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High Power Impulse Magnetron Sputtering: Current Research and Diagnostic

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Abstract. High Power Impulse Magnetron Sputtering or HiPIMS is a relatively recent sputtering technology used for the physical vapor deposition of thin film coatings based upon magnetron sputtering with a high voltage&current pulsed power source. Interest in the method of high-power impulse sputtering has grown steadily. Therefore, the task of first priority is to study the results of work already available in the scientific world in the field of high-power magnetron sputtering to determine the level of knowledge of this direction, as well as to identify the main trends in the development of new coating methods.This literature review outlines the state of the art in HiPIMS, as well as the foundations for more detail research of physical processes of high-power sputtering. The motivation for this review is to provide a brief summary of the HiPIMS technology, its history, its underlying physical mechanisms and diagnostic.

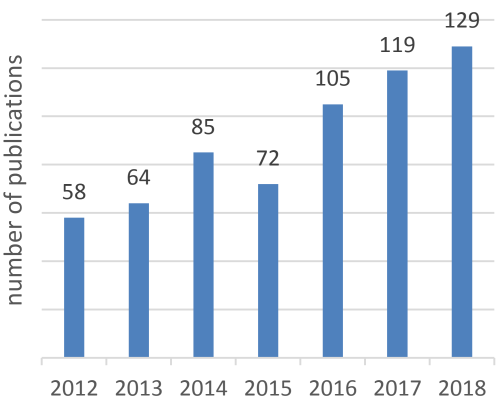
Current state of the problem

Over the past 40 years, the magnetron sputtering method has been subject of many modifications: (i) high-frequency power sources are used to sputter dielectric materials, (ii) pulsed power sources are used instead of direct current, (iii) electromagnetic systems are proposed instead of permanent magnets, (iv) spiral-shaped magnets are suggested to increase the rate of the target operation, (v) the ability to control the temperature of the sputtered target is added, etc.

In the early 2000s, scientific publications on the so-called high-power pulse sputtering (HiPIMS — High Power Impulse Magnetron Sputtering) began to appear in the scientific world. High power impulse magnetron sputtering introduced by Kouznetsov et al. in 1999 [1] is a promising technique for improving magnetron sputtering used in many industrial processes for thin film deposition [2].

In the course of time, interest in the HiPIMS method has grown steadily. Recently, this tendency is easy to see by the number of scientific papers related to this problem.

Figure 1a shows a histogram characterizing the increase in the number of publications over the past seven years; the geographical range of these researches is wide enough [3]. At the forefront, there are such countries as Germany, Great Britain, Sweden, USA, China, France, Czech Republic, Japan. Figure 1b illustrates the ratio of participation of different states in high-power magnetron sputtering. It is worth noting that in



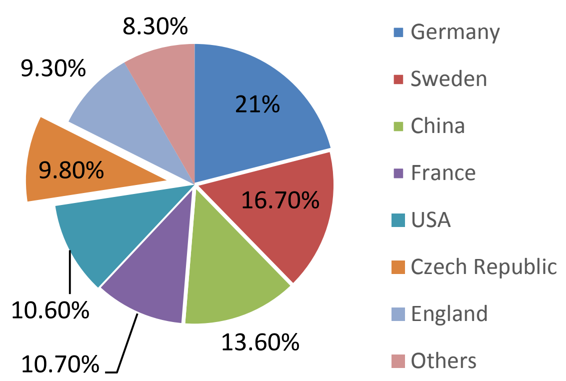


Figure.1. (a) Publications on High Power Impulse Magnetron Sputtering over the past seven years, (b) worldwide number of publications on HiPIMS (others — countries with the number of publications < 50).

a number of European countries (Great Britain, Germany, France) the national research societies and institutes have been created, whose goal is to form a theoretical and practical basis for developing tools for introducing universal and a qualitatively new method of coating for mass use. These societies unite various technological universities, research centers and industrial enterprises. High interest in the application of high-power impulse sputtering appears in the commercial sector. At international conferences and symposia on vacuum and plasma technology, a huge cluster is dedicated to HiPIMS.

HiPIMS parameters

High power impulse magnetron sputtering (HiPIMS) is a plasma-based thin film deposition technique in which extremely high power pulses are applied to a conventional magnetron sputtering system. The high-density discharge plasma is created by applying a high power pulse (1–2.4 MW) with pulse length 100 µs and repetition frequency of 50 Hz [4].

