Experimental study of the plasma resonance in a planar surface wave plasma

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In this study, the plasma resonance in a surface wave sustained plasma was investigated. Surface wave discharges have been successfully generated by a microwave planar vane-type slow wave structure. Experimental results clearly demonstrated that the amplitude of the electric field of the microwave always became a local maximum in the position where the plasma density was equal to the same value. When the operating gas pressure and the input microwave power were varied to change the plasma density profile, the location of the maximum of the electric field was found to shift in compliance with the plasma density profile. Meanwhile, the peak of the resonance response was found to be proportional to the plasma density gradient while the spatial width of plasma resonance was inversely proportional to the plasma density gradient. These results were qualitatively in accordance with the theory. © 2001 American Institute of Physics.

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I. INTRODUCTION

Surface wave (SW) sustained plasmas have been extensively studied experimentally and theoretically. Early studies,1,2 concentrated on the excitation and the physical properties of the SW plasma in cylindrical dielectric tubes. Recently, surface wave plasma sources of planar configuration have been successfully developed to increase the plasma area.3–5 The previous studies demonstrate that overdense plasmas can be generated due to the fact that surface wave can only propagate when the wave frequency is less than the spatial averaged plasma frequency. However, the plasma density decreases on the boundary area of the discharge and a sharp density gradient is created in this region. Consequently, the local plasma frequency may become below the wave frequency in this area. Above all, the local plasma frequency can become equal to the wave frequency. This condition can induce the plasma resonance as described in the following.

Consider the electric field component of the wave in a SW plasma. The direction of this field is parallel to the plasma density gradient. The associated electric flux density, \( D \), is given by

\[
D = \varepsilon_p E, \tag{1}
\]

where \( \varepsilon_p \) is the plasma permittivity and is defined as

\[
\varepsilon_p = 1 - \omega_p^2/j\omega(\omega - j\nu). \tag{2}
\]

In Eq. (2), \( \omega \) is the angular frequency of the wave, and \( \nu \) is the electron-neutral particle collision frequency. \( \omega_p \) is the angular plasma frequency and is determined by the electron density, \( N \), by

\[
\omega_p = (e^2 N/\varepsilon_0 m_e)^{1/2}. \tag{3}
\]

When the wave frequency is high enough (\( \omega \gg \nu \)), Eq. (2) indicates that \( \varepsilon_p \) becomes a minimum at a location where the plasma frequency is equal to the wave frequency. Moreover, Eq. (1) shows that the electric field becomes a maximum at this location due to the fact that the electric flux density must be continuous. Although the spatial averaged plasma frequency is larger than the wave frequency in SW plasmas, this resonance condition can take place in the vicinity of the wall of the discharge chamber as discussed previously.

The occurrence of the plasma resonance in SW plasmas has already been theoretically predicted for plasmas of cylindrical or planar geometry.6–11 It has also been predicted that the plasma resonance could play an important role in producing high density plasma at low pressure by inducing collisionless heating effects. On the experimental aspect, the electric field peaks have been observed and inferred as the result of the local plasma resonance.12–14 However, the spatial distribution of the plasma density directly supporting the plasma resonance has not been reported so far. In Ref. 14, microwave (2.45 GHz) signals were transmitted into plasma to clearly illustrate the plasma resonance. However, another rf generator (13.56 MHz) instead of the microwave signal itself was used to produce the plasma in that experiment.

The purpose of this study is to clearly identify and characterize the plasma resonance in the SW plasma. A large area surface wave plasma source is arranged to study the plasma resonance. In contrast with Ref. 14, a microwave power at 2.45 GHz is used to excite the discharge in different operating conditions. The spatial distribution of the electric field of this microwave is then measured. Meanwhile, the associated plasma density profiles are also measured for comparison.

II. EXPERIMENTAL SETUP

The SW plasma source used in this study is a modified version of the system developed at National Tsing Hua University.5 The plasma source consists of a planar tunable cavity and a vacuum chamber, which is schematically shown in Fig. 1. The cavity composed of a periodical vane-type
A Langmuir probe is used to measure the properties of the plasma. This probe consists of a tungsten wire only 0.1 mm in diameter inserted inside a quartz tube. The tungsten wire is extended out of the tube by 0.5 mm to collect charge particles. Once the current (I)–voltage (V) traces are obtained in the Langmuir probe measurements, the plasma potential is found by locating the minimum of the first derivative of the $I-V$ curve. The electron energy distribution function (EEDF) of the plasma is determined by the Druyvesteyn formula. The plasma density and the plasma temperature are then calculated by EEDF. It has to be pointed out that the accuracy of the Langmuir probe is limited by many factors like the precise collecting area of the charge particles, the effects of the finite resistance of the plasma, and the depletion of plasma caused by electron sinks on the probe. Moreover, the plasma parameters deduced by different Langmuir probe theories can give results of large difference. Therefore, it is very difficult to get the very precise value of the plasma density by the Langmuir probe measurement. Nevertheless, the probe method is the only technique easily available to obtain the spatial distribution of plasma parameters.

