Journal of Nano- and Electronic Physics
Vol. **17** No 6, 06003(10pp) (2025)

Журнал нано- та електронної фізики
Том **17** № 6, 06003(10cc) (2025)

REGULAR ARTICLE

Prerequisites and Prospects of Inductive-Magnetron Plasma Excitation in Cold-Cathode Sources

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(Received 14 August 2025; revised manuscript received 14 December 2025; published online 19 December 2025)

This article reviews the physical principles, current state, and development prospects of inductively-magnetron plasma excitation (IMP) in cold cathode-based sources. This hybrid plasma generation approach combines the high ion density of inductively coupled plasmas with the spatial control of magnetron systems, offering potential for advanced applications in micro- and nanotechnologies. The review systematically addresses major research directions, including plasma modeling, magnetron sputtering, ion-plasma technologies, high-frequency ion sources, and plasma etching and deposition techniques. Special attention is given to the historical development of cold cathodes, recent advances in inductive plasma excitation, and HiPIMS technologies. The article highlights significant research gaps, particularly in understanding the interaction between inductive and magnetron excitation in hybrid systems, and the lack of comprehensive theoretical models describing plasma behavior under combined excitation. Rather than offering technical solutions, the work aims to establish a conceptual framework for further development of compact, efficient plasma sources. The review targets researchers in plasma physics, surface engineering, and materials science.

Keywords: Induction-magnetron excitation, Cold cathode, Hybrid plasma systems, Systematic review, Optimization of plasma parameters.

DOI: 10.21272/jnep.17(6).06003 PACS numbers: 52.30.Cv, 52.30.Ex

1. INTRODUCTION

Inductively-magnetron plasma excitation in cold cathode sources represents a significant scientific interest due to its potential to create efficient hybrid systems that combine the advantages of inductively coupled plasma (high ionization density) with the precise control of particle flux characteristic of magnetron configurations. Despite the active development of both technologies independently, their integration remains insufficiently explored, which limits the advancement of new generations of compact plasma sources.

The aim of this review is to provide a systematic analysis of the current state of research in this field, with a focus on:

- the physical mechanisms limiting the efficiency of combined systems;
- optimal parameters for the interaction of inductive and magnetron excitation;
- identifying key gaps in theoretical and experimental studies.

Particular attention is given to a critical analysis of the possibilities for overcoming existing limitations by combining recent advances in cold cathode design with innovative approaches to plasma parameter control. It is important to emphasize that the article does not propose specific technical solutions but aims to establish a theoretical foundation for further research in this area.

The review covers a wide chronological range – from fundamental works that laid the groundwork for understanding the physics of the processes to contemporary publications reflecting current trends in the improvement of plasma technologies. This comprehensive study not only allows for an assessment of progress in the field but also helps to identify the most promising directions for future scientific investigation.

2. DIRECTIONS OF RESEARCH

2.1 Main Directions Related to the Use of Cold Cathodes and Inductive-Magnetron Plasma Excitation

Contemporary research on cold cathodes and inductive-magnetron plasma excitation highlights several key directions that encompass both fundamental aspects and applied technological developments. Special attention is devoted to the development of novel microwave oscillation generators, plasma process modeling, the design of ion-plasma systems for micro- and nanotechnologies, and the improvement of plasma control methods. Research in these areas aims to enhance the efficiency, reliability, and functionality of plasma systems.

Development and improvement of magnetron generators with cold cathodes. Side-mounted cold cathode magnetrons are promising for creating microwave (MW) oscillation generators with increased service life and reliability. The use of a secondary-emission cathode enables cold startup and extends the operational lifetime of the magnetron. Research in this area focuses on optimizing the design

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Cite this article as: Kh.S. Toiabina et al., *J. Nano- Electron. Phys.* 17 No 6, 06003 (2025) https://doi.org/10.21272/jnep.17(6).06003

and parameters of such generators [1, 2].

Ion-plasma systems for micro- and nanotechnologies. The use of combined electric and magnetic fields in ion-plasma systems opens new possibilities for micro- and nanotechnology. Research in this direction is aimed at developing high-efficiency plasma sources for coating deposition, etching, and other processes that require high precision and surface treatment uniformity [3].

Control of gas-discharge devices with plasma electron emitters. Studies of the physical and technical aspects of controlling high-voltage gas-discharge switching devices with plasma electron emitters aim to reduce control power requirements and improve the recovery of dielectric strength. The use of a cathode screen and two-level control pulses on the control electrode enables the achievement of these goals [4].

Modeling of ionization and emission processes in high-voltage electron-ion systems. Numerical modeling of ionization and emission processes in systems with cold cathodes and pulsed ion generators provides a deeper understanding of the underlying mechanisms and helps optimize parameters to improve efficiency. Such research is essential for the development of new electron and ion sources across various scientific and technological fields [5].

Plasma flow control using rotating magnetic fields. The use of a rotating magnetic field to control the spatial position of the arc in a plasma torch channel allows for dynamic adjustment of the plasma flow volume and parameter distribution. This approach opens up new possibilities for advancing surface engineering technologies and improving the efficiency of plasma processes [6].

