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THERMIONIC EMISSION STUDIES OF MICRO-FLAT SINGLE CRYSTAL LANTHANUM HEXABORIDE CATHODES

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Abstract

A new type of high brightness thermionic cathode has been developed. The cathode utilises emission from a small flat surface (generally less than 50 µm diameter) prepared parallel to a specific crystal plane on a single crystal of Lanthanum Hexaboride. Emission from the rest of the single crystal is suppressed by the use of a high work function coating of pyrolytic graphite. When used in a conventional triode gun, the maximum total electron emission is controlled by the area of the micro-flat, the work function and the temperature of the emitter. The Wehnelt potential serves a minor role in controlling the divergence of the beam. At certain emitter height settings, the gun produces the maximum axial brightness at zero bias. The field at the surface of the micro-flat is higher than that for pointed emitters in a conventional configuration and no longer limits the gun brightness. As the emitting region is now parallel to a specific crystallographic surface, the emission anisotropy of LaB_6 can now be utilized in developing emitters of optimum brightness. The new sources reduce Wehnelt aperture contamination and offer long lifetimes under favourable vacuum conditions.

Key Words: Thermionic Emission, High Brightness Triode Guns, Lanthanum Hexaboride, Single Crystals, Micro-flat Cathodes.

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Introduction

Lanthanum hexaboride electron sources are now commonly used in electron optical instruments such as scanning electron microscopes and electron beam writers. When correctly employed they provide both a higher gun brightness and longer filament life than that normally achieved with tungsten emitters. The application of LaB_6 cathodes has closely followed the general practice of tungsten cathodes in that the improved performance has been sought through changes in operating conditions in the conventional high voltage triode electron gun. In order to make use of higher cathode loadings at the emitting tip of the cathode, the axial electric field in this region is generally enhanced by the use of sharply pointed single crystal LaB_6 sources. This pointed emitter is the most commonly used LaB_6 electron source and is available from numerous commercial sources.

Unfortunately, this form of conical cathode structure presents several problems when attempting to optimise its performance in a triode gun. One limitation results from the operating characteristics of the triode gun itself. A second is the complex crystallographic nature of the emitting region of the pointed cathode. A third is the evaporation and oxidation of the large area of LaB_6 exposed to the internal surface of the Wehnelt aperture. These points warrant further discussion before describing a new cathode structure which overcomes some of these limitations.

The triode gun controls electron emission by changing the electric field at the surface of the cathode. At the "cut-off" potential, the zero equipotential of the gun is adjusted to be just in front of the cathode surface so that no electron emission occurs. As the Wehnelt potential is made less negative the zero equipotential begins to intercept the cathode surface so that emission is possible. When emission just begins, the field at the surface is very low and the cathode emission at normal operating temperatures (LaB_6 e.g. 1800-1900K) is strongly space charge limited. As the Wehnelt becomes less negative the total emission from the cathode increases as the conical area of the tip within the accelerating field region increases.

The field strength over the surface of this cone varies in a complex manner, being maximum at the apex and dropping to zero at the zero equipotential intercept. To increase further the field at the tip, the Wehnelt potential is reduced further and the total emission increases rapidly as the area of the emitting surface increases. For optimum performance of the gun, a balance is developed between a practical value of total emission and a maximization of the field at the apex. These conditions result in a complex beam structure which may contain an intense central spot surrounded by a diffuse halo or multiple lobes as observed for single crystal cathodes.[1 2 3] At high temperatures, the full theoretical brightness of a LaB_6 cathode is rarely obtained, even on the axial beam.

The area of electron emission around the tip of a conical single crystal emitter cannot be defined simply in terms of any particular single crystal face and hence complex emission characteristics come into play as the tip is allowed to emit by control of the Wehnelt potential. Tip structures developed by thermal evaporation and associated lobe patterns of emission have been described by several authors.[4 5] These emission patterns depend critically on the alignment of the tip within the Wehnelt aperture. To utilise the thermionic emission anisotropy that exists between specific crystal planes of LaB_6 [6 7] a simpler form of emitting surface is desirable. A flat cathode cut parallel to a specific crystal plane is preferred for fundamental studies of emission anisotropy.

