Iraqi Journal of Industrial Research, Vol. 11, No. 3 (2024)

Open Access

Iraqi Journal of Industrial Research (IJOIR)

Journal homepage: http://ijoir.gov.iq

Bohm Diffusion in Magnetron Sputtering System: A Review Article

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Article information

Article history:
Received: May, 03, 2024
Accepted: June, 17, 2024
Available online: December, 14, 2024

Keywords:
Instability mechanism,
Drift wave instability,
Classical diffusion,
Bohm diffusion,
Magnetron sputtering

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DOI:
https://doi.org/10.53523/ijoirVol11I3ID462

Abstract

This review provides a comprehensive analysis of recent advances in understanding Bohm diffusion in magnetron sputtering systems, a process critical for optimizing thin-film deposition. Bohm diffusion significantly influences the spatial distribution and energy of sputtered particles near the substrate, impacting the overall film quality and performance. The review delves into theoretical models, experimental findings, and computational simulations to uncover the mechanisms driving Bohm diffusion within the plasma sheath. Key factors, such as magnetic field strength, gas pressure, target-to-substrate distance, and plasma parameters, are examined for their impact on diffusion behaviors and, consequently, film deposition outcomes. By highlighting these interdependencies, the review underscores the importance of Bohm diffusion in achieving controlled, uniform deposition essential for high-performance coatings. Additionally, it addresses how advances in understanding Bohm diffusion can enable more effective tuning of deposition processes to meet specific application requirements in fields ranging from electronics to materials engineering. Through a synthesis of current research, this review offers valuable insights to scientists and engineers aiming to enhance the efficiency and precision of magnetron sputtering for tailored thin-film applications, ultimately contributing to the broader field of thin-film fabrication.

1. Introduction

Bohm diffusion plays a crucial role in understanding the transport of charged particles in plasma environments, including magnetron sputtering plasmas. In magnetron sputtering, a plasma is generated near the target material under the influence of a magnetic field, resulting in the removal of the material from the target surface. This technique finds extensive application in thin film deposition for industrial purposes such as semiconductor manufacturing and surface coatings. Named after the physicist David Bohm, Bohm diffusion refers to the spreading of charged particles in a plasma under the influence of electric and magnetic fields. Unlike classical diffusion, which is driven only by random heat, Bohm diffusion includes the electric and magnetic field effects of particle motion together with charged particles cause’s phenomena such as plasma confinement and particle heating. A knowledge of Bohm diffusion is vital for optimizing the efficiency and first-rate of thin-film deposition procedures [1-3]. Theoretical modeling and experimental validation when Bohm diffusion initiates in magnetron sputtering plasmas. Various theoretical methods, which includes kinetic principle and fluid simulations, are used to explain the behavior of charged particles in these complex plasma conditions [4].

Experimental strategies, consisting of laser diagnostics and probe measurements, are used to validate the theoretical predictions and show plasma characteristics that offer better prediction and manage, in order that thin-film deposition processes had been improved in performance, uniformity, and first-class. This expertise allows the manufacture superior plasma sources and the rising applications of loading strategies in electronics, optics, and substances technology [4, 5, 6].

This review aims to offer insights into how Bohm diffusion impacts the efficiency, uniformity, and quality of thin film fabrication, and to provide guidance for optimizing magnetron sputtering techniques for various industrial applications.

2. Instability Mechanism

Plasma instability arises when there are gradients or variations in the plasma parameters (e.g., density, temperature, magnetic field) along the direction of a particle's drift. These gradients can create a situation where particles experience different forces as they drift, leading to a net accumulation of particles in certain regions. This particle accumulation can disrupt the equilibrium of the plasma, leading to the development of instability. Instabilities may be classified according to the type of free energy available to drive them [7]. As a direct result of this, there are six main categories, as shown in Table (1).

Table (1): Types of plasma instabilities [7-9].

