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Types of Physical Vapor Deposition: A Review

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Abstract

Physical vapor deposition (PVD) methods have attracted more attention through recent years. PVD methods have applied in various fields such as electronic devices, optical coatings, biomedical implants, aerospace applications and decorative parts. The principle of PVD method is depositing a thin film by intensifying material from the target on the substrate in vacuum or inert gas. This article reviews PVD methods with respect to principles, types, characteristics, and field of application. Three methods of PVD, such as thermal evaporation, sputtering, and pulsed laser deposition will be demonstrated with details.

Keyword: Evaporation, Deposition, Sputtering, Substrate, Target

1.Introduction

There are a variety of surface alloying and coating methods extending from plain implementation of paints to others such as electroplating, nitriding, boronising[1]. These methods have many limitations; thus, advanced methods have been developed such as chemical vapor deposition (CVD), physical vapor deposition (PVD), spraying, as well as surface modifications by surface melting, and heat treatments [2]. The classification of surface modification methods is represented in Figure (1).

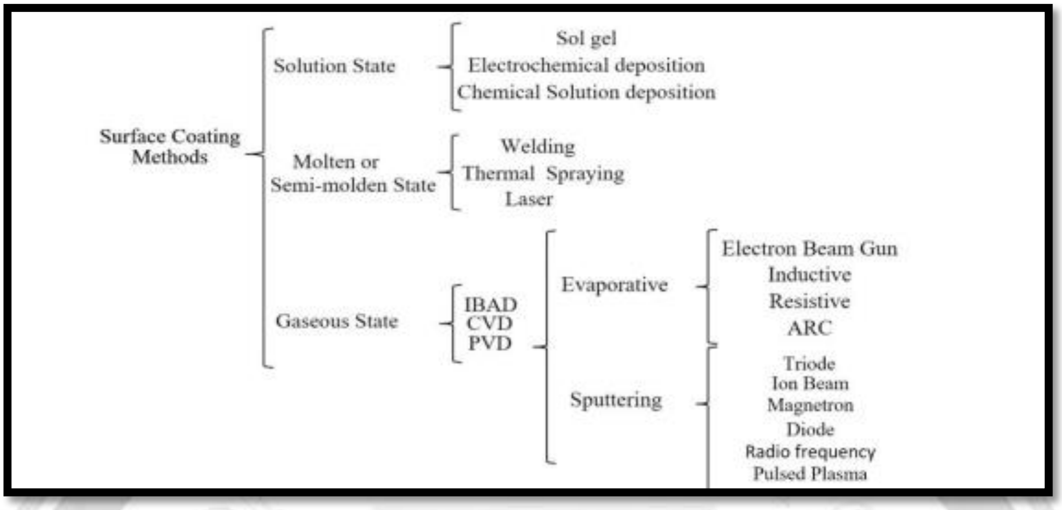


Figure (1):Classification of surface modification methods [3]

The methods of surface modification aim to decrease the dominance of friction, progress wear of surface and increase the resistance to corrosion, variation of the physical features and mechanical features of the constituent [4].

Physical vapor deposition (PVD) is a method of deposition thin film whereby the layer which covers a surface is formed on the substrate material atom by atom [5]. In PVD method the material is vaporized from a solid or liquid source in the form of atoms or molecules and transported in the form of a vapor through a vacuum or low pressure gaseous (or plasma) environment to the substrate, where it condenses [6].

Thin films often have more than one layer which range in thickness ranging from a few atomic layers to film several microns thick. PVD techniques produce new properties of transition zone between substrate and coated layer. The properties of films can be affected by the substrate material [7]. PVD process could be applied in a vacuum environment and others different forms of environments, such as inert gas, an electrolytic or plasma conditions. Deposition with vacuum reduces the contamination to very low level [6].

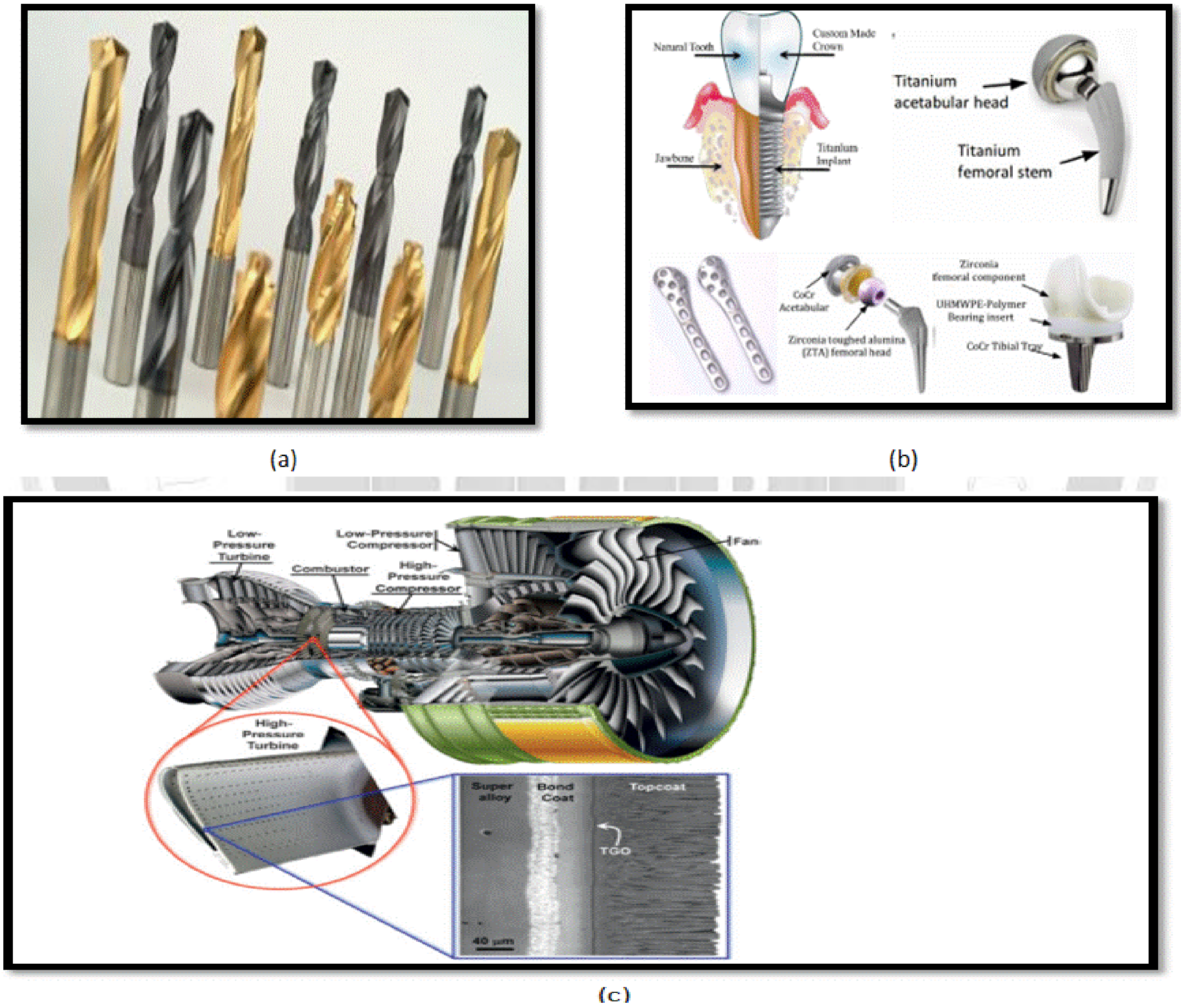
Methods of (PVD) depend on forming atoms or molecular layers on substrate. Primarily, layers of a single metallic element were evaporated and deposited on a substrate under vacuum conditions without demanding a chemical reaction [8]. Currently, organic and inorganic compounds are used in PVD as single metals or alloys. Depending on the differences in atmospheres, vapor source heating method, substrate electrical voltage, there are various techniques for PVD. All these factors take part in changing the structure, properties, and deposition rate of the coating [9].

