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Editorial

Advances and Challenges in Pulsed Laser Deposition for Complex Material Applications

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Various physical vapor deposition (PVD) techniques, such as molecular beam epitaxy, electron beam physical vapor deposition, pulsed laser deposition (PLD), arc discharge, magnetron sputtering and/or ion beam sputtering, are currently used for coating or growing thin films on solid substrates. Although the first time a PLD technique was mentioned was in 1965 [1], major breakthrough only began being reported in 1987, when Dijkkamp et al. [2] used this method to grow $YBa_2Cu_3O_{7x}$ thin films. Since then, huge interest and developments in the use of this unique PVD process have been evidenced [3–5].

One should note that the PLD process is based on the capability of laser radiation, usually in the ultraviolet range, to efficiently interact with solid-state or liquid targets, resulting in the congruent ablation of materials from the target surface and subsequent deposition on a substrate. Depending on the laser characteristics and target material properties, their interaction generates an intense nano/microscopic process, which, consequently, leads to instantaneous localized heating (in the order of tens of thousands of degrees Celsius [6]) and the vaporization of material.

Over the years, PLD has emerged as a relatively simple, highly versatile, and powerful method to fabricate either nanoparticles or high-quality thin films [7,8], both in single and variable compositions. In this respect, PLD became a noteworthy approach to fabricate either simple metals, ceramics, glasses, and polymer films or complex oxides, and even biological materials [9,10], to achieve peculiar or hardly to approach by other techniques functionalities in engineering, chemistry, biology, and medicine. In respect to other PVD techniques, this is mainly due to the fact that PLD exhibits some unique features, including (i) the ability to stoichiometrically transfer a target material to the substrate (even for very complex materials), (ii) versatility (the high-intensity, focused pulsed laser can ionize a majority of materials to obtain either simple or multielement complex compounds, multilayers, nanoparticles, and nanostructures), (iii) accurate control over the growth rate and flexibility in the use of experimental parameters (i.e., ambient gas nature and pressure, gas flow rate, substrate temperature, laser incident intensity, number of applied pulses, frequency repetition rate, pulse duration, and the wavelength, but also the substrate-to-target separation distance, target composition and structure, and power density), (iv) the ability to deposit multicomponent layers, (v) an unlimited degree of freedom in the geometry of the experimental set-up, and (vi) its clean and safe nature (due to the use of light).

In recent decades, sustained efforts have been carried out to modify and adapt the geometrical configuration of PLD experimental set-ups with the aim of improving the overall quality of the synthesized nanoparticles and thin films. In this respect, one should mention (i) scanning multicomponent pulsed laser deposition [11], (ii) combined PLD and magnetron sputtering [12], (iii) multibeam PLD [13], (iv) off-axis PLD [14], (v) combinatorial PLD [15,16], and (vi) reactive pulsed laser deposition [17–19]. Moreover, the PLD conventional technique was extended after the application of appropriate modifications for the processing of organic materials, ranging from polymers to proteins and even living cells, which were previously reported to be definitively altered after interacting with high-power

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laser radiation. This version of PLD is known as matrix-assisted pulsed laser evaporation (MAPLE) [20–22].

After various developments over more than half a century, PLD has evolved from simply being a pure laboratory-based research approach to an industry-relevant instrument for large-area applications [23,24]. Thus, the nanoparticles produced with PLD can be fabricated on an industrial scale for the generation of energy in optoelectronics, information, and data storage. Thin-film synthesis via PLD is now frequently used to improve the bulk material surface performances, such as structural, morphological, chemical, optical, electrical, and/or mechanical.

The aim of this Special Issue is, therefore, to discuss the recent progress in trends in PLD of both nanoparticles and thin-film applications. The topics of interest are devoted, but not limited to, the use in a range of different technologies, including medical implants, drug delivery, sustainable materials, environmental sensors, light emitters, the protection of cutting and drilling tools, multilayers, magnetic devices, high-temperature and high-current density superconductors, solar cells, energy storage, in situ microstructuring, and catalysts.

