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The Application of the Glow Discharge to Material Processing

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The mechanism and characteristics of the glow discharge are outlined. Energetic electrons and ions, which are generated in the cathode fall region, may be focused or guided to form a beam by geometrical arrangements of the discharge electrodes and by magnetic fields. Two practical arrangements are described: a spherical hollow cathode device, which produces a hot zone at its centre; and a hollow anode device, which produces well-collimated electron and ion beams. Glow discharge beam devices work at "rough vacuum" pressures, in the range 10^{-2} to 1 mm Hg, and are particularly suited to the processing of glass and oxide ceramics since, owing to the presence of plasma, no electrical charging of target insulating materials takes place. Limitations are set on the operating conditions of glow discharges by the heat input to the electrodes, by erosion due to sputtering, and by the glow-to-arc transition. Proper engineering, however, should allow cathode current densities of the order of 1 A/cm^2 when operated at an anode voltage of the order of 10 kV, and focusing should realise electron beam power densities of up to the order of 1 MW/cm^2, with efficiency of about 50%. Thus, the glow discharge may have a wide range of applications to material processing, from etching by sputtering at low power to processing by the most intense heating. New methods of forming and fabricating oxide bodies based on condensation of vapour and on powder deposition are discussed.

1. Introduction

The glow discharge was first discovered during the eighteenth century, and Geissler made his tubes over a hundred years ago. It is therefore a well-known phenomenon; although, despite many years of study, it is still not well understood. Fortunately, for many practical applications, it lends itself readily to semi-empirical design providing certain basic facts and principles are utilised.

Among the early investigations, an outstanding contribution was made in 1879 by Sir William Crookes [1] who, apart from many other characteristics, demonstrated the "focus of the molecular heat of impact". These terms are now known to refer to the focusing of energetic electrons by a concave cathode which Sir William appreciated by deflecting their trajectories, with a magnet, to the side of the discharge tube, where, upon touching it with his finger, he "immediately raised a blister". In another apparatus, containing a nearly hemispherical cathode, he showed that a platinum strip could be brought to a "white heat" when placed at the centre of curvature.

The glow discharge however has found practical application mainly in lighting and in electronics, and the ability to form energetic beams of particles has been employed only to a lesser extent. Thus, early X-ray tubes made use of the fast electrons present in the glow discharge, and early atomic and nuclear physicists employed it to generate beams of energetic ions. In this latter respect, the principle employed was to allow some of the energetic ions moving towards the cathode to pass down a hole or canal in the cathode to form the well-known canal rays (see for example the classic work of Oliphant and Rutherford [2]).

More recently, the application of intense

electron beams to material processing has re-opened interest in the glow discharge for this purpose. Electron beam welding, drilling, melting and evaporation of materials are now well-established techniques [3], but so far the high vacuum thermionic type of electron gun, operating at voltages in the range 10 to 200 kV, has been employed. It has been shown however that essentially similar electron beams can be generated in the glow discharge [4, 5]. There are a number of advantages associated with the glow discharge such as the use of simple vacuum techniques and commonplace materials in the gun structure, but design is empirical and the scope and limitations are not yet clearly defined. It is the intention in the present paper to discuss some novel glow discharge geometries developed by the writer to generate both electron and ion beams, to indicate some applications in material processing, and to attempt to list the principles required for the adaptation of the glow discharge to a specific application and to assess some possible limitations.

2. Characteristics of the Glow Discharge

A glow discharge occurs when two electrodes, immersed in a vessel containing gas at low pressure, are connected to a suitable voltage supply (see for example von Engel [6]). The nature of the discharge depends very much on the dimensions and geometry of the electrodes, the gas and its pressure, and the internal impedance of the power supply. For the present purpose, the glow discharge can be considered to consist electrically of two different regions, the anode plasma and the cathode fall. The anode plasma consists of partly-ionised gas in which electrons and ions have near-thermal energies, and which is a good electrical conductor at near anode potential; the electric field within it is therefore small. Most of the applied voltage appears between the diffuse termination of the anode plasma and the cathode, i.e. in the cathode fall region. Ions leaving the anode plasma fall to the cathode where they liberate electrons (they may also ionise gas in transit and suffer charge transfer). The electrons are accelerated across the cathode fall, ionising gas and multiplying as they go; the ions they form also yield electrons at the cathode, so do photons and fast neutrals generated in various parts of the discharge. Thus, most of the cathode current is carried by ions, which however have a wide range of energies, according to their spatial distribution when initiated in the cathode fall region. The electrons generated in this region tend to go into two groups, i.e. slow electrons and fast electrons. This arises due to the energy dependence of the total cross-section for electron collisions, which, typically, has a peak at an energy of a few electron volts, depending on the gas, and which gives rise to the so-called runaway electrons [7]. The direction of motion of the fast particles in the cathode fall is sensitive to the direction of the electric field and therefore to the cathode geometry.

