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Kelvin probe studies of cesium telluride photocathode for AWA photoinjector

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ABSTRACT

Cesium telluride is an important photocathode as an electron source for particle accelerators. It has a relatively high quantum efficiency ($>1\%$), is sufficiently robust in a photoinjector, and has a long lifetime. This photocathode is grown in-house for a new Argonne Wakefield Accelerator (AWA) beamline to produce high charge per bunch (≈ 50 nC) in a long bunch train. Here, we present a study of the work function of cesium telluride photocathode using the Kelvin probe technique. The study includes an investigation of the correlation between the quantum efficiency and the work function, the effect of photocathode aging, the effect of UV exposure on the work function, and the evolution of the work function during and after photocathode rejuvenation via heating.

1. Introduction

Cesium telluride (Cs_2Te) photocathodes are a proven electron source for particle accelerators and photodetectors. They have a high quantum efficiency (10% at 4.9 eV photon energy), a long lifetime (months) and are robust in a high gradient environment [1]. The new RF photocathode drive gun being commissioned at the Argonne Wakefield Accelerator (AWA) is a high peak-current electron beam source for the new 75 MeV linear electron accelerator to be used to excite wakefields in dielectric-loaded accelerating (DLA) structures and other novel high-gradient structures [2]. A unique requirement of the AWA experimental program is the ability to produce long trains of high-charge bunches, hence the need for a high quantum efficiency (QE) photocathode such as Cs_2Te. The AWA is producing Cs_2Te photocathodes for use in the new high-charge 1.3 GHz photoinjector [3]. In particular, an electron bunch train of 30 bunches with up to 50 nC per bunch is expected to be produced. The substantial demands on the photocathode necessitate a thorough understanding of the photocathode and its parameters. The QE at a particular photon energy and the work function (ϕ) are two important parameters of electron emission. Here, we present the results of Kelvin probe measurements of the work function on Cs_2Te photocathodes. We examined (i) the correlation between the QE and the work function, (ii) how QE and the work function evolved with photocathode aging, (iii) effects of rejuvenation of the photocathode via heating, and (iv) the effects on the work function upon exposure to UV light. This study may also shed some light into the properties of other high-QE photocathodes, such as the Cs-based multialkali antimonide, which are used in photomultiplier tubes.

2. Photocathode fabrication

The photocathodes studied were fabricated in the AWA photocathode laboratory using a standard recipe and procedure [4,5]. AWA photocathodes are deposited on a molybdenum plug designed to fit into the back wall of the gun. In preparation for deposition, the plug is polished and cleaned, placed under vacuum, then heated to 120 °C. A 22 nm layer of tellurium is deposited via thermal evaporation. When tellurium deposition is complete, cesium deposition commences and the photocurrent is monitored. Deposition continues for several minutes after maximum photocurrent is achieved. The result of this process is a Cs_2Te thin film photocathode on a molybdenum substrate with an effective photocathode diameter of 31 mm and a typical initial QE of 15%. QE is measured at 4.9 eV photon energy to closely match the photoinjector laser. The anode voltage is 450 V and the cathode is grounded. The separation between anode and cathode

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during QE measurements is about 2 cm, so the electric field on the cathode is approximately 22.5 kV/m. Assuming no field enhancement effects, the resulting Schottky work function lowering is negligible, about 0.005 eV.

3. Work function measurement with the Kelvin probe

3.1. Description of the Kelvin probe method

The Kelvin probe method is a non-contact, non-destructive technique that is used to measure the potential difference between a sample and the Kelvin probe tip (reference) when the two are in electrical contact. The tip and the sample are set in a parallel plate capacitor configuration and the circuit is completed through ground connection, thus aligning the Fermi levels of tip and sample. The electrical contact between the tip and the sample causes electron migration from higher to lower Fermi-level material, creating an electric field between the tip and sample. The potential associated with this electric field is called the contact potential difference (CPD), which when multiplied by the electron charge yields the difference of the work functions of the sample and tip. Hence, knowing the work function of the reference tip and measuring the CPD allows the sample work function to be calculated. The validity of the work function measurement therefore relies on the calibration of the tip using a known reference. The theory and details of the method have been described in detail elsewhere [6].

3.2. Work function of semi-conductors

Fig. 1 shows the band diagram for a p-type semiconductor. The work function is defined as the energy difference between the vacuum potential level and the Fermi level which is located in the energy gap between the valence and conduction bands. On the other hand, the photoemission threshold is defined as the difference between the vacuum level and the valence band maximum. Therefore the work function in a semiconductor is not the same as the photoemission threshold, unlike the case of a metal. In this experiment, what is measured is the semiconductor work function and not the photoemission threshold.