Considerable data on the evaporation of LaB_6 at typical operating temperatures have been published. [7 8] In addition to direct evaporation, the evaporation of oxidation products is also of importance if operating pressures in the gun are above about 7×10^{-6}Pa (5×10^{-8} Torr). [9] As a result of these processes a material deposit accumulates on the surface of the Wehnelt facing the cathode. In time this deposit may result in electrostatic charging effects or produce physical spalling of material. The development of whiskers or spalled layers of LaB_6 on the Wehnelt aperture can cause gun instabilities even in ultra-high vacuum conditions. A reduction in the area of exposed LaB_6 would reduce potential problems of this type.

For the above reasons efforts have been made to develop a new type of single crystal LaB_6 cathode. The initial interest was to explore thermionic emission anisotropy at high cathode loadings from small surfaces cut parallel to specific crystal planes. The resulting cathodes show promise as practical long life emitters operating at the full theoretical brightness anticipated from work function measurements.

Experimental

Filament Structure

In the new structure, electron emission from the major portion of the cathode has been suppressed by the use of a thermally stable, high work function coating of pyrolytic graphite. Two types of cathode configuration have been tested. One is the "mesa" or pedestal type structure formed on the arc bonded single crystal of LaB_6 by electric discharge machining (EDM). Steps in the formation of the cathode are shown in Fig. 1. After bonding of the single crystal to the rhenium heater[10], the "mesa" is formed by trepanning with a small aperture using very low energy electric discharge machining. The filament after this stage is shown in Figs. 1a and 1b. The height of the "mesa" is controlled to be about equal to the diameter. The next step requires heating the filament to normal operating temperatures in about 800 Pa (60 torr) of a hydrocarbon such as propane or ethylene to form a coating of pyrolytic graphite 10 to 20 µm thick[11]. Fig. 1c shows the filament of Fig. 1a after coating with graphite. The final stage is to support the filament and polish off the carbon coating on the "mesa" with a fine diamond abrasive until a polished LaB_6 surface is produced. This surface is surrounded by a shell of inert graphite as shown in Fig. 1d. A similar treatment can produce micro-flats on conventional pointed emitters, although in this case the diameter of the final flat varies as the cone tip is ground away.

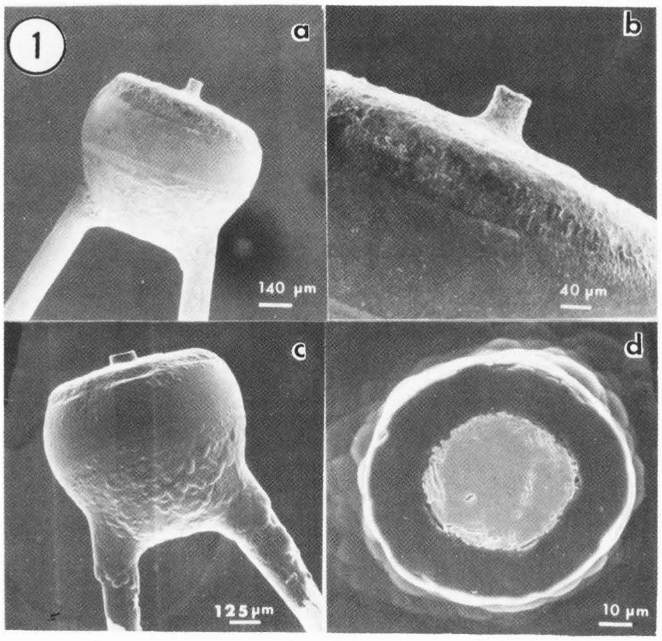
The desired diameter of the micro-flat can be determined from a consideration of the cathode loading (A/cm^2) and the total emission current that can be tolerated in the column, as indicated in Table 1. Here, source diameters of 10 to 70 µm are listed with their respective area in µm^2. The total emission current at selected cathode loadings from 2 to 50 A/cm^2 are indicated. It is seen that in order to limit total emissions to reasonable values (e.g. $\leqslant$ 400µA) cathode diameters of some 30 to 50 µm are desirable. Most cathodes tested to date have been between 30 and 70 µm diameter and the smallest "mesa" structure formed by electric disharge machining is about 20 µm diameter.