PVD methods produce thin films with thickness from 0.1 μm to 0.1mm while chemical vapor deposition method produces a wide range layer with thickness may reach 1mm [6]. The coatings produced by PVD methods have excellent adhesion and the layers are identical and well controlled morphology, designed structures, in addition to diversity of materials and properties [7].

PVD methods are applied in the semiconductors industry, aerospace industry, automotive industry, medical devices, and cutting tools. Machining tools are the most predominant applications of PVD methods as observed in Figure(2-a) [10]. Medical devices can be deposited by methods of PVD such as: surgical instruments, implantable medical devices and interventional medical devices according to the object and the way of application [11], as shown in Figure(2-b) [12]. Aerospace applications can be used PVD as engine turbine shown in Figure(2-c) [13].

2.Types of PVD Method:

The common categories of PVD can be classified as: thermal evaporation, sputtering, pulsed laser deposition. The methods are represented in Figure (3).



(a) (b)

(c)

Figure (2): Applications of physical vapor deposition: (a)machining tools[10], (b)biomedical applications [12],(c) cutaway view of engine alliance GP7200 aircraft engine [13]

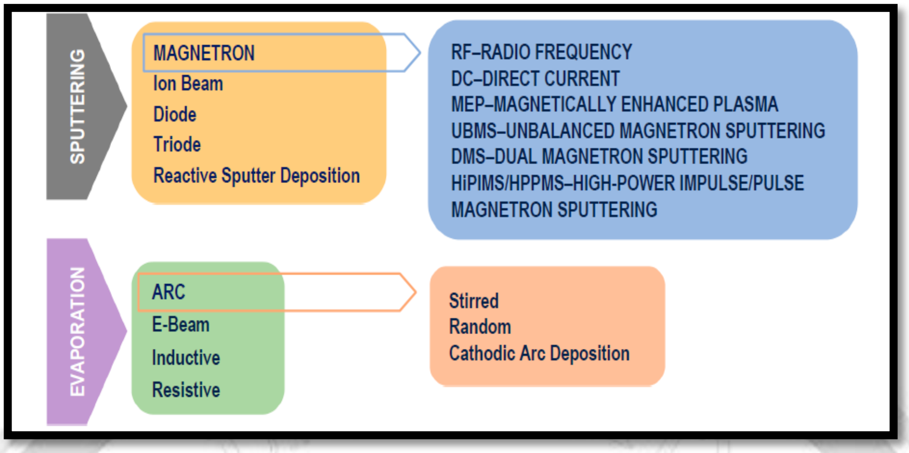


Figure (3): Schema of methods of physical vapor deposition [7]

2.1 **Thermal Evaporation:**

Thermal evaporation progress was prevented by large radiant heat loads and the absence of vacuum materials and methods that withstand heat, especially in demountable designs. Development of thermal evaporation started after 1930 when John Strong worked on aluminization of astronomical mirrors. There were significant risks and challenges in using aluminum in electroplating[14].

This method is one of the most well-known physical deposition methods. This is a simple method, and one can evaporate a large variety of materials on various substrates. After applying heat to the material until it evaporates, then the vapor condenses on surface of substrate forming a coating layer. The vaporization of the material can be done by direct resistance, radiation, electron beam, induction, laser beam or an arc discharge [15], [16]. The charge-holding boat or resistive coil is used in the shape of a powder or solid rod [17]. A container, spiral wire, ribbon or crucible made from W or (Mo, Ta, C, Pt, BN, TiB2) which is heated by a high electrical current and to evaporate material from there [18].

To reach a high melting point of the material the boat or coil is exposed to a large direct current. High vacuum lower than 10-4Pa facilitates the evaporation of material and carrying it to substrate [17]. This procedure is particularly feasible for materials with low fusing temperature [19]. The schematic of the thermal evaporation system is shown in Figure (4).

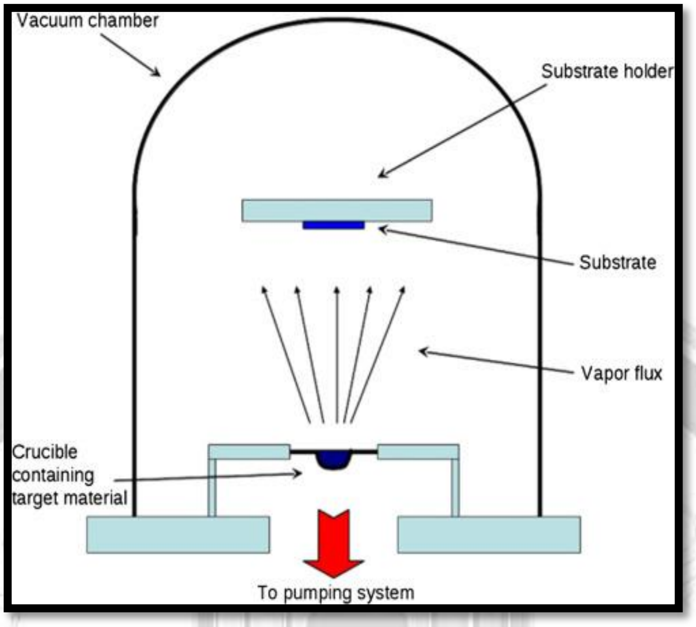


Figure (4): The principle of thermal evaporation [15]

This procedure was enhanced by electron beam evaporation that permitted refractory substances to deposit which has the advantage of directly heating the source material without heating the crucible which can be water cooled to prevent damage. This method is commonly used for the deposition of optical coating materials where excellent uniformity of deposition can be achieved over multiple substrates [19]. Electron beam evaporation and resistive heating evaporation are shown in Figure (5).

