Note on the thermal emittance of electrons emitted by Cesium Telluride photo cathodes

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Abstract

In this note early measurements by Powell et al [1] are used to estimate the thermal emittance of electrons emitted by Cesium Telluride (Cs$_2$Te) photo cathodes. The applicability of the estimations to the case of an rf gun is discussed and the necessity of additional measurements is emphasized.

Introduction

The thermal (i.e. initial) emittance of an electron beam generated by a (photo) cathode imposes a lower limit for the normalized emittance that can be generated by an injector. In case of the TTF FEL-injector the beam is generated by a Cs$_2$Te cathode illuminated by frequency quadrupled laser light from a Nd:YLF laser with a photon energy of $Eph=$ 4.72eV ($\lambda=263$nm). The normalized thermal emittance depends on the spot size, the momentum distribution and the angular distribution of the emitted electrons. While the spot size has to be optimized with respect to the emittance development in the gun (rf induced emittance vs. emittance growth due to space charge) the energy and the angular distributions are functions of the cathode material and the photon energy. The photoemission process can be considered in three steps: Optical excitation of electrons, migration of the electrons to the solid surface (with or without scattering) and, if the electron energy is high enough, escape across the surface potential barrier into the vacuum. For the excitation process direct and nondirect transitions have to be distinguished. Spicer [2] has suggested to explain strong nondirect transitions that occur for example in Cs$_2$Te but also in some metals like Cu in terms of many-body effects rather than in terms of phonon assisted transitions. While in a direct transition the photon energy is transferred completely to the electron, the energy is distributed between the electron and the remaining hole in case of the nondirect transition. According to Spicer the hole is localized for a time long compared to the excitation process and electronic and/or ionic relaxation processes lead to a many-body excitation. The photoemission data can be discussed in a model in which the probability $P(E_f,Eph)$ for a photon of energy Eph exciting an electron to a final state energy E_f, is proportional to:

$$P\left(E_f,Eph\right) \propto N_f(E_f) \cdot N_i(E_f - Eph) \tag{1}$$

where $N_f(E_f)$ and $N_i(E_f\text{-}Eph)$ are the density of initial and final states, respectively.

Photoemission data of Cs$_2$Te

Figure 1 shows the spectral response of a Cs$_2$Te cathode as measured by Powell and coworkers [1]. The little shoulder below 3.5eV is likely to be generated by an additional phase of Cs$_2$Te [4]. Since its quantum yield is low is will not affect the thermal emittance of the electrons. The threshold energy of Cs$_2$Te is hence $E_T= 3.5eV$. The quantum efficiency increases with increasing photon energy up to ~6.6eV. The photoemission behavior above 6.6eV is influenced by the onset of electron-electron scattering of the optically excited electron (producing an electron-hole pair). Since the scattered electrons have energies below threshold the quantum efficiency decreases. Electron-electron scattering can occur only for electron energies exceeding twice the gap width E$_G$, which is hence determined as $E_G = 3.3eV$. The electron affinity is given as: $E_A=E_T-E_G=0.2eV$.

Figure 2 shows the normalized energy distribution of emitted photoelectrons for various photon energies. The first peak P1 is located independently of the photon energy (nondirect transition) at 4.05eV above the valence band maximum. (The actual position of the maximum may lie somewhat lower but be obscured by the surface potential barrier [1].) The maximum is associated with a maximum in the conduction band density of states.

