Generation of vapor and concomitant plasma production in an electron-beam evaporator

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Abstract. Electron beam heating is a technique to generate vapor of refractory and high melting point metals. Vapor production finds application in thin film deposition and laser-based purification of materials. A strip electron-gun whose filament is heated by AC current is generally used because of larger molten pool formation and quiet evaporation. Electron-gun thus generates vapor. The incident beam of electrons is backscattered with large angular distribution. Both the electron groups, namely the primary and the backscattered electrons participate in production of plasma by electron-impact ionization. The plasma is weakly ionized (~ 0.1% degree of ionization) with ion density ~ 10^8 cm^-3 and has low electron temperature (~ 0.3 eV). The vapor and the simultaneously produced plasma expand in the space above the target. Plasma expands by ambipolar diffusion in a transverse magnetic field while the vapor expands as a collision-less atomic beam. In this paper we study vapor and plasma formation of copper and zirconium. Details shall be discussed.

1. Introduction

The technique of electron beam (e-beam) heating has become a favored method of atomic beam generation of refractory and high melting point materials [1, 2]. This finds application in laser-atom interaction studies of refractory materials such as charge-transfer collision experiments [3], production of isotopically pure elements [4], purification of alloy [5] etc. In such investigations, high-energy electrons from continuous electron gun (e-gun) impinge on a metal target. This creates a molten pool which becomes the source of evaporating atoms / atomic beam. By shining lasers on the atomic beam at a distance away from the evaporating target, the atoms are ionized. A photoplasma [6] is produced at the laser-atom interaction region, which becomes the focus of investigation. Weakly ionized, low-temperature plasma gets formed in the atomic beam near the target due to the presence of continuous e-beam. This plasma, sometimes called background plasma, expands with the atomic beam and interferes with the process parameters of the photoplasma experiments. There is a need to efficiently remove or deflect out the background plasma from the atomic beam so that the experiments become free from such interferences. It is therefore essential to understand the characteristics and dynamics of vapor and the concomitant plasma produced by continuous e-beam.

Formations of vapor and plasma generation are inherent characteristics of e-beam melting. This paper discusses few aspects of the studies carried out in our laboratory with copper (Cu) and zirconium (Zr) with e-gun. Techniques to characterize the vapor and plasma are mentioned. Typical
numbers are provided. The mechanisms of vapor and plasma formation and propagation are highlighted.

2. Experimental details

The experimental system consisted of an e-beam evaporator having a strip-type e-gun (rating: 50 kV, 2 A). It had segmented hot tantalum cathode that produced a thin sheet of electrons by thermionic emission. The electron trajectories were bent by 270° by a pair of magnetic coils in Helmholtz configuration that produced ~ 50 G magnetic field along the direction of the length of the chamber. This configuration was adopted to protect the anode-cathode space of e-gun from vapor entry causing discharge. It also prevented the back streaming of ions to the filament causing reduction in filament life. The evaporator was a double-walled water-cooled stainless steel cylindrical vacuum chamber (90 cm diameter, 80 cm length) operated typically at 5x10^-5 mbar. The ingots, either copper or zirconium were placed in a water-cooled copper crucible.

The molten pool was photographed with an internal standard and analyzed by image-processing software. Optical filters were used to avoid saturation of the photograph pixel. The dimension of the strip was measured to be of 12 cm length and 0.6 cm width.

The temperature of the evaporating liquid surface was measured by two-color pyrometer (M/s Keller, PZ40) using a periscopic arrangement. The two monitoring wavelengths were 950 nm and 1050 nm. Process generated thin film acted as the mirror. The pyrometer read the average temperature over a 0.6 cm diameter zone focused on the central region of the evaporating source and was kept at a distance of ~ 100 cm from the source.

A water-cooled quartz crystal thickness monitor (QCM) (M/s Sigma SQM-160) was used to measure the atom fluxes. It had a shutter that was controlled electronically. Measurements were carried out for various e-beam powers.

![Fig. 1. Schematic setup (length view) of the electron beam evaporator along with diagnostics.](image)

Velocity of the atomic beam was measured by a microbalance (M/s Setaram, model B-24). It was placed at the same height as that of the thickness monitor. Its mass resolution was 0.03 microgram. Appropriate precautions were taken to protect it from unwanted vapor.
For plasma diagnostics disk Langmuir probe was used. It was made of molybdenum (1 cm in radius) and was 0.2 cm thick. It had alumina insulation at the back so that down-streaming ions were not collected on it. Figure 1 shows the schematic of the experimental chamber along with the diagnostics.

3. Results and discussions

When high-energy (~45 kV) electrons from the e-gun impinge the target, they transfer concentrated heat flux. As a result the target melts and becomes the source of evaporating atoms. Photographs of melt pools of Cu and Zr are shown in Fig. 2. For Cu, the highest temperature measured was ~1950 K (at ~90 kW e-beam power) whereas the corresponding value for Zr was 3250 K at 100 kW. The temperature of the evaporating area depends on the incident power density of the e-gun and thermo-physical properties of the target material.

![Copper melt pool](image1)

![Zirconium melt pool](image2)

Fig. 2 Photographs of melt pools of Cu and Zr

Figure 3 shows the measured deposition rate as a function of e-beam power for Zr at a height of ~40 cm from the crucible. Typically, deposition rates vary in the range of tens of angstrom. But for Cu they are hundreds of angstrom. The measured velocities of Cu and Zr are similar, ~1x10^5 cm/s. The derived atom densities from the deposition rate are ~1x10^{13} cm^{-3} and ~1x10^{11} cm^{-3} for Cu and Zr respectively. Such wide difference (two orders of magnitude) in the atom densities is due to the difference in vapor pressure of the two metals. The vapor undergoes expansion in the evaporator. Near the target the atom-atom mean free path is smaller than the dimension of the vapor source. So the atoms collide among themselves and undergo adiabatic free expansion. For a point source, the spatial distribution of atoms follows \(r^{-2}\) dependence, where \(r\) is vertical distance (height) from the evaporating source. For an infinite linear source, the atoms follow \(r^{-1}\) dependence. So the atom distribution for a finite linear source (our case) will range between \(r^{-1}\) to \(r^{-2}\).

The expanding vapor intercepts electron flux and gets ionized. Typically measured plasma (ion) densities of Cu and Zr at a height of ~40 cm are ~1x10^9 cm^{-3} and 1x10^8 cm^{-3} respectively. The plasma formation mechanism can occur by two processes: electron-impact ionization of neutral atoms of the beam and thermal ionization. Their relative magnitudes depend upon various parameters like temperature of the evaporating source, e-beam currents, energies and path lengths, ionization cross...
Electron-impact ionization is the predominant process in most cases. The primary electrons (e-beam electrons) and backscattered electrons from the target contribute to ionization and hence in plasma generation. The plasma is weakly ionized and has low electron temperature (~ 0.1 eV).

The plasma co-expands with vapor thereby changing the spatial characteristics of both the vapor and itself. Ambipolar diffusion governs the plasma motion. The plasma potential decreases linearly in the propagation direction away from the source. Electric field, which is the negative gradient of potential, remains constant along the streamline and is directed upwards. As a result the electrons are decelerated while the ions are accelerated and gain drift energy. The plasma density decreases due to volume expansion and ion acceleration from ambipolar diffusion. When there exists a global transverse magnetic field, the Lorentz force creates a spontaneous polarizing electric field within the plasma and as a result cross-field propagation occurs in the vertical direction.

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