

A review of laboratory Plasma Generation Techniques: Principles and Applications

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Article History	Abstract
Original Research Article	<p><i>The artificial creation of plasma in a laboratory setting has received a lot of attention in recent years due to its numerous scientific and technical applications. This overview illustrates the basic ideas of plasma, its classification, and the main laboratory procedures used for plasma creation. In this sense, there are several ways to create plasma, such as dielectric barrier discharge (DBD), microwave plasma, atmospheric plasma jet, laser-induced plasma, and sputtering plasma. Along with representative studies published in the literature, the general characteristics and operating principles of these methods are described. Additionally, we go over the main uses of plasma technology, such as the creation of nanoparticles, thin-film deposition, surface modification, biomedical treatments, and environmental processing. The findings show that plasma generating methods are crucial to contemporary material science, nanotechnology, and biomedical applications, and their advancement keeps expanding the potential of plasma technology in a variety of scientific and industrial domains.</i></p> <p>Keywords: plasma generation, dielectric barrier discharge, microwave plasma, plasma applications, nanotechnology.</p>
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1. Introduction

Most of the universe is plasma [1]. Astrophysicists have noted that this substance makes up the majority of galaxies [2]. The term “plasma” was first used by the medical scientist Purkinje (1787–1869) to describe the clear liquid that remains after protoplasm and other fractions have been extracted from the blood [3]. However, this is not the state of matter that is called the fourth state of matter today. This state was first observed by William Crookes in 1879 [4], after which Irving Langmuir identified the state as “plasma” in 1928 [5].

Plasma is the ionized form of gas. Its behavior arises from the presence of charged particles, making it quasi-neutral in the majority of environments, ranging from astrophysical to terrestrial [6]. Particle features include specific parameters that describe plasma behavior, such as plasma temperature, plasma density, plasma frequency, Debye length, and plasma parameter. Such features make plasmas distinct from neutral gases [7].

Plasma attracts great attention due to its very wide range of uses in a variety of scientific and technical areas.

Plasma, for example, plays a key role in some nuclear physics processes related to controlled thermonuclear reactions and neutron-based operations, e.g., fission and fusion [8, 9]. Plasma is widely employed in industrial environments for surface modification, thin-film deposition, and treatment of inorganic materials (ceramics, alloys, glass, etc.) [10-12]. Plasma technology is increasingly important for modern medicine and biomedicine to allow sterilization and plasma therapy, blood coagulation, and biological treatment [13-16]. Plasma is a valuable subject for scientists and researchers due to its diverse applications in many fields. With these issues in mind, all researchers must know the common laboratory procedures of plasma generation. Therefore, in this study, we systematically investigated different plasma generation strategies, including pulsed laser plasma, atmospheric plasma jet, microwave plasma, sputtering plasma, and dielectric barrier discharge, and their principles, properties, and applications in the process. This kind of overview helps researchers select

suitable plasma sources applicable to experimental and technological applications.

2. Fundamentals of plasma physics

Plasma is formed when enough energy is applied to gas, causing atoms or molecules to ionize and form free electrons and ions [17]. Common ionization mechanisms include thermal heating, electrical discharges, and electromagnetic radiation to induce this ionization [18]. Physically, the gas will show signs like plasma when charged particles become relatively densely packed [19].

Various physical parameters are normally used to describe plasma behavior. These key parameters include the electron temperature (T_e) (the average kinetic energy of an electron) [20] and electron density (n_e), which is the number of free electrons per unit volume [21]. Other parameters that are fundamental are the Debye length (λ_D), which illustrates the shielding effect of the plasma [22], the plasma frequency (f_p), which is how the electrons in the sample oscillate naturally within the plasma [23], and the number of particles in a Debye sphere [24].

Unlike ordinary gases, plasma operates as a collective phenomenon through long-range electromagnetic interactions between charged particles. These interactions give plasma distinct electrical, optical, and magnetic qualities from other types of matter [25]. Not all ionized gases will pass all three of the requirements to become a plasma gas.

- The dimensions (L) of the plasma must be significantly greater than the length of the Debye space (λ_D), so the relationship is $L \gg \lambda_D$ [26],
- The collective behavior among charged particles must be significant; considering this, the number of particles in a Debye sphere (N_D) is much greater than one, denoting $N_D \gg 1$ [27].
- the plasma frequency must be greater than the average frequency of collisions ($\nu=1/\tau$) with neutral atoms [28].

