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On the Physical Vapour Deposition (PVD): Evolution of Magnetron Sputtering Processes for Industrial Applications

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Abstract

Advanced coatings play an important role in a wide range of industrial applications. These coatings are commonly used in machining tools due to their high hardness and wear resistance, but also can be applied in jewellery and decorative purposes. Deposition techniques have seen a strong evolution as result of the directly related devices, control evolution and software. Several variants have been developed around the main techniques: arc evaporation and sputtering. The coatings produced present significant differences in their characteristics, namely in terms of structure, mechanical properties and surface morphology. Depending on the substrate material and application, the deposition process needs to be properly selected, providing the particular characteristics requested. This paper intends to do a critical review of the evolution of the advanced coatings deposition process, mainly focused on the Physical Vapour Deposition (PVD) process, particularly in the Magnetron Sputtering technique, which is able to produce smooth surfaces, using lower temperatures, presenting excellent mechanical and tribological properties and having very good adhesion to the main materials used as substrate.

Keywords: PVD optimization process; PVD technique, Sputtering; Deposition Improvement; Reactors, Coating.

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1. Introduction

Physical Vapour Deposition (PVD) technique has collected a lot of variants and enhancements in the last decades, trying to improve the coatings characteristics and the deposition rate [1,2]. The term "physical vapor deposition" appears in the 60s where the industry needs led to the evolution of vacuum coating processes being possible through the development of technologies such as electricity, plasma technology, vacuum, magnetism, gas chemistry, thermal evaporation, bows and sputtering. This issue can be deeply explored in Powell's book [3].

This technique has known important improvements in particular in nanocomposite coatings, mainly those based on carbides and transition metal nitrides [4-8]. In the industrial context, the deposition rate is probably the best parameter to optimize but scientists have been usually focused on improving coating characteristics [9-11].

Generically, PVD can be divided into two main processes on how the particles can be extracted from the target: sputtering and evaporation. The evaporation process usually presents lower atomic energy, the need for high-vacuum pressure, lesser adsorbed gases into the coatings, a much more directional nature, particle transferring with higher mass (larger grains), more oriented grains, a lower adhesion to the substrate and higher deposition rates than the sputtering process. Thus, the evaporation process is usually more suitable for industrial applications and thick films where the surface morphology is not the main quality requirement. Furthermore, contaminant particles can be located in the crucible and can be moved from there to the parts to be coated, eventually decreasing the purity of the coatings obtained.

Hence, the sputtering process undertakes particular relevance in many applications where the roughness, the grain size, the stoichiometry and other quality requirements present greater significance than the deposition rate. Moreover, several applications present temperature limitation in terms of the deposition process, due to substrate melting temperature (polymers) or undesirable stresses generated during the cooling process [12-16]. Therefore, the sputtering process has assumed particular importance among the PVD deposition processes. However, market requirements are ever increasing, leading to new research needs impossible to solve using the initial techniques.

Thus, many systems have been developed and improved, being added to the initial systems and constituting even new achievements, which permit to obtain novel coating properties that fulfil the market and researchers requirements. Therefore, despite other developments also studied the evaporation process, sputtering deposition has registered more advances and more variants, bearing in mind really interesting results regarding advanced researchers' requests. Thus, this work is mainly focused on sputtering magnetron techniques.

2. PVD process introduction

PVD is a widely used technology for the deposition of thin films regarding many demands, namely tribological behaviour improvement, optical enhancement, look upgrading, and many other fields, with a wide range of applications already perfectly established [17-19].

Machining tools are, probably, one of the most common applications of this deposition technique [20-23], sometimes used together with Chemical Vapour Deposition (CVD) in order to increase their lifespan [24-26], decreasing the friction and improving the thermal properties [27-31]. The advantages of using PVD processes are numerous, allowing variation of coating characteristics continuously throughout the film. It also allows the deposition of alloy compounds, multilayer composition and special structures [32-34]. This versatility has given rise to a development, improvement and proliferation of techniques for the various processes. Table 1 gives only a few of several variants.

In PVD processes, the material to be deposited, namely the target, is transformed into atomic particles by a thermal physical process of collision and directed to the substrates in a vacuum environment or gaseous plasma under low-pressure conditions, where they condense to form a physical coating [16].