Table 1. Basic working parameters for HiPIMS. From [4].

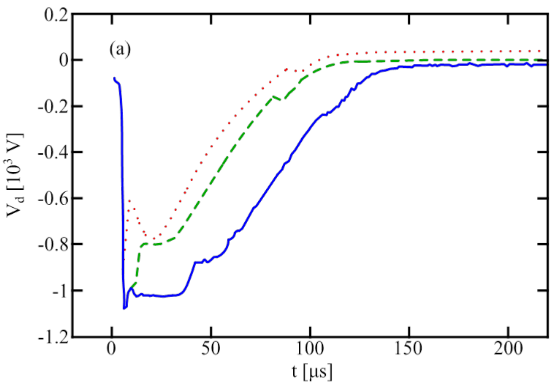
HiPIMS parameter	Value
Working pressure	$10^{-4} - 10^{-2}\ Torr$
Cathode Current Density	$J_{max} \leq 10\ A/cm^2$
Discharge Voltage	$0.5 - 1.5\ kV$
Plasma Density	$\leq 10^{13} cm^{-3}$
Cathode Power Density	$1 - 3\ kW/cm^2$
Ionization Fraction	30–90 %

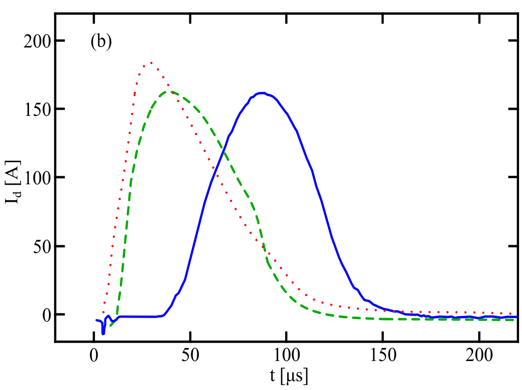
The HiPIMS discharge exists in the same pressure regime as the DC magnetron sputtering (DCMS) and the existing magnetic field assemblies which are used for DCMS can provide stable ignition and operation of HiPIMS discharge [5]. Therefore, by just changing the power supply in otherwise the same sputtering system the characteristics of the plasma can be changed and therefore the properties of the films as well.

The high-power pulses on the target in HiPIMS result in plasma electron densities up to 10^{19} m^{-2} which is three orders of magnitude higher compared to DCMS [6]. These high plasma densities promote ionization of the sputtered material forming an ionized sputtered material flux, where the ionization fraction can reach 90 % [7]. The ion flux is subject to electric and magnetic force so its direction and energy can be controlled. Being precisely controlled the target material ion flux can be used to perform substrate pre-treatment as well as to enhance film and device properties. Examples of enhancements are increased film density as well as significant improvements in film adhesion are presented in [8,9].

The high power pulsed discharge operates with a cathode voltage in the range of 500–2000 V which gives current densities of 3–4 $A \cdot cm^{-2}$ and power densities in the range of 1–3 $kW \cdot cm^{-2}$ [10,11]. Figure 2 shows typical voltage and current waveforms obtained for a HiPIMS discharge operated at different pressures [12].

The effect of discharge gas pressure on the shape of the target cathode voltage V_d and discharge current I_d are shown in Figures 2a and 2b, respectively. At low pressure (0.5 mTorr) the initial 40 µs of the discharge is characteristic of high voltage and very low target current like a conventional dc sputtering discharge. With increasing discharge pressure this ignition phase is shortened. These effects on the HiPIMS process are still largely unexplored.





(a) (b)

Figure 2. The (a) target voltage V_d and (b) discharge current I_d versus time from initiation of the pulse. The target was of Ta and the Ar pressure was 0.5 mTorr (solid line), 2 mTorr (dashed line), and 20 mTorr (dotted line). From [12].

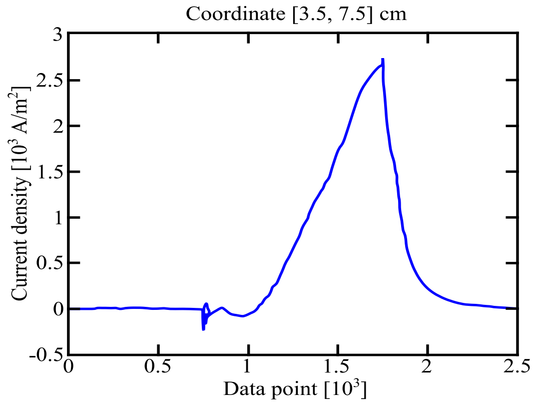


Figure 3. A typical integrated signal from the Rogowski coil. From [14].