The first criterion assumes a large number of charged particles in a Debye sphere. Once met (the primary condition), the two and three criteria are validations to ensure that plasma behavior is dominated by collective plasma phenomena, including the fundamental length and time scales of the plasma [29].

3. Plasma Classification

Plasma can be broadly classified into non-thermal (cold) plasma and thermal (hot) plasma according to electron temperature, with both types being of different ionization, atmospheric pressure, and temperature [30].

Hot (thermal) plasma has negative ions and positively charged heavy particles, which are in thermal equilibrium with respect to temperature [31]. Similar types of plasma are not only thermodynamically active but also widely experienced across the universe. It is produced using electrothermal and electromagnetic launchers [32], and it is also used in surface treatment, ion implantation, metallurgy, and the processing of high-temperature materials [33,34].

In contrast, non-thermal plasmas (cold plasmas) possess electrons at much higher temperatures than heavy charged particles. Cold plasma fails to behave within the thermodynamic balance [35]. Conventional ion sources are plasma generators for ion extraction and acceleration. The main methods that give rise to discharge from plasma generators are electron cyclotron resonance (ECR) and microwave frequency ionization sources [36,37]. Due to their relatively low gas temperatures, non-thermal plasmas have attracted great attention in recent years as a promising material for applications in nanotechnology, semiconductor fabrication, biomedical treatments, sterilization, wound healing, and the development of plasma-based devices [38].

4. Plasma Generation Methods

The methods of plasma generation are to provide the neutral gas with enough energy to initiate ionization to form the free electrons and ions [1]. Different modes of transport for generating energy can be employed, such as by electrical discharges, microwave power, electromagnetic radiation, or high-energy laser pulses. Determination of the preferred energy transfer technique, in combination with the operating factors including pressure, gas type, and power applied, produces distinct plasma sources that possess different physical properties. The most commonly used methods for the generation of plasma are described in the upcoming subsections.

4.1 Laser-Induced Plasma Generation:

Laser-induced plasma is one of the widely used techniques for plasma generation in laboratory experiments. Using this approach, a high-energy pulsed laser beam is focused onto the surface of a solid target, causing the target material to become rapidly heated, melted, and vaporized. When the laser energy increases beyond the ablation threshold, the ejected material becomes ionized and begins to form a dense plasma plume composed of electrons, ions, and neutral species. This method can be used under various experimental conditions [39]. In some configurations, the laser irradiation occurs in ambient atmosphere or liquid media, where the target is immersed in a solution such as distilled water for nanoparticle synthesis (Figure 1).

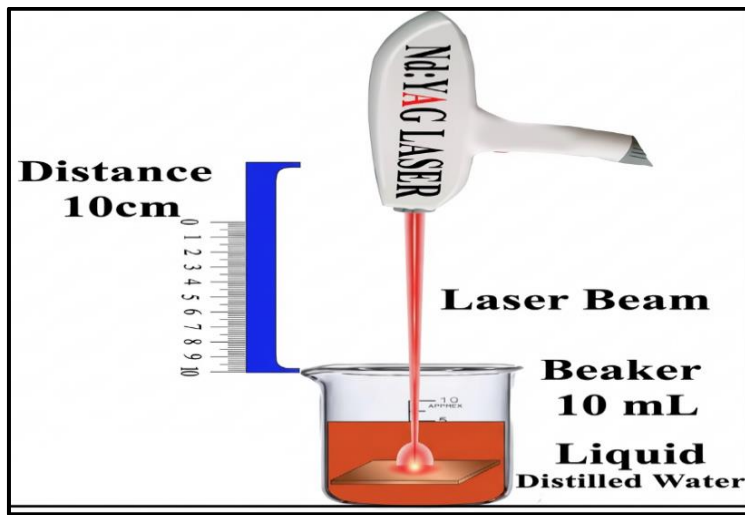


Figure 1: An illustration of the laser ablation technique.

In other configurations, this process is done in a vacuum chamber, such as pulsed laser deposition (PLD) [40], where the plasma plume created expands toward a substrate to deposit thin films (Figure 2).