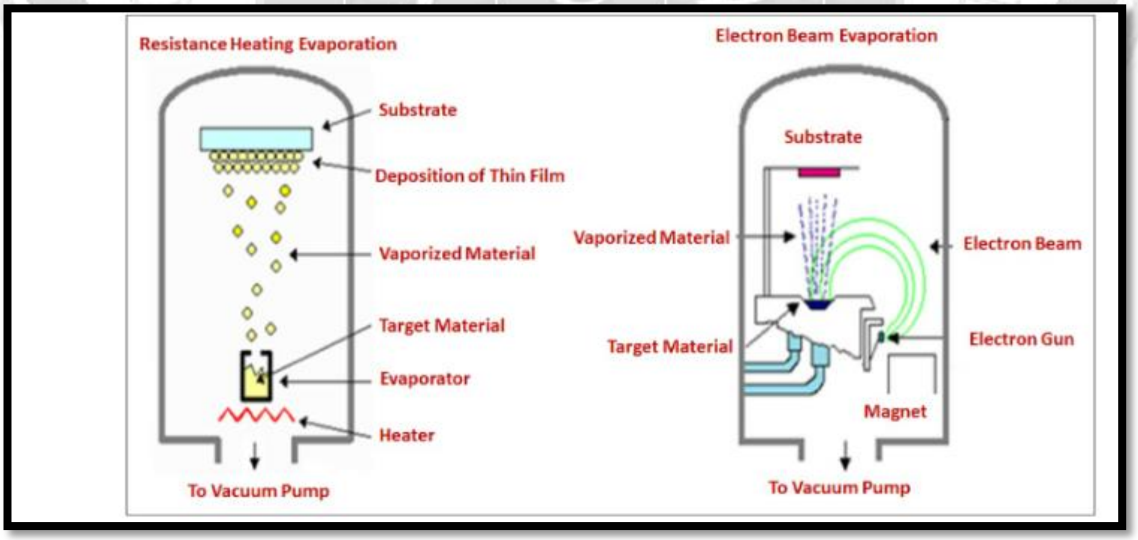


Figure (5): Kinds of thermal evaporation [20]

2.2 Sputtering Method:

Plasma is generated in the space between the target and the substrate by using electrical methods. The beginning of the sputtering method was by Sir William Robert Grove who invented the first fuel cell in 1852. He employed a steel needle as cathode and glossy silver plate as anode and tried in sequences until 16 trails [16], [17], [21].

Sputtering is one of the primary methods used in physical vapor deposition (PVD). Despite having a lower deposition rate compared to the evaporation method, sputtering offers numerous advantages. It allows for the use of a wide range of materials as both sources and films, including metals, semiconductors, insulators, alloys, and compounds. It is also an environmentally friendly process. It ensures a high degree of film adhesion and uniform thickness over large areas. The entire surface of the target is the source of deposition. The important applications of sputtering method are shown in Figure (6) [22], [23].

The sputtering method is used for patterning semiconductor wafers, micromachining, depth profiling, cleaning the surface and known as sputter etching as well as applications which require careful microscopic erosion of a surface [22], [24].

The ejection of atoms from the superficial layer of target by bombing of ions (of inert gas) by momentum transfer between the sputter gas and atoms of surface layers of the target is called sputtering method of coating (cathode sputtering). Argon gas is used as working gas in the deposition chamber because the mass of argon is greater than that of neon or helium, resulting in higher-energy collisions with the target material. Additionally argon gas is cheaper than krypton and xenon making it the preferred choice for sputtering process [24].

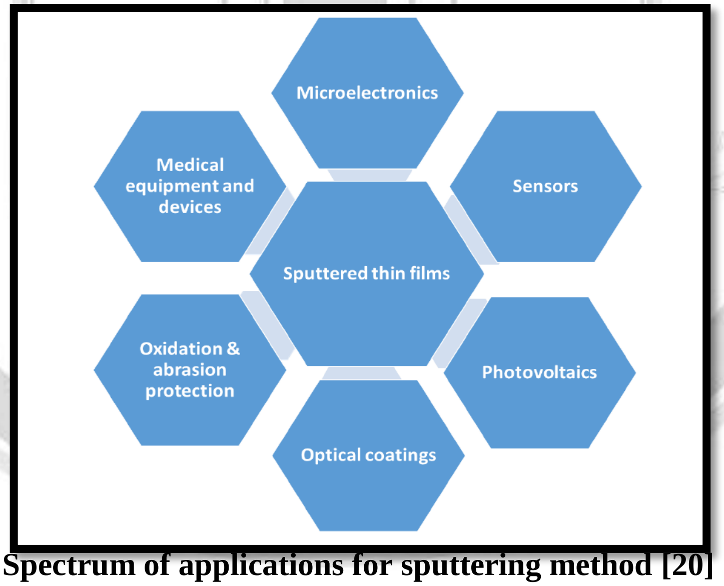


Figure (6): Spectrum of applications for sputtering method [20]

There is an optimal distance to condense the removed atoms from the target on the surface of substrate. The sputtered species are composed of neutral atoms with a small fraction of ions and electrons [22]. Sometimes clusters of atoms are formed in the sputtering process. The films deposited in this technique are predictable and stable [24].

