Spatial Profiling of Glow Discharge Plasma by Dual Magnetron Configuration

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Abstract
In this work, the effects of dual magnetron configuration on the spatial distribution of glow discharge plasma employed in sputtering technique are introduced. Three different configurations of magnetrons in a dc sputtering system were tested. Results showed that the configuration choice allows for fine-tuning the plasma column's width and focus, giving engineers unparalleled control over the properties of the resulting thin films, from thickness uniformity to structural quality.

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1. Introduction

Glow discharge plasmas are fundamental to modern materials preparation and processing, serving as a highly controlled and versatile environment for surface modification. Their primary importance lies in enabling precise thin-film deposition through sputtering and plasma-enhanced chemical vapor deposition (PECVD), which are critical for creating microelectronic circuits, hard coatings, and optical films [1-3]. Furthermore, these low-temperature plasmas are indispensable for surface activation, cleaning, and etching, effectively removing contaminants and functionalizing surfaces to improve adhesion. By providing an energy-efficient means to drive chemical reactions and modify surface properties at low temperatures, glow discharge technology is a cornerstone for advancing electronics, renewable energy, and functional materials [4-6].

A magnetron is a high-powered vacuum tube that generates microwaves through the interaction of a stream of electrons with a magnetic field [7-9]. Its key construction includes a central cathode surrounded by a cylindrical anode block containing resonant cavities, with a strong permanent magnet providing a perpendicular magnetic field. This configuration forces electrons into a circular path, exciting radio-frequency oscillations in the cavities [10-12]. The primary advantage of the magnetron is its ability to produce high-power microwave radiation very efficiently and compactly and remains the cost-effective heart of the common microwave oven, despite competition from solid-state sources in some applications [13-15].

Dual magnetron assemblies consist of two magnetron sputtering sources operated in tandem, often in a closed-field configuration. Their primary advantage lies in significantly enhancing plasma confinement and density above the target surfaces. This is achieved by the magnetic fields from each magnetron linking together, effectively "trapping" electrons and forcing them into longer, spiral paths. This intensified confinement dramatically increases the ionization efficiency of the sputtering gas, which enables high-rate, stable reactive sputtering of dielectric materials without the detrimental "disappearing anode" effect or target poisoning. Consequently, dual magnetron systems provide superior deposition rates, excellent film quality, and enhanced process control for coatings like oxides and nitrides [16-20].

In this work, the effects of dual magnetron configuration on the spatial distribution of glow discharge plasma employed in sputtering technique are introduced. Three different configurations of magnetrons in a dc sputtering system were tested.

2. Experimental Part

A dc sputtering system was used to introduce the effects of dual magnetron configuration on the spatial distribution of glow discharge plasma employed in such system. A dc power supply (0-5 kV, 100 mA) was used to generate glow discharge plasma between two electrodes using argon gas at a pressure of 0.8 mbar and flow rate of 50 sccm. Figure (1) shows the magnetron assembly used in designing the dual magnetron configuration while figure (2) shows the glow discharge plasma generated inside the vacuum chamber.

3. Results and Discussion

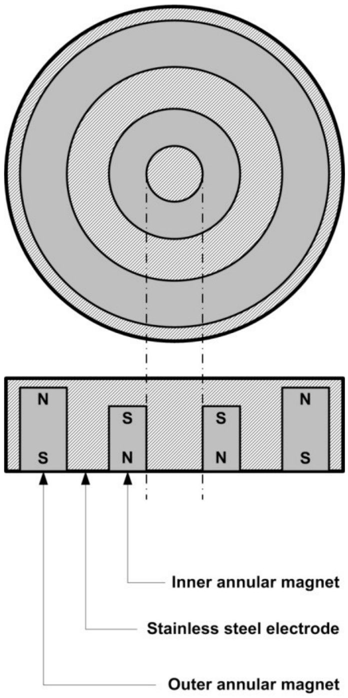
The dual magnetron configuration, particularly in an opposed setup, is one of the most effective methods for controlling the spatial distribution, density, and stability of a glow discharge plasma. Unlike a single magnetron, which localizes the plasma near the target surface in a 'racetrack,' the dual-opposed arrangement creates a sophisticated closed-field magnetic topology that fundamentally reshapes the plasma column, dramatically enhancing uniformity and ionization efficiency. This discussion explores the profound impact of this configuration on the spatial distribution of a plasma generated in argon between two electrodes (the magnetron targets).

A magnetron uses a static magnetic field configured at the cathode location. The magnetic field is located parallel to the cathode surface. Secondary electrons which are emitted from the cathode due to ion bombardment are constrained by this magnetic field to move in a direction perpendicular to both the electric field (normal to the surface) and the magnetic field. This is known as an E×B drift, which is also the basis for the Hall Effect [18]. This drift causes electrons to move parallel to the cathode surface in a direction 90° away from the magnetic field. If the magnetic field is set up correctly, this E×B drift can be arranged to close on itself, forming a current loop of drifting secondary electrons (Fig. 1).

