JOURNAL OF MATERIALS SCIENCE 4 (1969) 323–335

Glow Discharge Beam Techniques

R. A. DUGDALE, J. T. MASKREY, S. D. FORD, P. R. HARMER, R. E. LEE
AERE, Harwell, Didcot, Berks, UK

The cathode fall region of the glow discharge contains fast electrons and fast ions which are accelerated in the electric field between the cathode and a plasma at near anode potential. When operated at low pressure and high voltage (i.e. on the left-hand branch of the Paschen breakdown curve), the fast electrons tend to form a mono-energetic group, although the ions, owing to relatively large cross-sections for interaction with the gas, have their energies spread over a wide range and also give rise to fast neutrals by charge exchange. Both types of particle can be efficiently brought out of the discharge through orifices placed in the electrodes. Thin or broad beams or sheets of particles, converging or diverging, can be designed over a wide range of current and voltage. At lower voltages, electron beams may be applied to a target placed within the discharge. As the voltage is increased, extracted electron beams become penetrating and can be manipulated magnetically outside the discharge. The gas pressure required for operation depends on the gas, the anode to cathode distance, and voltage and current. By appropriate design, operation at a pressure of about 100 μm or more can usually be arranged thus demanding only the simplest vacuum techniques.

Both electron and ion beams may be applied to insulating materials as well as conducting materials. This is possible because electrical charging difficulties are avoided owing to the associated presence of ionised gas. A number of different types of glow discharge gun of novel design have been constructed and their characteristics investigated. This paper discusses the design principles employed and illustrates applications in the fields of crystal growing, vapour deposition, welding, thermal milling and etching and milling by sputtering.

1. Introduction

This paper is concerned with techniques for processing materials by bombardment with electrons, ions and neutral atoms at gas pressures of the order of 10^{-4} atm. It is particularly concerned with simple and cheap techniques for generating beams of these particles and focuses attention on the special suitability of these techniques to the processing of insulating materials such as glass, ceramics and organic materials.

All the techniques here described exploit low pressure, high voltage glow discharges, i.e. glow discharges operated on the left-hand branch of the Paschen breakdown curve at voltages in the range 1 to 30 kV (fig. 1). Glow discharges under these conditions were important to the early studies of particle and atomic physics at the turn of the century [1]. They were later applied in an empirical way to such fields as mass spectrometry, X-ray diffraction and nuclear physics. Eventually these applications were replaced by superior high vacuum techniques.

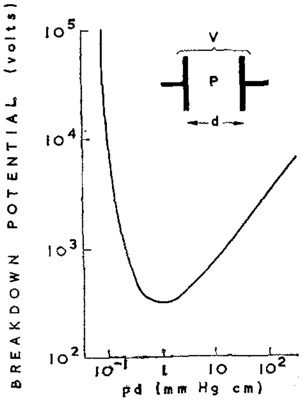


Figure 1 Typical Paschen breakdown curve (approximately correct for air).

Although now an old and well-known phenomenon, the high voltage, low pressure glow discharge, in its various ramifications, is still not well understood [2, 3]. Measured properties are sparse and incomplete and, as a physical process requiring further academic study, it attracts only intermittent and usually limited attention. Owing to the complexity of the processes involved, a complete theory must necessarily be complicated [4]. A quantitative understanding of the exact relationship between current, voltage, gas pressure, electrode and chamber materials, particle energy distributions and discharge geometry is not therefore available.

On the other hand, a simple qualitative view of the discharge mechanism, taken in conjunction with certain basic principles, allows considerable insight into the design of beam producing devices. The specific contribution made by the authors is the realisation that, on such a basis, it is possible to direct a high proportion of the fast electrons, ions and neutrals, present in the discharge, to a specific target in any desired way. This is usually done by first bringing the particles out of the discharge, but, in some conditions, especially at lower voltages, it is advantageous to work within the discharge itself. Thus, high or low particle fluxes over a small or large area can be obtained. In particular, electron beams can be focused at some distance from the discharge itself to give power densities of the order of 10^6 W/cm^2 and simple apparatus has been developed to deliver a kilowatt or more of electron beam power. Ion and neutral beams too have been produced giving a target flux of the order of 3×10^{18} particles/cm^2/sec. We have also learned something of the factors responsible for the glow to arc transition and how to avoid or minimise the occurrence of this undesirable process.

The feature of these techniques of special interest to us, however, is the property which allows that these beams may be brought to bear on electrically insulating materials just as easily as on conducting materials. This property is essentially due to operation in gas, at roughing pump pressures, which becomes partly ionised, at least in the vicinity of the target, and therefore provides an abundance of charge to preserve electrical neutrality at the bombarded surface. Thus many electron and ion beam techniques previously restricted to metallic applications may now be readily applied to glasses, ceramics and organic materials.

2. The Low Pressure, High Voltage Glow Discharge

2.1. General Features

A perhaps over-simplified diagram of the glow discharge, which, however, contains those features essential for the present purpose, is given in fig. 2. Emphasis is placed in this diagram on the presence of two electrodes, ionised gas near the anode, a cathode fall region near the cathode and fast electrons, ions and neutrals accelerated in the fall region. The discharge is sustained by a feedback mechanism by which each electron emitted at the cathode produces, through a variety of processes, another electron to be emitted at a later time. Boundary conditions at the sides of the discharge are conveniently overlooked at this stage.

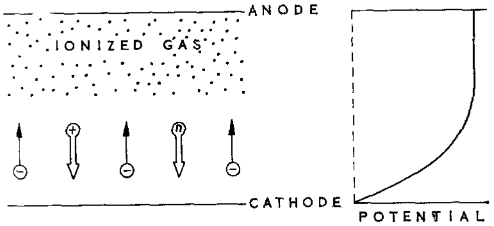


Figure 2 Glow discharge at low pressure: schematic diagram (n represents neutral atoms or molecules).