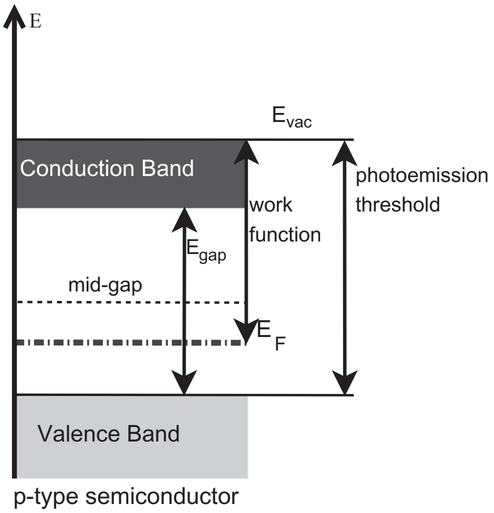

Fig. 1. Band diagram for p-type semiconductor. The work function is measured from the vacuum potential level (E_{vac}) to the Fermi level (E_F), while the photoemission threshold (E_t) is measured from E_{vac} to the valence band maximum. In this experiment, what is measured is the actual work function and not the photoemission threshold.

3.3. Hardware setup and operation

The experimental setup is pictured in Fig. 2. It included a large vacuum chamber where the Cs_2Te cathodes were fabricated. The Kelvin probe was housed in the smaller vacuum chamber connected to the back. A long-stroke actuator holding the cathode plug provided the means to easily move the plug back and forth from the deposition chamber (for fabrication and quantum efficiency measurements) to the Kelvin probe chamber (for work function measurements). All QE and Kelvin probe measurements were made in situ. Cs_2Te was fabricated and maintained under ultra-high vacuum (UHV) conditions with base pressure of 1.5×10^{-10} Torr.

3.4. Kelvin probe system

The Kelvin probe system is a McAllister Technical Services KP 6500 which includes control software and electronics, and data collection via a PCI National Instruments data acquisition card. The Kelvin probe was positioned in a port in the smaller chamber oriented at 45° with respect to the sample actuator. In order to keep the surfaces of the KP tip and the sample parallel, the tip was customized to face at 45° from the longitudinal axis of the tip (see Fig. 2, inset). The tip can probe a 2 mm diameter circular area where the work function measurement is the average work function over the probed surface. The coarse sample to tip distance was varied manually using a linear translator attached to the Kelvin probe chamber. The fine adjustment to the sample to tip distance and the tip oscillation along the longitudinal axis of the Kelvin probe were controlled by means of the computer-controlled voice coil system. The effect of stray capacitances was minimized by doing a spectral analysis to find the resonances of the vibrating probe and subsequently choosing to operate at an off-resonant frequency.

3.5. KP tip calibration

Since the Kelvin probe measures the position of the Fermi level of the sample relative to the reference tip, calibration of the latter is necessary in order to obtain the absolute value of the sample's Fermi level relative to the vacuum level, and thus to be able to

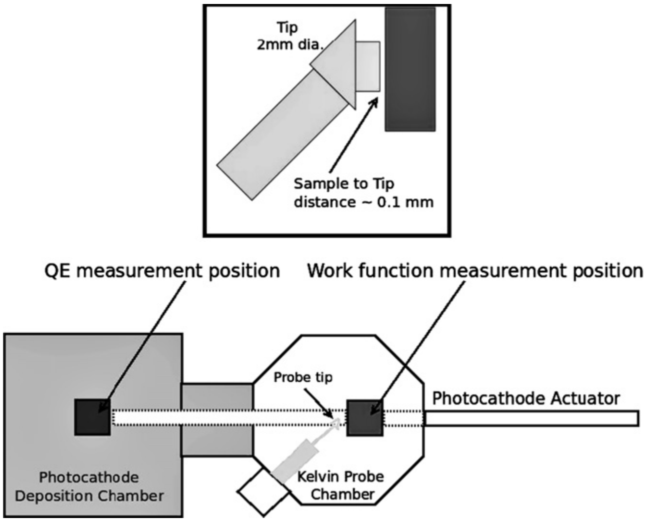

Fig. 2. Top view, schematic (not to scale) of experimental setup, showing the Kelvin probe chamber attached to the back of the deposition chamber. The actuator is used to move the photocathode from one chamber to the other at a distance of 1.5 m. Inset: Drawing of the Kelvin probe tip and sample (photocathode) illustrating the relative orientation as seen from above (zoomed view).