2.2.1 Steps of Sputtering:

The sputtering process involves four steps, which are highly important:

1. Ramp up: this step includes preparing the vacuum room by piecemeal increasing of the temperature through special heating technique. The vacuuming begins at the same time as the temperature rises, so when the room becomes hot enough, the pressure inside room is reduced. Pressure reduction is achieved through a primary vacuum which reduces pressure to 10^{-5} bar, and high vacuum by second pump produces 10^{-7} bar.
2. Etching: In this step ions from plasma bombard the surface of substrate to clean this surface of contamination and enhance the adhesion to the deposited film.
3. Coating: the coating material is deposited onto the surface layer of the substrate.
4. Ramp downstage: this step involves restoring the vacuum chamber to atmosphere conditions [7], [25]. These steps are illustrated in Figure (7).

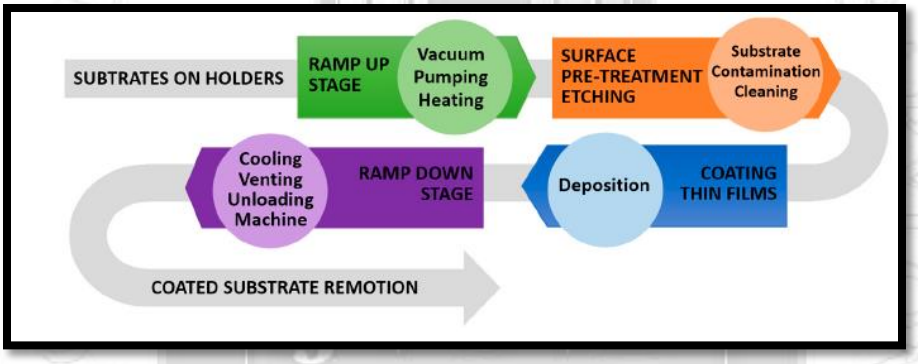


Figure (7): The main steps of sputtering process [7]

2.2.2 The Mechanism of Sputtering:

The sputtering method can be classified into two styles as in Figure (8). When heavier ions collide with a rigid surface layer, they transfer their energy to the surface layer, causing the collision to occur in successive steps. The ejection of atoms from the target is a result of the collision as mechanism (I) develops. Furthermore, incoming light ions cannot produce enough energy to create a collision cascade. The light ions reflected from the target and hit the atoms close to superficial layer, and those atoms may depart from the target if they have sufficient energy to overcome the superficial layer barrier as in mechanism II. So, mechanism No. II becomes more predominant when the ions become lighter. When using ions with moderate mass as the Ar+ the two mechanisms contribute to the actual sputtering process [5], [26].

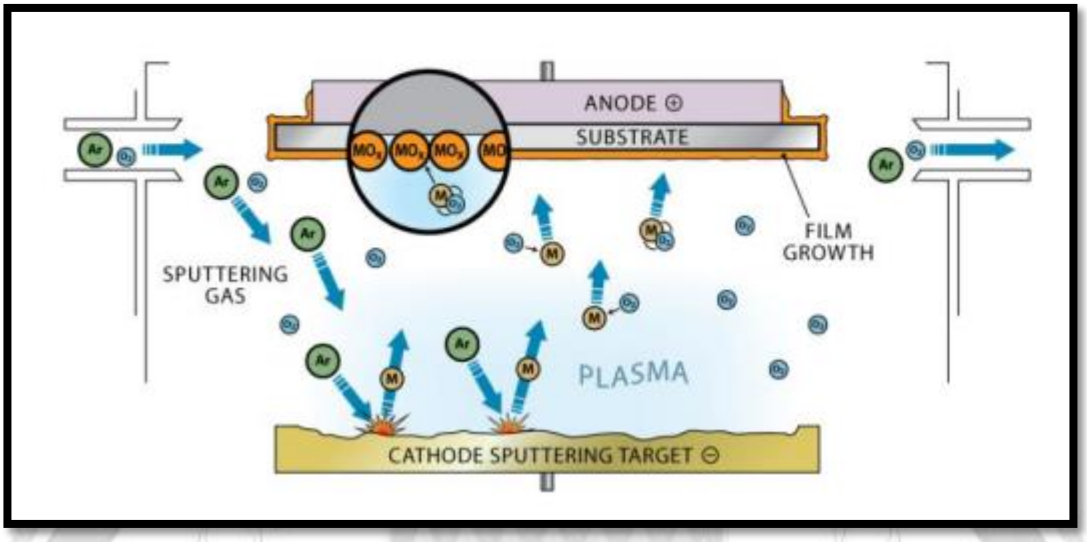


Figure (8): Schematic diagram of the sputtering mechanism [23]

2.2.3 Types of Sputtering:

Several kinds of sputtering have the same mechanism but in various styles are demonstrated as follow:

1. **Direct current (DC) diode sputtering:** This type of sputtering system is the simplest, where two electrodes are placed opposite each other as one opposite one a vacuum chamber. Noble gas, such as Ar, is used to fill the chamber. This type of sputtering cannot work on an insulator, because a positive surface charge would grow on the front side of insulator immediately [22].

2. **Radio Frequency (RF) –diode sputtering**: it is proper for insulators. The power supply for this type produces high frequency approximately 13.6MHz. This type is faster than DC sputtering with higher plasma density and larger ion currents [22]. This system produces enough energy for oscillators of electrons that leads to ionization collisions and maintains a self-sustained output [23] .

3. **Magnetron sputtering:** this type plays an important role in the most sputtering applications with low pressure. There are two designs: a cylindrical magnetron and a planar containing magnetron, as described in Figure (9). The surface of cathode and the field of magnetic are set parallel to each other [22]. The conductive materials can be coated using direct current (DC)

power supply and insulators can be deposited using radio frequency (RF) power supply. This method also has two configurations as balance and unbalanced [9].

