Plasma Generation Using Solid-State Microwave Technology

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Abstract

Microwaves are frequently used to produce high density plasmas for industrial and laboratory applications, because they present several advantages when compared to radio-frequency discharges and discharges created using electrodes. Stable and reliable microwave plasma equipment based on magnetrons, and designed for automatic control of the operating parameters has already proved its efficiency in low temperature diamond deposition, exhaust gas abatement, thin-film deposition, etc. However, larger-scale processing with high density and uniform plasma is mandatory for surface treatments to get uniform etching or deposition rates. To meet these industrial requirements *Aura-Wave*, an ECR microwave plasma source operating in the 10^{-2}–1 Pa pressure range, and *Hi-Wave*, a collisional plasma source for higher pressure gas processing (i.e. 1 – 100 Pa) have been designed. Furthermore, because each plasma source is powered by its own microwave solid-state generator, multiple sources operating in different conditions (gas type, microwave power) can be distributed together in the same reactor. In this design, the solid-state microwave generator can produce a forward wave with variable frequency (2.4–2.5 GHz) which enables an automatic adjustment loop of the reflected power, created occasionally by a change in the operating conditions. A Langmuir probe has been used for the measurement of plasma density, uniformity, and electron temperature in argon, oxygen, nitrogen and air.

Keywords:
Microwave plasma; solid-state technology; electron-cyclotron resonance; collisional regime; Langmuir probe.

Introduction

Microwaves combined with a static magnetic field at low pressure can result in a highly efficient electron-heating mechanism, the Electron Cyclotron Resonance (ECR). The resonance occurs when the frequency of the electric field equals the gyration frequency of the electrons in the magnetic field, and results in a conical spiral motion of the electrons. At 2.45-GHz microwave frequency, the resonant condition is reached when $B = 0.0875$ T. As such, the electrons gain considerable energy that allows the ionization of neutral particles in the gas, and breakdown the plasma due to cascade reactions[1].

ECR phenomenon is well-matched when the electron collision frequency ν is small compared to the angular frequency of the applied electric field ω_0 so that $\nu/\omega_0 = 10^{-2}$–10^{-4}. This way, the electrons accumulate high energy between two collisions leading to low-pressure plasma generation, typically in the range 10^{-2} – 1 Pa (10^{-4} – 10^{-2} mbar). Unlike ECR, the energy gained by the electrons in the collisional regime is the one imparted during collisions. Without magnetic field, the work of an electron on a full period of the applied microwave field is zero. Consequently, the maximum transfer efficiency[2] is obtained for $\nu = \omega_0$, i.e. when an electron has the highest chance to gain maximum energy of the electric field while having maximum probability to have a collision on the period of the wave.

To overcome the limitations of the critical plasma density, and increase the penetration depth of the electromagnetic wave in the plasma, new plasma sources based on solid-state microwave technology were developed: *Aura-Wave* (ECR coaxial plasma source) and *Hi-Wave* (magnet free, elementary collisional plasma source).

Both sources were designed to avoid power-loss within their own structures, and to be easily matched over wide operating conditions[3,4] without any additional tuning system. Each source is connected to its own 200-W, 2.45-GHz microwave solid-state (transistor-based) generator, which has very good power stability and allows the frequency of the emitted wave to be adjusted in the range 2.4–2.5 GHz for automatic impedance tuning[5], making it possible to control precisely the power transmitted to the plasma. The low mismatching created by changes in the operating conditions can be compensated automatically by the variation of the forward-wave frequency, which leads to a significant extension of the operating-condition range of the plasma sources.

Experimental

The coaxial antenna using the electron cyclotron resonance (*Aura-Wave* in Figure 1a) consists of encapsulated cylindrical permanent magnets, mounted in opposition within the coaxial structure[6]. This arrangement enables to generate a magnetic field in the direction of the center of the plasma chamber and hence, limiting losses on the walls. The source was designed to sustain plasmas from 10^{-2} to 10 Pa, and to reach plasma densities up to a few 10^{11} cm^{-3} in multisource configuration (Fig. 1b) at 10 cm from the source. The coaxial antenna based on collisional heating called (*Hi-Wave* in Figure 1c) was designed to sustain plasmas from 1 to 100 Pa and to reach plasma densities of 10^{11} - 10^{12} cm^{-3} at 10 cm from the source, depending on the gas, in multisource configuration (Figure 1d).

