A large-area plasma source excited by a tunable surface wave cavity

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A large-area high-density microwave plasma is successfully generated at low pressure by a tunable surface wave cavity which consists of a 12 period vane-type slow wave structure. This cavity is operated in the π mode and resonant at 2.45 GHz. The plasma area is in excess of 50 cm × 25 cm with a uniformity of ±10% at pressures less than 30 mTorr. A plasma surface wave has been excited so that a plasma density as high as 1.0 × 10^{12} cm^{-3} can be achieved at 30 mTorr for a microwave power of 2.0 kW. The plasma temperature is ~1.5 eV and the plasma potential is ~12 V. Above all, the number of the periods of the π-mode cavity can be increased without changing the resonance frequency and the distribution of the microwave fields such that this plasma source is easy to up-scaled. © 1999 American Institute of Physics. [S0034-6748(99)00305-6]

I. INTRODUCTION

Plasmas generated by radio frequency (rf) at 13.6 MHz have become important production tools in the microelectronics industry. On the other hand, there has been increased interest in the commercial use of plasmas excited by microwave at 2.45 GHz. Compared to rf plasmas, microwave-excited plasmas illustrate a higher plasma density and ionization ratio. It has also been shown that chemical radicals and molecule fragments can be effectively generated in microwave plasmas. They are crucial in material processing. Especially, there is no need of electrodes in microwave plasmas so that a substrate can be biased independently of the microwave power. Therefore, the flux and energy of ions bombarding the substrate can be separately adjusted, whereas they are irresolvable in the capacitively coupled rf plasmas. Meanwhile, the plasma sheath potential is much lower in microwave plasmas than in capacitively coupled rf plasmas. Then, contaminations due to the sputtering of electrodes and the surface damages of the substrate caused by ion bombardment can be alleviated. On practical aspects, microwave power generated by standard industrial magnetrons is much cheaper than the rf power system.

In spite of those attractive features, rf plasmas have more applications than microwave plasmas. The fundamental problem of microwave plasmas is the difficulty in creating large-volume homogeneous microwave plasmas serviceable for large-area material processes. This is due to the short microwave wavelength and the small penetration depth of the microwave into the plasmas. The wavelength of a 2.45 GHz microwave is 12.6 cm in free space; and the penetration depth is typically about 1 cm at pressure of about 1 Torr. It may reduce to millimeters at a pressure above the 10 Torr region. Meanwhile, it is inevitable to use over-moded waveguides to produce large-volume plasmas so that their dimensions are much larger than the wavelength and the penetration depth of the 2.45 GHz microwave. In the worst case, the plasma may be localized in the vicinity of the coupling antennas or windows, thereby preventing the microwave power from being transmitted into the applicators.

Furthermore, obstacles in producing large-volume homogeneous microwave plasmas limit the feasibility to scale up microwave plasma processes, which are promising in the laboratory to the production line. For instance, high-quality diamond films can successfully be deposited on a substrate of small area by a Bachman-type microwave plasma applicator. However, it is difficult to grow large-area diamond films by simply scaling up the applicator. Bosisio, Weissfloch, and Wertheimer were the first to develop a large-volume microwave plasma source by employing a linear strapped-bar periodic structure. A plasma volume in excess of 1000 cm$^3$ can be generated by a 2.5 kW microwave input power at 2.45 GHz. Nevertheless, the plasma is created in a quartz-tube reactor with a diameter of 19 mm so that this reactor is not suitable for processing silicon wafers of large area. Besides, the Bosisio system is based on a traveling wave interaction, and then only a part of the microwave power can be used in exciting the plasma. A dummy load is connected to the end of the microwave structure to absorb the rest of the energy. Therefore, the system requires more power than that required for generating the plasma, and this is inefficient. In addition, the power of the traveling wave, dissipated in the plasma excitations, is attenuated along the slow wave structure. To obtain a uniform plasma distribution, the quartz tube is tilted at a small angle with respect to the slow wave structure. Adjustments of this inclination are required for different discharge conditions.

In a later experiment, Komachi and Kobayashi successfully developed a plasma source adaptable for processing large-area substrates. Similar to the Bosisio design, a traveling surface wave is also used, but with different slow wave structure, which consists of a polytetrafluoroethylene (PTFE) line (20 cm × 48 cm), backed with an aluminum plate. Instead of the quartz tube used in the Bosisio experiment, the plasma is generated in a vacuum chamber with a glass plate placed beneath the slow wave structure. This glass plate serves as a coupling window to the microwave power. A uniform large-area plasma, 18 cm × 30 cm, was generated in this experiment.