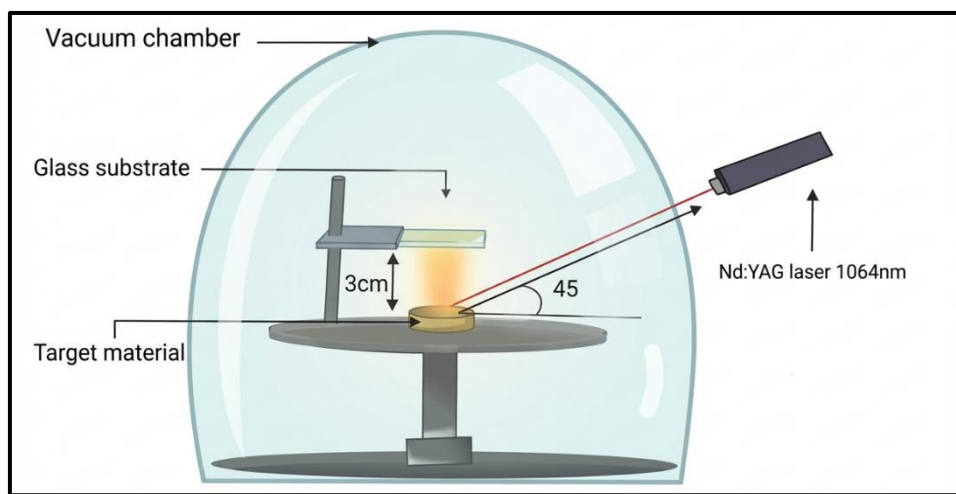


Figure 2: An illustration of the pulsed laser deposition (PLD) technique.

The characteristics of the generated plasma depend on parameters such as

- laser wavelength
- energy
- frequency
- number of shots
- ambient pressure
- target material.

For example, some researchers utilized laser ablation techniques to find out how laser setting parameters influence plasma characteristics.

Method	Parameter Variable	Main Result	Reference
PLD	Energy	ZnO thin films with good crystalline structure and optical properties.	[41]
PLD	Laser wavelength	The structural, morphological, and optical characteristics of LiNbO ₃ thin films are influenced by the PLD.	[42]
Laser ablation	Target material	CuO@Zn Core shell nanostructures were successfully created by laser ablation in liquid	[43]

Laser ablation	Number of shots	The structural and optical characteristics of WO ₃ nanoparticles created by PLAL are affected by the number of laser pulses.	[44]
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4.2 Atmospheric Pressure Plasma Jet (APPJ):

Atmospheric pressure plasma jet (APPJ) is one of the most widely used plasma generation techniques operating at atmospheric pressure. In this technique, plasma is generated by applying a high voltage between electrodes while a working gas, e.g., argon, helium, nitrogen, or air, flows through a narrow tube (figure 3). The electric field accelerates electrons within the gas, leading to ionization and the formation of a plasma plume that extends outside the discharge region [45]. Unlike low-pressure plasma systems, APPJ can operate in open air without the need for vacuum equipment, which makes it suitable for many practical applications [46].

