DOI: 10.30511/pcdp.2025.718447 - ISSN: 3060-8376 - Vol 2(1), 2025

POWER, CONTROL AND
DATA PROCESSING SYSTEMS
Available Online at: https://pcdp.qut.ac.ir/

Numerical Simulation of Electron Cyclotron Resonance Discharge Generated by Permanent Magnets

ARTICLE INFO

Article Type
Original Research

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Article History
Received: October 15, 2024
Accepted: November24, 2024
ePublished: March 01, 2025

ABSTRACT

In recent years, the technology of plasma processing and thin film deposition using electron cyclotron resonance plasma (ECR) sources has been developed and widely utilized in plasma processing at low pressures due to its higher ionization rate compared to DC and RF plasma sources, as well as its lower sheath potential. One of the challenges of ECR plasma processing systems is the requirement for expensive magnetic field generation systems. This issue can be addressed by using permanent magnets instead of magnetic coils for generating magnetic fields. In this article, magnetic field profile of four NdFeB grade 42 permanent block magnets have been computed using Magnetic Field No Current (MFNC) module of COMSOL Multiphysics software and the optimal arrangement of magnets, for which resonant surfaces are placed inside the discharge chamber, has been determined. Then, microwave generated discharge in the presence of permanent magnets have been computed using Plasma and Electromagnetic Wave (EMW) modules. Additionally, we calculated characteristics of the discharge such as plasma density and microwave power absorption.

Keywords: ECR plasma; Permanent magnets; COMSOL; Plasma processing.

1 Introduction

Microwave discharges that have an electron cyclotron resonance region in the discharge volume are called ECR discharges. Regardless of its shape or volume, the presence of such an electromagnetic coupling region at low pressures, significantly improves the coupling of microwave power to plasma. The overall improved efficiency in these types of discharges is partly related to the ability of static magnetic field to reduce diffusion loss of charged particles.

ECR plasma is a type of magnetized plasma, where the frequency of electromagnetic source is in microwave range. The resonance condition for electrons can be obtained by adjusting microwave frequency and synchronizing it with electron cyclotron frequency in magnetic field. The influence of the magnetic field on the breakdown electric field at microwave frequencies, which ultimately led to the development of ECR plasma sources, was first investigated by Lax [1] in the 1950s as a method for characterizing confined plasma. The idea of using this technique for plasma generation was first proposed in the early 1960s for research related to plasma acceleration and plasma fusion [2,3].

In the late 1970s, Suzuki and his colleagues [4] demonstrated that ECR plasma with divergent magnetic field structure could be used for plasma etching in micrometer scales. Since ECR plasmas typically operate at low pressures (below 10 mTorr), the mean free path is significantly long, enabling electrons to rapidly gain sufficient kinetic energy from electromagnetic wave to achieve high ionization efficiency and high plasma density. Preliminary experiments indicated that, despite the low plasma potential, ECR discharges can operate at relatively low pressures $10^{-4} - 5\times10^{-5} torr$ and high plasma density $10^{11} - 10^{12} cm^{-3}$. Under these conditions, ions constitute a significant fraction of chemically active species in discharge plasma. The amount and direction of ions velocity toward substrate, can be controlled by applying RF bias to substrate. Commercially available ECR etching tools for large-diameter (300 and 450 mm) wafers can ensure uniform plasma processing and generation. Results related to silicon oxidation [5,6], plasma etching [7,8], ion implantation [9,10] and dielectric deposition [11] by ECR plasma sources have been published.

ECR plasma has been used for various plasma enhanced chemical vapor deposition (PECVD) processes, such as silicon deposition, carbon coating and metal-oxide coating [12]. ECR-PECVD system has been utilized for deposition of high-optical quality silicon nitride thin films under low-temperature (140°C) and low-pressure (1.5 mTorr) conditions [13]. The produced thin films have been used in optical waveguides, particularly for visible and near-infrared (NIR) integrated photonic devices.

