WHITEPAPER

SIMULATION OF AN EXTENDED MICROWAVE PLASMA SOURCE

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Esgee Technologies Inc.
Analysis and Design through High-Fidelity Simulations

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Overview

Extended plasma sources are required in plasma enhanced chemical vapor deposition or etching of large surfaces. Microwave sources are suitable for generating high-density low-electron temperature plasmas with lower plasma potentials. The high density plasmas created using microwave power also generate sufficiently large quantities of active radicals that react with the surface and modify its properties. A challenge for creating an extended plasma source is present due to the shielding of the microwaves by high density plasma which limits the effectiveness of the microwave plasma source. An alternate approach is to generate microwave surface waves at the interface between the dielectric medium to be coated and the gas adjacent to it. In contrast to microwaves in the bulk, surface waves do not get attenuated in the presence of a high density plasma. In fact, surface wave propagation is enhanced in the presence of a high density plasma. In this white paper, we look at simulation of a microwave surface wave assisted extended plasma source that can be used for various applications. The simulation uses coupled plasma-electromagnetic wave model via the multi-physics non-equilibrium plasma software package VizGlow™.

Objective

The objective of the present study is to demonstrate the simulation of surface wave assisted microwave plasma source for a typical coaxial waveguide configuration using the coupled electromagnetic waves and non-equilibrium plasma modeling capability in VizGlow™. We present simulations that demonstrate the plasma - electromagnetic waves interactions and the role of surface waves in sustaining a high density plasma.

Introduction

First, we briefly discuss the basic physics of this problem with the aid of the schematic shown in Figure 1. A microwave generator creates a wave that propagates in the TEM mode in a coaxial waveguide. The microwave enters the chamber and heats the gas, initially in the volumetric mode. This process generates an initial plasma that eventually grows to form a dense conducting medium next to the dielectric surface. This in turn allows the microwave to propagate, without significant attenuation in the surface wave mode, in an environment where the electron density is larger than the critical electron density. We mention the synergy between the plasma and the electromagnetic wave. The electromagnetic waves heat up the electrons, raise their temperature and promote ionization reactions that sustain the plasma. The plasma in turn creates the channel for the electromagnetic surface wave to propagate. This basic plasma phenomenon can be found in numerous other applications where electromagnetic waves of high frequency is used to generate a plasma. The interested reader can check out more details of the relevant physics and other applications in Refs. 1–3.

Simulation setup

The geometry to be studied is shown in Figure 2. It consists of a coaxial tube (axisymmetric with horizontal axis) with a dielectric (quartz, $\epsilon = 3.9$) layer. The wave is fed in from the left side as shown with a thin metal plate to guide the wave. Details of this setup are shown in the small inset in Figure 2. The wave enters a larger chamber of gas that is half a meter long and 85 mm in the radial direction. The total number of cells used in the simulation is 51920. The mesh is fairly refined as we need to capture several small-scale phenomena such as the surface and volume wave skin depths and the epsilon-zero resonance.\[4, 5\]
Table 1: Modules used for simulation

<table>
<thead>
<tr>
<th>Module</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Non-Equilibrium Plasma</strong></td>
<td>Two-temperature Cold Plasma Model</td>
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<tr>
<td><strong>Electromagnetic Waves</strong></td>
<td>Full-wave Maxwell Equations Solver (Frequency Domain)</td>
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**VizGlow™ (Non-equilibrium plasma modeling tool)**

The non-equilibrium plasma modeling tool VizGlow™ is used to simulate the discharge. VizGlow™ is packaged with an electromagnetics module, VizEM that solves the full wave Maxwell’s equations in both the time and frequency domain. It is seamlessly integrated within the VizGlow™ package for coupled plasma-electromagnetics problems. The physical settings for the simulation are as follows. The microwave frequency is 2.45 GHz and the total power deposited into the plasma is 400 W. The plasma mode is quasineutral with fluid equations for species density ion momentum and electron energy. The Maxwell’s equations in the frequency domain are solved to compute the power deposited into the plasma. The zero-dimensional Boltzmann solver “Bolsig”[6] is used to compute reaction rate coefficients. Additional details of the model and its use in microwave plasma simulations can be obtained from Ref. 7.

**Results**

As a background to discussing the results, we briefly discuss the various regimes of the plasma - electromagnetics wave interaction for this problem. The nature of the wave attenuation and the power deposition depends entirely on the electron number density. In Figure 3, we plot the magnitude of the imaginary part of the electric field phasor with assumed uniform electron density profiles. The top panel of the figure shows the waves in vacuum, no plasma. For the considered TEM mode, the wavelength of the wave is equal to the vacuum wavelength with some distortion of the wave profile due finite geometric enclosure. In the center panel a uniform “slab” plasma of density $10^{16}$ m$^{-3}$, which is smaller than the critical density for the microwave frequency, is assumed. We observe power deposition in the bulk (volume) of the plasma as the wave penetrates unhindered into the plasma up to the skin depth. In the bottom panel a uniform slab plasma density of density $10^{18}$ m$^{-3}$, i.e. well above the critical density, is assumed. This is the surface-wave power deposition mode in which the
power deposition is almost entirely confined in a very thin zone next to the dielectric-plasma interface. This mechanism sustains the microwave heating even in the presence of a very high density plasma. In Figure 4, we show the various results from the fully coupled plasma simulations. The top left plot shows the electron density at steady state. We see presence of a high density plasma but the plasma profile is not totally uniform with larger electron density near the two ends where the microwave enters and exits the domain. We also show the critical density contour in black that denotes a boundary between the under-dense and over-dense plasma. Being mostly a surface wave driven phenomena the epsilon-zero resonance\cite{4, 5} does not play a leading role in the power deposition. Its effect can be seen in the secondary electron density peak near the right. In the top right we plot the microwave power that is absorbed by the electrons. Most of the power is deposited in a very thin zone near the dielectric interface as expected. The bottom two plots show the electron temperature and the electron production rate due to gas phase chemistry. The electron temperature and electron production rates peak in regions where the microwave power deposition is the strongest. To establish the reason for weaker
Figure 5: Illustration of electromagnetic wave energy flow and dissipation. Top: Poynting Vector (W m⁻²); Bottom: Electromagnetic Wave Energy (J m⁻³)

Figure 6: Monitoring of transient evolution of the electron density and its approach to steady state at four points along the length of the tube.

wave power as the wave travels along the waveguide we can check the Poynting vector (here the magnitude of the vector is shown) and the electromagnetic energy of the wave. In Figure 5, the top panel shows the Poynting vector magnitude that quantifies the flux of the electromagnetic wave power. We see that the flux is largest in the first few wavelengths. This means that most of the incoming electromagnetic wave power flows into and is dissipated within this region resulting in larger heating of the plasma near the wave entry. Consequently, there is less energy available for subsequent heating of the plasma further down the waveguide. This is also confirmed by the plot for the electromagnetic wave energy shown in the bottom panel. In order to extend the high-density plasma further, more wave power needs to be supplied. Finally, an essential component of plasma simulation is to ensure that the convergence to steady state has been established. This is especially true for the large, meter scaled reactors as used in this study where the ion ambipolar diffusion time scale that determines the large scale distribution of the plasma can be rather slow. In Figure 6, we track the transient evolution of the electron number density at four stations along the length of the tube. We note that indeed the results are steady.
References


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