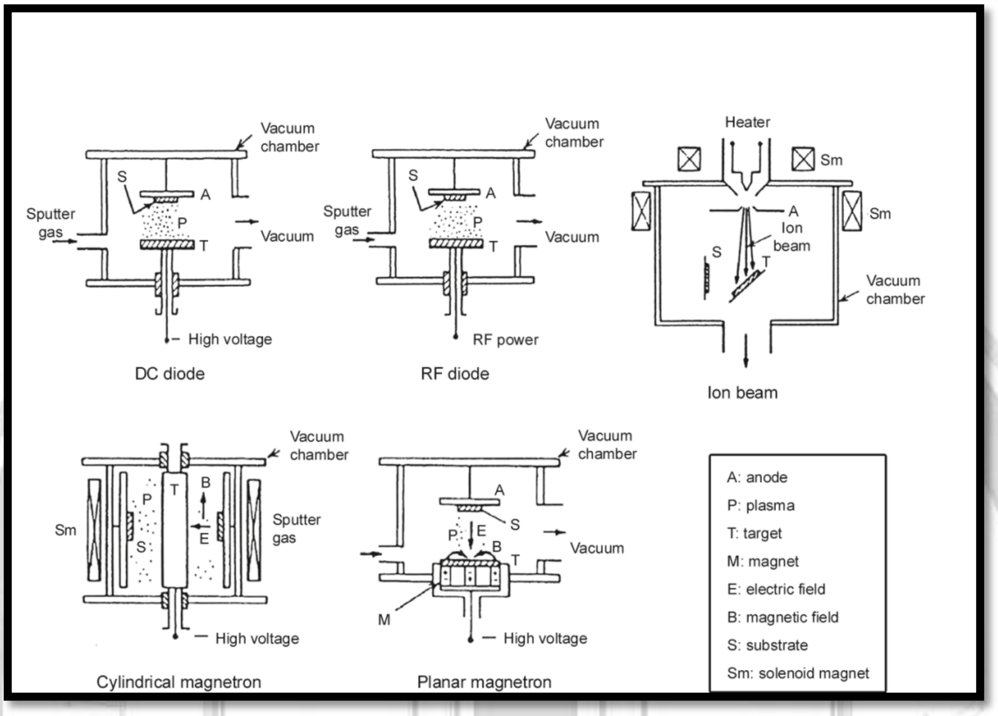


Figure (9): Sputtering deposition systems [22]

There are new techniques depending on magnetron sputtering such as: dual magnetron sputtering (DMS), reactive bipolar pulsed dual magnetron sputtering (BPDMS), modulated pulsed power magnetron sputtering(MPPMS),high power impulse magnetron sputtering HiPIMS , high power pulse magnetron sputtering HiPPMS, and dual anode sputtering (DAS) [26].

4.The ion beam sputtering system: In this system the ions produced come from source outside the sputtering chamber. The systems of ion beam sputtering are used for thin film deposition and sputter etching for semiconducting devices [22].

5. Reactive sputtering: This type is used for making compound thin films. Through sputtering, nitrogen gas or oxygen gas as the reactive gas is introduced to the deposition chamber and reacts with the target material forms a compound that deposits on the surface layer of the substrate [9].

2.3 Pulsed Laser Deposition (PLD):

Smith and Turner were the first to employ PLD in 1965 to produce thin films of semiconductors and dielectrics using a ruby laser. The laser source is positioned outside the deposition chamber. PLD procedure can be done in ultra-high vacuum or in a controlled gas atmosphere. The particles generated by laser ablation have large kinetic energy up to keV. In this procedure, a thin film with high adhesion is deposited at a lower temperature compared with other procedures. Inside the vacuum chamber (UHV chamber), targets are hit a 45° angle by a high energy pulsed laser beam [27].

The interaction between the laser beams and solids plays an important role in various domains containing solids processing, laser-induced mass spectrometry and target film [9]. The laser elevates the target surface temperature to the level of vaporization. Ejected plumes of evaporated material make the collet on the substrate [27].

There are two characteristics that make PLD of great importance when compared to thermal evaporation or sputtering. First of them, a smaller magnitude of material growth during few microseconds. The second is that the growth process is stoichiometric because of the strong heating of the target and the short duration of time [28].

The outcome of irradiating a rigid material or fluid using a strong beam of laser is the evaporation of a restricted amount of substance upon the surface layer of part, and its expulsion from the target material. Produced vapor comprises collected atoms, molecules, ions and electrons. The precise rate and kinetic energy are determined by the laser parameters (intensity, wavelength, pulse width) as well as the target sample. The subsequent repetition of laser pulsing and vapor plumes deposit material onto the surface, forming a so-called thin film [27, 29].

Various factors influence the quality and volume of deposited film as type and temperature of substrate, values of kinetic energy, and speed of components in the plume. This might be further influenced by the excitation wavelength chosen, the strength of laser beam, the duration of pulse exposure, and the energy (along with availability of a background gas), and additional activation of the plasma between the target and substrate [29].

2.3.1 Steps of Pulsed Laser Deposition

The PLD process consists of several steps which are illustrated in Figure (10): 1. Interaction of laser beams with the target 2. Expansion of plume 3. Deposition of the film.

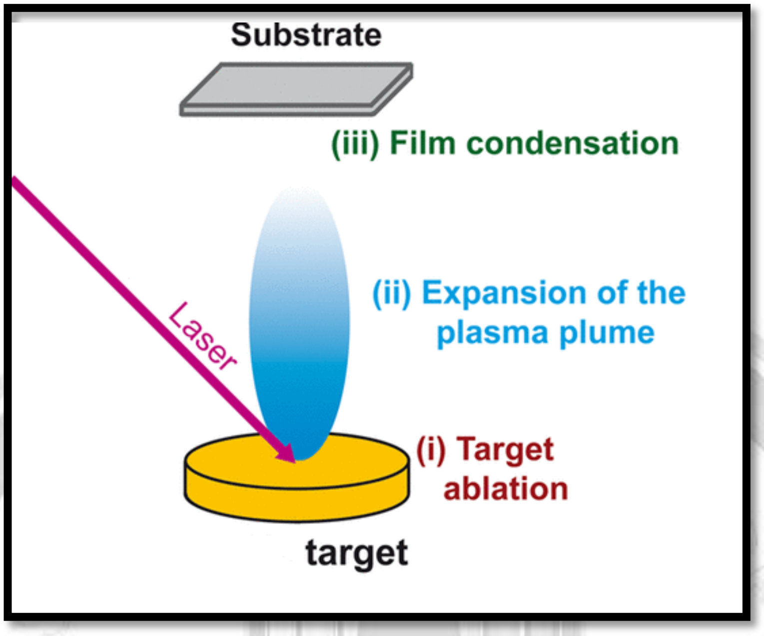


Figure (10): The steps of PLD process [24]

Each step is conditional on the substance itself and experimental agents such as: the wavelength of laser, pulse width, pressure, background gas, type of material and temperature. The types of lasers used in PLD research diverge in their wavelength, ranging from the 10.6 µm wavelength of a CO2 laser beam, which is the near mid-infrared range, and increase to wavelength of the Nd-YAG laser that nearly infrared and visible, having fundamental and second harmonic outputs at 1064 nm and 532 nm, respectively, down to the UV. There are many types of laser such as excimer lasers, operating at several UV wavelengths, such as 308 nm (XeCl), 248 nm (KrF), 193 nm (ArF) and 157 nm (F2) [29] and Figure (11) depicts the PLD system.