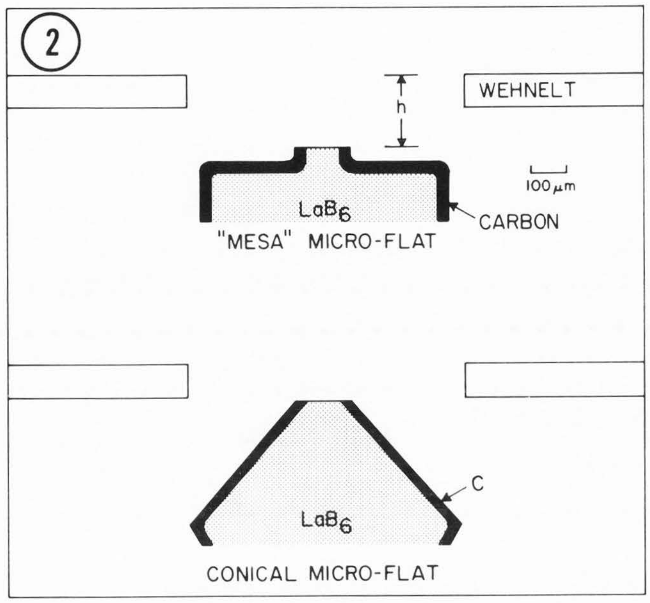
Cathodes are individually calibrated for heater current versus temperature in a vacuum comparable to the operating conditions of the gun. Due to increased radiation losses, coated

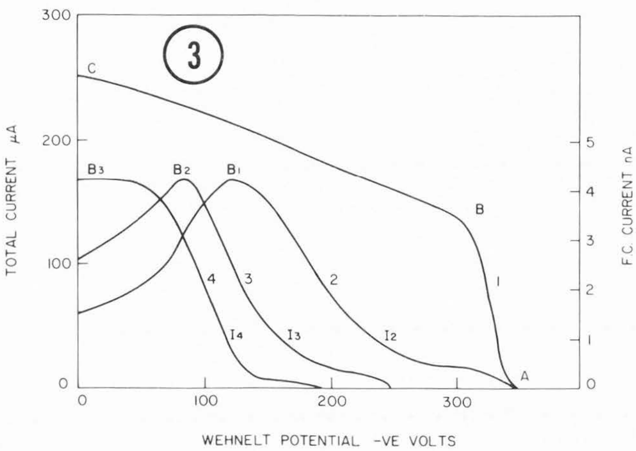
TABLE 1

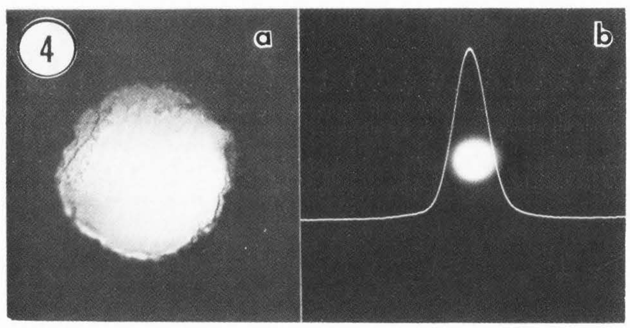
Emission Current µA from Circular Micro-Flat Cathodes

Source Dia. µm	Area µm^2	Cathode Current Density A cm^{-2} 2	5	10	25	50
10	78	1.6	3.9	7.9	19.6	39.3
20	491	6.3	15.7	31.4	78.5	157.1
30	761	14.1	35.5	70.7	176.7	353.4
40	1257	25.1	62.8	125.7	314.2	
50	1963	39.3	98.2	196.3		
60	2827	56.5	141.4	282.7		
70	3848	77	192.4	384.8		









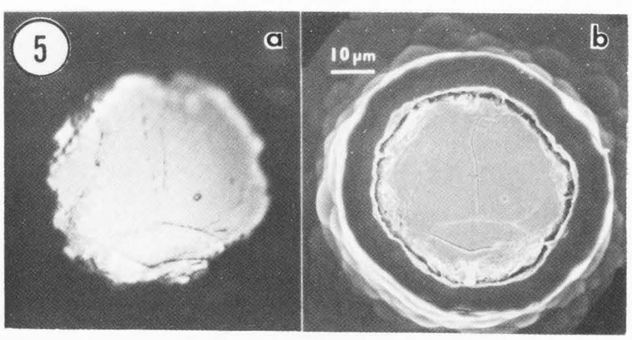


Fig. 5 Comparison of thermionic emission image and SEM image of (001) micro-flat cathode after 150 hours of operation at 1800K. (a) image from the beam profile mode under conditions similar to Fig. 4a, original image magnification x 500. (b) secondary electron SEM image after removal of cathode from gun.

