METAL CATHODES WITH REDUCED EMITTANCE AND ENHANCED QUANTUM EFFICIENCY

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Abstract

In this paper, we report experimental results on photoemission from copper and silver surfaces. Using the technique of angle resolved photoemission spectroscopy (ARPES), we demonstrate that, for excess energy around 0.5 eV, the photoelectrons from the Cu(111) and Ag(111) surfaces generated by p-polarized light originate primarily from the well-known surface state with normalized emittance only a fraction of that of the polycrystalline copper cathode presently used in the RF guns. Meanwhile, we demonstrate that the enhancement of the quantum efficiency (QE) at grazing angle is closely related to the surface state as well. Furthermore, we show that the surface state can be easily restored by a simple anneal process, thus pointing to a practical way to reducing the emittance and QE of a metal cathode simultaneously.

INTRODUCTION

Over the past four decades, the free electron laser (FEL) has grown from a novel idea [1,2] to a sophisticated scientific tool generating the brightest x-ray pulses made by man [3,4]. The successful user operation of soft x-ray facilities such as FLASH [5] and hard x-ray facilities such as LCLS [6] has help to make significant progress in science. The success of the existing facilities in turn fuels demand for more FELs, some are under construction and others are in the planning stage. Meanwhile, research activities to develop even better FELs in the future greatly intensified in recent years, making FEL arguably the most active branch in the field of accelerator physics. At present, the research activities on FELs have been largely focused on two areas. On the one hand, many new schemes of the FEL have been proposed, including methods of generating attosecond [7-9] and short wavelength x-ray pulses [10,11]. Notably, one new and simpler way of producing high harmonics called ECHO has recently been confirmed experimentally [12].

On the other hand, significant improvement in the design and performance of the front end has been achieved [13,14]. As a result, the final transverse emittance of the beam, which is a key indicator of the quality of the beam, both in terms of brightness and the photon energy reach, is only a factor of 2 larger than the initial value out of the cathode [15]. In another word, the largest contribution to the transverse emittance comes from the cathode itself, which may potentially become even larger if the new schemes of generating ellipsoidal bunches become readily available [16-18]. This demand for lower emittance, together with the goal of higher quantum efficiency to support high repetition rate FELs, has stimulated a strong resurgence of the research activities in photocathodes [19]. Along with steady improvement of understanding for traditional photocathodes such as cesieted GaAs and copper, new types of photocathodes such as the diamond-amplifier cathode, the needle cathode and the metal cathode covered with thin oxide layers have been investigated, both experimentally and theoretically, which is a direct result of the increasingly close collaboration between accelerator physicists and the surface scientists. In addition, experimental studies have been carried out to determine the lower bound of the emittance under various conditions [20,21]. In this paper, we report results of our experimental investigation of the photoemission properties of the copper and silver, with the emphasis on finding a way to improve the performance of the copper cathode, which is widely used in RF guns.

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EXPERIMENTAL DETAILS

Our experiments were carried out in our surface science lab built for cathode research. The single crystal copper sample is mounted in a magnetically shielded UHF chamber equipped with standard surface science apparatus such as an Ar ion gun and an LEED. A continuously tunable plasma laser provides the light souce to acurately measure the work function. A pulsed Ti:Sapphire laser (Coherent MIRA) is used to generate photoelectrons when the quantum efficiency and energy-momentum spectrum are measured. The energy-momentum spectrum is obtained using a delay-line detector manufactured by Surface Concept, which measures the transverse position and time-of-flight simultaneously. As a result, the complete information of energy and momentum is obtained without rotating the sample, thus removing those errors caused by the motion. Sample preparation usually involves Ar ion bombardment at around 1 keV and annealing at 600 K. LEED pattern is checked regularly to ensure the cleanliness of the surface.

