Langmuir probe characterization of electron beam ablation plasmas

M. Nistor, F. Gherendi, N. B. Mandache

National Institute for Lasers, Plasma and Radiation Physics (NILPRP), Plasma Physics and Nuclear Fusion Laboratory, L22, P.O. Box MG-36, 7712 Magurele-Bucharest, Romania

In this work we present the characterization of the plasma plume produced by ablation of a ZnO target by a pulsed electron beam using a Langmuir ion probe. Probe signals were recorded with temporal resolution at different bias voltages and were used for determining the ions energy by the time of flight method. The Langmuir current-voltage curve was traced and the electron temperature of the ablation plasma (~1.9 eV) and the electron density (5 x 10^{14} cm^{-3}) were determined.

1. Introduction

Transparent conducting oxide thin films are widely studied for thin film transistors due to their excellent optical transmission in visible region, tunability of the electrical properties and chemical stability [1-4]. The huge demand for high resolution and large panel displays leads to the necessity of low-cost applications. Zinc oxide (ZnO) is one of the most studied transparent materials as an alternative to expensive indium tin oxide. In this approach a fine tuning of the electrical and optical properties of oxide films is required for applications. A low cost growth method, the pulsed electron beam deposition (PED), was used in this work for the deposition of ZnO thin films. PED has features in common with pulsed laser deposition (PLD), but uses a pulsed electron beam instead of the laser beam for ablating the target [5-9].

The properties of the oxide thin films were found to be strongly dependent on the gas pressure and gas composition, electron beam parameters, substrate temperature, varying from stoichiometric to largely oxygen deficient films, from epitaxial to amorphous and from highly transparent to absorbing films [10, 11]. For PLD and PED, knowledge about the propagation of the ablation plasma plume is crucial, due to the influence of the kinetic energy and density of the species emitted from the target over the quality of the films (composition, crystalline quality and surface morphology). Langmuir ion probes have been proven as a very useful tool to investigate laser ablation plumes [12, 13]. In this work we report on investigation of a plasma plume produced by pulsed electron beam ablation of a ZnO target using a Langmuir ion probe to estimate the kinetic energies of the species and plasma parameters.

2. Experimental set-up

The PED set-up consists of a pulsed electron beam source in the channel-spark configuration and a vacuum chamber for the thin film growth [7, 9, 10]. An external capacitor (16 nF) charged at -16 kV is discharged between a hollow cathode and a grounded anode (the vacuum chamber), through a capillary tube of 6 mm diameter and 110 mm length. The intense pulsed electron beam generated in the discharge, having 110 ns FWHM pulse width, interacts at 45° angle with a rotating ZnO target, producing an ablation plasma in argon gas at a pressure of 10^{-2} mbar. The repetition rate is 1 Hz and the fluence at the target surface about 2.5 J/cm^2.

In a separate experiment, the electron beam current was measured with a Faraday cup placed instead of the ablation target. The pulsed electron beam is polyenergetic with electron energies in the range 0 - 16 keV [8].

A planar Langmuir probe was placed at 37 mm distance in front of the ZnO target, normal to the ablation plume flow and biased with respect to ground. To record the ion flux, the probe collecting area of 3 mm diameter was reduced by using a screen with 1 mm diameter aperture, placed at 2 mm in the front of the probe. Because the probe was oriented normal to the plasma flow, the aperture also contributed to reduce the ZnO deposition on the probe surface.

Time resolved probe signals were recorded for different positive and negative bias voltages. The current-voltage characteristic of the Langmuir probe was traced from the probe signals by plotting the current values as function of bias voltages at the moment of maximum ion flux.

3. Results and Discussions

In order to establish a relationship between pulsed electron beam parameters and ablation plasma and their influence on thin films properties we performed electrical measurements.

Typical oscillograms of the discharge voltage (U) and beam current are shown in Fig. 1. The electron beam current was measured with (solid line, I_{sb}) and without (dot line, I_b) self-biasing of a Faraday cup, using a 0.3 Ω shunt [7, 8]. The self-biasing was obtained by connecting the Faraday cup to ground through a resistor of 4.6 Ω in series with the shunt.

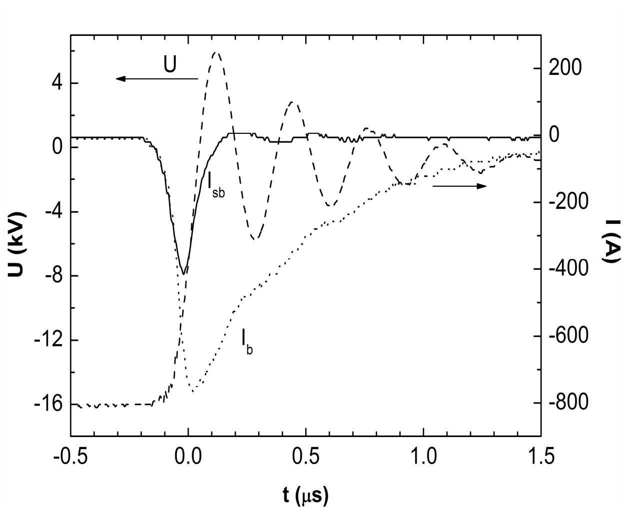

Figure 1 Oscillograms of the discharge voltage (U) and electron beam current with (solid line, I_{sb}) and without (dot line, I_b) self-biasing of the Faraday cup

In the case of self-biasing, the maximum value of the beam current is I_{sb} = 400 A with FWHM = 110 ns (solid line). The corresponding self-biased potential is 1.84 kV, that means that the beam of 400 A is carried by electrons having energies higher than 1.84 keV.