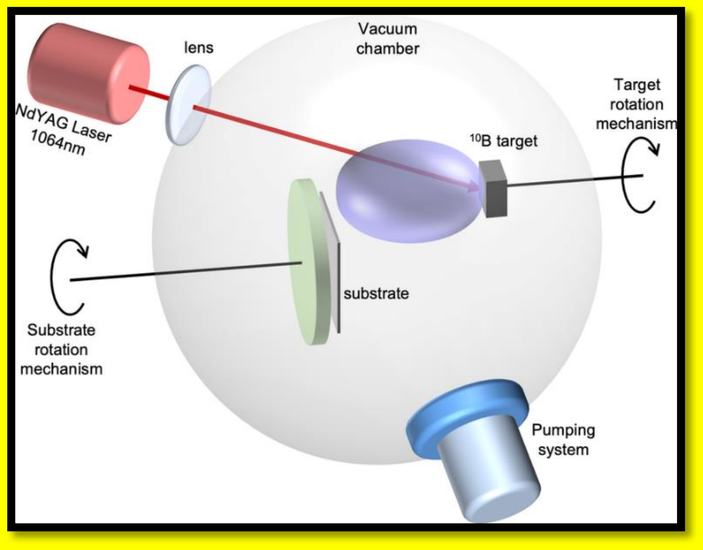


Figure (11): The main elements in PLD system [29]

2.3.2 Advantages and Applications of PLD

The advantages of PLD are the stoichiometric transfer of the material from the target, the generation of energetic species, the hyperthermal reaction between ablated cations and the background gas in the ablation plasma, as well as compatibility with background pressures ranging from ultrahigh vacuum to 133 Pa [30]. The time of each step differs from that of the other steps. While laser pulse needs nanosecond to interact with target, the expansion of the plume lasts about microseconds. The last step of film deposition and growth continued until the next pulse is output within milliseconds [29]. Applications of PLD are ferroelectric thin films, multiferroics, superlattices, engineered interfaces, photovoltaics , photocatalysis, conducting thin films for electrodes [30], sensors, solar cells, bioactive coatings for implants, and in lithography [31].

2.2.4 Growth Modes of Thin Films

Generally, there are three modes of thin film growth, namely island or the Volmer–Weber mode, layer-by-layer or the Frank–van der Merwe mode and layer plus island or the Stranski–Krastanov mode. Island or the Volmer–Weber mode: an island growth occurs when the cohesion between the atoms of the target material is greater than the adhesion between the target atoms and the substrate. As a result, the adatoms (atoms deposited on the surface of the substrate) are more bound to each other than to the substrate, hence forming clusters as shown in Figure(12-a) [32]. This mode of growth is characterized by Layer-by-layer or the Frank–van der Merwe mode: layer-by-layer growth occurs when the adhesion between the adatoms and the substrate is greater than the cohesion between the adatoms.This mode of growth generally results in 2D growth with the adatoms forming smooth monolayers on the surface of the substrate [30] (Figure 12-b). Layer plus island or the Stranski–Krastanov mode: layer plus the island growth mode occurs when islands are formed after the formation of one or two monolayers on the surface of the substrate (Figure12-c)[30].

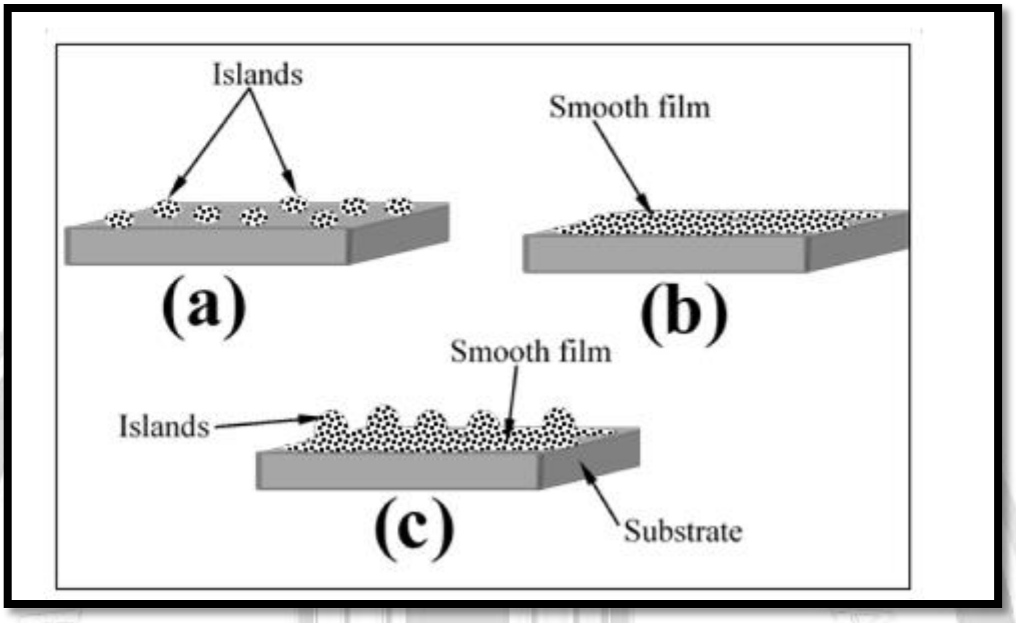


Figure (12): Growth modes by thin film deposition [33]

2.2.5 Types of PLD method

The principal types of PLD are:

1. **Scanning multi-component pulsed laser deposition:** This method realizes uniform depositions of desired coatings by a modified pulsed laser deposition process, more desirably with a femto-second laser-system. By this method multi-component coatings (single or multilayered) are deposited onto substrates via laser induced ablation of segmented targets, characterized by horizontal line-scanning of a focused laser beam over a uniformly moving target's surface as shown in Figure(13-a). This process allows us to deposit the desired composition of the coating simultaneously, mixed from the different segments of the target, by variation of the scan line referring to the geometry of the target. The sequence and thickness of multilayers can easily be adjusted by target architecture and motion, enabling inter/intra layer concentration gradients and thus functional gradient coatings [34].

