

PHOTOEMISSION PROPERTIES OF LaB₆ AND CeB₆ UNDER VARIOUS TEMPERATURE AND INCIDENT PHOTO ENERGY CONDITIONS

K. Morita, H. Zen[†], K. Masuda, K. Torgasin, T. Katsurayama, T. Murata, S. Suphakul, H. Yamashita, T. Nogi, T. Kii, K. Nagasaki, H. Ohgaki,
Institute of Advanced Energy, Kyoto University, Uji, Japan

Abstract

Photoemission properties of LaB₆ and CeB₆ were investigated at various cathode temperatures and different wavelengths of excitation laser to study for application of electron gun, especially for RF injector of infrared FEL facilities. It was found that the LaB₆ had higher photoemission property than CeB₆ at the same cathode temperature. In addition, LaB₆ can emit a measurable photoemission current being irradiated by laser with energy below work function at the cathode temperature higher than 1400 K. With increasing laser energy (over work function), a photoemission dependency on cathode temperature was getting lower. As the result, LaB₆ is revealed to have better properties than CeB₆ since LaB₆ has higher quantum efficiency than CeB₆ at same temperature.

INTRODUCTION

Thermionic and photo-electron injectors are widely adopted in FEL facilities. The usage of photocathodes for generation of high brightness electron beam has the disadvantage of high sensitivity to vacuum conditions and short lifetime. Very high quantum efficiency (> 1%) semiconductor photocathodes such as Cs₂Te, CsK₂Sb and GaAs, require extreme high vacuum (XHV) to keep the quantum efficiency for a long time. On the other hand, low quantum efficiency (0.001 – 0.01%) materials such as metal photocathodes usually have long lifetimes but require laser with a high peak power causing additional costs. When thermionic cathode materials are used as a photocathode, they have long lifetimes and can be operated at modest vacuum condition. In addition, the energy distribution of electron in the conduction band could be controlled by a thermal energy supplied by a heater, which is usually used for controlling the amount of thermionic emission in case of a thermionic cathode. The thermionic tungsten dispenser cathodes were already reported to be suitable for operation in photo-injectors [1, 2]. Hexaboride materials have high significances for thermionic cathodes, such as low work function, high melting temperature, high emission current, and low evaporation rate [3]. The LaB₆ cathode has already been successfully used as a photocathode [4-8]. Hence studies on the photoelectron emission from thermionic cathode materials are important to accelerate technology development.

In this study we focus on two representative hexaboride thermionic cathode materials, LaB₆ and CeB₆, and investigate their photoemission properties under various temperature and incident photon energy conditions in order to understand the effect of thermal excitation on the

photoemission yields. Table 1 summarises main properties of both cathode materials [3]. A significant difference between them is represented by Richardson constant indicating higher electron emissivity by LaB₆ at same temperature. In an ideal case, thermionic emission can be described by Richardson-Dushman current density equation:

$$j = AT^2 \exp\left(-\frac{\varphi}{k_B T}\right)$$

where φ is work function, A is Richardson constant, k_B is Boltzmann constant and T is temperature in Kelvin. On the other hand, it was reported that CeB₆ has higher resistivity to carbon contamination and lower evaporation rate than LaB₆ [9]. Due to its lower evaporation rate, CeB₆ has longer lifetime than LaB₆ when it is used as a thermionic cathode.

Although photoemission properties of those materials have already been reported in references [4-8, 10], these were tested by different laboratories with different experimental conditions. Therefore, in this study, photoemission properties of LaB₆ and CeB₆ have been measured under the same electrostatic conditions.

Table 1: Main Properties of LaB₆ and CeB₆ Cathodes [3]

| | CeB ₆ | LaB ₆ |
|---|------------------|------------------|
| Richardson constant (A cm ⁻² K ⁻²) | 3.6 | 29 |
| Melting point (K) | 2463 | 2483 |
| Work function (eV) | 2.65 | 2.7 |

MEASUREMENT SETUP

The entire measurement setup is shown in Fig. 1. The applied voltage between the cathode and the anode was 1 kV and the electric field about 0.1 MV/m. A nanosecond YAG laser (SureliteII-10, Continuum) with 2 Hz repetition rate and around 5-ns pulse length was used as the laser source. The fundamental wavelength of the laser was 1064 nm. Three laser wavelengths, 532, 355 and 266 nm, were generated by harmonic generation crystals and introduced to the test chamber. The polarization directions of the laser beams were not measured and controlled. The vacuum conditions were 5×10⁻⁸–1×10⁻⁷ Torr. The vacuum condition had slight sensitivity to changes on the cathode temperature and on the thermionic current. The cathode temperature was controlled by changing the supplying

[†] email address zen@iae.kyoto-u.ac.jp

current to the cathode heater and measured by an IR thermometer. The tested cathodes were single crystals with 1.72 mm diameter in <100> orientation, supplied by Applied Physics Technologies. The equivalent circuit diagram of the experimental setup is shown in Figure 2. As shown in Figure 2, pulsed photoemission current was AC coupled and measured by an oscilloscope. The DC thermionic current was measured by an analog amperemeter.