All the discharges with which we have been concerned have current voltage characteristics of the type indicated schematically in fig. 3 and work at values of *pd* (pressure times distance between the electrodes) of the order of 10^{-1} mm Hg cm. The fast electrons, accelerated across the cathode fall, tend to penetrate through the

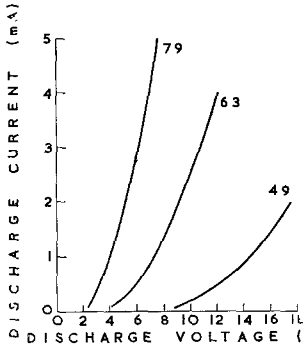


Figure 3 Typical current-voltage characteristics (air pressure in μm Hg: geometry, plane cathode, hollow anode of diameter 2.2 cm).

ionised gas at the anode side, particularly as the discharge voltage is increased. This penetration effect is due essentially to the fact that the cross section for interaction with the gas decreases as the electron energy increases [5, 6]. At high voltage the fast electrons are almost monoenergetic [4, 7-9] and retain this property for considerable distances of penetration into the gas. The fast ions accelerated in the cathode fall region do not behave in this way however, but undergo collisions with the gas which, besides giving them a wide spread in energy, lead to the production of fast neutral atoms and molecules by charge exchange processes [3, 10]. Other relatively energetic particles such as secondary electrons, back scattered electrons and photons play a part in sustaining the discharge.

2.2. Lower Voltage Discharge

At lower voltages (e.g. 1 to 3 kV) the cathode fall region tends to occupy only a small fraction of the cathode to anode space.The boundary of the cathode fall on the anode side tends to be parallel to the cathode surface and the discharge form and characteristics are insensitive to the geometry or position of the anode. Thus equipotentials tend to be parallel to the cathode surface and hence electric field lines tend to be perpendicular to it. At lower voltages, therefore, the electrons accelerated across the cathode fall tend to travel perpendicular to the cathode surface. This property can be exploited to produce a concentration of the energetic electrons by employing a spherically curved cathode [11]. Providing the radius of curvature is considerably greater than the cathode fall distance, the majority of the electrons will pass through or near to the centre of curvature.

Boundary conditions at the sides have little influence on the lower voltage discharge although edge effects at the extremities of the cathode might be subject to modification. Solid bodies of insulating or conducting material may be inserted into the ionised gas of the lower voltage discharge without too much effect on the operating characteristics. Thus, by employing suitable cathode shaping such a body or target can be subjected to a desired distribution of fast electron bombardment. There is no difficulty due to electrical charging effects provided the body remains in the ionised gas outside the cathode fall region. To some extent, not fully investigated, two or more cathodes can be operated independently to control the distribution of the energetic electrons at the target material.

About half of the input electrical power may be dissipated as heat in electron bombardment of a target in the ionised gas (the exact fraction depends on various parameters such as voltage, cathode material, gas, etc). Something under half the input power is dissipated in the cathode by ion and neutral bombardment.

2.3. Higher Voltage Discharge

As the discharge voltage increases the cathode fall region takes up an increasing part of the discharge space and boundary conditions at the sides have an increasing influence on the form of the discharge. Our interest has been mainly confined to two extreme cases, (i) a short discharge in which the cathode to anode distance is small compared with the lateral dimension, (ii) a long discharge in which the lateral dimension is small. In both cases the electrodes are shaped to provide the sideways boundaries. These two geometries are indicated schematically in fig. 4.

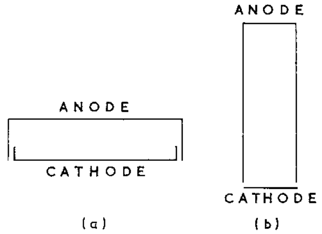


Figure 4 High voltage discharge geometries, a planar, b hollow anode.

For obvious reasons we call them the "planar" and the "hollow anode" geometries, respectively.

When operated at voltages in the range 3 to 30 kV they characterise themselves by, (1) a broadly spread discharge in the planar geometry which covers most of the anode and cathode, (2) an axially confined discharge in the hollow anode geometry which concentrates ion and neutral bombardment and electron emission at the centre of the cathode.

We have also been interested in a hybrid in which the hollow anode geometry has a large dimension perpendicular to the section shown in fig. 4b. In this case the ions, neutrals and electrons are concentrated about a line at the middle of the cathode. Thus the discharge has a large extension in one dimension producing a sheet-like structure of fast particles at the midplane of the anode.

Our experiments indicate that, in fact, many geometries can be derived from the two basic sections given in fig. 4. Thus, these sections can be rotated about any axis or simply extended perpendicular to the plane of the section. Composite geometries which retain some of the features of both basic sections may also be successfully realised. In every case the cross section through the discharge retains the relevant features described above. The pressure p at which the discharge operates is simply a function of the cathode to anode distance d (anode diameter or width for a hollow anode structure), applied voltage, gas and electrode material. The geometry can be scaled to operate with the same voltage current characteristic provided the product pd is kept constant.

2.4. Extracted Beams

To bring the fast electrons out of the discharge it is sufficient simply to perforate the anode. Thus the anode of the planar geometry is conveniently replaced by a mesh. The mesh pitch should be small compared with the cathode to anode distance, otherwise the discharge becomes sensitive to conditions outside the mesh. To bring out as many fast electrons as possible the mesh transparency should be high; we find 95% transparency quite operable. In this way about 80% of the input power (depending mainly on voltage and cathode metal) can be brought out as fast electrons.

In the case of the hollow anode geometry it is sufficient to have the end remote from the cathode open. Again most of the input power may be brought out as fast electrons.

To bring out the ions and neutrals is not quite so straightforward. If the cathode is perforated to allow more than a small fraction to come out, instability of the discharge, in the form of large amplitude oscillations, usually occurs. Experiment indicates that this instability is associated essentially with the diffusion of electrons, liberated in the gas outside the cathode, back into the main discharge. These electrons arise through ionisation of the gas by the ions and neutrals passing through the cathode.