According to Tracton [14], the sputtering deposition is one of the most complex methods, being as well the most expensive in some cases. This technique allows a better composition control of the multilayers deposition films and a greater flexibility in the types of materials to be deposited [16,35,36]. As can be seen in Fig. 1, the PVD reactors are constituted of a vacuum chamber and two electrodes connected to a high voltage power source [16,35,37].

Table 1. PVD techniques for advanced coatings [12-14].

Sputtering		Evaporation	
Ions Beam		E-Beam	
Diode		Inductive	
Triode		Resistive	
Reactive Sputter Deposition		Arc	Stirred Random Cathodic Arc Deposition
Magnetron	RF- Radio Frequency DC- Direct Current MEP - Magnetically Enhanced Plasma UBMS - Unbalanced Magnetron Sputtering DMS – Dual Magnetron Sputtering HiPIMS/ HPPMS - High-Power Impulse/ Pulse Magnetron Sputtering		

In sputtering processes, a magnetron is positioned near the target. The ionic gas is introduced in an accelerated way into the vacuum chamber which blasts the target, releasing atomic-sized particles to be deposited, which will be violently projected onto the substrate. This technology permits to clean the previous surface of contaminations located on the substrate face by inverting the difference of potential between the target and the substrate whenever desired, characterized by cathodic cleaning [16].

In a typical e-beam evaporation process, the target has an evaporation source containing the material to be evaporated, which acts as a cathode. Electron beam heating allows the particles evaporation, whose are also of atomic size. The released particles will clash with the gas molecules that are introduced into the reactor to accelerate the particles, forming a plasma that passes through the deposition chamber, which will be more intense in the middle of the reactor chamber. The particles will be deposited on the substrate, forming successively compressed layers, allowing a good film adhesion to the substrate [12-16].

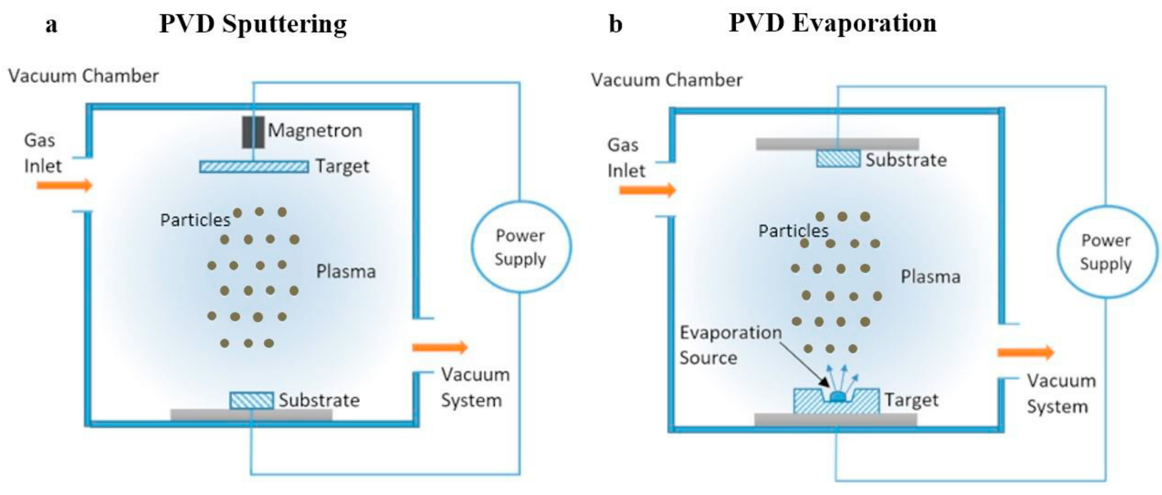

Fig. 1. Schematic diagram of the PVD (a) sputtering and (b) evaporation coating methods [16,35,37].

The sputtering process allows better film densification because it is a cleaner process, introducing fewer stresses on the substrate since it allows deposition at temperatures since 50°C [38-40]. On the other hand, the evaporation process has the disadvantage of contaminating the film by the diffusion of the evaporation source and is limited by the materials that can be deposited in function of their melting temperature. In table 2, a brief comparison between the evaporation and the sputtering techniques can be observed [12-16].

Table 2. Overview of typical features of the PVD depositions techniques: Sputtering and Evaporation [14,15].

