Development of High Power Electron Beam Gun (Report I)

— Generation of High Power Electron Beam with LaB_6 Cathode —

M. TOMIE*, N. ABE*, Y. KATO** and Y. ARATA***

Abstract

Although LaB_6 is often used for the cathodes of electron microscopes, electron beam lithographers and similar devices which emit a very small quantity of thermal electrons, the authors tried applying LaB_6 for the cathode of a high power, high energy density electron beam. The electron beam properties generated by a directly heated type and indirectly heated type (bombardment type) LaB_6 cathode were then investigated. It was found that the LaB_6 cathode generated a stable high power electron beam. A beam current of 450 mA was obtained with a 3.5 mm ϕ directly heated type cathode at an acceleration voltage of 60 kV and a cathode temperature of 1890 K, about 1000 K lower than that of a tungsten cathode.

KEY WORDS : (LaB_6 Cathode) (Electron Beam) (Directly Heated Cathode) (Bombardment Type Cathode)

1. Introduction

LaB_6 (lanthanum hexa-boride) has the highest emission current among boride cathodes and is widely used as a cathode material of emitting source of thermal electrons for electron microscopes, electron beam lithographers, which utilizes a very small current. The thermal electron temperature of LaB_6 is much lower than that of other cathode materials, especially the W (tungsten) used for high power electron beam heat sources. If a LaB_6 cathode with a low emission temperature is applied to a high power electron beam heat source, the distortion of the cathode caused by thermal expansion during beam generation can be reduced, ensuring greater beam power stability.

This investigation was performed with the purpose of applying LaB_6 as a cathode for a high power, high energy density electron beam generator. The authors have been developing various kinds of cathodes for high power electron beams and have been studying their characteristics[1]. In this report, the characteristics of power generation using a directly heated and an indirectly heated (bombardment type) LaB_6 cathode developed by the authors are described, and the stability of electron beam emission is also discussed.

2. Experimental Apparatus and Procedure

A directly heated type and a bombardment type electron gun using a LaB_6 cathode were designed and manufactured. Although the directly heated type has the merit that the input heat is lower than that of the bombardment type because the cathode is heated by Joule heating, there is the demerit that the electrons emitted from the cathode are deflected by the magnetic field generated around the surface of the cathode by the DC heating current. On the other hand, the bombardment type requires a much larger input heat for cathode heating, but there is no magnetic field at the cathode surface which would cause electron deflection. As each type has both merits and demerits, their influence on electron beam generation for a high power electron gun using a LaB_6 cathode was investigated.

In order to measure the temperature characteristics of the cathode, a micro pyrometer was used. The output characteristics of the electron beam were measured under a high voltage (DC 50 ~ 80 kV). The time dependence of the electron beam output was investigated with regard to stability.

Figure 1 shows a schematic diagram of the electron beam apparatus used in this experiment. The experimental apparatus was divided into an electron gun room and a beam collection room by an intermediate valve and a slit. The electron gun part consists of a cathode, a wehnelt, an anode and a magnetic coil for beam focusing. A beam deflection coil and a water-cooling beam collector were set up in the beam collection room. A faraday cup was set on the beam collector to measure the electron beam emitted from the cathode and transmitted through the anode hole.

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The electron gun room and the beam collection room both had their own vacuum pump systems. The electron gun room was evacuated to 10^{-5} Pa by a turbo molecular pump (evacuating speed of 160 l/sec) and an oil rotary pump, and a vacuum level of 10^{-4} Pa was maintained in the electron beam collection room by an oil diffusion pump (570 l/sec) and an oil rotary pump.