Thus to prevent instability the back diffusion of electrons must be stopped. This is achieved if the potential of the ionised gas is made sufficiently positive with respect to cathode potential. The magnitude of the necessary positive potential is related to the dimension of the cathode perforation. It is evident that a space charge sheath must be set up which is sufficiently extensive to "pinch off" the plasma of ionised gas from the cathode fall region. We find that a plasma potential of not more than a few hundred volts positive with respect to the cathode allows the majority of ions and neutrals to be brought out of the discharge when operating in the range 10 to 20 kV. It is interesting to note that under these conditions the discharge adapts itself to operate on only 10 or 20% of the particles which would have struck an unperforated cathode under the same current conditions.

In the case of the planar geometry (fig. 4a) the perforated cathode is conveniently made of fine mesh, while for hollow anode geometry (fig. 4b) a hole or slit at the centre of the cathode suffices.

It is important to note that the glow discharge is usually less efficient as a generator of ion and neutral beams compared with electron beams. To obtain the best results for ion and neutral beams, the coefficient of secondary electron emission γ at the cathode, caused by ion and neutral bombardment, must be low (e.g. copper or stainless steel). Conversely, high γ (aluminium) gives high efficiency for generating electrons. As the voltage increases the efficiency of power conversion to an electron beam tends to increase, while the efficiency of conversion to ion and neutral beam power decreases.

2.5. Focusing Extracted Beams

The ions and neutrals passing out through a perforated cathode travel approximately perpendicularly to the cathode. The fast electrons emerging from a mesh anode in a planar discharge also travel approximately perpendicularly. Thus, in the case of the planar discharge the emergent particles can be brought to a crude focus by giving a spherical curvature to the electrode geometry. This simple scheme has the advantage that the beam is always focused independently of the operating conditions.

The same crude approach can be adopted for the hollow anode geometry. This geometry however has special features particularly suited to the sharp focusing of the energetic electrons. These electrons are mainly emitted from a small area at the centre of the cathode. Their energy spread when they emerge from the anode is small and they can be focused with a magnetic lens to produce a reduced image of the source at a target material. The optics may be further improved by appropriate design of cathode geometry, as discussed below (section 2.7). In this way power densities in the focused beam of the order of 10^6 W/cm^2 have been achieved.

2.6. Auxiliary Electrode Control

Under given voltage and pressure conditions discharge current can be strongly influenced by the potential of an auxiliary anode. In effect a subsidiary discharge between the main and auxiliary anode influences the degree of ionisation in the gas and hence the ion current to the cathode. Secondary electrons liberated by the energetic primaries on striking the anodes appear to be especially important to the control process. Potential difference between the anodes of the order of 100 V has a considerable effect on discharge current provided (a) the auxiliary anode is not too far away, (b) the more negative of the two anodes is struck by some of the energetic primaries. A typical control characteristic, obtained with hollow anode geometry, is shown in fig. 5. Similar data are obtained with a mesh electron gun containing a beam intercepting auxiliary anode just outside the mesh.

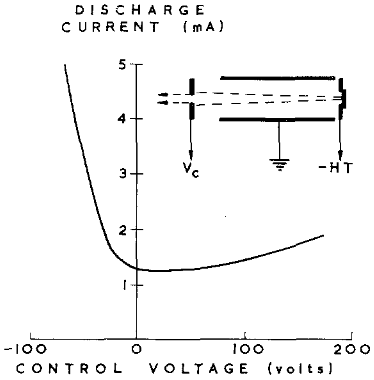


Figure 5 Auxiliary anode control characteristic.

In this connection, reference should be made to the work of Mahl [12] who showed that considerable control of the current could be obtained in hollow anode geometry by means of a magnetic field situated in an optimum region of the anode. A simple dependence of discharge current, and hence beam current, on the current in a field generating coil was found.

Auxiliary cathodes too can influence discharge characteristics. The stabilising electrode necessary for the extraction of ion beams, as discussed above (section 2.4.) provides an example. Under conditions in which only a small proportion of the ions and neutrals are allowed to pass through the cathode, the total discharge current can be controlled by leaking electrons back through the cathode perforation into the main discharge. This is achieved by varying the potential of the plasma outside the cathode and hence the space charge pinch off (see section 2.4.) at the perforation (control ceases when electron back diffusion is cut off completely).

These control processes are not well understood at present. In some conditions discharge oscillations appear, usually when the control characteristic is steep, i.e. when the sensitivity is high.

Another method of influencing the discharge, which is particularly relevant to the hollow anode geometry, depends on electric-field shaping at the cathode by an auxiliary electrode. Such an electrode, which itself contributes little to the electron emission, can influence the trajectories of the fast electrons constituting the emergent beam. Examples of practical arrangements for this purpose are given later in figs. 9 and 10. A diaphragm, situated between cathode and anode, acts in a manner rather similar to the Wehnelt electrode or grid of a conventional high vacuum thermionic electron gun. Its potential is kept near to or equal to that of the cathode. The three electrode arrangement forms an immersion lens such that the electron trajectories depend on relative dimensions and potentials of the parts. As the potential of the diaphragm, or its position in relation to the cathode, is varied the optical properties of the lens change. Thus under certain operating conditions a real image of the cathode electron emission may be formed within or outside the anode. The focal length of the lens and the position of the beam cross-over can be varied by simply changing the diaphragm potential. In one special condition the cross-over can be taken to infinity giving an approximately parallel electron beam along the axis of the anode. If the diaphragm is split so that two different potentials can be applied the beam may be deflected off-axis. It is apparent that considerable control over the fast electron current arriving at a target outside the discharge is possible by beam manipulation with auxiliary electrodes near the cathode. Experiment indicates that there is little if any frequency dependence for this type of control (up to 10 mc/s at least).

Once the fast electron beam has been brought out of the discharge it may be further manipulated or controlled by magnetic fields. Owing to the tendency towards a mono-energetic beam as the discharge voltage is increased, this type of control is more appropriate to high voltage discharges.

Provided electron or ion beams extracted from one gun do not enter into the discharge space of another, several guns can be operated simultaneously and controlled independently in the same low pressure chamber. It is only necessary that gun dimensions satisfy the *pd* requirement for the desired operating voltage.

2.7. Design Principles and Constructional Techniques

Some practical designs of electron and ion guns, based on the principles discussed above are given in figs. 6 to 10.

