

HABILITATION THESIS REVIEWER'S REPORT

Masaryk University

Applicant

Mgr. Jaroslav Hnilica, Ph.D.

Habilitation thesis

Diagnostics of High-Power Impulse Magnetron Sputtering Discharge

Reviewer

Prof. RNDr. Milan Tichý, DrSc.

Reviewer's home unit, institution

Charles University, Faculty of Mathematics and Physics

Habilitation thesis submitted by Mgr. Jaroslav Hnilica, Ph.D. focuses on the non-invasive spectroscopic diagnosis of the discharge plasma used for magnetron sputtering by the HiPIMS system. The actual text of the habilitation thesis is divided into two parts, called "Spokes in High Power Impulse Magnetron Sputtering" and "Dynamics of sputtered particles in High Power Impulse Magnetron Sputtering". The first part deals with the study of regions of increased ionization above the planar magnetron target, which rotate in the ExB direction, called "spokes". The second part is dedicated to determining the concentration of particles sputtered in the magnetron discharge and their velocities. The "effective branching fractions" method, laser-induced fluorescence and atomic absorption spectroscopy are used for this purpose. Both parts have their own introduction and conclusion. The habilitation thesis is organized as a commentary on already published papers, in which the habilitation candidate participated, and which are attached to the habilitation thesis. In addition to the mentioned two chapters discussing the essence of the work, a general introduction, a list of works discussed in the habilitation thesis and a list of used literature are also included. As an appendix, all already published works are listed, which are commented on in the mentioned two chapters. There is a total of 8 of these publications, they are listed at the beginning of the volume, and each publication is supplemented by a table showing the contribution of the author of the habilitation to, in following order: experimental work, supervision, manuscript writing and choice of research direction. In three of these papers is Dr. Hnilica listed as the first author, these works were published in the period 2015-2020. Four of these publications are discussed in the first of the two chapters mentioned above, 4 in the second. In addition, the habilitation volume is also accompanied by a list of publications in high-impact foreign scientific journals, of which the habilitation candidate is a co-author, but which are not discussed in the habilitation thesis; this list contains 30 publications. Publications at conferences are not listed in the habilitation. The habilitation thesis has a total of 41 pages, including the list of publications, and provides the reader by a more detailed analysis of the given study, research motivation, and also explains the connection between the individual parts of the thesis. It is written in good quality English.

I consider the topic of the work to be up to date. Understanding the physical processes taking place in a magnetron discharge operated in the HiPIMS mode required the choice of appropriate diagnostic methods. The basic method for observing spoke-type instabilities was

a fast camera, with which it was possible to determine the frequency of rotation of these instabilities and their speed. The dependence of these parameters on the experimental conditions and their connection with the parameters of the discharge plasma in the magnetron and with the rate of deposition of layers were also studied. A significant contribution of the work is also the classification of the types of "spokes" and finding the connection of individual types with the properties of the plasma and processes on the surface of the magnetron target. An experiment was carried out in collaboration with the University of Liverpool, which confirmed that the observed changes in the current with the so-called strip probe are caused by the existence of "spokes". With the same workplace, a model was developed that made it possible to reconstruct the configuration of the "spokes" from the measured data. In these measurements, the habilitation candidate demonstrated the ability to construct a suitable experiment, supplement it with an appropriate diagnostics, and interpret the obtained data.

The mentioned abilities of dr. Hnilica is also documented in the second chapter dealing with the development of non-invasive diagnostics for determining the concentration of titanium sputtered particles. By combining the methods of "effective branching fraction" (EBF), laser-induced fluorescence (LIF) and atomic absorption spectroscopy (AAS), it was possible to obtain data suitable for explaining the physical processes taking place in different types of HiPIMS systems (single-pulse HiPIMS and multiple-pulse HiPIMS). For this, a special magnetron anode developed by the author was used, which enabled the observation of "spokes" during deposition. That resulted in the construction of a spatial map of the density of titanium ions and neutral atoms above the magnetron target in the case of a DC magnetron discharge and a HiPIMS magnetron discharge in dependence on the pressure of the working gas (argon). From the obtained data, it is possible to deduce, among other things, to the occurrence of the so-called poisoned magnetron mode and subsequently to avoid it.