Thus, the glow discharge contains essentially two regions, the electrically-conducting anode plasma and the cathode fall, in which high particle energies occur and in which the discharge has a beam-like nature (fig. 1). It should be added that only a qualitative description of the cathode fall structure can generally be given.

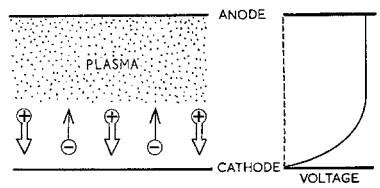

Figure 1 Schematic diagram of a planar glow discharge, illustrating the main features of interest in the present context.

An important parameter which characterises any glow discharge is the product of the pressure and the anode-to-cathode distance, *pd*. The dependence of the breakdown potential on this parameter was first realised by Paschen [8]. Typical Paschen curves for planar geometry are given in fig. 2. If, for a given *pd*, the voltage supply will not meet the condition given by

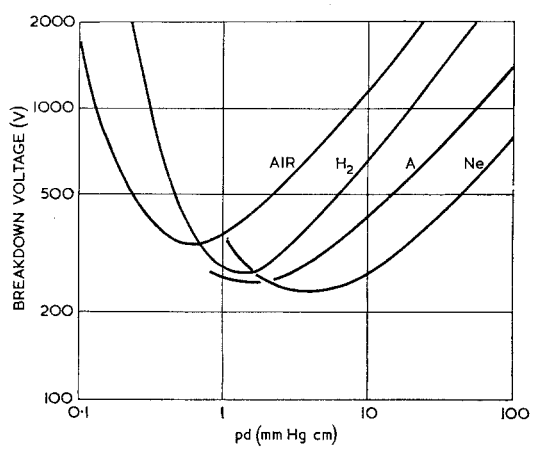

Figure 2 Typical Paschen curves for planar geometry [6].

these curves, a glow discharge cannot take place. While the curves will not strictly apply to other geometries, their qualitative features will nevertheless be pertinent, and the principle can be applied in a multi-electrode assembly to direct the path of the discharge.

A discharge operated near the minimum of the Paschen curve, i.e. a low voltage discharge, has a regime in which the current is independent of the voltage and this is termed a normal discharge. However, when operated at small pd, the current usually increases with the voltage giving an abnormal characteristic. This is the type of discharge of interest in the present context. An upper limit to the current is set by the overheating of some part of the apparatus or by a glow-to-arc transition.

Since in most glow discharges the significant processes by which they are sustained depend on the ratio of the electric field to the pressure, i.e. E/p, it is possible to scale a given discharge predictably, provided this ratio remains the same. This principle, known as the similarity principle, predicts that two geometrically similar discharges scaled in dimension by a factor k will operate at the same voltage and current provided the pressure is scaled by a factor k^{-1}; current density will scale by a factor k^{-2}, and temporal changes by the factor k. The principle is obviously of great value in predicting the characteristics of a given discharge when scaled for a particular application. Processes which do not depend on E/p however can set limitations to scaling, e.g. the emission of electrons from electrodes at $E > 10^4$ V/cm [9] and thermal effects at electrodes.

Only the glow discharge near the minimum of the Paschen curves has been well studied. Other forms, particularly at high voltages, are less well understood (see for example the work of McClure [10], who discovered that the primary electrons from the cathode pass almost without energy loss across the high voltage discharge, and proposed that the anode plasma is supported by secondary electrons from the anode and vessel walls). The glow discharge mechanism appears to be very adaptable however and, providing the principles discussed are borne in mind, lends itself readily to semi-empirical design.

3. A Hollow Cathode Glow Discharge Heater

The apparatus sketched in fig. 3 was constructed in an attempt to provide a small spatial volume in which specimens of the most refractory materials could be heated to their melting points. It consists of an open-ended spherical assembly containing a cathode of about 7·5 cm diameter screened by an anode conveniently made of mesh (not important) spaced concentrically at a small distance (~ 6 mm). All subsidiary metal parts in the system are connected to the anode, and the support for the cathode is enclosed in a close-fitting anode tube up to the lead-through insulator made of, and specially shaped in, pyrophyllite.

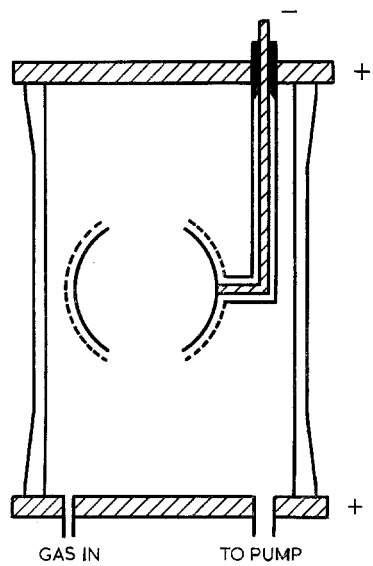

Figure 3 Schematic diagram of the hollow cathode heater.