Peaks P2 and P3 change the position with the photon energy (direct transition) and are associated with maxima in the valence band density of states. The final state energies are given as:

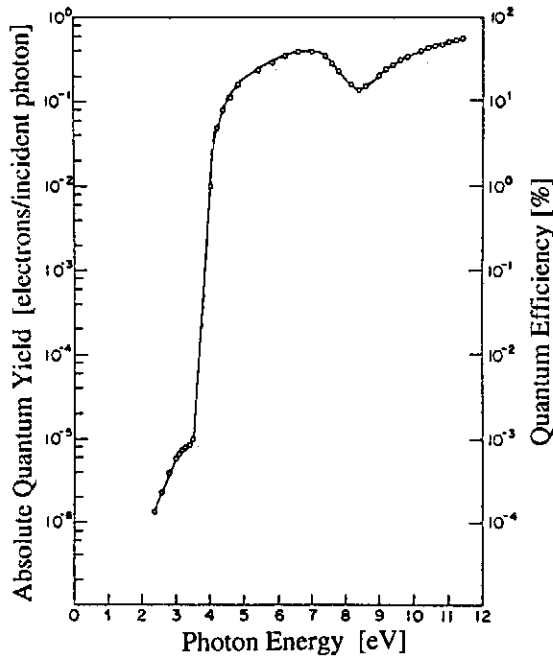$$E_{P2} = Eph - 0.7eV$$

$$E_{P3} = Eph - 1.4eV \qquad (2)$$

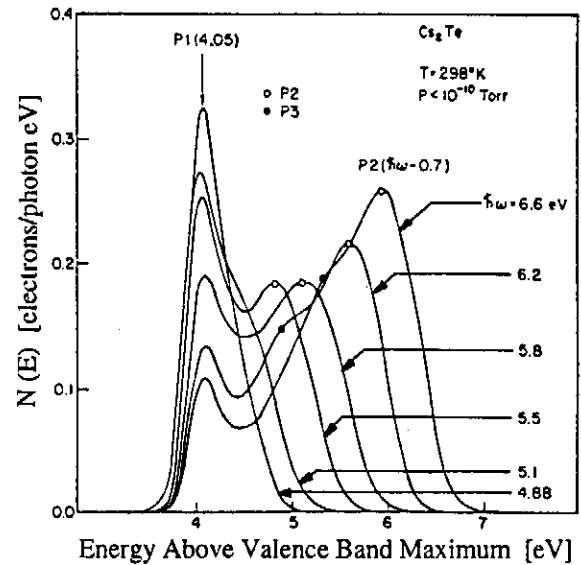Figure 1 Spectral distribution of the photoelectric yield of Cs$_2$Te (from ref 1).

Figure 2 Energy distributions of the photoemitted electrons. The curves have been normalized to the absolute quantum yield shown in Figure 1 (from ref 1).

Higher energy levels in the conduction band density of states will not be discussed, since they can not be excited with the available photon energy of 4.72eV. Neglecting the slight asymmetry of the energy distribution in Figure 2 (for Eph=4.88eV) it can be concluded that the electrons are excited to an average final state energy of E_f=4.05eV. Figure 3 compiles the data obtained by Powell in a schematic band structure of Cs_2Te.
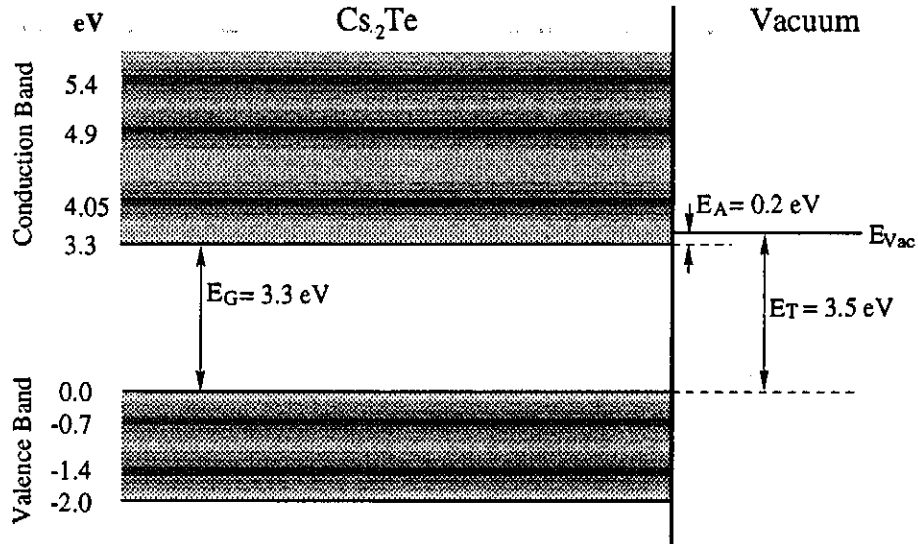