No.	Type	Examples	Arises
1	Hydrodynamic Instabilities	Rayleigh-Taylor Instability	Occurs when a lighter fluid is accelerated into a heavier fluid, potentially causing intermixing.
		Kelvin-Helmholtz Instability	Arises at interfaces with velocity shear (e.g., when layers of plasma or fluid flow past each other at different velocities).
2	Electromagnetic Instabilities	Two-Stream Instability	Occurs when two streams of charged particles flow past each other with different velocities, leading to the growth of electromagnetic waves.
		Cyclotron Instability	Involves the interaction of charged particles with magnetic fields, resulting in the amplification of wave energy.
3	Drift Wave Instabilities	Ion Acoustic Instability	Involves fluctuations in ion density and pressure waves in the plasma, often linked to drift in the ion population.
		Electron Drift Instability	Arises when there is a drift in the electron population, often due to an electric field, which can lead to the growth of waves.
4	Resistive Instabilities	Resistive Tearing Mode	Involves tearing or reconnection of magnetic field lines due to resistivity in the plasma, often leading to a drop in magnetic confinement.
		Resistive Drift Instability	Occurs when resistivity affects the motion of charged particles, leading to the growth of drift waves.
5	Gradient-Driven Instabilities	Pressure-Gradient Instability	Caused by spatial variations in pressure, resulting in the growth of waves and turbulence.
		Temperature-Gradient Instability	Occurs when there are temperature gradients in the plasma, leading to the growth of instabilities.
6	Parametric Instabilities	Parametric Decay Instability	Occurs when a wave decays into two or more waves with lower frequencies, potentially affecting energy distribution in the plasma.

3. Drift Wave Instability (Gradient Instability)

The drift wave is defined as a low frequency electrostatic wave that propagates in inhomogeneous plasma in the direction normal to the magnetic field and the existing density gradient. Moreover, this type of wave can occur in any plasma with a gradient of temperature, pressure, magnetic field, and plasma density. In agreement with these gradients, the plasma current, or particle drift wave generates. The kinetic energy of these drifts can be transferred to the wave, thus creating instability is called drift wave instability and sometimes called gradient instability [10]. The physical mechanism of the instability is that, the E × B drift motion of resonant electrons along the density gradient tends to increase (or decrease) the number of those electrons that are decelerated (or accelerated) by the parallel electric field, thereby reversing the relative number of accelerating to decelerating electrons as compared with that in a homogenous plasma [11]. Nevertheless, drift wave instability can be classified into two types: universal drift wave instability and transverse Kelvin-Helmholtz instability. The universal drift wave derives its energy from diamagnetic currents. But, the transverse Kelvin-Helmholtz instability is driven by the kinetic energy of non-uniform plasma rotation. Therefore, the universal drift wave instability occurs in the inner region (where the density gradient is maximum), while the transverse Kelvin-Helmholtz instability is concentrated in the outer region (where a larger electric filed may cause the plasma to rotate non-uniformly). Coming to central point of our concern, let us assume that the plasma has a density gradient (∇n) in the X- direction, the magnetic field is in Z- direction, and the drift wave instability has a propagation velocity in the Y- direction (as we see in Figure (1)). At the beginning, whenever there is a density gradient in plasma, the ions and electrons will be drifted by V_D in the normal direction to both B and ∇n as:

$$\boldsymbol{V_{Di} = +\frac{KT_i}{eB}\frac{\nabla n}{n}\ \hat{Y},\ \ and\ \ \ V_{De} = -\frac{KT_e}{eB}\frac{\nabla n}{n}\ \hat{Y}} \tag{1}$$

Where V_{Di} and V_{De} are the diamagnetic drift velocities for ions and electrons, respectively. From the equations indicated above we can expect that, the drift wave has a phase velocity for order V_{Di} or V_{De}. Theoretically, the transverse drift phase velocity is characteristics by the electron diamagnetic velocity, and the parallel phase velocity is larger than ion thermal velocity and smaller than electron thermal velocity. That means, according to theory, the phase velocity (V_{ph}) of the drift wave instability, is calculated according to the maximum growth rate as predicated by linear theory as:

$$\boldsymbol{V_{ph} = \frac{1}{2}V_{De} = -\frac{1}{2}\ \frac{KT_e}{eB}\ \frac{\nabla n}{n}} \tag{2}$$

