2.45-GHz microwave plasma sources using solid-state microwave generators. ECR-type plasma source

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ABSTRACT
To meet industrial requirements for large-scale processing with high-density and uniform plasma, mandatory for surface treatments to get uniform etching and high deposition rates, we have conceived a new electron cyclotron resonance (ECR) coaxial microwave plasma source which can sustain stable plasmas from $10^{-2}$ Pa to a few Pa, whatever the processing gas, the minimum sustaining microwave power being only a few watt. Furthermore, because the plasma source is powered by its own microwave solid-state generator, multiple ECR plasma sources operating in different conditions of gas type and microwave power can be distributed together in the same reactor. In this design, the solid-state microwave generator produces a forward wave with variable frequency from 2400 to 2500 MHz; this feature is used in an automatic adjustment loop which enables to lower the reflected power created occasionally by changes in the operating conditions. The advantages of the new technology are reported in connection with the plasma scaling-up requirements to distribute uniformly the electric field over large areas. Optical emission spectroscopy and Langmuir probe have been used for the measurement of plasma density, uniformity and electron temperature in argon, oxygen and nitrogen. The results are reported in as a function of the gas type, number of sources and their distribution inside the plasma reactor. The new plasma source enables the production of plasma densities $>10^{11}$ cm$^{-3}$ in all tested gases – Ar, O$_2$, N$_2$, air – at $d = 85$ mm.

KEYWORDS
Microwave plasma; electron cyclotron resonance; solid-state microwave generator; plasma source; Langmuir probe; optical emission spectroscopy

Introduction
The most important parameters when scaling up plasma applications are the distribution and the uniformity of the electric field over large processing areas. At pressures of approximately 0.1 Pa, distributed electron cyclotron resonance (DECR) plasmas (Pichot & Pelletier 1992; Pelletier 1995; Lagarde et al. 1997a, 1997b; Pichot et al. 1998; Pelletier et al. 2001) that combine multipolar magnetic field confinement and microwave excitation at electron cyclotron resonance (ECR) by using linear microwave applicators appeared particularly well suited for the production of large-area plasmas. However, due to the necessity of microwave propagation along the applicators, the DECR plasma density cannot...
exceed the critical value $n_c$ (Lagarde et al. 1997b), calculated as follows:

$$\omega_0^2 = \omega_{pe}^2$$

(1)

where $\omega_0$ is the angular frequency of the microwaves and $\omega_{pe}$ is the electron plasma angular frequency defined by

$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}$$

(2)

where $e$ is the elementary charge, $n_e$ the plasma density, $\varepsilon_0$ the vacuum permittivity and $m_e$ is the mass of the electron. At the microwave frequency $f_0 = \omega_0/2\pi = 2.45$ GHz, Equation (1) leads to $n_c = 7.5 \times 10^{10}$ cm$^{-3}$. To overcome this limitation, a recently proposed solution consists of producing large uniform plasmas from two- or tri-dimensional networks of elementary sources sustained at ECR. These multi-dipolar sources (Lacoste et al. 2002), where every elementary plasma source consists of a cylindrical magnet (magnetic dipole) fed with microwaves at the end of a coaxial line, can produce plasma densities between $10^{11}$ and $10^{12}$ cm$^{-3}$. However, this technology requires a very good distribution of the microwave power between the sources and equally, the use of matching impedance devices that makes it more difficult to use it in industrial reactors and perhaps more suited to laboratory applications.

Microwaves combined with a static magnetic field at low pressure can result in a highly efficient heating mechanism of the electrons, the ECR, obtained when the gyration frequency of the electrons in the magnetic field is equal to the frequency of the applied electromagnetic wave. An electron with an initial axial path placed in a static and uniform magnetic field will have a helical motion with the electron cyclotron angular frequency:

$$\omega_{ce} = \frac{eB}{m_e}$$

(3)

where $B$ is the magnetic field strength. Superimposed with a perpendicular electric field, the electrons will sustain additional forces at the frequency $\omega_0$ of the applied electric field. The resonance occurs at $\omega_0 = \omega_{ce}$ 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 energies that allow to ionize neutral particles of the gas and breakdown the plasma due to cascade reactions.