Process parameter	Sputtering	Evaporation
Vacuum	Low	High
Absorption	Higher absorption	Less absorbed gas without film
Atomized particles	More dispersed	Highly directional
Adhesion	High	Low
Uniform film	More	Less
Grain size	Smaller	Bigger
Deposited species energy	Can be high (1–100 eV)	Low (~0.1–0.5 eV)
Deposition rate	Low except for pure metals and dual magnetron	Can be very high (up to 750,000 A/min)

2.1. Sputtering Processing Flow

Regarding what happens in the chamber during the deposition cycle, it is necessary to understand the steps involving the whole equipment associated with the reactor, contributing to the thin films deposition. All substrates must be properly cleaned prior deposition. The advantage presented by this technique is allowing for the use of the same reactor for the substrate cleaning and coating deposition [16,36]. A disadvantage in industrial terms is that the duration of the substrate cleaning process is remarkable, which increases the final product cost and requires a good time management of the machine use. It is expected an evolution in the optimization of the process through the reduction of production time once this parameter is a serious concern for the industry. All steps must be considered and the parameters studied to respond to the industrial requirements that favors the deposition rate and, of course, the adhesion of the films to the substrates [41]. It should be noted that it is not less important to clean the substrates before they are placed on the satellites, that are their holders inside the chamber [42]. Poor substrates handling, as well as poor maintenance of the entire vacuum system, can be sources of contamination and this should be taken into account. Thus, films can be contaminated by bad surface conditions or system related sources. The vacuum pumping system and the size of the deposition chamber are determinants in the process cycle time [12].

After mounting of the substrates on the corresponding holders in the chamber, the deposition process consists of the following steps: **Ramp up stage** - entails the preparation of the vacuum chamber for the cleaning process, the temperature increase and then the deposition process. Usually, the PVD reactors have two pumps, one for a primary vacuum where pressure can reach 10^{-5} bar, which is followed by the operation of a high vacuum pump in order to reach 10^{-7} bar pressure. During the activation of the pumps, one also has in parallel the gradual heating of the chamber using a tube heating system and a modular control. **Pretreatment** - involves the cleaning of substrate contaminations that may exist by bombarding ions called Plasma Etching. The cleaning thus enables preparation for deposition by increasing the adhesion of the material to be deposited. It is well-known that adhesion depends not only on the properties of the film but also on the characteristics of the substrate: material, surface quality and hardness [43,44]. **Coating** - will allow the deposition of different metals such as titanium, zirconium and chromium nitrides or oxides which will then be vaporized and condensed on the surface of the substrate with various microns thickness. **Ramp Down Stage -** machine cooling and unloading should not damage the film and the desired substrate hardness. The reactors require a cooling system which may be a disadvantage in the PVD process. The cooling can be done through a chiller having usually two sets of water knockout drums: one is used for vacuum pumps and the other is used for targets cooling. Venting is useful for returning the vacuum chamber to the ambient pressure.

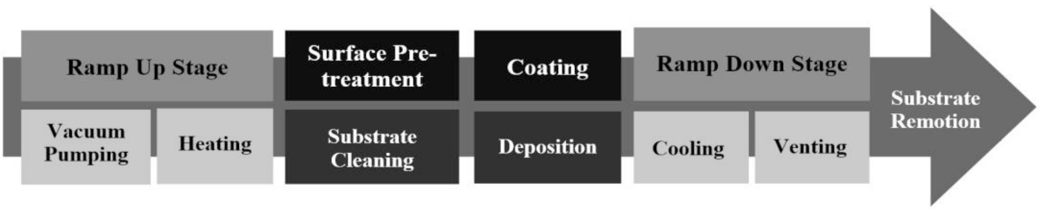

Fig. 2. The processing flow of sputtering deposition processes [45].

The energy consumption of the process is an industry concern. Energy consumption studies and material flows in hard coating deposition processes have been made, showing that the PVD process exhibits greater consumption when compared to the CVD process, which can be reduced, for example, by recycling target materials or otherwise interchange heat exchange modules in order to recover residual heat. The energy consumption for the case of the Sputtering Magnetron deposition process shows that the coating step can consume more than three-quarters of the total energy and the cathodes consumption is even more than half of the global energy spent in the deposition cycle. Thus, the contributions of heating, etching and refrigeration are much lower [45]. Energy consumption is a global concern, leading to costs' reduction for the industry, which is expected to be exploited in future work.