Research on inductive plasma excitation. Inductive plasma excitation is a key process in the generation of high-temperature plasma for various scientific and technological applications. It is based on the use of alternating electromagnetic fields to generate currents in the plasma, resulting in heating and ionization. The Institute for Nuclear Research of the National Academy of Sciences of Ukraine is conducting theoretical research on nonlinear wave – particle interactions in non-equilibrium plasma, which influence heating and energy transport processes [7]. Additionally, the Institute of Plasma Electronics and New Acceleration Methods is carrying out theoretical and experimental studies of wake field excitation in plasma, which are important for understanding inductive excitation mechanisms [8]. These studies contribute to the development of new methods for plasma generation and control, which are vital for advancing technologies involving cold cathodes and inductive-magnetron plasma excitation.

2.1.1. Principle of Operation of RF Ion Sources

Radio-Frequency Ion Sources (RFIS) utilize an inductive discharge to generate low-temperature, electrode-free plasma.

The core component is an ionization chamber made of dielectric material, surrounded by a spiral inductor supplied with radio-frequency (RF) electric power. As a result, the inductor produces an axial alternating magnetic field, which in turn induces an azimuthal electric field. This field accelerates electrons that ionize neutral atoms or gas molecules, thereby generating plasma.

The ions formed in the chamber are extracted and focused through an ion-optical system (IOS), which consists of three electrodes (emission, acceleration, and ground/suppression), arranged in a multi-aperture configuration. This design enables the formation of a high-density ion beam with defined energy.

Key characteristics of such a discharge include:

- Operating frequency: from 1 to 13.56 MHz and higher;
- Power: from a few watts to several tens of kilowatts;
- Ion beam diameter: from 1 to 35 cm (RIM, RIT, PRIS series) [9];
- Ion current: from milliamperes up to 85 amperes (e.g., RIG-HEX 25 × 50) [10];
- Gas type: inert (Xe, Ar) or chemically active (O_2 N_2, CO_2, SF_6);
- Ion energy: from 0.2 to 10 keV.

2.2.2. Principle of Operation of RF Ion Sources

Efficient operation of RF ion sources (RFIS) is only possible with careful coordination between various parameters:

1. RF frequency and power: these must match the chamber dimensions and gas pressure. If the frequency or power is mismatched, ionization efficiency decreases, or excessive energy losses occur.
2. Ion current efficiency: the ratio of consumed RF power to ion beam current (Prf/Ji) should be minimized, as it serves as a key efficiency metric for the source.
3. Ion beam focusing: requires a balanced combination of plasma parameters (electron temperature, density), IOS electrode geometry, and applied potentials to ensure the desired ion energy at the output.
4. Power losses in the supply system: RF power losses in feed cables and return currents in metallic parts can be significant. These losses must be minimized to maintain overall system efficiency.

Thus, radio-frequency ion sources offer high potential due to electrode-free plasma heating, a wide range of working gases, and precise control over beam energy. However, achieving maximum efficiency demands precise engineering coordination of many parameters – frequency, geometry, pressure, power, and gas type. Without proper optimization, these factors can significantly reduce the source's performance.

These research directions contribute to a deeper understanding of the physical phenomena in electron sources with cold cathodes and inductive-magnetron plasma excitation, as well as the development of new technological applications across various fields of science and engineering.

2.2 Various Approaches to the Modeling and Experimental Study of these Systems

The study of systems with cold cathodes and inductive-magnetron plasma excitation requires the use of various modeling and experimental analysis methods.

The main approaches can be categorized into numerical modeling of physical processes, experimental investigations of plasma characteristics, and combined methods that integrate theory and practice.

Numerical modeling of physical processes in plasma systems enables detailed investigation of phenomena occurring in the plasma, including ionization, electron emission, plasma flow generation, and their interaction with electric and magnetic fields. One example of this approach is the modeling of processes in dielectric barrier discharges, which allows for quantitative assessment of plasma parameters and optimization of excitation conditions [11].

Specifically, the use of numerical modeling to study cold plasma in dielectric barrier discharges in air enables analysis of non-stationary processes associated with streamer development and decay. This approach is important for understanding plasma dynamics and improving plasma actuators [11].

Experimental investigations of plasma characteristics provide valuable data on physical processes in systems with cold cathodes and both inductive and magnetron excitation. For example, studies of cold cathode magnetron generators include analysis of operating conditions, generation stability, and device longevity [1].

Combining numerical modeling with experimental methods allows for more accurate insights into plasma system characteristics. For instance, modeling ionization and emission processes in high-voltage electron-ion systems with cold cathodes not only explains experimental observations but also helps predict potential improvements and identify optimal design parameters [5]. Such approaches are crucial for the development and optimization of new plasma sources in terms of efficiency, reliability, and operational stability.

In summary, diverse approaches to modeling and experimental research of systems with cold cathodes and inductive-magnetron plasma excitation allow for detailed analysis of physical processes, optimization of system parameters, and expansion of their applications in scientific and technological fields. The integration of numerical and experimental methods is particularly promising for achieving high research accuracy and enhancing the performance of plasma systems.

3. MEANING AND APPLICATION

3.1 Practical Significance of Research

Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) is widely used for accurate determination of elemental concentrations in various samples. This is crucial for water quality control, soil analysis, environmental impact assessment, and food safety assurance (Fig. 1) [12].