The unique design features in the Bosisio and the Koma-
chi plasma sources, which lead to successful excitation of microwave plasmas of large dimensions, can be deduced from their designs. The first feature is that the microwave power coupling is distributed along the desired plasma area. This distributed microwave coupling scheme is essential for generating a large-area microwave discharge because of the short penetration depth of the wave into the plasma, which contributes to the failure of producing a large-volume plasma by conventional coupling schemes. In other words, the electromagnetic wave power is directly used to generate a large-area discharge for large-area material processes without resorting to producing large-volume plasmas. In the Komachi experiment, a planar slow wave structure distributes microwave power over a large-area glass plate under which a large-area plasma can be created.

The second feature is to separate the main microwave propagation structure from the plasma production region. As discussed above, the presence of the plasma could significantly change the dispersion relation of the guiding structure if the plasma is created in the region where the major portion of the wave propagates. A reflection of a large amount of the wave power can then take place, or the plasma could shield the wave from further propagation in the worst case. Consequently, the distributed power coupling scheme as mentioned above cannot be realized to create large-area plasmas. In the Bosisio and the Komachi experiments, a surface wave is launched along the slow wave structure, of which the electric field exponentially decays with the distance normal to the plane of the slow wave structure. The plasma is excited by this fringe field by placing the plasma reactor at the proper distance normal to the surface of the slow wave structure where most of the wave power propagates.

In this article, we report a microwave large-area plasma source that is also based on the two features discussed above. Nevertheless, a cavity formed by a 12 period vane-type slow wave structure is used to excite a plasma surface wave, instead of the traveling wave structure employed in the Bosisio and the Komachi experiments. The major advantages of this design are: (1) A stronger electric field can be generated in a cavity than in a traveling wave structure for an equal amount of input microwave power. Additionally, the total microwave power can be used in the cavity so that the drawback of less power efficiency in the Bosisio experiment can be alleviated. (2) The cavity is made of metal instead of PTEE, as used in the Komachi experiment. Then, its power handling capability is much higher such that more microwave power required for generating large-area high-density plasma can be transmitted. (3) As will be shown in the following section, the cavity formed by the vane-type slow wave structure is operated in the $\pi$ mode, of which the resonance frequency will not change as the number of periods increases. Meanwhile, the spatial distribution of the wave field will not vary either. Those factors make the scaling of the experimental results easier. (4) The resonant frequency of the cavity can be easily tuned by changing the height of the vane of the slow wave structure to compensate the perturbations caused by the plasma. This scheme of tuning does not introduce local inhomogeneities in the spatial distribution of the wave.

II. EXPERIMENTAL DESIGN

The plasma source consists of a tunable surface wave cavity and a vacuum chamber. It is schematically shown in Fig. 1. The cavity is composed of a vane-type slow wave structure, which is 25 cm wide $\times$ 60 cm long. Two 2.0 cm thick rectangular quartz plates are placed on the top of the vacuum chamber as coupling windows for the microwave power. Each quartz plate is 30 cm $\times$ 30 cm. The distance between the cavity and the quartz plate is set at 3.0 cm. It has to be pointed out that a single large-area quartz plate instead of two plates is a better design as far as the plasma uniformity is concerned. However, it is expensive and difficult to acquire such a quartz plate. Microwave power at 2.45 GHz provided by an industrial magnetron is transmitted with a WR-284 waveguide and is introduced into the cavity through a specially designed coupler. A three-stub tuner is also incorporated to facilitate impedance matching.

The vacuum system consists of a turbomolecular pump and a rotary backing pump. Pressure measurements are performed by a Baratron and an ionization gauge. The pressure control is accomplished by an automatic throttle valve and a
controller. The gas supply is regulated by a mass flow controller.

The cavity is designed by using the dispersion relation of an infinite period vane-type slow wave structure, as shown in Fig. 2. It is assumed in the derivation of the dispersion relation that the structure is infinite in the x direction or, if it is finite, edge effects are to be neglected. Therefore, the amplitude of the wave is assumed to be uniform in this direction. In region I, a wave of TM mode is assumed to propagate. This wave consists of infinite numbers of spatial harmonics according to Floquet’s theorem. Further, a TEM mode is assumed in the slot (region II). By matching boundary conditions at \( y = b \), the dispersion relation can be obtained and is given by

\[
\frac{\cot(k_0s)}{kL} = a \sum_{n=-\infty}^{\infty} \frac{1}{k_n} \coth(k_nb)[\sin(\beta_n^a/2)/(\beta_n^a/2)]^2. 
\]