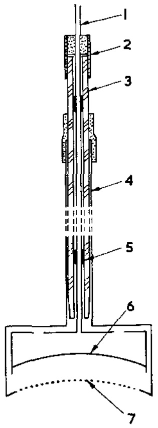


Figure 6 Mesh anode gun. 1 cathode support and gas inlet tube, 2 rubber sleeving vacuum seal, 3 silica tube insulator, 4 anode support and lead-through tube, 5 spacers, 6 spherically curved cathode, 7 mesh anode.

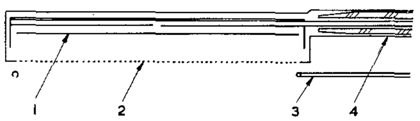


Figure 7 Mesh cathode ion gun, 1 planar anode, 2 mesh cathode, 3 stabilising electrode, 4 lead-through assembly.

Planar or mesh guns are conveniently made from refractory metal sheet and wire. In simple form no cooling is applied to the electrodes which can be allowed to operate red hot, or hotter if necessary.

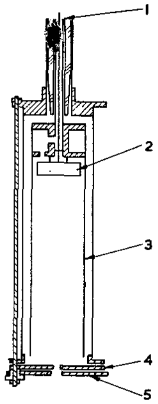


Figure 8 Hollow anode ion gun with current control, 1 gas inlet and lead-through assembly, 2 auxiliary anode for current control, 3 anode, 4 cathode, 5 stabilising electrode.

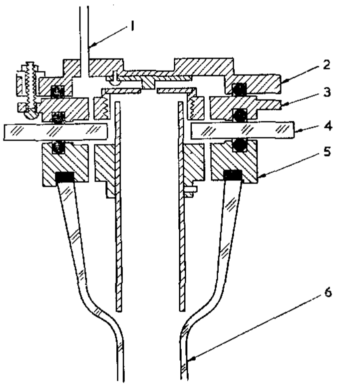


Figure 9 Hollow anode electron gun for micro-machining, 1 gas inlet, 2 cathode assembly, 3 grid assembly, 4 glass plate insulator, 5 anode assembly, 6 glass flight tube.

Insulation is conveniently provided by fused silica tubing of about 2 mm wall thickness. It is important that the termination of insulation within the low pressure chamber be given proper attention. Thus it must not be in a position subject to deposition of metal by sputtering. Also it is necessary to taper the tubing so that it does not contact metal within about 2 cm from the extremity. This precaution avoids breakdowns over the insulator termination.

To ensure that the discharge is confined to the cathode-anode space the electrode structure must always consist of an inner member at one polarity closely surrounded by an outer member at the opposite polarity. The gap between members must be small enough to avoid spurious glow discharges (i.e. the product *pd* must be too small to support a discharge under the desired operating conditions; see the Paschen breakdown curve, fig. 1). The gap must however be large enough to withstand vacuum breakdown. A gap of 2 mm operates satisfactorily in the voltage range of interest (i.e. up to 30 kV).

It is usually an advantage if the guns can be

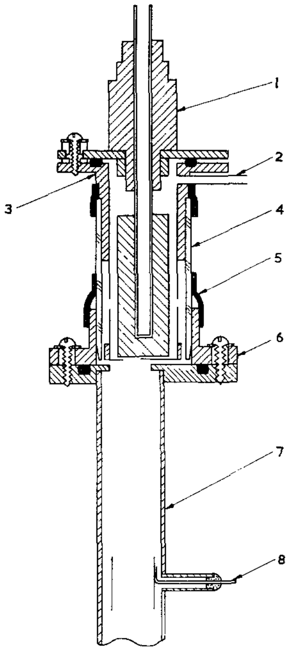


Figure 10 Electron gun for welding and milling, 1 cathode assembly (air cooled aluminium cathode), 2 gas inlet, 3 grid assembly, 4 glass tube insulator with resin shoulder, 5 rubber sleeve vacuum seal, 6 alignment flange, 7 anode, 8 auxiliary anode current regulator.

dismantled easily for cleaning. This is readily achieved if vacuum seals depend on rubber sleeving and grease. It is usually possible to keep the seals in a cool position well away from the hot parts of the gun.

Essentially similar remarks apply to hollow anode guns although it is often more convenient to employ glass plate or glass tubing for insulation.

Cathode metal is a parameter which influences the efficiency of the discharge as electron or ion source through its electron emission coefficient γ. Other factors such as heat dissipation and sputtering rate often make overriding considerations however. Tantalum is a good choice for uncooled mesh guns owing to its refractoriness, whereas aluminium is very suitable as cathode in hollow anode electron guns owing to its high coefficient γ and high thermal conductivity. It appears that the main limitation to electron emission current at the cathode is the dissipation of the thermal energy of the ions and neutrals which bombard it (about 10% of the input power with an aluminium cathode at 10 to 20 kV). In previous work, 13 kV glow discharges have been operated, in pulsed mode, at currents up to 200 A [13] and 100 kV discharges up to 10 A (Pollock, see McClure [4]).

2.8. The Glow to Arc Transition

In certain circumstances the glow discharge, operating at high voltage, can make a rapid transition to an arc operating at low voltage. The arc, which forms in a time of less than a microsecond, is characterised by a high current density of the order of 10^6 A/cm^2 and a voltage of the order of 10 to 100 V. This type of arc is known as a cold cathode arc. It may be extinguished, however, almost as fast as it began by a properly designed circuit. This is possible owing to the fact that a cold cathode arc cannot be sustained at a current of less than 1 to 10 A [14]. Thus, provided that the circuit impedance is so large that a steady current of this magnitude cannot be maintained, the arc must go out.

The arc spot rapidly vaporises cathode material and to minimise damage to the cathode the arc must be extinguished rapidly. It is therefore important that the circuit store as little electrical energy as possible. Thus the gun should be connected to the high voltage supply through a current limiting resistor with the minimum of associated inductance or capacitance.

