## Plasma and Vapor Deposition Processes
## Room Town & Country B - Session PP2-2-WeA

## HiPIMS, Pulsed Plasmas, and Energetic Deposition II

**Moderators: Arutiun P. Ehiasarian**, Sheffield Hallam University, UK, **Tetsushide Shimizu**, Tokyo Metropolitan University, Japan

2:00pm **PP2-2-WeA-1 Understanding the Hyper-Power Impulse Magnetron Discharge and related Arc Transition**, ***Tiberiu Minea [tiberiu.minea@universite-paris-saclay.fr]***, *Erwan Morel, Zakaria Belkaid, Adrien Revel,* University of Paris-Saclay, France **INVITED**

High-power impulse Magnetron Sputtering (HiPIMS) has already proven its advantages over conventional magnetron discharge. Using refractory metals or graphite as target materials paved the way for much higher current densities in HiPIMS exceeding 10 A $cm^{-2}$ [1]. In addition, replacing the argon with helium leads to even higher currents, despite the discharge transition from glow to arc, under certain conditions.

The experimental findings suggested the crucial role played by self-sputtering at high voltage (~1 kV) and gas recycling at a lower pulse voltage [2]. Recent global modeling proved this scenario and unveiled microscopic information on the He/Mo HiPIMS discharge [3]. A cross-correlation with a high-speed gated camera and optical emission spectroscopy measurements revealed the plasma evolution [2]. The electron density is highly dependent on the presence of metal vapor in the plasma.

Gas preionization (low DC current) significantly improves the current rise to 1 kA when a high voltage pulse is applied, even for long pulses of 1,000 µs. Five times more power can be transferred into the plasma compared to the HiPIMS without preionization. Consequently, this operation mode has been referred to as the Hyper-Power Impulse Magnetron (HyPIM) [4]. The metastable gas states effectively sustain this high-density plasma in glow mode [5].

The glow-to-arc transition is known to be triggered by very high current densities impinging on the target or high plasma densities. Both are present in the new HyPIM discharge. The early stage of cathodic spot formation, observed as bright dots, can preserve the glow mode or turn into a hot spot. The energy of cohesion and sublimation of the target material certainly play a key role in the transition to arc [6].

Finally, the co-existence of an arc with a diffusive glow discharge, initiated by a HiPIMS pulse, shows a hybrid glow-arc regime with interesting properties. [7]

[1] E. Morel et al., PSST 30 (2021) 125001; https://doi.org/10.1088/1361-6595/ac3341

[2] E. Morel et al., J. Appl. Phys. 133 (2023) 153301; https://doi.org/10.1063/5.0145547

[3] Z. Belkaid et al., *in preparation*

[4] E. Morel, T. Minea, Y. Rozier, Euro. Phys. Lett. (EPL) 138 (2022) 24001; https://doi.org/10.1209/0295-5075/ac2e2b

[5] A. El Farsy, E. Morel, T. Minea, Y. Rozier, PSST - Letter to Editor –31 (2022) 12LT01; https://doi.org/10.1088/1361-6595/acacc4

[6] E. Morel, Y. Rozier, T. Minea Appl. Phys. Lett. 170 (2024) 204103 – https://doi.org/10.1063/5.0238958; DOI: 10.1063/5.0238958

[7] E. Morel, Y. Rozier, T. Minea, Phys. of Plasmas – 2025 – *under revision*

2:40pm **PP2-2-WeA-3 Plasma Characteristics, Microstructure, and Mechanical Properties of Tetrahedral Amorphous Carbon Thin Films Deposited by Time-Resolved High-Power Impulse Magnetron Sputtering with Synchronized Bias Control**, ***Fu-Sen Yang [D11103004@mail.ntust.edu.tw]***, *Yu-Lin Kuo,* National Taiwan University of Science and Technology, Taiwan*; Chi-Lung Chang,* Ming Chi University of Technology, Taiwan, Republic of China

Time-resolved ionization analysis of graphite plasma discharges was conducted using optical emission spectroscopy (OES) and plasma mass spectrometry (PSM) during high-power impulse magnetron sputtering (HiPIMS). During the pulse-on period, the generation sequence of argon and carbon ions is synchronized with the HiPIMS target power supply through the bias control system. The timing of the bias output is then regulated to adjust the incident flux and kinetic energy of these ions, thereby enabling the deposition of a tetrahedral amorphous carbon (ta-C) thin film. The effects on plasma characteristics, microstructure, chemical composition, and mechanical properties were studied. Plasma characteristics were analyzed using time-resolved OES and PSM on a graphite target.Time-resolved analysis revealed that argon ions were generated first, followed by carbon ions. By setting synchronization (Syn.) and delay times (TD = 0, 25, 50, 75, 100, 125, and 150 µs) at the bias trigger, the attraction and arrival sequence of argon and carbon ions at the substrate were controlled, thereby regulating the incident ion flux and energy to facilitate the deposition of the tetrahedral amorphous carbon (ta-C) thin film. The thin film analysis results indicate that all ta-C thin films deposited under different trigger synchronization and delay times exhibit an amorphous structure. However, transmission electron microscopy (TEM) analysis reveals that the crystallinity of carbon nanocrystals improves progressively with increasing delay time. The density of the ta-C thin film was determined using X-ray reflectivity (XRR) analysis, and the results showed that the thin film reached a maximum density of 2.95 g/$cm^3$ at a trigger delay time of 125 µs. The chemical and mechanical analyses revealed that in the synchronous mode, the maximum compressive stress reached -5.6 GPa, the $I_D/I_G$ ratio was 0.52 at a trigger delay time of 125 µs, the $sp^3$ content was 70%, the hardness reached 48 GPa, and the Young's modulus was 263 GPa. This is primarily because a longer trigger delay time allows more carbon ions to be attracted for bombardment while reducing argon ion bombardment, thereby preventing the conversion of $sp^3$ to $sp^2$ bonds caused by thermal effects.