In the above, \( L \) is the period, \( s \) is the height of the vane, \( a \) is the distance between two vanes, \( b \) is the normal distance between the bottom plate and the surface of the vane; \( k = \omega/c \) and \( \omega \) are the angular frequency of the wave; \( \beta_n \) is defined as \( \beta_n = \beta_0 + 2\pi n/L \), where \( \beta_0 \) is the propagation constant of the wave and \( n = 0, \pm 1, \pm 2, \ldots \), is the spatial harmonic number, and \( k_n \) is defined as \( k_n = \sqrt{\beta_n^2 - k^2} \). If the distance \( b \) is large enough (\( > 2\pi/\beta_0 \)), the solutions of Eq. (1) become insensitive to \( b \). It can also be shown that each spatial harmonic of the wave in region I is maximum at \( y = b \) and decays in exp(-k_ny) from along the direction to the bottom plate. Therefore, most of the microwave power is confined and transmitted along the surface of the vane-type structure. This is the so-called surface wave. Due to this property, the wave power can be distributedly coupled into the vacuum chamber and the region of the discharge can be effectively separated from the main structure of the wave transmission, as illustrated in Fig. 1.

The dispersion relation can be normalized with respect to period \( L \). Thus, it becomes a function of \( s/L \) and \( a/L \) and its solution can be expressed as \( kL \) vs \( \beta_0L \). A typical plot of \( kL \) vs \( \beta_0L \) of a vane-type periodic slow wave structure is shown in Fig. 3, where \( \beta_0L \) is actually equal to the phase difference of the wave traveling one period. As is well known, there are infinite branches of the solutions for a periodic structure, representing different passbands. Only the fundamental passband is shown in Fig. 3. Meanwhile, a physical parameter \( F \) is worthwhile to discuss. It is defined as \( E_z^2/2W_T \) where \( E_z \) is the electric-field strength in the z direction on the surface of the slow wave structure and \( W_T \) corresponds to the power flow of the wave. It has been found in the linear theory that \( F \) approaches infinity for \( \beta_0L = \pi \). This means that a small power flow can produce a large amount of electric field, which plays a crucial role in creating plasmas. Therefore, \( \beta_0L = \pi \) is chosen as our design parameter. Another design factor is the attenuation ratio of the wave in the y direction. As discussed above, the main microwave transmission area must be separated from the plasma production region. On the other hand, the electric-field strength still needs to be strong enough to discharge gas for a reasonable power level. Under these two considerations, an e-folding length of 2.0 cm is chosen, which means the unit wave strength will decrease to 1/e after this distance. With the parameters chosen above, i.e., \( \beta_0L = \pi \), e-folding length=2 cm, and operating frequency=2.45 GHz, the dimensions of the vane-type slow wave structure can be determined by solving the dispersion relation. The results are: \( L = 4.9 \text{ cm}, a = 3.92 \text{ cm}, \) and \( s = 1.3 \text{ cm} \).

One important issue needs to be further addressed. It is the scheme used to terminate a periodic structure to form a cavity. An improper termination of the structure can lead to the distortion of the periodicity so that Eq. (1) cannot be used since it is derived for an infinite periodical structure. The key factor of the proper termination is to place the shorting plate in a position which does not strongly perturb the original field distribution of the periodic structure. In our case, the middle plane between the two vanes satisfies this requirement because the direction of the electric field is in the z direction at this place and is normal to the surface of the shorting plate so that the boundary condition on the metal plate is satisfied automatically. On the contrary, the position in the center of the vane is not suitable, where the field is in the y direction. As a result, two half periods are installed on either end of the slow wave structure to form a cavity, as shown in Fig. 4. The electric field has also been depicted for illustration. It is obvious that the metal plates at the two ends simply act as mirrors converting a finite-period structure into an infinite one. Note that the electric field in each period of the cavity mode, of which \( \beta_0L = \pi \) mode, are of the same amplitude due to the reflection of the proper phase. Finally, the cavity is made of 12 periods, corresponding to...
The resonance frequencies of this cavity can be obtained by a simple analysis. For each resonant cavity mode, the round-trip phase shift through 12 periods must be an integral multiple of $2 \pi$ rad. We know the phase difference per period is equal to $\beta_0 L$, thus $2 \times 12 \times \beta_0 L = 2 \pi m$, where $m = 1, 2, ..., 12$. Therefore, $\beta_0 L$ of the cavity mode must satisfy the following relation:

$$\beta_0 L = m \pi / 12.$$  \hspace{1cm} (2)