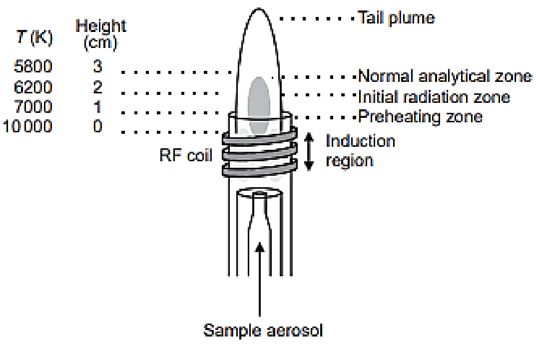


Fig. 1 – Schematic diagram of the ICP unit showing three concentric tubes forming the torch, the radio-frequency coil, different plasma regions, and the temperature as a function of the height above the load coil. Adapted from work [12]

For example, ICP-OES is used to analyze drinking water quality and assess environmental pollution by heavy metals.

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is applied in medical and forensic research to determine metal levels in biological fluids, which aids in diagnosing poisonings and metabolic disorders (Fig. 2) [13].

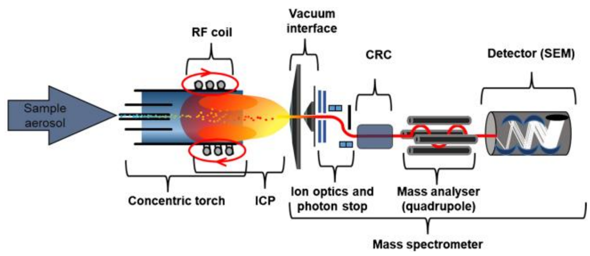


Fig. 2 – Schematic setup of the ICP-MS system operating with a collision/reaction cell (CRC) and a quadrupole mass analyzer Adapted from work [13]

This method provides high sensitivity and accuracy in measurements, making it indispensable in biomedical research.

Plasma technologies, particularly magnetron sputtering, are widely applied for depositing thin films and coatings on various materials, improving their physico-chemical properties. This is important in the production of electronics, optics, and other high-tech industries. The use of inductively-coupled magnetron plasma enables the creation of coatings with enhanced mechanical and electrical properties, which finds application in microelectronics and nanostructure manufacturing (Fig. 3) [14].

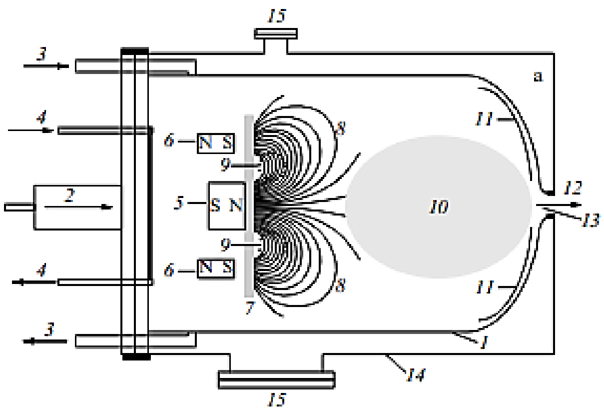
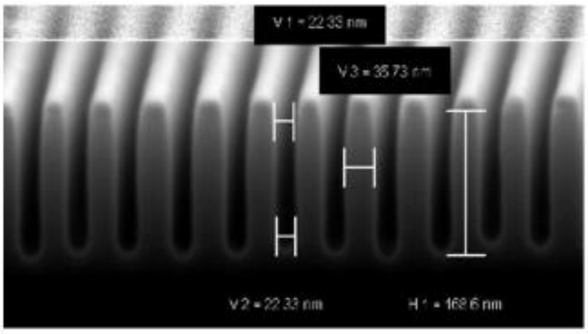


Fig. 3 – Diagram of the magnetron (aggregation) chamber: 1 – magnetron (aggregation) chamber, 2 – buffer gas flow, 3 – liquid nitrogen for chamber cooling, 4 – water cooling for the magnetron, 5 – inner cylindrical magnet, 6 – outer ring magnet, 7 – cathode, 8 – magnetic field lines, 9 – ring of trapped electrons (racetrack), 10 – secondary plasma, 11 – electrode for secondary plasma, 12 – buffer gas flow with clusters, 13 – orifice, 14 – housing, 15 – vacuum pumping Adapted from work [14]

Inductively coupled plasma is also used for etching and surface modification in the production of microelectronics and nanostructures. This allows for the creation of complex structures with high precision and controlled properties (Fig. 4) [15].



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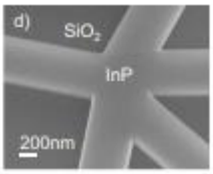

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Fig. 4 – Nanostructures on surfaces: a – 22-nm Si trench etched to 169 nm by cryogenic process, b – Etching results and CH_4-based cyclic ICP etch recipe parameters for a laser light guide network node, demonstrating good pattern transfer into the active medium. Adapted from work [15]

The use of plasma methods in waste treatment and water purification is gaining increasing attention. For instance, plasma gasification technology can be applied to break down harmful substances and neutralize toxic compounds [16]. This helps to reduce the negative impact of industrial waste on the environment and to develop environmentally friendly technologies.

3.2 Potential Applications of Induction Magnetron Plasma

Inductively magnetron plasma (IMP), which combines the properties of inductively coupled plasma (ICP) and magnetron plasma, is considered a promising direction in the field of plasma technologies. This hybrid approach is theoretically capable of providing enhanced control over plasma parameters, opening up new possibilities for the fabrication of functional coatings, surface modification, and precision material processing. These assumptions are based on a theoretical extrapolation of the characteristics of ICP and magnetron systems, but they require experemental validation.