Figure 3 Schematic band structure of Cs_2Te. The maxima of the density of states are indicated as dark shaded areas. The vacuum level is 3.5eV above the valence band maximum. At a photon energy of ~4.7eV electrons are excited to a final state energy of 4.05eV, corresponding to a kinetic energy of a free electron of 0.55eV.

Calculation of the thermal emittance

The rms-emittance ε_{rms} and the normalized rms-emittance $\varepsilon_{n\ rms}$ of a beam with large divergence are defined as:

$$\varepsilon_{rms} = \frac{1}{\overline{pz}} \cdot \sqrt{\langle x^2 \rangle \langle px^2 \rangle - \langle x \cdot px \rangle^2}$$

$$\varepsilon_{n\ rms} = \frac{1}{m_0 c} \cdot \sqrt{\langle x^2 \rangle \langle px^2 \rangle - \langle x \cdot px \rangle^2} \tag{3}$$

$\langle\ \rangle$ = second central moment of the distribution

$\overline{pz}$ = average longitudinal momentum

At the source $\langle x \cdot px \rangle$ is zero, the normalized emittance can therefore be written as:

$$\varepsilon_{n\ rms} = x_{rms} \cdot \frac{px_{rms}}{m_0 c} \tag{4}$$

We consider the case of a uniform radial distribution with radius r=1.5mm, hence:

$$x_{rms} = \frac{r}{2} = 0.75 \cdot 10^{-3} m \tag{5}$$

Powell's measurements are made in a spherical geometry, i.e. they represent an integration over all emission angles in the half-sphere over the cathode (details of the measurement device can be found in ref. 3). In order to investigate the effect of the surface potential barrier we consider two model cases:

The first case might be thought of as if a little gap exists between the surface of the cathode and the potential barrier. The electrons are emitted isotropically into the half-sphere over the cathode with the kinetic energy $E_{kin} = E_f - E_G = 0.75eV$. If no scattering occurs in the barrier only the average longitudinal momentum is changed and the normalized emittance would be conserved if all particles would overcome the barrier. Particles with angle φ larger as $\varphi_{max} = \arccos\sqrt{\frac{E_A}{E_{kin}}}$ (with respect to the surface normal) will however not pass the potential barrier. The emittance can therefore be calculated by restricting the emission angle accordingly. The transverse momentum px is given as:

$$px = p \cdot \sin\varphi \cdot \cos\Theta \tag{6}$$

where φ=[0, φ_max] and θ=[0, 2π] are the azimuth and meridian angles, respectively. With

$$p = m_0 c\sqrt{\gamma^2 - 1} \cong m_0 c\sqrt{\frac{2E_{kin}}{m_0 c^2}} \tag{7}$$

and

$$px_{rms} = \sqrt{\frac{\iint px^2 \sin\varphi d\varphi d\Theta}{\iint \sin\varphi d\varphi d\Theta}} \tag{8}$$

the normalized rms emittance is given as:

$$\varepsilon_{n\,rms} = \frac{r}{2} \cdot \sqrt{\frac{2E_{kin}}{m_0 c^2}} \cdot \frac{1}{\sqrt{3}} \cdot \sqrt{\frac{2 + \cos^3\varphi_{max} - 3\cos\varphi_{max}}{2 \cdot (1 - \cos\varphi_{max})}} \tag{9}$$