By referring to the $kL$ vs $\beta_0 L$ plot, as shown in Fig. 3, the resonance frequency of each mode can be determined. This method is valid only when a proper termination of the periodic structure has been used as discussed above. In our design, $\beta_0 L$ corresponding to 2.45 GHz is equal to $\pi$, which satisfies Eq. (3) by $m = 12$. Generally, this is called the $\pi$ mode. Note that the integer number $m$ also indicates the number of peaks in the spatial distribution of the associated cavity mode. Above all, the resonance frequency of the $\pi$ mode does not change if the number of periods is increased. This is important as far as the scaling rule is concerned. Due to this property, the periods of the cavity can be increased without altering the characteristics of the microwave fields. Those factors make our design easy to be scaled up.

Further, a scheme to fine tune the cavity to be resonant at 2.45 GHz is essential because the presence of the plasma and possible errors in manufacturing of the slow wave structure could change the resonance frequency. Instead of inserting an object to perturb the cavity as used in conventional microwave technology, the height of the vane is mechanically adjusted to tune the resonance frequency to 2.45 GHz so as not to introduce inhomogeneities into the electric-field distribution. A mechanical arrangement is shown in Fig. 5 which has been devised for this purpose. All vanes are supported by a rectangular plate which can be moved up and down by 2 $\mu$m at both ends. In Fig. 6, the theoretical resonance frequency of the $\pi$ mode is depicted as a solid line. It shows that the resonance frequency monotonously decreases with increasing the height of the vane. Meanwhile, the measured resonance frequencies are also shown as dots in Fig. 6. The agreement between the theoretical and experimental results are good and the difference is $\sim 7\%$. The resonance frequencies are measured by the voltage standing-wave ratio (VSWR) method and double checked with a transmission method. Meanwhile, the results show the quality factor $Q$ of the $\pi$ mode at 2.45 GHz is 200.

Extensive measurements of the electric-field distribution have been made for identifying the cavity modes. It is performed by a dipole probe and a network analyzer (Hp 8722). The dipole probe is made of a semirigid coaxial cable of which the center conductor is extended by 2 mm long. The experimental arrangement is schematically shown in Fig. 7. The dipole probe is oriented in the $y$ direction so that the probe can only couple to the electric field in the $y$ direction. Meanwhile, the probe can be moved in the $x$ or $z$ direction by a step motor controlled by a computer. The ratio between the local wave power measured by the probe to the output power from the network analyzer is recorded to characterize the spatial distribution of the electric-field component of each cavity mode. The $\pi$ mode has been identified as indicated in
Fig. 8. It shows the measured field strength as a function of $z$, which is measured at $x = 10$ cm. The center of the cavity is defined as the origin of the coordinate. The results show 12 periodical variations with almost equal amplitude. In addition, the spatial distribution of the field strength in the $x$ direction has also been measured and is shown in Fig. 9, which is measured at $z = 20$ cm. A relatively uniform distribution has been illustrated. This behavior is consistent with the assumption used in deriving the dispersion relation of the vane-type slow wave structure.

A Langmuir single probe is used to measure the properties of the plasma such as density, temperature, and potential. The probe is a tungsten wire only 0.01 cm in diameter inserted inside a quartz tube. The total length of the probe is 80 cm with only 0.2 cm of the tungsten wire exposed to the plasma so that it does not draw too much current from the plasma. To obtain the spatially resolved plasma measurement, the Langmuir probe is driven by a step motor controlled by a computer. The vacuum seal of this movable probe is ensured by using the differential pumping technique.

III. EXPERIMENTAL RESULTS

The microwave plasma source described above has been successfully operated at a wide variety of working conditions. In this study, Argon gas is used as the working gas. Microwave powers of up to 2.0 kW have been applied and the gas pressure varies from 0.5 mTorr to 20 Torr. Figure 10 shows the measured saturated ion current density as a function of position in the $z$ direction for different pressures at an input microwave power of 1.2 kW. In the measurements, the
Langmuir probe is located at the center in the $x$ direction and is moved along the $z$ direction as indicated in Fig. 1. The normal distance from the tip of the probe to the quartz plate is 4.0 cm. The initial position of the measurement ($z = 0$) is indicated in Fig. 1. As indicated by the results, a uniform plasma region in excess of 50 cm can be achieved at pressures less than 30 mTorr. However, two separated plasma regions can be seen as pressures higher than 0.6 Torr. This is simply due to the fact that two quartz windows, separated by 5.0 cm, are used on the top of the vacuum chamber as shown in Fig. 1. Consequently, plasmas are produced in two regions under the quartz plates. Nevertheless, the diffusion of the charge particles becomes significant at low gas pressure so that a uniform plasma of large area can be realized. Figure 11 shows the dependence of the saturated ion current on the lateral position (in the $x$ direction) for different pressures.

