Measurements of Microwave Induced Plasma using Microwave Technique

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Abstract

A novel microwave measurement technique for microwave induced plasma is presented. The main advantage of the technique is its simplicity and low cost. This technique is based on measurements of the reflection coefficient from a plasma column using a network analyzer. The experimental results obtained using this technique are in good agreement with the modeling predictions.
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Introduction

The interaction of plasma with external radiation to determine plasma parameters is the most frequently used technique. The biggest advantage of this technique is that it does not require any assumption about the nature of the plasma. Plasma parameters are determined from the changing characteristics of the radiation transmitted through or reflected from the plasma. When microwave radiation is used the plasma properties are derived from the change of plasma permittivity caused by variations in the electron number density and electron collision frequency [1].

Microwave Induced Plasma (MIP) System

Microwave energy, generated by a magnetron at 2.45 GHz, is transmitted by the transmission line to the plasma applicator, which provides an efficient transfer of electromagnetic energy to the plasma. The plasma vessel is placed in the center of the plasma applicator and connected to a gas supply system. In this work a WR340 waveguide based plasma applicator was used and details of the generation system are presented in [2, 3].

The system for measurements of the reflection coefficient from the MIP column is shown in Figure 1. The reflection coefficient is measured using a WR229 waveguide placed on the top of the plasma applicator. To protect the reflection coefficient measurement system from the damage by the high power 2.45 GHz microwave signal the dimensions of the WR229 waveguide are below cutoff for
this signal. The MIP is initially ignited inside the quartz tube and plasma expands to fill a part of the tube placed in the WR229 waveguide. The reflection coefficient is measured in the frequency range from 2.9 to 4.8 GHz using an 8410A Hewlett Packard network analyzer, 8742A Hewlett Packard reflection test unit, and 8620C Hewlett Packard sweep oscillator. The WR229 waveguide is terminated with a CPR229-660 dummy load (Arra, USA) and connected to the network analyzer by a coaxial to waveguide adaptor CPR229-460 (Arra, USA).

![Diagram of the reflection coefficient measurement system](image)

**Figure 1** Reflection coefficient measurement system.

To eliminate errors, introduced due to imperfection of the instruments, the measurement system was calibrated using the two-port error box procedure [4]. The measurement errors of the reflected wave amplitude and phase were 0.1 dB and 2 deg, respectively. The error due to unsteadiness of the plasma was reduced by ensuring good initial equilibration of the system.
Verification of Numerical Model

The measured values of the reflection coefficient were compared with the modeling results. To verify the reflection coefficient model the modeling results were compared with measurements of the reflection coefficient from three types of dielectric rods: Teflon, Plexiglass and a quartz tube filled with distilled water. The reflection coefficient was calculated assuming that the dielectric rod is divided into a series of concentric cylinders in which the electric field is estimated by a series of Bessel functions [2]. For the Plexiglass and Teflon rods, and the frequency range from 3.1 to 4.3 GHz, the modeling results are in 3.5% and 3 deg agreement with the experimental results for the modulus and phase, respectively. For the quartz tube filled with distilled water and the frequency range from 3.1 to 4.3 GHz, the experimental results agree with theoretical results within 4% and 5 deg for the reflection coefficient modulus and phase, respectively.

Measurements of Plasma Column

The measurements of the reflection coefficient from the plasma column generated at atmospheric pressure were done for three diameters of the quartz tube, microwave power range from 50 W to 170 W and various gas flows. Experimental results are compared with modeling results obtained using the two temperature plasma model and the reflection coefficient model [3]. The modulus of the reflection coefficient for various gas flows as a function of frequency is shown in Figure 2. For low gas flow rates from 0 to 23.9x10^6 m^3 s^{-1}, the differences between the theoretical and measured reflection coefficient are up to 25%. These differences decrease when the gas flow increases and the plasma column expands into the auxiliary waveguide. The best agreement between the experimental and theoretical results is obtained for the gas flow rate of 31.9x10^6 m^3 s^{-1} and the frequency range from 3.2 to 4.3 GHz. For the frequencies below 3.2 GHz, the experimental error increases due to the increasing waveguide attenuation. At frequencies above 4.3 GHz, the holes in the waveguide through
which plasma is introduced, affect the reflection coefficient values. Since for low gas flow rates the plasma did not expand fully to the auxiliary waveguide further measurements were limited only to the gas flow rate of 31.9x10^-6 m^3 s^-1.

Figure 2  Comparison of the modeling and the experimental moduli of the reflection coefficient from 18.6 mm diameter plasma at various gas flows as a function of frequency.
The measured and predicted values of the modulus and phase of the reflection coefficient at a frequency of 3.6 GHz as a function of absorbed power are shown in Figure 3. The amount of microwave power absorbed by the plasma column increases its electron temperature. Thus, it is expected that the reflection coefficient will also increase due to an increase of plasma conductivity. However, the skin effect limits the penetration of microwaves and the reflection coefficient is determined mainly by the plasma temperature on the wall of the container.

Figure 3  Modulus and phase of the reflection coefficient from 14 mm diameter plasma at a gas flow rate of 31.86×10⁻⁶ m s⁻¹ and 3.6 GHz as a function of absorbed power.
Conclusions

The described technique can be used for the measurements of the reflection coefficient from a plasma column. To obtain good accuracy of the results high gas flow rates have to be employed to ensure expansion of the plasma column from the main waveguide to the auxiliary waveguide. The reflection coefficient values are determined by the plasma temperature in the region near the wall of the container. This is because plasma is a conducting medium and microwaves decay very rapidly inside the plasma column. The best agreement between the measured and predicted values of the reflection coefficient is obtained for the frequency range from 3.2 to 4.3 GHz.

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References