As mentioned above, ECR plasma sources can generate stable plasma even at very low pressures, and their spatial distribution can be easily controlled using static magnetic field distribution. Additionally, ECR plasma sources can generate plasma away from chamber walls, reducing contamination, and produce uniform plasmas for consistent processing.

Despite numerous advantages of ECR plasma sources, they are costly and involves multiple complexities, such as applying electromagnetic wave to plasma and generating the magnetic field. Usually, electromagnetic coils have been used to generate the required magnetic field to satisfy the ECR condition. However, the requirement for large diameter coils for uniform processing of large area substrates results in an increase in the electric power required for coils, as well as an increase in the weight and volume of the device. Moreover, a strong magnetic field would exist in front of the substrate, even if it has been located far from the coil. This problem can be solved by using permanent magnets instead of electromagnetic coils for generating the magnetic field. Permanent magnets are capable of providing the required magnetic field to satisfy ECR condition in narrow regions of the discharge tube, thus achieving a magnetic field-free area in front of the substrate.

From this point of view, ECR plasma sources that utilize permanent magnets, for generation of resonance zones are promising and have gained considerable attention for plasma processing [14].

The arrangement and design of magnetic fields, such that the resonance surfaces are located in the discharge chamber and near the microwave input window, influence the microwave coupling with plasma and its resonant heating. In reference [15] dependence of ECR plasma characteristics on the profile of magnetic field have been investigated.

The magnetic field profile plays a crucial role in determining the characteristics of an ECR plasma, including its density, temperature, and uniformity.

The magnetic field profile must be carefully designed to create a well-defined resonance zone where the electron cyclotron frequency matches the microwave frequency. This resonance zone is essential for efficient energy transfer from the microwaves to the electrons, leading to plasma generation and heating. Moreover, a well-designed magnetic field profile can enhance electron confinement, leading to higher plasma densities.

Numerical simulations and experimental techniques are essential tools for optimizing the magnetic field profile of an ECR plasma source, which is a critical factor in determining plasma properties.

In this manuscript, we have employed numerical simulations using COMSOL Multiphysics software to investigate the characteristics of plasma generated in an ECR device equipped with permanent magnets. The primary objective of this study is to gain a deeper understanding of the electron density distribution and power absorption in this type of plasma. Here, we have simulated the process of ECR plasma formation in three dimensions and the optimal positioning of permanent magnets, such that the resonance surfaces are located in discharge chamber using COMSOL Multiphysics software. The results indicate magnetic field profile and characteristics of microwave-generated plasma. The relatively high density of

generated plasma makes this source suitable for plasma processing applications.
Section 2 introduces the numerical model used in this study. Numerical results obtained from the simulations are presented in Section 3. Finally, the paper concludes in Section 4.

2 Numerical modelling

In the ECR plasma source simulated in this paper, we assume that the microwave with a frequency of 2.45 GHz enters the cylindrical plasma chamber through a WR340 rectangular waveguide. The microwave electric field can be rewritten as $E = E_0 \cos(\omega t)$, where ω is microwave frequency. In the presence of a uniform and static magnetic field,
electrons will experience circular or helical motion along magnetic field lines due to Lorentz force. The circular motion of electron has a Larmor radius $r_L = mv/qB$ and a cyclotron angular frequency $\omega_c = qB/m$, where v is electron velocity perpendicular to magnetic field. This circular motion will not transfer energy to electrons in vacuum and without collisions. By adding the microwave electric field with angular frequency ω to the problem, the electron 's trajectory will change. The resonance effect occurs when the condition $\omega = \omega_c$ is satisfied. As a result, electrons move in phase with the electric field and continuously accelerate, which is called electron cyclotron resonance (ECR) effect. For a microwave frequency of 2.45 GHz, the resonance effect occurs when magnetic field intensity is 875 Gauss.
Here, in order to generate ECR resonance surfaces, we use four $100 \times 50 \times 10\ mm$ grade 42 neodymium block magnets around a 10 cm diameter 304 stainless steel cylindrical chamber.
Due to the availability of neodymium block magnets with suitable magnetic properties, and simulation results demonstrating the feasibility of creating a uniform resonant magnetic field with four magnets arranged around the chamber, we chose this configuration. After computing the magnetic field profiles generated by permanent magnets, it was found that the optimal arrangement for placing magnets around chamber is to position the opposite poles facing each other at equal distances around chamber. We have used Magnetic Fields No Currents (MFNC) module of COMSOL software, for computing magnetic field profile.