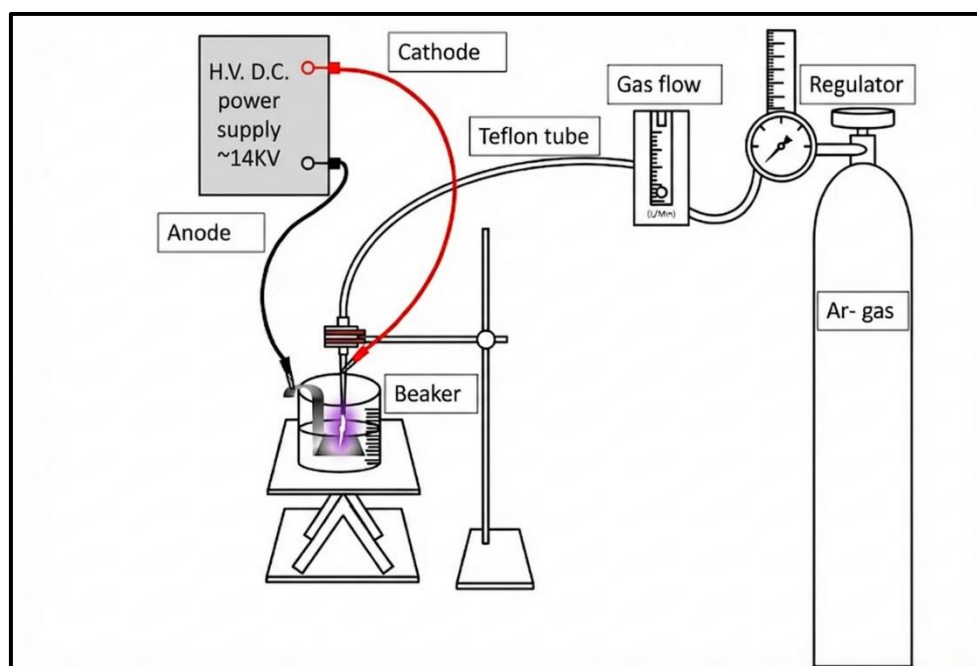


Figure 3: An illustration of the plasma jet technique.

The plasma produced by APPJ depends upon several parameters, including

- the applied voltage.
- the gas type.
- the gas flow rate.
- operating frequency.

Several researchers used the plasma jet method. To determine how parameters affect plasma characteristics.

Method	Parameter Variable	Main Result	Reference
Plasma jet	Gas type	In aqueous solutions, an oxygen plasma jet promotes the generation of reactive oxygen and nitrogen species.	[47]
	Gas flow rate	The length of the plasma jet and the temperature of the gas are greatly influenced by the flow rate.	[48]

4.3 Microwave plasma

The microwave plasma technique is to ionize the working gas with microwave electromagnetic radiation, typically at a 2.45 GHz frequency (Figure 4). If this field interacts with gas, free electrons will be accelerated and collide with neutral atoms or molecules, which leads to ionization, giving rise to plasma [49]. Microwave plasma sources can provide stable plasma with relatively high electron density under low or atmospheric pressure [50].