Fig. 1 Stages in the preparation of "mesa" type micro-flat cathodes from a single crystal of LaB_6. (a) Crystal arc-bonded to rhenium heater wire with 50 micron diameter "mesa" formed by EDM methods. (b) Higher magnification of "mesa" in a. (c) Specimen a after coating with 20 microns of pyrolytic graphite. (d) (001) emitting surface of LaB_6 surrounded by 20 microns graphite after removal of graphite cap.

Fig. 2 Schematic showing location of two types of micro-flat cathodes within the Wehnelt aperture.

Fig. 3 Electron emission characteristics of micro-flat cathode as described in text.

Fig. 4 a) Beam profile image of a 50 μm diameter micro-flat cathode at I_2 of curve 2, Figure 3. Original magnification as a thermionic emission image x 550. b) Beam profile of same source at the maximum brightness position B_1 of curve 2.

cathodes require slightly more current for operation than uncoated cathodes. A typical "mesa" cathode required about 2.4 A at 1700K and 2.9 A at 1900K. Temperatures of the cathode during electron optical testing were estimated from the operating current and the calibration curves.

Gun Vacuum Conditions

To date, the new filaments have been evaluated in a Nanolab 7 SEM equipped for LaB_6 operation having independent bias and both beam profiling and specimen current monitoring facilities. The gun pumping conditions were such that even during operation at 30kV and 400μA emission, a base pressure in the gun was maintained at 1.3×10^{-5} Pa (10^{-7} torr) or better. A small quadrupole mass spectrometer fitted to the gun housing was used to monitor both total and partial pressures. At the base pressure, the major gas component was found to be water vapor with smaller contributions from nitrogen and oxygen resulting from gas permeation through the viton seals of the vacuum system. To reduce outgassing from the copper liner tube in the double condenser portion of the column, this unit was outgassed in a vacuum furnace at 900K for several hours prior to insertion in the microscope. This pretreatment markedly reduced liner tube outgassing during high power operation of the gun. Modifications to the gun pumping system permitted a starting vacuum of 3×10^{-4} Pa (2×10^{-6} torr) to be reached within about 20 minutes. This was sufficient to check newly installed filaments for basic operating performance. All long term tests were conducted close to the base pressure of 1.3×10^{-5} Pa (1×10^{-7} torr).

The gun was the conventional triode used in The Nanolab 7 SEM. A removable tantalum Wehnelt aperture was used, having a thickness of 100 μm and an aperture diameter of 750 μm. The Wehnelt to anode separation was 4 mm. The configuration of the coated filaments in the region of the Wehnelt aperture is shown in Fig. 2, where the normal convention for the filament height setting is indicated. Due to the diameter of the "mesa" type cathodes, these could not be set with a filament height of zero with the 750 μm Wehnelt aperture. However for optimum performance this was not necessary.

Results

Electron Optical Characteristics

The behaviour of the gun can best be compared with conventional sources by measuring the total emission current as a function of Wehnelt potential for a fixed accelerating potential and filament temperature. In addition an estimate of the peak axial brightness is obtained by measuring the current in a Faraday cup at the specimen level with a high excitation of the double condenser lens and a small beam limiting aperture. This Faraday cup current is directly proportional to the axial brightness and serves for comparison of the relative brightnesses of other filaments operating under the same conditions of column excitation.

Fig. 3 illustrates the general behaviour of all the limited emission micro-flats tested. These results are from a "mesa" type cathode set at an initial height of 0.2 mm in a Wehnelt aperture of 750 μm diameter. These results were obtained at 15kV and are similar to those obtained at 5 and 30kV. The behaviour of the total emission current and the specimen current for this initial setting is shown in curves 1 and 2 respectively. As the Wehnelt potential is reduced below the "cut-off" value of -350 V, the total emission current rises rapidly over the region A-B as an increasing area of the micro-flat is allowed to emit. Over the regio B-C the current rises less rapidly as the field at the surface of the micro-flat increases, but no further area is available for emission. At zero bias, the total current is limited by the temperature of the micro-flat, the work function of the surface and the surface area. This behaviour is markedly different from the normal pointed LaB_6 source where the total emission at zero bias would rise continuously to many thousands of microamperes as an increasing area of the cone is allowed to emit.

