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Simple parallel plate energy analyser for measuring the energy distribution of metal vapours in a discharge

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Abstract The design and performance are described of a simple and inexpensive parallel-plate energy analyser used for measuring the energy distribution of ions reaching the cathode of an abnormal glow discharge particularly under the actual conditions pertaining during the evaporation of a metal in the ion plating process.

1 Introduction

The study of the energy distribution of ions reaching the cathode of an abnormal glow discharge in the absence or during metal evaporation, requires an analysing system which is equipped with a metal evaporation source. A knowledge of this energy distribution, would assist in the control of the processes occurring in an 'ion plating' deposition system, which requires a self-sustaining abnormal glow discharge as its working medium (Mattox 1973, Ahmed 1974, Teer 1977).

In the ion plating process, atoms of the material to form the plating are injected into the gas discharge. During the sputter cleaning portion of the process the substrate acts as a sputtering cathode. Some of the gas atoms are ionised by electron–atom collisions and are accelerated across the cathode dark space. Many of these ions become high energy neutrals by charge exchange processes (Davis and Vanderslice 1963). The high energy particles (atoms or ions) may become incorporated into the surface of the substrate, alternatively they may be neutralised and reflected as high energy neutrals or metastables. In addition, high energy particles cause secondary electron emission, which serves to maintain the discharge; they also cause sputtering of the surface material, which may be scattered back to the substrate, ionised by electron or metastable collision (Penning ionisation) and then accelerated back to the substrate, or be deposited in other parts of the vacuum system (Holland 1972).

During the last few decades, several authors have reported energy distribution measurements, in the absence of evaporant, for ions passing through a cathode aperture in a glow discharge. For example, Chaudri and Oliphant (1932) used the combination of a retarding lens and a 127° electrostatic analyser to measure the energy distribution of positive ions passing through a small aperture in the cathode of a glow discharge. Davis and Vanderslice (1963) carried out similar measurements using a sector field type electrostatic analyser. In slightly different context, Theard (1968) has used an electrostatic parallel plate energy analyser developed from that used by Yarnold and Bolton (1949) to measure the energy distribution of Ar^+ ions extracted from a non-magnetic hot-cathode gas-discharge ion source.

Although there is an abundance of information concerning the measurement of the energy spread of ions reaching the cathode of an abnormal glow discharge, to the author's knowledge there have been no published measurements of the energy distribution of ions reaching the cathode with either an abnormal or normal glow discharge during evaporation of a metal.

In this paper a simple and inexpensive analysing instrument for this purpose is described. This instrument is capable of measuring the energy distribution of ions reaching the cathode of an abnormal glow discharge in the absence or during the evaporation of a metal. The energy analyser employed in this work is a modification of the type used by Harrower (1955) and Theard (1968).

2 Description and operation of the energy analyser system

In view of the fact that the energy analyser system was required to operate at a pressure of about $1{\cdot}33 \times 10^{-3}$ Pa while maintaining a discharge pressure of 1·33 Pa, it was necessary to provide differential pumping facilities. To avoid using an additional pumping system it was decided to assemble the evaporation system within a small glass discharge tube mounted inside the main chamber of a conventional vacuum pump system. By feeding the discharge gas directly into the small chamber the required pressure differential could be maintained across the small sampling aperture in the cathode if the pumping rate was 50 l/s. Such an arrangement is important if it is intended to carry out the analysis under the *exact* conditions used in the ion plating technique, in which metal, gas and impurities all co-exist in the evaporation chamber to give the superior results determined by the ion plating technique.

2.1 *The discharge tube*

The discharge for which the energy distribution study was made took place inside a small glass tube 120 mm in height and 100 mm in diameter. A diagram showing the tube (D), the arrangement of the gas inlet (A), the anode (C) and cathode (E) is illustrated in figure 1. The argon gas was fed directly into the discharge tube via a hollow feedthrough in the base-plate of the main system. The evaporation boat (C) which also served as the anode, was mounted on two copper holders connected to high current tungsten 'feedthrough' sealed into the glass wall of the tube. The boat was situated 80 mm away from the cathode which provided the reference or zero point for the ion energy measurements and was maintained at earth potential. This made it possible to operate all the energy analysing and measuring equipment near earth potential rather than at the high voltage which would have been the case if operating with a grounded anode. Grounding the cathode presented no difficulties from the point of view of the discharge since it was now contained inside the glass tube. Operation of the boat at high voltage simply required the use of suitable 1:1 2 kV isolating transformer.