QUANTUM EFFICIENCY OF Cu (111)

The first experiment on single crystal copper was measuring the quantum efficiency as the function of the incident angle. Fig. 1 shows the normalized quantum efficiency using p-polarized light on Cu(111) surface, exhibiting the well-known large enhancement [22,23] which can't be explained by the 3-step model [24]. The fact that the enhancement increases as the photon energy decreases (between 5.9 eV and 5.6 eV) indicates the close relation between the presence of the surface state and the

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abnormal enhancement, since, at lower photon energy, larger fraction of the emitted electrons are from the surface state [25]. This relation appears to be confirmed by our data on Cu(100) surface, shown in Fig. 2. Note that there is no free parameter in the theoretical prediction by the 3-step model and that the photon energy is too low to excite the electrons in the surface state band.

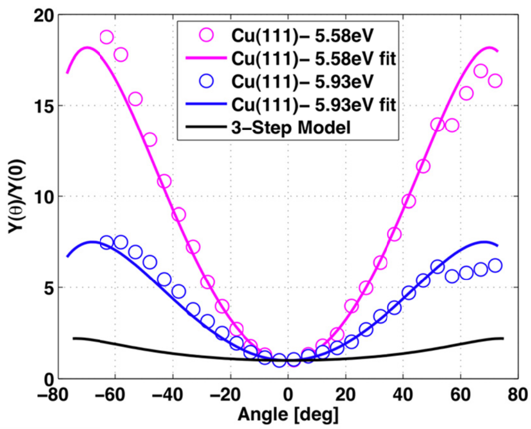

Figure 1: Normalized quantum efficiency versus the incident angle with p-polarized light on Cu(111) surface.

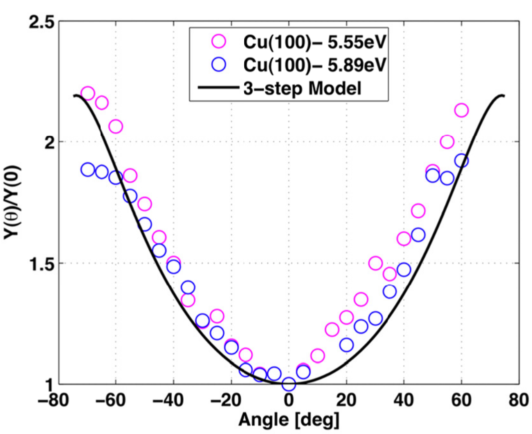

Figure 2: Normalized quantum efficiency versus the incident angle with p-polarized light on Cu(100) surface.

THERMAL EMITTANCE OF Cu(111)

Using the delay line detector, we obtained the energy-momentum distribution of the photoelectrons. The data for the Cu(111) surface is presented in Fig. 3, showing the dominance of the surface state and consistent with published results [26,27]. Furthermore, the transverse emittance of the photoelectrons can be obtained using the data of the transverse momentum. Assuming that x and p_x are uncorrelated, the transverse emittance is defined as

$$\varepsilon_x = \sigma_x \frac{\sigma_{p_x}}{mc}$$

Where σ_x and σ_{p_x} are *rms* values of x and p_x. While σ_x is proportional to the transverse profile of the laser beam, σ_{p_x}, on the other hand, is determined by the cathode material. For metal cathodes, the most commonly used model is the so-called 3-step model, which predicts that the emittance is

$$\epsilon_x = \frac{\sigma_x}{\sqrt{6}} \frac{p_{x,max}}{mc},$$

Where $p_{x,max} = \sqrt{2m(\hbar\omega - \phi)}$ and $\hbar\omega$ and ϕ are the photon energy and the work function, respectively [28]. Yet the 3-step model doesn't take into account the presence of the surface state. To that end, we arrived at the emittance of the photoelectrons from the surface state, assuming that $\frac{d^2N}{dp_x dp_y}$ is a constant, which is