In operation, gas is admitted to a suitable pressure (typically 0.1 to 1 torr), and, on application of the voltage through a ballast resistor (500 to 5000 Ω), a glow discharge forms in which the anode plasma penetrates inside the cathode, no discharge taking place between the outside of the cathode and the surrounding anode mesh. This mode of operation depends on the principle contained in the Paschen curves of fig. 2. On inspecting the discharge inside the cathode, a dark space can be seen concentric with the cathode, the thickness of which depends on the operating conditions. This is the cathode fall and the majority of the applied voltage will appear across it. Thus, the electric field lines are all perpendicular to the cathode surface and fast electrons crossing the fall are directed to the centre of the sphere.

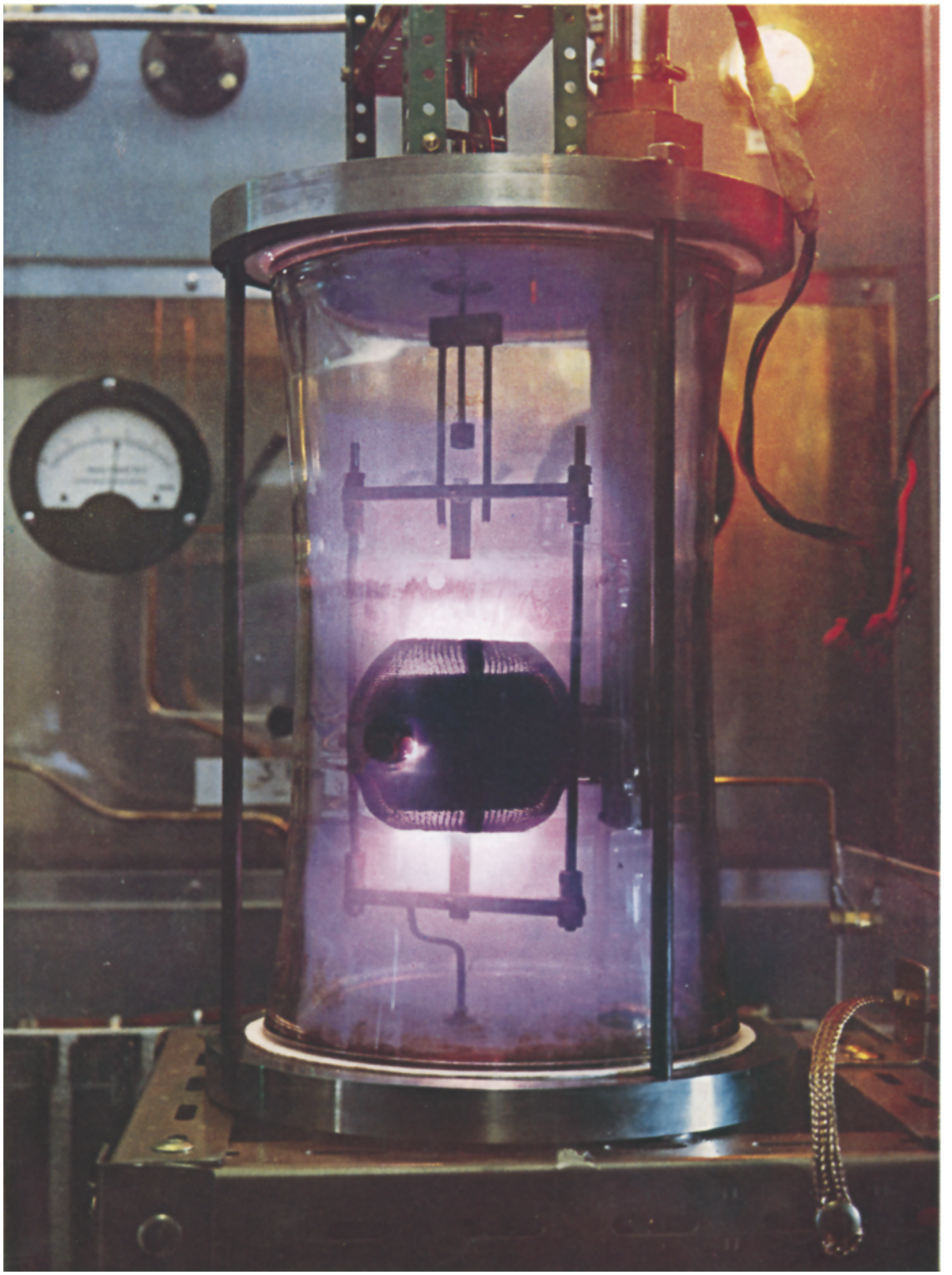

Figure 4a Growth of sapphire in the hollow cathode heater.