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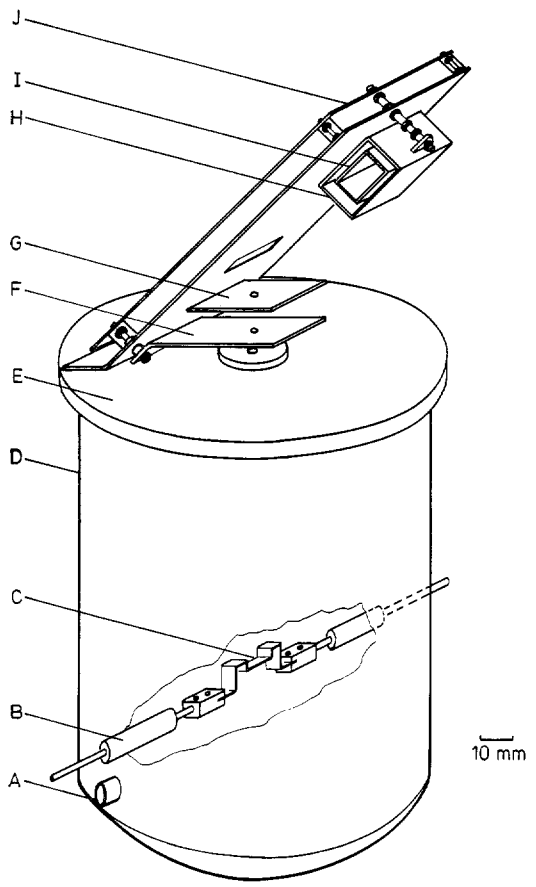

Figure 1 Experimental arrangements of the discharge tube and analysing systems: A, gas inlet; B, tungsten feedthrough; C, boat; D, discharge tube; E, cathode; F, electron suppressor; G, earthed slit; H, screened shield; I, Faraday collector; J, parallel plate energy analyser. The discharge tube and analysing system are placed inside a main vacuum chamber.

2.2 *The cathode*

The cathode was a stainless steel circular disc 110 mm in diameter and 6 mm thick. A circular groove 2 mm wide and 95 mm internal diameter was machined in the lower face of the disc, such that a very low vacuum conductance seal could be made between the ground end of the glass discharge tube and the cathode (see E, figure 1). At the centre of the cathode there was a circular hole 8 mm in diameter which was covered by 500 μm thick stainless steel foil with a 1 mm diameter aperture in the centre of it. The size of this aperture was chosen so that easily measurable ion currents could be extracted without an excessive rise in the pressure in the analysing region. The size of this aperture, however, was found to be limited by the capabilities of the differential pumping system and an estimate of the maximum permissible size was obtained by calculating the conductance in l/s of the aperture which would lead to a pressure rise to $1{\cdot}33 \times 10^{-2}$ Pa in the main pumping chamber when a pressure of 1·33 Pa was maintained in the discharge tube (Ahmed 1974).

2.3 *The energy analyser system*

Ions extracted from the gas discharge were energy analysed using the arrangement shown in figure 1. The complete analyser and detector assembly was rigidly mounted on the cathode. It was positioned so that the ion beam entered the analyser at an angle of 45°, the beam direction was accurately defined by means of the two 1 mm wide apertures situated in front of the entrance slit.

The parallel plate analyser consisted of two 80 mm × 50 mm stainless steel plates 1 mm thick separated by a distance of 20 mm. The lower earthed plate contained the entrance and exit slits of effective width 1 mm and length 8 mm which were 40 mm apart, giving a resolving power of about 40. The measurements of the energy spectrum of extracted ions were made by applying a linear positive voltage sweep to the upper plate of the analyser. A low voltage output obtained across a 1 kΩ resistor was used to drive the X deflection amplifier of an X–Y recorder, the Y deflection amplifier being driven from the output of a picoammeter (Keithley 600B).