3 Numerical results

The computed magnetic field inside plasma chamber and resonance surface with a magnetic field of 875 Gauss have been shown in Figure 1. After calculating magnetic fields, we use Plasma and Electromagnetic Wave (EMW) modules to calculate the evolution of plasma. We consider an input power of 100 watts, an initial temperature of 300 Kelvin, and a background pressure of $7 \times 10^{-4} torr$. The electromagnetic waves are generated by a magnetron and reach the magnetic field inside the chamber by passing through the waveguide. The magnetic field along the axis of plasma chamber forces the electrons to rotate around the magnetic field lines, increasing probability of ionization. When the frequency of microwave source matches the cyclotron frequency of particles, resonance occurs, and the energy of charged particles increases. As a result, the number of collisions increases and ionization occurs. The location and density of plasma are controlled by arrangement of magnetic field, the neutral particle pressure, and the input power to the chamber. Where the frequency of microwave source matches the cyclotron frequency of charged particles, resonance occurs, and this area is called the "ECR absorption region".

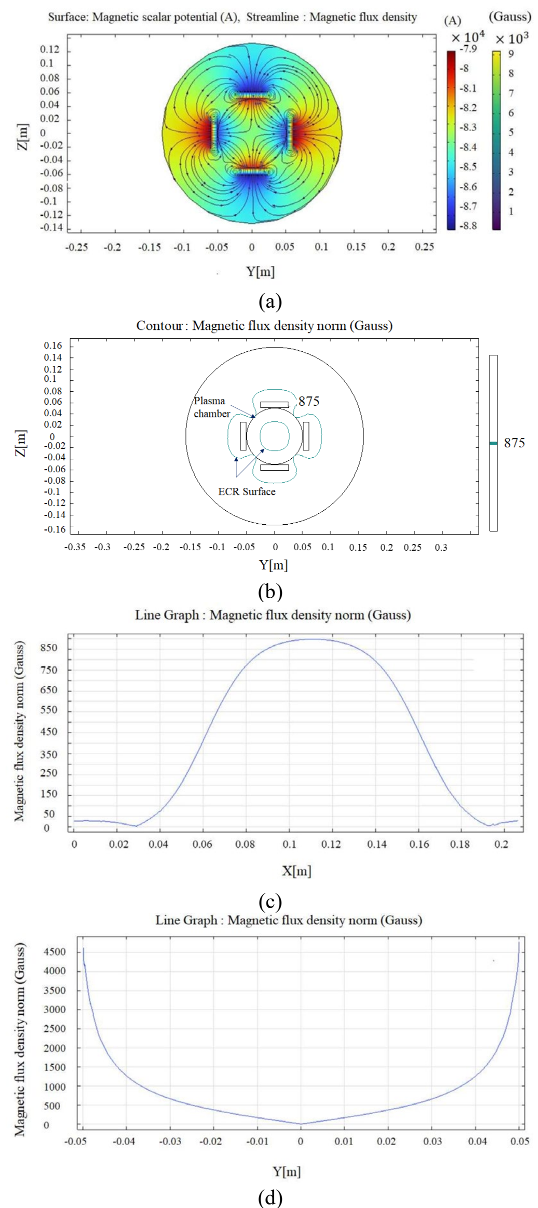

Figure 1: (a) Magnetic scalar potential and the arrangement of magnetic poles, and the shape of magnetic flux surfaces, (b) Resonant surface with a magnetic field of 875 Gauss in the y-z plane, (c) Resonant surface with approximately 875 Gauss along the axis of plasma chamber, (d) Magnetic field along the radius of plasma chamber.

Figure 2 shows electron density of plasma. According to Figure 3, electrons absorb energy from the injected microwave power under resonant conditions and on resonant surfaces.

