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Situation Cavity Effect on Power Absorbed by Plasma Microwave

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Abstract: We present in this study a 3D numerical modelling of a microwave discharge (2.45GHz) excited by a surface wave in a large and small diameter cylindrical plasma cavity. Our first studies have been focused on the influence of the vertical situation of a short circuit in order to optimize the power coupling in the discharge. We used the CST microwave studio commercial code which solves Maxwell equations using the Finite Integration Technique (FIT).

Key words: Plasma microwave, Finite Integration Technique (FIT), cavity effect, power absorbed

INTRODUCTION

Plasma materials processing for microelectronics fabrication, formerly an empirical technology has in recent years greatly benefited from the use of Modelling and Simulation (MS) for equipment and process design. The maturation of plasma equipment and feature scale MS has resulted from a better understanding of the underlying physics and chemistry, from innovation in numerical algorithms and in the development of a more comprehensive fundamental database. A summary of the historical development, present status and future potential of MS for feature evolution and plasma reactor design can be found in (David *et al*., 2003).

The electromagnetic modelling, which is very useful to improve the conception and to optimize the systems, requires numerous mathematical techniques. These models can be based on several methods (analytic, semi-analytic and numeric). We mention in our paper the Finite Integration Technique (FIT), used to obtain electric field distributions and delivered power in the aboved described plasma reactor (including both excitation waveguide and plasma cavity).

MATHEMATICAL MODEL

All macroscopic electromagnetic phenomena occurring in a medium characterized with a charge density can be mathematically described with the complete set of Maxwell's equation:

$$\oint_{\partial A} \vec{E}.d\vec{s} = -\int \frac{\partial \vec{B}}{\partial t}.d\vec{A}$$

$$\oint_{\partial A} \vec{H}.d\vec{s} = -\int (\frac{\partial \vec{D}}{\partial t} + \vec{J}).d\vec{A} \tag{1}$$

$$\oint_{\partial V} \vec{D}.d\vec{A} = -\int_V \rho.dV$$

$$\oint_{\partial V} \vec{B}.d\vec{A} = 0$$

To which one adds the law of Ohm:

$$\vec{J} = \sigma\vec{E} \tag{2}$$

And the relation:

$$\vec{B} = \mu\vec{H} \tag{3}$$

In harmonic case:

$$(\partial/\partial t \rightarrow j\omega)\,.$$

In the plasma: $\sigma = \sigma e$

Where is the electronic conductivity of the plasma, given by:

$$\sigma_e = \frac{n_e e^2}{m_e}\frac{1}{j\omega + \nu} \tag{4}$$

Where n_e is the electron density and ν the electron-neutral collision frequency.

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One shows as well as plasma can be assimilated to a dielectric, under the condition to put, $\varepsilon_r = \varepsilon_p$, the relative permittivity of plasma:

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2} \frac{1}{1 - j\nu/\omega} \tag{5}$$

Where, ω_p represents the plasma pulsation, given by:

$$\omega_p^2 = \frac{n_e e^2}{m_e \varepsilon_0} \tag{6}$$

In the case of a 2.45 GHz microwave discharge, $\omega_p > \omega$,. and the relative permittivity of plasma is negative.

From the dispersion equations in a cylindrical structure (Eric, 1995) one can get the cut frequency fc_{mn} for each transverse electric TE or transverse magnetic TM mode:

$$fc = \frac{c}{2\pi d\sqrt{\varepsilon_r}} Xmn \tag{7}$$

With: Xmn: nth zero of Bessel of mode TM_{mn} (noted for mode Te_{mn}).

ε_r : Medium permittivity (=1 for vacuum),
d : Diameter of the outside metallic cylinder (=160 mm),
c : Speed of light in vacuum.

NUMERICAL MODEL

Historically, Weiland (1977) introduced the Finite Integration Technique (FIT) three decades ago in electrodynamics, where FIT was applied to the full set of Maxwell's equations in integral form. The method uses all 6 vector components of electric field strength and magnetic flux density on a dual grid system Weiland reformulated the Finite Integration Technique in terms of global quantities assigned to space objects-like the electric and magnetic (grid) voltage assigned to a contour and the electric and magnetic (grid) flux assigned to a surface-which allows a matrix formulation, also valid for irregular and non-orthogonal grid systems (Weiland, 1977).

