New Horizons in Coatings and Thin Films
Room Pacific Salon 6-7 - Session F2-1-ThM
HiPIMS, Pulsed Plasmas and Energetic Deposition I

Moderators: Jon Tomas Gudmundsson, University of Iceland, **Tiberiu Minea**, Université Paris-Sud

8:40am **F2-1-ThM-3 Recent Insights into HiPIMS Physics via Coherent and Incoherent Thomson Scattering**, ***Sedina Tsikata,*** CNRS, ICARE, France*; T Minea,* Université Paris-Sud/CNRS, France*; B Vincent,* CNRS, France*; A Revel,* Université Paris-Sud/CNRS, France **INVITED**

The emergence of the HiPIMS operating regime for planar magnetrons offers new possibilities for the generation of thin films. HiPIMS operation, characterized by high-current, short-duration plasma pulsing, produces high plasma densities which can favor improved mechanical properties of thin films. For HiPIMS plasmas to be fully exploited and for their adoption to become commonplace in industry, it is necessary to understand the basic physical processes associated with this operation.

HiPIMS operation involves complex, transient plasma states and processes which are much more challenging to model than conventional DC operation. Although a consensus has emerged that fully kinetic, three-dimensional models offer the best chance at capturing the physics of this state, such codes are in their infancy and cannot be feasibly applied to large-scale industrial development. A key missing ingredient for such codes remains the knowledge of the particle dynamics and properties.

In this talk, we report on recent new approaches to understanding the HiPIMS plasma using a combination of advanced laser diagnostics. With coherent Thomson scattering, we have recently obtained for the first time information on the nature of microturbulence affecting the confinement of electrons in the planar magnetron magnetic trap [1]. Studies with this experimental technique show that large-scale and small-scale behavior are inextricably linked. With incoherent Thomson scattering [2], we have also obtained time-resolved measurements of electron density and temperature during the evolution of a HiPIMS pulse, establishing the link between these properties and the current characteristics. The implementation of these diagnostics gives access to information on electron dynamics and properties which was previously inaccessible. We discuss the import of these experimental findings in the context of recent numerical models [3], and explain our current understanding of the physics of the HiPIMS state.

[1] S. Tsikata and T. Minea. Phys. Rev. Lett. 114, 185001 (2015)

[2] B. Vincent, S. Tsikata, S. Mazouffre, T. Minea and J. Fils. Plasma Sources Sci. Technol. 27, 055002 (2018)

[3] A. Revel, T. Minea and S. Tsikata. Phys. Plasmas 23, 100701 (2016)

9:20am **F2-1-ThM-5 Process Gas Rarefaction and Other Transport Phenomena in High Power Impulse Magnetron Sputtering Discharges Studied by Particle Simulations**, ***Tomas Kozák,*** University of West Bohemia, Czech Republic

The high power impulse magnetron sputtering (HiPIMS) technique has recently been increasingly used in the coating industry. For tailoring film properties, it is necessary to know and control the energy delivered to the film by process gas and film-forming particles. Computer simulations can help understand the relations between discharge process parameters and fluxes of particles onto the substrate. Due to the complexity of the HiPIMS discharge, it is not feasible to simulate the deposition process self-consistently. Various modelling approaches have been used to give simplified predictions of the HiPIMS plasma parameters.

A fully three-dimensional simulation using the Direct Simulation Monte Carlo (DSMC) method was developed to model the transport of neutral and ion species in a vacuum chamber of realistic size, to improve upon the existing volume-average [1,2] or Monte Carlo [3] models. The time-dependent evolution of gas and target material species densities in the discharge chamber during sputtering pulses as well as the fluxes of particles onto the substrate and their energy distributions were studied under various conditions.

First, the effect of process gas rarefaction by momentum transfer from sputtered target material atoms (Zr, Al and C) was systematically investigated. The effect of target material mass and the target current amplitude is reported. The argon density decreases during the pulse-on time to 50% of its initial value for the current density of sputtered Al atoms of around 0.5 Acm^{-2}. For Zr and C, the minimum argon density is 43% and 57%, respectively. Thus, the dependence on the mass of the target material was found to be rather weak. During the pulse-off time, argon density returns back to equilibrium within 1 ms after the pulse end.

Second, ionization of sputtered target material atoms and the transport of ions in a given electrostatic potential is further investigated. This will help us understand the complex dynamics of HiPIMS discharges and the energies of ions incident onto the substrate observed in diagnostic experiments.