Any material placed at the centre of the sphere is therefore heated by the kinetic energy of the fast electrons. Since the material is immersed in ionised gas, no electrical charging can occur, thus allowing insulating materials to be heated just as well as metals.

The apparatus was constructed of stainless steel, but this metal, while having various advantages, is not at all essential. As shown in fig. 4, the apparatus was used to grow a single crystal of alumina by forming a molten zone in a sintered alumina rod (6 mm diameter) suspended through the centre of the sphere and then lowered slowly through it. The operating conditions were: hydrogen at ~ 0.5 mm Hg; cathode voltage 1.5 kV; current 0.4 A. It has also been used to melt tungsten and other refractory materials and serves readily as a high temperature annealing furnace for small specimens.

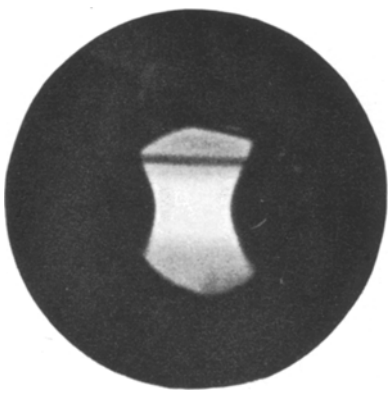

Figure 4b The molten zone seen through the viewing port (the black line is a wire crossing the field of view).

Some electrical and thermal characteristics (constant flow water calorimeter) obtained in argon at various pressures are given in fig. 5. The anode current curves (fig. 5a) were obtained without a specimen present. When a specimen is present at the centre of the sphere such curves obtained at a given pressure have a smaller slope which decreases as the size of specimen increases. Under the best conditions investigated, over 40% of the input power was dissipated in a 6 mm diameter copper calorimeter tube passing through the sphere centre. Experiments in helium, which requires a pressure about a factor 10 higher, gave essentially similar characteristics, but the efficiency reached 60% at 2.5 kV input.

One disadvantage of this simple geometry is

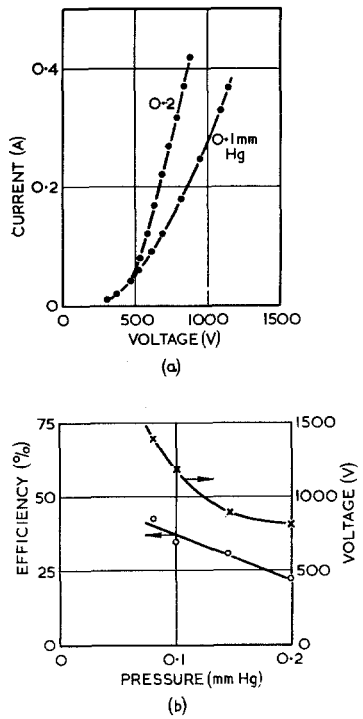

Figure 5 Hollow cathode heater characteristics in argon: (a) current-voltage curves (no specimen present); (b) efficiency (percentage power input to a specimen calorimeter) and voltage as a function of pressure at 300 W electrical input.

the occurrence of the glow-to-arc transition in the early stages of operation, when the cathode is cold. The transient arcs so formed vaporise cathode metal and deposit it on the specimen. As the cathode itself warms up, these arcs cease, unless the specimen itself evaporates strongly. When growing sapphire crystals, the cathode was operated at dull red heat and no arcing occurred even though some alumina was deposited on it.

The operation of the discharge under pulsed conditions was investigated to a small extent. Fig. 6 shows current and voltage waveforms obtained with hydrogen when a 1 μF capacitor, charged to approximately double the steady voltage, was discharged through the apparatus (alumina specimen present). A large transient current pulse occurs before the glow adjusts to the new voltage. With this technique, the threshold for the glow-to-arc transition was obtained at high power input, an arc being recognised by the sudden transition to a low discharge voltage together with exponential

discharge of the capacitor governed by circuit resistance. In this way it was found that current pulses of 10 to 20 A could be sustained at voltages up to 7 kV before an arc was initiated, but this threshold varied with the steady operating conditions.

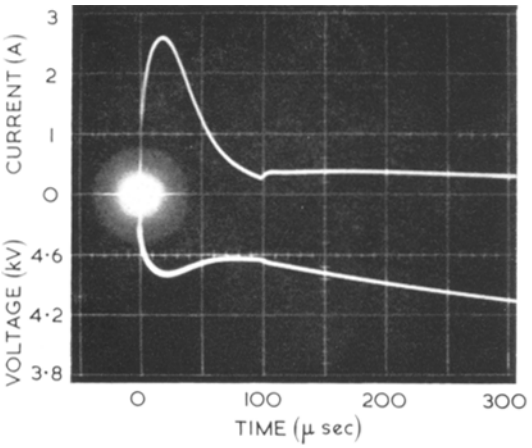

Figure 6 Hollow cathode heater: transient current and voltage given by the superposed discharge of a 1 μF capacitor when the steady operating conditions were 0.2 A at 2.4 kV in hydrogen (alumina specimen present).