The measurements are performed at the center of the second quartz plate as shown in Fig. 1. The results illustrate that the uniformity of the plasma is within ±10% over 25 cm in the lateral direction. Figures 10 and 11 indicate that the employment of a large-area quartz plate instead of two small plates can significantly improve the uniformity of the plasma.

In the following, the plasma source is characterized at the low-pressure regime (<50 mTorr). The dependence of the incident microwave power needed to ignite the discharge on the pressure is depicted in Fig. 12. This ignition power decreases as the pressure increases because the ionizing collision becomes more frequent at higher pressures. At pressures less than 10 mTorr, the ignition power is more than 2.0 kW. On the other hand, the power required for sustaining the discharge is much less than the ignition power since the absorption of the microwave power is proportional to the...
charge density. To measure the sustaining power, the input microwave power is gradually decreased after the plasma is ignited; and the discharge will be terminated if the incident power is less than the sustaining power. In our experiment, the sustaining power is about 1 kW at pressures less than 10 mTorr; and becomes less than 500 W at pressures higher than 20 mTorr. We cannot measure the exact value of the sustaining power at pressures higher than 20 mTorr because the minimum power provided by our microwave power generator is 500 W and a high-power microwave variable attenuator is not available in our laboratory.

The characteristics of the electron density, electron temperature, and plasma potential are determined from the current–voltage curve of the Langmuir probe and are shown in Figs. 13–15. In the measurements, the probe is fixed and placed under the center of the second quartz plate as shown in Fig. 1. First, the plasma density versus pressure for different incident microwave powers is plotted in Fig. 13. Note that a plasma density as high as $1.0 \times 10^{12} \text{cm}^{-3}$ can be achieved, indicating the threshold of the excitation of the plasma surface wave is satisfied. For the plasma surface wave mode to be excited, the plasma density must be high enough such that $\omega_p/\omega > (1 + \epsilon_e)^{1/2}$, where $\omega$ is the angular frequency of the wave and is equal to $2\pi v_e$, $\omega_p$ is the plasma frequency and is defined as $(n_e e^2/m_e\epsilon_0)^{1/2}$, where $n_e$ is the electron density, $e$ is the electron charge, $m_e$ is the electron mass, and $\epsilon_0$ is the permittivity of a vacuum; and $\epsilon_e$ is the permittivity of the quartz plate. The electron density corresponding to the threshold condition is $\sim 10^{11} \text{cm}^{-3}$. Therefore, the experimental results displayed in Fig. 13 imply that a plasma surface wave is excited under the quartz plates.

The electron temperature as a function of pressure is depicted in Fig. 14, indicating the plasma temperature is not very sensitive to the incident microwave power and decreases with the pressure. The averaged value of the plasma temperature is $\sim 1.5$ eV. The associated plasma potential is also depicted in Fig. 15. It illustrates that the potential decreases with the pressure. At pressures of less than 30 mTorr, the plasma potential is about 12 eV.

IV. DISCUSSION

In summary, a high-density microwave plasma source with an area over 50 cm×25 cm has been successfully developed by a tunable surface wave cavity composed of a 12 period vane-type slow wave structure. The uniformity of this plasma source at pressures less than 30 mTorr is ±10%. A plasma density as high as $1.0 \times 10^{12} \text{cm}^{-3}$, which is much larger than that of the capacitively coupled plasma widely used in wafer processings, can be achieved at 30 mTorr for a microwave power of 2 kW. The plasma temperature is $\sim 1.5$ eV and the plasma potential is $\sim 12$ V. The characteristics of this plasma source at the low-pressure region are comparable to those of other high-density plasma sources, such as inductively coupled plasma, and indicate that it is promising for large-area wafer processings. In addition, increasing the number of periods of our surface wave cavity does not change its resonance frequency since the $\pi$ mode is used in our design. The area of the cavity can then be easily increased. Moreover, a distributed microwave coupling scheme and the cavity are separated from the plasma generation region in our design. Consequently, the plasma source presented in this study is straightforward to be scaled up. To further improve the uniformity of our plasma source, a single large-size quartz window will be used in the next experiment to replace the present microwave windows.

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