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Letter

Thermionic emission properties of rare-earth-added LaB_6 crystal cathodes

Shigeki Otani
National Institute for Research in Inorganic Materials, Namiki 1-1, Tsukuba, Ibaraki 305 (Japan)

Hideo Hiraoka and Masaru Ide
Shibukawa Plant, Denki Kagaku Kogyo Inc., Nakamura 1135, Shibukawa, Gunma 377 (Japan)

Yoshio Ishizawa
National Institute for Research in Inorganic Materials, Namiki 1-1, Tsukuba, Ibaraki 305 (Japan)

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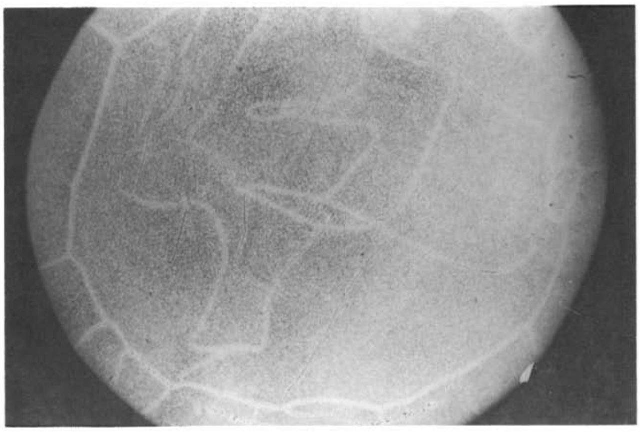
Abstract

Subgrain boundaries were removed from LaB_6 crystals prepared by the floating zone method, by adding the rare earth hexaborides CeB_6, PrB_6 and NdB_6. In this work the thermionic emission properties of cathodes made from the boundary-free crystals were examined and compared with those of an LaB_6 crystal cathode. Addition of the rare earth borides did not influence the emission properties (emission current density, brightness and life) under practical working conditions.

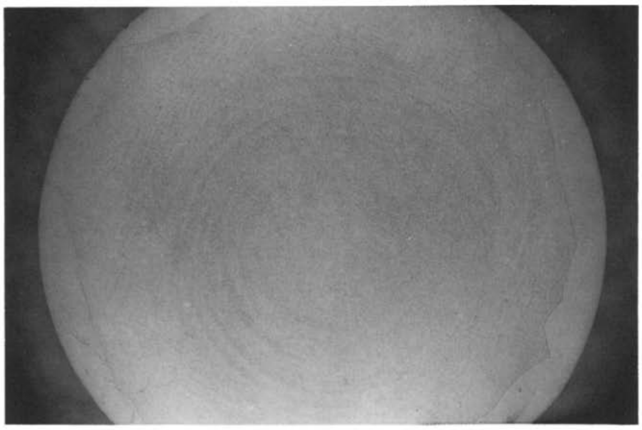
1. Introduction

Single-crystal LaB_6 cathodes are widely used as an electron source of high brightness and longevity [1]. The crystals are mainly prepared by the floating zone method, which gives high purity and large size [2, 3]. However, the crystals contain subgrain boundaries, as shown in Fig. 1(a), and accordingly the cathodes are made from only the high quality part. Recently, boundary-free crystals were prepared by adding the rare earth hexaborides CeB_6, PrB_6 and NdB_6 [4–6], as shown in Fig. 1(b). This is of commercial interest, since the process of making the cathodes should become simpler. Further, the boundary-free crystals should be useful for constructing cathodes with large emission areas.

The thermionic emission properties of (La, rare earth)B_6 solid solutions have already been examined by several workers [7–10] using polycrystalline samples and needle-like crystals prepared by the aluminium flux method, but their results are not mutually consistent. Further, there are only a few data on the composition dependence. Therefore the emission properties cannot be estimated in the composition ranges where boundary-free crystals are obtained by the floating zone method. In this work, using boundary-free crystals, the thermionic emission properties were examined and compared with those of an LaB_6 crystal cathode.



(a)



(b)

Fig. 1. (100) etching patterns of (a) LaB_6 [3] and (b) $La_{0.7}Ce_{0.3}B_6$ [4] crystals.

2. Experimental details

The samples were the boundary-free crystals $La_{0.7}Ce_{0.3}B_6$, $La_{0.82}Pr_{0.18}B_6$ and $La_{0.85}Nd_{0.15}B_6$, which were prepared by adding minimum quantities of rare earth borides to LaB_6 [4–6]. They were cut into small rectangular prisms of dimensions $1.0\times1.2\times2.8$ mm^3 using a spark corrosion cutter. Their axial orientation was ⟨100⟩.

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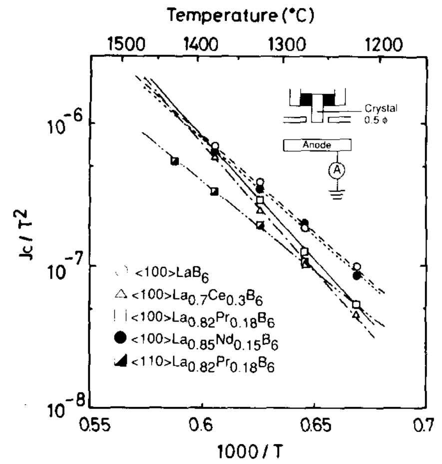

Fig. 2. Richardson plots for LaB_6 and rare-earth-added LaB_6.