For the same setting of the filament, the Faraday cup current rises to a maximum B_1 at about -130 V and then decreases as the bias is further reduced. As the filament height setting is increased to 0.25 and 0.3 mm the behaviour of the current is shown in curves 3 and 4. For curve 4 the maximum Faraday cup current and hence the maximum axial brightness of the gun is obtained at zero bias. This behaviour would seem to be a unique feature of this type of cathode and offers simplification in the design of the high voltage gun.

An additional observation that can be obtained during the course of the above measurements is that of the beam profile. This type of measurement has been described in detail [12 13] and is now a regular feature of most commercial SEM's. At the Wehnelt potential I_2 on curve 2 the beam profile appears as a thermionic emission image of the micro-flat cathode. A similar image appears at the potential I_3 and I_4 of curves 3 and 4 respectively. At the potentials B_1, B_2 and B_3 of curves 2, 3, and 4 the beam profile decreases in diameter to uniform circular beam of near gaussian profile. Images typical of these two conditions are illustrated in Figs. 4a and 4b.

The direct association of the beam profile with the thermionic emission image of the source is shown in Fig. 5. Here, as shown in Fig. 5a another cathode is imaged in the beam profile mode at a potential about 100 V below "cut-off". Shortly after this observation, this cathode was removed from the gun for structural examination in the SEM. A regular SEM image of the micro-flat is shown in Fig. 5b, where the correlation of surface features with the beam profile image Fig. 5a is obvious. It is clear from this comparison that the carbon coating and any reaction products between the carbon and the LaB_6 are not contributing to the thermionic image. Hence estimates of the current density from the cathode can be made from a consideration of the measured surface area of LaB_6 and the total emission current.

Current Density Measurements

To date, seven micro-flat cathodes of near (001) orientation have been studied in some detail. The longest period of operation for any one cathode has been about 300 hours and the total accumulated time for all cathodes about 800 hours. All seven cathodes have shown the same general emission characteristics as described in the previous section.

For comparison of performance, the zero field cathode current density has been estimated from the measured cathode surface area and the total emission at zero bias. The results from four different cathodes at various temperatures are shown in Fig. 6. These results are compared with calculated values of current density for various values of work function shown as the solid curves A, B and C. The results are in good agreement with a work function value of 2.69 eV, close to the value suggested by Swanson [14 21] for the (001) surface of LaB_6.

Comparison with other Cathodes

Although direct axial brightness measurements have not been made to date, the new cathodes have been compared with conventional cathodes in the same experimental arrangement. The Faraday cup current at the specimen level has been compared for emitters operating at the same accelerating potential, with the same beam limiting aperture and over the same range of condenser lens excitation. All gun parameters were adjusted for optimum performance of the cathodes. The results of such comparisons are shown in Fig. 7. For the Nanolab 7 SEM, the condenser excitation of spot size setting range from 2 to 3 corresponds to normal high resolution operation.

For a tungsten hair-pin cathode operating at about 2900°K a typical specimen current at spot size 2-0 is 3-4 x 10^{-12} A and the change in current over the range from 2-0 to 3-0 is shown. For pointed (001) LaB_6 cathodes (conical cathodes) operating at 1850 to 1900K specimen currents are higher and a typical current at 2-0 is about 10^{-11} A. The performance of the micro-flat cathodes has been consistently better than the regular pointed cathodes and higher specimen currents are recorded even with cathodes operating at lower temperatures. In the extreme

