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# FROM EXPERIMENTAL RESEARCH METHODS: ADVANTAGES AND DISADVANTAGES OF THE MAGNETRON SPUTTERING METHOD

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**Abstract.** Magnetron sputtering vacuum deposition (MSVD) has undergone significant development since its inception. This review examines the evolution of MSVD, its fundamental principles, various techniques (including jet sputtering, pulsed magnetron sputtering, and high-power pulsed magnetron sputtering), and its wide range of industrial applications.

While highlighting key advantages such as high deposition rates, versatility in material selection, and precise control over film properties, the review also addresses inherent challenges, including low target utilization and plasma instability. A significant portion of the study focuses on the important role of MSVD in the automotive industry, emphasizing its application in producing durable, high-quality coatings for both aesthetic and functional purposes.

In addition, the transition from traditional electroplating methods to environmentally sustainable MSVD technologies is discussed, reflecting the growing demand for cleaner and more efficient manufacturing processes.

**Keywords:** magnetron sputtering, thin films, plasma, vacuum technology, sputtering, semiconductors, electronics, metal oxides

**Annotatsiya.** Magnetron purkash orqali vakuumda qoplama hosil qilish (MSVD) usuli yaratilganidan buyon sezilarli darajada rivojlandi. Ushbu sharhda MSVD ning evolyutsiyasi, asosiy ishlash tamoyillari, turli texnologik usullari (jumladan, jet-purkash, impulsli magnetron purkash va yuqori quvvatli impulsli magnetron purkash) hamda uning keng koʻlamli sanoat qoʻllanilish sohalari tahlil qilinadi.

Tadqiqotda yuqori qoplama hosil qilish tezligi, material tanlashdagi moslashuvchanlik va yupqa qatlam xossalarini aniq boshqarish kabi asosiy afzalliklar yoritiladi. Shu bilan birga, nishon materialidan foydalanish samaradorligining pastligi va plazma barqarorligidagi muammolar kabi mavjud cheklovlar ham koʻrib chiqiladi.

Maqolaning muhim qismi MSVD usulining avtomobil sanoatidagi oʻrniga bagʻishlanib, uning estetik va funksional jihatdan yuqori sifatli hamda chidamli qoplamalar olishdagi qoʻllanilishi tahlil qilinadi. Shuningdek, an’anaviy elektroximik qoplama usullaridan ekologik jihatdan barqaror MSVD texnologiyalariga oʻtish jarayoni ham yoritilib, barqaror ishlab chiqarishga boʻlgan ortib borayotgan talab aks ettiriladi.

**Kalit soʻzlar:** magnetron purkash, yupqa qatlamlar, plazma, vakuum texnologiyalari, sputtering, yarimoʻtkazgichlar, elektronika, metall oksidlar

**Аннотация.** Метод вакуумного напыления с использованием магнетронного распыления (MSVD) претерпел значительное развитие с момента своего появления. В данной работе рассматриваются эволюция MSVD, его основные принципы функционирования, различные технологические методы (включая струйное распыление, импульсное магнетронное распыление и высокомощное импульсное магнетронное распыление), а также широкие области промышленного применения.

В исследовании освещаются такие ключевые преимущества, как высокая скорость осаждения покрытий, гибкость в выборе материалов и точное управление свойствами тонких пленок. Одновременно рассматриваются и существующие ограничения, включая низкую эффективность использования мишени и нестабильность плазмы.

Особое внимание уделяется роли MSVD в автомобильной промышленности, где данная технология применяется для получения долговечных и высококачественных покрытий, выполняющих как эстетические, так и функциональные задачи. Также рассматривается переход от традиционных гальванических методов к экологически устойчивым технологиям MSVD, что отражает растущий спрос на устойчивые производственные процессы.