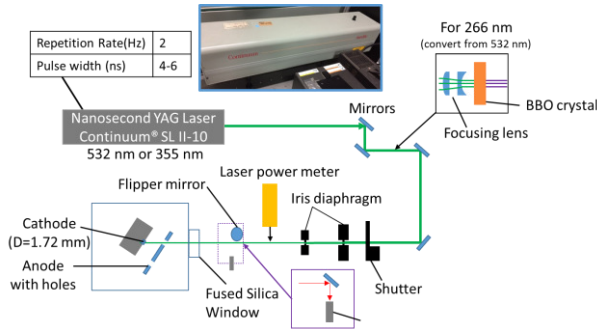


Figure 1: Experimental setup.

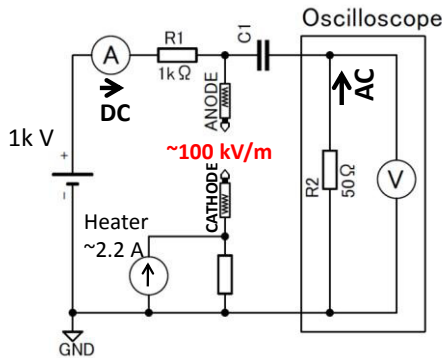


Figure 2: Equivalent circuit of measurement setup.

RESULTS AND DISCUSSION

The point of our interest is to understand the effect of thermal excitation on the photoemission properties of metal hexaboride materials. Another point is feasibility of the electron extraction by photon energy below work function of the cathode material which is excited by thermal energy. Therefore we measure photoemission at different excitation wavelengths, 266, 355 and 532 nm.

Thermionic Emission of LaB₆ and CeB₆

Result of thermionic current measurement is shown in Fig. 3. The measured thermionic current of LaB₆ is higher than that of CeB₆ at the same temperature. This can be expected from the Richardson constant. The LaB₆ can be operated at lower temperature than CeB₆ in similar current density.

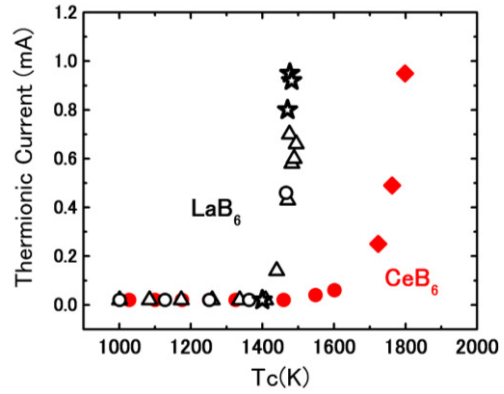


Figure 3: Thermionic emission from LaB₆ and CeB₆.

Photoemission @ 355 nm

In order to compare the photoemission properties of LaB₆ and CeB₆ cathodes, photoemission under different temperature condition have been tested with the laser wavelength of 355 nm. The results are shown in Figure 4. For comparison the photoemission current was normalized by laser power and expressed in relative QE by following relationship.

$$\eta = \frac{\text{number of electrons detected}}{\text{number of incident photons}}$$

The typical laser pulse energy in this experiment was around 13 μJ/pulse. Photoemission tendency shows the benefit of LaB₆ cathode with higher current slope rising around 1400 K. For CeB₆, we have to increase the cathode temperature up to 1550 K to obtain a similar rising as LaB₆. The photoemission dependency on the cathode temperature corresponds to that of the thermionic emission in both materials.

However, as CeB₆ has lower evaporation rate and higher resistivity to the carbon contamination [9], comparison of the lifetime of those cathode materials under photocathode operation is required for final conclusion of the better material.

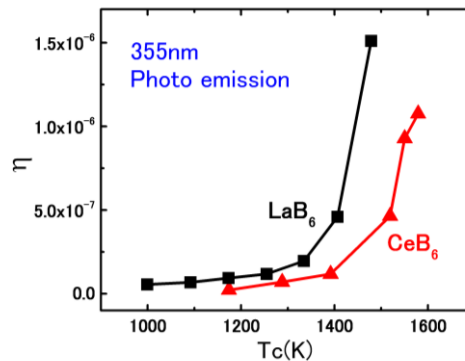


Figure 4: Photoemission properties of LaB₆ and CeB₆ irradiated by 355 nm.

