ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF081

INTRINSIC EMITTANCE OF SINGLE CRYSTAL CATHODES

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Abstract

The transverse momentum of electrons is conserved during photoemission from atomically ordered surfaces of single crystal materials. Photocathodes used in all photoinjectors today have disordered surfaces and do not exploit this phenomenon. Recently, using this conservation of transverse momentum, significant reduction in intrinsic emittance was demonstrated from the (111) surface of silver [1]. Here, we present measurements of transverse momentum distributions of electrons photoemitted from the ordered surfaces of Ag and Cu single crystals at several photon energies. These measurements will help in understanding the photoemission process and show how band-structure and the conservation of transverse momentum can be used to obtain further reduction in intrinsic emittance from photocathodes.

INTRODUCTION

The brightness of electron beams from photoinjectors is inversely proportional to the mean transverse energy (MTE) of the emitted electrons. All photocathodes used to-date in photoinjectors have disordered surfaces. Electrons emitted from such surfaces get scattered during emission and the direction of emission gets randomized. This causes the MTE to become proportional to the excess energy (defined as the difference between the photon energy and the work function). Assuming a constant density of states, according to Dowell's 3-step photoemission model, the MTE = $E_{ex}/3$ when $E_{ex} \gg 0$ and MTE $\rightarrow k_B T$ as the excess energy goes below zero [2]. Here, E_{ex} is the excess energy, k_B is the Boltzmann constant and T is the temperature of the electrons in the cathode. Thus, by tuning the photon energy to the photoemission threshold one can reduce the MTE to near $k_B T$ and increase brightness. However, the quantum efficiency also reduces with the excess energy and is proportional to $E_{ex}^{1/2}$. Thus, as the photon energy approaches the work function, the QE goes to very small values making the extraction of large charge densities with the reduced MTE impossible due to the laser heating of electrons [3].

One way around this issue is to use atomically ordered surfaces of single crystal cathodes. During photoemission from such surfaces, the transverse momentum of the electrons is conserved and hence the MTE is not simply proportional to the excess energy, but is dependent on the electronic band structure of the cathode material. Recently, reduction of MTE due to the conservation of transverse momentum was demonstrated from the ordered (111) surface of Silver [1]. The Ag(111) surface exhibits a Shockley surface state. The band structure of this state is such that the MTE reduces with increasing excess energy and reaches a minimum of ~25 meV at excess energy of ~120 meV, with a QE as high as 4×10^{-5}.

In this proceeding, we explore photoemission from the ordered surfaces of Ag(111) and Cu(111) for use as single crystal photocathodes. Transverse momentum distributions and QE from the Ag(111) and Cu(111) have been measured. These measurements will allow us to develop a better understanding of the photoemission process from ordered single crystal surfaces enabling an automated high-throughput computational search for single crystal photocathodes capable of delivering smallest possible MTE with a large QE.

EXPERIMENTAL DETAILS AND MEASUREMENT TECHNIQUES

Sample Preparation

Commercially available single crystals of Ag(111) and Cu(111) were prepared by several cycles of Ar ion bombarding (using 1 keV ions) and annealing to ~550°C. These cycles were continued until all C and O impurities were removed from the surface as measured using Auger Electron Spectroscopy. The surface order was verified using Low Energy Electron Diffraction (LEED). The base pressure in the preparation chamber during this process was better than 5×10^{-10} torr. After cleaning, the samples were transferred into the measurement chamber for transverse momentum distributions and QE measurement. The base pressure in the measurement chamber was less than 1×10^{-10} torr.

QE and Transverse momentum measurement

QE was measured as a function of incident photon energy by measuring the photocurrent emitted by the samples while light from a tunable wavelength monochromator with a laser based plasma lamp [4] was incident on it.

Transverse momentum distributions were measured using the acceleration-drift technique [5]. In this technique, the electrons emitted from a small spot (< 100 μm) on the sample are accelerated to a few keV in the longitudinal direction through a fine mesh. Post acceleration, the electron beam is allowed to drift and expand under the transverse momentum of the emitted electrons. The transverse momentum distributions and the MTE can then be calculated from by measuring the transverse profile of the beam after the drift region. Light from the tunable wavelength monochromator [4] can be used to measure MTE in a wide range of photon energies using this setup.

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RESULTS

Ag(111)

The QE as a function of the photon energy has been presented elsewhere [1, 6]. Figure 1a shows the MTE as a function of the photon energy for the Ag(111) surface along with the values calculated from the one-step photoemission model [6]. The acceleration-drift method also gives 2-D maps of the transverse momentum distributions. Figure 1b shows such a 2-D transverse momentum map for a photon energy of 4.8 eV. Figure 2 shows the transverse momentum distribution along the $k_y = 0$ cut for various photon energies as measured by the acceleration-drift technique and as computed using the one-step photoemission model.

