Investigation of an Expanding Copper Plasma Across a Transverse Magnetic Field Generated by Strip-type Electron-Beam

A. Majumder, G. K. Sahu, R. A. Patankar, K. B. Thakur and V. K. Mago
Laser and Plasma Technology Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India
e-mail: v_mago@barc.gov.in

Abstract. The electron beam assisted thermal processes are well-established technique for various applications such melting, evaporation, isotope purification, ion-implantation etc. The processes are time average, wherein process is carried out over a larger duration so that real time dependent variations gets averaged out. During electron beam evaporation and atomic beam generation, ions also get generated inherently due to interaction of primary and back-scattered electrons with the atomic vapour along with other routes like Saha ionization, secondary electron ionization etc. The presence of ions has a bearing in the quality of deposited films and influence the ion implantation process. It also has strong effect on dilution factor in isotope purification. Thus the knowledge of ion content, its distribution and evolution in the freely expanding atomic beam in vacuum is important for any process optimisation in electron beam evaporation applications. The thermal ion content in atomic vapour for a given element as a function of aspect ratio (height/length) and source Knudsen number can be used as most inexpensive technique to characterized the evaporation on time average as well as real time processes. With this intension, a series of experiments were carried out in a 100 kW strip beam evaporator with 130mm strip electron gun with copper as target material. A wedge shaped copper atomic beam is generated from a two dimensional evaporating source (120mm x 6mm) by impingement of the electron beam up to 90kW power. Disk type Langmuir probe is used for measuring I-V characteristic plots for deriving the thermal ion flux. The measurements are carried out as a function source Knudsen number (depends on incident electron beam power), and the probe distance from source that defines the aspect ratio. Along with probe data, the atom flux is also simultaneously measured using quartz crystal thickness monitor. The evolution of ions and atoms with distance from source is compared.

1. Introduction
Electron beam evaporators are widely being used in the thin film industry. Over the years they have become a favored method of atomic beam generation to efficiently vaporize refractory and high melting point materials. In applications of electron beam assisted evaporation like purification of materials by laser-atom interaction [1], the flow properties play an important role. When high-energy electrons from electron gun impinge on the metal surface, a melt pool is created which becomes the
source of evaporating atoms [2]. Together with this a weakly ionized low-temperature plasma [3] gets formed which remains embedded in the beam. The plasma formation mechanism [4] can occur by two processes: electron impact ionization of neutral atoms of the beam and Saha (thermal) ionization. Their relative magnitudes depend upon various parameters like temperature of the evaporating source, electron beam currents and energies, cross section / probability of processes, path length of electron beam etc. An inventory of processes is responsible for the production of electrons that take part in electron impact ionization. They are the primary beam electrons, backscattered electrons, secondary electron emission from the target, thermonic emission, photoelectron emitted by X-ray and Auger electrons. The plasma cloud formed very near the evaporating surface expands adiabatically with the atomic beam. Evolution of the plasma and neutral atoms may follow different dynamics. The plasma evolves in a weak magnetic field (~ 40 G-50 G) that is present over the entire vacuum chamber to bend the electrons of the electron gun by 270°. When there exist a global transverse magnetic field \( B \), the Lorentz force creates a spontaneous polarizing electric field \( E_p \) within the plasma and as a result a cross-field propagation occurs with \( E_p \times B \) drift [5] in the vertical direction. This drift is in addition to that of the ambipolar drift. So it is very much essential to characterize the plasma and understand its evolution characteristics along with the characteristics of the major neutral component.

This paper characterizes a wedge-shaped copper (Cu) plasma and describes its expansion behavior in a weak (~ 50 G) transverse magnetic field. A high power (100 kW) strip-type electron gun produces rectangular (120 mm x 6 mm) plasma, which remains in the atomic beam and flows vertically with it. Diagnostics like a quartz crystal monitor and a disk-shaped planar Langmuir probe are used to measure atom and ion fluxes respectively. Measurements are carried out for various electron beam powers and distances from the evaporating surface. Investigation is done at a distance far away from the primary electron beam trajectories and at regions with high (~ \( 10^{12} \) cm\(^{-3} \)) atom densities.

2. Experimental methods

The experimental system primarily consists of an electron beam evaporator having a strip-type 270° bend electron gun with diagnostics for plasma and vapor measurements located inside it. The schematic setup is shown in Fig. 1. The evaporator is a double-walled water-cooled cylindrical vacuum chamber operated typically at 5x10^-5 mbar. The copper ingot is placed in a water-cooled copper crucible. The electron gun [6] has segmented hot tantalum cathode that produces a thin sheet of electrons by thermionic emission. It is bend by 270° using a pair of magnetic coils in Helmholtz configuration that produces ~ 50 G uniform magnetic field over the diameter of the chamber and along the direction of its length. By applying -50 kV and varying the current to a maximum of 2 A, the electrons impinge on the Cu target at normal incidence and generate a melt pool of evaporating surface. The temperature of the liquid evaporating surface is measured by two-color pyrometer (M/s Keller) using a periscopic arrangement. The pyrometer reads the average temperature over a 6 mm diameter zone focused on the central region of the two-dimensional melting source and is kept at a distance of approximately 1.2 meter from source.

