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Influence of background gas pressure on copper film deposition and ion current in a hot refractory anode vacuum ARC

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Abstract

A 200 A Hot Refractory Anode Vacuum Arc (HRAVA) was studied. The arc was sustained between a cylindrical Cu cathode and an Mo anode spaced ~10 mm apart. In the HRAVA, metallic plasma (from cathode material) expands radially. He, N_2 or Ar gas was introduced into the arc chamber through an electrically controlled valve. Films were deposited onto glass microscope slide substrates. The angular film distribution and the influence of different background gases on films deposited by the HRAVA were measured. The film thickness was measured by profilometry. The ion current was measured by a circular flat probe.

It was shown that the film thickness was uniform with respect to the azimuthal angle around the electrode axis within approximately 10%. The film thickness was independent of gas pressure p, below a critical value p_{cr}. For $p > p_{cr}$, the film thickness decreased with p, eventually reaching 0. The value of p_{cr} was less for gases with larger molecular weight—60, 10 and 5 mTorr (0.67, 1.33 and 8 Pa) for He, N_2 and Ar, respectively. The ion current to a 78 mm^2 probe in vacuo increased with time and reached a saturation value of approximately 4.5 mA after about 60 s from arc ignition. The ion flux fraction in the total deposition mass flux was estimated to be about 60% in the fully developed HRAVA ($t = 60–90$ s).
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Keywords: Copper film deposition; Hot refractory anode; Vacuum arc; Plasma plume; Deposition in background gas; Cathode spots; Coating thickness

1. Introduction

The metallic plasma generated in electrical arcs is a source of metal vapor for thin film deposition in vacuum and for coatings of compound materials on tools in the presence of reactive background gases [1]. Different methods are used for filtering macroparticles (MPs) produced in the cathodic arcs in order to improve the coating quality [2,3]. The dependencies of ion current [4–6], cathode erosion rate [4,7], and MP number in the deposition flux [8,9] on gas pressure and composition were investigated in cathodic arcs. It was shown that ion current decreases with background gas pressure beginning from some critical pressure p_{cr} and eventually disappears. The value of p_{cr} depends on gas type, and the distance between substrate and cathode. The observed dependencies were explained by the cathode erosion rate decreasing with gas pressure [4,7,10]. The measured MP number decreased with pressure, which was explained by the decreasing erosion in the liquid phase and by the increasing electrostatic repulsion of the MPs from the substrate [11].

Recently, the Hot Refractory Anode Vacuum Arc (HRAVA) was shown to be a metallic plasma source with considerably less macroparticle contamination than conventional cathodic vacuum arcs [12]. A dense plasma plume of cathode material is formed by re-evaporation of metal from the arc-heated anode which was previously deposited from cathode plasma jets. Physical aspects of the HRAVA were experimentally and theoretically studied [13,14] and deposition characteristics including deposition rate and MP distribution were measured [15]. It was shown that in the HRAVA, an almost MP-free film (few MPs per mm^2) with

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high deposition rates (0.5 μm/min) may be achieved using an arc current of 200 A and a substrate–electrode distance of 110 mm. The plasma flux radially expanding from the interelectrode gap may deposit film over a large substrate area placed circumferentially around the electrode axis. An HRAVA interelectrode plasma with a graphite anode was analyzed spectroscopically [16]. The spectral lines of Cu I, Cu II and Cu III were observed in the interelectrode space while the spectral line of the anode material was not found. However important technological information for compound film deposition was not yet obtained for the HRAVA, including the angular distribution of the depositing flux, the influence of background gas pressure on the deposition characteristics, and the elemental composition of the deposited coating.

The objectives of this study were to measure the angular distribution of the deposition around the electrode axis, to determine the dependence of film thickness on pressure with different background gases, and to determine the coating composition in the HRAVA.