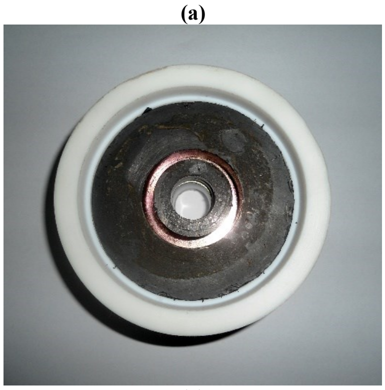
The primary mechanism by which the dual magnetron controls the plasma column is the interaction between the two magnetic fields. A standard magnetron uses a center pole (e.g., North) and an outer ring pole (South) to create a magnetic bottle near the target surface. In the dual-opposed configuration, the targets are typically positioned face-to-face, with the magnetic poles often aligned to ensure field lines from one target's outer pole are directed toward the other target's outer pole [21,22].

When two magnetrons are properly opposed, their individual, localized magnetic fields are superimposed, forming a macroscopic magnetic trap that extends far into the space between the targets. The magnetic field lines often close upon themselves, creating a magnetic 'cage' or closed-field confinement volume. Electron trapping topology is crucial because it efficiently traps the secondary electrons—the lifeblood of the glow discharge—that escape the immediate vicinity of the target racetrack. Instead of being lost to the chamber walls or anode, these electrons are forced to follow helical paths along the closed-field lines. The increased path length and dwell time of the energetic electrons within the plasma volume lead to a significantly higher number of ionizing collisions with the background argon gas. This translates directly to a dramatically increased plasma density and a more voluminous plasma column [23,24].

Figure (3) illustrates this macroscopic confinement: the plasma column is shown as an hourglass shape that bridges the gap between the two magnetrons. The narrowing in the center, often called the plasma waist or a region of a magnetic null point, is a characteristic feature of this extended confinement zone. The spatial distribution of the plasma column is directly defined by the density of the argon ions and electrons. The dual-opposed configuration excels at creating a plasma distribution that is both denser and more uniform than single-magnetron systems [25,26].



(a)



(b)

Fig. (3) (a) Typical design of annular-shaped plane magnetron for plasma discharge [19-20], and (b) The magnetron assembly used in designing the dual magnetron configuration

Fig. (2) DC sputtering system used in this work as the glow discharge plasma is seen inside the chamber

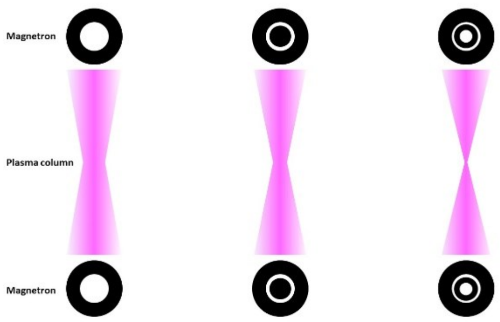


Fig. (3) Schematic explanation of effect of dual magnetron configuration on spatial distribution of plasma

In a single magnetron, the plasma density peaks sharply at the racetrack and drops off quickly. The dual-opposed setup effectively smoothens this gradient. By confining electrons across the entire inter-target space, the plasma column transitions from a highly localized layer to a broad, volumetric distribution. For thin-film deposition, a substrate is typically placed within this volumetric plasma column. The high uniformity of the ion flux across the volume ensures that the substrate receives a near-constant bombardment of argon ions, which is vital for achieving uniform film thickness and stoichiometry over large deposition areas. The ability to control the radial size of this plasma column, as suggested by the varying ring sizes in your images, is a key engineering parameter [27,28].

The design of the individual magnetrons (represented by the varying ring sizes in the image, which denote different magnetic pole configurations) directly impacts the shape of the plasma waist. A stronger magnetic field or a smaller gap between the inner and outer poles can create a tighter, more focused confinement zone. This results in a sharper plasma waist (a more pronounced hourglass shape) and potentially a higher peak plasma density in the center, which can be useful for focusing ion flux [29,30]. On the other hand, a weaker or wider magnetic field configuration results in a broader, more diffuse magnetic field closure. This leads to a wider plasma waist and a flatter, more extended plasma column, prioritizing large-area uniformity over peak density.

The dual magnetron configuration fundamentally re-engineers the spatial distribution of the argon glow discharge. By moving beyond the localized 'racetrack' of single systems, the opposed magnetic fields create a sophisticated, closed-field magnetic cage that traps energetic electrons across the entire inter-electrode volume. This results in a plasma column that is volumetric and bridged, as forming the characteristic hourglass shape that fills the space between the targets. It also results in dramatically increase in the ionization efficiency and smoothing the plasma density gradient over the deposition area [31-33].