**Ключевые слова:** магнетронное распыление, тонкие пленки, плазма, вакуумные технологии, напыление, полупроводники, электроника, оксиды металлов

## INTRODUCTION

In the context of the depletion of natural resources and the continuous pursuit of improved quality of life and environmental protection, the development and application of new materials with unique properties have become increasingly important for modern industry. Contemporary technologies in nanoelectronics, energy, medicine, and other fields impose high requirements on the surface properties of engineering materials, as well as on the functional thin films applied to them. Therefore, modern materials science is focused on developing and enhancing the functional properties of thin films through advanced manufacturing methods and optimized material configurations.

It is well known that the most significant mechanical wear occurs at the surface of materials. In addition, chemical corrosion becomes particularly pronounced when materials are exposed to aggressive environments. Consequently, research efforts are increasingly directed toward improving surface characteristics and performance through the application of advanced surface modification techniques.

Recent studies have focused on the formation and characterization of innovative nanostructured thin films deposited on a wide range of materials for applications in the automotive, aerospace, shipbuilding, biomedical, electronics, and energy industries, among others. Electrical machines, apparatus, and equipment used in these sectors often operate under demanding conditions, including high current, elevated temperatures, high gas pressure, and accelerated wear. Such conditions can result in substantial material degradation and potential failure of components with unprotected surfaces.

To enhance durability, various metal and ceramic protective thin films are widely employed. These coatings not only provide corrosion resistance but also improve key properties such as hardness, strength, electrical conductivity, insulation, elasticity, plasticity, capacitance, and other electrical and mechanical characteristics. Electrical contact systems, which are critical components of electrical circuits and devices, are typically composed of conductive materials such as copper, silver alloys, and gold.

## LITERATURE REVIEW

Currently, physical vapor deposition (PVD) techniques are widely used for the production of thin films in electrical engineering. PVD is considered an economical, reliable, and environmentally sustainable method for coating applications. Various PVD-based methods enable the deposition of thin films with high purity, low internal thermal stress, excellent adhesion, and other desirable properties [1].

Research efforts worldwide are increasingly focused on the development and characterization of oxide- and nitride-based nanostructured thin films. These materials are classified as multifunctional and are widely applied across various industries, with ongoing developments aimed at expanding their use in emerging technological fields. In particular, transition metal nitride thin films have been extensively studied for their tribological properties, which determine their suitability for applications requiring high resistance to mechanical stress and friction.

These films are characterized by high hardness, smooth surface morphology, low friction coefficients, and excellent corrosion resistance. Combined with their ability to maintain mechanical stability at relatively high temperatures, these properties make them highly suitable for use in high-friction environments, as well as in cutting and metal-forming tools [2].

## RESEARCH METHODOLOGY

Thin-film materials play a crucial role in the advancement of modern science and technology. In particular, physical vapor deposition (PVD) methods are widely used for the fabrication of nanoscale structures. One of the most prominent techniques is magnetron sputtering, which enables the formation of high-quality thin films.

Compared to other deposition methods, magnetron sputtering is characterized by high precision, operational stability, and the ability to work with a wide range of materials.

Magnetron sputtering is a physical process in which atoms are ejected from a target material and deposited onto a substrate through ion bombardment. The process can be described as follows:

an inert gas (typically argon) is introduced into a vacuum chamber;
the gas is ionized under the influence of an electric field;
the resulting $Ar^+$ ions are accelerated toward and strike the target material;
atoms are ejected from the target and subsequently deposited onto the substrate surface.

During this process, electrons are confined within a magnetic field, which increases ionization efficiency and enhances the overall deposition rate [3] (Figure 1).