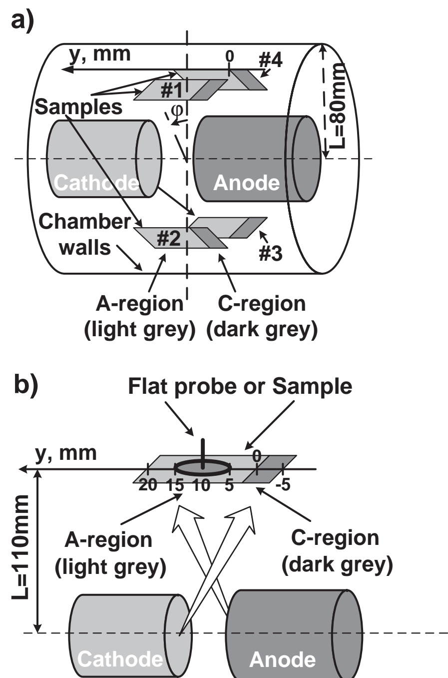

Fig. 2. Schematic diagram showing the placement of substrates and a flat probe in the chamber (a—type 1 substrate locations, b—type 2 substrates or flat probe location).

2. Experimental details

2.1. Experimental apparatus

Experiments were conducted in a cylindrical vacuum chamber (400 mm length, 160 mm diameter), as shown schematically in Fig. 1. The chamber was pumped by a diffusion pump to 2×10^{-5} Torr (2.66×10^{-3} Pa). The arc was ignited between two cylindrical co-axial electrodes: a water-cooled copper cathode (30 mm diameter) and an Mo anode (diameter 32 mm and length 30 mm). The electrodes were surrounded by shields as shown in Fig. 1: the cathode by a boron nitride shield with diameter 50 mm, and the anode by two cylindrical Mo radiation shields with diameters 60 and 70 mm. The distance between the electrodes was about 10 mm and the arc current was $I=200$ A.

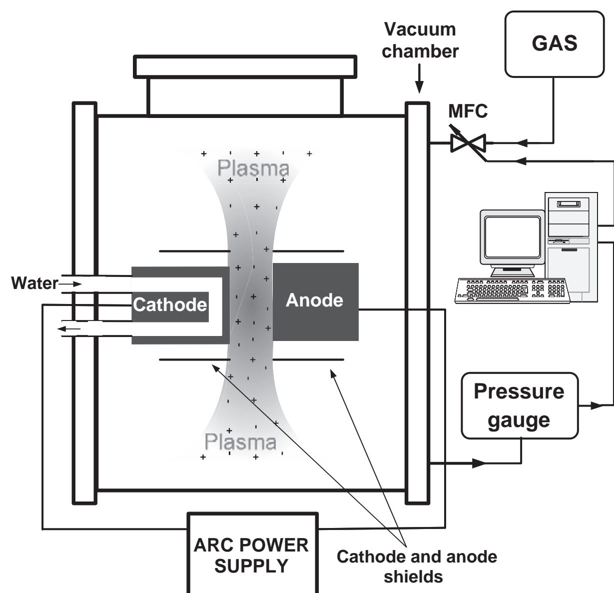

Fig. 1. Schematic diagram of the HRAVA experimental setup, plasma expansion and pressure control system.

2.2. Pressure control

Arcs were conducted in the nitrogen, helium and argon atmospheres. The pressure was measured by thermocouple and ionization gauges which were previously calibrated against a baratron gauge for each gas. A closed-loop control system using an electrically controlled mass flow controller (MFC), a digital-analog converter input card for a personal computer (PC) and pressure gauges was used to control the pressure in the chamber (see Fig. 1). After arc ignition, the pressure could be set in the range from about 10^{-4} Torr (1.3×10^{-2} Pa) (MFC completely closed) to about 1 Torr (133 Pa) (MFC completely opened).

2.3. Substrate preparation and mounting

Glass substrates were pre-cleaned using a detergent and dried with compressed air. Two types of substrate configurations were used: (1) an array of four microscope slides (25×75 mm^2) were placed on the inside wall of the chamber (distance from the electrode axis $L=80$ mm) along the y-axis ($y=0$ was chosen at the edge between the A- and C-regions [12,15]) at azimuthal angles φ of $\pm\pi/4$ and $\pm3\pi/4$ as shown in Fig. 2a, and were deposited during $t_{dep}=15$, 30, 45, 60, 90, 120, 150 s after arc initiation in vacuum. In this

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