KELVIN PROBE STUDIES OF CESIUM TELLURIDE PHOTOCATHODE FOR THE 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 (QE) ($> 1\%$), is sufficiently robust in a photoinjector, and a long lifetime. This photocathode is grown in-house for the new Argonne Wakefield Accelerator (AWA) to produce high charge per bunch (50 nC). We present a study of the work function of a cesium telluride photocathode using the Kelvin Probe technique. The study includes an investigation of the correlation between QE and work function, the effect of photocathode aging, the surprising effect of UV exposure on the work function, and the puzzling behavior of the work function during and after photocathode rejuvenation via heating.

A proven high-charge electron source for particle accelerators, Cesium telluride (Cs_2Te) photocathodes have many distinguishing characteristics including high quantum efficiency (QE) (10% at 4.9 eV photon energy), long lifetime (months) and survival in a high gradient environment [1]. The RF photocathode drive gun at the Argonne Wakefield Accelerator (AWA) is a new high peak-current electron beam source for the new 75 MeV linear electron accelerator. Primary application will be to create wakefields in dielectric-loaded accelerating (DLA) structures and other novel structures [2]. AWA's experimental program requires the ability to produce high-charge bunches, often in long bunch trains. This calls for a high QE photocathode such as Cs_2Te. The AWA fabricates Cs_2Te photocathodes for use in the new high-charge, 1.3 GHz photoinjector [3]. Electron bunch train of 30 bunches with up to 50 nC per bunch is planned. A thorough understanding of the photocathode is required because of the high performance demand. The QE at a particular photon energy and the work function (ϕ) are two key parameters of electron emission. We present some results of Kelvin probe measurements of ϕ on Cs_2Te photocathodes [4]. We examined the correlation between the changes in QE and the work function; how QE and the work function evolved with photocathode aging; effects of rejuvenation of the photocathode via heating, and effects on the work function upon exposure to UV light.

The Kelvin probe method is a non-contact, non-destructive technique used to measure work function. The theory and details of the method have been described in detail elsewhere [5]. The work function is defined as the energy difference between the vacuum potential level and the Fermi level, located in the energy gap between valence and conduction bands. 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 equivalent to the photoemission threshold, unlike the case of a metal. What is measured in this experiment is work function and not the photoemission threshold.

The photocathodes studied were fabricated in the AWA photocathode laboratory using a standard recipe and procedure [6],[7]. 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 experimental setup included a vacuum chamber where the Cs_2Te cathodes were fabricated. The Kelvin probe was housed in a smaller vacuum chamber connected to the back. An actuator provided the means to easily move the cathode plug 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 were fabricated and maintained under ultra-high vacuum (UHV) conditions with base pressure of 1.5×10^{-10} Torr.

The Kelvin Probe system was a McAllister Technical Services KP 6500. 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. **??**, inset). The tip can probe a 2 mm diameter area. The 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 was done by means of the computer-controlled voice coil system. The effect of stray capacitances was minimized, in part by doing a spectral analysis to find the resonances

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of the vibrating probe and choosing to operate at an off-resonant frequency.

Since the Kelvin probe measures the position of the Fermi level of the sample relative to the reference tip, calibration is necessary to be able to obtain the sample's work function. Calibration was performed using three references of known work function: polycrystalline molybdenum with work function 4.6 eV [8], polycrystalline tellurium with work function 4.95 eV [8],and highly oriented pyrolytic graphite (HOPG) with work function 4.6 eV [9]. The resulting tip work function value was 4.6 ± 0.1 eV.

For this experiment, six Cs_2Te photocathodes were fabricated and studied. The initial average value of the QE for the cathodes in the study was 16.7%, the range was [15.5,18.8%], and standard deviation was 1.3%. The initial average value of the work function was 2.3 eV, the range was [2.22,2.36], and standard deviation 0.055 eV. The work function and QE were recorded and tracked for five indexed points on the cathode surface. For a photocathode of this size, uniformity in QE could be an issue. The photocathodes fabricated were relatively uniform, both in QE and in the measured work function. Applying the rigid band picture and using an average measured value of 2.3 eV as the work function for Cs_2Te, band gap of 3.3 eV and electron affinity of 0.2 eV [10],[11] this places the Fermi level $\approx$ 0.5 eV below the middle of the band gap, characteristic of a p-type semiconductor.

While it is uncertain if the rigid band model is accurate to describe the aging effect of QE and the work function, it is still a useful model to obtain an initial quantitative comparison on how much the Fermi level may have changed. Thus, applying the same calculation for the typical cathode after aging for 2-3 weeks, with an average value of the work function of 2.8, the position of the Fermi level is now $\approx$ 1 eV below the mid-gap, a shift of 0.5 eV towards the valence band. There may be other factors that can cause a change in the work function that we measured beyond a shift in the Fermi level, ie. an increase in the electron affinity due to surface contaminants, etc.

Previous studies have shown QE of Cs_2Te diminishes over time [1], [7]. We tracked changes in QE and work function together. The plot in Fig. 1, top shows the correlation between QE and work function at a point on the photocathode over a period of 3 weeks. As QE declined, the work function correspondingly increased. The variation over a period of time can be seen in Fig. 1, bottom. The value for the QE initially dropped rapidly and then leveled off after 15 days. The work function followed this pattern inversely, and appeared to change very little after 20 days. The observed trend of increased work function with decreasing QE is similar to that observed previously [12] for Cs_2Te photocathode after operation.