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References

1. Smith, H.M.; Turner, A.F. Vacuum deposited thin films using a ruby laser. *Appl. Opt.* **1965**, *4*, 147–148. [CrossRef]
2. Dijkkamp, D.; Venkatesan, T.; Wu, X.D.; Shareen, S.A.; Jiswari, N.; Min-Lee, Y.H.; McLean, W.L.; Croft, M. Preparation of Y-Ba-Cu oxide superconductor thin films using pulsed laser evaporation from high Tc bulk material. *Appl. Phys. Lett.* **1987**, *51*, 619–621. [CrossRef]
3. Eason, R. *Pulsed Laser Deposition of Thin Films: Applications-Led Growth of Functional Materials*, 1st ed.; Wiley & Sons Interscience: Hoboken, NJ, USA, 2007; pp. 1–705.
4. Duta, L. In Vivo Assessment of Synthetic and Biological-Derived Calcium Phosphate-Based Coatings Fabricated by Pulsed Laser Deposition: A Review. *Coatings* **2021**, *11*, 99. [CrossRef]
5. Duta, L.; Neamtu, J.; Melinte, R.P.; Zureigat, O.A.; Popescu-Pelin, G.; Chioibasu, D.; Oktar, F.N.; Popescu, A.C. In Vivo Assessment of Bone Enhancement in the Case of 3D-Printed Implants Functionalized with Lithium-Doped Biological-Derived Hydroxyapatite Coatings: A Preliminary Study on Rabbits. *Coatings* **2020**, *10*, 992. [CrossRef]
6. Habermeier, H.U. Pulsed laser deposition-a versatile technique only for high-temperature superconductor thin-film deposition? *Appl. Surf. Sci.* **1993**, *69*, 204–211. [CrossRef]
7. Mattox, D.M. *A Short History: Film Deposition by Pulsed Laser Deposition (PLD)*; SVC Bulletin Spring; Society of Vacuum Coaters: Albuquerque, NM, USA, 2015; pp. 38–39. Available online: https://www.svc.org/DigitalLibrary/documents/2015_Spring_DMM.pdf (accessed on 31 January 2023).
8. Duta, L.; Popescu, A.C. Current Research in Pulsed Laser Deposition. *Coatings* **2021**, *11*, 274. [CrossRef]
9. Norton, D.P. Pulsed Laser Deposition of Complex Materials: Progress Towards Applications. In *Pulsed Laser Deposition of Thin Films: Applications-Led Growth of Functional Materials*; Eason, R., Ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2007; pp. 3–31.
10. Duta, L.; Popescu, A.C. Current Status on Pulsed Laser Deposition of Coatings from Animal-Origin Calcium Phosphate Sources. *Coatings* **2019**, *9*, 335. [CrossRef]
11. Fischer, D.; de la Fuente, G.F.; Jansen, M. A new pulsed laser deposition technique: Scanning multi-component pulsed laser deposition method. *Rev. Sci. Instrum.* **2012**, *83*, 43901–43908. [CrossRef] [PubMed]
12. Benetti, D.; Nouar, R.; Nechache, R.; Pepin, H.; Sarkissian, A.; Rosei, F.; MacLeod, J.M. Combined magnetron sputtering and pulsed laser deposition of TiO_2 and BFCO thin films. *Sci. Rep.* **2017**, *7*, 2503–2511. [CrossRef] [PubMed]