Relative QE of LaB₆ at Different Wavelengths

In order to study on the photoemission property upon the photon energy, LaB₆ was irradiated by laser with 3 different wavelengths, 266, 355 and 532 nm. Figure 5 shows the result of the measurement. Photoemission at shorter wavelength can be expressed by two exponential curves with different slope. The longest wavelength has an exponential dependence at least our measured temperature region. The highest photon energy (266 nm) shows the smallest dependency on the cathode temperature. This behaviour indicates that the effect of thermal excitation is reduced when using photons with higher energy. As shown in Fig.5, electrons could be extracted by using 532 nm photons whose energy (2.33 eV @ 533nm) is below the work function (2.66 eV) when the cathode temperature was higher than 1400 K.

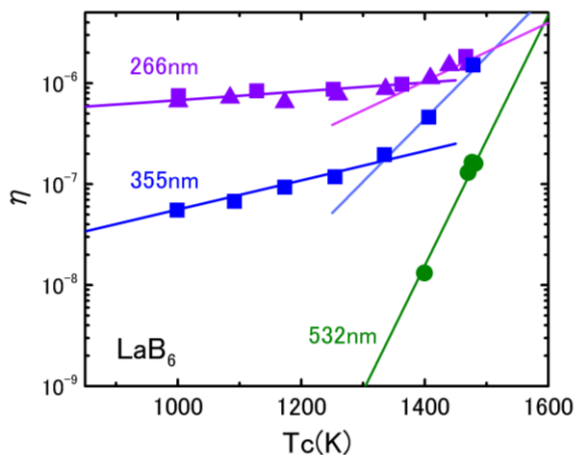


Figure 5: Results of relative quantum efficiency measurement of LaB₆ cathode being irradiated at 3 different laser wavelengths, 266, 355 and 532 nm. The solid lines are just for eye-guides.

SUMMARY

In the present work, photoemission properties of two thermionic cathodes, LaB₆ and CeB₆, were investigated. The photoelectron current dependence on the cathode temperature was measured. Additionally the LaB₆ cathode was tested for excitation at 3 different laser wavelengths (266, 355, 532 nm). It was found that the LaB₆ has higher photoemission property than CeB₆ at the same temperature which corresponds to the thermal emission property of two materials. However, as CeB₆ has lower evaporation rate and higher resistivity to contamination, it is required to compare the lifetime of those materials in photocathode operation for final determination of preferable photocathode material.

For LaB₆ the photon energy dependence on photoemission current was stronger for excitation by low photon energy. When LaB₆ was excited by 532 nm laser whose photon energy is below work function, measurable photocurrent appears at the cathode temperature higher than 1400 K. In this region, thermionic current can also be extracted from the cathode.

We conclude that the assistance of thermal excitation improves quantum efficiency of metal hexaboride cathode and with this technique, photoemission by laser with lower photon energy than the work function is feasible. This fact allows us to adapt various types of lasers for photoexcitation for sake of cost reduction. For the practical application of this technique, the contrast between the photoemission current and thermionic current must be taken into consideration.

ACKNOWLEDGEMENT

We would like to thank for valuable help and comments given by Dr. M. Bakr from the IAE, Kyoto Univ.

REFERENCES

- [1] S. Thorin et al., "Characterization of the beam from thermionic RF-gun adapted for photo cathode operation" Proceedings of FEL2009, Liverpool, UK.
- [2] S. Giermann et al., "Operating a tungsten dispenser cathode in photo-emission mode", Proceedings of PAC09, Vancouver, Canada.
- [3] J. M. Lafferty, "Boride Cathodes", Journal of Applied Physics 22, 299 (1951).
- [4] P.G.O'Shea et al., "Radio frequency photoinjector using LaB₆ cathode and a nitrogen drive laser" App. Phys. Lett., Vol. 73, No. 3, 20 July 1998.
- [5] H. Zen et al., "Feasibility Study of Photocathode Operation of Thermionic RF Gun at KU-FEL" Proceedings of IPAC'16, Busan, Korea, MOPOW018.
- [6] D.J. Bamford et al., "The search for rugged, efficient photocathode materials", Nucl. Instrum. Meth. A318 (1992) 377-380.
- [7] S. Mogren et al., "Thermionic and threshold photoemission energy distributions from LaB₆(110).", Surface Science 186 (1987) 232-246.
- [8] M. Boussoukaya et al., "Pulsed Photocurrents from Lanthanum Hexaboride Cathodes in The ns Regime", Nucl. Instrum. Meth. A264 (1988) 131-134.
- [9] S.L.Zhou et al., "Synthesis and properties of CeB₆ thermionic cathode with {001} fiber texture by reactive spark plasma sintering method", IVESC 2010, Nanjing, China.
- [10] H. Sugawara et al., "Extreme Ultraviolet Photoemission of CeB₆ and PrB₆", J. of the Physical Society of Japan, Vol. 51, No. 3, March, 1982, pp.915-921.