Figure 1. (a) *Aura-Wave* ECR microwave plasma source. (b) Multisource reactor consisting of 8 *Aura-Wave* units (shown in argon for a total microwave power of 160 W at 1 Pa). (c) *Hi-Wave* collisional microwave plasma source. (d) Multisource reactor consisting of 8 *Hi-Wave* units (shown in nitrogen for a total microwave power of 1600 W at 10 Pa).

The experimental setup used to perform the experiments consists of a multisource plasma reactor within which up to 9 *Aura-Wave* or *Hi-Wave* plasma sources were installed (see Figure 2). Each plasma source was connected to its own microwave solid-state generator (200-W maximum power), which produces a wave with variable frequency from 2.4 to 2.5 GHz (in 100 MHz steps). This setup allows control of both the transmitted microwave power to each plasma source by 1-W increments, and the process parameters.

The solid-state microwave generators were chosen due to the spectral quality, which is considerably superior to that of a magnetron generator, whose frequency is dependent on the magnetron geometry. During operation, the frequency of the magnetron shifts due to metal dilatation and therefore can depend on the temperature and on the output microwave power. The change of the output power of a magnetron also impacts the quality of the frequency spectrum. Magnetrons are known to produce an acceptable spectrum between 10% of their nominal power, up to full power. Due to the fact that solid-state generators act like amplifiers, they are able to produce an excellent frequency spectrum over the full range of power from the very first watts[7].

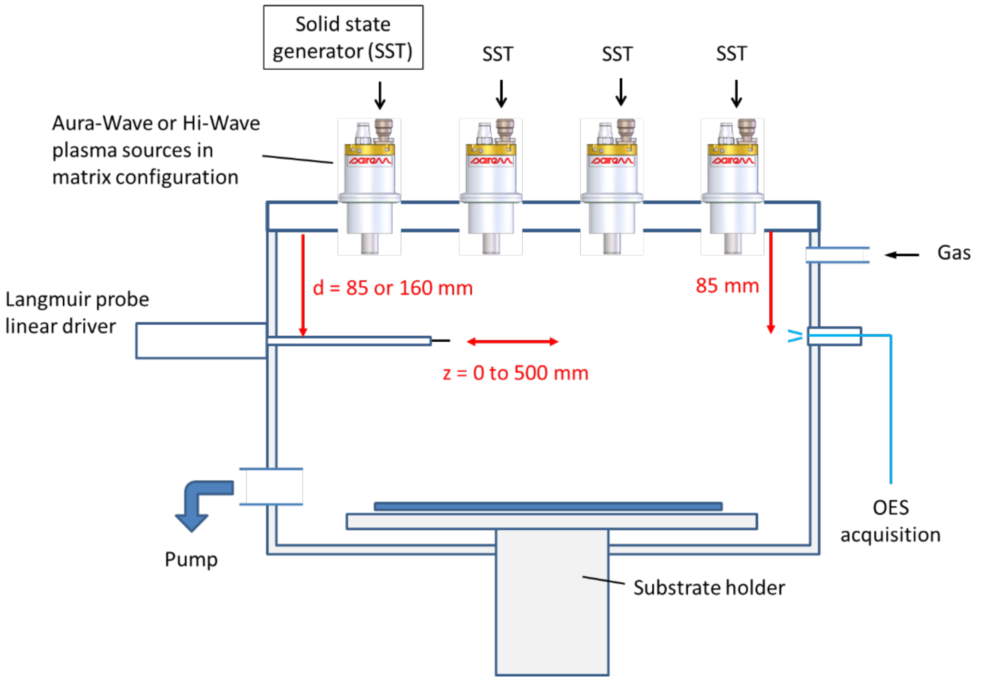

Figure 2. The multisource plasma reactor with Langmuir-probe and Optical Emission Spectroscopy (OES) diagnostics.