Potential applications of IMP include:

1. Precision material etching. IMP may be adapted for deep anisotropic etching, which is particularly relevant in micro- and nanoelectronics. It is expected that the combination of magnetic confinement of electrons and inductive excitation will enable high plasma density while maintaining process stability and cleanliness.

2. Deposition of thin films with tailored properties. IMP can be employed for the deposition of thin films with complex structures and specific electrical or mechanical characteristics. Hypothetically, the combination of magnetron sputtering with inductive excitation support may improve coating uniformity and enable precise control over its structure at the micro- and nanoscale.

3. Physicochemical surface modification. According to current hypotheses, IMP may serve as an effective tool for surface functionalization – particularly for enhancing adhesion, corrosion resistance, or electrical conductivity. Theoretically, the high plasma energy in combination with flexible process parameters could offer new approaches to developing adaptive surfaces for biomedical or electronic applications.

Thus, inductively magnetron plasma excitation represents a promising research direction that may integrate the advantages of two established technologies. Further experimental studies and modeling are necessary to validate assumptions regarding the stability, efficiency, and adaptability of this type of plasma source.

4. HISTORICAL OVERVIEW AND ANALYSIS OF CURRENT RESEARCH

4.1 A Brief Overview of Early Works

The early stages of development of cold cathode electron sources and magnetron plasma excitation are associated with the first experiments of the 1960s–1980s. This period was characterized by limited control over plasma parameters and low process efficiency, primarily due to underdeveloped theoretical frameworks and technological constraints of the time.

A significant breakthrough was the invention of the planar magnetron, patented in 1974 by R. G. Chapin. Its design was based on a closed magnetic field configuration, which allowed efficient plasma confirement near the target. This innovation enhanced discharge stability and improved sputtering efficiency compared to traditional magnetrons of that era. The patent emphasized that this configuration enabled operation at lower pressures and provided uniform energy distribution over the target surface, which was critical for producing high-quality thin films [17].

In their 1986 study, Window and Savvides [18] investigated the performance of planar magnetrons with various magnetic field configurations. They found that Type II systems (with a peripheral magnet, Fig. 5b) generated significantly higher fluxes of charged particles to the substrate compared to Type I systems (with a central magnet, Fig. 5a).

Specifically, for the Type II configuration, they recorded ion currents up to 5 mA ($\sim 3 \times 10^{16}$ ions/s) on an 8 mm diameter substrate, which exceeded the flux of deposited atoms by a factor of two. In contrast, for the Type I configuration, the ion flux amounted to only ~ 0.025 % of the deposition flux. This means that in Type II systems, strong ion bombardment is inevitable – even for electrically isolated substrates – leading to significant self-bias and ion energies of around 40 eV, which critically influence film growth. Thus, the study by Window and Savvides clarified the specific conditions under which Chapin's conclusions regarding minimal ion bombardment remain valid. While this holds for Type I configurations, the results showed that in Type II systems, ion bombardment can exceed the neutral atom flux.

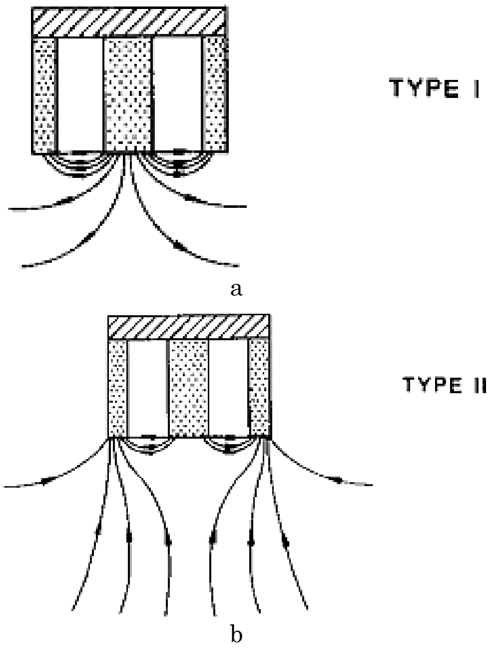


Fig. 5 – Magnetron systems forming magnetic field configurations: a – with a central magnet, b – with a peripheral magnet. Adapted from work [18]

In his 1974 work [19], Thornton compared the structure of coatings deposited using planar and cylindrical magnetron geometries (Fig. 6). He demonstrated that film morphology correlates strongly with the ratio of the substrate temperature to the melting point of the deposited material (T/T_m). Specifically:

- At $T/T_m < 0.3$, porous structures with elongated crystallites separated by voids are formed.
- In the $T/T_m = 0.3\text{-}0.5$ range, dense columnar structures with grain boundaries extending through the entire film thickness are observed.
- At $T/T_m > 0.5$, especially under high-temperature conditions and deposition rates of 10.000-20.000 Å/min, Thornton observed the formation of coarse-grained equiaxed structures with smooth grain surfaces.