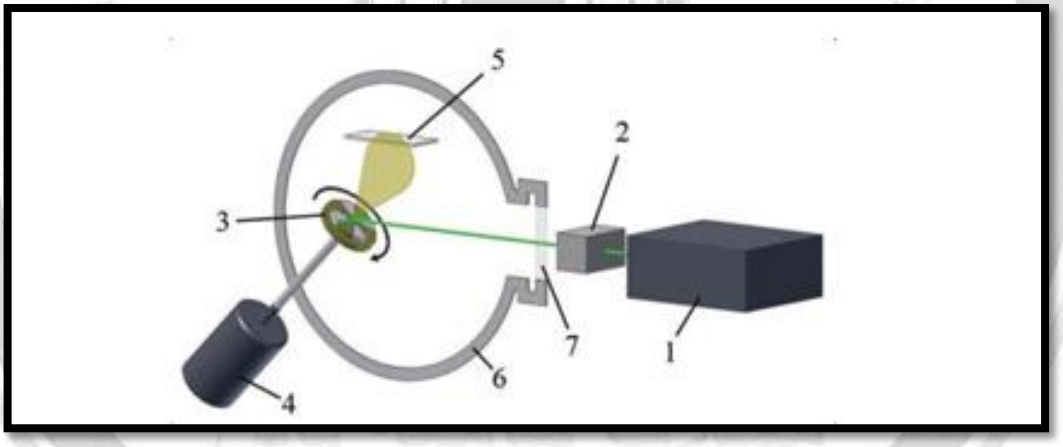
2. **Matrix assisted pulsed laser evaporation (MAPLE)** has many benefits over conventional methods for manufacturing coatings containing pharmacologic agents on medical devices. In particular, the thickness of the coating that is applied to the surface of the medical device can be tightly controlled. MAPLE process involves laser evaporation of a frozen solution containing the pharmacologic agent in a matrix composed of a volatile solvent. Solvents used with MAPLE have a high vapor pressure and preferentially absorb the energy associated with laser wavelength; the absorption of laser energy by the solvent matrix instead of the pharmacologic agent protects the agent from photodegradation. The laser ablation of the

solvent matrix carries molecules of the pharmacologic agent into the vacuum where the high vapor pressure solvent is vaporized and removed. Thus, the pharmacologic agent forms most of the molecules deposited onto the substrate [35].

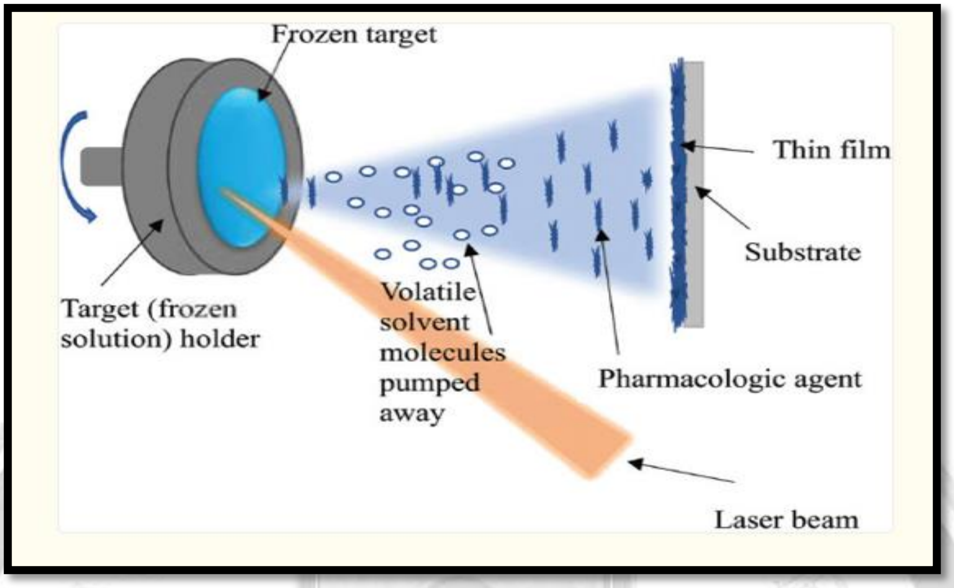
3.**Combined PLD and magnetron sputtering:** The successful demonstration of a hybrid system that combines pulsed laser deposition (PLD) and magnetron sputtering (MS) to deposit high quality thin films is shown in Figure(13-c). The PLD and MS simultaneously use the same target, leading to an enhanced deposition rate [36].

4.**Multi-beam PLD:** It involves a simultaneous deposition of a thin film from a multitarget of dissimilar material by mixing more than one plume. This is usually achieved by the observation of different targets with a different laser beam. A schematic showing a typical multitarget PLD experimental set-up is presented in Figure(13-d). It is comprised of three rotatable targets, which can be ablated using three different lasers [33].

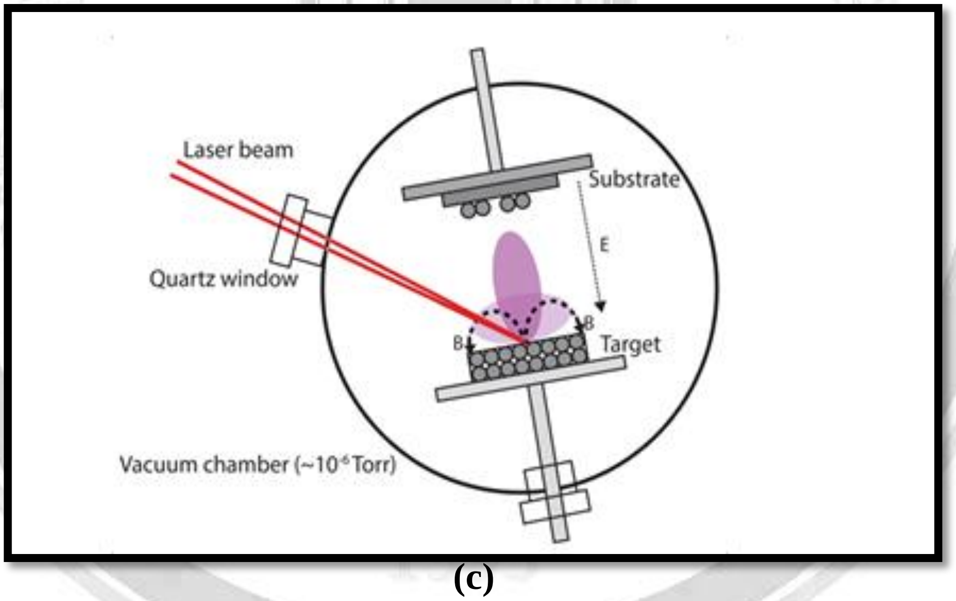
5.**Off-axis PLD**: This manner is used for ferroelectric oxide thin films. The substrates are mounted “upside-down” and are rotating. The maximum substrate size is 2 inches in diameter [37]. Thin films deposited using the off-axis technique have shown superior qualities such as about seven times thinner, 15 nm compared to 100 nm obtained from the film deposited using on-axis setup and uniform films with a larger film area, up to 2 inches (~5 cm) in diameter [33].