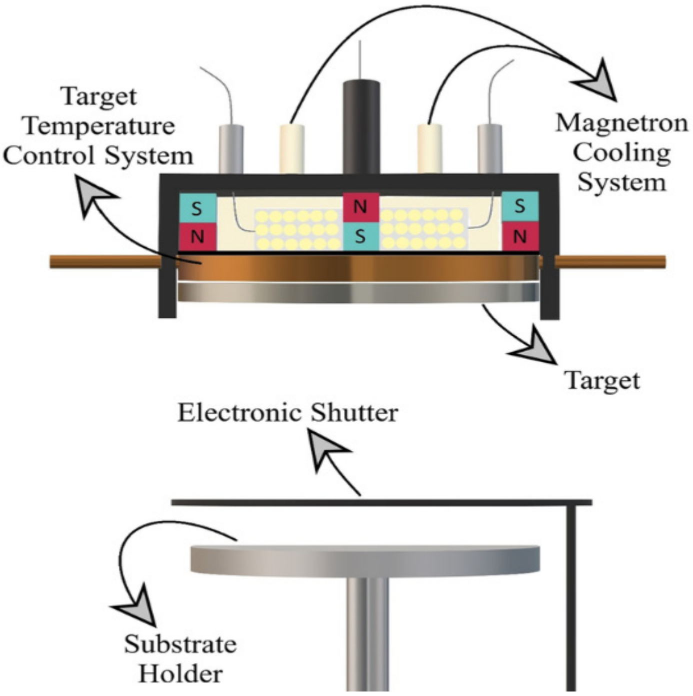

Figure 1. Magnetron sputtering[1]

The development of magnetron sputtering vacuum deposition (MSVD) has progressed significantly since its initial conception in 1852. Over time, it has evolved from a simple method for depositing metal films into a highly sophisticated process with wide-ranging industrial applications. Magnetron sputtering is a subset of physical vapor deposition (PVD) technologies and has become an essential tool for thin-film deposition. This advancement has been driven primarily by developments in vacuum, plasma, and magnetic field technologies.

Today, MSVD is widely utilized due to its ability to deposit films with precise control over nanostructure, chemical composition, and physical properties. This makes it suitable for a broad range of applications, including electronics, optics, energy storage systems, and protective coatings. The continuous evolution of sputtering techniques—such as jet sputtering, pulsed magnetron sputtering, and high-power pulsed magnetron sputtering—demonstrates the method's adaptability and capacity for innovation in response to evolving industrial requirements [4].

It should be noted that PVD processes, in general, have undergone substantial advancements over recent decades, primarily aimed at improving coating properties and increasing deposition rates. These developments were enabled by the integration of technologies that emerged in the 1960s, including plasma technology, vacuum techniques, thermal evaporation, and sputtering methods. As a result, modern vacuum-based coating processes have achieved significantly higher efficiency and reliability.

Magnetron sputtering is one of the most widely used techniques for thin-film deposition. It is based on the principle of ion sputtering; however, in this method, magnets are placed directly beneath the target material. The magnetron configuration is typically considered balanced due to the presence of a horizontal magnetic field.

The generated magnetic field significantly enhances plasma efficiency. It not only traps electrons moving toward the target but also alters their trajectories. Instead of moving directly across the target surface, electrons follow spiral paths, which increases their interaction time with the gas and enhances ionization efficiency. As a result, the sputtering process can be sustained at lower power supply voltages.

The main advantages of the magnetron sputtering technique include a higher deposition rate compared to conventional ion sputtering, improved process efficiency, and reduced substrate damage due to the lower energy of ions (Figure 2).

