COMPARISON BETWEEN HEXABORIDE MATERIALS FOR THERMIONIC CATHODE RF GUN

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Abstract

Thermionic RF guns are widely used as highly brilliant electron source for linac-driven oscillator FEL (free electron laser). They can potentially produce an electron beam with high energy, small emittance, inexpensive and compact configuration in comparison with other high brightness electron sources. The most critical issue of the thermionic RF gun is the transient cathode heating problem due to the electron backbombardment when the gun is used for an FEL driver. The heating property of cathode not only depends on the emission properties of the cathode material, but also the physical properties such as electron stopping power and range. We investigated the heating property of six hexaboride materials against the backbombarding electrons by numerical calculation of the stopping power and range. In this investigation, the emission property of the cathode was taken into account, since high electron emission is required for generation of high brightness electron beam. As a result, cerium hexaboride material has best properties for thermionic RF gun cathode material in the backbombardment effect point of view.

INTRODUCTION

RF gun is considered one of the high beam quality electron sources, which has been first used with thermionic cathode and photocathode at Stanford University [1] and Los Alamos National Laboratory [2] respectively. The high electric field in a RF gun cavity can be used to accelerate electrons emitted from the cathode quickly to the state of $v \approx c$ (light velocity) [3]. Moreover, it has features of compactness, easy-handling and high brightness of the output beam, for these reasons thermionic RF gun has been chosen for electron source of Kyoto University free electron laser (KU-FEL). KU-FEL thermionic RF gun consists of a 4.5-cell cavity driven by 10-MW RF power, which provides up to 10 MeV electron beam. Because of the cavity field altered in time, electrons that are emitted late in RF period lose the chance to cross the cavity before the accelerating field reverse its direction. A number of these electrons accelerate back towards the cathode. If these electrons hit the cathode its energy will be lost with penetrating cathode through interaction with bound electrons in cathode material. Most of the electron's kinetic energy is converted to thermal energy, and heat up the cathode, then, cathode temperature and beam current increase during the macropulse. As a result, acceleration voltage of RF cavity decreases. Eventually electron beam energy decreases [4]. Borides with single crystal as electrons emitter materials not only have high resistance to ions sputtering but also have high stability and reproducibility of the emission properties. Moreover, MB_6 compounds exhibit an unusual combination of low work function and low volatility. Thus, these materials have attracted interest as thermionic cathode candidates. The primary single crystals of hexaboride considered in this work are (Ca, La, Ce, Pr, Gd, Ba)B_6.

In the present work, a comparison between six hexaboride materials as thermionic cathode in RF gun numerically has been done. We examined the thermionic emission properties of the borides, then, the range, stopping power and the heat deposited inside the cathode surface by backbombardment electrons are determined.

CALCULATIONS

1-Current density

The emission current density from a hot cathode is governed by Richardson-Dushiman equation,

$$j_c = AT^2 \exp\left(-\frac{\phi}{k_B T}\right), \tag{1}$$

where ϕ (V) is the emitter work function, which is a material dependant property. It can be seen from Eq. 1; a higher work function requires higher temperature and ultimately more power to achieve the desired electron current density. A (A cm^{-2} K^{-2}) is Richardson's constant; k_B (JK^{-1}) is Boltzmann's constant. The values of work function, Richardson's constant and melting temperature for the materials under investigation are listed in table 1.

2-Range and stopping power

The range R and stopping power of electrons inside target material is useful for various purposes in measurement and utilization of electrons, and effective tool for understanding their interaction mechanism with matter. Range R of monoenergetic electrons in the energy region 0.3 keV–30 MeV for the absorbers of atomic number 6–92 has been found to be expressed by a single semiempirical equation of the form [5],

$$R = \frac{a_1}{\rho}\left[\frac{\ln(1 + a_2\tau)}{a_2} - \frac{a_3\tau}{1 + a_4\tau^{a_5}}\right], \tag{2}$$

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Table 1 : Physical and chemical properties for the hexaboride materials used in the calculations