The main advantage of this discharge, however, is that it operates at a relatively low voltage, which tends to minimise sputtering of the cathode and contamination of the specimen. When operated in hydrogen, the sputtering rate is particularly low and might be further reduced by an appropriate choice of metal for the cathode (see the review by Behrisch [11]).

It should be possible with a discharge of this type to achieve certain desired distributions of the heat input over the specimen by appropriately shaping the cathode profile. For example, a spherical section followed by a conical section could produce, in addition to a localised molten zone, an adjacent annealing region. Techniques of this type could be useful in crystal growing and refining.

4. The Hollow Anode Glow Discharge

An entirely different discharge which is capable of giving focused well-defined beams of electrons or ions at relatively high voltages has been investigated at up to 20 kV [12]. The essential features of this geometry are shown diagrammatically in fig. 7a in which electrostatic equipotentials and field lines have been sketched schematically. When the gas pressure is adjusted to allow a glow discharge to take place, an anode plasma fills the right-hand end of the anode and a cathode fall, having a curved boundary related to the general shape of the static equipotentials, forms at the cathode end. The ions moving to the cathode tend to funnel to its centre, with the result that most of the cathode electrons are generated there. The fast electrons crossing the fall tend to be directed along the central region of the anode. Typical characteristics of this type of discharge are given in fig. 8 (cylindrical anode $\sim$ 7 cm long by 2 cm bore). The current voltage characteristics are of the abnormal type; at the higher voltages about 40% of the input power is delivered to the end of the anode remote from the cathode by the energetic electrons and about 20% to the cathode.

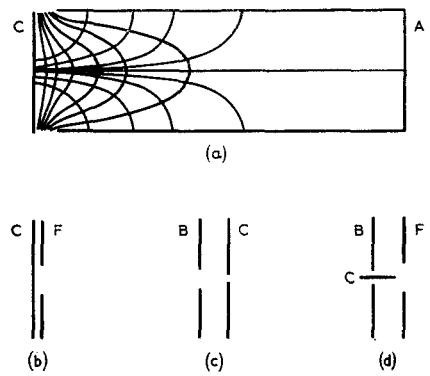

Figure 7 Hollow anode A geometries: (a) simple geometry with plane cathode C showing schematically the equipotentials and electric field lines; (b) plane cathode with focusing electrode F; (c) plane cathode with ion beam hole and bias electrode B; (d) butt cathode with focusing and bias electrodes.

This description of the main features of the discharge applies whether the anode has a circular or rectangular cross-section. With a circular cross-section, a central slightly-diverging electron beam occurs; when a rectangular cross-section has a large dimension at right angles to the section shown in fig. 7a, the discharge has symmetry about the central plane and a slightly-diverging sheet of fast electrons is produced. In both cases, the electrons can be brought out of the discharge through an anode aperture. The electron beam can be focused by including a field-shaping electrode between the cathode

and anode as shown in fig. 7b. The field-shaping electrode contains an aperture larger than the cross-sectional area occupied by the majority of ions approaching the cathode and as a consequence it draws very little current. Its function is to distort the equipotentials near the cathode surface to give an inward component to the electric field at the cathode. The focusing action depends on the exact geometry of the electrode, but is easily adjusted in practice by the application of a relatively small potential of the order of $\pm$ 100 V to it. The arrangement acts as an electrostatic lens and produces a magnified image of the electron source at any desired position in the anode plasma.

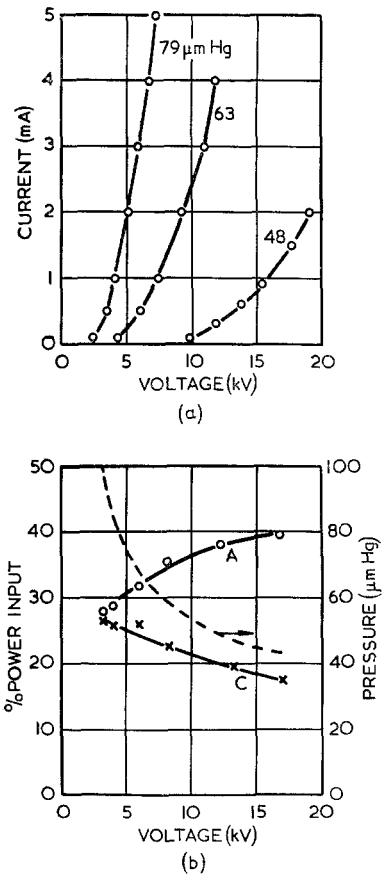

Figure 8 Hollow anode discharge characteristics in air (plane cathode): (a) current voltage curves; (b) percentage of the power input to the closed end of the anode A and to the cathode C while operating at an electrical input of ~ 10 W.