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[1] Author's development

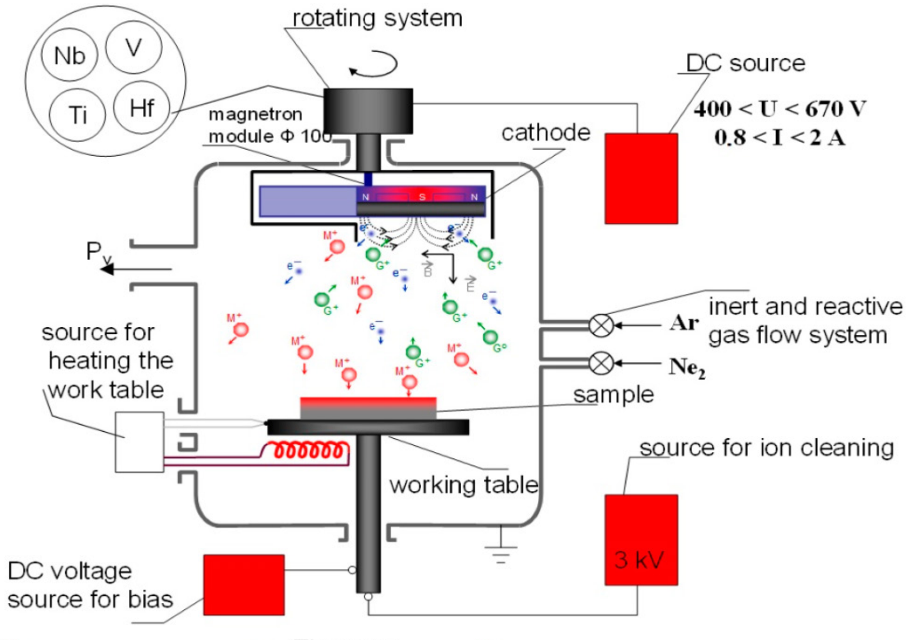

Figure 2. Reactive DC magnetron sputtering scheme[2]

Thin films deposited using an unbalanced magnetron configuration exhibit improved uniformity, stronger adhesion, reduced surface roughness, and more refined crystal structures compared to those produced using a balanced magnetron sputtering configuration.

However, this approach also presents certain limitations. The increased interaction of ions with the substrate leads to higher substrate temperatures, accelerated target wear, and increased interaction of ions with the walls of the vacuum chamber, which may result in a higher risk of contamination [6].

Reactive DC magnetron sputtering can be performed using various magnetron configurations. In this process, a reactive gas (typically oxygen or nitrogen) is introduced into the vacuum chamber during deposition in order to produce transition metal oxides (TMO) or transition metal nitrides (TMN).

The reactive gas molecules interact with the sputtered metal atoms to form compound materials such as metal oxides or metal nitrides. These reactions can occur either in the plasma phase or on the substrate surface. In some cases, contamination or “poisoning” of the target surface may also occur, which requires careful process control.

One of the most critical factors in this technique is the proper selection of the ratio between the inert gas and the reactive gas. This ratio directly influences the stoichiometry and properties of the resulting thin films. An excessive inert gas flow may reduce the interaction between reactive gas species and sputtered particles, while an excessive reactive gas flow may lead to target surface contamination and instability in the deposition process (Figure 3).

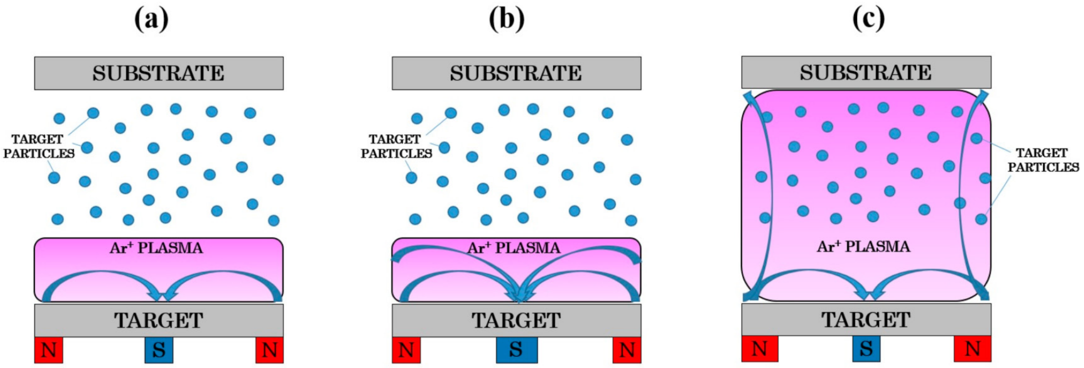

Figure 3. ( a ) balanced magnetron sputtering, ( b ) unbalanced magnetron sputtering with a stronger south pole, ( c ) unbalanced magnetron sputtering scheme with a stronger north pole[3]

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[2] Author’s development

[3] Author’s development

Careful selection of process parameters in magnetron sputtering is essential for the formation of thin films with optimal structure and performance. In particular, the ratio of inert gas to reactive gas plays a critical role, as it can lead to the formation of different crystal phases, some of which may be undesirable for specific applications.