Arcs appear to be caused by the presence of volatile contamination such as adsorbed water or organic contamination on the cathode [15]. They may be avoided therefore by maintaining the cathode at an elevated temperature, sufficient to drive off or decompose the contaminant. In this respect the most successful cold cathode discharge is in fact a warm cathode discharge. A cathode temperature of 200 to 300° C reduces the chance of a glow to arc transition very markedly. Inorganic contamination of low volatility seems to be relatively innocuous. We have operated mesh discharge electron guns successfully with a red hot tantalum cathode largely covered with a layer of deposited alumina (contamination in this form however can be minimised by large cathode to target distance and by cooled baffles between gun and target). Such a cathode arcs when cold, but stops arcing when hot.

2.9. Cathode Sputtering

The erosion of the cathode by sputtering, caused by ion and neutral bombardment, is minimised by operating in light gases such as hydrogen and helium and by choosing cathode metals known to give low sputtering yields, such as aluminium and tantalum [16]. Sputtering can actually be beneficial in the sense of keeping the cathode clean and this may be important when the cathode is subject to contamination from vaporised target material and other sources. On the other hand, sputtering can be very undesirable when the shape of the cathode is electron optically important, as in hollow anode discharge electron guns. The only solution in these circumstances appears to be to re-shape the cathode from time to time or else to design into the gun a continuously replaced cathode surface.

2.10. Basic Requirements and Costs

Guns of the types shown in figs. 6 to 10 do not require high precision in manufacture and are therefore not expensive to make. To generate and apply a beam to a target material requires essentially a roughing pump, vacuum chamber, leak valve and high voltage supply. High voltage supplies, up to 20 or 30 kV unsmoothed, cost about £200 a kilowatt. For some purposes the guns operate adequately on unsmoothed DC but smoothing can be added without much extra expense. Roughing pumps cost from £30 to £150 depending on capacity. Allowing £200 for accessories and for the incorporation of safety devices and features to protect the operator from electric shock and X-radiation, it is apparent that simple installations can be built for a few hundred pounds.

3. Applications

3.1. General Considerations

Our experience indicates that, at beam power up to the order of 1 kW, it is easy to design apparatus to operate at a pressure of the order of 0.1 mm Hg. It is possible that much higher powers may also be operated at this pressure. This means that vacuum systems may be unsophisticated and material to be processed by particle bombardment may be readily and quickly introduced to or removed from the work chamber. Also at this pressure it is a simple matter to regulate the pressure with a leak valve to achieve the correct operating conditions.

The presence of the gas in the work chamber ensures that an ionised atmosphere envelops the target. The ionisation is sustained by either the primary beam itself (ion and neutral beams or low energy electron beams) or by back scattered or secondary electrons and photons from the target (high energy electron beams). Thus there need be no difficulty due to electrical charging effects at the target since the ionised gas virtually connects it electrically to the surroundings. The glow discharge beam technique is therefore especially suited to the processing of insulating materials in addition to electrically conducting materials.

The presence of gas has another advantage. Evaporated material or gaseous contaminants, released by bombardment, must diffuse away from the source. Their distribution in space and on condensing surfaces is therefore a diffusion problem. Thus, by appropriate design, the gas can be made to act as a filter to vapours without at the same time, obstructing the beam.

Glow discharge beams may be applied to any process exploiting ionisation and excitation in the target material, or heating, sputtering and particle injection effects in it. Low or high current and power densities of bombarding particles are practicable and particle energies in a wide range up to of the order to 10^5 eV are possible. In particular, finely focused electron beams can be designed which can be manipulated magnetically to perform many of the tasks previously considered to be in the province of the high vacuum thermionic gun.

Thus processes involving radiation chemistry, heat treatment, melting, evaporation, sputtering and ion and atomic injection are in the province of glow discharge beam techniques. Our experience so far has been confined to crystal growing (refractory oxide crystals from the melt and from the vapour), vapour deposition (oxides onto metal or oxide substrates), welding and thermal milling (metals, ceramics and glass) and etching or milling by sputtering (glass and ceramics). There are obviously other applications.

3.2. Crystal Growing and Vapour Deposition

Two arrangements which exploit electron bombardment within a low voltage discharge (1 to 3 kV) are indicated schematically in figs. 11 and 12. Single crystal sapphire has been grown in both arrangements. Of these two methods the second, the "Verneuil" method (fig. 12) appears to be the more promising. The floating zone technique (fig. 11) has given difficulties associated with temperature distribution through the zone (caused by heat transmission through the transparent medium) and loss by evaporation. It should also be possible to construct apparatus for crystal growing by the pulling or Czochralski method.

We have also attempted to grow alumina and

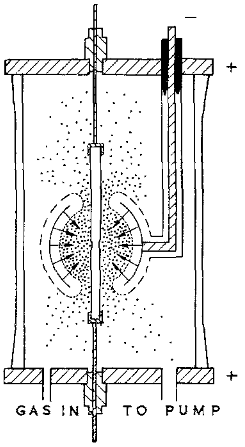


Figure 11 Spherical cathode floating zone crystal growing apparatus.

magnesia crystals from the vapour using a mesh gun of the type shown in fig. 6 to evaporate the stock. An elementary form of apparatus is shown in fig. 13 (in a later version the guns carried baffle systems to discourage diffusion of vapour to the cathodes). Transparent deposits have been achieved on heated ceramic, tantalum, nickel and stainless steel substrates (heated by the second mesh gun). It seems likely that whether single or polycrystalline deposits are obtained is governed by substrate temperature conditions. It is envisaged that pulsed thermal treatment of the condensing surface with a separate beam can be arranged to favour a polycrystalline deposit.