$$= 0.58\pi\ mrad\ mm \text{ for } E_A = 0.2eV$$

In the second case it is assumed that due to scattering the electrons are emitted isotropically with an average kinetic energy of $E_{kin}=E_f-E_G-E_A =0.55eV$ into the half-sphere over the cathode (already behind the surface potential barrier). With φ_max=π/2 equation 9 reduces to

$$\varepsilon_{n\,rms} = \frac{r}{2} \cdot \sqrt{\frac{2E_{kin}}{m_0 c^2}} \cdot \frac{1}{\sqrt{3}} = 0.64\pi\ mrad\ mm \tag{10}$$

Figure 4 shows a comparison of the two models as function of the ratio $E_A/(E_f-E_G)$. The difference of the thermal emittance is only small even though the phase space looks somewhat different for the two cases.
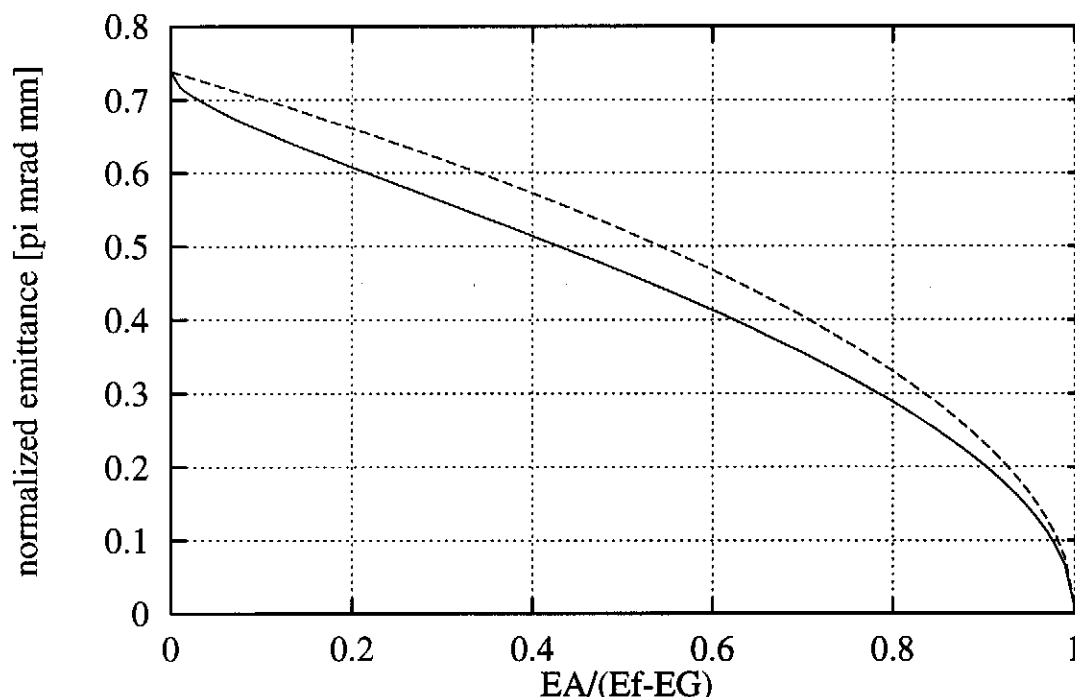
Figure 4 Estimated normalized thermal emittance of electrons emitted from Cs_2Te cathodes as function of the electron affinity (radius of the source r=1.5mm, photon energy Eph=4.72eV). The solid line refers to case one (no scattering), the dashed line refers to case two (with scattering).

The nature of the surface potential barrier and the details of the emission process are not well known. The barrier may act as a much stronger filter for particles with large transverse momenta as discussed before. Only angular resolved measurements of the emission spectra will allow a precise determination of the thermal emittance. The previously estimated thermal emittance may hence be considered as an upper limit only.