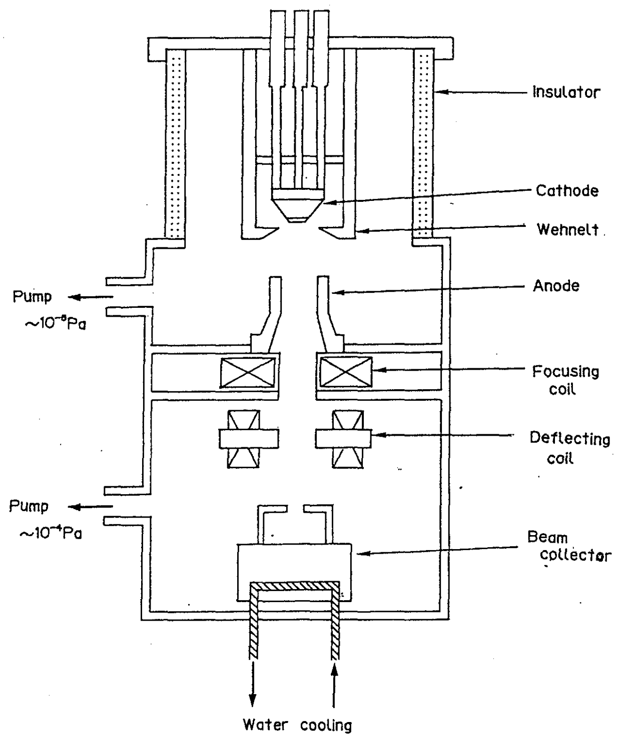

Fig. 1 Schematic diagram of electron beam apparatus.

Figure 2 (a) and (b) show the electric circuits for the directly heated and bombardment type electron guns.

3. Experimental Results and Discussion

3.1 LaB_6 Cathode

Although a single crystal cathode is used for almost all electron microscopes and electron beam lithographers, the LaB_6 cathode used in this experment was manufactured from a sintered material and its density was 98% that of a single crystal. As it is hot-pressed, sintered LaB_6 includes bubbles and impurities, which are concentrated along the grain boundary. Although these bubbles and impurities influence the stability of electron emissin, sintered LaB_6 was selected since it offers a large thermal electron emission area for higher power electron beam generation.

A LaB_6 cathode with an electron emission area of 3.5mm ϕ was used for the directly heated type electron gun. A rod type cathode on which a 3.0 mm ϕ LaB_6 tip was fixed with a stopper was developed for the bombardment type electron gun. Photographs of the cathodes' appearance are shown in **Fig. 3**(a) (directly heated type) and **Fig. 3**(b) (bombardment type).

Figure 4 shows a comparison of the thermal electron emission characteristics, the most important factor for the cathode material, of LaB_6 and W, which is usually employed for the cathode of an ordinary electron gun. These curves were calculated with the Rechardson-

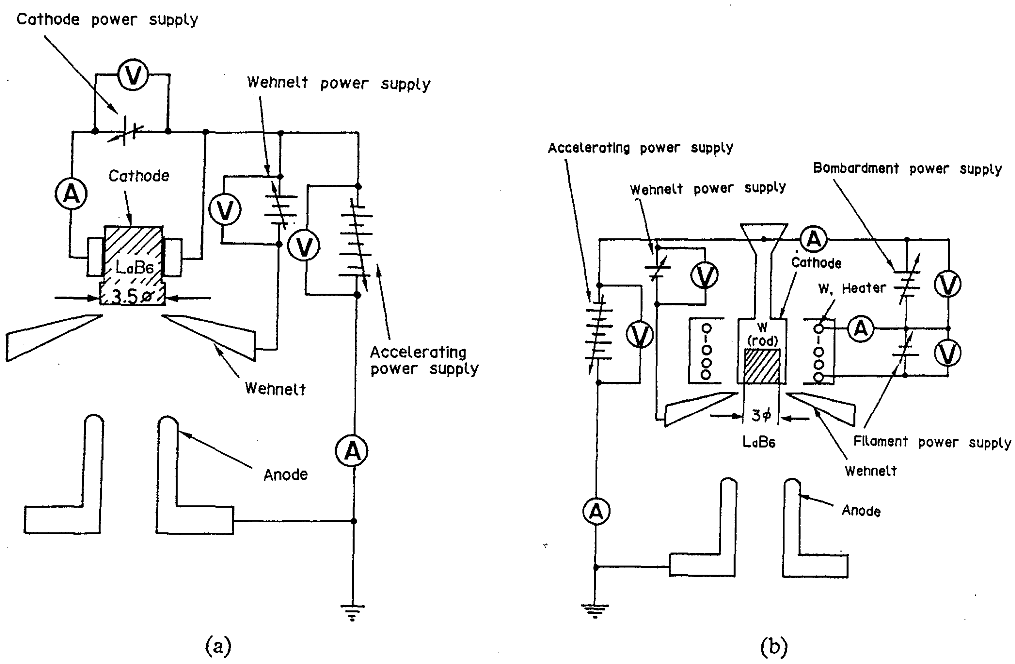

Fig. 2 Schematic diagram of circuits.
(a) directly heated type
(b) bombardment type