4. Conclusion

In concluding remarks, the configuration choice - as subtly indicated by the varying magnetic pole gaps in the schematic - allows for fine-tuning the plasma column's width and focus, giving engineers unparalleled control over the properties of the resulting thin films, from thickness uniformity to structural quality.

References

[1] P.J. Kelly and R.D. Arnell, Surf. Coatings Technol., 112, 170-176 (1999).
[2] P.J. Kelly and R.D. Arnell, Vacuum, 56, 159-172 (2000).
[3] I. Safi, Surf. Coatings Technol., 127, 203-219 (2000).
[4] P.J. Kelly, R.D. Arnell and J.W. Bradley, Surf. Coatings Technol., 188-189, 158-163 (2004).
[5] O.A. Hammadi, M.K. Khalaf, F.J. Kadhim and B.T. Chiad, Bulg. J. Phys., 41(1) (2014) 24-33.
[6] R. Raju, L. Meng, R. Flauta, H. Shin, M.J. Neumann, T.A. Dockstader and D.N. Ruzic, Plasma Sources Sci. Technol., 19, 1-9 (2010).
[7] S. M. Borah, J. Mater., 852859 (2013).
[8] M.K. Khalaf, F.J. Kadhim and O.A. Hammadi, Iraqi J. Appl. Phys., 10(1) (2014) 27-31.
[9] V.S. Mitin, E.I. Sharipov and A.V. Mitin, Surf. Eng., 22(1), 1-6 (2006).
[10] O.A. Hammadi, W.N. Raja, M.A. Saleh and W.A. Altun, Iraqi J. Appl. Phys., 12(3) (2016) 35-42.
[11] T.E. Sheridan, M.J. Goeckner and J. Goree, J. Vac. Sci. Technol. A, 8(1), 30-37 (1990).
[12] M.A. Hameed and Z.M. Jabbar, Iraqi J. Appl. Phys., 12(4) (2016) 13-18.
[13] A.S. Penfold, Handbook of Thin Film Process Technology, IOP (1995), sec. A.3.2, p. 1.
[14] E. Martines, R. Cavazzana, G. Serianni, M. Spolaore, L. Tramontin, M. Zuin and V. Antoni, Phys. of Plasma, 8(6), 3042-3050 (2001).
[15] O.A. Hammadi, W.N. Raja, M.A. Saleh and W.A. Altun, Iraqi J. Appl. Phys., 12(4) (2016) 19-28.
[16] B. Window and N. Savvides, J. Vac. Sci. Technol. A, 4(2), 196 (1986).
[17] M.A. Hameed and Z.M. Jabbar, Silicon, 10(4) (2018) 1411-1418.
[18] T. Makabe and Z. Petrovic, Plasma Electronics: Applications in Microelectronic Device Fabrication, Taylor & Francis, New York (2006) 301.
[19] J.A. Thornton, A.S. Penfold, in: J.L. Vossen, W. Kern (Eds.), Thin Film Processes, Academic Press, New York (1978).
[20] J.A. Thornton, J. Vac. Sci. Technol., 15, 171 (1978).
[21] F.J. Al-Maliki and E.A. Al-Oubidy, Physica B: Cond. Matter, 555 (2019) 18-20
[22] M. Yusupov, E. Bultinck, D. Depla and A. Bogaerts, New J. Phys., 13, 033018 (2011).
[23] O.A. Hammadi, M.K. Khalaf and F.J. Kadhim, Proc. IMechE, Part L, J. Mater.: Design & Appl., 231(5) (2017) 479-487.

[24] R. Parsons, in Thin Film Processes II, J.L. Vossen, W. Kern (Eds.), Academic Press, New York (1991) 178.
[25] C.H. Shon and J.K. Lee, Appl. Surf. Sci., 192, 258-269 (2002).
[26] T.E. Sheridan, M.J. Goeckner and J. Goree, J. Vac. Sci. Technol. A, 16(4), 2173-2176 (1998).
[27] C.-T. Liu, M.-C. Lai and C.-C. Hwang, IEEE Trans. on Magnetics, 46(6), 1614-1617 (2010).
[28] O.A. Hammadi, Iraqi J. Appl. Phys., 16(1) (2020) 15-20.
[29] U.H. Kwon, S.H. Choi, Y.H. Park and W.J. Lee, Thin Solid Films, 475, 17-23 (2005).
[30] M. Ohring, The Materials Science of Thin Films, Academic Press, California (1992) 126.
[31] I.V. Svadkovski, D.A. Golosov and S.M. Zavatskiy, Vacuum, 68, 283-290 (2003).
[32] A. A. Solov'ev, N. S. Sochugov, K. V. Oskomov, and S. V. Rabotkin, Plasma Phys. Rep., 35(5), 399-408 (2009).
[33] F.J. Kadhim, O.A. Hammadi and N.H. Mutesher, J. Nanophot., 16(2) (2022) 026005 DOI: 10.1117/1.JNP.16.026005.