$$\epsilon_x = \frac{\sigma_x}{2} \frac{p_{x,max}}{mc}.$$

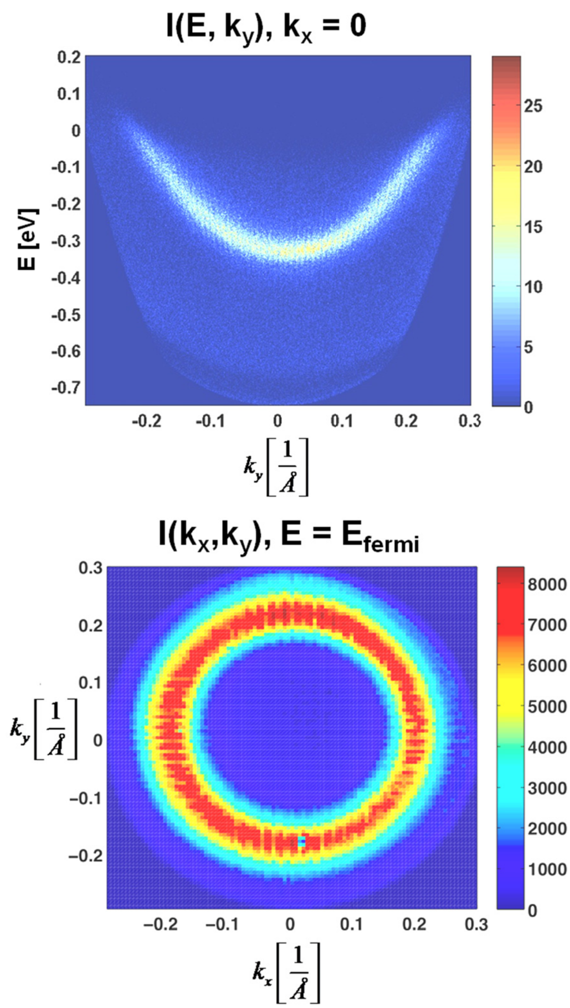

Figure 3: Energy-momentum dispersion relation (top) and the distribution of the transverse momentum at the Fermi level (bottom) for the Cu(111) surface state.

From the ARPES data obtained using the delay line detector, we calculated the emittance of the photoelectrons from the Cu(111) surface. The photon energy is 5.77 eV and the work function is 4.94 eV. Together with the predictions from the theoretical models, they are shown in Table 1. It is clear that the value from the experimental data is much closer to that given by the model based on the surface state than that from the 3-step

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model, which shows further that most of the photoelectrons are from the surface state.

Table 1: Comparison of The Measured Emittance to Two Theoretical Models

Method	3-step model	surface state	data
Emittance (μm)	0.74	0.42	0.49

In order to study the relation between the surface state and the abnormal enhancement of the QE, the clean Cu(111) sample was bombarded by 1 keV Ar ions. As the work function lowers, the intensity of the electrons from the surface state decreases and so does the peak of the enhancement in QE. At the minimum of the work function, the signal of the surface state disappears completely and the QE behaves virtually the same as that of the Cu(100) surface as the incident angle changes. Furthermore, after merely one cycle of annealing process, the surface state, along with the work function and the peak of enhancement in QE recovers to very close to the levels of the clean surface. We also observed the persistence of the Cu(111) surface state after 4 months of storage at 2e-10 Tor level vacuum. The peak of enhancement in QE was around 8.

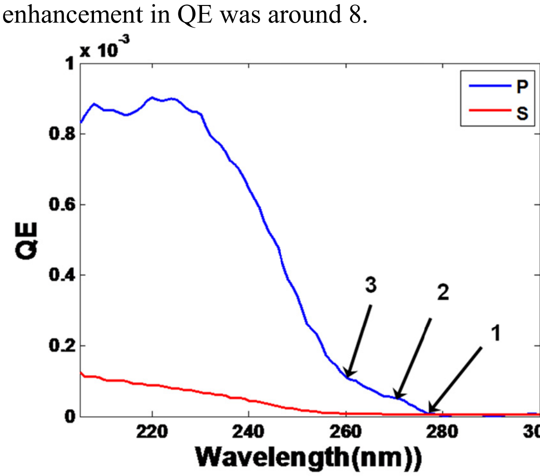

Figure 4: Quantum efficiency of the Ag(111) for the s and p polarized light at 70 degree incident angle.