slow wave structure is installed on the top of the plasma chamber. The length of the period is 2.5 cm and the number of the periods is 14. The electromagnetic wave propagating in the vane-type slow wave structure is a surface wave, of which the wave intensity reaches a maximum on the top of vanes and decays in an exponential form along the direction to the quartz plate. The magnetic and electric field components of this surface wave are $H_z$, $E_y$, and $E_z$, in the coordinates as shown in Fig. 1. The resonance frequency of the cavity is 2.45 GHz and can be mechanically tuned by adjusting the height of the vanes. A 2-cm-thick rectangular quartz plate is placed on the top of the vacuum chamber as the coupling window for the microwave power. Meanwhile, an industrial magnetron provides microwave powers at 2.45 GHz to excite the resonance mode in the cavity. The design of this cavity and the details of the system can be found in Ref. 5.

In the following experiments, argon gas is used as a working gas and plasmas are excited by a microwave power at 2.45 GHz. The critical plasma density corresponding to $\omega_p = \omega$ is $7.4 \times 10^{10}$ cm$^{-3}$. Figure 2 shows the plasma density distribution and the electric field profile of the wave as a function of the distance from the quartz plate for pressures equal to 2.9 and 3.7 mTorr, respectively. It indicates that the plasma densities in the uniform region are above the critical plasma density, indicating surface wave plasmas are excited. And the plasma density and the density gradient in front of the quartz plate increase with pressure. Notably, the electric field profile shows that there is a local peak inside the density transit region, in addition to the initial peak close to the quartz plate. And this electric field peak moves as the pressure changes. Above all, the local plasma density associated with this electric field peak at different pressure is almost the same and is close to $1.1 \times 10^{11}$ cm$^{-3}$. The appearance of the second peak of each electric field profile will be discussed in the following paragraph. Furthermore, Fig. 3 illustrates the
measured spatial distribution of the electric field of the wave for different pressures at a microwave power of 2 kW. At 5.5 mTorr, a spatially decaying electric field profile is observed, demonstrating the normal field distribution of a SW plasma without the plasma resonance.\textsuperscript{1,2} It is consistent with the fact that at this pressure, the measured plasma density in the density transit region is above the critical density, although it is not shown here. As the pressure is less than 5.5 mTorr, the electric field profile totally changes and a large local peak of the electric field takes place. Similar to Fig. 2, the position of the electric field peak moves away from the quartz plate when the pressure decreases. Meanwhile, the measured plasma density corresponding to each electric field peak is also close to 1.1\textsuperscript{\texttimes}10\textsuperscript{11} cm\textsuperscript{-3} with a deviation of 10%, which is within the error range of our measurement system. This result clearly indicates that the occurrence of the electric field peak is related to a specific value of the plasma density.

For further investigation, the input microwave power is varied from 1.1 to 2.2 kW at a pressure of 4 mTorr to change the plasma density and the spatial distribution. Experimental results show that the plasma density increases with the microwave power. Meanwhile, the density transit region in the vicinity of the quartz plate becomes shorter as the microwave power is increased. The measured electric field profiles are depicted in Fig. 4, indicating that the electric field peak moves closer to the quartz plate as the microwave power increases. For a clear illustration, Fig. 5 shows the electric field peak and the plasma density profile for microwave powers of 1.1 and 1.6 kW, respectively. Results clearly show that movements of the peaks are consistent with the variations of the plasma density profile. Notably, the local plasma density associated with each electric field peak is around 1.2 \texttimes 10\textsuperscript{11} cm\textsuperscript{-3}. This plasma density deviates from the value shown in Fig. 2 by less than 10%.

Figures 2–5 clearly illustrate that the electric field becomes a local peak when the local plasma density reaches the same value, which is equal to 1.1\texttimes 10\textsuperscript{11} cm\textsuperscript{-3} (±10%) in our experiments. As was pointed out previously, 7.4 \texttimes 10\textsuperscript{10} cm\textsuperscript{-3} is the theoretical value for the plasma resonance to take place at the wave frequency equal to 2.45 GHz. The difference between these two values is 49%. To estimate the systematic error of our Langmuir probe measurements, a 35 GHz microwave interferometer is used to measure the averaged plasma density under the same operating condition. Comparisons show that the difference ranges from 10% to 30% depending on the operating condition.

