Research Paper

Development of High-precision RF Sensor

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Abstract

Because radio frequency (RF) sensors typically experience interference between their capacitive detector and inductive detector, it becomes difficult for them to precisely measure voltage and current waveforms. We developed a high-precision RF sensor by using novel double walls (NDWs), which can minimize the interference. The geometrical construction variables of the NDWs are determined by analyzing the results from three-dimensional electro-magnetic simulation. The phase difference between voltage and current waveforms for the designed RF sensor is approximately 1.32° at a matched load, and that for an ENI probe (VIP1004) is 24.78° , as a result of which the developed RF sensor has better performance in preventing such interferences, compared with the other commercial sensor.

Keywords: RF sensor, Plasma, Voltage monitor, Current monitor, Novel double walls, 3D-EM simulation, Capacitive detector, Inductive detector

I. Introduction

In many radio frequency (RF) systems, not all the output power of the RF generator reaches the load because of power losses in line and matcher [1-4]. Furthermore, upon using plasma chamber as a load, the power loss of the chamber is non-intuitive because plasma is a non-linear dielectric material [5]. Therefore, to measure the correct power loss of the chamber, an RF sensor can be connected to the chamber for detecting voltage and current waveforms [6]. By measuring the waveforms of the chamber as close as possible, excellent indication of plasma fabrication can be obtained. This, in turn, yields better control of the etching or deposition characteristics for a silicon wafer or other workpiece in the chamber.

Because of their various applications, RF sensors [7] have been widely studied for performing high-precision measurement of waveforms, impedance, and power. For performing high-precision measurement, it is extremely important to detect voltage and current waveforms independently. These waveforms can be obtained using capacitive detector and inductive detector, respectively. A capacitive detector detects voltage waveforms by using its capacitive electric field (CEF), and

an inductive detector detects current waveforms by using its inductive electric field (IEF) [8]. However, the inductive detector picks up the voltage both by the CEF and the IEF. Because of this behavior, the interference between both the detectors is practically unavoidable. To reduce the interference, Ibuki and Brown [9,10] used a metal wall between the detectors to design RF sensors. Nevertheless, these RF sensors still had the interferences, which resulted in imprecise measurement by the hardware itself.

In this paper, we developed a high-precision RF sensor, in two steps, by using novel double walls (NDWs). First, we analyzed voltages at specific locations inside of the RF sensor for minimizing the interference during three-dimensional electro-magnetic (3D-EM) simulation. The interference-minimizing process is detailed in the simulation study section. Second, we measured the phase differences between voltage and current waveforms by using the RF sensor at a matched load. The results were compared with those for the other commercial sensor.

II. Experimental details

In this section, the design of the RF sensor is discussed, following which a process for minimizing the interference between the voltage and current wave-

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Figure 1. (Color online) Inside section of the RF sensor including the NDWs. (a) represents the front view, (b) represents the side view, and (c) the 3-D view.

forms is presented.

Figure 1 depicts the inside of the RF sensor, including the NDWs. As depicted in Fig. 1(a), the capacitive and inductive detectors are patterned on a single printed circuit board (PCB). The NDWs, which comprise three inner walls and four outer walls, penetrate the PCB. The geometrical construction variables of the NDWs are determined by D , H , and θ , as shown in Figs. 1(a) and 1(b). The materials of each part of the NDWs are composed as: the PCB is made of polyimide; the capacitive and inductive detectors, and core-conductor are made of copper; the cylinder near the core-conductor is made of teflon; the house including the NDWs is made of aluminum (the perspective view Fig. 1(c) will be helpful for better understanding this model). In this model, the CEF that cannot be shielded from the inner walls, but it can be shielded by the outer walls. Therefore, the NDWs can reduce the interference more effectively as compared with conventional cylindrical walls [9,10] used for designing high-precision RF sensors.

Thereafter, it is necessary to minimize the interference for performing high-precision measurement of electrical parameters such as impedance and waveforms. The interference depends on the geometrical variables of the NDWs because the geometrical variables affect the capacitances that are formed among the core-conductor and the NDWs. In this regard, the interference can be minimized by changing the geometrical variables of the NDWs. To evaluate the inter-

ference, voltages $V1$, $V2$, $V3$, and $V4$ are indicated at specific locations, as shown in Fig. 1(a). The capacitive detector picks up voltage $V2$, which increases as voltage $V1$ decreases, because both the voltages are connected in series.

Meanwhile, the inductive detector picks up voltage $V3$, but this voltage comes from not only the IEF but also the CEF (that causes the interference). To distinguish between IEF and CEF in the inductive detector, voltage $V4$ is measured. Moreover, $V4$ is the voltage driven by the CEF in the inductive detector, because the IEF is minimum at this location. Therefore, the maximum condition of $V3$ over $V4$ means the inductive detector being affected only by the IEF.