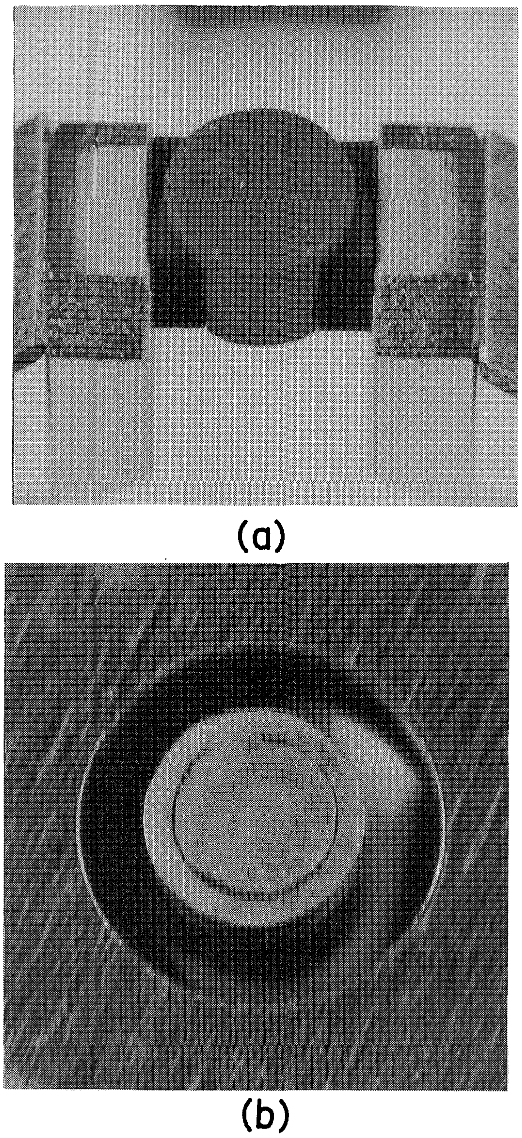

Fig. 3 (a) Directly heated type LaB_6 cathode and (b) Bombardment type LaB_6 cathode.

Dashman equation[2)] as follows:

$$i_{th} = A \cdot D \cdot T^{2\ -e\phi/kT} \qquad \cdots\cdots (3\text{-}1)$$

A : constant (60 for W, 29 for LaB_6)
D : penetration coefficient (~1 for metal)
T : temperature of electron emitter (K)
ϕ : work function (eV)
k : Boltzman constant

For the work function value, 2.7 eV[3)] was used for LaB_6 and 4.5 eV for W. The emission current density of LaB_6 is apparently higher than W because the work function is lower than W for the same temperature. In contrast, the temperature of W which gives the same radiation current density as LaB_6 is higher than that of LaB_6. For example, to obtain a current density of 10 A/cm^2, the LaB_6 and W must be 1900 K and 3000 K, respectively. The difference in temperature between the LaB_6 and W is about 1100 K,

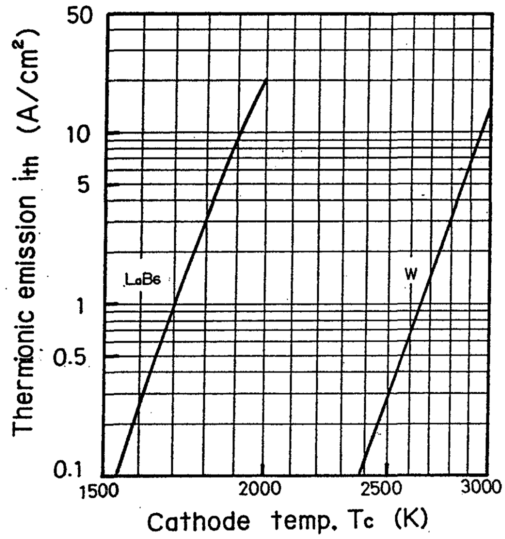

Fig. 4 Thermionic emission of LaB_6 and W.

a large difference for a high power electron gun, because the increased cathode temperature induces heat deformation of the materials used for the element of the electron gun and reduces the resistance of the insulator against high voltage, destabilizing electron beam generation.

The lifetime of a cathode, i.e. whether the electron beam is generated stably for a long time, is a very important factor for a cathode. The relationship between the brightness and lifetime of single crystal LaB_6 was investigated by Hagiwara et al[3)]. They reported that the lifetime of LaB_6 was 10 times longer than W and was strongly related to the working temperature, working gas pressure and crystalline axis.