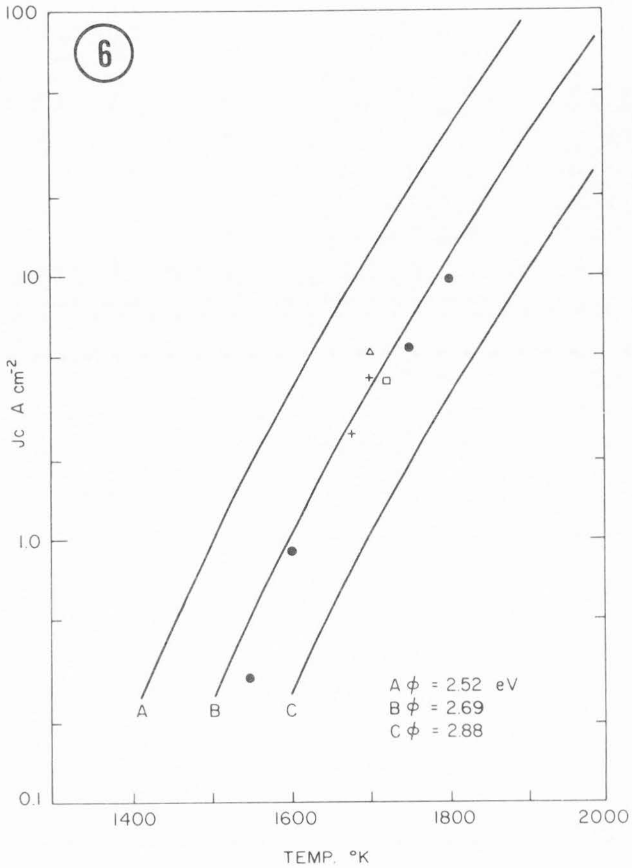


Fig. 6 Plot of measured zero field cathode current density as a function of temperature for a series of LaB_6 micro-flat cathodes, ●, □ , +, Δ. Curves A, B, C theoretical values for work function 2.52, 2.69 and 2.88 respectively.

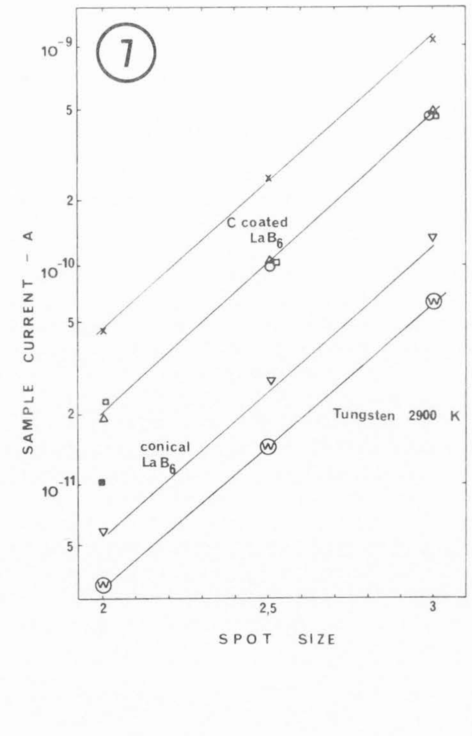


Fig. 7 Comparison of specimen currents (and hence relative brightness) for cathodes in the same gun at 15 kV and conditions of optimum brightness. Tungsten hair-pin at 2900K (w); pointed [00] single crystal LaB_6 1850K (▼); 1900K (■); micro-flat cathodes near (001) orientation at various temperatures (Δ, □ , o); microflat cathode J-4 at 1750K (x)

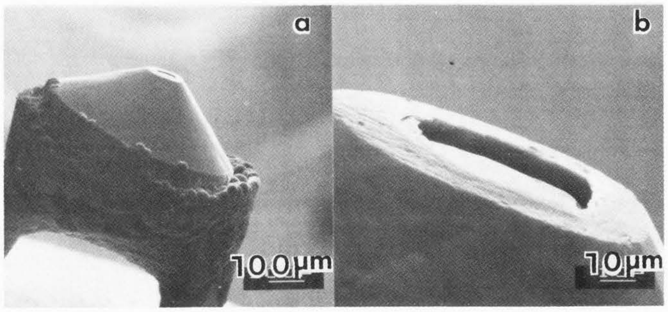


Fig. 8 Conical micro-flat after 265 hours of operation between 1750 and 1800K. Set-back of LaB_6 about 6 µm due to evaporation and oxidation.

case the conical micro-flat cathode J-4 gave a specimen current of 5×10^{-11} A at 2-0 when operating at 1750K. This cathode was found to be 14° off the [001] zone towards the [120] zone.

Material Loss from Cathode

For some cathodes operated in poor vacuum for extended periods of time, it was noticed that for a fixed cathode temperature and gun operating parameters, that the Faraday cup current at the brightness maxima began to decrease. This decrease in brightness is associated with the loss of material from the cathode surface by evaporation and oxidation. Since the pyrolytic carbon coating has proven to be extremely stable, the level of the LaB_6 emitting surface recedes below the level of the outer carbon coating. For a micro-flat surface some 50 µm diameter, it has been found that this reduction in brightness becomes measurable after about 10 µm of material has been lost from the surface of the emitter.