ECR phenomenon is well matched when the electron collision frequency is small compared to the angular frequency of the applied electric field ($v/\omega_0 = 10^{-2} - 10^{-4}$); this way the electrons accumulate high energy between two collisions leading to low-pressure plasma generation, typically in the range of $10^{-2} - 1$ Pa ($10^{-4} - 10^{-2}$ mbar). The pressure should not be too low, otherwise the electrons, although having accumulated high energy, would start losing the energy on the walls rather than via collision with gas particles. In the $10^{-1}$ Pa pressure range, applications are limited to processes that require high ion assistance, such as plasma-based ion implantation (PBII), anisotropic etching or sputtering (Béchu et al. 2004).
To meet novel plasma industrial applications towards reactors of increasing size while maintaining high density and high uniformity plasmas, a new ECR coaxial microwave plasma source has been developed. This source was designed to avoid power loss within the source and to be easily matched over wide operating conditions. The connection with a 200 W, 2.45 GHz microwave solid-state generator, which is very stable in power and which allows to vary the frequency of the emitted wave for automatic impedance tuning (Latrasse et al. 2012) makes 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 allowing to extend significantly the operating condition range of the source.

**Experimental**

The coaxial antenna using the ECR in Figure 1(a), consists of encapsulated cylindrical permanent magnets mounted in opposition within the coaxial structure (Béchu et al. 2009), allowing to generate a magnetic field in the direction of the centre of the plasma chamber and hence, limiting losses on the walls. The source was designed to be self-adapted once the plasma ignited and to avoid power loss within the structure (Latrasse et al. 2013), to sustain plasmas from $10^{-4}$ mbar up to $10^{-1}$ mbar and to reach plasma densities up to a few $10^{11}$ cm$^{-3}$ in multisource configuration – Figure 1(b) – at 10 cm from the source.

The experimental set-up used in this study consists of a multisource plasma reactor within which maximum 9 off × ECR plasma sources were installed; each plasma source was connected to its own microwave solid-state generator, maximum power 200 W, which produces a wave with variable frequency from 2.4 to 2.4 GHz (adjustable with 100-MHz increment) (Figure 2). This set-up allows to control both the transmitted microwave power to each plasma source by 1–W increment and the process parameters.

Microwave plasma parameters were measured with a Langmuir probe placed at two heights, $d = 85$ mm and $d = 160$ mm from the plasma sources; a step motor moves the probe linearly in direction $z$ from position 0 to 500 mm to enable the evaluation of spatial resolved plasma parameters, i.e. plasma density, electronic temperature and uniformity.

![Figure 1.](image) (a) ECR-type microwave plasma source; (b) multisource reactor consisting of eight off × ECR plasma sources. Photo in argon, total microwave power 160 W, 1 Pa.
In parallel, the plasma optical emission was channelled through a 200-μm fibre optic and measured with a spectrometer in the 200–1000 nm range. The optical fibre was always placed at 85 mm from the plasma source plane.

Results and discussion

Plasma density and optical emission lines

A total of 9 off × ECR plasma sources have been distributed inside the multisource reactor in a 3 × 3 square lattice matrix configuration, lattice mesh 82.5 mm. Each plasma source was operated at 200 W microwave (MW) power, i.e. 1800 W total power; the plasma density was measured at $d = 85$ mm and $d = 160$ mm. This set-up has been used for the measurements of argon, oxygen and nitrogen plasma.

Argon plasma

Figure 3(a) shows the argon plasma density as a function of the pressure; the plasma density increases from $2 \times 10^{10}$ to $2.8 \times 10^{11}$ cm$^{-3}$ when the pressure increases from 0.25 to 2 Pa; as the pressure increases above 2 Pa, the plasma density begins to decrease.

From Figure 3(b) it can be noticed that the plasma density increases linearly with the microwave power at fixed pressure, 1 Pa in the example, at both $d = 85$ mm and $d = 160$ mm.