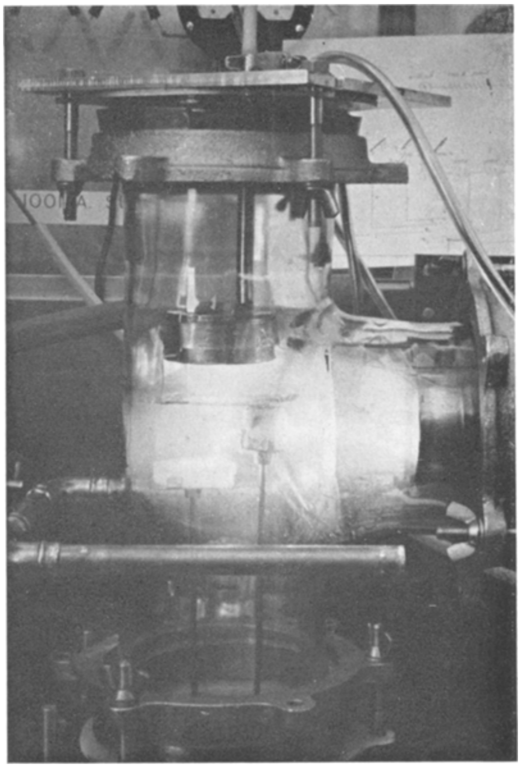


Figure 13 Two gun evaporation system. The vertical electron gun is evaporating silica onto a rotating ceramic substrate which is heat treated by the horizontal electron gun.

The vapour pressure of the material near its melting point will dictate the most appropriate technique for crystal growing.

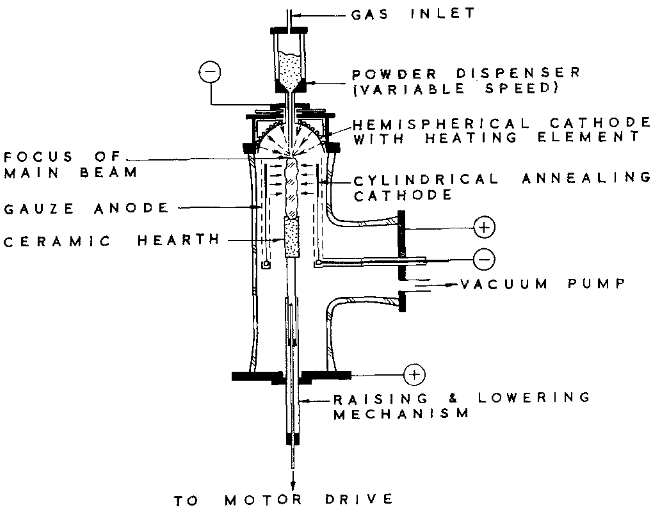


Figure 12 "Verneuil" crystal growing apparatus.

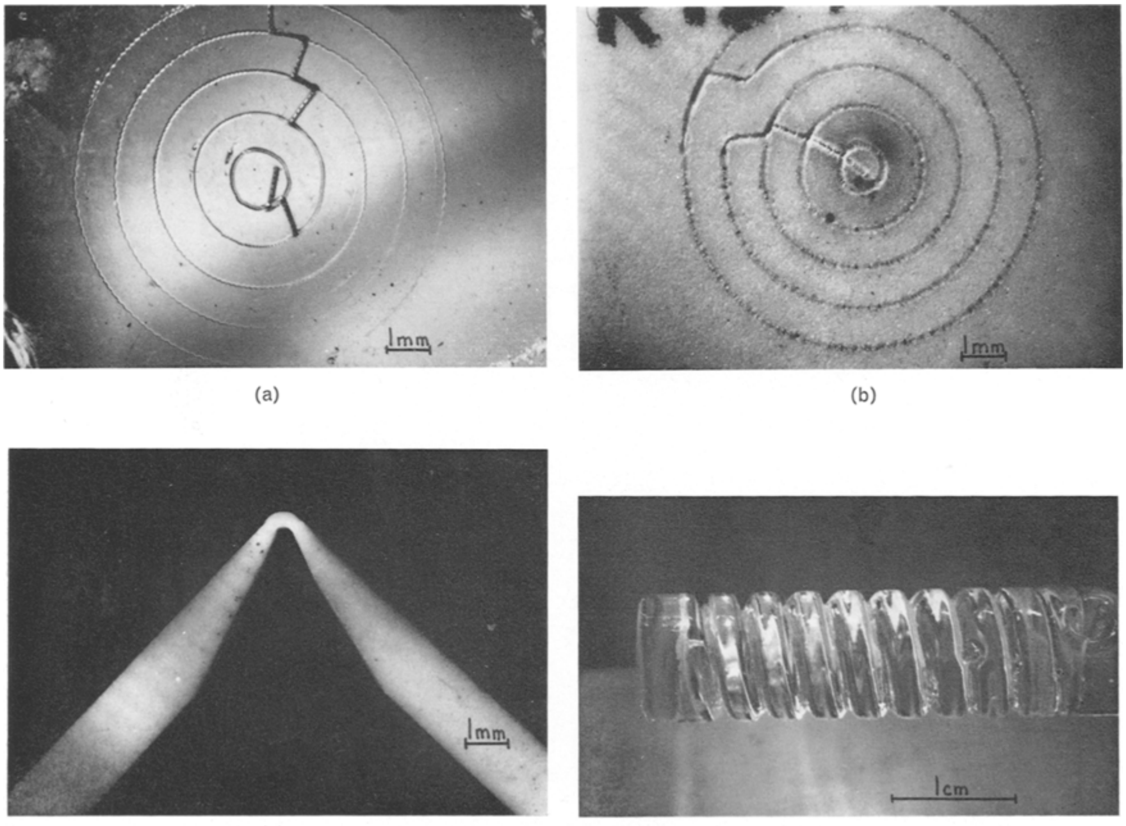
3.3. Welding and Thermal Milling

A high beam power density can be achieved with electron guns of the types shown in figs. 9 and 10 (hollow anode guns) when used in conjunction with magnetic focusing. Thus we have been able to focus to a spot diameter of $\sim 3 \times 10^{-3}$ cm with a single lens and to mill thermally glass and ceramic materials when operating the gun shown in fig. 9 at 20 kV, 1 mA. We have also welded metals and ceramics (fig. 14).

The gun shown in fig. 10 is a coarser design, of an experimental nature, intended for less precise but more power-consuming applications. Fig. 14d shows a screw thread turned on a piece of silica rod with this gun. This result was obtained at 20 kV, $\sim$ 3 mA in one pass. The gun however will operate at 50 mA or more to produce a high concentration of power at considerable distance from the cathode. High rates of evaporation from the target material are therefore possible without contaminating the cathode. If focusing requirements are not too demanding, such a gun can be operated from an unsmoothed single-phase power supply since the discharge tends to occur only at the peaks of the wave-form.