	CaB_6	LaB_6	CeB_6	PrB_6	GdB_6	BaB_6
Molecular weight (g mol^{-1})	104.946	203.772	204.986	205.774	222.116	202.193
Density (g cm^{-3})	2.490	4.720	4.797	4.840	5.270	4.390
Melting temperature (K)	2508	2483	2463	2883	2373	2543
Richardson constant (A $cm^{-2}K^{-2}$)	2.6	29	3.6	120	7.6	16
Work function (V)	2.86	2.66	2.59	3.12	2.51	3.45
Effective atomic number	10.728	40.447	41.228	41.978	53.837	39.639
Effective molecular weight ($gmol^{-1}$)	22.518	94.735	96.035	97.056	110.514	93.194

where ρ (g cm^{-3}) is the material density, τ is the incident kinetic energy in the units of the electron rest energy, and the parameters a_i (i=1,2,…,5) are defined by simple function of atomic number Z, and the atomic weight A. In case of mixture or compound Z and A should be replaced by the effective values of the atomic number Z_{eff} and effective atomic weight A_{eff} [5]. The effective atomic number and the effective atomic weight for the materials under consideration are listed in table 1. The stopping power of electrons inside matter, which defined as energy increment lost in infinitesimal material thickness, is given as $\Delta E/\Delta R$, [5].

RESULTS AND DISCUSSIONS

Assuming that, all the considered cathodes which will be used as thermionic cathode for RF gun have the same conditions of pressure, vacuum level, heating method, electric field in RF cavity, area and diameter. Moreover, the backbombardment electrons which hit the cathode have the range 0.3keV-1MeV. The emission current densities calculated by Eq. 1, for materials in table 1 are plotted in Fig. 1 as a function of the emitter temperature. It can be seen from Fig. 1, that all cathode materials under investigation could emit current density >10 Acm^{-2}, before its melting temperature except BaB_6. This value of current density is the minimum requirements for FEL amplification [4]. The stopping range of the backbombardment electrons in the cathode materials of (Ca, La, Ce, Pr and Gd) B_6 was calculated by using Eq. 2, and the results are depicted at Fig. 2. After the range calculations the stopping power for the above-mentioned materials was calculated and given in Fig. 3.

The calculations for the backbombardment electrons inside the cathode materials indicated that CaB_6 has longer range and lower stopping power comparison with other materials as shown in Figs. 2 and 3 respectively. Contrary, GdB_6 has shorter range and higher stopping power. The above mentioned behaviours can be clearly explained for small and high effective atomic weight for CaB_6 and GdB_6, respectively as shown in table 1. The contrast of range and stopping power behaviours for (La, Ce and Pr) B_6 can be explained by the contrast of both the densities and atomic weights for these materials as shown in Figs. 2 and 3.

The deposited heat at 1 μm from the cathode surface was calculated in this analysis, after considering the monoenergetic property of backbombardment electrons and the fixed number of electrons (from PARAMELA simulation at KU-FEL). Under these considerations, the change of the cathode surface temperature determined by using one dimensional thermal diffusion equation. as,

$$\frac{C\rho\ S\ z\ \Delta T}{\Delta t} = Q\ , \tag{3}$$

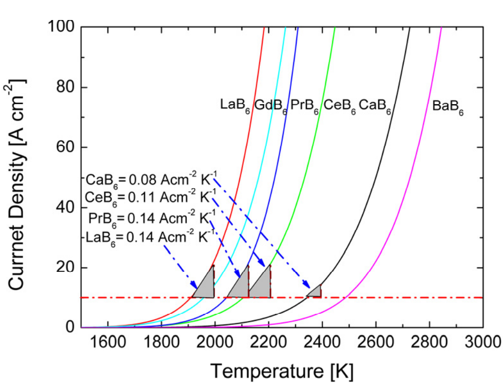

Figure 1: Current densities of a six borides against the emitter temperature, and the change of current density corresponding to cathode surface temperature change.

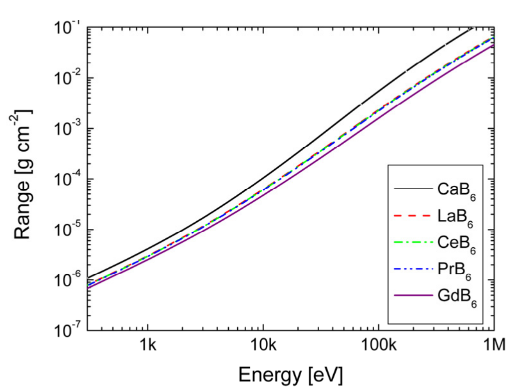

Figure 2: Comparison between the ranges inside the cathode materials by using semiempirical Eq. 2.