Some of the ions falling on the cathode can be brought out of the discharge by making a hole in the central region. It is not possible however to bring out more than a small fraction unless a second electrode biased positively with respect to the cathode is positioned on the side of the cathode remote from the anode, as shown in fig. 7c. The reason for this, which is very interesting, is associated with the back diffusion of electrons produced by ionisation of the gas outside the discharge in the path of the ion beam and which gives rise to instability [12]. The positively biased electrode, the "bias plate", prevents this and ensures that a stable discharge can be maintained by those ions which do not pass through the cathode hole, but instead strike the cathode to produce the necessary electrons. It is possible with appropriate hole dimensions and a positive bias of 100 to 1000 V to bring out the majority of the ions. With planar geometry, a parallel ion beam is produced. The kinetic energy of the ions, and the neutrals which appear with them, will however be spread over a wide range.

It is possible to combine the two effects of the focusing electrode and the bias plate with a cathode of small area such as a wire butt (cylindrical geometry) to produce almost a point source of electrons. The electrode arrangement employed is indicated in fig. 7d. Only the ions which fall on the end of the wire produce electrons for the fast electron beam which, when focused, produces a correspondingly sharper spot.

Calorimetric measurements showed that, with focusing, up to about 50 % of the input power can appear as fast electrons and up to 17 % as ions in an extracted beam. Obviously other arrangements of electrodes in the cathode region are possible to achieve desired effects. The addition of magnetic focusing and deflection can allow the manipulation of the beams outside the discharge.

The hollow anode geometry can be readily extended to produce sheets of ions or electrons converging in some desired manner. Thus, as already mentioned, it can be extended perpendicular to its section, or it can be rotated about any axis outside the section to produce planar, conical or cylindrical sheets of fast particles. One specific application, intended for zone refining refractory materials by ion bombardment heating, is shown in fig. 9. In this case, the geometry is arrived at by rotating a hollow anode section containing the cathode structure of fig. 7c about an axis on the left of

the bias plate B, perpendicular to the anode axis, to produce a planar sheet of converging ions (see Patent Application No. P 51543/64). A narrow well-defined heating zone is produced which is relatively free from contamination by atoms sputtered from the cathode.

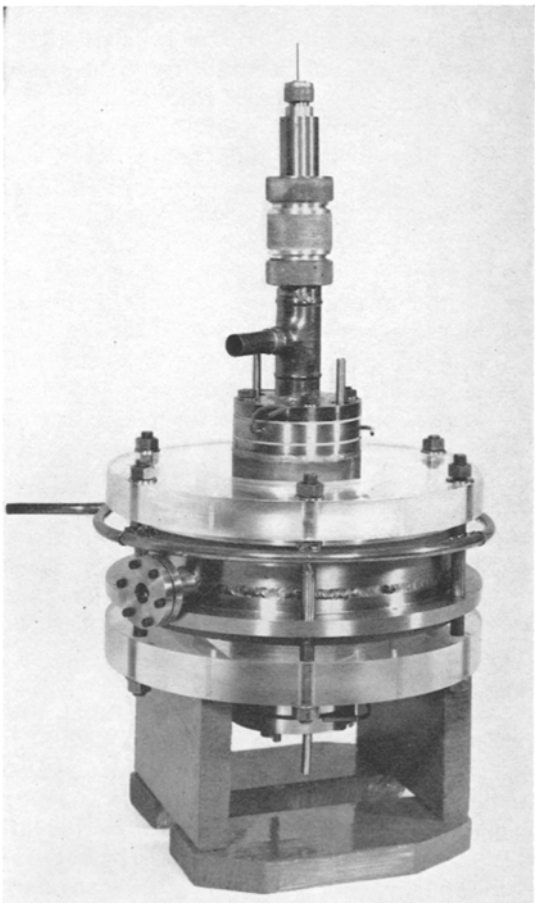

Figure 9 Concentric ion gun for zone refining. The gun is symmetrical about the vertical axis and produces a thin sheet of ions which converge to produce a molten zone in the axially-mounted rod of material.