Since a sintered cathode of LaB_6 was used under hard working conditions in which it was applied to thermal processing such as welding, where ions generated along the beam channel were accelerated reversely from the anode to the cathode, thus strongly bombarding the cathode, it was very difficult to compare the lifetime of LaB_6 and W.

3.2 Temperature Characteristics

The temperature characteristics of a directly heated type LaB_6 cathode (diameter of electron emission area is 3.5 mm ϕ) is shown in **Fig. 5**(a), where a cathode current was stabilized by using a constant current DC power supply. The cathode temperature shows a saturation curve because of heat radiation and conduction to the supporters of the cathode. It reaches 1900 K at a cathode current of 1 A (with an electron gun input power of about 50 W).

The temperature characteristics of a bombardment type LaB_6 cathode (diameter of electron emission area is

3.0 mm ϕ) is shown in **Fig.** 5(b). In the case of the bombardment type cathode, heat was input to the cathode through bombardment electric power and radiation heat from a heater. However, since the cathode was mainly heated by bombardment power, it was used as a variable for the temperature characteristics. In order to increase the cathode temperature to 1900 K, a bombardment power of 50 W and a heater power of 100 W were required.

3.3 Beam Generation Characteristics

3.3.1 Directly heated LaB_6 cathode

Figure 6 shows the relationship between the beam acceleration voltage (40 ~ 70 kV) and the beam current under the following conditions: a cathode-anode distance of 17 mm, a constant wehnelt voltage of 300 V and a cathode heating current of 9.0~11.0 A. Langmuir derived the relationship between the acceleration voltage and the beam current in the space charge limitation region as following equation:

$$I_b = G \cdot V_b^{3/2} \quad \cdots\cdots (3\text{-}2)$$

I_b : beam current

V_b : beam acceleration voltage

G : parviance

That is, if the parviance determined by the configuration of the electron gun is constant, the beam current is proportional to the 3/2 power of the beam voltage. The parviance of the gun used was derived from the characteristics obtained from Fig. 6 to be $G = 2.9 \times 10^{-8}$ ($A/V^{3/2}$). The saturated part of the figure is the temperature limited region. As the beam current is limited by the electron emission ability of a cathode, it displays saturation characteristics at increased beam voltage. This tendency toward saturation is directly influenced by the properties of the cathode, the structure of the electrode, and the temperature of the cathode.

For example, when the cathode temperature directly measured by the micro-pyrometer was 1780 K, the theoretical electron emission density calculated using Eq. 3-1 was 2.11 A/cm^2 while the experimental result for the LaB_6 used was 1.5 A/cm^2. This is because the theoretical value comes from the diode model, while the experimental value is obtained from the triode configuration where the direction of the electrons from the cathode is controlled by the wehnelt voltage, which restricts the beam current like the grid of an electron

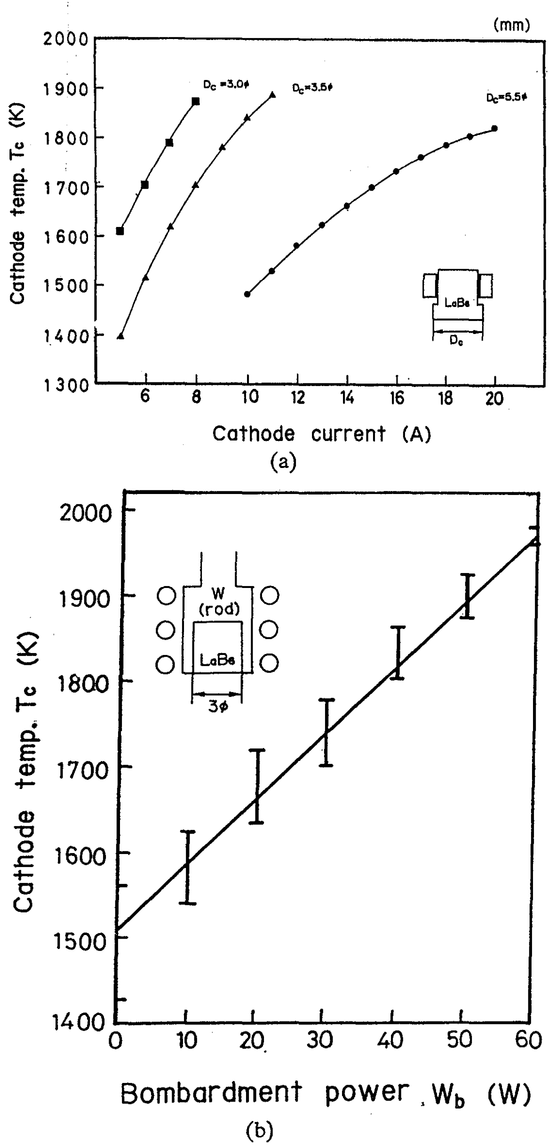

Fig. 5 Cathode temperature characteristics.
(a) directly heated type
(b) bombardment type

