taken for the P6, P7 and P8 Cs-Te cathodes at room temperature and cryogenic temperatures of 178 K, 188 K, and 191 K as a function of illumination wavelength. The red dotted line at 25 meV shows the minimum achievable MTE at room temperature. We do not show the P5 MTE data as this cathode was dropped inside the TESS, so we have no supporting XPS data. Figure 3 shows the calculated relative QE for P6 which generally declines as the illumination wavelength increases. The relative QE is calculated using a combination of the corrected photoemission image intensity

($I_{corrected}$), the data acquisition time (t), optical power falling on the photocathode (P_{opt}), and the detector gain during the measurement (G_{mcp}), as shown below:

$$QE_{relative} \propto \frac{I_{corrected}}{t \cdot P_{opt} \cdot G_{mcp}} \text{ [arb units]}$$

It is included to demonstrate the sensitivity of the TESS instrument, showing that the MTE measurement included in Fig. 2 may actually be associated with a very low level of photoemission at the given illumination wavelengths.

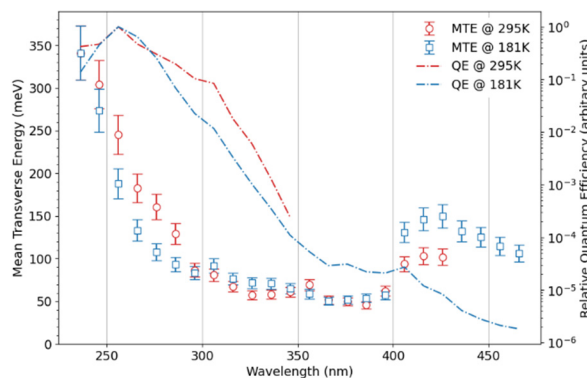


Figure 3: Comparison between extracted MTE values and estimated relative QE values based on known gain parameters and optical power for the Cs-Te P6 cathode at illumination wavelengths of 236 - 436 nm at both room and cryogenic temperatures.

We can see that for illumination wavelengths below 326 nm, all cathodes exhibit decreasing MTE values as the illumination wavelength increases. At illumination wavelengths longer than 326 nm, differences emerge with two of the cathodes showing an increased level of MTE response at longer wavelengths. The MTE of the P6 cathode

increases beyond 386 nm, while the P7 and P8 cathodes do not exhibit the same increase in their MTE. We also see a difference in the emission threshold, with the P7 cathode photoemitting up to 396 nm, and the P8 cathode up to 426 nm.

We believe this effect arises from surface compounds with a low surface coverage and therefore low effective QE, whose presence is supported by the XPS summary table below.

Table 1: Summary of XPS compositional data and specific chemical bonds detected for the P6, P7 and P8 cathodes

| Core level | Bond Configuration | Cathode Atomic Concentration [%] / (Peak Binding Energy) [eV] | | |
|------------|--------------------|---------------------------------------------------------------|------------------------|------------------------|
| | | P6 | P7 | P8 |
| - | - | | | |
| Cs 3d | Cs _x Te | 49.2 (725.9) | 48.5 (725.0) | 51.0 (725.0) |
| | Cs _x O | 5.1 (726.8) | 5.7 (726.0) | |
| Te 3d | Cs _x Te | 35.3 (572.3) | 21.8 (571.2) | 19.4 (571.2) |
| | Te | | 20.5 (572.8) | 29.6 (572.8) |
| O 1s | Cs _x O | 2.1 (531.2) | 3.5 (531.2) | |
| | C=O | 4.1 (532.3) | | |
| C 1s | C=O | 4.2 (286.9) | | |

Table 1 shows the XPS compositional data for the cathodes presented in Fig. 2, highlighting the differences in atomic concentration of each element and their respective bonding environments. Considering only the CsTe bonding environment, we see that the Cs:Te ratio for the three cathodes considered are 1.4:1; 2.2:1 and 2.6:1 for the P6, P7 and P8 cathodes, respectively. The performance differences exhibited by each cathode in their spectral response can be linked directly to this data.

The XPS data of P6 shows a notable level of oxygen (6.2 at. %) and carbon contamination (4.1 at. %), with some oxygen detected (3.5 at. %) on the P7 cathode. The presence of Cs_xO is significant as this compound has a very low work function [13] and readily emits at longer wavelengths, therefore, is most likely to be the source of the high MTE photoemission tail beyond 400 nm. Fig. 3 shows that the QE of this component is small.

The P7 cathode exhibits larger MTE at short wavelengths than the P8 cathode, and while it does exhibit a small level of oxygen contamination in comparison to the P8 cathode, which is likely to be below detectable limits, the P7 cathode has a Cs:Te ratio closer to the ideal composition of 2:1. The reason for the larger MTE at shorter wavelengths could be due to the contribution of CsO in the

grown film that has a lower work function; this would lead to an increase in the overall MTE.

At illumination wavelengths beyond 356 nm, the differences in the cathode's chemical concentrations become more apparent. For the P7 cathode, the MTE plateaus and the cathode ceases its emission at 396 nm without reaching the thermal floor. This non-monotonic behaviour is most likely due to different Cs_xTe compounds with lower work functions which drive a slight increase in the MTE [14]. The P6 and P8 cathodes however continue to emit beyond the P7 cathode threshold.

The XPS data shows an excess of un-reacted Te for both the P7 and P8 photocathodes. This will be due in part to the sequential deposition process whereby a thick layer of Te was deposited before Cs deposition commenced. The XPS technique probes to a depth of around 10 nm, while the photoemission process occurs over a depth of only 3 nm, so the elemental Te detected in P7 and P8 is most likely below the active photoemitting Cs_xTe layer. Furthermore, as the work function of Te is close to 5 eV [15], there is no contribution to the photoemission once the illumination wavelength exceeds approximately 255 nm.

Our data shows that the MTE for the P8 cathode reached the thermal floor once the illumination wavelength exceeded 400 nm. The XPS data suggests that the reason for this is due to this being the only cathode that did not exhibit any notable CsO component that may drive low-level photoemission at longer wavelengths. Of the four cathodes, the P7 cathode exhibited the lowest level of thermal dependence in its room temperature and cryogenic data sets, with all values matching closely over the whole range of its emission. With this taken into account, the P7 cathode performs worse than the P8 cathode in terms of its MTE. While the P7 cathode is closer to the ideal stoichiometry of Cs₂Te, the presence of CsO acts as an MTE spoiler that limits the performance of the cathode.

CONCLUSIONS

Published literature contains a wealth of information on the challenges identified in the synthesis of Cs₂Te photocathodes with consistent levels of performance [8,16,17]. The Cs-Te photocathodes examined in this paper show a high degree of variability, evident in their visual appearance (Fig. 1), their surface composition (Table 1) and their MTE performance (Figs. 2 and 3). The differences in appearance and performance are driven by chemical stoichiometry and film thickness, and it is known that Cs and Te form a range of Cs_xTe compounds [18] with a corresponding range of work functions. Our results agree with published literature, and show that variability in the deposition process and the corresponding XPS spectra can account for differences seen in the spectral response and MTE of the finished photocathode. Even small changes to the chemical composition and the surface chemical bond environment drive performance differences in photoemissive films, highlighting the importance of consistency during the growth of Cs-Te photocathodes.

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