They will then obey the Boltzmann relation:

$$\boldsymbol{\frac{n_1}{n_0} = \frac{e\Phi_1}{KT_e}} \tag{3}$$

Where n_1 and Φ_1 are fluctuation plasma density and plasma potential, respectively. Figure (1) shows that, the plasma density is larger than in equilibrium at point A, then is positive and is positive too. Similarly, at point B, the and is negative. The differences in plasma potential between points (A and B) mean that, there is an electric field (E_1) in the Y-direction. As a result of this field, the plasma will be drifted by E × B drift [12, 13]:

$$\boldsymbol{V_{EXB} = \frac{EXB}{B^2}} \tag{4}$$

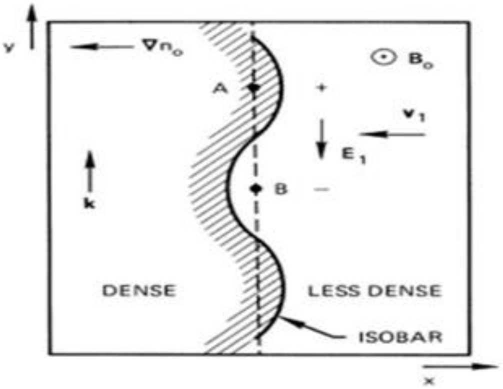

Figure (1): Physical mechanism of collisional drift wave instability [14].

4. Fundamentals of Plasma Diffusion

Diffusion in plasma refers to the process by which particles (typically ions and electrons) move from regions of high concentration to regions of low concentration (density gradient) within a plasma environment. Plasma, often referred to as the fourth state of matter, consists of ionized gas containing free electrons and positive ions. Due to its unique properties, diffusion in plasma exhibits characteristics different from those in solids, liquids, or ordinary gases. There are two mechanisms through which diffusion occurs in plasma [15, 16]:

A) Classical Diffusion: Similar to diffusion in other mediums, classical diffusion in plasma arises from the random thermal motion of particles. Collisions between particles lead to a net movement from regions of higher concentration to regions of lower concentration. The classical diffusion coefficient ($D_{\perp}$) of plasma across a magnetic field in fully ionized plasma can be written as:

$$\boldsymbol{D_{\perp} = \frac{\eta_{\perp}\, n\, K\, T}{B^2}} \qquad \textbf{(5)}$$

Where ($\eta_{\perp} = m/nq^2$) = is specific resistively.

The diffusion of ions and electrons in plasma across a magnetic field can occur in the presence of collisions. But this diffusion (classical diffusion) cannot regard as a serious cause of charge leakage in high temperature experiments. That is due to fact that the rate of collisions between ions and electrons are very low. The classical diffusion is inversely proportional to B^2. For this reason, using a strong magnetic field can diminish this type of loss [8].

B) Anomalous Diffusion: In addition to classical diffusion, plasma can also exhibit anomalous diffusion, where particles move more rapidly than predicted by classical theories. Anomalous diffusion is often attributed to complex interactions such as turbulence, wave-particle interactions, or non-linear effects in the plasma environment [17].

5. Bohm Diffusion

Bohm diffusion (Anomalous Diffusion) refers to a concept in plasma physics that describes the propagation of particles in a magnetic field. In a plasma, energetic particles such as electrons and ions are subject to Lorentz forces due to magnetic fields. This force causes the particles to move in spiral paths around the magnetic field lines. However, particle collisions can generate energy diffusion, where particles move from material-rich regions to even low-density regions along magnetic field lines Bom diffusion occurs when particles in a plasma acquire energy comes from the electromagnetic field of the plasma. This can occur when there are changes or turbulence in the plasma, which can accelerate the movement of the particles. Bohm diffusion is often associated with anisotropic transport because it can be much faster than classical diffusion and is not well understood in all its details Bohm diffusion refers specifically to a diffusion regime in which the diffusion rate is determined by the Bohm diffusion coefficient. These parameters are affected by factors such as the density and temperature of the plasma, which determine how fast the particles diffuse along magnetic field lines due to plasma processes such as collisions, and the intensity of the magnetic field. In plasmas, collisions between charged particles play an important role in expansion. These collisions involve the transfer of momentum and energy, causing the particles to move and redistribute in the plasma [17-22].

Bohm diffusion is the diffusion of a plasma in a magnetic field whose diffusion coefficient is:

$$\boldsymbol{D_{Bohm} = \frac{1}{16}\,\frac{KT}{eB}} \qquad \textbf{(6)}$$

Where: K is the Boltzmann constant, B is the magnetic field strength, T is the temperature, and e is the electron charge. The differences between classical and Bohm diffusion are summarized as shown in Table (2).

Table (2): The differences between classical and Bohm diffusion [12, 21].