2.2. How main properties can be conditioned by the deposition process

All parameters involved in the process, both for cleaning the substrates and coating deposition, such as the deposition technique, current density, gas type and flow, bias, temperature, pressure, number of vacuum pumps, number of targets, substrates occupation and their arrangement within the chamber and targets, are subject to change. These parameters can result in different types of films with diverse thicknesses, grain size and adhesion to the substrate, determining by this way the coating characteristics: hardness, chemical composition, morphology, microstructure, Young's modulus, etc. [46]. The conditions of operation: number of satellite holders, substrate rotation, conjugation between global holder area and satellites area, holders rotation, and different initial positions of the substrate face are conditions those have effect on the coating homogeneity [42,47]. Over time, new PVD coating techniques for magnesium alloys have been developed in order to improve the corrosion properties of this material. The Hoche's et al. (2014) work had as focus a comparison between Direct Current (DC) and High Power Impulse Magnetron Sputtering (HiPIMS) mode, also known as High-Power Pulsed Magnetron Sputtering (HPPMS), for a different number of targets and their composition involving other parameters. This comparison has shown "that the corrosion properties of the TiMgN coated magnesium alloys depend significantly on the deposition conditions and on the coating microstructure, while the defect density seems to be of minor influence" [18]. In order to improve adhesion in the PVD process, it is relevant the duration of the bias and etching sub-processes. A good adhesion depends on plasma etching and on its cleanliness. Plasma etching facilitates a good mechanical interlocking at the interface and plasma cleaning process removes oxides and other contaminants from the substrate surface. Normal vacuum conditions must be guaranteed to avoid the presence of residual oxygen in the chamber. Thus, the pressure must be kept between 10^1 Pa with a base pressure of 10^4 Pa [44]. Another parameter that most influences the microstructural and mechanical properties of thin films is the flow and type of gas used. Jiang et al. (2017) used HiPIMS/ HIPIMS/ HPPMS to study the influence of these properties, concluding that the microstructure and mechanical properties of the AlSiN were strongly influenced by the N_2/Ar flow ratios (ranging from 5% to 50%) during the deposition process [48]. On the other hand in recent years reactive gases such as oxygen or nitrogen have been used in the HiPIMS/HPPMS process. This technique is used to improve and adapt the properties of the growing films by their high fraction of ionized sputtered material during the process [49]. An evolution in the researchers' approach in this subject was also observed. Indeed, initially their studies were oriented to the quality of the film and later realized the importance of all the process that contributed to the appearance of new techniques and reactors for the optimization of the industrial processes. It is unquestionable that the films properties are directly related to the deposition process, so the future is to invest in overcoming some problems that the industry is facing, by the upsurge of new simulation software able to support the necessary continuous improvement

3. Sputtering improvements

In order to improve this technique, several studies have been carried out, optimizing the PVD technique by increasing plasma ionization, or decreasing the areas where there is no deposition into the reactor (dark areas), or improving the targets' use, or enhancing the atomic bombardment efficiency, or even increasing the deposition rate and optimizing the gases selection [48,50,51]. However, the process energy efficiency improvement regarding the industrial context has not been the focus of the most important studies.

3.1 Reactors' characteristics

The industry presents a wide range of vacuum chambers dedicated to the coating of tools and components. [22,23,34] With the evolution of this equipment over time, they are becoming increasingly automatic and autonomous, designed with the aim of mass production for better profitability, low maintenance and management costs, converging for low human labor use as an advantage. The constant development of software for a user-friendly process and remote control are also focus on technological evolution [52-54].

The flexibility of the process allows the use of this technology in different materials and geometries. Currently, the easy access to the coating zone provides the operator easier substrates load and unloading tasks. The main available reactors' characteristics and parameters are: (a) the usable vacuum chambers′ diameter, which will limit working pressures, as well as the size of the substrates, which diameter usually varies between 400 mm and 650 mm [53,54], but can reach up to 2500 mm [52]. (b) The number of coating access doors can vary between one to three, (c) The number of satellites can reach twenty, being more common the use of six or ten, (d) Relatively fast cycle times, for 3 μm deposition usually takes less than 5-6 hours, (e) Power and number of pumps, (f) Weight and dimensions, (g) Type of gas, (h) Number and size of sputter cathodes and (i) Substrate rotation. Rotating substrates systems of industrial PVD machines have been studied. These studies showed the effects of substrates rotation velocity on the industrial process and proved that the rotation is determinant in the layer deposition sequence which is reflected in the macroscopic properties of the coated substrates [42,47,55].