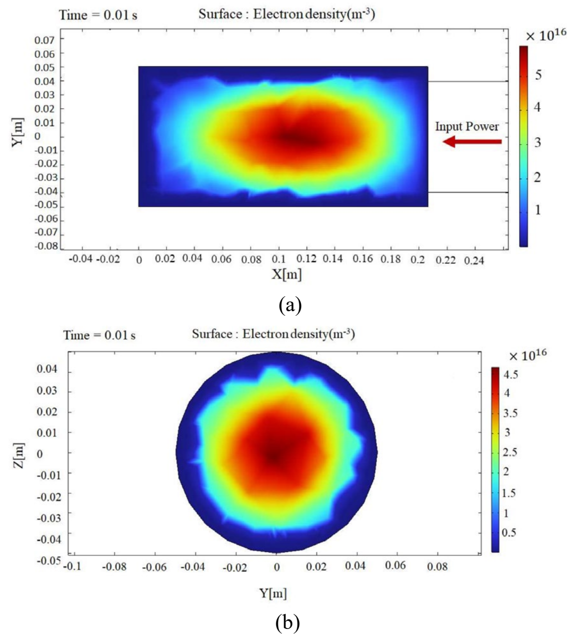

Figure 2: Electron densities (a) in x-y plane and $z = 0$ (b) in y-z plane and $x = 0.155\ m$, at 0.01 second after the start of the simulation.

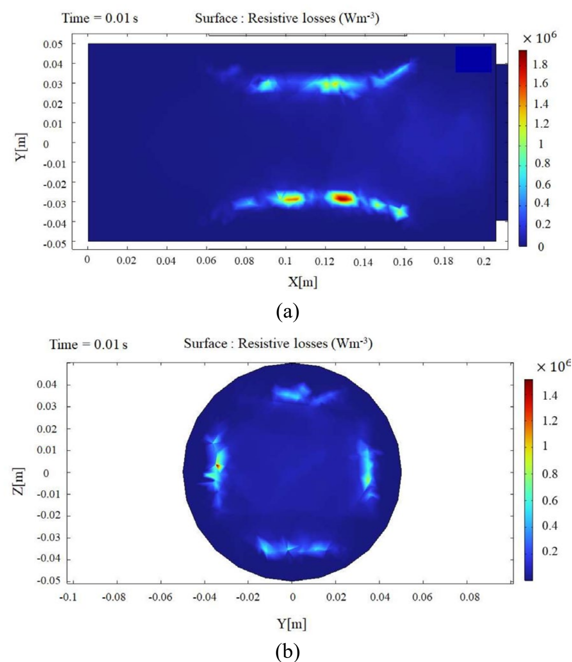

Figure 3: Absorbed power (a) in x-y plane at $z = 0$ (b) in y-z plane and $x = 0.155\ m$, at 0.01 second after the start of the simulation.

All power absorption from electromagnetic wave field in plasma occurs on ECR resonant surfaces. Electrons continuously accelerate in the ECR absorption region. These high-energy electrons lose their energy through collisions with neutral particles, leading to ionization and momentum transfer. Since ECR plasma primarily operates at low pressures (less than 10 millitorr), the mean free path is long, allowing electrons to rapidly gain sufficient kinetic energy to achieve high ionization efficiency and plasma density.

4 Conclusion

ECR plasma sources offer several advantages, including resonant microwave absorption for operation over a wide pressure range, high ionization degrees compared to RF and DC sources, and electrodeless operation for simpler configurations and longer lifetimes.

Numerical simulations are indispensable tools for understanding and optimizing ECR plasma sources. By modeling the complex interplay between electromagnetic fields, particles, and plasma processes, simulations enable researchers to design efficient magnetic field configurations, optimize microwave coupling, and predict plasma parameters such as electron density, temperature, and ion energy distributions. Furthermore, simulations can facilitate the exploration of innovative source designs and predict the performance of novel configurations. Ultimately, numerical simulations contribute to the advancement of ECR plasma technology by providing valuable insights and guiding experimental efforts.