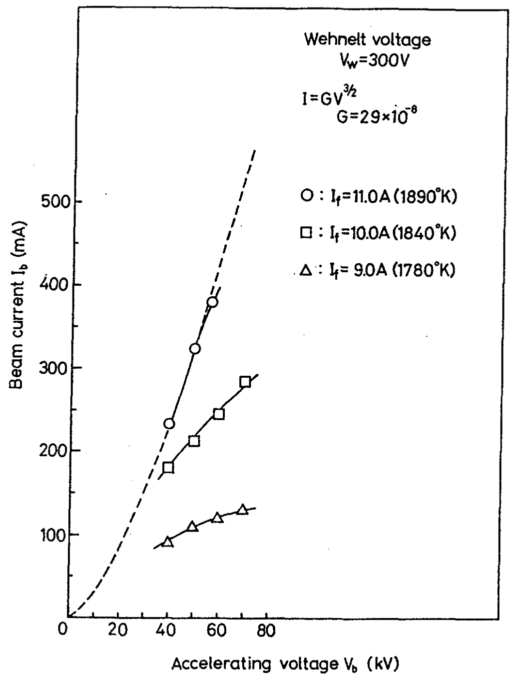

Fig. 6 Relation between current and accelerating voltage. (directly heated type)

tube.

3.3.2 Bombardment type LaB_6 cathode

The relationship between the beam acceleration voltage (50 ~ 80 kV) and the beam current is shown in **Fig. 7** for a LaB_6 cathode with an electron emission area diameter of 3.0 mm ϕ under the following conditions: a cathode-anode distance of 20 mm, a constant wehnelt voltage of 300 V, and a bombardment power W_B of 45 ~ 55 W (bombardment current of 200 ~ 220 mA).

At W_B = 55 W, a cathode temperature of 1930 K and a beam accelerating voltage of 80 kV, a beam current of 180 mA was obtained: i. e. the beam power was 15 kW. The parviance of the electron gun used was $G = 7.4 \times 10^{-9}$ $(A/V^{3/2})$ which was calculated from Langumuir's theoretical equation Eq. 3-2. Below W_B = 55 W, the beam current was influenced by the temperature limited region and displayed characteristics similar to the directly heated type cathode. Furthermore, it was found that this electron gun follows the space charge effect.

3.3.3 Stability of electron beam generation

The most important and necessary property required for an electron gun is to generate and accelerate an electron beam stably over a long period. However, this is a very difficult problem for a high power electron gun which is required to generate a high beam current. As this property is influenced by a complicated combination of many different factors, there is no easy way to achieve it. However, stabilization of thermal electron emission from the cathode solves the main part of this problem of realizing a stable electron beam. In order to achieve such stabilization, it is important to maintain the electron emitting surface of the cathode at the constant temperature required for a specific beam current.

While the cathode temperature of directly heated type electron gun is controlled with the cathode current, that of a bombardment type electron gun is controlled both with the heater current and the bombardment power. However, control is easier using only the bombardment power. In this report, the stability of electron beam generation was examined for a bombardment type electron gun. The diameter of the electron emitting area of the LaB_6 cathode was 3.0 mm ϕ, the distance from the anode to the cathode was 20 mm, the wehnelt voltage was 300 V, and the bombardment power was 55 W. After starting bombardment heating of the cathode, a substantial amount of heat was conducted through the tungsten supporting pillars to the structural element of the electron gun and the cathode temperature decreased as a result. After 30 minutes of preheating the cathode with a bombardment power of 55 W and instantaneous impression of a beam voltage of 60 kV, the fluctuation of the beam current over time was measured (**Fig. 8**). The initial beam current of 110 mA decreased quickly with time to almost 70 mA within 30 seconds and the rate of fluctuation reached as high as 40 %. This phenomenon was caused by a decrease in the surface temperature of the cathode caused by electron emission. The large temperature decrease was caused by heat conduction from the holding system of the cathode to the W supporting rod, where the thermal conductivity from the W supporting rod to the cathode may not have been sufficient.