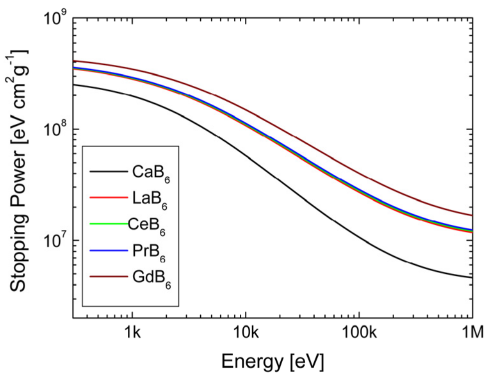

Figure 3: Stopping power for (Ca, La, Ce and Pr)$_6$B.

in shorter useful cathode life [7]. Care must be taken to properly optimize cathode temperature to obtain the required emission without overheating the crystal. On the other hand, in case of applications with small beam size with high current density >30 Acm^{-2} which is required for FEL gain saturation [4], (La, Ce and Pr)B_6 are the materials of choice in a variety of advanced. Even with, CeB_6 cathode has smaller current density than LaB_6 and PrB_6 at the same temperature as shown in Fig. 1, the slope $\Delta J/\Delta T$, due to the backbombardment electrons slightly lower than the slop in case of (La and Pr)B_6. Moreover, it's reported that CeB_6 has low evaporation rate comparison with other borides used as electrons emitter. From applications with small beam size and high current point of view, CeB_6 is best candidate to be used as thermionic cathode in RF guns. Experiments data are required to find the suitable cathode material for KU-FEL.

Table 2: the change of the cathode surface temperature and corresponding change in the current density for (Ca, La, Ce and Pr)B_6 calculated by Eq. 3, and shown in Fig. 1

Electrons energy keV	CaB_6		LaB_6		CeB_6		PrB_6	
	ΔT K	ΔJ Acm^{-2}	ΔT K	ΔJ Acm^{-2}	ΔT K	ΔJ Acm^{-2}	ΔT K	ΔJ Acm^{-2}
20	44.5	3.6	90.9	13.1	93.6	10.4	95.7	13.3
200	9.4	1.2	24.4	3.0	25.2	2.2	25.8	3.2
600	6.5	0.7	16.7	2.1	17.2	1.3	17.6	2.2

where C denotes the specific heat capacity, ΔT (K) the cathode surface temperature change within time Δt (s). S and z the cathode surface area and depth respectively. Q the heat inputted to the cathode surface due to the backbombarding electrons. The change in the cathode surface temperature for (Ca, La, Ce and Pr)B_6 was determined at 1 μm depth from the cathode surface within a 5 μs equals to macropulse duration at KU-FEL, for different energies of backbombardment electrons 20, 200 and 600 keV. The change of the cathodes current density starting from the minimum current density requirements for amplification in KU-FEL (10 A cm^{-2}), due to cathodes surface temperature change was determined and listed in table 2. As one can obviously see from table 2 and Fig. 1, emission slope $\Delta J/\Delta T$ in case of CaB_6 is lower than other borides. This means CaB_6 has low effect by backbombardment electrons from other borides. From the above mentioned results CaB_6 it seems the best candidate material to be used for KU-FEL thermionic RF gun for low current density applications. For high current density applications >30A cm^{-2}, CaB_6 cathode temperature is near from the melting temperature, for that reason, using CaB_6 attached with two considerations. First one, to achieve >30 Acm^{-2} cathode area has to be doubled, as a result, the thermal emittance will be twice, and even with thermal emittance increasing it still under the preferable emittance in FEL amplification in KU-FEL (12 πmm mrad). Secondly, backbombardment heat will be added to cathode temperature as a result the cathode temperature will be closed to the melting temperature, then; evaporation rate from the cathode surface will be increased. However, high cathode temperature will result,

CONCLUSIONS

Six hexaboride were investigated in the way to find which material has low effect to backbombardment electrons in KU-FEL thermionic RF gun. The strategy started with checking the current density of the hexaborides, BaB_6 did not match the required current density for FEL amplification (10 Acm^{-2}) below the melting temperature. Then, the range and stopping power for (Ca, La, Ce, Pr, Gd)B_6 were calculated as a function of backbombardment electron energies in the range of 0.3 keV- 1 MeV. Finally, the change of the cathode surface temperatures and the current densities were determined. Among the hexaboride single crystals investigated here, CaB_6 is found to be promising electron emissive material for low current density applications form backbombardment point of view. However, CeB_6 is the most promising material not only due to high current emission, but also for excellent stability and extracted beam quality. We will perform experiments to confirm the above mentioned results.

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