5. Further Developments, Prospects and Limitations

The cathode current density in glow discharge devices appears to be limited by the following factors: temperature limitations due to heat dissipation; erosion due to sputtering; damage due to the glow-to-arc transition; and, if operated in a pulsed mode, damage due to thermal fatigue [13]. Refractory cathodes might be operated at a power input of up to 10 kW/cm^2 and, at this level in a hydrogen atmosphere, sputtering would erode the surface of heavy metals at a rate of the order of 10^{-6} cm/sec (taking ion energies of 10 keV and a sputtering yield of $\sim 10^{-2}$ atom/ion [11]). Thus, an ion current density of the order of 1 A/cm^2 at the cathode is probably an upper limit for continuous operation, although higher loadings could be sustained in pulsed operation [14]. A clean cathode at this current density should not suffer a glow-to-arc transition [15], but this limitation in the presence of condensing vapour, produced, say, by evaporation of target material, is not well defined. Cathode damage by arcing could be made small by adopting the minimum area principle of Robson and Hancox [16], by which the cathode would be constructed of independent elements for each of which the current would be limited to about 1 A.

On the basis of the data given in this article it should be possible, by geometry and perhaps by magnetic focusing, to achieve electron beam current densities 10 to 100 times higher than the cathode ion current density. Thus, electron beam power densities of up to 1 MW/cm^2 might be possible; the total power would seem to be a question of engineering design; the efficiency, as indicated by the work described, would be about 50%. The glow discharge therefore might be adapted to produce intense electron beams for material processing equivalent to and perhaps exceeding those currently achieved with high vacuum thermionic guns for this purpose [3]. It would be especially suitable for the processing of glasses and ceramics, owing to the property of not electrically charging insulating materials. The volatility of the target material might provide a limitation in simple systems, but, with the aid of suitable baffles, magnetic manipulation, and differential pumping, even this difficulty might be overcome. To realise its full potential however a quantitative understanding of the glow discharge mechanism is required.

Thus, an important prospect offered by the glow discharge is the ability to generate intense heat fluxes, continuous or pulsed, at glass and ceramic materials, refractory or otherwise. New methods of refining and of fabrication might result; for example, glass and ceramic bodies might be synthesised by the condensation of evaporation products generated by the electron beam heating of raw material. The process of

evaporation at a high heating rate is discussed in the appendix, where it is shown that almost all the heat input will go into producing vapour, very little being lost in other processes. The heat required to evaporate refractory materials under these conditions is only a few kilocalories per gram and is comparable, for example, with the heat required to fire stoneware bodies in the conventional methods used by the pottery industry (2 to 3 kcal/g [17]). A process based on these principles would allow the manufacture of graded structures having novel mechanical and other properties. Another related method of fabrication of glass and ceramic bodies would rely on the deposition of powder, followed by its transient melting and freezing in a controlled manner. This technique could be applied to crystal growth by the Verneuil method and to bodies of complicated shape by appropriate manipulation of a substrate former. Annealing of the growing structure could be achieved with auxiliary beams. Unlike the plasma jet heater, there is negligible momentum associated with the electron beam and therefore no ablative force. In pulsed operation, powder deposition and melting could be separated in time with very little loss of heat by conduction and radiation, owing to the short time required to reach the melting point (see Appendix); shaping of the pulse waveform could assist in this respect.

A well-focused electron beam from the glow discharge, readily manipulated by electric and magnetic fields, could also be applied to the machining of insulating materials by evaporation. At the other extreme, a focused ion beam from the glow discharge could be applied to micro-machining of materials by sputtering (e.g. to glasses and ceramics [13]). It could also be used for etching materials, for the ion injection of semi-conductors [18], and for other purposes.

The glow discharge has the advantage of simplicity of construction, mainly with cheap and readily available materials, and is readily operated with simple vacuum equipment. The scope for its application to material processing, particularly to glasses and ceramics, seems to be considerable.

6. Conclusions

The principles relevant to the construction of beam-producing glow discharges have been outlined and some experimental devices have been described. These include a hollow cathode discharge heater operating at relatively low voltage and high current, and hollow anode devices in which well-defined electron and ion beams can be generated at relatively high voltages. The main limitations on glow discharge devices appear to be due to thermal damage to the cathode and its erosion by sputtering, and to the glow-to-arc transition. By appropriate design however, it should be possible to produce electron beams having power densities up to ~ 1 MW/cm^2, perhaps higher in pulsed operation. Intense ion beams should also be realised. The application of these beams to material processing has been discussed, and it is pointed out that they are very suitable for application to insulating materials, owing to the absence of electrical charging in the presence of an ionised atmosphere. The high heat fluxes allow novel methods of fabrication to be considered; for example, by condensation from the vapour. The glow discharge beam technique offers the prospect of constructing glass and ceramic bodies atom by atom to finished shape in a controlled manner.

7. Appendix

7.1. Evaporation of Glasses and Ceramics at a High Surface Heating Rate

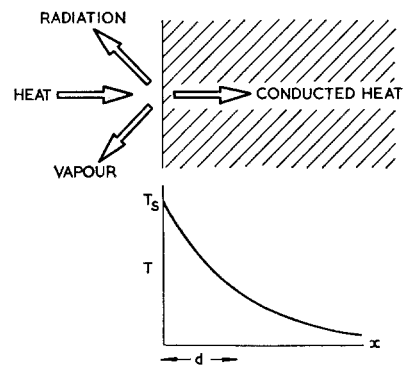

Figure 10 Thermal conditions during evaporation by surface heating.

