Proceedings of ISAP'04, Sendai, JAPAN

Dual-Ellipsoid Type Microwave Plasma Equipment

Wen-Liang Huang[1], Shih-Pu Chen[1], Ching-Her Lee[2], Ching-Sung Hsiao[1]
[1] Energy & Resources Laboratories, Industrial Technology Research Institute
Bldg. 64, 195, Sec. 4, Chung Hsing Rd., Chutung Hsinchu, Taiwan 310, ROC
[2] Department of Electronic Engineering, National Changhua University of Education
1, Jin-De Rd., Changhua, Taiwan 500, ROC
E-mail address: wen_l@itri.org.tw

Abstract

This paper presents a newly developed dual-ellipsoid type microwave plasma cavity. The cavity consists of two half-elliptical-ball chambers and is intended for application in large area carbon nanotube growth. Making use of the focusing characteristic of the elliptical surface, this new microwave plasma cavity can effectively increase the plasma reaction region. With the aid of the High Frequency Structure Simulator (HFSS) software, a dual-ellipsoid type microwave plasma cavity with relatively larger plasma excited region (diameter greater than 10 cm) is designed, fabricated, and tested. Good performance is observed.

1. Introductionc

Since the discovery of carbon nanotube (CNT) by Iijima in 1991 [1], many researches have been carried out on their synthesis, field-emission property analysis, and mechanical and thermal properties analysis. Among the reported techniques, arc discharge, laser ablation, and chemical vapor deposition (CVD), have been the most often used methods to deposit carbon nanotubes. However, the arc discharge [2] and laser ablation [3] techniques are of high temperature process (more than 3000°C), and the obtained CNT purity is low (only 5 ~ 40%). The CVD method can lead to carbon nanotubes of 70% purity. But the process temperature is still as high as 1000°C, and this technique can not deposit evenly-oriented carbon nanotubes. As mentioned above, the high temperature in the carbon nanotube growth process has been the key problem for applications of these techniques in silicon IC technology and CNT-based field emission displays (FEDs) fabrication. Therefore, to fabricate the CNT-based materials with better control over their various properties, an improved technique should be developed. The technique should be able to scale-up to a large plasma reaction area with high uniformity and low process temperature. Recently, we in ITRI have developed a microwave plasma enhanced chemical vapor deposition (MPE-CVD) equipment to grow carbon nanotubes on Si and glass substrates using Ni as catalyst. Such equipment possesses good scaling-up capability for large area deposition with excellent uniformity. Moreover, it requires a relative low deposition temperature (less than 500 °C) and therefore, it is compatible with the well-developed silicon IC technology.

This novel dual-ellipsoid type microwave plasma cavity as shown in Fig.1 consists of two half-elliptical chambers with the focal points of these two elliptical chambers separately positioned. Making use of the focusing characteristic of the elliptical surface, this newly developed microwave plasma cavity is expected to effectively increase the plasma reaction region and to improve the plasma uniformity. In this research, the High Frequency Structure Simulator (HFSS) software is used for simulation before practical implementation. Then a dual-ellipsoid type microwave plasma cavity with a relatively larger plasma excited region (diameter greater than 10 cm) is designed and fabricated. The performance is verified by measurement.

2. Analysis and Design

To obtain large and uniform plasma reaction region, we need a corresponding

ISBN: 4-88552-207-2 C3055©IEICE

electromagnetic energy distribution in the cavity. For analysis of the field distribution, the finite element method (FEM) is employed in this work. To do that, the inside space of the microwave plasma cavity shown in Fig. 1 is divided into many continuous individual tetrahedral elements. Then the field in each element is represented by some known function. By combining solution of each element in the cavity structure, we can obtain the total field solution for this cavity [4]. By electromagnetic theory, field in the cavity satisfies the following Maxwell's equation

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times \vec{E} \right) - k_0^2 \varepsilon_r \vec{E} = 0 . \tag{1}$$

To solve Eq. (1) by FEM, the electric field $\vec{E}$ is expressed in terms of known basis function F_n as follows

$$\vec{E} = \sum_{n=1}^{N} a_n \vec{F}_n , \tag{2}$$

where a_n is the unknown amplitude coefficient yet to be determined. The function F_n has value only in the corresponding tetrahedral element, and is zero elsewhere. In order to solve for a_n, we need N linearly independent equations in a_n. This can be obtained by testing Eq. (1) with the same expansion function F_m, where m = 1, 2,…, N. To do this, we multiply Eq. (1) by function F_m and then take volume integration of both sides to get

$$\int_V \left[\vec{F}_m \cdot \nabla \times \left(\frac{1}{\mu_r} \nabla \times \vec{E} \right) - k_0^2 \varepsilon_r \vec{F}_n \cdot \vec{E} \right] dv = 0 . \tag{3}$$