After aging, the photocathode was rejuvenated via heating at 120° C for 4 days. Previous studies on photocathode rejuvenation via heating have shown a QE recovery up to about 60% of the original value [6], [13]. In our experiment, five of six photocathode's QE went from 30% of the original QE prior to heating to an average of about 60% of the original value after heating. Curiously, however, this increase in QE after rejuvenation was accompanied by an increase in the work function. This was contrary to the pattern seen in Fig. 1, top, where QE and work function were inversely related during the aging process.

There are many possible explanations for such an observation, including the possibility that the process of heating has changed the chemistry or nature of the photocathode, especially on the surface, resulting in an increase in the photocathode's electron affinity [14]. Additional studies are planned to further our understanding of these phenomena..

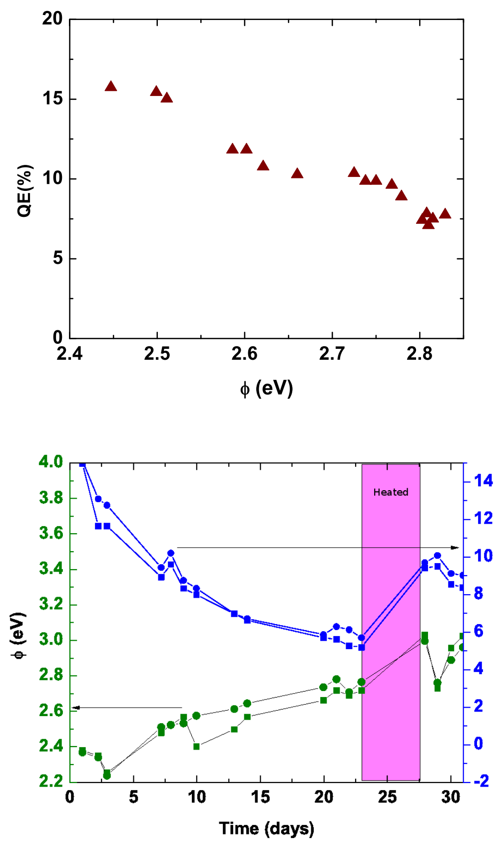

Figure 1: Top: QE vs. work function; typical data. Data taken at two locations on the cathode over a period of about 3 weeks. Bottom: Time evolution of the QE and ϕ. The box represents the time period the cathode was heated to 120°C to rejuvenate the QE. Data tracks changes observed at 2 different locations on the cathode. The work function measurement was performed first followed by QE measurement.

We also found that exposure to 4.9 eV light has an effect on the workfunction of the photocathode (see Fig. 2.) The photocathode was illuminated with 4.9 eV light for 2 minutes inside the deposition chamber. After the light exposure, the photocathode was transferred to the Kelvin Probe chamber and the work function was measured. There is a time delay of about 3 minutes from the end of light exposure to the start of work function measurement. A clear drop in the value of the work function by at least 150 meV was observed. The work function appeared to recover its original value over a time period of $\approx$ 30 minutes. When exposed to 3.7 eV light, the work function showed no obvious effect similar to that of the 4.9 eV light. (see plot in top curve of Fig. 2). It was also found that 3.7 eV light produced measurable photocurrent with a QE 0.1-0.2%, indicating that 3.7 eV is above the photoemission threshold, consistent with the literature [10],[11]. There is a curious similarity with the result reported earlier by Sertore et al although changes in the work function were not reported. They found that QE rejuvenation took place while simultaneously heating to 300°C AND illuminating with 4.9 eV light, but illuminating with 3.7 eV light produced no rejuvenation effects on its own [7].

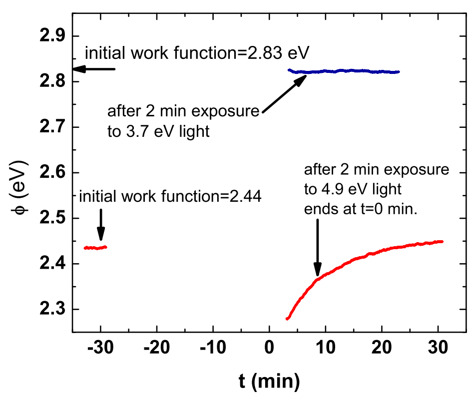

Figure 2: Comparison of the effect of exposure to 3.7 eV light and 4.9 eV light. Light exposure ends in both cases at time t=0 and work function measurement begins about 3 minutes later. Pre-exposure work function data is also plotted.

We performed two further investigations on the UV exposure effects. First, the exposure time using 4.9 eV light was varied. Longer exposure time caused a larger drop in the work function and a longer recovery time. However, it appeared that the exposure time saturates at approximately 20 minutes, whereby longer exposure time did not seem to cause the work function to drop further. Secondly, the intensity of the 4.9 eV light was varied. The cathode was illuminated for 2 minutes at a particular spot, then the cathode was moved into the Kelvin probe chamber for the work function measurement. The drop in the work function diminished as the intensity decreased. We found that the induced work function reduction scaled with the light intensity.

In conclusion, work function measurements of Cs_2Te photocathodes grown for the AWA photoinjector have been made with a UHV Kelvin probe. The initial work function of about 2.3 eV increased to 2.8 eV while the QE declines. The QE scaled inversely with the work function over time. The effect of rejuvenation via heating resulted in a different correlation: both QE and the work function increased after heating. Exposure to 4.9 eV light produced a temporary drop in measured work function, with a long recovery time. The magnitude of the drop in work function depends on both exposure time and intensity of the 4.9 eV light. Exposure to 3.7 eV light did not produce a similar effect. Further studies are planned.

Acknowledgements

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