No.	Classical Diffusion	Bohm Diffusion
1	Diffusion coefficient (D) is inversely proportional with $\mathbf{B}^2$	Diffusion coefficient (D) is inversely proportional with **B**
2	Diffusion coefficient (D) is dependent on the plasma density	Diffusion coefficient (D) is independent on the plasma density
3	The magnitude of classical diffusion of plasma is less than from magnitude of Bohm diffusion.	The magnitude of Bohm diffusion of plasma is greater than from magnitude of classical diffusion.
4	The classical diffusion is caused by collisions	Bohm diffusion (Anomalous diffusion) is caused by existence of electric field
5	In classical theory, the plasma decay is inversely proportional with time	In Bohm's theory, the decay of plasma with time is exponential.

6. Magnetron Sputtering Plasmas: Basic Characteristics

Magnetron sputtering is a technique used to deposit thin films on substrates for various industries (e.g., semiconductors, optics, coatings, and electronics). It is a physical vapor deposition (PVD) process in which the target material is bombarded with high-energy ions in order to remove atoms or molecules from the surface of the target material. As the ejected particles condense on the substrate a thin film is formed [4].

- **Basic Principle:** In magnetron sputtering, a low-pressure gas (typically argon) is introduced into a vacuum chamber. A high-intensity electric field is injected into the gas, creating a plasma. Plasma contains positively charged ions and free electrons. A negatively charged target (cathode) is injected into this plasma. In the plasma, electrons are accelerated towards the target material by an electric field, and this results in their collision with the atoms of the target. These collisions cause the removal of atoms or molecules from the target, which subsequently traverse through the plasma before depositing themselves onto a substrate nearby (anode) [5].

- **Magnetron Configuration:** In the 1920s, it was found that the magnetic field created by a magnetron sputtering system was capable of trapping electrons near the target. This accelerates the process by enabling more plasma to interact with the surface. The magnetic field is usually produced by an arrangement of permanent magnets or electromagnets around the target area. These magnetic field lines confine electrons, enhancing gas ionization and thereby promoting higher rates of sputtering [11].

- **Controlled Deposition:** Film deposition can be controlled more precisely by magnetron sputtering since the process also modifies the characteristics of the deposited film, including thickness, composition, and microstructure. This technique can be used to rapidly influence deposition, and can be used to produce films with specific desired properties for a variety of applications [11].

- **Uniformity and Thickness:** Magnetron sputtering can be used to obtain thin films that are most accurately deposited on large areas of the substrate. The method reduces scatter, making it easier to determine specific values for properties.

Sputtering occurs when matter in two extreme states interacts with one another, such as a hot plasma and a solid, or when a directed stream of energetic particles hits a surface. The sputtering yield (Y), defined as the number of target atoms (or molecules) expelled per incoming ion [23, 24], is a relevant parameter in this problem. The yield is determined by the incident ion's mass, the target atoms, and the incident ion's energy. This reduction is thought to be achieved by bombarding ions penetrating deep into the target's lattice, where a considerable percentage of their energy is lost to the bulk of the target rather than the surface. This drop occurs at higher energy with heavier bombarding ions [24] as shown in Figure (2).

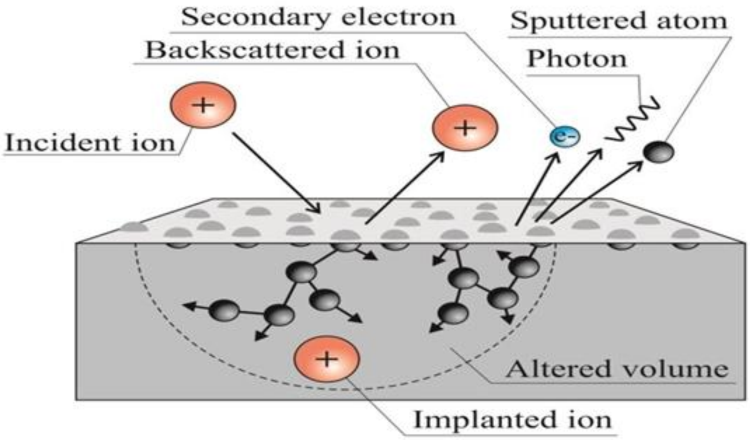

Figure (2): Ion interaction with surfaces [25].

Compared to thermal evaporation, this method offers various advantages, including the fact that the precipitated films have the same composition as the source metal. Since fewer pollutants are able to reach the surface of the substrate in the same period of time, a faster sedimentation rate leads to less incorporation of impurities and the material to be sprayed does not need to be heated.