3.4. Etching, Milling and Deposition by Sputtering

The ion beam devices shown in figs. 7 and 8 are especially suitable to the processing of electrically insulating or poorly conducting materials by sputtering. Thus etching of ceramics to reveal microstructures [17] may be achieved with advantages over thermal or chemical methods. A mesh cathode focusing gun for this purpose is shown operating in fig. 15. Owing to the atomic nature of the process, sputtering is also eminently suitable for very fine scale milling operations such as working optical surfaces and shaping microcircuit topography. In the latter respect a broad beam gun of the type shown in fig. 7 could be applied to many microcircuit units simultane-



(a) (b) (c) (d)

Figure 14 a Tracks milled on fused silica, b tracks milled on alumina, c welded alumina ceramic, d screw thread turned on fused silica.

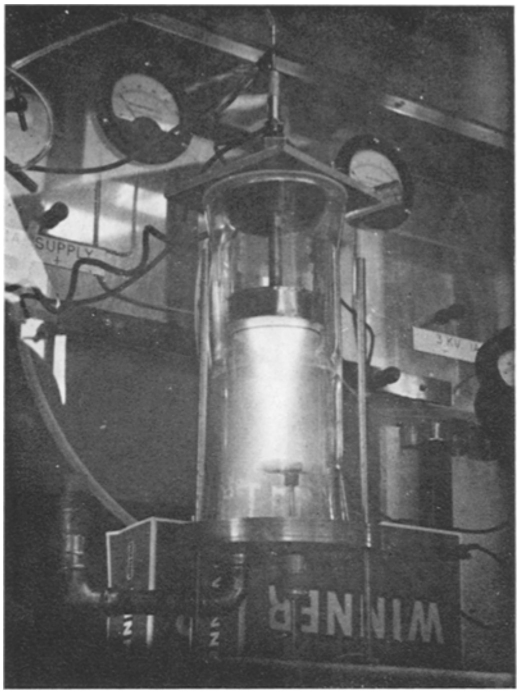


Figure 15 Mesh cathode focusing ion gun operating in air at 11 kV, 10 mA (stabilising electrode voltage + 120 V).

ously each appropriately masked with photoresist or other organic materials (glow discharge electron beam apparatus might be employed to write the mask [18]). In fig. 16 the broad beam ion gun is shown etching a pattern, drawn in aquadag, onto a complete microscope slide (7.5 × 2.5 cm).

Deposited films made by sputtering stock material have long been applied to applications exploiting metal films [19]. The possibilities with deposits of insulating materials have hardly been explored as yet owing to difficulties associated with electrical charging effects. These difficulties are circumvented by the present techniques. A device which exploits the hollow anode geometry for high rate sputtering of glass and ceramic stock for deposition on a nearby surface is shown in fig. 17. The current density of ions and neutrals at the target may be of the order of 10^{18} to 10^{19} particles/cm^2, over an area of 10^{-1} cm^2 in this apparatus. Melting of the target under the high power density sets the limit to the current density (the apparatus was in fact originally intended for zone refining alumina by the floating zone method). The beam width at the target is of the order of 1 mm when operated at 5 to 15 kV (3 mm cathode slit, stabilising bias + 500 V). Conical geometry rather than this cylindrical geometry might be preferable for some applications to exploit ion and neutral bombardment at high concentration.

4. Summary

The exploitation of the glow discharge for processing materials by beam techniques at pressures of about 10^{-4} atm, has been discussed. The discharge is operated on the left-hand

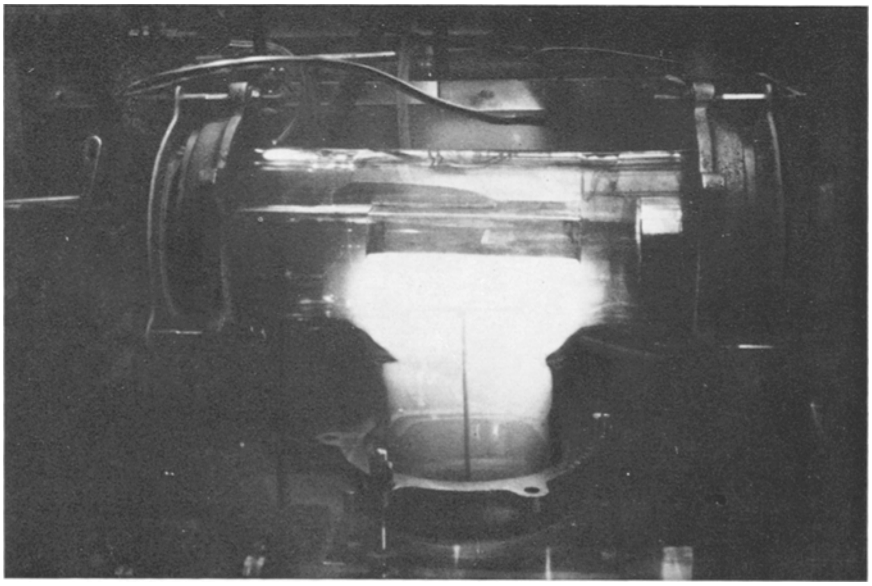


Figure 16 Broad beam ion gun etching a microscope slide (argon 9 kV, 10 mA, stabilising voltage + 200 V).

branch of the Paschen breakdown curve and experience in the range 1 to 30 kV has been described.

As the voltage is increased, fast electrons, produced in the discharge, become penetrating and can be taken outside the discharge region with efficiency, in terms of power conversion, of about 80%. These electrons tend to be monoenergetic and can be magnetically manipulated as in conventional thermionic electron-optical devices.

Discharge geometry governs the initial spatial distribution of the fast electrons. At low voltage (e.g. 1 to 3 kV) only cathode geometry is important, but, as the voltage increases, anode geometry and boundary conditions at the sides become important. Low voltage discharges are specially suitable for electron beam applications in which the target material may be placed within the discharge itself.