To measure local current flow patterns inside a plasma a probe can be inserted. A Rogowski coil in close proximity to a voltage source with a large dV/dt may pick up voltage signal instead of the change in current [13]. Now the Rogowski coil is a probe, which is commonly used when measuring a change in the magnetic field strength, which is directly proportional to the change in time of current flowing through the probe [14]. The main concerns regarding inserting a Rogowski coil inside the plasma chamber is that it might affect the plasma or that the probe is damaged by, e.g., the heat flux [15].

The typical integrated signal from the Rogowski coil is presented in Figure 3 has been measured at a distance from the target of 7.5 cm on *z*-axis and 3.5 cm on *r* from the target center. As it is seen in the figure discharges of the HiPIMS type typically show sharp peaking of discharge parameters for relatively short times (≈ 100 μs) [14].

The major disadvantage of the HiPIMS technique is the typically lower deposition rate as compared to DCMS for the same average power [16,17,18,19]. The corresponding deposition rate efficiencies ($\text{Åmin}^{-1}/\text{Wcm}^{-2}$) range typically from 15–40 % of those for DCMS [20]. The main reason for this loss is known, but overall not fully understood. Several suggested contributing factors are given in the literature. The largest loss is believed to be due to sputtered atoms ionised close to the target being attracted back to the cathode [21]. These back-attracted ions may partake in the sputtering process, however at a penalty, since the self-sputtering yield (sputtering yield of a target material when bombarded by ions from the same element) is typically lower than the Ar-sputtering yield [22]. The ion back-attraction concept is elaborated upon, and a possible route for mitigating the effect of this mechanism is described by Brenning et al. [23].

The use of HiPIMS method

Here we discuss some aspects for technical implementation of the HiPIMS discharge and applications in thin film growth. Despite the fact that the high-power sputtering method is known for a relatively short time, it is already actively used in industry as a new technology for applying high-quality conducting and dielectric coatings. The unique features of a high-power discharge suit for a wide range of applications.

The HiPIMS discharge generates a highly ionized plasma with large quantities of energetic metal ions [24] due to very high pulse power densities with, in some cases, a direct flux of charged species [25]. The high degree of ionization of the sputtered species has several advantages for thin film growth. The first one is a huge fraction of ionized atoms in a flow (more than 60 %) [26,27,28,29] that is useful for preliminary preparing the surface of the substrate for further deposition of various coatings. Compared to conventional DC magnetron sputtering systems the HiPIMS represents a method how to increase ionization degree of sputtered particles and ion flux towards the substrate [30].

The method of high-power pulsed sputtering can also become a new instrument for high-speed deposition of films, especially if the objects of coating are precision instruments and/or devices of modern electronics. The most common is the application of conductive [25,27,28,31,32,33,34,35,36,37] films (Cu, Al, Ti, Ta, Ni, etc).

Metal coatings are deposited in an inert gas discharge, most often in argon. In the study of the characteristics of the high-power discharge in the metal mode, also other working gases are used such as krypton [38,39], xenon, neon, helium [40], etc. Their application is justified only from the point of view of the fundamental study of the process. In industry, however, they are not used either because of the high cost or low sputtering ratio. Also, the method of sputtering a target made of alloy [41,42], or the use of a double magnetron [41] in an argon medium is used for the deposition of a film with a wide range of metal components.

Moreover, HiPIMS method is widely used to form elements of integrated circuits [43,44]. The paper [43] shows the possibility of applying this method for use in microelectronic technology of logical integrated circuits creation (including processor devices). Here the authors note the numerous advantages of the method over alternative technologies. Used substances (metals and gases) are environmentally safe components, chemical reactions occur without the release of harmful substances. The process of substance flow formation includes such mechanisms as physical dispersion and evaporation, which are characterized by high controllability and determinism of the entire deposition process as a whole. Therefore, for the electronics industry, this method has good prospects in the field of creating high-quality interconnects.