7. Experimental Techniques for Studying Bohm Diffusion

Studying Bohm diffusion, a phenomenon related to the diffusion of charged particles in plasmas, often requires sophisticated experimental techniques due to the complex nature of plasma environments, as shown in Table (3).

Table (3): Some experimental techniques commonly employed for studying Bohm diffusion [14-16].

No.	Techniques	Definition
1	Langmuir Probe	Langmuir probes are one of the most common diagnostic tools for measuring plasma parameters such as electron density, electron temperature, and plasma potential. They can be used to indirectly infer the presence and characteristics of Bohm diffusion by observing deviations from classical plasma behavior.
2	Interferometry	Plasma density and density changes are measured using laser interferometry or microwave interferometry teachings. By detecting changes in density profiles as researchers observe, the existence of diffusion processes including Bohm diffusion can be inferred.
3	Microwave Diagnostics	Microwave diagnostics such as microwave imaging and microwave interferometry can be used to measure plasma density profile changes. Whereby changes occurring in density due to Bohm diffusion can be detected by using these techniques
4	Thomson Scattering	Thomson scattering involves shining a laser into a plasma and analyzing the scattered light to calculate plasma properties such as electron temperature and density. Variations of these parameters with time may indicate the presence of diffusion processes, including Bohm diffusion.

Often used in conjunction with one another, these experimental techniques enable researchers to study Bohm diffusion and its implications in plasma physics and related fields. Each technique provides unique insights into how particles are a property of the plasma membrane, contributing to our understanding of plasma dynamics [14].

8. Theoretical Techniques for Studying Bohm Diffusion

Bohm diffusion plays a significant role in plasma transport, especially in magnetron sputtering plasmas where it affects the transport of ions and electrons [14, 16]. Here, we review the theoretical model used to describe Bohm diffusion in magnetron sputtering plasmas, as shown in Table (4).

Table (4): Theoretical models used to explain Bohm diffusion [13, 15, 16].

No.	Theoretical model	Definition
1	Particle-in-Cell (PIC) Models	PIC simulations combine particle-based methods with electromagnetic field solvers to model the behavior of energetic particles in plasma. These simulations can explicitly capture Bohm diffusion by tracking individual ions and electrons as they interact with electric and magnetic fields in the plasma.
2	Fluid Models	Plasma is often described using fluid models. These models treat plasma as a fluid. They do not look at individual particles. Fluid models add Bohm diffusion to equations. These equations cover momentum and energy transport. Fluid models show overall plasma behavior. However, they may lack details to fully describe Bohm diffusion.
3	Monte Carlo Models	Computers use Monte Carlo modeling to simulate the movement of particles in a plasma. Such models are adept at facilitating analyzes of collisions and interactions, and enable analysis of plasma diffusion under complex conditions The use of Monte Carlo modeling provides a means therefore plasma transport mechanisms are understood, including deductions of Bohm diffusion.
4	Kinetic Models	The kinetic model describes the particle activity distribution in phase and the effect of particle collisions on said distribution. Collision mechanisms can be represented in this model, and the Bohm diffusion phenomena are well captured. Sophisticated mathematical techniques are needed to solve the kinetic model and provide comprehensive insights into plasma behavior.

Different theoretical models provide different insights into Bohm diffusion in magnetron sputtering plasmas. Researchers can use these models to understand and predict plasma behavior under various conditions. The choice of model depends on the specific case study and the desired depth and computational effort.

9. Observations and Insights

Bohm diffusion is an observed phenomenon in plasma physics, especially in fusion research. It shows how charged particles diffuse along the magnetic field lines in the plasma. Several factors affect the Bohm width, e.g.

- **Magnetic Fields:** There is a very critical position for the presence of magnetic fields in Bohm diffusion. The diffusion of charged particles is slowed down by using this strong force, preventing them from shifting in spirals along the field traces. These particles will flow all at once when there's instability or turbulence, and they may unfold out in a magnetic field on the ropes. This spreading can be described by Bohm diffusion [25].

- **Gas Composition:** As Bohm diffusion may be affected by plasma properties such as ions and electrons, their existence influences the diffusion characteristics. Ions and electrons have varying interactions with magnetic fields and among themselves, which play a role in determining their diffusion behavior. Damage, impurities, or the particles in the plasma could alter the transport characteristics and the conditions under which Bohm diffusion occurs [24].