If the separation between the two analyser plates is made equal to the distance between the entrance and exit slits, the X deflection is linear in terms of ion energy (Hutchinson 1962).

However, it was found that the application of a negative voltage of 150 V to the first collimating aperture (F) in figure 1, led to a significant increase in the transmission of the overall analyser system and also a complete suppression of a negative current reading that was obtained when this electrode was earthed. The increase in transmission can be explained by the fact that this electrode in conjunction with the earthed cathode and earth second collimator (G), formed an Einzed lens and hence focused the ions into the analyser. The negative current reading was found, by means of retarding field measurements, to be due to low energy electrons reaching the Faraday cup (figure 2). It had been shown that such electrons

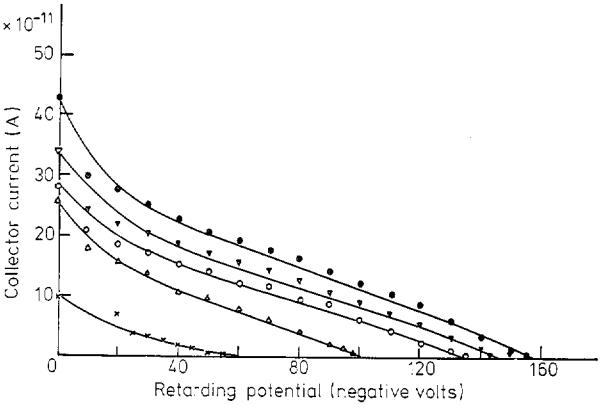

Figure 2 Retarding analysis of electron suppressor (F) at a discharge pressure of 1·2 Pa argon and for different discharge potential and currents of: ×, 500 V, 1·1 mA; △, 700 V, 1·8 mA; ○, 800 V, 1·0 mA; ▽, 900 V, 1·5 mA; ●, 1000 V, 1·9 mA.

were emitted from the edges of a cathode aperture (Pettifer 1970). Consequently, application of 150 V negative to the first collimating electrode (F) in figure 1 would be expected to provide adequate suppression (figure 2). Variation of the voltage applied to this electrode did not change the form of the energy spread curves and consequently it was assumed that the discharge conditions were not affected by its application.

The Faraday cup collector (I) used in the present work was made of thin molybdenum foil, it was mounted inside a screening can (H) and was maintained at 60 V negative. This screening was found necessary since ion currents of the order of 10^{-11} A were being measured with the picoammeter (Keithley 600B).

3 Results and discussion

The behaviour of the analyser was tested by measuring the energy distribution of positive ions impinging on the cathode of an abnormal glow discharge for several different discharge voltages and a number of different pressures.

Typical examples of the ion energy spectrum obtained are illustrated in figure 3 and figure 4 respectively. They are for dischage tube pressures of 1·2 Pa and 6·65 Pa and for discharge tube voltages of 914 V, 952 V, 990 V and 1128 V respectively. The energy distributions shown in these figures are not the 'true' energy distribution due to the dependence of the analyser on the ion energy transmission.