In [45], the researchers note the advantages of using the method of high-power impulse sputtering to develop active high-quality antibacterial coatings based on a two-layer Cu/TiO_2 structure. The authors mark that the thickness of the structures (less — better) strongly affects the rate of harmful effects on such pathogens as *E. coli* and *Staphylococcus aureus*. The HiPIMS film with a thickness of 38 nm required ≈ 10 min to inactivate bacteria compared with a thickness layer of 600 nm when applying DC/DCP sputtering. That may allow the widespread use of thin films to prevent the spread of viruses and bacteria in public places. In addition, these coatings can be a tool for effective control of pathogens of dangerous diseases in schools, hospitals and other crowded places.

High-power sputtering is well suited for fast optical coatings, which primarily include anti-reflective and anti-static films, optical filters, various protective structures and translucent mirrors. Typically, these devices are based on physical effects occurring in dielectric and semiconductor films based on transition metal oxides. These materials are synthesized in a reactive mode: the metal target is sputtered with inert gas ions (in most cases it is argon) in an oxygen atmosphere. Following films are used for optical coating: TiO_2 [46,47,48,49,50,51], SnO_2 and ZnO [52], Al_2O_3 [53], Nb_2O_5 and SiO_2 [54], ZrO_2, MgO and Y_2O_3 [55].

One of the largest applications of the high-power sputtering method is the wear-resistant and anti-corrosion coatings for various uses. In recent decades, machine-building and machine tool industries have been actively using plasma nitriding, as well as deposition of films with low friction coefficients by arc to improve the parameters of the surface layer of various mechanisms. HiPIMS method becomes the latest technology for the manufacture of high-quality functional coatings operating at high temperatures, with even lower friction coefficients and greater corrosion resistance, as well as the level of adhesion comparable to the arc method of film synthesis. Yet another positive point is obvious: the complete absence of the droplet phase in the flow of matter, which has a positive effect on the quality of film structures.

In addition to the industrial application of high-power impulse magnetron sputtering, theoretical research is being undertaken to further study the discharge and to simulate the sputtering process. The creation of physical models enables to predict the results of experiments. Computer models thus provide many opportunities for improvement of the HiPIMS method in mass production. As an example the paper can be quoted [17], where a simulation of the transport-of-ions-in-matter showed that the apparently low deposition rate can be understood based on the non-linear energy dependence of the sputtering yields.

HiPIMS diagnostics using the probe techniques

The relevant plasma diagnostics is needed in reactive HiPIMS plasma systems applied directly during the deposition process. This is important for the research of physical processes during the deposition and for reliable repeatability of deposition conditions. Several fast time-resolved probe systems were already used for this purpose as presented in [56,57,58] for example. These methods employ a time-resolved Langmuir probe characteristics measurement. The probe current and voltage sampling is done synchronously with the HiPIMS pulses over many pulsing periods in the defined time of pulsing period (boxcar method). In general, these methods can be used for time-resolved data acquisition but in HiPIMS applications, the measurement of one characteristics takes relatively long time due to the low pulsing frequency (≈ 100 Hz). During the longtime of measurement, an insulating layer can deposit on the probe surface rending the probe data unusable. To get around this problem several methods — so called AC floating probes — were already presented in [59] where an AC signal was involved in the measurement together with the harmonic analysis of measured probe current.

Although the AC probe diagnostic systems work quite reliably, they have their limitations that restrict their use in the field of material science or industry. Consequently, for our future work we prepare a fast-swept Langmuir probe to be applied during the deposition of insulating thin films by HiPIMS. This method is based on a subtraction of capacitive current flowing through the parasitic capacitances in the probe circuit and the capacity of the space charge sheath formed around the surface of the probe during the application of the fast-swept bias voltage. An assessment of this capacitive probe current will be performed numerically from the current and voltage waveforms recorded by employing the probe circuit within a specially designed plasma impedance monitor. After eliminating the disturbing capacitive current, the part of probe characteristics in the region of saturation ion current and around the floating potential will be obtained by this method. From this data, the part of the probe characteristic close to the floating potential is used for calculation of the electron temperature and the ion density is obtained from the ion saturation current part. The sweep frequency of the probe voltage will be in the range 200–350 kHz. Due to the fast sweep frequency, we expect this method to be rather insensitive on the coating of probe surface by a dielectric layer.