Deposition temperature is another key parameter for achieving high-quality films. It is especially important when materials with significantly different thermophysical properties are used. In addition, temperature can be employed to tailor the microstructure of the deposited layers, including phase composition, crystallographic orientation, grain size, and internal stresses. These characteristics directly influence the functional properties and potential applications of the films [7].

The use of an AC power source results in periodic reversal of electrode polarization, which can influence plasma behavior. However, this alternating polarization is essential for polymer deposition, as it prevents charge accumulation between the target and the substrate.

The key advantages of RF magnetron sputtering include the formation of denser films with smoother surfaces, reduced internal stresses, improved adhesion, and enhanced process control. Importantly, this method enables the deposition of polymer films, which is not feasible with DC sputtering.

High-power impulse magnetron sputtering (HiPIMS), introduced by Vladimir Kouznetsov and colleagues, is an advanced variant of magnetron sputtering.

As a result, a significantly larger fraction of sputtered particles becomes ionized, leading to the formation of a dense plasma. The increased number of charged particles enhances their interaction with the substrate, resulting in films with higher density, improved adhesion, greater purity, and superior mechanical properties.

The high ionization degree also allows for precise control of the deposition process, enabling the fabrication of thin films with tailored structures and advanced functional properties. Another important advantage is that HiPIMS can be implemented on conventional magnetron systems by integrating a high-power pulsed source.

## ANALYSIS AND RESULTS

The global market for magnetron sputtering systems reflects the growing adoption of this technology across multiple industries, including the automotive sector. In 2024, the global market for magnetron sputtering systems was valued at approximately USD 2,523.33 million. Although precise statistics regarding the extent of magnetron sputtering adoption in the automotive industry remain limited, the sector's increasing emphasis on advanced manufacturing technologies indicates a positive development trend.

The demand for high-quality and durable coatings in the automotive industry is a key driver behind the integration of magnetron sputtering vacuum deposition (MSVD) into modern manufacturing processes. At the same time, certain challenges—particularly the relatively high cost of sputtered components—have historically constrained broader market penetration.

For instance, the application of magnetron sputtering can increase the cost of a tool by up to 35%, with an additional cost increase of approximately 8% when combined with gas nitrocarburizing processes. However, these initial investments are often justified by the substantial improvement in performance characteristics. Specifically, tool service life can be extended by up to 32 times compared to uncoated tools, thereby offsetting the higher initial costs and demonstrating strong economic efficiency over time.

Magnetron sputtering is increasingly recognized within the automotive industry for its capability to produce high-performance coatings that meet strict durability and aesthetic requirements. As the technology becomes more cost-effective and its advantages gain broader recognition, its application in industrial coating processes is expected to expand further (Table 1).

Table 1
Effect of magnetron sputtering parameters on layer properties[4]

| № | Spray power (W) | Gas pressure (Pa) | Substrate temperature (°C) | Layer thickness (nm) | Conductivity (%) | Resistivity **(Ω·cm)** |
|---|---|---|---|---|---|---|
| 1 | 100 | 0.5 | 100 | 120 | 82 | $1.8\times10^{-2}$ |
| 2 | 150 | 0.7 | 150 | 180 | 85 | $1.2\times10^{-2}$ |
| 3 | 200 | 1.0 | 200 | 250 | 88 | $8.5\times10^{-3}$ |
| 4 | 250 | 1.2 | 250 | 310 | 90 | $6.2\times10^{-3}$ |
| 5 | 300 | 1.5 | 300 | 380 | 92 | $4.8\times10^{-3}$ |

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[4] Author's development

When the sputtering power was increased from 100 W to 300 W, the film thickness increased from 120 nm to 380 nm. At the same time, optical transmittance improved from 82% to 92%, indicating the formation of a high-quality thin film. The electrical resistivity decreased from $1.8\times10^{-2}$ to $4.8\times10^{-3}$ $\Omega\cdot\text{cm}$, which reflects a significant improvement in electrical conductivity.