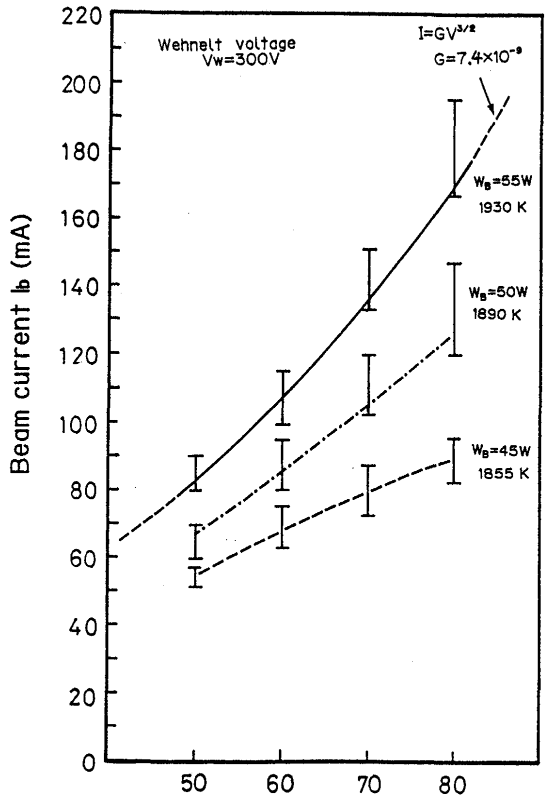

Fig. 7 Relation between current and accelerating voltage. (bombardment type)

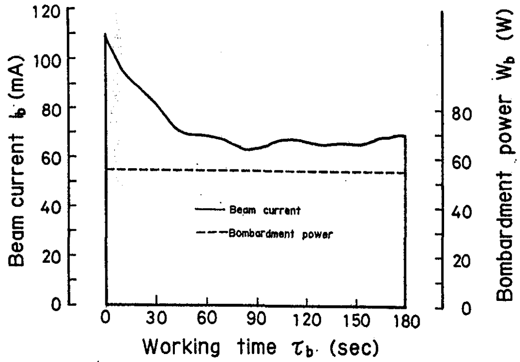

Fig. 8 Initial instability of beam current at the beginning of acceleration with constant bombardment power.

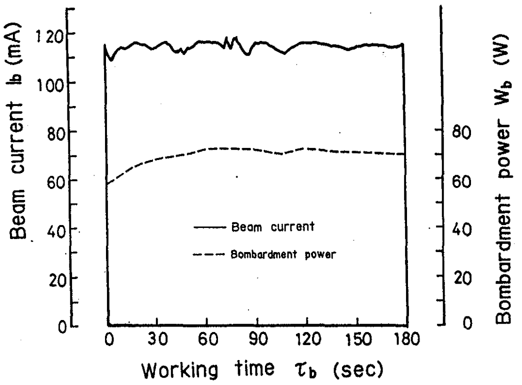

Fig. 9 Stabilization of beam current with feedback control of bombardment power.

When the bombardment power was maintained at a constant power of 55 W and after instantaneous impression of a beam voltage of 60 kV, the bombardment power was manually controlled at a constant value and the beam current was measured over time. As shown in **Fig. 9**, the fluctuation of the beam current was easily stabilized within ± 2 % of the set value by manually controlling the bombardment power. The profile of the electron beam obtained had a round distribution which could be strongly focused to a high energy density. A stable beam was emitted for over 50 hours.

4. Conclusion

The applicability of LaB_6, which has a low work function compared with W, for the cathode of a high power electron gun was investigated. The following results were obtained:

1. A beam current of a few hundred mA was obtained using sintered LaB_6.
2. The temperature of the LaB_6 cathode during electron beam generation was 1800 ~ 1950 K, which was 1000 K lower than for a W cathode. This low cathode temperature resulted in only small thermal distortion of the cathode of the electron gun and enhanced electron beam stability. It was also effective in suppressing arcing of the electron gun.
3. A bombardment type LaB_6 cathode was developed, which had been thought difficult to manufacture compared with a W cathode. A long lifetime of over 50 hours was achieved.
4. Fluctuation of the beam current was suppressed to within ± 2 % of the set value by using bombardment power control of the bombardment type electron gun, which required a higher input heat compared with the directly heated type.

The authors thus established that sintered LaB_6 can be applied for the cathode of an electron gun for a high power electron beam heat source.

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