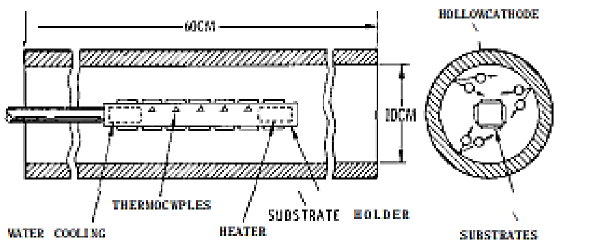


Fig. 6 – Diagram of a sputtering apparatus with a hollow cathode and a substrate holder with a high-temperature gradient. Adapted from work [19]

These results indicate that higher temperatures, due to increased surface mobility, lead to granular or even recrystallized film structures. In contrast, at lower T/T_m, the resulting morphology remains porous and mechanically weak. It was also shown that elevated argon pressure can sustain a porous structure even at higher T/T_m values by suppressing surface atom mobility [19].

Thus, while the early magnetron systems significantly improved sputtering processes, they had major limitations in plasma parameter control, necessitating further research and advancements.

In parallel with improvements in magnetron geometry, one of the key research directions became the development of efficient cold cathode electron sources capable of stable emission without the need for thermionic heating. Progress in this area was closely linked to advances in understanding field, photon, and ferroelectric emission mechanisms.

Field emission, based on quantum tunneling of electrons through a potential barrier under a strong electric field, was originally described in the classical work of Fowler and Nordheim [20, 21]. The development of thin-film field emitters in 1968 [22] marked a new stage in cold cathode technology. Field emitter arrays demonstrated high current densities and notable reliability, making them promising candidates for display technologies and microwave electronics [21].

In parallel, research on photocathodes was actively developing, particularly at Brookhaven National Laboratory. In 1991, it was demonstrated that copper- and yttrium-based photocathodes were capable of generating high-quality electron beams suitable for use in free-electron lasers [23, 20].

Another approach to achieving cold emission involved the use of ferroelectric materials capable of releasing electrons under changes in polarization. Studies from the 1990s showed that ferroelectric cathodes could provide high current densities and stable operation in pulsed mode [24, 20].

A significant contribution to the development of cold cathode technology also came from research into silicon-based structures. In 1984, Philips researchers developed a silicon cold cathode with a *p-n* junction, capable of delivering current densities exceeding 1000 A/cm^2 after cessation of the surface [25].

Further studies, published in 1987 [26], revealed even more groundbreaking results. The operation of such a cathode was based on the avalanche breakdown effect in a reverse-biased silicon *p-n* junction, enabling the generation of so-called "hot" electrons with an effective temperature of up to 5700 K. A key innovation was the use of a planar *p-n* junction geometry, aligned parallel to the surface, with an ultrathin n^+-layer approximately 10 nanometers thick. The researchers focused on miniaturizing the emission area to diameters of 1-10 microns, which prevented current "pinch-off" in the narrow channel. A breakthrough solution was the application of a monomolecular cesium layer on the silicon surface, which drastically reduced the work function from 4.5-5 eV to 2-2.5 eV, thereby increasing emission efficiency by a factor of 400-1000 compared to untreated samples.

These cathodes demonstrated stable operation at current densities of up to 1500 A/cm^2 at 10 kV, outperforming conventional thermionic cathodes by orders of magnitude. A major advantage was instant startup without the need for preheating, as well as the ability to modulate the current at frequencies up to 1 GHz, owing to the low capacitance of the structure. However, the technology also had its limitations – most notably the high sensitivity of the cesium coating to oxidation and the requirement for ultrahigh vacuum, which complicated industrial implementation.

Thus, by the early 2000s, the fundamental principles of various types of cold cathode operation had been established, laying the groundwork for the further development of high-efficiency, stable electron sources. These gradually began to replace traditional hot cathodes in many applications, particularly in vacuum electronics and plasma systems.

4.2 Potential Applications of Induction Magnetron Plasma

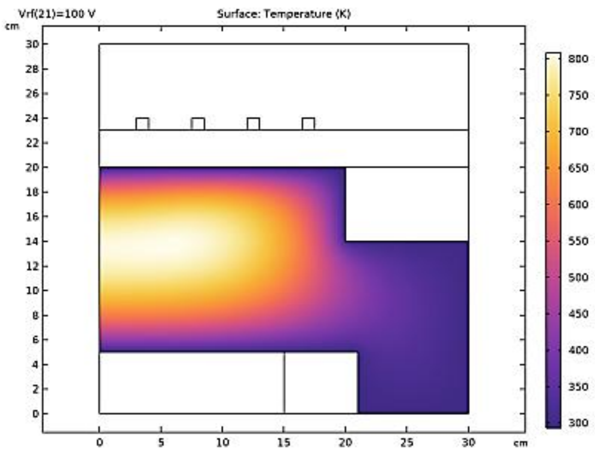
Over the past three decades, inductively coupled plasma (ICP) sources have undergone significant scientific and engineering advancements. Contemporary research has focused primarily on improving plasma generation efficiency, reducing parasitic capacitive components, controlling ion flux density, and integrating these sources into complex technological platforms.

Compared to developments from the 1980s-1990s, modern ICP systems demonstrate substantially improved performance due to optimized coil designs, chamber geometries, and excitation conditions. In particular, study [27] showed that minimizing capacitive coupling to the plasma enables the generation of a stable, uniform ionization field even at low power levels (down to 200 W), with plasma densities exceeding 10^{17} m^{-3}.

Furthermore, the active use of radio-frequency (RF) modeling and numerical methods – especially in environments like COMSOL Multiphysics – has made it possible to analyze resonant modes and localized effects in high-frequency ICP configurations (Fig. 7) [28]. These tools help predict and control field configurations to prevent discharge asymmetry.