PROPERTITIES OF AG(111)

Recently, we repeated the experiments on Ag(111) and found similar behavior to Cu(111). Furthermore, we measured absolute quantum efficiency and found that, at 70 degree incident angle, the quantum efficiency of the p-polarized light is rather high (see Fig. 4). Table 2 lists the photon energy and quantum efficiency of 3 important points. Point 1 indicates the onset of the photoemission process, which is essentially the work function of the sample. At point 2, the curve turns flat, corresponding to the bottom of the surface state. After point 3, the quantum efficiency increases dramatically, showing the full presence of the bulk band. At point 3, electrons normal to the surface can be emitted from the lower branch of the sp band. What's interesting to the FEL community is that, at the excess energy of around 0.1 eV, most electrons are from the surface state and the quantum efficiency is comparable to poly-crystalline copper.

Table 2: Photon Energy and Quantum Efficiency of the Points Indicated in Fig. 4

Point	E_{ph} (eV)	QE (10^{-5})
1	4.48	0.30
2	4.57	4.85
3	4.77	10.61

The fact that most electrons are from the surface state at the excess energy of around 0.1 eV has strong implication on the emittance, which is illustrated in Fig. 5. The shaded area shows the range in energy and momentum, according to the 3-step model, of the photoelectrons emitted from poly-crystalline copper for excess energy of 0.5 eV. The red and blue curves show the dispersion relations of the surface states of Cu(111) and Ag(111), respectively, based on data published in ref. [29]. Table 3 lists the theoretical predictions of the emittance of the photoelectrons emitted from the three surfaces. Note that the letter "P" stands for poly-crystalline.

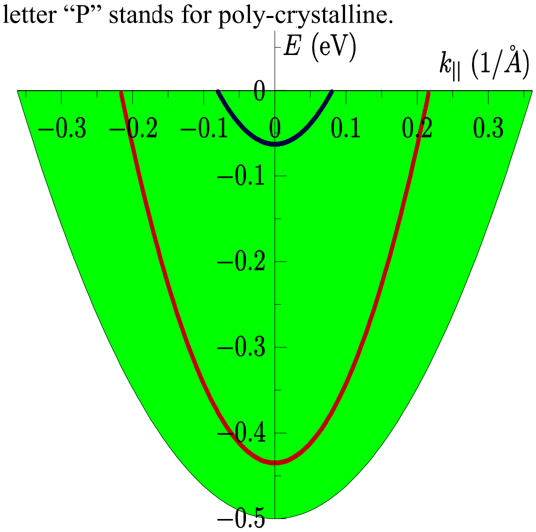

Figure 5: Energy-momentum dispersion relation of the Ag(111) (blue curve) and Cu(111) (red curve) surface states and the bulk emission described by the 3 step model (green shaded area).

Table 3: Theoretical Predictions of the Thermal Emittance of Various Metal Surfaces

Surface	Cu(P)	Cu(111)	Ag(111)
$\hbar\omega - \phi$ (eV)	0.5	0.5	0.15
$p_{x,max}$ (1/Å)	0.362	0.217	0.08
ε_x (μm)	0.57	0.42	0.15

CONCLUSIONS

In summary, these experiments point to a practical way of improving the performance of the metal cathode. Through the combination of the single crystal metal of the

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(111) orientation and grazing incident angle, we can achieve an order of magnitude gain in QE and a sizable reduction in transverse emittance. The robustness of the (111) surface makes it a feasible choice for application in an electron gun. This is particularly the case for silver since it is much less reactive than copper.

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