Microwave plasma parameters were measured with a Langmuir probe placed at two heights, $d = 85$ mm and 160 mm, from the plasma sources. A step motor moves the probe linearly in direction z from 0 to 500 mm position, to enable the evaluation of spatial resolved plasma parameters, i.e. the plasma density, electronic temperature and uniformity. For the evaluation of the plasma density and uniformity in a circular network, 8 *Hi-Wave* plasma sources were tested (see the source positions in the inset of Figure 3). The microwave power supplied to each source is 200-W at 5-Pa pressure. The circular configuration diameter is 247 mm. The resulted plasma density profiles are plotted in Figure 3 for oxygen. Uniformity of 1.65% at $d = 85$ mm, and 1.8% at $d = 160$ mm, was measured over 250-mm diameter plasma.

Table 1 summarizes the comparison results for *Aura-Wave* and *Hi-Wave* sources (8 sources in circular network configuration) in different gases. The *Aura-Wave* plasma source attains densities >10^{11} cm^{-3} at $d = 85$ mm for each of the gases tested (Ar, O_2, N_2, air), while the *Hi-Wave* plasma source attains densities >10^{12} cm^{-3} in argon and densities >10^{11} cm^{-3} in molecular gases (O_2, N_2, H_2 and air). The plasma density and the measured line intensity are both higher with the *Hi-Wave* plasma source than those measured with the *Aura-Wave*.

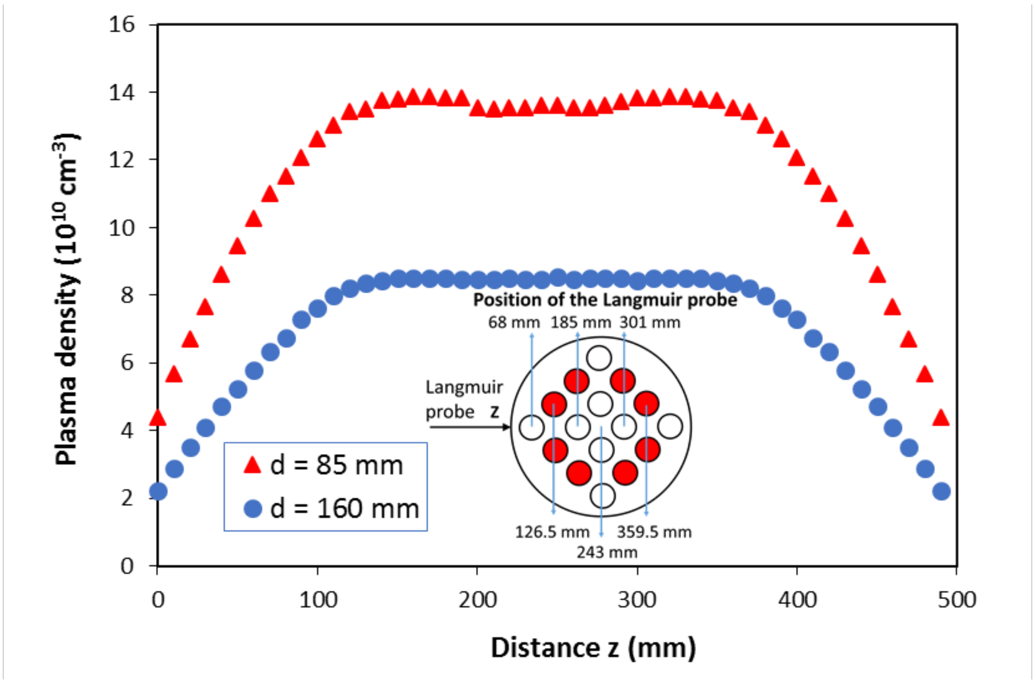

Figure 3. Oxygen plasma density vs. distance and diameter at d = 85 mm and d = 160 mm from the *Hi-wave* source.

Table 1. Comparative results of *Aura-Wave* and *Hi-Wave* plasma sources

Plasma source type	Operating pressure range [Pa]	Min. MW power to sustain plasma [W]	Max. plasma density x 10^{10} cm^{-3} 9 sources, 1800 W, *d* = 85 mm				Electron temp. [eV]	Plasma uniformity, 8 sources in circular network
			Ar	O_2	N_2	Air		
Aura-Wave	~ 0.1 - 5	1 - 5	28	21	17	17	2.5 – 3.5	<4%, 200mm area diameter, d=85mm and d=160mm
Hi-Wave	~ 1 - 50	>10	207	28	30	22	1.5 - 2	<3%, 240mm area diameter, d=85mm and d=160mm
								<1%, 200mm area diameter, d=160mm