The electronic excitation intensity of the 750 and 811 nm lines of argon is plotted in Figure 3(c). It is easy to observe that the intensity line follows the same trend as the plasma density.
Figure 3. (a) Plasma density vs. argon pressure, $d = 85$ mm; (b) argon plasma density vs. MW power at $d = 85$ mm and $d = 160$ mm, 1 Pa; (c) argon intensity lines at 750 and 811 nm vs. pressure.
**Oxygen plasma**

The variation of oxygen plasma density vs. pressure is shown in Figure 4(a); the total microwave power is 1800 W and the plasma density is measured at 85 mm. It can be seen that the plasma density reaches maximum $2.1 \times 10^{11}$ cm$^{-3}$ at 2 Pa. At fixed pressure, 1.5 Pa and $d = 85$ mm, the plasma density increases linearly with the microwave power (Figure 4(b)).

The intensity of electronic excitation of the 777 and 844 nm lines as a function of the oxygen pressure is presented in Figure 4(c). This plot shows that the line intensity follows quite well the variation of the plasma density; the maximum intensity was obtained at the same pressure, 2 Pa.

**Nitrogen plasma**

The variation of the nitrogen plasma density was obtained as a function of the pressure and the microwave power (Figure 5(a,b)). The maximum plasma density reaches $1.7 \times 10^{11}$ cm$^{-3}$ at 2 Pa; similar to argon and oxygen, the plasma density increases linearly with the microwave power.

The intensity of electronic excitation of the 337, 357 and 390 nm lines of nitrogen is presented in Figure 5(c). The intensity of the 357 nm follows exactly the variation of the plasma density.

**Plasma uniformity**

To evaluate the influence of the gas type and the distribution of plasma sources on the value of the plasma density, multiple configurations have been set up and investigated. Each configuration is indicated on the top view of the reactor: plasma sources in solid dots, their relative position to the Langmuir probe is equally represented. Measurements at $d = 85$ mm and $d = 160$ mm were performed using combinations of up to nine ECR plasma sources in argon, oxygen, nitrogen and air.

**Linear configuration**

For this set of trials, two off × plasma sources were measured. Each plasma source was supplied with 200 W; argon plasmas were ignited at 0.5 Pa and the plasma density was measured at $d = 160$ mm. Figure 6(a) shows the results obtained for each individual plasma source as well as for both sources measured together. The algebraic sum is plotted on the same graph and corresponds exactly to the measurement of the two sources together. The profile obtained for a single source is important in the extrapolation of the results for an unlimited number of plasma sources. An example of extrapolation using eight off × plasma sources in straight line configuration is shown in Figure 6(b); the distance between two sources is 175 mm. The plasma density profile was measured at $d = 160$ mm, 1 Pa in argon and is repeated eight times, curves 1–8. The sum of all sources shows that 2% linear uniformity can be obtained up to 1 m linear configuration.

**3 × 3 Matrix configuration**

The argon plasma density profile measured at $d = 85$ mm and $d = 160$ mm using nine off × plasma sources is plotted in Figure 7; argon pressure = 1 Pa and total microwave power = 1800 W, i.e. 200 W/source. It can be noticed that in these operating conditions
Figure 4. (a) Oxygen plasma density vs. pressure, $d = 85$ mm; (b) oxygen plasma density vs. MW power at $d = 85$ mm, 1.5 Pa; (c) oxygen intensity lines 777 and 844 nm vs. pressure.
Figure 5. (a) Nitrogen plasma density vs. pressure, \( d = 85 \) mm; (b) nitrogen plasma density vs. MW power at 85 mm, 1 Pa; (c) intensity of 337, 357 and 390 nm nitrogen lines vs. pressure.
Figure 6. (a) Argon plasma density profile at $d = 160$ mm from the source, 0.5 Pa; (b) argon plasma density profile at $d = 160$ mm – extrapolation for eight sources in linear configuration.

Figure 7. Argon plasma density profile at $d = 85$ mm and $d = 160$ mm.
good plasma uniformity cannot be obtained over large diameters. For example, at \( d = 85 \) mm, the uniformity is 3.5% over \( \sim 100 \) mm diameter, while at \( d = 160 \) mm, the obtained uniformity is 1.6% over \( \sim 120 \) mm diameter. Results obtained for argon, nitrogen and oxygen are summarized in Table 1.