Consider the one-dimensional case in which a semi-infinite isotropic material, bounded by vacuum, is heated by a uniform heat flux, W, upon its surface, as shown in fig. 10. In general, the material will lose heat by evaporation (W_V), by radiation (W_R) and by conduction (W_C), so that

$$W = W_V + W_R + W_C \qquad (1)$$

Consider the terms one by one; then

$$W_V = Q\frac{dm}{dt} \tag{2}$$

where Q is the heat required to evaporate unit mass of material and dm/dt is the rate of evaporation per unit area of surface. Neglecting the thermal energy of the vapour

$$Q \simeq \frac{H}{M} \tag{3}$$

if the products of evaporation are fully dissociated, where H is the heat of formation and M the molecular weight. Now by kinetic theory it can be shown that

$$\frac{dm}{dt} \simeq P\left(\frac{M}{2\pi RT_S\eta}\right)^{\frac{1}{2}} \tag{4}$$

where P is the vapour pressure, η is the number of atoms per molecule, R is the gas constant, and T_S the surface temperature. Thus

$$W_V = \frac{PH}{(2\pi RT_S\eta M)^{\frac{1}{2}}} \tag{5}$$

In general, P depends exponentially on inverse temperature (reference 19), so that W_V is very temperature dependent.

The energy radiated per unit area of surface will be of the order

$$W_R \sim \sigma T_S^4 \tag{6}$$

where σ is Stefan's constant.

After a sufficient time, thermal diffusion within the material will lead to a temperature distribution which is unchanging and simply advances at the same rate as the evaporating surface. The condition for this equilibrium state is

$$\frac{dT}{dx} = -\frac{1}{v}\frac{dT}{dt} \tag{7}$$

where x is the dimension perpendicular to the surface, t is the time, and v the velocity of advance of the surface. Combining equation 7 with the thermal diffusion equation gives

$$\frac{d^2T}{dx^2} + \frac{c\rho v}{k}\frac{dT}{dx} = 0 \tag{8}$$

where c is the specific heat, ρ the density, and k the thermal conductivity of the material. With the condition $\frac{dT}{dx} = 0$ at $T = 0$, and $T = T_S$ at $x = 0$, the solution of equation 8 is

$$T = T_S \exp\left(-\frac{c\rho vx}{k}\right) = T_S \exp\left(-\frac{x}{d}\right) \tag{9}$$

Thus, at equilibrium, an exponential temperature distribution will occur of characteristic depth, d, and in this condition

$$W_c = 0 \tag{10}$$

Note that the velocity, v, is

$$v = \frac{1}{\rho}\frac{dm}{dt} \tag{11}$$

and that the total heat, h, in the material is

$$h = \int_0^\infty c\rho\, T dx = \frac{T_S k}{v} \tag{12}$$

For a constant heat flux, W, the time required to raise the surface temperature to T_S can be shown to be

$$t_e = \frac{\pi k c \rho T_S^2}{4W^2} \tag{13}$$

This time will be approximately that required to reach equilibrium.

If interest is confined to common systems containing oxygen, silicon, aluminium, etc, the various parameters in these equations do not vary too much from one material to another. Thus, to indicate orders of magnitude, the following set of approximate formulae is derived from a consideration of the properties of silica and alumina when evaporating into a vacuum at a rate corresponding to vapour pressures of 10^{-1} to 10 atmospheres. Surface temperatures will lie in the range 2000 to 4000° K and thermal conductivities are taken to be of the order of 10^{-2} cal/cm (° C). The vapour is assumed to be completely dissociated, requiring 3 to 4 kcal/g to produce (H/M). Under these conditions, the radiated heat, W_R, amounts to 0·1 to 1 kW/cm² and is negligible.

The approximate formulae are then

$$\frac{dm}{dt} \sim 4P \text{ g/cm}^2 \text{ sec} \tag{14}$$

$$W \sim 60P \text{ kW/cm}^2 \tag{15}$$

$$v \sim P \text{ cm/sec} \tag{16}$$

$$h \sim \frac{30}{P} \text{ cal/cm}^2 \tag{17}$$

$$d \sim \frac{10^{-2}}{P} \text{ cm} \tag{18}$$

$$t_T \sim \frac{3 \times 10^{-4}}{P^2} \text{ sec} \tag{19}$$

in which the units of P are atmospheres.

Thus, high rates of evaporation with small loss of heat may be expected under the conditions of electron bombardment, which may be produced in the glow discharge.

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