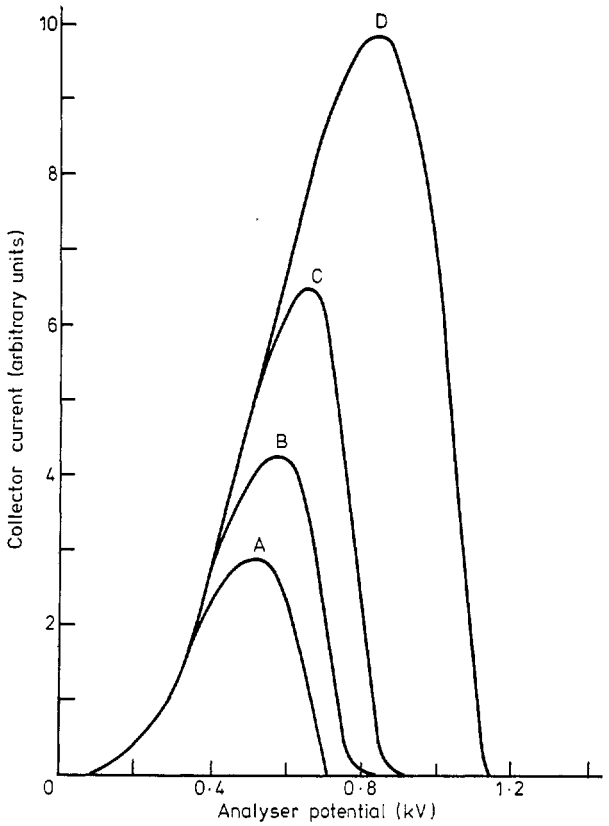

Figure 3 The energy distribution for Ar ions at the cathode in a 1·2 Pa and discharge potential and currents of: A, 914 V, 0·3 mA; B, 952 V, 0·4 mA; C, 990 V, 0·5 mA; D, 1128 V, 0·6 mA (taken from X–Y recorder plot).

The energy resolution ΔV is proportional to V so that the collector current is favoured at high V values, the 'true' energy distributions, therefore, are corrected by dividing the measured current I_m by the corresponding value of V. A set of corrected curves corresponding to those shown in figure 3 are shown in figure 5. It is observed, as expected, that the corrected curves are very close to the experimental curves on account of the relative narrowness of the energy peaks encountered (Yarnold and Bolton 1949), and for this reason, other results are shown as recorded and without correction. If the analysis is carried out at a slightly higher discharge pressure (6·65 Pa), then two distinct peaks appear in the energy spectrum (figure 4). In the absence of mass analysis facilities, which are not provided on the simple and inexpensive apparatus described herein, it is not possible to explain this effect with certainty, but references to previous publications (Houston and Uhl 1971, Holland 1973) and recent studies (Armour 1980, private communication),

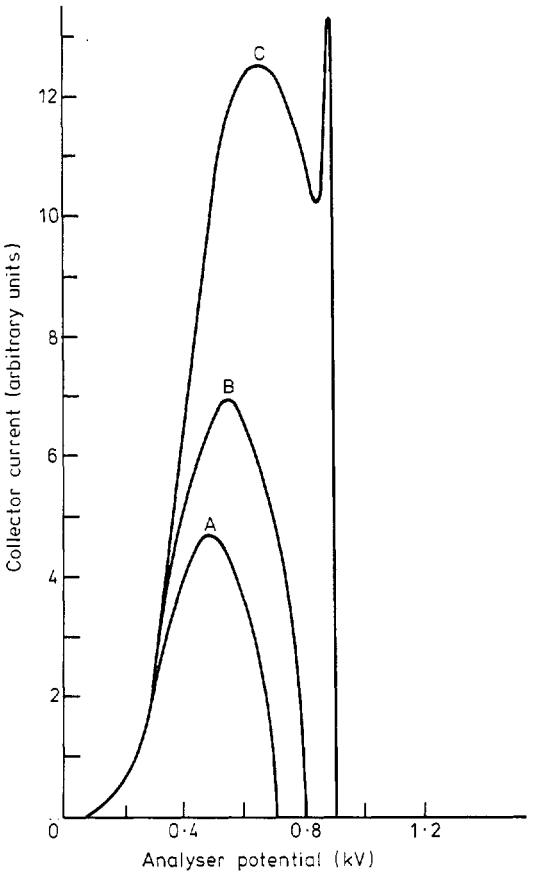

Figure 4 The energy distribution for Ar ions at the cathode in a 6·65 Pa and at discharge potential and currents of: (A), 700 V, 0·2 mA; B, 800 V, 0·4 mA; C, 900 V, 0·5 mA (taken from X–Y recorder plot).

indicate that the high energy peak may be due to the formation of doubly charged argon ions Ar^{++} for which the charge transfer cross section is lower than that for the singly charged ion; therefore Ar^{++} ions would be expected to have an average energy higher than that of the singly charged ion Ar^{+}.