References

[1] M.A. Raadu et al., *Plasma Sources Sci. Technol.***20** (2011) 65007

[2] J.T. Gudmundsson et al., *Plasma Sources Sci. Technol.***25** (2016) 65004

[3] S. Kadlec, *Plasma Process. Polym.* **4** (2007) S419–23

9:40am **F2-1-ThM-6 Insight on the Sputtered Material in HiPIMS by 2D PIC-MCC Modeling**, ***Adrien Revel,*** Université Paris-Sud/CNRS, France*; T Minea,* Université Paris-Sud, Université Paris-Saclay, France

The development of High Power Impulse Magnetron Sputtering (HiPIMS) since the early 2000 has boosted the research much beyond the Conventional Magnetron Sputtering (CMS), worldwide used in industries. In HiPIMS regime, the quantity of sputtered material from the target is greatly improved during the on time compared to the DC regime. Combined with the higher plasma density, the fraction of the sputtered material being ionized is considerably increased reaching a value between 10% and 80% depending on the discharge parameters and target characteristics. An important part of these ionized particles come back to target leading to the self-sputtering effect.

Beyond this, the plasma behavior in magnetron discharge involves complex phenomena such as ExB gradient, curvature and drift coupled with kinetic reactions and plasma-surface interactions. Hence, the motion of individual particles and the whole plasma is subject to intricate phenomena difficult to apprehend and not completely understood yet. The presence of important quantities of sputtered particles complicate even more the study of magnetron plasma, especially when focusing on their spatial distribution and evolution and not only on the global balance of plasma species.

Over the past few years, the OHiPIC model (Orsay High density Particle-in-Cell) has been developed at the LPGP (Laboratoire de Physique des Gaz et des Plasmas) for the modeling of magnetron plasma. OHiPIC code has been used in DC and in HiPIMS regime. It now takes into account the sputtered particles and their ionization. The results provided by OHiPIC are insightful and give a better understanding of the process involved in magnetron discharges. The OHiPIC and its latest improvements will be presented. The 2D density map of the different species and their evolution will be presented and discussed.

10:00am **F2-1-ThM-7 Spoke Formation in Large Scale Rectangular Magnetrons**, ***Arutiun P. Ehiasarian,*** Sheffield Hallam University, UK

Rectangular magnetron cathodes are widely used in the sputter deposition industry, however spokes have been studied mainly in the circular target geometry. The variation in magnetic field strength between the corners and straight sections of the cathode as well as the smaller spoke-to-cathode size ratio influence the motion and formation of the spokes. Fast camera imaging was used to study High Power Impulse Magnetron Sputtering (HIPIMS) discharges on 200×600 mm cathodes in a Hauzer HTC 1000/4 system. Spokes were observed at peak current densities as low as 0.6 Acm^{-2}. Spoke number (mode) was found to decrease and the velocity increase with magnetic field. Spokes were triangular for strong fields and diffusive for weaker fields for the same peak current of 1 Acm^{-2}. The splitting of spokes due to acceleration of a portion was observed. At low pressure the spoke shape was a diffuse triangle which widened and advanced in the **E**×**B** direction. The spokes turned diffusive at the corners and narrow sections of the magnetron and reformed upon re-entry into the straight sections. The shape of the spokes is generally triangular due to the sequential processes of build-up of ionisation to a critical value, rupture of the field and restoration of confinement. In strong confinement fields these processes are faster and produce triangular spokes. In weaker fields the triangle is stretched out resulting in larger volumes of escaping plasma. The behaviour of spokes in the corners is discussed in terms of electron dynamics and the weaker magnetic fields. At low pressures the spokes may be dominated by metal sputtering and ionisation which are initiated in the centre of the racetrack and spread across.

It is argued that spoke formation could be linked to the ratio of plasma density and magnetic field (beta, β).Spokes are associated with localised rupture in confinement and ejection of intense particle beams. Thus spokes are a route for the escape of plasma from the confinement field which leads to a greater degree of freedom, greater number of accessible states and greater entropy. It is suggested that the increase in entropy is the driving force for the creation of zones of intense ionisation which leads to high plasma pressure and localised rupture of the confinement field.