Conclusion

This paper provides a review of the HiPIMS technology. We revealed the current state of HiPIMS research, discussed the characteristics of the HiPIMS discharge, its diagnostic and possible applications. The advantages of HiPIMS were demonstrated compared with dc sputtering for fast optical, wear-resistant and anti-corrosion coatings. Nowadays the benefits from using the high power magnetron sputtering are well investigated to develop active high quality of antibacterial coatings. Moreover HiPIMS allows to obtain thin films with higher adhesion capacity and strength characteristics, which are important for use on flexible structures.

Previous investigations have provided important insights into understanding the physics of HiPIMS plasma. We expect that by the indicated new diagnostic method applied in the field of material science we contribute to further understanding and development of this technique.

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References

[1] Kouznetsov V., Macak K., Schneider J.M., Helmersson U., Petrov I., A novel pulsed magnetron sputter technique utilizing very high target power densities. Surface and Coatings Technology 122 (1999) 290–293.

[2] Helmersson U., Lattemann M., Ionized physical vapor deposition (IPVD): A review of technology and applications. - Thin Solid Films 513 (2006) 1–24.

[3] Web-site https://wcs.webofknowledge.com/

[4] Gudmundsson J.T., Alami J., Helmersson U., Spatial and temporal behavior of the plasma parameters in a pulsed magnetron discharge. Surface and Coatings Technology, 161 (2002) 249–256.

[5] Lundin, D., Sarakinos K., An introduction to thin film processing using high-power impulse magnetron sputtering. Journal of Materials Research, 27 (2012) 780–792.

[6] Alami, J., et al., Plasma dynamics in a highly ionized pulsed magnetron discharge. Plasma Sources Science and Technology, 14 (2005) 525–531.

[7] Greczynski, G. and Hultman L., Time and energy resolved ion mass spectroscopy studies of the ion flux during high power pulsed magnetron sputtering of Cr in Ar and Ar/N 2 atmospheres. Vacuum, 84 (2010) 1159–1170.

[8] Münz, W., et al. Industrial applications of HIPIMS. Journal of Physics: Conference Series. 100 (2008) 082001.

[9] Ehiasarian, A.P., High-power impulse magnetron sputtering and its applications. Pure and applied chemistry, 82 (2010) 1247–1258.

[10] Bugaev S.P., Koval N.N., Sochugov N.S., and Zakharov A.N., Investigation of a high-current pulsed magnetron discharge initiated in the low-pressure diffuse arc plasma. Proceedings of XVIIth International Symposium on Discharges and Electrical Insulation in Vacuum, July 21–26, 1996, Berkeley, CA, USA, p. 1074.

[11] Kouznetsov V., Macák K., Schneider J.M., Helmersson U., and Petrov I., A novel pulsed magnetron sputter technique utilizing very high target power densities. Surf. Coat. Technol., 122 (1999) 290.

[12] Helmersson U., Lattemann M., Alami J., and Bohlmark J., High Power Impulse Magnetron Sputtering Discharges and Thin Film Growth: A Brief Review. 48th Annual Technical Conference Proceedings (2005) ISSN 0737-5921, p. 458.

[13] Torbert E., Furno I., Intrator T., and Hemsing E., A plasma-shielded, miniature Rogowski probe. Review of Scientific Instruments, 74 (2003) 5097–5100.

[14] Magnus Karlsson, Measurement of internal current densities during a HiPIMS discharge with a Rogowski coil. Master's Thesis. Department of Physics, Linkoping, Sweden, 2011.

[15] Hutchinson I.H., Principles of Plasma Diagnostics. Cambridge UniversityPress, 2nd edition, 2002.

[16] Emmerlich J., Mraz S., Snyders R., et al. The physical reason for the apparently low deposition rate during high-power pulsed magnetron sputtering. Vacuum 82 (2008) 867–870.

[17] Samuelsson M., Lundin D., Jensen J., et al. On the film density using high power impulse magnetron sputtering. Surface & Coatings Technology, 205 (2010) 591–596.

[18] Sarakinos K., Alami J., Klever C., Wuttig M., Process stabilization and enhancement of deposition rate during reactive high power pulsed magnetron sputtering of zirconium oxide. Surface & Coatings Technology, 202 (2008) 5033–5035.

[19] Stranak V., Hubicka Z., Cada M., et al. Investigation of ionized metal flux in enhanced high power impulse magnetron sputtering discharges. Journal of applied physics, 115 (2014) 153301–153307.