Additionally, Cheng et al. explored the use of ICP combined with RF magnetron sputtering for depositing nanostructured SiC films, demonstrating the feasibility of integrating ICP with magnetron systems to create hybrid plasma sources [29]. However, as with the MIP–ICP configuration, these studies primarily focused on technological outcomes – such as improved film characteristics – while the fundamental plasma physics in such hybrid regimes remains insufficiently explored.

A major development in magnetron technologies was the introduction of High Power Impulse Magnetron Sputtering (HiPIMS) – a promising approach to thin film deposition that combines magnetron sputtering with high-power pulsed operation. The use of short pulses with high amplitudes and low duty cycles enables a high degree of ionization of the sputtered material, improving control over ion energy parameters and the resulting film properties [30].



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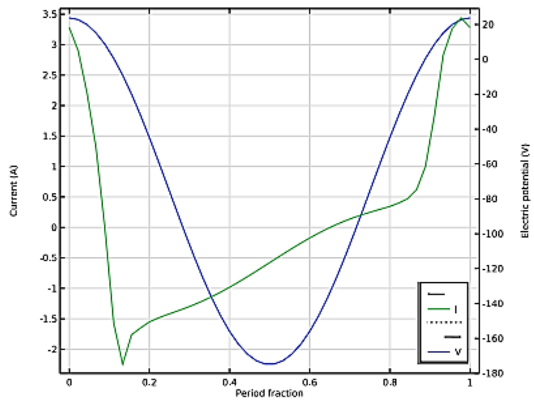

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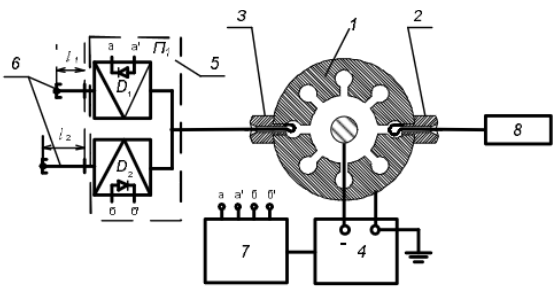
Fig. 7 – Physico-topological numerical model of inductively coupled plasma: a – two-dimensional plasma temperature distribution in the reactor at a solenoid power of 250 W, b – one-dimensional distribution of voltage and current above the electrode. Adapted from work [28]

Studies have shown that HiPIMS produces films with high density and uniformity. For instance, in aluminum oxide film deposition, increased ionization contributed to better density and coverage, even compensating for shadowing effects on textured surfaces [31]. HiPIMS also offers advantages in tailoring mechanical properties. In particular, W-C films deposited by HiPIMS exhibited excellent wear resistance in abrasive environments [32].

Moreover, HiPIMS allows for precise control over film microstructure and electrical properties. Investigations into pulse width effects on copper films revealed that changing pulse parameters significantly influences plasma density and, accordingly, film characteristics [33].

An additional enhancement involves applying a positive reverse voltage pulse after the main negative pulse in HiPIMS, effectively "pushing" ionized target material toward the substrate. This is especially useful for coating insulating or complex 3D structures [34], enabling the deposition of dense coatings at low substrate temperatures without requiring additional biasing.

Beyond HiPIMS sources, novel magnetron designs are actively being developed. Of particular interest are dual-output magnetrons, which offer improved operational performance compared to traditional single-output designs.



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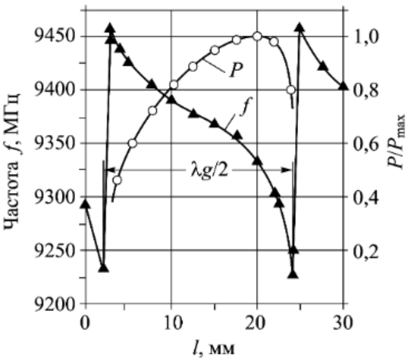

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Fig. 8 – High frequency magnetron: a – structural diagram of a magnetron with two power outputs and pulse-to-pulse frequency tuning, where: 1 – magnetron, 2, 3 – active and reactive power outputs respectively, 4 – modulator, 5 – switch on PIN diodes D1 and D2, 6 – short-circuited waveguide stubs, 7 – pulsed power supply for the switch, 8 – external load, b – experimental tuning curve of the magnetron's output frequency and power level using dual power outputs. Adapted from work [1]

This configuration enables not only frequency stabilization, but also continuous dynamic frequency tuning. Experimental results presented in [1] show that a dual-output magnetron (Fig. 8a) operating in continuous mode achieved a tuning range exceeding 230 MHz, with only a 1.6× variation in output power (Fig. 8b).

Numerical modeling of such systems has been carried out using multi-period computational methods: the particle-in-cell (PIC) approach combined with finite-difference techniques. This enables precise analysis of the closed electron flow dynamics in the magnetron and its frequency characteristics. A developed numerical-analytical model of the "cold" magnetron anode block, based on the equivalent circuit method, allows for an extended tuning range of 450-500 MHz. The use of a diode section with a varactor provides additional frequency adjustment (up to 10 MHz) in continuous mode. A dual-output energy design minimizes frequency fluctuations and ensures stable operation during generation. For a magnetron operating at the *I-V* characteristic point (U_a = 610 V and I_a = 0.15 A), the average output power reaches 28 W with a pulse duration of 16 μs. Thus, dual-output magnetrons offer more efficient control over frequency characteristics and operational stability, making them promising for plasma systems with inductive-magnetron excitation.