The Maxwell's equations are formulated for each of the cell facets separately under shapes of the ordinary differential equation. Considering Faraday's law, the closed integral (Weiland, 1977; Clemens and Weiland, 2001).

$$e_i + e_j - e_k - e_l = -\frac{\partial}{\partial t} b_n \tag{8}$$

This equation can generalize for the global system:

$$Ce = b - \frac{\partial}{\partial t} = b \tag{9}$$

With:

$$\begin{pmatrix} . & . & . & . & . & . & . & . \\ 1 & . & 1 & . & -1. & -1 \\ . & . & . & . & . & . & . & . \end{pmatrix} \begin{pmatrix} e_i \\ . \\ e_j \\ . \\ e_k \\ . \\ e_l \end{pmatrix} = -\frac{\partial}{\partial t} \begin{pmatrix} . \\ b_n \\ . \end{pmatrix} \tag{10}$$

In like for the other the Maxwell's equations:

$$Ce = -\frac{d}{dt} b,$$

$$\tilde{C}h = -\frac{d}{dt} d + j, \tag{11}$$

$$\tilde{S}d = q,$$

$$Sb = 0.$$

With:
$d = M_\varepsilon e$
$b = M_\mu h$
$j = M_\sigma e + js$

Here M_ε is the permittivity matrix, M_σ the conductivity matrix and M_μ the permeability .matrix

Compared to the continuous form of Maxwell's equations, the similarity between both descriptions is obvious. Once again it should be mentioned that no additional error has yet been introduced. This essential point of FIT discretization is reflected in the fact that important properties of the continuous gradient, curl and divergence operators are still maintained in grid space:

$$\text{div rot} \equiv 0 \Rightarrow SC = \tilde{S}\tilde{C} = 0$$
$$\text{rot grad} \equiv 0 \Rightarrow \tilde{C}S^T = C\tilde{S}^T$$

The transient solver is based on the solution of the space discretized set of Maxwell's Grid Eq. 11, in which

Fig. 1: The principle of discretization in time domain

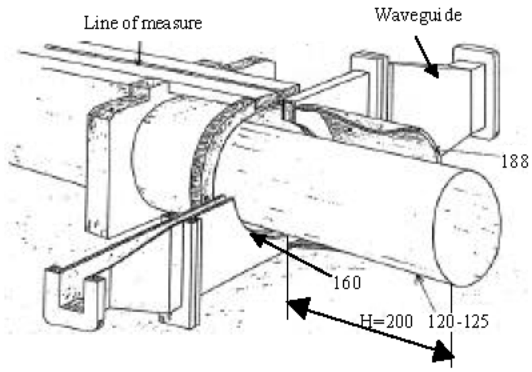

Fig. 2: The plasma reactor (Eric, 1995)

the time derivatives are substituted by central differences yielding the explicit update formulation for the loss-free case:

$$e^{(n+1/2)} = e^{(n-1/2)} + \Delta t M_\varepsilon^{-1}[\tilde{C} M_\mu^{-1} b^n + j_s^n] \quad (12)$$

$$b^{(n+1)} = bn - \Delta t C e^{(n+1/2)} \quad (13)$$

Both unknowns are located alternately in time, as in the well-known leap-frog scheme, as demonstrated in Fig. 1.

GEOMETRIC DIMENSIONS

We present the modelled microwave plasma sustained by a surface wave. In CST microwave studio, the main settings for this configuration can be done using the waveguide template, defining the Perfectly Conducting (PEC) boundary conditions on the waveguide.

The model takes into account the coupling waveguide, the quartz cylindrical tube containing the plasma and the cylindrical reactor itself (Fig. 2). The double excitation signal is a gaussian shaped pulse (1watt/port) defined in order to get a frequency response of the system in the chosen 2.2 to 2.7 GHz range.

The dimensions of the waveguide are (mm) 43.35×86.7 and the dimensions of the cylinder are 420 mm height and 160 mm diameter. The permittivity of the quartz tube is $\varepsilon_q = 4$, both inner and outer diameters are 2a = 120 mm and 2b = 125 mm. $\upsilon = 5\times10^9 s^{-1}$ is the electron-neutral collision

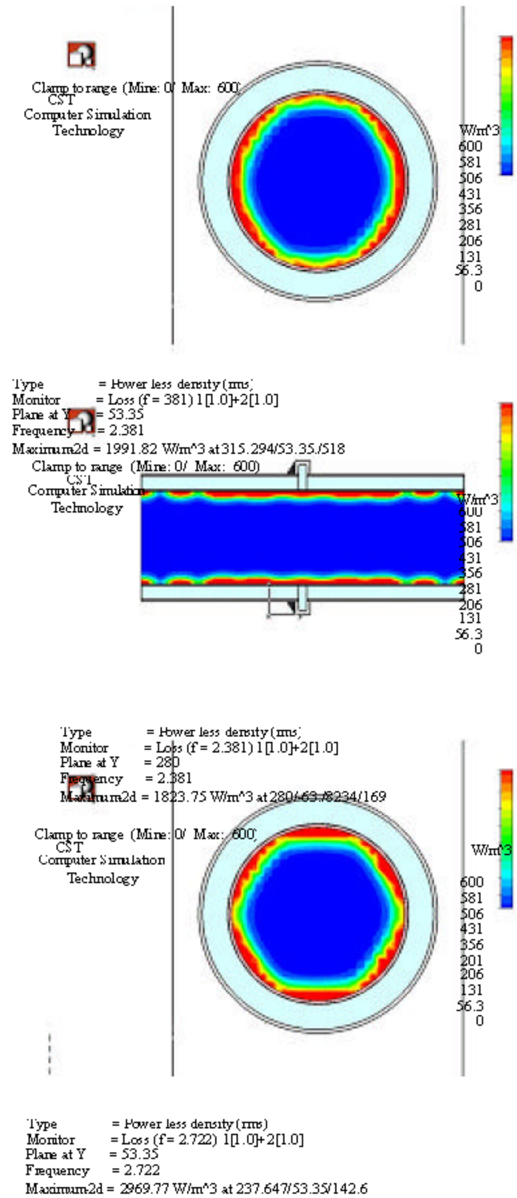

Fig. 3: Situation cavity closed

frequency and ne= 10^{12} cm^{-3} is the plasma electron density. This reactor is used in the LPGP laboratory (Eric, 1995).