Sputtering can be done in Ions Beam, Diode, Triode, Reactive Sputter Deposition and Magnetron. Its development has more impact on the magnetron reactors. In the last years, new pulsed techniques with many potentialities have appeared. The sputtering magnetron in DC and Radio-Frequency (RF) gave rise to other techniques. However, DC continues to be one of the cheaper power supplies with easy process control, although the sputter yield is usually much lower [56]. The cathodic spray method soft films are one of their strengths, however, its disadvantage is the low ionization rate because just about a fraction of 1% of the species sprayed from the target is ionized [12]. The use of DC power is common in magnetrons, RF or pulsed power. The DC source is applied in situations where the targets are made of conductive materials. For the use of non-conductive or low conductivity targets, the RF source is applied. In this process an alternating high-frequency signal is applied, allowing for current pass through the target, avoiding the accumulation of charges and in this way, keeps the plasma. Typical systems of these deposition sources are composed of: a pumping system and a DC or RF power source, a high vacuum chamber, where the substrates and the target are mounted and an inlet for the gases which will give rise to the plasma. As an alternative to the use of DC and RF sources, there is a dual magnetron sputtering process using Mid Frequency (MF). The methods of choice for reactive deposition in large area coaters are the process of Dual Magnetron Sputtering (DMS). There are now increasingly sophisticated systems for magnetron rotation [57,58]. This method is broadly characterized by a different composition of the target and growing film. Process parameters such as reactive gas partial pressure, voltage and sputter rate are sensitive to small changes in the supplied gas, because they can change the surface oxidation [57]. In addition, the pulsed power supply allows switching components configured to receive DC power and apply pulsed-DC power to the magnetrons. To reduce the heat load on the substrate, some technologies like Dual Anode Sputtering (DAS) also allow switching from the commonly used Alternating Current - Mid Frequency (AC-MF) mode to a process DC power. DMS Studies using the Reactive Bipolar Pulsed Dual Magnetron Sputtering (BPDMS) technique demonstrate good high deposition rate around 0.044 μm/min, operating in mid-frequency range (80-350 kHz). This method also prevents the arc formation [59]. The technical sputtering tested in laboratory equipment showed that the deposition rates presented a low value in order to obtain cost-effective absorbers compared to industrial techniques [60]. Therefore, in the last years, studies have been conducted in an industrial context. These studies have been focused on obtaining better absorbers, the stability of the process, novel segmented targets, gas flow and different gases, the influence of bias voltage, enhanced ionization sputtering, among others.

The Reactive Pulsed DC magnetron sputtering using the reactor CemeCon CC800/9®, in an approach with triangle-like segmented targets, showed to be able to reduce the workload in the economic development of the coating material. To reinforce the good results obtained from the tribological properties, with low friction values 0.4 and wear coefficients up to 1.8×10^{-16} m^3/Nm, using $Cr_{1-x}Al_xN$ ($0.21 \leqslant x \leqslant 0.74$) as a coating material, the maximum hardness of 25.2 GPa has been a good potential for the industry process [61,62].

The deposition rate of 20 µm/h has already been observed in studies of gas-flow sprayed zirconia coatings on flat substrates. Some researches on gas flow sputtering and influence of bias voltage also indicate that increasing of the temperature of the substrate and applied bias voltage results in a decrease of deposition rate. Applying bias voltage at -10V to a substrate temperature of 650°C can obtain a 20 µm/h deposition rate however at -20 V the deposition rate is reduced by around 5 µm/h [63,64]. Another study using the same deposition material comparing the techniques of DC, MF pulsed and HiPIMS/HPPMS in the plastics industry, states that the sputter rate of aluminium is increased by using HiPIMS/HPPMS. Different connected targets (Al, AlCr20, CrAl20 and Cr) were used by varying the Al content.

The results showed that the rate of chromium deposition is reduced by HiPIMS/HPPMS when compared to DC and MF. The deposition rate of aluminium increases when compared to chromium due to the lower mass and higher ionization energy [62]. Numerical simulation is used to study the behavior of the gas flow regime using the Knudsen number based on geometric considerations [65]. These studies have the advantage of being later validated in an industrial context. The most recent studies focused on the development of HiPIMS/HPPMS, however, the earliest studies date back to the decade of 90's. This process combines many technological advantages such as ion plating and cathodic arc plasma deposition [66]. The HiPIMS/HPPMS is used to enhanced ionization sputtering through the pulsed power which influences plasma conditions and coating properties. This technique can be used in many ways however, this can lead to a difficulty in obtaining consistent and repeatable results [67].