Two used to measure the ion and atom fluxes respectively. The planar disk and the QCM are placed vertically above the diagnostic tools, a planar disk Langmuir probe and a quartz crystal thickness monitor (QCM) (M/s Sigma) are strip source. They are symmetrically located at a distance of 60 mm with respect to the center, along the length of the source and at the same height. They are mounted on a shaft, which can be moved mechanically in vacuum in the vertical direction. There is a vapor-protecting shutter below these diagnostic tools which can be rotated from outside. The QCM has an additional shutter that is controlled electronically. Measurements are carried out for various electron beam powers (~50 kW – 90 kW) and at different vertical positions (~250 mm – 450 mm). The planar disk, made of Cu is 10 mm in radius and 2 mm thick. It has alumina insulation at the back so that down-streaming ions are not collected on it. The I-V characteristic is recorded electron by varying probe voltage from – 30V to 8V and measuring the probe current. The fluctuations in probe current are taken care by measuring both minimum and maximum value from which the mean current
is calculated. It is observed that the electron beam oscillates at 50 Hz along the length and the evaporating surface temperature fluctuates at ~ 0.1 Hz. This periodically produces dense vapor. The instability caused by this periodic plasma-electron beam interaction makes the plasma inherently noisy. The vapor flux is measured by the QCM. It is assuming that the sticking coefficient of Cu on quartz crystal is unity. Together with the vapor the ions also reach the crystal but its contribution can be neglected since the ions are ~ 0.01 % of the vapor. So it can be assumed that the QCM correctly measures

3. Results and discussions

Figure 2 shows the dependence of the ion current on the disk probe as a function of electron beam current. The probe is biased at –20 volts and kept at a height of 430 mm from the source. The electron gun is kept at -45 kV and its current is varied. It is observed that there exists a threshold electron beam current (~1000 mA) below which ions are not formed. This indicates that the presence of ions is linked with vapor generation. Ionization can occur by electron impact ionization and Saha ionization. For our case it is estimated that Saha ionization has negligible contribution. The ionized Cu gas so formed satisfies the condition for plasma [7].

The Cu plasma together with the Cu atoms (vapor) propagates in the vertical direction in a transverse magnetic field. The dependence of the atom and ion fluxes on distance (height) is shown in Fig. 3 and Fig. 4 respectively. Plots are for various electron beam powers. The flux of either the ions or atoms can be denoted as

\[ \Phi(\theta = 0, r) = C \frac{\Phi_0}{r^n} \]

where \( \Phi_0 \) is the flux at the source location, \( r \) is distance (height) and \( n \) is the exponent. So the slope of log-log plot of the flux and distance gives a measure of the exponent. It is observed that in the range of experimental conditions the vapor and the plasma evolve differently. The vapor has \( r^2 \) dependence while the plasma has \( r^4 \) dependence. The plasma is expected to evolve differently than the vapor because the charge particles (electrons and ions) interact with the internal electric field and the external magnetic field. Because of the higher mobility of the electrons than the ions, some fraction of the electrons leaves the plasma thereby creating a local electric field. This electric filed tries to decelerate the electrons and accelerate the ion whereby the plasma gets an ambipolar velocity. Further, the external magnetic field generates a \( E \times B \) drift velocity to the plasma. So the plasma is expected to have ambipolar and drift velocity whereas the vapor will have a mean thermal velocity.
Fig. 2: Ion current on disk as a function of electron beam current when the disk is biased at -20 Volts. The disk is placed at a height of 43 cm from the evaporating surface.

Fig. 3: Log-Log plot of atom flux as a function of source distance for various incident powers.
Fig. 4: Log-Log plot of ion saturation current as a function of source distance for various incident powers.

4. Conclusions
A Cu plasma is produced by electron impact ionization when a strip-type electron gun (270° bend) evaporates vapor. The plasma together with the vapor moves in the vertical direction in a transverse magnetic field. The plasma has been investigated with planar Langmuir probe while the vapor by thickness monitor. It is observed that the spatial evolution of the vapor and the plasma are different. Further investigations are in progress.

5. Acknowledgement
The authors thank Dr. I. M. Gantayet, Head, Laser & Plasma Technology Division and Dr. A. K. Ray, Director, Beam Technology Development Group, BARC for their constant support and encouragement.
References
[1] Letokhov V. S, Mishin V. I, Puretzky A. A, Prog. Quant. Elect. 5, 139 (1977).
[2] Schiller S, Heisig U and Panzer S, Electron Beam Technology, (J. Wiley, New York, 1982).
[3] Graper E. B, J. Vac. Sci. Technol. 7 282 (1970)
[4] Nishio R, Tuchida K, Tooma M, Suzuki K. J. Appl. Phys. 72 4548 (1992)
[5] Nishio R, Suzuki K, Phys. Fluid B 5 2036 (1993)
[6] Thakur K.B, Sahu G. K, Tamhankar R. V, Patel K, Rev. Sci. Instrum. 72 207 (2001)
[7] Chen F. F, Introduction to plasma physics and controlled fusion, (Springer, 1983)