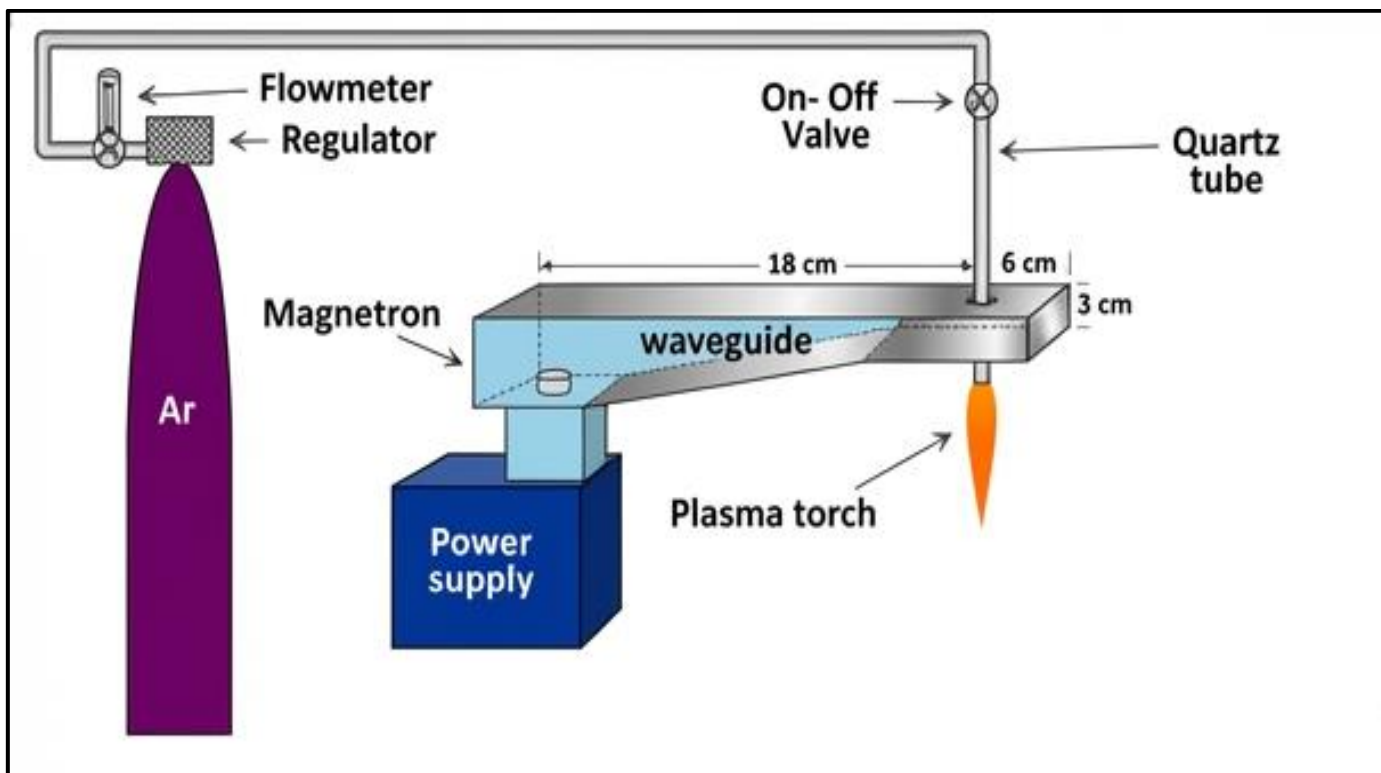


Figure 4: An illustration of the plasma microwave technique.

The properties of the microwave plasma are influenced by a range of parameters, including

- microwave power
- gas pressure
- gas type
- geometry of the plasma reactor.

Some researchers used the plasma microwave method. To determine how parameters affect plasma characteristics.

Method	Parameter Variable	Main Result	Reference
Plasma microwave	Gas flow	The spectrum properties and emission intensity of microwave-induced plasma are greatly impacted by the gas flow rate.	[51]
	Gas type	The type of gas species under a magnetic field that is external has an important influence on the propagation of microwave plasma.	[52]
	Gas pressure	Diamond development in microwave plasma CVD systems is greatly impacted by pressure.	[53]

4.4 Dielectric Barrier Discharge (DBD)

Dielectric Barrier Discharge (DBD) plasma is created when two electrodes are separated by dielectric material (glass or ceramic) and a high alternating voltage is introduced between the electrodes (figure 5). Due to the dielectric barrier, the discharge current is limited and prevents arc discharge, and non-thermal plasma can be produced at atmospheric pressure [54]. When the applied voltage is greater than the breakdown voltage of the gas, electrons accelerate and collide with gas molecules, leading to ionization and plasma formation on the surface of the dielectric barrier [55].

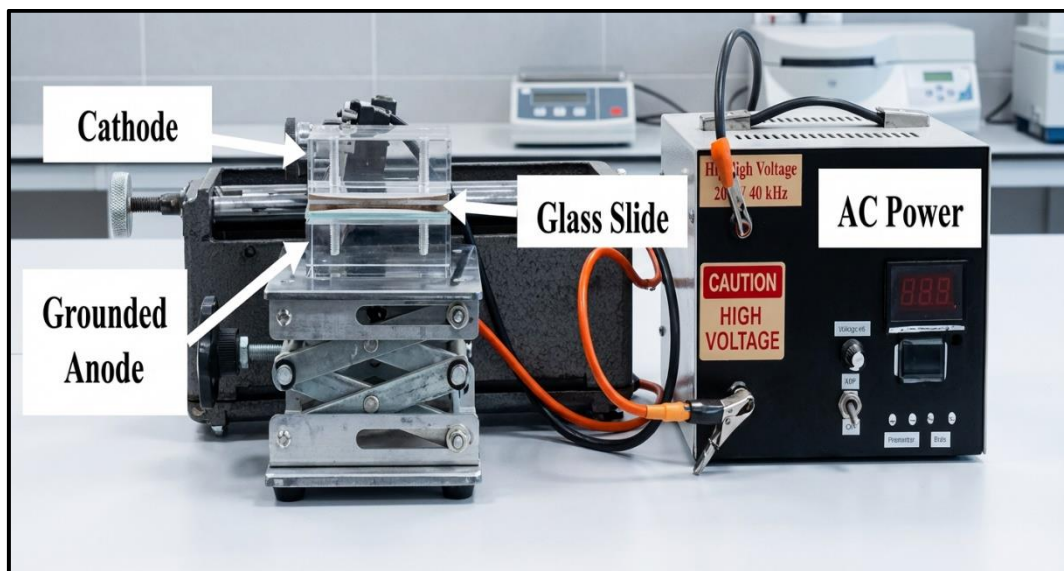


Figure 5: image of the DBD system.