Despite the excellent agreement between the measured and calculated MTE at all photon energies, we see that the transverse momentum distributions show a staggering discrepancy between the measurements and calculations at photon energies close to the threshold (figures 2d and e).

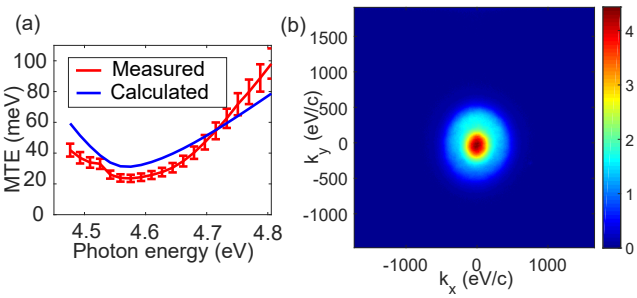

Figure 1: (a) MTE vs. Photon energy for Ag(111), (b) 2-D transverse momentum map for a photon energy of 4.8 eV

The Ag(111) surface shows a surface state with energy ~60 meV below the Fermi level at zero transverse momentum and a Fermi level crossing at ~160 eV/c in transverse momentum. According to the conservation of energy and transverse momentum, at a photon energy of 4.8 eV (figure 2a), electrons from both the surface state and the bulk states are emitted. In the transverse momentum distribution in figure 2a, the electrons from the surface state form the central peak while the bulk state electrons form the wings at the sides. A similar shape is predicted by the one-step photoemission model. For a smaller photon energy of 4.7 eV (figure 2b), the contribution of the bulk states reduces and the wings get smaller. At 4.6 eV photon energy (figure 2c), the contribution of the bulk states is negligible and only the surface state is emitted. At even lower photon energies, only the surface state electrons close to the Fermi level can get emitted. These electrons have a high transverse momentum and should result in a ring in the 2-D transverse distribution map thus increasing the MTE at these photon energies. Such a ring will be expressed as two peaks in the transverse momentum distribution along the $k_y = 0$ cut as seen in the theory calculations for photon energies 4.54 eV and 4.51 eV (figures 2d and 2e). However, the measured transverse momentum distributions do not exhibit such a ring and simply show a broader central peak.

Cu(111)

Figure 3a and b show the measured MTE and QE for the Cu(111) surface respectively. The Cu(111) surface also exhibits a surface state at an energy of ~400 meV below the Fermi level at zero transverse momentum and a Fermi level crossing at ~450 eV/c in transverse momentum.

According to the conservation of energy and transverse momentum the MTE from the Cu(111) surface (just as in the Ag(111) case) should first decrease with photon energy when only a portion of the surface state is allowed to emit, reach a minimum at the photon energy where the entire surface state is allowed to emit and then increase with increasing photon energy when electrons from the bulk bands are allowed to emit. However, as seen in figure 3a the MTE vs photon energy curve shows a more complex behavior with one maxima at ~5.05 eV photon energy and a minima at ~5.20 eV photon energy.

Figure 4 shows the transverse momentum distribution along the $k_y = 0$ cut at various photon energies. According to the conservation of transverse momentum and energy, no electrons should be emitted at photon energy equal to the work function (4.94 eV). However, at this photon energy we see a broad central peak in the $k_y = 0$ cut of the transverse momentum distribution. At higher photon energies, electrons only from the intersection of the Fermi level and the surface state should be emitted, forming a ring in the 2-D momentum map (or two peaks with no intensity at $k_x = 0$ in the $k_y = 0$ cut). However, as seen in figure 4, the measurements at higher photon energies (5 eV, 5.04 eV and 5.10 eV) show the two peaks (indicating a ring) with a significant intensity at $k_x = 0$. Then as the photon energy increases (5.17 eV, 5.19 eV and 5.25 eV), smaller transverse momentum electrons from the surface state get emitted and fill the center of the ring. At even higher photon energies (5.25 eV), the entire surface state gets emitted along with high transverse momentum electron from the bulk states as expected from the conservation of energy and transverse momentum.

CONCLUSION AND FUTURE WORK

In conclusion, even though we see excellent agreement between the one-step photonemission model and the QE and MTE measurements for the Ag(111) surface at all photon energies, a detailed study of the transverse momentum distributions reveals a glaring discrepancy very close to the photoemission threshold. Moreover, at these photon energies the measured transverse momentum distributions seem to violate the conservation of transverse momentum. A detailed study of the transverse momentum distributions from Cu(111) also reveals a similar trend. Further, for the Cu(111) surface, the MTE vs photon energy measurements do not agree with the qualitative predictions based on the conser-