[20] Helmersson U., Lattemann M., Bohlmark J., Ehiasarian A., Gudmundsson J., Thin Solid Films 513 (2006) 1-24.

[21] Christie D.J., Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films 23 (2005) 330-335.

[22] Besocke K., Berger S., Hofer W.O., Littmark U.A., Search for a thermal spike effect in sputtering. I. Temperature dependence of the yield at low-kev, heavy-ion bombardment. Radiation Effects, 66 (1982) 35–41.

[23] Brenning N., Huo C., Lundin D., Raadu M.A, Vitelaru C., Stancu G.D., Minea T., and Helmersson U., Plasma Sources Sci. Technol., 21 (2012) 02500.

[24] Alami J., Eklund P., Andersson J.M. et al., Phase tailoring of Ta thin films by highly ionized pulsed magnetron sputtering. Thin Solid Films, 515 (2007) 3434–3438.

[25] Vasina P., Mesko M., Imbert J.C. et al., Experimental study of a pre-ionized high power pulsed magnetron discharge. Plasma Sources Sci. Technol., 16 (2007) 501–510.

[26] Lin J., Moore J.J., Sproul W.D., et al. Ion energy and mass distributions of the plasma during modulated pulse power magnetron sputtering. Surface & Coatings Technology, 203 (2009) 3676–3685.