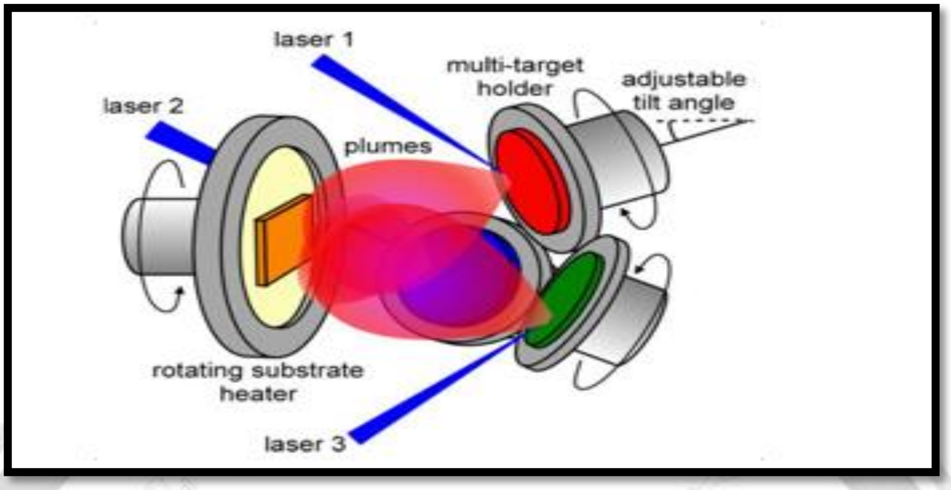
(a)


Frozen target
Thin film
Substrate
Target (frozen solution) holder
Volatile solvent molecules pumped away
Pharmacologic agent
Laser beam

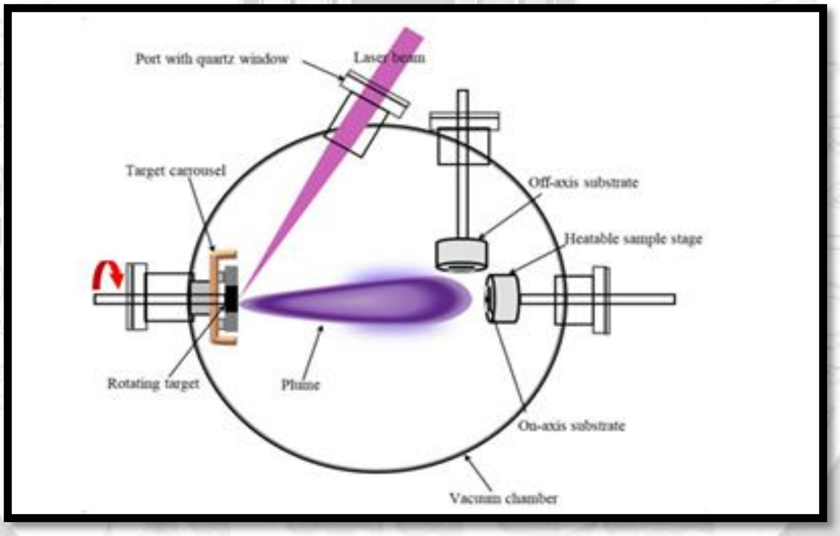
(b)


Laser beam
Substrate
E
Quartz window
B
B
Target
Vacuum chamber (~10-6 Torr)

(c)



(d)



(e)

Figure(13) : Rcent types of PLD: (a) scanning multi-component PLD (34), (b) matrix assisted pulsed laser evaporation (MAPLE) (35),(c) combined PLD and magnetron sputtering,(d) multi-beam PLD,(e) off-axis PLD (33)

A summary of three types of PVD, focusing on efficiency and cost, material suitability, typical applications, and key decision factors is listed in table 1.

Type of PVD	Efficiency and cost	Material Suitability	Typical applications	Key decision factors
Thermal evaporation	Noted for simplicity and cost-effectiveness, ideal for small-scale operations and research	Suitable for a wide range of materials including metals and organics	Microelectronics thin films, resistors, dielectrics	Cost simplicity, research and development focus
Sputtering	High material utilization but more expensive due to equipment complexity	Versatile, works with metals, ceramics, and polymers	Electronics, coatings for glass, and solar panels	Efficiency, material versatility, equipment cost
Pulsed laser deposition	Precise control over film properties, high costs associated with laser equipment	Best for complex oxides and precision applications	Advanced electronics, photovoltaics, research applications	Precision, cost of equipment, research focus

3-Conclusions:

PVD is a deposition method as a surface modification. The thermal evaporation method with electron beam is suitable for metals with high and low melting point. The sputtering method is characterized by good adhesion, low-stress films, and high film density and purity. It can be produced thin film for polycrystalline. The pulsed laser deposition method is described by versatility in material deposition, stochiometric transfer, high-quality films, and reduced contamination. It is very favorable to achieve fine structures and high mechanical performance.

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انواع الترسيب الفيزيائي بالبخار: مراجعة

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الخلاصة

تمتلك طرق الترسيب الفيزيائي بالبخار اهمية كبيرة في السنوات الاخيرة . حيث يتم تطبيق هذه الطرق في مجالات متنوعة مثل المعدات الااليكترونية و الطلاءات البصرية والزروعات الطبية الحيوية و تطبيقات الفضاء و للديكور. اساس طريقة الترسيب الفيزيائي للبخار معتمد على ترسيب طبقة من مادة الهدف على المادة الاساس اما في جو مفرغ من الهواء او في وسط محاط بغاز خامل. يهدف البحث الى استعراض طرق الترسيب الفيزيائي للبخار من حيث الاساس والانواع و المزايا و اتجاه التطبيق. سيتم مناقشة التبخير الحراري و التشتيت و الترسيب بالليزر التبضي بشكل مفصل.

الكلمات الدالة:– التبخر، الترسيب، التشتيت، الاساس، الهدف