A set-back of some 6 µm is shown for a conical micro-flat in Figs. 8a and 8b. This emitter was examined after 265 hours of operation between 1750K and 1800K. At this point no loss of brightness had been detected. From published data[7], the evaporation loss at 1800K for 265 hours would be about 3 µm. The remaining loss is attributed to evaporation of the oxidation product formed during operation at 1.3×10^{-5} Pa (1×10^{-7} torr). From observation of the mass spectrum at this pressure the oxidizing species (H_2O and O_2) contribute about 50% of the gaseous species. From estimates of oxidation rates at 7×10^{-6} Pa (5×10^{-7} torr)[9] the material loss after 265 hours is about 6 µm. The estimated loss of 3 µm corresponds to a partial pressure of the oxidizing species of 3×10^{-6} Pa (2.5×10^{-8} torr). The discrepancy is within the limits of error of the estimations for this process. However, the importance of maintaining low operating pressures for the cathodes is clearly estalished. Another effect associated with the background pressures is the sensitivity of the total emission from these cathodes to small changes in the gas pressure. This was noticed as a reduction in total emission current as a function of time after the beam was allowed to impinge on the liner tube. No rise in pressure at the gauge was recorded during this behaviour. However, the effect was attributed to gas from local outgassing of the liner tube impinging on the single crystal surface of the cathode which would be in direct line of sight of such a gas source. Similar effects have not been observed when using pointed single cathodes which contain many different crystal faces. The problem has been eliminated by high temperature outgassing of the liner tube.

Grid Aperture Contamination

The physical location micro-flat cathodes within the Wehnelt aperture is shown in Fig. 2. The protective coating of pyrolitic graphite inhibits the evaporation of LaB_6 and thus reduces the amount of material depositing of the inner surfaces of the aperture. The area (a) a micro-flat is typically some 2×10^{-5} cm^2, about 200 times less than the surface area of the exposed conical surface of regular pointed emitters. Furthermore, due to the location of the micro-flat most evaporation and oxidation products are directed towards the anode rather than the Wehnelt aperture. Examination of top-hat apertures removed from the Wehnelt structure after 200 hours of filament operation has not detected aperture contamination by weight gain measurements or in optical or electron micrographs. This is in contrast to the results reported previously[9] for regular LaB_6 filaments.

Material Reactions

Pyrolytic graphite is widely used as an electrical contact for LaB_6 emitters in the compression type structure developed by Vogel[15]. The reaction of graphite with LaB_6 in such emitters appears to have no deletarious effects after several hundreds of hours of operation. However, in these structures the graphite is not in close proximity to the emitting area at the tip of the emitter.

For the present emitters a graphite-LaB_6 interface is in the immediate vicinity of the emitting surface and problems associated with the diffusion of carbon into or onto the surface of the LaB_6 micro-flat might be anticipated. Evidence of interdiffusion is seen in micrographs of the interface regions, with the diffusion of components from the LaB_6 into the carbon being most readily observed. However, to date no deleterious effects due to the long term reactions between these materials have been evident in the electron emission experiments. Thermionic emission images of the cathode never show any detectable emission from the graphite shell surrounding the LaB_6. Conversely, no reduction in the emission from micro-flats has yet been attributed to the diffusion of carbon into the emitting region although such an effect might be expected [4 16].

With increasing time of operation, a gap develops between the graphite and the LaB_6 as seen in Fig. 5b. This material loss, presumably due to evaporation, results in a reduction in the diameter of the micro-flat and this in turn may well set the limit to the useful life of these emitters.

Discussion

The electron optical behaviour of the restricted emission micro-flat LaB_6 cathode, resembles that of the oxide-cored cathode developed by Uyeda[17]. This is not surprising as the physical configuration of the two cathodes is very similar. For the oxide-cored cathode, a central emitting core of barium-strontium oxide about 70 μm diameter is encased by a high work function tube of platinum. The electron optical characteristics of such cathodes have been studied in some detail[18 19]. In the article by Ando et al[18], their Fig. 8 resembles closely the results presented here in Fig. 3. The similarity in performance is particularly interesting as the results of Ohno[19] for a cored cathode suggest that electron energy spread from such cathodes is less than from conventional cathodes. It was concluded that anomalous energy broadening is caused by the effect of the biased Wehnelt on the electrons emitted from off central areas of conventional cathodes.