From an industrial perspective, High Power Pulsed Magnet Technologies are the ones that demonstrate the greatest potential which is leading the scientific community to study the improvement of these pulsed techniques. These emerging technologies allow significantly higher ionization rates, with values up to 30% and higher charge states of the target ions. One of the many advantages is the homogeneous distribution of the film in complex objects, and it presents an excellent adhesion that is related to its high level of ionization [56,68]. A variation of HIPiMS/HPPMS is the technique Modulated Pulsed Power Magnetron Sputtering (MPPMS) which reveals great advantages when compared to the conventional magnetron sputtering techniques [69]. The industrial perspective shows the receptivity of the HPPMS/HIPIMS/HPPMS technique taking into account the range of reactor power supply.

3.2 External devices and other considerations

On monitoring the evolution of technologies, as well as the responses to the industry needs to improve its products, external devices are increasingly used. The production of plastics covers various sectors, which are present in our daily routine. The automobile sector is undoubtedly one of the major investors in the evolution of plastics injection. One knows that the plastics characteristics have a strong influence in the process, however, it is in the techniques for injection molds that the production gain can be more significant. Therefore, using the PVD coating combined with the processing of plastics by injection molding with recourse laser micro-structuring in two injection molds were studied. This study used the deposition of films to increase the durability of micro-structures and also to enhance the quality of plastic components and obtain an increase in the replication ratio up to 30%. In the tribological research, using the (Cr, Al)N coating, a significant decrease of the friction coefficient has been achieved [70]. Co-coatings films were also studied, using the pulsed laser deposition method, to understand the effect of an external magnetic field on structural and magnetic properties. The external applied magnetic field has been provided by a permanent magnet, during the studied deposition processes. The use of simulation software allowed to observe the effect of the external magnetic field on vapor flux and film surface. This one supported the experimental results proving a correlation between the structural and magnetic properties of the specimens and the deposition rate of the films used [71].

One of the industry concerns is the low electrons efficiency and the ionization rate of the metal particles. The use of the HiPIMS/HPPMS process can respond to these concerns since this method, as previously seen, allow significantly higher ionization rates [67]. Although these results are promising, they still do not provide answers to the industry needs because it is necessary to improve the electrons' use. To solve the efficiency problem of the electrons use utilizing the HiPIMS/HPPMS technique, one needs to improve the system and overcome its disadvantages. Chunwei Li et al. (2016), develop his work focused on the improvement of HiPIMS/HPPMS using an external magnetic field which allowed the study of the plasma characteristic of the discharge directly from to the magnetic electric field. For the electric and magnetic fields, a more simplified and more efficient discharge method was used. Furthermore, a coaxial electromagnetic coil was used in order to optimize the magnetic field distribution. The auxiliary anode, shown in Fig 3 (b), allowed for adjusting of the distribution in the vacuum chamber of the electric field and electric potential and also enhanced the discharging. Moreover, the current improvement in HiPIMS/ HPPMS has been also demonstrated in plasma. It was observed that the application of the external magnetic field substantially restricted the plasma and increased the uni-directionality, "The plasma density at each location in the system with the electric-magnetic cooperatively enhanced HiPIMS was improved to a high extent, and the increased amplitude after enhancement is approximately five times of the plasma density without outer-field HiPIMS" [72].

Chunwei Li et al. (2017), continued his experimental research to improve the HiPIMS/HPPMS discharge using an external unbalanced magnetic field through a conventional magnetron and a coaxial electro-solenoid coil. The vanadium target was used and to modulate the magnetic field, the current through the coils was adjusted between 0 and 6 A. The study of ion flow distribution was carried out in the vacuum chamber in different positions to form angles of 0°, 45°, 90°, 135°, and 180° with the magnetron cathode, as shown in the figure 3 (a). It was observed that 0° position with the cathode target was the one that indicates a substantially higher substrate ion current. Analyzing the measured data for substrate ion current, it was verified that the use of an external unbalanced magnetic field "can increase the plasma density in the substrate region to increase the substrate ion current. Increasing the target discharge voltage or coil current, the substrate ion current varies with the change of the target current". It was concluded that the unbalance coefficient of the field was altered with the application of an external electromagnetic field. The limitation of energetic electrons by the external magnetic field was increased, as well as the substrate ion current with the coil current at fixed target voltage. This led to an increase in total population of ions. [73].