10:20am **F2-1-ThM-8 The Use of Bipolar-HiPIMS for the Design of Ion Energies in Thin Film Growth***, **Ulf Helmersson,** J Keraudy, R Viloan,* Linköping University, Sweden*; N Brenning, M Raadu,* KTH Royal Institute of Technology, Sweden*; D Lundin,* Université Paris-Sud, Université Paris-Saclay, France*; I Petrov,* University of Illinois, USA, Linköping University, Sweden, USA*; J Greene,* University of Illinois, USA, Linköping University, Sweden, National Taiwan Univ. Science & Technology, Taiwan*; J Gudmundsson,* University of Iceland, Iceland

The effect of a positive pulse following a high-power impulse magnetron sputtering (HiPIMS) pulse are studied using energy- and time-resolved mass spectrometry. This includes exploring the influence of a 200 µs long positive voltage pulse (U_{rev} = 10-150 V) following a typical HiPIMS pulse on the ion-energy distribution function (IEDF) of the various ions. We find that, a portion of the Ti^+ flux is affected by gaining energy which corresponds to the acceleration over the full potential U_{rev}. The Ar^+ IEDF on the other hand illustrates that a large fraction of the Ar^+accelerated, gain energy only to a portion of U_{rev}. The Ti^+ IEDFs are consistent with the assumption that practically all the Ti^+ that become accelerated during the reverse pulse come from a region adjacent to the target, in which the potential is uniformly increased with the applied potential U_{rev}, while much of the Ar^+ come from a region further away from the target that contains a boundary with a drop in potential from U_{rev} to a lower potential consistent with the plasma potential achieved without the application of U_{rev}. The deposition rate is only slightly affected and decreases with U_{rev} to ~90% at U_{rev}= 150 V. Both the Ti^+ IEDF and the small deposition rate change indicate that the potential increase in the region close to the target is uniform and essentially free of electric fields, with the consequence that the motion of the ions inside it are not much influenced by the application of U_{rev}. In this situation, Ti^+ will flow towards the outer boundary of the target-adjacent region, due to their momentum achieved during the HiPIMS discharge pulse, independent whether the positive pulse is applied or not. The metal ions that cross the boundary in the direction towards the substrate, and do this during the positive pulse, all gain an energy corresponding to the full positive applied potential U_{rev}.

10:40am **F2-1-ThM-9 Latest Developments in HIPIMS with Positive Pulsing***, **Ivan Fernandez,*** Nano4Energy, Spain*; A Wennberg,* Nano4Energy SL, Spain*; F Papa,* GP Plasma, Spain

Recently, it has been demonstrated for highly ionized discharges that the application of a positive voltage reversal pulse adjacent to the negative sputtering pulse gives rise to the generation of high fluxes of energetic ions. This effect allowed unprecedented benefits for the coating industry, where the key factor is the ability to tailor both the energy and flux of the high fraction of ionized material present in a HiPIMS discharge. Now, this can also be achieved by controlling the amplitude of the positive voltage reversal. A description of this technology as well as the experimental results obtained in different coating systems from a wide variety of industrial sectors (hard metal nitrides, optical coatings, semiconductor trench filling, roll-to-roll applications…) will be presented in this paper.

11:00am **F2-1-ThM-10 HIPIMS- Advantages of a Positive Kick Pulse***, **Jason Hrebik,*** Kurt J. Lesker Company, USA

HIPIMS is an ionized PVD technique that produces a high density, high performance films. The extreme power densities in HIPIMS create a higher ionized plasma that creates a very high energy of material being deposited onto the substrate.

A key feature to the maturing HIPIMS technology is the ability to apply a positive kick pulse. Having a full range of control over this kick pulse is key in the ability to dial out stress, build thicker deposition layers, increase rate, and tune for specific film morphology and or crystallinity and microstructures. This presentation will share examples of applications and performance data to support the many advantages of the IMPULSE power supply. The available configurations and examples of ideal operating parameters will be shared.

11:20am **F2-1-ThM-11 Plasma Parameter Determination in a HiPIMS Discharge Using Laser Thomson Scattering***, P Ryan, **James Bradley**, M Bowden,* University of Liverpool, UK

The temporal evolution of the electron density and temperature in a HiPIMS discharge has been measured using laser Thomson scattering and Langmuir probing as comparative techniques. Measurements were performed (non-simultaneously) at two positions within the plasma; in the low magnetic field region on the discharge centreline and in the high magnetic field region of the magnetic trap above the racetrack, for peak power densities of 450 Wcm^{-2} and 900 Wcm^{-2} respectively. The maximum plasma densities and temperatures were found to be 6.9×10^{19} m^{-3} and 3.7 eV in the pulse-on time, decaying to values of 4.5×10^{17} m^{-3} and 0.1 eV some 300 µs into the afterglow. The results indicate that although intrusive, the Langmuir probe can provide a good indication of electron properties in regions of different electron magnetization in the HiPIMS discharge.

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