The thermionic emission current density was measured as shown in Fig. 2. The ⟨100⟩ cylindrical crystal rod, 0.5 mm in diameter, into which the crystal block was shaped using a centreless grinder, was supported at both sides by two graphite blocks and directly heated by current flow through pyrolytic graphite. The basal pressure was 1.3×10^{-5} Pa (1×10^{-7} Torr) in the chamber.

The brightness of the ⟨100⟩-oriented cathode was measured in a scanning electron microscope (SEM) modified for the present measurements. The cathode tip was made by mechanically shaping the crystal block into a cone with an angle of 90° and a radius of 15 μm. The pressure during the measurements was 1.3×10^{-4} Pa (1×10^{-6} Torr). The cathode temperature was 1550 °C. The accelerating voltage was 20 kV. The spread of the electron beam was determined from the geometrical configuration in the SEM. The beam current was measured with a Faraday cup. The beam diameter was measured by scanning normal to the knife edge. The details have been described elsewhere [1].

3. Results and discussion

The boundary-free crystals were surrounded by polycrystalline rims with a thickness of 0.5–0.7 mm, as shown in Fig. 1(b). More than 30 crystal blocks with a cross-section of 1.0×1.2 mm², were cut out of the boundary-free parts, about 8 mm in diameter. They were all of high quality, contained no boundaries or inclusions and were of a size large enough for the cathodes.

Figure 2 shows plots of $\ln(J_c/T^2)$ against $1/T$ for LaB_6 and rare-earth-added LaB_6. The densities of emission current from the cerium- and praseodymium-added crystals were lower than that of LaB_6 in the low temperature range. However, with increasing temperature the current densities tended to be close to that of LaB_6. In the case of neodymium-added LaB_6 the current density was the same as that of LaB_6 over the whole temperature range. In practice, LaB_6 cathodes are used at temperatures around 1550 °C; accordingly, Fig. 2 suggests that the current densities of the rare-earth-added cathodes are the same as or a little higher than that of the pure LaB_6 cathode. The work functions obtained from the gradients were 2.73 eV for LaB_6 and 3.53, 3.44 and 2.70 eV for cerium-, praseodymium- and neodymium-added crystals respectively.

Figure 2 also shows the data obtained from a ⟨110⟩ praseodymium-added LaB_6 crystal. The current density was lower than that for the ⟨100⟩ praseodymium-added crystal. This dependence on the crystal orientation is the same as for the pure LaB_6 cathode. The work function was 2.51 eV.

The relationship between the total emission current and the brightness is shown in Fig. 3. The brightness was maximum, 10^6 A cm^{-2} sr^{-1}, at a current of about 100 μA and the cathodes of $La_{0.82}Pr_{0.18}B_6$ and $La_{0.85}Nd_{0.15}B_6$ had the same brightness as the LaB_6 cathode. The former showed a little higher brightness than LaB_6 in the range above 100 μA. The additions were found not to decrease the brightness. This result is consistent with the results obtained from the Richardson plots shown in Fig. 2.

In practice, these cathodes were used in the SEM for up to 864 h. No differences in emission characteristics from the LaB_6 cathode were found. In addition, there seemed to be no problem with regard to the lifetime, because the cathodes could be used for longer than the guaranteed lifetime of the commercially available LaB_6 cathode for the SEM, 500 h. After use in the SEM the decrease in size of the cathode due to evaporation was measured. The evaporation loss was 0.07 μm h^{-1}, with no difference between the rare-earth-added cathodes. This value is the same as that of the LaB_6 cathode. Therefore the lifetime of these cathodes can be estimated to be the same as that of the LaB_6

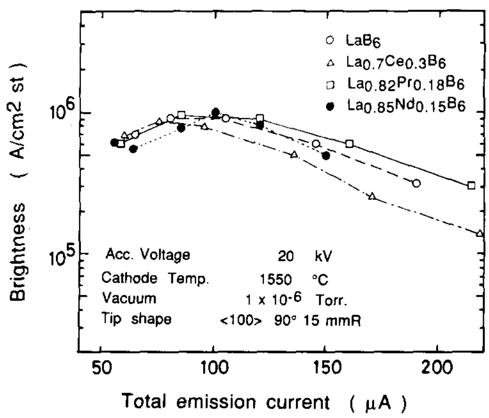

Fig. 3. Relationship between total emission current and brightness.

cathode, because the evaporation causes a change in the shape of the cathode tip, which in turn determines the lifetime.

4. Conclusions

In summary, addition of the rare earth borides CeB_6, PrB_6 and NdB_6 did not damage the emission characteristics of the LaB_6 cathode. It was demonstrated that these cathodes can be used in a scanning electron microscope in the same way as the LaB_6 cathode. This is of commercial interest, since addition of the rare earth borides produces boundary-free crystals.

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