Ions and neutral particles approaching a perforated cathode can also be taken out of the discharge. Owing to relatively high cross-sections for scattering and charge exchange, these particles always have a wide spread in energy and their trajectories can only be influenced by discharge geometry. The majority may be brought out since, by pressure adjustment, the discharge can be sustained on the proportion (as little as 20%) which strike the cathode.

Two special features of glow discharge beam devices are (1) the vacuum system may be simple and cheap, since operation at a pressure of the order of 0.1 mm Hg may be designed, (2) the beams can be applied to insulating material just as readily as to conducting material. This latter arises owing to the presence of ionised gas in the vicinity of the target, and this supplies the necessary charge to maintain neutrality at the bombarded surface. Several guns of different types can be operated independently in the same vacuum chamber.

Discharge current is essentially dependent on gas pressure. At roughing pump pressures, however, it is a simple matter to control the pressure in a continuously pumped system by means of a leak valve. In addition, the current may be controlled with auxiliary electrodes or magnetic fields so that means are available for automatic regulation of discharge current against minor pressure fluctuations.

Maximum current appears to be limited only by thermal dissipation at the cathode. Glow to arc transitions can be made unlikely by avoiding contamination of the cathode and by maintaining cathode temperature above about 200° C (in this sense the successful discharge may be described as a "warm" cathode discharge). Cathodes may be operated hot to temperatures at which thermionic emission commences. Sputtering, which erodes the cathode, may be minimised by a suitable choice of operating conditions.

Applications of glow discharge beam devices include any process exploiting ionisation and excitation in the target material or of heating, or sputtering and particle injection effects in it.

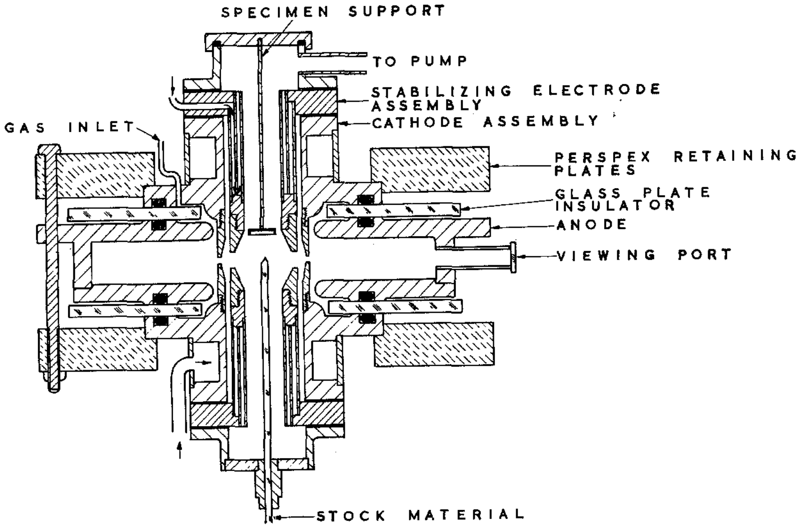


Figure 17 Concentric ion gun set up for high rate sputtering.

Experience in crystal growing, vapour deposition, welding, thermal milling, etching and deposition by sputtering is given.

References

1. J. J. THOMSON and G. P. THOMSON, "Conduction of Electricity through Gases", Vol 2 (Cambridge UP, 1933).
2. B. N. KLYARFEL'D, L. G. GUSEVA, and A. S. POKROVSKAYA-SOBOLEVA, *Sov. Phys.-Tech. Phys.* **11** (1966) 520.
3. D. KAMKE and F. W. RICHTER, *Ann. Physik.* **10** (1963) 360.
4. G. W. MCCLURE, *Phys. Rev.* **124** (1961) 969; G. W. MCCLURE and K. D. GRANZOW, *Phys. Rev.* **125** (1962) 3; K. D. GRANZOW and G. W. MCCLURE, *Phys. Rev.* **125** (1962) 1792.
5. A. VON ENGEL, "Ionized Gases" (Clarendon Press, Oxford, 1955).
6. G. FRANCIS, "The Glow Discharge at Low Pressure" Handbuch der Phys. Vol. 22 (Springer-Verlag, 1956) p. 53.
7. G. INDUNI, *Helv. Phys. Acta* **20** (1947) 463; "La Cathode Froide et Ses Applications" Les Techniques Recentes Microscopie Electrique Corpusculaire (Toulouse, 1955) p. 189.
8. G. MÖLLENSTEDT and H. DUKER, *Z. Naturforsch.* **8A** (1953) 79.
9. M. VON ARDENNE, "Tabellen zur Angewandten Physik", Vol 1 (Veb Deutscher Verlag der Wissenschaften, Berlin, 1962) p. 640.
10. R. M. CHAUDRI and M. M. CHAUDRI, "Energy Spectrum of Cathode Rays in Glow Discharge in Gases at Low Pressures" Proc. Seventh Int. Conf. on Phenomena in Ionized Gases, Vol I (Beograd, 1966) p. 392.
11. W. CROOKES, *Phil. Trans.* **170** (1879) 135.
12. H. MAHL, *Ann. Physik.* **31** (1938) 425.
13. A. S. POKROVSKAIA-SOBOLEVA and B. N. KLIARFEL'D, *Sov. Phys. JETP* **5** (1957) 812.
14. A. E. ROBSON and R. HANCOX, *Proc. Inst. Elec. Eng.* **106A** Supplement 2 (1959) 47.
15. J. T. MASKREY and R. A. DUGDALE, *Brit. J. Appl. Phys.* **17** (1966) 1025.
16. R. BEHRISCH, "Festkörperzerstäubung durch Ionenbeschuss", Ergebnisse der Exakten Naturwissenschaften Vol 35 (Springer-Verlag, 1964) p. 295.
17. R. A. DUGDALE and S. D. FORD, *Trans. Brit. Ceram. Soc.* **65** (1966) 165.
18. G. W. HILL, *Microelectronics and Reliability* **4** (1965) 108.
19. L. HOLLAND, "Vacuum Deposition of Thin Films" (Chapman and Hall, London, 1956).