In matrix configuration, the lattice mesh is too small to ensure uniformity over large diameters especially at the chosen measurement distance. In small lattice mesh, each source diffuses ionized species to the nearest neighbour and even to the second neighbour, as such generating high diffusion in the centre of the configuration. It is expected that as the distance from the sources decreases, the influence of the diffusion of the distant sources will be reduced allowing to increase the uniformity over larger diameters.

We can conclude that a compact matrix configuration can present a real interest for processes carried out at \( d < 85 \) mm, which can lead to higher diameter of plasma uniformity while maintaining high plasma density.

**Circular network configuration**

For the evaluation of the circular configuration, eight off \( \times \) plasma sources were used; each source was supplied with 200 W microwave power, i.e. 1600 W total microwave power. The radius of the circular configuration is 123.5 mm (diameter \( \sim 250 \) mm). The plasma density profiles at 1 Pa are plotted in Figure 8(a–d) for argon, oxygen, nitrogen and air, respectively. The argon plasma gives 4.9% uniformity at \( d = 85 \) mm over 250 mm diameter and 3.2% at \( d = 160 \) mm over 210 mm diameter. For the oxygen plasma, the obtained values are 5% uniformity at \( d = 85 \) mm, 250 mm diameter and 2.2% at \( d = 160 \) mm, 210 mm diameter.

Nitrogen plasma distribution uniformity at \( d = 85 \) mm is 3.7%, 250 mm in diameter and at \( d = 160 \) mm, 4%, 210 mm diameter. For the air plasma, the obtained values are 5% distribution uniformity at \( d = 85 \) mm, 250 mm diameter and 2.6% at \( d = 160 \) mm, 210 mm diameter.

For better understanding and comparison, the results are equally summarized in Table 2.

Generally speaking, the uniformity of the plasma density is better at \( d = 160 \) mm than at \( d = 85 \) mm, but plasma diameter is smaller. At high distance from the source plane, there is high diffusion in the centre of the configuration, while closer to the plane, the influence of the diffusion of the distant sources in direction \( z \) is reduced, limiting the edge effects. Hence, the edge effects are more consequent at high distance while uniformity is good but on a reduced diameter. Contrary, at \( d = 85 \) mm, two peaks always appear at the position of the sources; therefore, the uniformity is lower than at higher distance but edge effects are less important and allow to obtain larger uniformity diameter.
Figure 8. Plasma uniformity vs. distance and diameter (a) argon; (b) oxygen; (c) nitrogen; (d) air.
Conclusions

It was demonstrated that the new ECR microwave plasma sources distributed in a multi-source reactor allow to obtain plasma densities $>10^{11}$ cm$^{-3}$ in Ar, O$_2$, N$_2$ and air at $d = 85$ mm from the source. ECR plasma sources can easily ignite and sustain plasmas from a few W at pressures from $10^{-2}$ to a few Pa.

Two per cent to 5% distribution uniformity can be obtained whatever the tested gas over 200–250 mm areas, without any specific optimization. Nevertheless, higher uniformity is obtained if the distance between two neighbour sources is optimized as a function of the operating conditions: pressure, gas, power, etc. A solution to keep large uniformity diameter together with high plasma density uniformity consists of the addition of a plasma source in the centre of the circular configuration; the transmitted microwave power to the additional plasma source must be optimized to obtain high overall uniformity.

The results prove that the new ECR plasma source allows to produce large, uniform and high-density plasma without scale limitation, whatever the lattice mesh and dimension of the treated surface; the configuration choice depends on the intended application. Plasma uniformity can be easily optimized due to the flexibility of the microwave power control and the distribution of each plasma source; e.g. adding a plasma source to increase the density or regulating the transmitted microwave power of the outer plasma sources to limit edge effects.

The ECR plasma source is well suited when the electron collision frequency is small compared to the angular frequency $\omega_0$ of the applied electric field. At higher pressure, the collision frequency is higher, decreasing ECR heating mechanism efficiency, and cancelling it when $\nu = \omega_0$ making the plasma source unsuitable for plasma processing. At high pressure $\nu \gg \omega_0$, the probability to reach a maximum energy of the electric field is low but the probability to have a collision during a period of the wave is high. A second coaxial plasma source, the Hi-Wave, has been developed for processing pressure range 1–100 Pa. The results will be reported in a second publication.

Disclosure statement

No potential conflict of interest was reported by the authors.

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