- **Pressure:** The Bohm diffusion parameter is correlated with plasma pressure, which is dependent on plasma density and temperature. Increased pressure will accelerate the transport of particles since they will decelerate faster due to gravitation. Besides, high pressure will make the plasma have fewer densities, thus enhancing turbulence and diffusion [23].

- **Temperature:** The temperature of plasma is associated with the collision and transport forces (increased temperature means increased thermal conductivity of the particles, thus causing reactions with magnetic fields and their strength).

- **Plasma Density:** Plasma density is a factor affecting Bohm diffusion. Increased plasma density can increase collision rates, affecting the diffusion of charged particles along the magnetic field lines.

Understanding and controlling Bohm diffusion is critical to the success of fusion research efforts, as it can affect both plasma damping and plasma performance in fusion devices. Experimental observations and theoretical models are often used to study the interactions and effects of these factors on Bohm diffusion under various plasma conditions [22]. A recap of key findings and insights from the study as shown in Table (5).

Table (5): Overview of Bohm diffusion effects in magnetron sputtering systems.

Authors	Diagnostic Technique	Generation Method	Effects	Ref.
Z. Zhang, et al.	Optical Emission Spectroscopy	DC Magnetron Discharge	Scanning electronic microscopy (SEM) images show that crystalline grain size of the films increases with the annealing temperature.	26
Y. Xu, et al.	Optical Emission Spectroscopy	DC Magnetron Discharge	With increasing bias voltage in HiPIMS, the ion bombardment is continuously enhanced due to the increasing flux and energy of ionized particles reaching the films.	27
L. Chen, et al.	Optical Emission Spectroscopy	High-Power DC	The work illuminates the development of deposition apparatus for continuous high-power discharges and offers a theoretical foundation for the implementation of C-HPMS.	28
N. Rake, et al.	Monte Carlo (DSMC) Method	DC Magnetron Discharge	The modelling of BN coatings reveals that the deposition rate decreases as the substrate voltage increases.	29
M. Athmani, et al.	Optical Emission Spectroscopy	DC Magnetron Discharge	Annealing has a beneficial effect on the hardness and elastic modulus of the coatings due to the changes on the structure.	30
K. Takahashi, et al.	Optical Emission Spectroscopy	High-Power DC	It is demonstrated that the push generated by the material ejection is caused by the plasma pressure force.	31
Y. Liu, et al.	Langmuir Probe	RF Magnetron Discharge	The 27.12 MHz substrate bias led to a further increase of electron density and ion flux, but made the IVDFs narrow.	32

R. Tadjine, et al.	Langmuir Probe	RF Magnetron Discharge	The eroded target raises the ion current density at the substrate, decreases the self-bias voltage by 50%, and decreases the deposition rate by nearly 40%.	33
A. P. Ehiasarian, et al.	Optical Emission Spectroscopy	High-Power DC	When compared to the most advanced plasma nitriding techniques, the process productivity was increased fourfold, mainly because of the high flux and high ion energy.	34
Y. Sato, et al.	Monte Carlo (DSMC) Method	Microwave Magnetron Discharge	Within the discharge chamber, there is less electron loss toward the downstream surface, and this reduction in electron loss also helps to raise the extraction efficiency.	35
M. Rudolph, et al.	Optical Emission Spectroscopy	High-Power DC	The substructure observed in the spokes at low working gas pressure of 0.2 Pa may be due to the diocotron instability previously anticipated by computer calculations.	36
T. Hrbek, et al.	Langmuir Probe	IR Magnetron Discharge	The phase of commercial mass production for proton exchange membrane water electrolyzers, or PEM-WEs, is about to commence. Still unresolved is the anode's iridium catalyst problem.	37
R. Rane, et al.	Langmuir Probe	DC Magnetron Discharge	When the magnetron configuration was inverted, there was a noticeable shift in the surface morphology of the copper thin film. This could be because of additional ionization caused by the anode falling.	38
S. Raggl, et al.	Langmuir Probe	DC Magnetron Discharge	The measured parameters show the biggest variations close to the target surface. Specifically, it is observed that when mean grain size increases, the electron density decreases.	39
J. Rezek, et al.	Optical Emission Spectroscopy	High-Power Impulse Magnetron Sputtering	Our findings show that ZrO2 film crystal orientation can be influenced to favor certain orientations over others by intense ion bombardment and timing of substrate biasing.	40
K. E. Evdokimov, et al.	Langmuir Probe	AC Magnetron Discharge	In order to forecast the outcomes and optimize the operating modes of a mid-frequency magnetron sputtering system for depositing Ti–O–N compositions, probe measurements of reactive magnetron–discharge plasma were carried out.	41
P. C. Jiménez, et al.	Langmuir Probe	IR Magnetron Discharge	It was observed that a nanoporous structure with a high electrochemically active surface area and a mixed oxide and metallic character was generated	42