Recent results[8,9] show that uniform deposition of nanocrystalline diamond on 4” diameter can be obtained in H_2–CH_4 at $d = 50$ mm from source plane using solely 4 *Hi-Wave* units in a matrix configuration (with a lattice mesh of $a = 8$ cm). However, the *Aura-Wave* plasma source is more flexible in operation, especially given that *Aura-Wave* plasmas can be sustained with solely a few watts, and they are easier to breakdown. Moreover, an *Aura-Wave* can be used at lower pressure, with higher electronic temperature, meaning higher particle energy and, in case of deposition processes, better layer adherence to the substrate. Even if *Hi-Wave* shows good tuning for wide operating conditions, *Aura-Wave* is more efficient on the whole pressure and power range.

It has been proved that multiple *Aura-Wave* or *Hi-Wave* microwave plasma sources can be distributed together in the same reactor in connection with industrial plasma scaling-up requirements in order to obtain high uniformity plasma over wide processing areas. The current projects include the development of a reactor which can host from 16 to 25 plasma sources in various configurations. It is controlled by a compact rack of solid-state microwave generators with a touch screen and a user-friendly interface. At the moment, such a rack is available for the control of 4 plasma sources, individually or simultaneously upon user’s choice.

For further reading:

1. Latrasse L., Radoiu M., Lo J., Guillot P., “Langmuir probe and OES measurements of 2.45-GHz microwave plasmas in multisource configuration - Aura-Wave ECR plasma and Hi-wave collisional plasma sources,” submitted to Plasma Sources Science and Technology.
2. Moisan M., Pelletier J., 2006, Physique des Plasmas Collisionnels (Collection Grenoble Sci.), pp 211-216.
3. Latrasse L., Radoiu M., "Dispositif élémentaire d’application d’une énergie micro-onde avec applicateur coaxial," Patent BR085601.
4. Latrasse L., Radoiu M., "Dispositif élémentaire de production d’un plasma avec applicateur coaxial," Patent BR085602.
5. Latrasse L., Radoiu M., Jacomino J-M, Grandemenge A., “Facility for microwave treatment of a load”, Patent WO 2012/146870.
6. Béchu S., Bès A., Lacoste A., Pelletier J, “Device and method for producing and/or confining a plasma,” Patent WO 2010049456
7. Guillet D., Jacomino J-M., Radoiu M., Latrasse L., “Solid-state microwave generators for industrial applications,” 14th Int’l AMPERE Conf. Microwave & High Freq. Heating, (Nottingham, UK, Sept. 2013).
8. Antonin O., Latrasse L., Taylor A.A., Michler J., Raynaud P., Rats D., Nelis T., “A novel microwave source for collisional plasma for nano-crystalline diamond (NCD) deposition,” Int’l Conf. Phenomena in Ionized Gases (Iasi, Romania, 2015).
9. Antonin O., Taylor A.A., Michler J., Raynaud P., Rats D., Latrasse L., Nelis T., “Nanocrystalline diamond film deposition by matrix elementary plasma sources,” Diamond and Carbon Materials (Bad Homburg, Germany, 2015).

About the Author

Kostiantyn Achkasov finished his Bachelor in 2010 at the Department of Physics and Technology of V.N. Karazin Kharkiv National University, in Ukraine. He pursued his studies with the European Master in Nuclear Fusion Science and Engineering Physics (Erasmus Mundus FUSION-EP) at the University of Stuttgart and Ghent University. His Master thesis, entitled “Evaluation of beam emission spectroscopy as a diagnostic tool for the TJ-II stellarator”, was based on research performed at Ciemat Laboratory, Madrid, and was defended in 2012.

Dr. Achkasov received his PhD in Physics from Aix-Marseille University in 2015. The research was conducted at PIIM laboratory (Aix-Marseille University) in joint supervision with CEA Cadarache in the field of low-temperature plasma and surface physics. His PhD thesis was entitled “Study of negative ion surface production in cesium-free H_2 and D_2 plasmas: application to neutral beam injectors for ITER and DEMO”. The results of this investigation were presented in several int’l conferences and gave the author two awards for the best oral presentation.

In 2016, Dr. Achkasov joined a private company, Sairem SAS (based in Neyron, France), which produces highly technical equipment for industrial microwave and high-frequency applications. He is a member of the R&D and export-sales departments of Sairem.