Using Green's theorem and divergence theorem in Eq. (3), it can be rewritten as

$$\int_V \left[\left(\nabla \times \vec{F}_m \right) \cdot \left(\frac{1}{\mu_r} \nabla \times \vec{E} \right) - k_0^2 \varepsilon_r \vec{F}_m \cdot \vec{E} \right] dv = \int_S (\text{excitation/boundaryterms}) ds . \tag{4}$$

In Eq. (4), the excitation or boundary terms have been considered. Finally, substitution of the (2) in Eq. (4) yields

$$\sum_{n=1}^{N} a_n \left\{ \int_V \left[\left(\nabla \times \vec{F}_m \right) \cdot \left(\frac{1}{\mu_r} \nabla \times \vec{E} \right) - k_0^2 \varepsilon_r \vec{F}_m \cdot \vec{E} \right] dv \right\} = \int_S (\text{excitation/boundaryterms}) ds . \tag{5}$$

In matrix form, Eq. (5) can be written as [A][x] = [b], where [A] is an N × N matrix of basis function, [x] is the coefficient matrix, and [b] is the known excitation matrix. Once the coefficients a_n's are determined, the electric field $\vec{E}$ can be evaluated using (2).

In this work, we utilize the commercial electromagnetic simulation software, HFSS (developed based on FEM), for numerical analysis of the plasma cavity. The simulation results will then be used as a reference to determine the dimensional parameters of the proposed dual-ellipsoid type microwave plasma cavity. To validate this approach, the designed plasma cavity is fabricated and tested. Results are presented in the following section.

3. Results and Discussion

With the aid of simulation, a prototype of the dual-ellipsoid type microwave plasma cavity is designed, as shown in Fig. 2. The length for the major axis of each half-ellipsoid is 300 mm and that for the minor axis is 150 mm. The focus of the ellipsoid (distance from focal point to center) is 259.81 mm. The stainless cylindrical chamber under the dual-ellipsoid structure is the plasma reaction region. To introduce electromagnetic energy down to this cylindrical chamber, a half-ball type structure is inserted between the two half-ellipsoid chambers. Two rectangular waveguides of WR340 type located at the bottom ends are used to feed microwave source. For practical application in the industry, the cylindrical chamber should be vacuumized. For this purpose, a quartz plate, which possesses low loss at microwave frequency less than 5 GHz and very low thermal conductivity, was used to separate the cavity and the chamber. In addition, a stainless wafer holder, which can be moved up and down and can tolerate high temperature, is also equipped in this chamber.

The field distribution in the designed microwave plasma cavity is analyzed using HFSS, and the simulation result is presented in Fig. 3. It is seen that the field distribution is quite symmetric in the cavity, and the energy can actually be introduced down and focused on the top surface of the wafer-holder. In this study, we found that the dimension of the dual-ellipsoid type cavity, the location of the quartz plate, and the position of the wafer-holder all play an important role for system performance. For the sake of fabrication convenience, we choose varying vertical distance between the quartz plate and the wafer-holder to tune to the optimal condition. The structural parameters obtained from the simulation result are used in fabrication of the real plasma cavity, and the photo of such system is shown in Fig. 4. The system includes the microwave power supply, the pumping system, the mass flow control system, the dual-ellipsoid type cavity, the plasma reaction chamber, and the cooling system. In Fig. 5, the measured result of the excited plasma is presented. The microwave plasma area with a diameter of about 100 mm shown in this photo is excited in the chamber at 30 torrs. The excited ball-type plasma pattern is seen to be in good agreement with that obtained from simulation as shown in Fig. 3.

4. Conclusions

In this research, we propose a newly developed dual-ellipsoid type microwave plasma cavity for applications in carbon nanotube growth and IC technology. With the aid of the existing EM simulation software, the cavity structure is designed and fabricated. An excited ball-type plasma pattern with a diameter of 100 mm in the cylindrical reaction chamber is observed, and is found to be in good agreement with that obtained from simulation. The capability of exciting relative large area and uniform plasma makes the dual-ellipsoid type cavity a potential candidate for application in the industry.

References

[1] S. Iijima, *Nature* 354, pp. 56-58, 1991.

[2] L. A. Montoro, et al. “Study of oxygen influence in the production of single-wall carbon nanotubes obtain by arc method using Ni and Y catalyst”, *Diamond and Related Materials*, pp. 846-850, 2003.

[3] C. D. Scott, S. Arepalli, P. Nikolaev and R. E. Smalley, “Growth mechanisms for single-well carbon nanotubes in a laser-ablation pross”, *Appl. Phys*. A72, pp. 573-580, 2001.

[4] Ansoft High Frequency Structure Simulator (HFSS) Training, (version 7), with optimetrics™.

[5] M. Moisan and J. Pelletier, *Microwave Excited Plasma*, 1992.