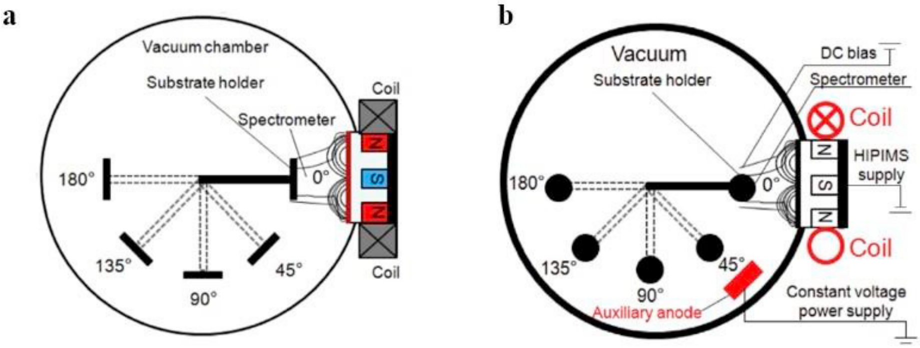

Fig. 3 – Vacuum system during HiPIMS/HPPMS discharge for measuring the ionic current of the substrate in different positions (a) external unbalanced magnetic field [72], (b) external electric and magnetic fields. Auxiliary anode [73].

Others considerations to make the sputtering process more efficient can be seen in recent works, that simulate solar cell production in-line vacuum, such as the duo solar cell manufacturing system of Midsummer®. In a simple way, this equipment is composed of two chambers, as can be seen in Fig. 4, represented by A and B.

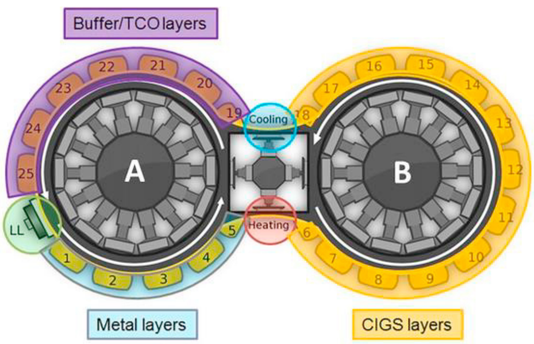

Fig. 4. The schematic process sequence of DUO cell manufacturing system. Transparent conductive oxide (TCO), Cadmium-free $Cu(In,Ga)Se_2$ (CIGS) solar cells, load-lock (LL) [74].

It has 25 cathodic spray stations, own cooling and heating systems and the cells are loaded and discharged using an automated arm. In this study, for solar cells with a total area of 1 cm^2, values of 15.1% efficiency were obtained and for a total area of 225 cm^2, values of 13.2% efficiency were achieved [74]. The external equipment arise through the conjugation of techniques in order to solve real deposition problems, improving its efficiency.

4. Concluding remarks

The PVD process continues to be subject to huge research. In the last decades, the research interest was more directed to the improvement of the films' properties. However, in the last years, these works have been more focused on the improvement of the reactors with the application of external devices in industrial context.

The market also increasingly calls for multilayer coatings with different properties between bottom and top. Accompanying the technology evolution, the simulations with the help of dedicated software begin to be a reality. One of the industry concerns is also to optimize the energy consumption of the PVD process since it has a higher consumption when compared to the CVD process. The studies show that the reduction of the energy consumption in the magnetron processes must focus on the coating step since this one is the largest energy consuming in the whole process.

The DC source continues to be the most widely used source in the sputtering magnetron. The RF source is less used although the appearance of the MF source has brought new opportunities, allowed the combination of the two sources and led to the appearance of new techniques such as DAS that allow for reducing the heat load in the substrate. External devices have been used for the improvement of PVD techniques in particular in the HiPIMS/HPPMS method, advancing coatings deposition processes. This technology presents great potential in the coatings area because it allows significantly higher ionization rates and higher charge states of the target ions. The concerns of the industry have been accompanied by researchers who increasingly try to give answers taking into account the industrial requirements. New developments are expected as technology advances in deposition systems.

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