RESULTS AND DISCUSSION

Table 1 permits the comparison here under between closed and open case for a height cavity (h = 420 mm):

The set following figures represents the different cuts horizontal and vertical of the structure for situations closed and open of cavity plasma (Fig. 3 and 4).

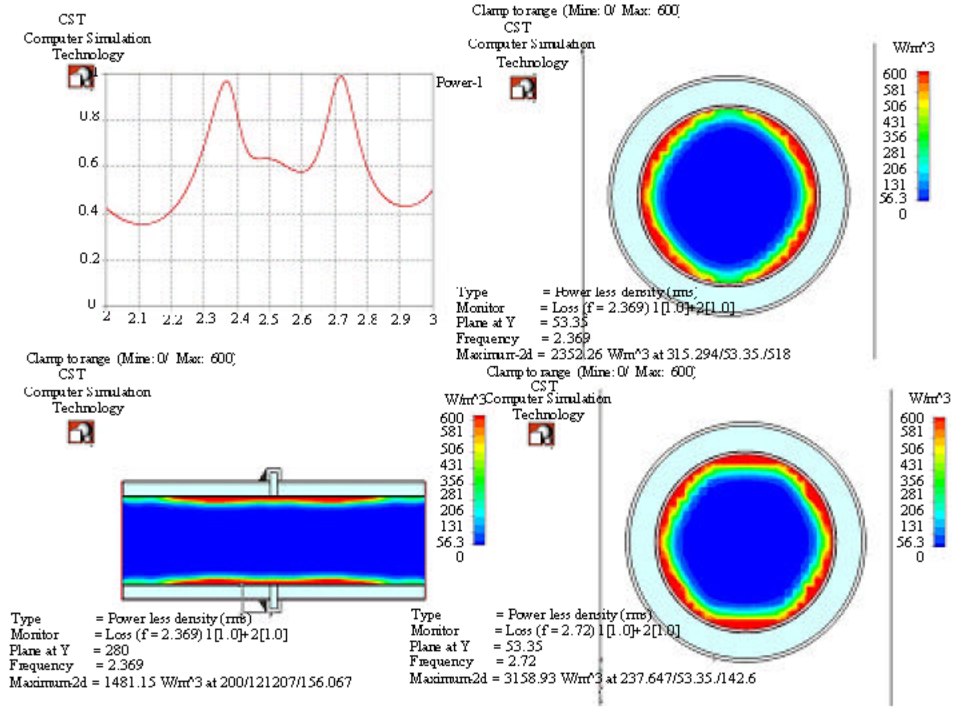

Fig. 4: Situation cavity open

Table 1:The comparison between closed and open case for a height cavity

Cavity	The resonance frequencies (MHz)	Mode m = ?	% of coupling	Absorbed (watts)	Power % of absorption
Closed	2381	1,3, 4	95.9	1.47	73.5
	2721	1,3, 4	98.4	1.45	72.5
Open	2369	1,3, 4	96.9	1.273	63.6
	2720	2,3, 4	98.9	1.384	69.2

Table 2: The influence of υ on the absorbed power

Cavity	The resonance frequencies (MHz)	Mode m = ?	% of coupling	Power absorbed (watts)	% of absorption
Open $\upsilon=510^8 s^{-1}$	2370	1,2,3, 4	95.9	0.46	23
	2721	1,2,3, 4	98.8	0.92	46
Open $\upsilon=510^9 s^{-1}$	2369	1,3, 4	96.9	1.273	63.6
	2720	2,3, 4	98.9	1.384	69.2

The absorption of power by plasma is maximal to the neighborhood of the quartz tube is homogeneous azimuthally. For this electrons-neutral collision frequency, one clearly sees the attenuation of the waves along the cavity (in the case where the open cavity, as in the case where the closed cavity). It appears that in the closed case, the power coupled to plasma is hardly superior to the open case (the difference being radiated through the openings in top and below).

Table 2 presents the influence of υ (the electron-neutral collision frequency) on the absorbed power and ne = 10^{12} cm^{-3} is the plasma electron density (open cavity).

In this study, where the frequency of electrons-neutral collisions is weak, the power coupled to plasma (in relation to the frequency coupled total) is weak (especially if one considers that the length of the plasma column is bigger than in the previous cases), it being linked to the attenuation of the waves along the column of plasma, that is a lot weaker than in the case of strong frequency of electrons-neutral collisions.

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