The characteristics of the plasma resonance have been theoretically analyzed in Ref. 18, where the effects of field growth of an electromagnetic wave obliquely incident on an inhomogeneous plasma is studied. In our case, a surface wave propagates along the surface region of the plasma. Nevertheless, the methods and results reported in Ref. 18 are found to be adoptable for our case. By assuming the electron–neutral collision frequency is low and the plasma density is a linear function of the position around the plasma resonance location \((y = 0)\), the plasma permittivity can be expressed as\textsuperscript{18}

\[ \varepsilon_p(y) = -ay - is. \]  \textsuperscript{(4)}

In Eq. (4), \(a\) is proportional to the plasma density gradient, \(s = \nu/\omega\), \(\nu\) is the electron–neutral collision frequency, and \(\omega\) is the wave frequency. With this expression for the plasma permittivity, the electric field intensity at the point where the plasma resonance occurs is given by

\[ I(y = 0) = I_0 \frac{\varepsilon_0}{\varepsilon_p} \text{cos}(\omega t), \]

where \(I_0\) is the incident microwave power and \(\varepsilon_0\) is the permittivity of free space. The electric field intensity at this point is proportional to the plasma density at this point.

FIG. 3. The spatial profile of the electric field of the microwave for a microwave power of 2 kW at different pressures.

FIG. 4. The electric field profiles at 4 mTorr for different microwave powers.

FIG. 5. The spatial profile of the electric field of the microwave and the plasma density for a pressure of 4 mTorr at 1.1 kW [the electric field (■), the plasma density (●)], and 1.6 kW [the electric field, plasma density (○)].
is the angular frequency of the wave. With \( \epsilon_p \) given by Eq. (4), the approximate solution of the electric field, \( E_y \) in the plasma resonance region can be given by

\[
|E_y| = \sqrt{2/\pi p e^{-S_0}}|ay + is|
\]

where

\[
S_0 = \frac{\tau}{\omega c a} q^3, \quad \rho = \omega c a.
\]

\( c \) is the speed of light and \( q \) is the ratio between the wave vectors of the wave in the free space and that of the surface wave in the plasma. Equation (5) indicates that the spatial width (\( \Delta y \)) of the resonance response is inversely proportional to the spatial gradient of the plasma density and the maximum value of the resonance response is proportional to the spatial gradient of the plasma density. The experimental results shown in Figs. 2 and 5 clearly illustrate these two properties. In the position of the plasma resonance, the peak of the field intensity increases and the resonance curve becomes narrow when the local gradient of the plasma density increases.

It is interesting to note that another peak appears in the electric field profile in Figs. 2–5 on the left-hand side of the plasma resonance position. At first, it could be interpreted by the idea that a portion of the electromagnetic wave is reflected from the plasma resonance location and forms a standing wave pattern by the interference with the incident wave. However, the distance between two peaks in Figs. 2–5 is apparently much shorter than the half wavelength of a 2.45 GHz microwave in the free space. This discrepancy of the wavelength becomes even larger when taking into account the dispersion relation of the EM wave in plasmas (\( \omega^2 = \omega_p^2 + k^2 c \)). On the other hand, the second peak may be considered as resulting from the short-wavelength electrostatic wave (ES wave), which may be excited in the location of the plasma resonance.\(^{19}\) This ES wave can only propagate along the direction on which the plasma density decreases because the wave is excited near the cutoff location, according to the dispersion relation of the ES wave. As a result, a standing wave pattern can only be established in the direction opposite to the density gradient as observed in our experiment. However, the wavelength of the ES wave is determined by the temperature of the electrons and is then much less than 1 cm in our experiment. Apparently, the distance between the electric field peaks in Figs. 2–5 is much longer than the wavelength of the ES wave. Further theoretical analysis is needed to investigate the detailed structure of the electric field profile. For instance, the effects of the vane-type slow wave structure and the quartz plate located on the top of the plasma must be taken into account.

IV. SUMMARY

In summary, the plasma resonance in a surface wave plasma has been clearly identified and characterized in this study experimentally. Experimental results illustrated that the amplitude of the electric field of the microwave always became a local maximum in the location where the local plasma density was equal to the same value. Meanwhile, the shifts of the location of the plasma resonance agreed well with the variation of the plasma density profile in different operating conditions. Those experimental results clearly illustrated the occurrence of the plasma resonance in surface wave plasmas. In addition, the measured spatial resonance width became narrow and the maximum of the plasma resonance response increased when the gradient of the plasma density increased. These results qualitatively agree with the theoretical prediction.

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