The quality of the results of the habilitation work is confirmed in particular by the attached articles in prestigious foreign scientific journals: *Plasma Sources Science and Technology* (3 publications), *Journal of Physics D: Applied Physics* (3 publications), and *Journal of Applied Physics* (2 publications). In my opinion, the basic contribution of the habilitation work is a wide range of diagnostic methods of plasma physics, in which the habilitation candidate gained thorough knowledge. I appreciate that in practically all cases discussed in the habilitation, Mgr. Jaroslav Hnilica, Ph.D. did not limit himself to experimental work, but that he devoted considerable effort to the physical interpretation of the obtained data. The described experimental work required considerable invention, which the habilitation candidate, judging by the results mentioned, undoubtedly demonstrated.

The habilitation is written in good quality English, as well as the attached copies of the publications. The habilitation volume is well graphically processed, the pictures are of high quality and adequately illustrate the explanation in the text. In the Introduction of the thesis and in the introductions of the two main chapters, the conducted research is well placed in the context of current research and applications of low-temperature plasma. In my opinion, the text of the introductory chapters documents the author's didactic experiences. The style of the introductory part of the habilitation thesis is favourable for the reader, as it also contains an explanation of the further used/described physical processes and diagnostic techniques. I did not find any typographical errors.

The presented habilitation thesis summarizes the available resources and new findings from the field of plasma application for magnetron deposition of thin layers of new materials. The

author's scientific erudition is documented by the acceptance of articles he co-authored in foreign peer-reviewed journals. From the content of the habilitation thesis, I can state that the habilitation candidate achieved original results in the field of plasma physics. Practically the entire habilitation thesis has already gone through a peer-review process during the publication of the individual scientific works that are part of it. The number of publications of the habilitation author is adequate for the habilitation procedure.

Habilitation thesis by Mgr. Jaroslav Hnilica, Ph.D. entitled "Diagnostics of High-Power Impulse Magnetron Sputtering Discharge" undoubtedly contributes to the development of the scientific field. In my opinion, it meets the standard requirements for habilitation theses in the field of plasma physics. I propose it to be accepted as a habilitation thesis in frame of the habilitation procedure.

Reviewer's questions for the habilitation thesis defence (number of questions up to the reviewer)

I have the following questions about the thesis, on which the habilitation candidate could take a position during his presentation for the defense of the habilitation thesis:

1. In your thesis, you present the application of the method of effective branching factors on titanium. Can this method also be applied to other elements used in magnetron sputtering such as aluminium, chrome, and the like?
2. Describe the specific advantages and disadvantages of multi-pulse magnetron sputtering using high-power pulses and compare with single-pulse HiPIMS and DC magnetron sputtering.
3. In your work, you show and describe spatially and temporally resolved concentrations of titanium atoms and ions in the ground state in the HiPIMS discharge obtained using laser-induced fluorescence (LIF). In magnetron sputtering, the working gas plays an important role, most often it is argon. What does the spatially resolved concentration of argon atoms and ions look like in a HiPIMS discharge? Have you dealt with this question already or did you find an answer in literature?
4. What direction will you take in the study of ionization zones, the so-called spokes, in magnetron sputtering using high power pulses?
5. In the case of reactive magnetron sputtering using high-power pulses, the literature and your articles are devoted to the study of ionization zones almost exclusively in mixtures of argon and nitrogen. Does that mean that the ionization zones in mixtures of argon and oxygen are not present?

Conclusion

The habilitation thesis entitled "Diagnostics of High Power Impulse Magnetron Sputtering Discharge" by Jaroslav Hnilica **fulfils – does not fulfil** requirements expected of a habilitation thesis in the field of Physics of Plasma.

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