			following the selective acid leaching of the Co.	
M. Čada, et al.	Optical Emission Spectroscopy	High-Power Impulse Magnetron Sputtering	The energy and the composition of the film forming species strongly influence the properties of the films being deposited. In	43
S. Sailler, et al.	Langmuir Probe	DC Magnetron Discharge	Deposition techniques like sputter deposition or pulsed laser deposition at ambient temperature produce amorphous films, which need a postannealing step to induce crystallization.	44
Y. Luo, et al.	Monte Carlo (DSMC) Method	High-Power DC	The deposition shows that a thicker, denser, and smoother Ti layer may be prepared by applying a pulsed coil current for around 50 μs before the positive pulse beginning.	45
R. Marquardt, et al.	Langmuir Probe	DC Magnetron Discharge	The outcomes confirm that plasma characterisation has the potential to be an effective technique for maximizing the deposition of thin NbN films and foretelling their film	46
A. Hecimovic, et al.	Langmuir Probe	Pulsed-DC Magnetron Discharge	Superior-performing synthesis thin layers on a substrate.	47
A. M. Han, et al.	Langmuir Probe, A Monte Carlo Model	Pulsed-DC Magnetron Discharge	The high-energy electrons can escape the magnetic trap and gradually diffuse to further axial positions	48
G. K. Sabavath, et al.	Langmuir Probe, A Monte Carlo Model	DC Magnetron Discharge	In light of the simulated and experimental results, the impact of the magnetic field configuration and modification of the plasma parameters on the deposition rate were examined.	49
Y. G. Li, et al.	Optical Emission Spectroscopy	DC Magnetron Discharge	Magnetic field strength plays a vital role in determining the discharge behavior in magnetron sputtering.	50

10. Applications and Technological Implications

a) Plasma Uniformity: Magnetron sputtering is widely used in thin film deposition processes for various applications such as semiconductor manufacturing, display technology, and coatings Bohm diffusion can affect the uniformity of the plasma on the substrate surface by affecting the distribution of charged particles. Bohm diffusion understanding and control can help achieve uniform deposition rates and film thicknesses over large substrate areas [21].

b) Plasma Stability: In magnetron sputtering systems, the stability of the plasma is critical for its consistency and reliability. Bohm diffusion can cause instability of plasma by impeding the transport of charged particles through the extraction site. Through control of parameters like magnetic field strength and gas pressure, Bohm diffusion may be managed to stabilize the plasma and decrease the fluctuations in deposition rates [21].

c) Etching and Deposition Rates: One of the implications of Bohm diffusion might be the delay in getting ions to the surface, and this will certainly affect the process of material deposition or etching. Bohm diffusion can be controlled in such a way as to reach optimal etching and deposition rates by cross-referencing plasma parameters that include gas content and power input. Optimization here is vital for precise pattern transfer to microelectronic device fabrication and also for obtaining thin film coatings [21].

d) Plasma Confinement: The magnetic field of a magnetron sputtering system confines plasma to the target area and improves sputtering efficiency. Bohm diffusion is responsible for allowing high-energy particles to escape along magnetic field lines, thus affecting plasma shielding [21].

11. Conclusions

An understanding of Bohm diffusion is essential to determining the dynamics and response properties of magnetron sputtering plasmas. It helps explain some basic phenomena, such as particle transport, plasma equilibrium, and energy redistribution. The theoretical explanation and empirical evidence of Bohm diffusion facilitate further investigation of plasma physics and contribute to more accurate theories and predictions. Furthermore, Bohm diffusion affects the actual performance of magnetron sputtering and its properties for many industrial processes such as thin-film deposition. Importantly, because of the excellent understanding of Bohm diffusion, researchers and engineers can adapt and enhance the technique to make even higher-quality films. Improved understanding of Bohm diffusion can lead to breakthroughs in materials science, leading to the development of new coatings with tailored properties for applications such as electronics, optics, and surface engineering.

Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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