[27] Anders A., Discharge physics of high power impulse magnetron sputtering. Surface and Coatings Technology, 205 (2011) 51–59.
[28] Anders A., Self-sputtering runaway in high power impulse magnetron sputtering: The role of secondary electrons and multiply charged metal ions. Applied Physics Letters, 92 (2008) 501–503.
[29] Lin J., Sproul W.D., Moore J.J., et al., Recent advances in Modulated Pulsed Power Magnetron sputtering for surface engineering. Journal of Materials, 63 (2011) 48 –58.
[30] Stranak V., Hubicka Z., Cada M., Wulff H., Hippler R., Time-resolved investigation of dual high power impulse magnetron sputtering system with closed magnetic field during deposition of Ti-Cu thin films. 1st International Conference on HiPIMS. Abstract book (2010).
[31] Ehiasariana A.P., Newa R., Munza W.-D., et al., Influence of high power densities on the composition of pulsed magnetron plasmas. Vacuum 65 (2002) 147–154.
[32] Hubička Z., Zlámal M., Čada M., Kment Š., Krýsa J., Photo-electrochemical stability of copper oxide photocathodes deposited by reactive high power impulse magnetron sputtering. Catalysis Today, 328 (2019) 29–34.
[33] Gudmundsson J. T., Sigurjonsson P., Larsson P., et al., On the electron energy in the high power impulse magnetron sputtering discharge. J. Appl. Phys., 105 (2009) 302–306.
[34] Raadu M.A., Axnas I., Gudmundsson J. T., et al., An ionization region model for high-power impulse magnetron sputtering discharges. Plasma Sources Sci. Technol., 20 (2011) 65007–65017.
[35] Drache S., Stranak V., Herrendorf A.-P., et al., Time-resolved Langmuir probe investigation of hybrid high power impulse magnetron sputtering discharges. Vacuum, 90 (2013) 176–181.
[36] Behrisch R., Eckstein W., Sputtering yield increase with target temperature for Ag. Nuclear Instruments and Methods in Physics Research, B 82 (1993) 255–258.
[37] Brenning N., Lundin D., Alfvén's critical ionization velocity observed in high power impulse magnetron sputtering discharges. Phys. Plasmas, 19 (2012) 505–510.
[38] Sigurjonsson P., Gudmundsson J.T., Plasma parameters in a planar dc magnetron sputtering discharge of argon and krypton. Journal of Physics: Conference Series, vol. (No) 100 (2008) 18–21
[39] Besocke K., Berger S., Hofer W.O., Littmark U.A., Search for a thermal spike effect in sputtering. I. Temperature dependence of the yield at low-kev, heavy-ion bombardment. Radiation Effects, 66 (1982) 35-41.
[40] Bohdansky J., Lindner H., Hechtl E., et al., Sputtering yield of Cu and Ag at target temperatures close to the melting point. Nuclear Instruments and Methods in Physics Research, B18 (1987) 509–514.
[41] Matsui H., Toyoda H., Sugai H., High-energy ions and atoms sputtered and reflected from a magnetron source for deposition of magnetic thin films. Journal of Vacuum Science & Technology, 23 (2005) 671-675.
[42] Gudmundsson J.T., Ionization mechanism in the high power impulse magnetron sputtering (HiPIMS) discharge. Journal of Physics: Conference Series, 100 (2008) 82013–82016.
[43] Wiatrowski A., Posadowski W.M., Radzimski Z.J., Pulsed-D selfsputtering of copper. Journal of Physics: Conference Series, 100 (2008) 62004–62007.
[44] Hopwood J., Ionized physical vapor deposition of integrated circuit interconnects. Phys. Plasmas, 5 (1998) 1624–1631.
[45] Kiwi J., Rtimi S., Pulgarin C., Cu, Cu/TiO2 thin films sputtered by up to date methods on non-thermal thin resistant substrates leading to bacterial inactivation. Microbial pathogens and strategies for combating them: science, technology and education (A. Méndez-Vilas, Ed.) (2013), p. 74–82.
[46] Ratova M.,West G.T., Kelly P.J., Optimisation of HiPIMS photocatalytic titania coatings for low temperature deposition. Surface & Coatings Technology, 250 (2014) 7–13.
[47] Billard A., Mercs D., Perry F., Frantz C., Influence of the target temperature on a reactive sputtering process. Surface and Coatings Technology, 119 (1999) 721–726.
[48] Domaradzki J., Prociow E., Kaczmarek D., Ti–Zr Dielectric Layers Deposited by Hot Target Reactive Magnetron Sputtering. The Fourth International Conference on Advanced Semiconductor Devices and Microsystem (ASDAM'02), Smolenice Castle, Slovakia, 14–16 October 2002, proceedings, p. 47–50. Available at https://ieeexplore.ieee.org/document/1088471 .
[49] Domaradzki J., Kaczmarek D., Prociow E.L., et al. Microstructure and optical properties of TiO2 thin films prepared by low pressure hot target reactive magnetron sputtering. Thin Solid Films, 513 (2006) 269–274.
[50] Wasielewski R., Domaradzki J., Wojcieszak D., et al., Surface characterization of TiO2 thin films obtained by high-energy reactive magnetron sputtering. Applied Surface Science, 254 (2008) 4396–4400.
[51] Böhlmark J., Fundamentals of High Power Impulse Magnetron Sputtering. Plasma & Coatings Physics Division Department of Physics, Chemistry, and Biology Linköping University, SE-581 83 Linköping Sweden, 2006, 78 p. Available at http://www.diva-portal.org/smash/get/diva2:22370/FULLTEXT01.pdf .
[52] Aiempanakit M., Aijaz A., Lundin D., et al., Understanding the discharge current behavior in reactive high power impulse magnetron sputtering of oxides. J. Appl. Phys., 113 (2013) 302–310.
[53] Thomann A.L., Cormier P.A., Dolique V., et al., Energy transferred to the substrate surface during reactive magnetron sputtering of aluminum in Ar/O2 atmosphere. Thin Solid Films, 539 (2013) 88–95.
[54] Chau R.Y., Ho W.-S., Wolfe J.C., Licon D.L., Effect of target temperature on the reactive dc-sputtering of silicon and niobium oxides. Thin Solid Films, 287 (1996) 57–64.
[55] Sarakinos K., Alami J., Klever C., Wuttig M., Process stabilization and enhancement of deposition rate during reactive high power pulsed magnetron sputtering of zirconium oxide. Surface & Coatings Technology, 202 (2008) 5033–5035.
[56] Bradley J.W., Backer U.H., Kelly P.J., Arnell R.D., Time-resolved Langmuir probe measurements at the substrate position in a pulsed mid-frequency DC magnetron plasma, Surface and Coatings Technology 135 (2001) 221–228.
[57] Bäcker H. et al., Using Langmuir probes to measure the plasma decay rates in pulsed RF magnetron discharges J. Phys. D: Appl. Phys. 34 (2001) 2709–2714.
[58] Yu-Sin Kim, Dong-Hwan Kim, Hyo-Chang Lee, Chin-Wook Chung., On uniform plasma generation for the large area plasma processing in intermediate pressures, J. Appl. Phys., 117 (2015) 153302.
[59] Zanaska M., Turek Z., Hubicka Z., Cada M., Kudrna P., Tichy M., Floating harmonic probe for diagnostic of pulsed discharges, Surface and Coatings Technology 357 (2019) 879–885.