[6] D. K. Cheng, *Field and Wave Electromagnetics*, 2nd ed. New York: Addison-Wesley, 1989.

[7] R. J. Meredith, *Engineers’ Handbook of Industrial Microwave Heating*, London: IEE, U.K., 1998.

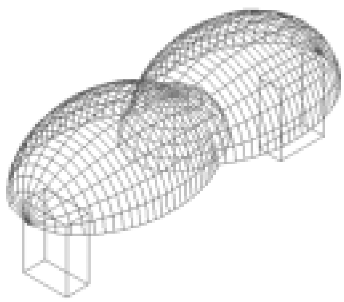

Fig. 1. Simplified configuration of the dual-ellipsoid type microwave plasma cavity.

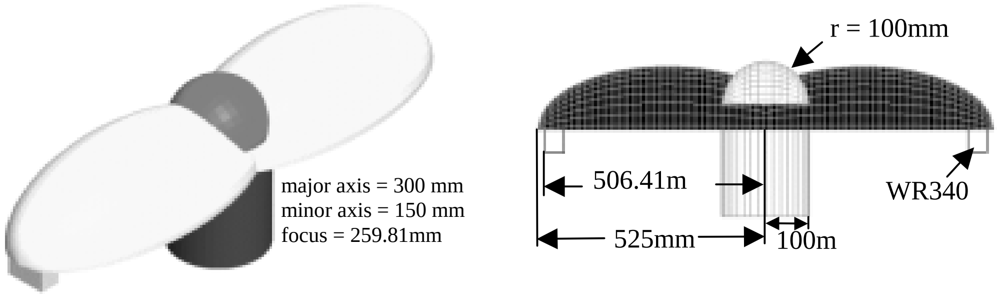

Fig. 2. Schematic diagram of the dual-ellipsoid type microwave plasma cavity.

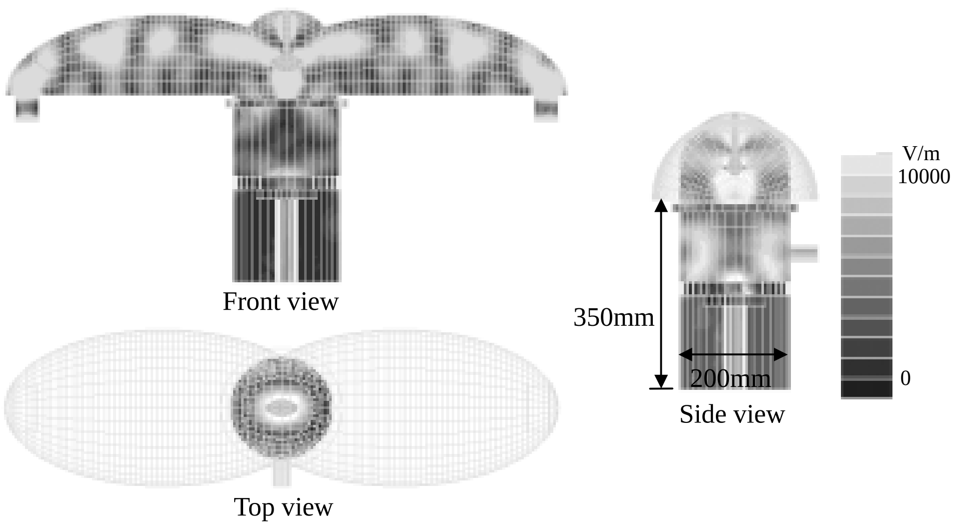

Fig. 3. Simulation result of the electric field distribution in the dual-ellipsoid type microwave plasma cavity.

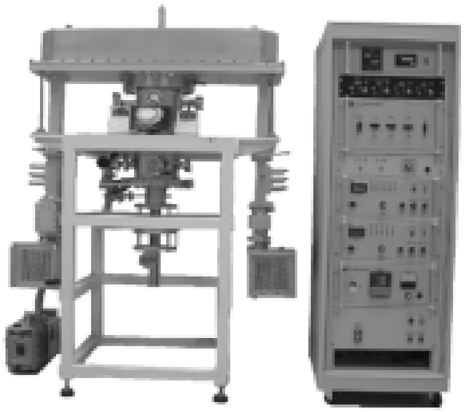

Fig. 4. Photo of the dual-ellipsoid type microwave plasma system.

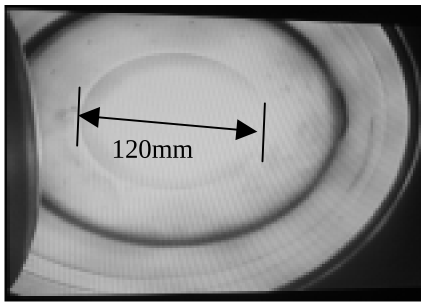

Fig. 5. Photo of the plasma excited in the cylindrical chamber.