Investigations of a Cavity-Hollow Cathode Sputtering Source for Titanium Thin Films

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Abstract: A cavity-hollow cathode, consisting of two specifically formed disks of Ti with an additional cavity intended for enhancement of the pendulum effect of the electrons, was investigated as a low-cost sputtering source. A discharge in Ar gas was produced inside the hollow cathode. Measurements using Langmuir probes yielded evidence for the formation of a space charge double layer in front of the cathode. The sputtered atoms form negatively charged clusters, which bombard the film substrate. Titanium thin films were produced on highly oriented pyrolytic graphite. Film morphology and elemental composition were investigated by scanning tunnel microscopy (STM) and X-ray photoelectron spectroscopy (XPS).

1. Introduction

Various techniques are used for thin film deposition. Hollow cathodes are among the most simple and inexpensive devices [1,2,3,4] since a high ion density is produced by the electron pendulum effect inside the hollow cylinder. Hence they do not need a magnetic field which makes them particularly useful for sputtering of ferromagnetics. The hollow cathode effect is known since long [5,6,7]). Often an additional cavity is used for further enhancement of the pendulum-like effect of the electrons inside the cathode. Thus, high-density fluxes of energetic Ar ions are produced, which intensively sputter off the material of the inner cathode walls. The sputtered metal/compound particles are transported in the gas flow towards the film substrate in a jet exiting from the muzzle of the hollow cathode. Film quality is enhanced by intense bombardment of energetic species during condensation on the substrate.

As sputtering source the cavity hollow cathode (CHC) configuration was first described in [8,9]. It was used to grow good quality thin films of TiN_xO_y, TiN, Ni and Fe [10,11,12,13]. The configuration was investigated in dc regime and pulsed regime [12]. Inside the plasma jet negatively charged clusters were found [14,15]. Here, we present probe measurements in the CHC plasma during the growth of titanium thin films on **h**ighly **o**riented **p**yrolytic **g**raphite (HOPG). The thin films were investigated by a **s**canning **t**unneling **m**icroscope (STM) and by **X**-ray **p**hotoelectron **s**pectroscopy (XPS).

2. Experimental set-up and results

A detailed description of the CHC used in these experiments is given in [14]. After evacuation, Ar gas is applied in front of the muzzle of the CHC. Typical current-voltage (I_{dis}-V_{dis}) characteristics of the CHC for 0,1 and 0,5 mbar, are shown in Fig. 1; I_{dis} is the discharge current, V_{dis} is the voltage applied to the CHC. The discharge starts as a normal glow discharge (region A). For a certain ignition voltage, the system suddenly jumps into the hollow cathode discharge mode (region B). This regime is characterized by a dramatic increase of I_{dis}. The negative glow is confined inside the cavity and a conical plasma jet exits from the muzzle.

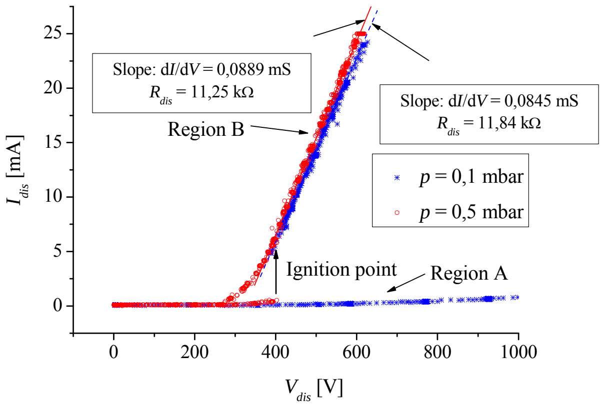

Fig. 1: Current-voltage characteristic of the CHC for two different pressures: Region A: glow discharge regime, Region B the hollow cathode regime.

2.1 Langmuir probe measurements

Electrostatic measurements were performed with a cylindrical tungsten wire probe (diam. 0,125 mm). Fig. 2 shows a typical characteristic of the probe, $I_p(V_p)$, inserted 10 mm above the CHC muzzle on the axis. The characteristic (blue line) shows two bends, one at $V_p = -24{,}5$ V and one at $-1{,}5$ V. The red line shows the first derivative of the smoothed characteristic, the olive line the second derivative. Based on the arguments in [16] and [17] we take the first derivative as the best indication of the electron energy distribution (EED) (here shown on a negative scale).

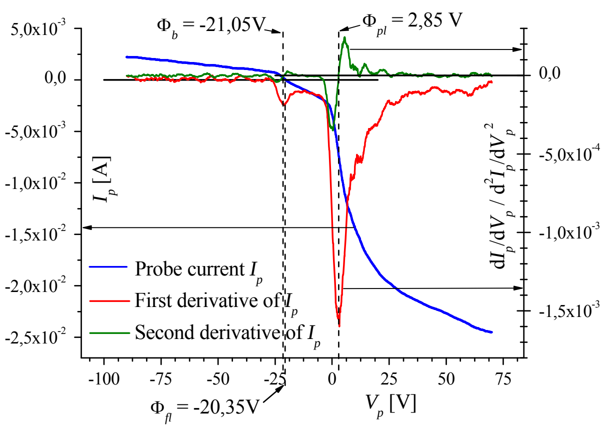

Fig. 2. I_p-V_p characteristic (blue) with its first (red) and second (olive) derivative of the probe for I_{dis} = 20 mA, pressure p = 0,1 mbar 10 mm above cathode on axis. The x-axis for the first (red) and the second (blue) derivative (right y-axis) is shifted slightly above the x-axis for the probe current (left y-axis).