In this paper, we employed COMSOL Multiphysics software to simulate the magnetic field configuration required to generate ECR resonance surfaces. Subsequently, we used these calculated fields to determine the plasma density and power absorption. At a pressure of 0.7 mTorr, the simulated electron density was found to be on the order of $10^{16} m^{-3}$, which is promising for achieving higher deposition rates in various applications.

Disclosure of Potential Conflicts of Interest

The Authors declare that there is no conflict of interest

Reference

[1] B. Lax, et al., "The Effect of Magnetic Field on the Breakdown of Gases at Microwave Frequencies" J. Appl. Phys., 21(12): 1297 (1950).

[2] J. Musil and F. Zacek, "Penetration of a strong electromagnetic wave in an inhomogeneous plasma generated by ECR using a magnetic beach," Plasma Phys., vol. 13, pp. 471–476, (1971).

[3] R. Geller," New high intensity ion source with very low extraction voltage", Appl. Phys. Lett., 16: 401 (1970).

[4] K. Suzuki, S. Okudaira, N. Sakudo, and I. Kenomato, "Microwave plasma etching," Jpn. J. Appl. Phys., vol. 16, no. 11, pp. 1979–1984, Nov. 1977.

[5] L. Bardos, et al., "A method of formation of thin oxide films on silicon in a microwave magnetoactive oxygen plasma", J. Phys. D: Appl. Phys., vol 8: L195 (1975).

[6] K. Saito, Y. Jin, T. Ono, M. Shimada, "Low-Temperature Silicon Oxidation with Very Small Activation Energy and High-Quality Interface by Electron Cyclotron Resonance Plasma Stream

Irradiation", Japanese Journal of Applied Physics, 43(No. 6B), L765–L767(2004).

[7] J. E Stevens and J. L Cecchi, "Wave propagation and plasma uniformity in an electron cyclotron resonance plasma etch reactor", Japan. J. Appl. Phys. 32 3007 (1993).

[8] V. M Donnelly and A. Kornblit, "Plasma etching: yesterday, today, and tomorrow", J. Vac. Sci. Technol. A 31 050825-1(2013).

[9] T. Watanabe, K. Yamamoto, O. Tsuda, A. Tanaka, Y. Koga," Synthesis of amorphous carbon films by plasma-based ion implantation using ECR plasma with a mirror field", Surface and Coatings Technology, 156(1-3), 317–321 (2002).

[10] S. Béchu, O. Maulat, Y. Arnal, D.Vempaire, A. Lacoste, J. Pelletier, "Multi-dipolar plasmas for plasma-based ion implantation and plasma-based ion implantation and deposition", Surface and Coatings Technology, 186(1-2), 170–176 (2004).

[11] S. Peter, Y. Vasin, F. Speck, M. Schmidt, V. Wittstock, T. Seyller," ECR plasma deposited a-SiCN:H as insulating layer in piezoceramic modules", Vacuum, 155, 118–126 (2018).

[12] Junkang Wang. "Novel Concepts in the PECVD Deposition of Silicon Thin Films: from Plasma Chemistry to Photovoltaic Device Applications". Plasma Physics [physics. plasm-ph]. Université Paris Saclay (COmUE). English. ffNNT: 2017SACLX079ff. fftel-01688695ff (2017).

[13] D. B. Bonneville, J. W. Miller, C. Smyth, P. Mascher, J. D. B. Bradley, "Low-Temperature and Low-Pressure Silicon Nitride Deposition by ECR-PECVD for Optical Waveguides". Applied Sciences, 11(5), 2110 (2021).

[14] S. Iizuka and N. Sato, "Electron cyclotron resonance devices with permanent magnets for production of large-diameter uniform plasmas", Ipn, J. Appl. Phys. Vol.33 pp. 4221-4225 (1994).

[15] S. Samukawa, T. Nakamura," Dependence of Electron Cyclotron Resonance Plasma Characteristics on Magnetic Field Profiles. Japanese Journal of Applied Physics, 30(Part 1, No. 11B), 3147–3153 (1991).