In addition to designs with tunable magnetrons, systems with cold cathodes remain a promising direction. Cold cathodes show significant potential in developing environmentally friendly and energy-efficient plasma sources, particularly under low-pressure conditions. In [35], an experimental study was conducted on the interaction between radio-frequency (RF) waves and plasma generated in a cold cathode discharge tube. The authors used simulations in Magic3D and COMSOL Multiphysics to analyze plasma properties. A glass tube 100 mm in length and 22 mm in inner diameter was fabricated, with 12 mm brass electrodes. Argon plasma was sustained at 500 V and a pressure of 3.8 Torr. The calculated plasma density was 2.529×10^{19} m^{-3}, corresponding to a plasma frequency of 7.18 GHz. Reflection coefficient (S11) measurements showed a shift from − 40 dB in the off state to − 13 dB after plasma ignition, indicating effective reflection of a 3 GHz RF wave. Additionally, a 180° phase shift of the reflected wave was observed when the plasma was ignited [35].

In the context of high-voltage switching devices, cold-cathode plasma switches are of particular interest, especially for HVDC systems. In [35], the influence of plasma parameters on switching speed was investigated. An experimental device with four electrodes (anode, cathode, two grids) operated in a helium environment (6.5 Pa), showing response times from 923 μs (with 11 mA plasma current) to 4.4 μs (at anode voltage of 3 kV). Reducing the distance between grids from 30 mm to 15 mm decreased the switching time by 88 %. The voltage drop in the open state was ~ 100 V, attributed to the oxide layer on the cathode.

Interesting results were also obtained in the study of extended radio-frequency plasmas. In [36], plasma sources based on parallel-plate electrode configurations were investigated, with electrode gaps of 1-5 mm and a nozzle (0.5-3 mm) in the grounded electrode. These systems operated in a wide pressure range from 10^{-3} mbar to above atmospheric pressure, using argon, nitrogen, and air. At low pressure (0.1 mbar), the plasma uniformly filled the gap and expanded into the vacuum chamber. At atmospheric pressure, a stable jet discharge was formed, with gas temperatures ranging from 40 °C to 1200 °C depending on power (15-600 W) and gas type. These sources were used for synthesizing carbon nanotubes and nanowalls (250 W, 10^{-2}-3 mbar), removing carbon deposits at a rate of 2.5×10^{-4} g/min (nitrogen, 600 W), and modifying PET surfaces (reducing the contact angle from 75° to 34° after four scans at 15-25 W). The source designs ranged in size from 60 to 8 mm and could operate without dielectric barriers, including in underwater conditions.

Recent advances in plasma technologies – particularly the development of high-efficiency ICP sources (density > 10^{17} m^{-3}) and pulsed magnetron systems (ionization > 80 %) – have created unique preconditions for the design of hybrid inductive-magnetron plasma sources. Especially relevant to our work is the fact that modern technologies allow for combining the advantages of both approaches: inductive excitation provides a stable, highly ionized plasma, while the magnetron configuration enables precise control over the spatial distribution of particles. The latest developments in cold cathodes and source miniaturization are particularly significant, as they enable the creation of compact, low-inertia systems. At the same time, modern modeling techniques allow for accurate prediction of such hybrid plasma parameters, which is critically important for optimizing electron source performance. These factors – the ability to precisely control plasma parameters in a combined system and the potential for compact, energy-efficient sources – make inductive-magnetron excitation a highly promising direction for further research.

4.3 Identifying Gaps and Promising Areas

The current state of research in plasma generation demonstrates significant progress in the development of both magnetron systems and inductively coupled sources. However, a review of the scientific literature reveals substantial gaps in understanding the physical principles underlying their combined operation. This limits the ability to develop efficient next-generation hybrid systems, particularly those utilizing cold cathodes.

The historical overview and recent advances presented in Sections 4.1 and 4.2 have made it possible to identify key unresolved issues. First, existing research on magnetron systems is primarily focused on optimizing individual parameters (e.g., magnetic field configuration or sputtering regimes), while the integration of these systems with other types of plasma sources remains largely unexplored. Second, although inductively coupled plasma (ICP) has proven effective in achieving high ionization density, the mechanisms of its interaction with magnetron configurations are still insufficiently studied.

Of particular concern is the lack of systematic studies on the combination of inductive excitation with magnetron configurations. The literature review shows that most studies focus either on ICP or on magnetrons independently, while the potential of their integration remains unrealized. For example, it is not yet known how the magnetron's magnetic field influences the resonance characteristics of an ICP coil, or how inductive excitation might enhance the efficiency of magnetron sputtering.

Another critical gap is the absence of comprehensive theoretical models capable of describing plasma behavior under combined excitation. Existing models are generally designed for individual source types and do not account for the specifics of their interaction. This significantly complicates plasma parameter prediction and system optimization.

A promising direction for further research is the investigation of the integration of inductive excitation with a magnetron configuration, especially using a cold cathode. Such an approach could offer several advantages, including improved discharge stability, increased plasma density, and better control over plasma parameters. However, realizing this potential requires extensive theoretical and experimental efforts.