Discussion

Powell's measurements were made on 120nm thick Cs_2Te specimens on Mo and Pt substrates at room temperature and at a vacuum pressure below 10^{-10}mbar. The cathodes for the TTF gun are produced in a preparation chamber under construction at INFN Milan. They are only about 20nm thick and are deposited on a Mo substrate. Measurements of the spectral response show a similar behavior than Powell's results (Figure 1) [4] indicating that Powll's measurements are applicable in case of the fresh prepared cathodes. In the gun itself, however, the thermal emittance might be influenced by

-the temperature of the cathode

-poisoning of the cathode due to the increased vacuum pressure

-rf fields.

The transition processes in Cs_2Te are known to be insensitive to temperature variations. For this reason Spicer argued about many-body effects rather than phonon assisted

nondirect transitions [2]. Measurements at CERN [5] showed no significant variation of the quantum efficiency up to ~120°C. Therefore an effect of the temperature on the thermal emittance is not to be expected in case of Cs_2Te.

While in a high vacuum environment the quantum efficiency of Cs_2Te cathodes is highly independent of time, it drops from the initial value of ~10% down to a level of ~2% in a few hours in the gun environment. At this level the quantum efficiency stays nearly constant for some month. The reduced quantum efficiency is attributed to the increased vacuum pressure in the gun. Poisoning of the cathode with gases like oxygen and carbondioxide has been investigated in some detail under laboratory conditions [4]. Depending on the partial pressure of the gas the reduction of the quantum efficiency seems to be due to a diffusion process into the cathode film or by a passivation of the cathode surface. In the first case the structure of the density of states might be changed while in the second case the electron affinity is changed. Especially in the latter case a reduction of the thermal emittance is to be expected according to the previously discussed models. As a first hint a measurement of the threshold energy of cathodes with reduced quantum efficiency would be useful. It should be noted, that an effect of gases like oxygen on the thermal emittance might be useful in order to reduce the thermal emittance as part of the production procedure.

High electric fields may reduce the surface potential barrier and hence increase the thermal emittance in an rf gun. Schottky has investigated the effect for the electron emission from metals [6, 7]. He assumes that the form of the surface potential barrier is determined by the retracting force of image charges in the metal. Cs_2Te is a dielectric semiconductor, hence Schottky's theory is not applicable. The electron affinity might also be influenced by other effects, for example by to a polarized surface layer due to an asymmetric electron density at the surface. A measurement of the thermal emittance under high field conditions would be difficult but a measurement of the quantum efficiency at different fields can be made in an rf gun. (First indications of a modified Schottky effect at Cs_2Te cathodes have been found at CERN [8].) The quantum efficiency depends on the total number of electrons with energy above the electron affinity, thus it is a function of the density of states. Therefore no general relation exists between the quantum efficiency and the electron affinity as in case of metals. For a given photon energy an approximate relation can be calculated by integrating the energy distribution (Figure 2) as function of the lower integration boundary. Since the density of states between 3.5eV and 3.3eV above the valence band maximum is not known in detail this relation holds only, if the electron affinity is above 0.2eV during the measurement, i.e. if the cathode is appropriately poisoned.

Conclusion

The photoemission of electrons from Cs_2Te is for photon energies below ~5eV dominated by a nondirect transition with a final state energy of 4.05eV. The electron energy is insensitive for a small variations of the photon energy and insensitive to temperature variations. The normalized thermal emittance of electrons emitted from Cs_2Te cathodes in an ultra high vacuum environment has been estimated to be $\varepsilon_{n\,rms} \le 0.65\pi$ mrad mm (for a spot size of $r=1.5mm$). In the rf gun environment it is probably lower due to an increased

electron affinity. In order to improve the understanding of the thermal emittance, measurements are required that reveal the angular distribution of the emitted electrons. The effect of cathode poisoning and the effect of high electric fields on the thermal emittance have to be investigated experimentally.

Acknowledgment

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