Loeffler[20] developed a complex cathode structure which limited the area of emission from a polycrystalline LaB_6 cathode and established that this type of operation resulted in experimental electron energy spread of about 0.6V in good agreement with the theoretically estimated value at 1850K. A thin rhenium foil containing a 7.2 μm diameter aperture was located within 100 μm of the cathode surface and operated at a potential of +100V with respect to the cathode. Only 2.7μA of the 40mA of total cathode emission to the rhenium electrode passed through the aperture and was used for beam formation. This corresponded to about 6.6 A/cm^2 from the cathode operating at 1850K and is in reasonable agreement with the current density estimated from curve C of Fig. 6 for a work function of 2.88 eV, a value commonly quoted for polycrystalline LaB_6.

A more practical type of micro-flat structure on a single crystal LaB_6 cathode has been described by Swanson et. al.[21]. This emitter, referred to as a truncated cathode, has a small flat about 40 μm diameter ground normal to the cone axis of a regular pointed emitter. Such a cathode still emits from the conical surface and can give rise to complex emission patterns as the electric field at the tip increases. This structure serves to increase the area of the (001) plane that is involved with emission, a factor which has been shown to be important from the correlation of electron emission characteristics and the thermal faceting of pointed cathodes[4].

The present cathode combines features of the truncated cathode and the cored oxide cathode and was developed specifically for the study of thermionic emission anisotropy of LaB_6 in high brightness triode guns. To date studies have been conducted only on (001) emitters. It is anticipated that studies on lower work function surfaces may lead to improve brightness at lower temperatures. Such increases in the cathode loading can be estimated from Fig. 6 where curve A for a work function of 2.52 eV indicates cathode loadings of 10 A/cm^2 at 1700K and about 50 A/cm^2 at 1900K. Recent work[20] suggest a work function of 2.41 eV for the (346) surface of LaB_6.

For cathodes operating at 1700K the evaporation losses would be about 1 μm in 380 hours[7]. If the base pressure in the gun is further reduced to about 4×10^{-6} Pa (3×10^{-8} torr), the oxidation losses would also be about 1 μm. Under such conditions, a cathode would loose about 6 μm of material over 1000 hours of operation. Hence it is not unreasonable to anticipate that practical changes in the conditions of operation and the selection of cathode surfaces of low work functions will result in a micro-flat cathode operating for 1000 hours at 1700K with a higher brightness than that obtained from a conventional pointed (001) emitter operating between 1850 and 1900K.

Conclusions

A new type of single crystal LaB_6 cathode structure has been developed. Preliminary observations on the electron optical performance of this cathode have been presented and show that in the present electron gun, the cathode provides a higher brightness than pointed cathodes operating under similar conditions.

Some advantages to the new cathode are as follows:

1. The crystallographic orientation and the area of the emitting surface is known.
2. At specific height settings of the cathode, the gun can be operated at zero bias, permitting high fields at the cathode surface.
3. The beam profile (and hence the cross-over) is circular and near gaussian containing no complex lobes from the walls of the cathode.
4. The total loss of material from the cathode by evaporation and oxidation is greatly reduced as only a small area of LaB_6 is directly exposed to the vacuum. Hence, troublesome contamination of the Wehnelt apertures is eliminated.
5. The carbon coating contributes to the mechanical strength and stability of the bond between the LaB_6 and its support.

The main problems that have been experienced with these cathodes are:

1. The sensitivity of the single crystal surface to electron beam induced outgassing from the walls of the column.
2. Material loss at the interface between the LaB_6 and the carbon coating resulting in a reduction in diameter of the emitting area.

Neither of these problems would appear to limit the practical usefulness of the micro-flat cathodes. Further detailed electron optical studies of these new emitters are in progress.

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Discussion with Reviewers

L. Swanson: In order that the beam current be proportional to brightness as the Wehnelt bias or emitter structure is varied, the beam size and angle at the specimen plane must be changed. Can the authors comment on this?

Authors: In the SEM the overall demagnification of the source (cross-over) is about 10,000 times. At the specimen plane, or entrance to the Faraday cup, the collection angle at the source as seen by the specimen is only about 10^{-6} radians, a very small percentage of the total beam divergence angle (typically 0.01 - 0.02 radians). Small changes in the total beam divergence from the gun or small changes in the cross-over position have little effect on the apparent axial brightness as estimated from the specimen current. In this particular case, the interest is to compare sources in the gun set to operate under best performance conditions of smallest cross-over consistent with maximum axial brightness. The measurements are relative and not absolute.