Different physical and chemical effects caused by dielectric barrier discharge (DBD) plasma in various operating circumstances have been studied by several researchers.

Method	Plasma system	Studied effect	Reference
DBD	Air plasma	Energy conversion processes	[56]
	Argon plasma	Surface modification of PLA	[57]
	Air plasma and NOx	Generation of reactive species in water	[58]

4.5 DC and Magnetron Sputtering

In this approach, plasma is generated inside a vacuum chamber, with a DC voltage applied between a cathode and an anode along with argon as a low-pressure inert gas (figure 6). An applied electric field creates an accelerated field of electrons that interacts with gas atoms, ionizing and creating plasma. The positively charged ions created in the plasma are accelerated towards the target surface and atoms from the target material are expelled by sputtering. These atoms then deposit on the substrate, which form thin films [59].

A more developed form of this method is magnetron sputtering, wherein a magnetic field is applied near the target surface and serves as a confinement for electrons and improves the ionization efficiency (figure 7). It translates to increased plasma density, sputtering rates [60].

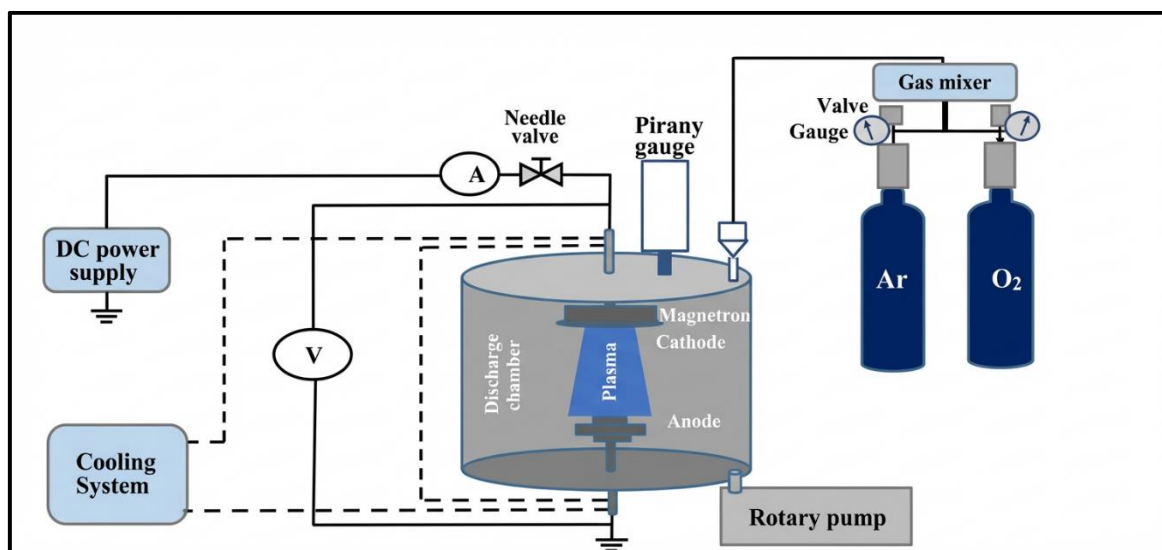


Figure 6: Schematic of DC reactive Sputtering system.