The beam of energetic electrons (I_{sb}), which ablates the target, is generated during the discharge voltage fall which lasts about 210 ns. After this beam phase of the channel spark discharge, the current collected by the Faraday cup without its self-biasing (I_b) is due to thermal electrons from the channel-spark discharge, corresponding to the damped oscillations of the voltage (argon plasma phase). In this case the maximum electron beam current is I_b = 750 A.

This pulsed electron beam generates at the interaction with the ZnO target an ablation plasma, which mediates the transport of the film constituents from the target to substrate, during the PED process. High quality ZnO thin films in terms of composition, crystallinity and surface morphology were grown using these beam parameters [7, 10].

The ZnO ablation plasma produced in argon gas at a pressure of 10^{-2} mbar was investigated by Langmuir ion probe in the same conditions as for the film growth.

Fig. 2 shows the temporal variation of ion current (solid line) recorded with 1 mm aperture in front of the probe biased at -12.5 V for repelling electrons. When the probe is used without screen (dash line) the most of the signal is due to the Ar ions produced in the argon plasma phase of the channel-spark discharge, superimposed on the signal of Zn ions.

The negative peak in Fig. 2 at the beginning of the signal is due to the fast electrons from the pulsed electron beam reflected/scattered on the target, which could not be stopped by the -12.5 V bias. They are synchronized with the high voltage fall (Fig. 1) and reach the probe in a very short time compared to the ion time of flight, representing the time origin for the time of flight method.

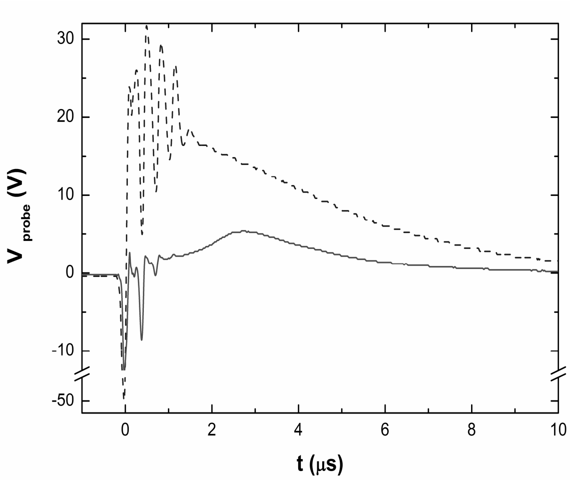

Figure 2 Ion probe signals with aperture (solid line) and without aperture (dash line)

The ion signal rises rapidly and has a maximum at 3 μs, corresponding to a velocity of the Zn ions of 1.23 cm/μs and energy of 52.8 eV. In fact the ion energies are distributed in a relatively broad range, from a few eV to one hundred eV, peaking at 52.8 eV. This distribution allows an enhancement of the adatom mobility at the film surface when ions are arriving on the substrate for growing smooth, dense, congruent and crystalline thin films at relatively low substrate temperatures [7, 9, 10].

These results are consistent with previous meaurements by fast imaging and optical emission spectroscopy, for which the kinetic energies of the species in the plume front varied in the energy range of 10 to 60 eV [14].

The current-voltage characteristic was recorded for the time of maximum ion flux at 3μs (Fig. 3).

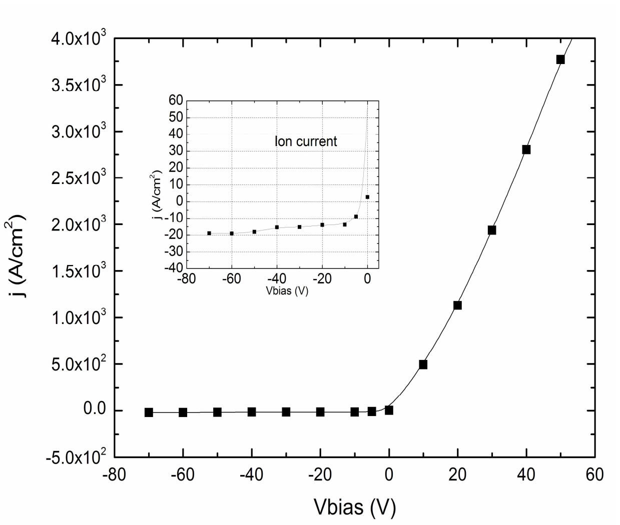

Figure 3 Current-voltage probe characteristic at 3 μs after the beginning of the electron beam; in the inset is shown the ion current density

By linear fitting the logarithm of the probe current density in the vicinity of ion saturation, magnified in the inset of the Fig. 3, we determined the electron temperature from the slope of the linear fit [12]. The electron temperature obtained is about 1.9 eV for a target-probe distance of 37 mm and a electron beam fluence of 2.5 J/cm^2. An electron density of about 5 x 10^{14} cm^{-3} was estimated from the saturation of ion current density (Fig. 3). The temperature and density deduced from these measurements are in agreement with the existing models for the laser ablation plasmas [12, 13].

3. Conclusions

The plasma plume produced by ablation of a ZnO target in PED method was investigated using a Langmuir ion probe. At the moment of maximum ion flux, a velocity of Zn ions of 1.23 cm/μs corresponding to energy of 52.8 eV was measured for an electron beam fluence of 2.5 J/cm^2. The broad distribution of ion energies, from a few eV to one hundred eV, leads to the enhancement of the adatom mobility at the film surface and influences the quality of ZnO thin films grown at relatively low substrate temperatures.

The electron temperature, estimated from the Langmuir probe current-voltage characteristic, was about 1.9 eV and the electron density was about 5 10^{14} cm^{-3}. The knowledge of these parameters is of interest for the growth of high quality ZnO thin films by PED method.

4. References

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