An increase in substrate temperature also contributed to the enhancement of the crystal structure. These results demonstrate the high efficiency of the magnetron sputtering method and confirm that thin-film properties can be effectively optimized through precise control of process parameters.

From an industrial perspective, high-power pulsed magnetron technologies show considerable potential, as they continue to stimulate scientific research aimed at improving pulsed deposition techniques. These advanced technologies achieve significantly higher ionization rates—up to approximately 30%—resulting in enhanced ionization of target particles. Among their key advantages are improved film uniformity in complex geometries and excellent adhesion, both of which are associated with high ionization levels.

Based on the discussion presented in this study, the fundamental principle of magnetron sputtering involves the interaction between electrons and argon atoms under the influence of an electric field (E). As electrons move toward the substrate, collisions with argon atoms result in the formation of positively charged argon ions $(Ar^+)$ and additional free electrons.

The generated electrons are accelerated from the cathode and typically move toward the anode under the influence of the electric field. In contrast, the argon ions are accelerated toward the negatively charged target, where they impact the surface with high energy and eject atoms through the sputtering process.

It is evident that magnetron sputtering has undergone rapid development since its introduction and has become widely used, significantly influencing the advancement of other coating technologies. Therefore, it is essential to examine in detail the fundamental advantages and limitations of this method [9].

Magnetron sputtering offers numerous advantages that make it a highly effective method for thin-film deposition across a wide range of applications.

First, it provides a relatively high deposition rate while maintaining a low substrate temperature, thereby minimizing the risk of thermal damage to temperature-sensitive materials. This characteristic is particularly important for applications in electronics and optics, where precise thermal control is required.

Second, the sputtering process is highly versatile, enabling the deposition of a wide variety of materials, including metals, alloys, and oxides. These materials can be deposited individually or in combination, allowing for the fabrication of complex multilayer and composite structures.

Third, thin films produced by magnetron sputtering exhibit excellent adhesion to the substrate. This is due to the relatively high energy of sputtered particles, which promotes strong interfacial bonding.

Finally, the resulting films are characterized by high purity, dense microstructure, and uniform thickness distribution. These properties make magnetron sputtering particularly suitable for critical applications where material integrity, uniformity, and performance are essential [10].

## CONCLUSION AND RECOMMENDATIONS

Magnetron sputtering offers several notable advantages. It enables relatively high deposition rates while maintaining low substrate temperatures, thereby minimizing thermal damage and making it suitable for temperature-sensitive materials. The method supports a wide range of target materials, including metals, alloys, and oxides, provided they can be fabricated into sputtering targets.

Additionally, magnetron sputtering is known for producing films with excellent adhesion, high purity, dense microstructures, and uniform thickness distribution. These characteristics are essential for applications in microelectronics, optics, and functional coatings. The process also ensures high reproducibility, allowing consistent film quality over large surface areas. Furthermore, the ability to adjust film properties—such as grain size and microstructure—through process parameters provides a high level of control. The capability for co-sputtering enables the deposition of multi-component and composite films, and the technology is readily scalable for industrial applications.

Magnetron sputtering remains a highly effective and widely used technique for thin-film deposition due to its high deposition rates, strong film adhesion, and excellent material quality. Its versatility and precise controllability make it particularly attractive for industrial applications. Nevertheless, challenges such as low target utilization, plasma instability, and limitations in processing certain materials must be carefully managed. Therefore, optimizing magnetron sputtering processes requires a balanced approach that leverages its strengths while mitigating its inherent limitations.

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