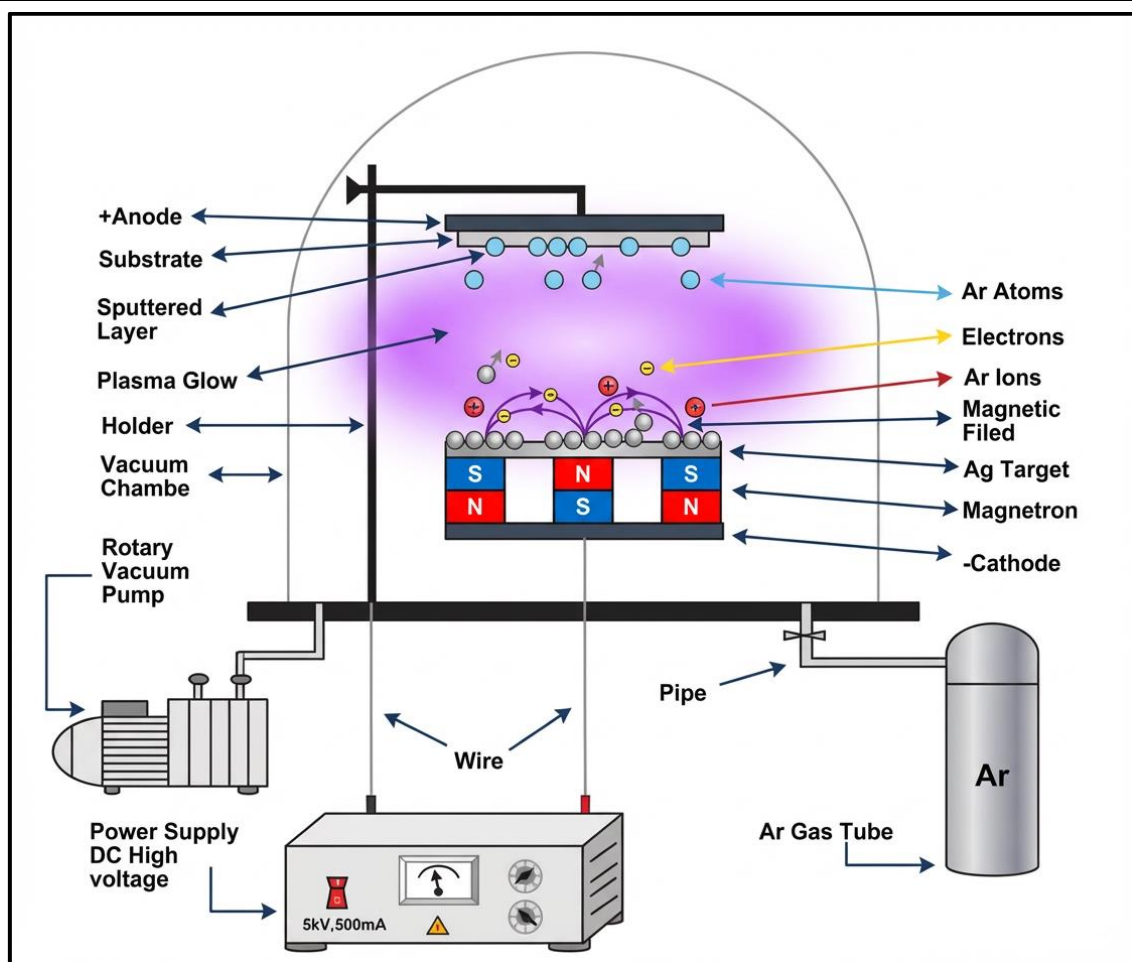


Figure 7: Schematic diagram of the DC plasma sputtering magnetron setup.

Method	Studied Effect	Reference
DC Sputtering	Deposition of thin films using DC discharge plasma under low-pressure argon gas	[61]
DC Sputtering	Influence of discharge voltage and gas pressure on thin film growth	[62]
Magnetron Sputtering	Magnetic field confinement enhances plasma density and sputtering efficiency	[63]
Magnetron Sputtering	Magnetron configuration improves deposition rate and film uniformity	[64]

5. Application of plasma

Each method for creating plasma has special advantages that make it suitable for specific applications. Table 1 summarizes the primary uses of the plasma-generating techniques covered in this work.

Table 1: Application of plasma

Plasma Generation Method	Typical Applications	Reference
Laser-induced plasma	Nanoparticle synthesis (laser ablation), thin film (PLD)	[65]
Plasma jet (APPJ)	Surface treatment, sterilization, and biomedical applications	[66]
Microwave plasma	Chemical vapor deposition (CVD), material processing	[67]
DC / Magnetron sputtering	Thin film deposition, semiconductor fabrication	[68]
Dielectric barrier discharge (DBD)	Surface modification, sterilization, and environmental treatment	[69]

Conclusions

All plasma generation methods come with certain advantages and operational conditions to suit certain applications. Nanoparticles and thin films being deposited use the laser plasma technique. Plasma jet systems are employed in biomedical therapies and surface-modifying processes. High plasma densities generated during microwave plasma production are suitable for material processing and chemical vapor deposition. Methods for sputtering plasma are used for thin film fabrication and the semiconductor industry. DBD plasma is widely used for environmental remediation, sterilization, and surface property changes.

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