The energy distribution of the ions reaching the cathode during the plating metal evaporation has also been investigated. A typical curve obtained during the evaporation of lead is illustrated in figure 6 where it is seen that the high-energy portion of the spectrum is slightly shifted towards a lower energy. Due to outgassing and evaporation, the pressure during these measurements was, as may be inferred from the marked reduction in discharge current at constant voltage, considerably higher than those during the previous measurements. This effect was always observed in the course of the standard ion-plating process. The contribution by the metal vapour to the total pressure increase is not measurable with the present apparatus. However, recent measurements carried out by Armour (1980, private communication), using a mass spectrometer attached to discharge equipment has indicated that the amount of Pb^{+} evaporant in such an Ar discharge during the ion-plating process is about 1 % of the total number of ions present in the discharge.

4 Conclusion

In conclusion, therefore, the system outlined in the present paper is capable of accomplishing the initial requirements,

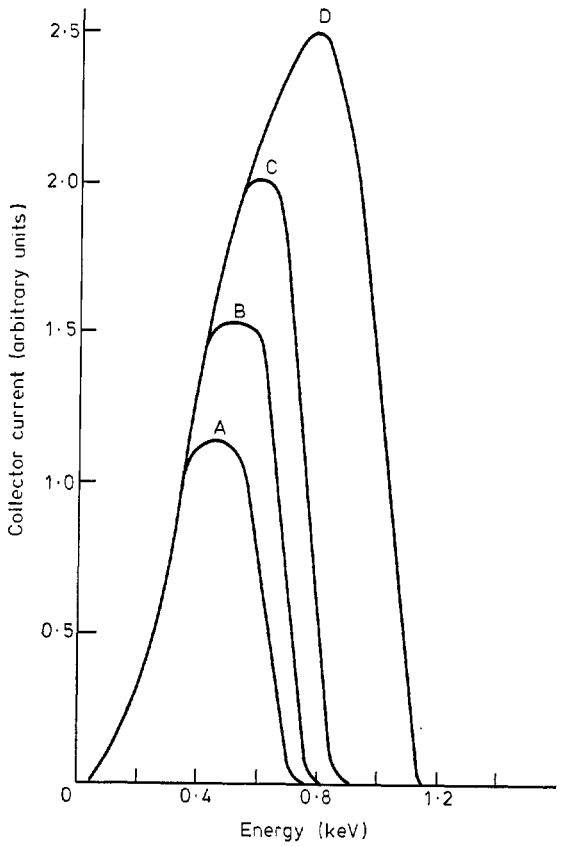

Figure 5 The 'true' energy distribution of figure 3 for Ar ions at the cathode in a 1·2 Pa and at discharge potential and currents of: A, 9·4 V, 0·3 mA; B, 952 V, 0·4 mA; C, 990 V, 0·5 mA; D, 1128 V, 0·6 mA.

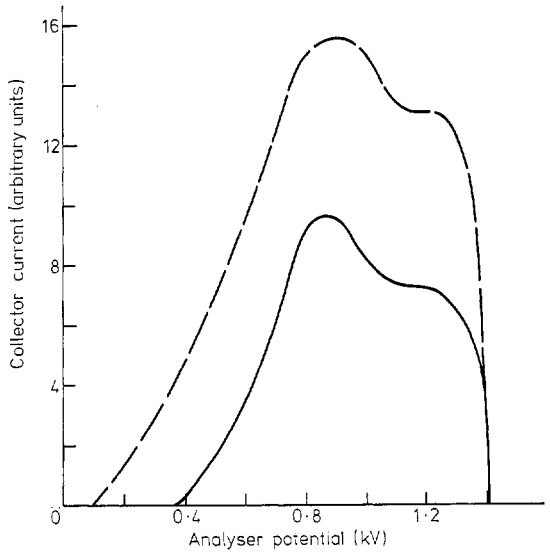

Figure 6 The energy distribution for Ar ions at the cathode in a 1·33 Pa, 1414 V discharge potential (– – –) before the evaporation of lead, and (———) during the evaporation of lead (taken from an X–Y recorder plot).

namely, the inexpensive measurement of the energy distribution of the ion ensemble reaching the cathode under the evaporation conditions of the ion plating process.

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