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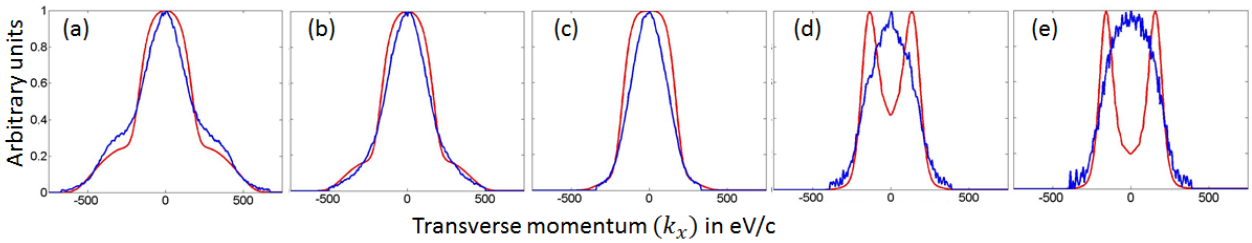

Figure 2: Transverse momentum distribution along the $k_y = 0$ cut for photon energy (a) 4.8 eV, (b) 4.7 eV, (c) 4.6 eV, (d) 4.54 eV, (e) 4.51 eV. The blue curves are the measurements and red curves are the calculated distributions using the one-step photoemission model [6]

vation of transverse momentum close to the photoemission threshold.

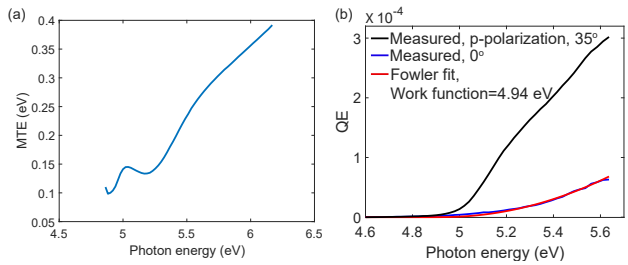

Figure 3: (a) MTE vs. Photon energy for Cu(111), (b) QE vs. Photon energy for Cu(111). The back curve is the QE measured at 35° angle of incidence in *p*-polarized light, the blue curve is the QE measured at normal incidence and the red curve is a Fowler fit to the blue curve with work function of 4.94 eV

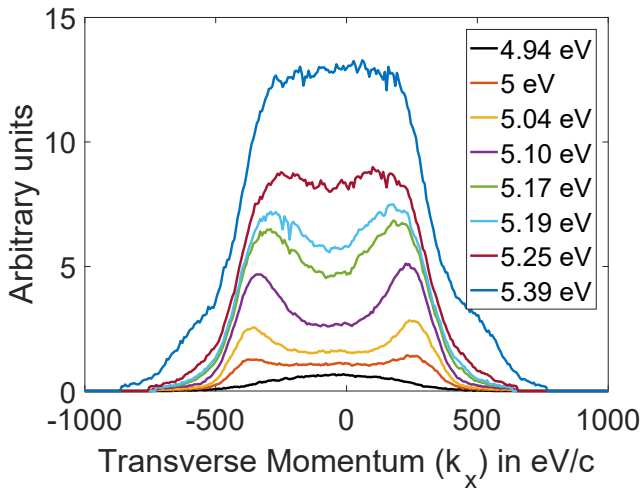

Figure 4: Transverse momentum distribution along the $k_y = 0$ cut for various photon energies for Cu(111)

One explanation for these discrepancies is the break down of the conservation of transverse momentum at photon energies very close (within 100 meV) to the photoemission threshold. Electrons emitted at these photon energies have a kinetic energy in the range of few to 100 meV. At such small kinetic energies the de Broglie wavelength of the electrons is several nm. Hence, surface defects spaced at distances greater than several nm may cause these electrons to scatter causing them to violate the conservation of transverse momentum.

Another effect that can cause the violation of transverse momentum conservation is the interaction of the emitted electron with changes (phonons or plasmons) within the surface. The emitted electrons have a long de Broglie wavelength and move away from the surface slowly. This may allow them to interact with the phonons or plasmons within the surface causing the sudden approximation [7] to break.

Further investigations are needed to determine the exact cause of these discrepancies and develop a better understanding of photoemission at near-threshold energies. Future work in this direction includes measuring the energy resolved transverse momentum distributions of the various surfaces of Ag, Cu and Mg single crystals at room and cryogenic temperatures. These measurements will be performed using a time-of-flight based electron energy analyzer capable of measuring near zero kinetic energy electrons. Such an analyzer has been developed at the Lawernce Berkeley Lab and preliminary measurements are underway.

These measurements will allow us to determine the cause of the previously mentioned discrepancies and help develop a photoemission model better suited for near-threshold photon energies enabling an automated high-throughput computational search for single crystal photocathodes capable of delivering smallest possible MTE with a large QE.

ACKNOWLEDGMENT

This work has been supported by the US National Science Foundation (grant PHY-1549132) and by the Department of Energy, Basic Energy Science (contract No. KC0407-15ALSJNT-I0013, No. DE-AC02-05CH11231 and No. DE-SC0017621).

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