The two maxima yield evidence for two electron populations: a large one with a maximum at Φ_{pl} = 2,85 V and a small one with a maximum at $\Phi_b = -21{,}05$ V. The large peak of the EED has to be interpreted in relation with the bulk plasma, whereas the small peak signifies an additional population of electrons with a mean kinetic energy of $E_b \cong 23{,}9$ eV. This corresponds to the difference between the two peaks in the EED: $\Delta V_p = (\Phi_{pl} - \Phi_b) = E_b/e$. The latter population of the EED can be interpreted as evidence for an electron beam, accelerated by a plasma **d**ouble **l**ayer (DL) [18] with an approximate height of 24 V, situated at the muzzle of the CHC. Consequently, Φ_{pl} is the plasma potential at this position determined by the bulk electrons and ions. The beam electrons lead to additional ionization and help thus to sustain the DL.

A semi-logarithmic plot of the (inverted) I_p-V_p characteristic (the blue line in Fig. 2) shows two distinctly different linear regimes of $\ln|I_p(V_p)|$, which also indicates the presence of two groups of electrons with different energies and densities. The first linear regime occurs between about –25 V and –20 V and yields the electron temperature of the beam electrons as $T_{e\text{-}beam} \cong 3{,}2$ eV. The linear regime of the main electron population is visible between about 0 and +5 V and delivers at first glance an uncorrected temperature of around 3,8 eV. But for a more precise determination of $T_{e\text{-}bulk}$, the current carried by the beam electrons has to be subtracted. After this we can find a corrected value of the bulk electron temperature as $T_{e\text{-}bulk} \cong 1{,}6$ eV. By analogous procedure we derive approximate values for the beam and bulk electron densities as $n_{e\text{-}beam} \cong 1{,}87 \cdot 10^{16}$ m^{-3} and $n_{e\text{-}bulk} \cong 3{,}56 \cdot 10^{17}$ m^{-3}, respectively.

As for the DL, such space charge structures often appear in plasmas with strong electron currents, especially at sudden variations of the diameter of the current channel, there where the current density changes [19]. Thus it seems plausible that also the widening of the channel of the CHC in the muzzle gives rise to the formation of a DL. The plasma potential inside the CHC is supposed to have a value corresponding to the first small peak of the EED, i.e. $\Phi_b \cong -21{,}05$ V approximately.

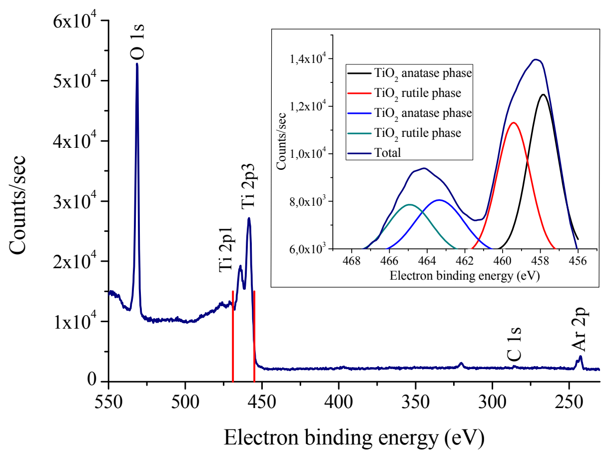

Fig. 3. XPS survey spectrum of a thin film deposited in a CHC discharge with a titanium cathode. A high-resolution XPS spectrum is shown in insert, depicting the Ti 2*p* peak (limited by the two vertical red lines in the survey spectrum).

2.2 Results of Ti thin film sputtering

Fig. 3 shows a typical XPS survey spectrum along with a detailed view of the Ti $2p_{3/2}$ and $2p_{1/2}$ peaks derived from a high-resolution XPS measurement. The deconvolution of the

XPS peaks of the films deposited using Ti electrodes in the CHC sputtering source demonstrated large atomic concentration values of Ti^{4+} ions bonded to oxygen, along with dominant non-reacted titanium Ti^0 atoms. The occurrence of Ti^{4+} ions, associated with the presence of titanium dioxide in the films is related to slight traces of oxygen in the residual vacuum. Due to the large affinity of titanium surface for oxygen [20], significant amounts of TiO_2 are present in the films, both in the case of the development of the rutile phase (under high deposition rate conditions) or anatase phase (developed under low deposition rate of the material on heated substrate). The above-mentioned assertion is further substantiated by the presence of the strong O 1s peak in the XPS spectra. Further details on films morphology and the chemical state analysis upon the deconvolution of the XPS peaks will be discussed in the full-length manuscript.

Acknowledgement

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