13. Eason, R.W.; May-Smith, T.C.; Sloyan, K.A.; Gazia, R.; Darby, M.S.B.; Sposito, A.; Parsonage, T.L. Multi-beam pulsed laser deposition for advanced thin-film optical waveguides. *J. Phys. D Appl. Phys.* **2014**, *47*, 034007–034021. [CrossRef]
14. Hinton, M.J.; Yong, J.; Steers, S.; Lemberger, T.R. Comparison of 2-D quantum and thermal critical fluctuations of underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ with ultrathin $YBa_2Cu_3O_{7-\delta}$. *J. Supercond. Nov. Magn.* **2013**, *26*, 2617–2620. [CrossRef]
15. Socol, G.; Galca, A.C.; Luculescu, C.R.; Stanculescu, A.; Socol, M.; Stefan, N.; Axente, E.; Duta, L.; Mihailescu, C.N.; Craciun, V.; et al. Tailoring of optical, compositional and electrical properties of the $In_xZn_{1-x}O$ thin films obtained by combinatorial pulsed laser deposition. *Dig. J. Nanomater. Bios.* **2011**, *6*, 107–115.
16. Wolfman, J.; Negulescu, B.; Ruyter, A.; Niang, N.; Jaber, N. Interface Combinatorial Pulsed Laser Deposition to Enhance Heterostructures Functional Properties. In *Practical Applications of Laser Ablation*, 1st ed.; Yang, D., Ed.; IntechOpen: London, UK, 2020; pp. 3–21.
17. Mihailescu, I.N.; Gyorgy, E.; Teodorescu, V.S.; Steinbrecker, G.; Neamtu, J.; Perrone, A.; Luches, A. Characteristic features of the laser radiation-target interactions during reactive pulsed laser ablation of Si targets in ammonia. *J. Appl. Phy.* **1999**, *86*, 7123–7128. [CrossRef]
18. Fominski, V.; Demin, M.; Nevolin, V.; Fominski, D.; Romanov, R.; Gritskevich, M.; Smirnov, N. Reactive pulsed laser deposition of clustered-type MoS_x (x~ 2, 3, and 4) films and their solid lubricant properties at low temperature. *Nanomaterials* **2020**, *10*, 653. [CrossRef] [PubMed]
19. Popescu, A.C.; Stan, G.E.; Duta, L.; Nita, C.; Popescu, C.; Surdu, V.-A.; Husanu, M.-A.; Bita, B.; Ghisleni, R.; Himcinschi, C.; et al. The Role of Ambient Gas and Pressure on the Structuring of Hard Diamond-Like Carbon Films Synthesized by Pulsed Laser Deposition. *Materials* **2015**, *8*, 3284–3305. [CrossRef]
20. Piqué, A.; McGill, R.A.; Chrisey, D.B.; Leonhardt, D.; Mslna, T.E.; Spargo, B.J.; Callahan, J.H.; Vachet, R.W.; Chung, R.; Bucaro, M.A. Growth of organic thin films by the matrix assisted pulsed laser evaporation (MAPLE) technique. *Thin Solid Films* **1999**, *355–356*, 536–541. [CrossRef]
21. Cristescu, R.; Popescu, C.; Popescu, A.C.; Grigorescu, S.; Duta, L.; Mihailescu, I.N.; Andronie, A.; Stamatin, I.; Ionescu, O.S.; Mihaiescu, D.; et al. Laser processing of polyethylene glycol derivative and block copolymer thin films. *Appl. Surf. Sci.* **2009**, *255*, 5605–5610. [CrossRef]
22. Yang, S.; Zhang, J. Matrix-Assisted Pulsed Laser Evaporation (MAPLE) technique for deposition of hybrid nanostructures. *Front. Nanosci. Nanotechnol.* **2017**, *3*, 1–9. [CrossRef]
23. Dave, H.A.B.; Matthijn, D.; Guus, R. Pulsed laser deposition in Twente: From research tool towards industrial deposition. *J. Phys. D Appl. Phys.* **2014**, *47*, 034006. [CrossRef]
24. Yao, J.D.; Zheng, Z.Q.; Yang, G.W. Production of large-area 2D materials for high-performance photodetectors by pulsed-laser deposition. *Prog. Mater. Sci.* **2019**, *106*, 100573. [CrossRef]