One possible design is an electron source with a secondary emission cathode [37]. This device utilizes the phenomenon of secondary electron emission. The proposed technical solution involves enhancing the electron source by improving the characteristics of the electron flow and reducing energy losses. The core idea is that the electron source includes a cathode with a high secondary emission coefficient placed in a vacuum environment. The introduction of additional electrodes and the optimization of spatial geometry enable effective control over the trajectory and density of the electron beam (Fig. 1).

The advantages of this design include greater electron flux intensity with lower energy consumption, reduced thermal load (since, unlike thermionic cathodes, secondary emission cathodes do not require high temperatures for electron generation), and increased reliability and longevity. Reduced mechanical and thermal wear extends the device's service life. Furthermore, there is the possibility of scaling the geometry for specific applications.

Table 1 systematizes the key characteristics of inductively coupled plasma (ICP) and magnetron systems, along with hypothetical expectations for hybrid inductive–magnetron plasma (IMP) sources, based on a logical analysis of their properties. This comparison clearly demonstrates the potential of combining the two technologies and identifies key research gaps that require further investigation.

Table 1 – Comparison of known plasma excitation technologies with hypothetical expectations for IMP

Criterion	ICP	Magnetron	IMP systems (hypothetically)	Justification
Plasma density	High	Medium	High (near ICP)	Combination of induction excitation (high ionization) and magnetic confinement (as in magnetrons)
Plasma shape control	Weak	Precise (localization)	Medium (partial localization)	The magnetron's magnetic field can limit the expansion of the ICP plasma
Ion flux to the sub-strate	Low	High	High	Combination of high ionization (ICP) and directed flow (magnetron)
Energy effi-ciency	Low	High	Medium/high	Magnetron configuration can reduce ICP losses
Plasma temperature	High	Lower	Medium	Inductive excitation raises the temperature, but a magnetic field can stabilize it
Application for thin film application	Limited	Wide	Promising	Combination of high ionization (for quality films) and flow control (for uniformity)

As shown in Table 1, hybrid IMP systems could theoretically combine the advantages of both technologies: the high plasma density typical of ICP and the precise spatial control characteristic of magnetrons. However, these expectations are based solely on logical extrapolation of existing data, as direct studies of such systems are absent from the scientific literature.

Special attention should be given to the following aspects:

- Field interaction: It is necessary to determine how the magnetron's magnetic field will affect the resonance characteristics of the ICP coil.
- Discharge stability: The combination of two excitation methods may lead to unpredictable phenomena, which must be modeled and experimentally verified.
- Parameter optimization: The absence of comprehensive theoretical models makes it difficult to predict the behavior of hybrid systems.

These issues form the basis for future research in this area. Their resolution will enable the realization of the IMP technology potential for applications such as precision thin film deposition and plasma-based surface processing.

Thus, the literature analysis confirms the relevance of continued research in this direction. The lack of systematic studies on inductive–magnetron excitation indicates the scientific novelty of future investigations, which could serve as a foundation for developing fundamentally new, efficient plasma sources. The next step in this direction should involve developing a theoretical model and conducting experimental studies to validate the proposed concepts.

5. CONCLUSION

The current state of research into inductive–magnetron plasma excitation in cold cathode sources reveals strong potential for creating new hybrid plasma systems. The key advantage of this approach lies in the synergistic combination of the high plasma density typical of inductive excitation with the precise spatial control characteristic of magnetron configurations. However, our analysis reveals critical gaps in the fundamental understanding of the nonlinear interaction between these excitation mechanisms, especially under low-temperature plasma conditions with a cold cathode.

Promising future directions include the development of numerical multiphysics models that account for nonstationary effects in combined systems, experimental optimization of discharge geometry, and the advancement of new plasma diagnostics methods. Special attention should be given to minimizing energy losses and enhancing discharge stability. Realizing this potential could lead to the development of a new class of compact, energy-efficient plasma sources for the precise formation of micro- and nanostructures.

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Передумови та перспективи індукційно-магнетронного збудження плазми в джерелах з холодним катодом

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У статті розглянуто фізичні передумови, сучасний стан та перспективи розвитку індукційно-магнетронного збудження плазми (ІМП) у джерелах із холодним катодом. Зазначене збудження об'єднує переваги індуктивно-зв'язаної плазми (висока густина іонів) і магнетронних систем (просторове керування потоком частинок), утворюючи гібридне джерело з високим потенціалом для мікро- і нанотехнологій. Проведено систематичний огляд основних напрямків досліджень, зокрема моделювання та експериментів у галузі магнетронного розпилення, іонно-плазмових технологій, високочастотних джерел іонів, а також плазмового травлення й осадження плівок. Особливу увагу приділено аналізу історичних рішень, стану сучасних досліджень, досягнень у створенні холодних катодів, високочастотному збудженні та технологіям HiPIMS. Визначено ключові прогалини у розумінні взаємодії індукційного та магнетронного збудження, зокрема в контексті оптимізації конфігурацій котушок і магнітного поля. Стаття не пропонує готових технічних рішень, а окреслює теоретичну базу для подальшої розробки ефективних компактних плазмових джерел. Огляд спрямовано на дослідників у галузі плазмових технологій, мікроелектроніки, матеріалознавства та інженерії поверхні.

Ключові слова: Індукційно-магнетронне збудження, Холодний катод, Гібридні плазмові системи, Систематичний огляд, Оптимізація параметрів плазми.