3:00pm **PP2-2-WeA-4 Carbon Discharge Dynamics by Pulse Sequencing: Pulse Parameter Control in Multipulse Hipims**, *Ryo Sakamoto,* ***Tetsuhide Shimizu [simizu-tetuhide@tmu.ac.jp]***, Tokyo Metropolitan University, Japan

Amorphous carbon (a-C) thin films exhibit excellent mechanical properties. However, a-C films formed by sputtering often show reduced density and hardness due to the low ionization rate of carbon species. The High-Power Impulse Magnetron Sputtering (HiPIMS) technique employs high-density plasma generated by applying short, high-power pulses to the target. A major issue in HiPIMS, however, is ion back-attraction, in which ionized sputtered species are drawn back toward the target by the applied voltage. To address this issue, the multipulse HiPIMS approach applies a train of ultra-short pulses to enhance discharge efficiency through pre-ionization and suppress ion back-attraction, thereby promoting the transport of carbon ions toward the substrate. In this study, the effects of pulse parameters, specifically pulse width and pulse interval on HiPIMS carbon discharge were investigated using energy-resolving time-of-flight mass spectrometry (ETOFMS) during multipulse HiPIMS discharges of a graphite target in an argon atmosphere. The discharge conditions included varying the pulse width to 20, 30, and 50 µs, and the pulse interval to 10, 20, and 50 µs, with the number of sequential pulses fixed at five. Under these conditions, ion energy distribution functions (IEDFs) were measured for $Ar^+$, $Ar^{2+}$, $C^+$, and $C^{2+}$ ions in both time-averaged and time-resolved modes. As results, a high-energy tail was observed in the $C^+$ion energy distribution at shorter pulse width ($t_{on}$), while both $C^+$ and $Ar^+$ion fluxes increased with a higher number of pulses at longer $t_{on}$. In contrast, shortening the pulse-off time ($t_{off}$) led to a significant increase in the ion energy of $C^+$ ions. Furthermore, time-resolved measurements revealed that the $C^+$ ion intensity continued to increase with the number of pulses when $t_{off}$ was reduced to 10 µs, indicating enhanced pre-ionization in after-glow plasma by short pulse interval.

3:20pm **PP2-2-WeA-5 Understanding the Impact of Kinetic and Potential Ion Energies on Thin Film Structure Toward Low-Temperature Deposition**, *Dmitry Kalanov, Andre Anders,* ***Yeliz Unutulmazsoy [yeliz.unutulmazsoy@iom-leipzig.de]***, Leibniz Inst. of Surface Eng. (IOM), Germany **INVITED**

Over recent years, we have investigated how energetic thin film deposition techniques can reduce conventional substrate temperature requirements, focusing on pulsed filtered cathodic arc deposition. Our work investigates the effect of ion potential energy on thin film structure. The main research questions are: How can the influence of ion kinetic energy, ion potential energy, and ion flux on film structure be studied while decoupling these parameters as much as possible? What is the isolated effect of ion potential energy?

Decoupling these effects is challenging because ion kinetic and potential energies are inherently coupled in cathodic arc plasmas. We applied an external magnetic field to preserve multiply charged ions and conducted comparative studies. The results demonstrate that an increased fraction of multiply charged ions enables the formation of crystalline films without conventional substrate heating. Crystalline, dense, and macroparticle-free metallic (V-Al) and ternary nitride (V-Al-N) films were successfully

deposited at room temperature, facilitated by the ion potential energy provided by multiply charged ions[1,2], due to a mechanism known as *"atomic-scale heating."*

These insights could help to reduce or partially replace conventional substrate heating in various energetic deposition processes, lowering energy consumption and enabling thin film deposition on temperature-sensitive substrates. This approach can be critical for sustainable surface engineering across various materials systems.

[1] Y. Unutulmazsoy, D. Kalanov, K. Oh, S. Karimi Aghda, J. W. Gerlach, N. Braun, F. Munnik, A. Lotnyk, J.M. Schneider, A. Anders, **2023**, *J. Vac. Sci. Technol.* A 41, 063106, https://doi.org/10.1116/6.0002927

[2] D. Kalanov, S. Mandazhiev, J. Franze, A. Anders, Y. Unutulmazsoy, **2025,** Surf. Coat. Technol. 497 131720, https://doi.org/10.1016/j.surfcoat.2024.131720

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