In addition, we have to determine a less sensitive condition of performing voltage detection with respect to the geometrical variables of the NDWs. In the sensitive condition, when RF sensors are manufactured in large numbers, the degree of the interference for each sensor can be different because of manufacturing error. It results in poor repeatability of the RS sensor production.

In short, the voltage of the capacitive detector is increased as the ratio $V2/V1$ increases, and the interference of the inductive detector is decreased as the ratio $V3/V4$ increases. In addition, the less-sensitive condition must also be considered for minimizing the interference. We call these three conditions as the key conditions for minimizing the interference.

Figure 2 depicts voltages $V1$, $V2$, $V3$, and $V4$ with respect to the geometrical variables of the NDWs. In Fig. 2(a), voltage $V1$ increases upon increasing H because the capacitance formed by the capacitive detector and the NDWs increases. In contrast, voltage $V2$ decreases upon increasing H because the capacitance formed by the NDWs and the aluminum house (ground) decreases. Voltages $V3$ and $V4$ are less sensitive than H , meaning that H rarely affects the interference. Regardless of this, they become zero at $H = 52$ mm, because all the electric fields are shielded by the NDWs, as the ends of the NDWs reach the aluminum house. In Fig. 2(b), voltages $V1$ and $V2$ are varied faster than that in Fig. 2(a). It means the capacitance formed by the capacitive detector and the inner walls of the NDWs play an important role in detecting the voltage of the capacitive detector. In Fig. 2(c), voltages $V1$ and $V2$ are varied irregularly, but the variation is not so high. Voltages $V3$ and $V4$ are less sensitive versus θ as well. Figures 2(a)–(c)

Figure 2. (Color online) Voltage versus the geometric variables of the NDWs. (a) Voltage versus H at $D = 4$ mm and $\theta = 60^\circ$. (b) Voltage versus D at $H = 45$ mm and $\theta = 60^\circ$. (c) Voltage versus θ at $D = 3$ mm and $H = 45$ mm.

depict that voltages $V1$ and $V2$ are inversely proportional to each other, and that the results have a good agreement with our expectation.

A four-step process is conducted to minimize the interference. First, voltages $V1$, $V2$, $V3$, and $V4$ are computed after setting arbitrary values for the geometrical variables of D and θ according to the value of H . Subsequently, H 's value that satisfies the key conditions is determined. Second, the value of D is determined for the geometrical variables of H and θ in the same manner. Third, the value of the θ is determined for the geometrical variables of D and H , which have been determined. Fourth, the value of H is determined for the geometrical variables of D and θ . The process is repeated until the values of the geometrical variables H , D , and θ converge to specific values; those specific values for the geometrical variables are finally determined as the minimizing condition of the interference.

Figure 3 depicts the voltage ratios $V2/V1$ and $V3/V4$, versus the geometrical variables H , D , and θ . The pink region satisfies the less-sensitive condition. During the computation process, the intermediate value in the pink region is selected, and the process is conducted in five steps as depicted in Figs. 3(a)–(e). As a result of the process, the geometrical variables of the NDWs are finally converged to $D = 3$ mm, $H = 45$ mm, and $\theta = 70^\circ$. After minimizing the interference, the RF sensor was built. The assembly of the RF sensor is depicted in Fig. 4.

Figure 3. (Color online) Voltage ratio versus the geometric variables of the NDWs. (a) Voltage ratio versus H at $D = 4$ mm and $\theta = 60^\circ$. (b) Voltage ratio versus D at $H = 45$ mm and $\theta = 60^\circ$. (c) Voltage ratio versus θ at $D = 3$ mm and $H = 45$ mm. (d) Voltage ratio versus H at $D = 3$ mm and $\theta = 70^\circ$. (e) Voltage ratio versus D at $H = 45$ mm and $\theta = 70^\circ$.

III. Results and discussion

Upon directly applying the output power of the RF generator to a load of impedance 50Ω , the phase difference between the voltage and current waveforms at the load is ideally zero. Under this condition, if the interference of the RF sensor is minimized, the phase difference obtained from the RF sensor will be close to zero.

Figure 5 depicts a schematic of the experimental setup. The RF sensor is connected between an RF generator (NPG-1250A) and a matcher (Path Finder PF0113) by using N-type coaxial cables, and the sensor is also connected to an oscilloscope (TDS-3052B) by using SMA coaxial cables for measuring the waveforms. The oscilloscope is, in turn, connected to a PC by using the GPIB communication cable, and the probe condition of the oscilloscope is 50Ω , as depicted in Fig. 8. RF power, ranging from 100 to 1000 W, at 13.56 MHz is applied to the matched capacitively coupled plasma chamber, and the chamber pressure is 5.4×10^{-6} Torr for preventing the generation of the dark discharge.

Figure 6 depicts the phase differences versus the

Figure 4. (Color online) Assembly of the RF sensor hardware.

Figure 5. (Color online) Schematic of the RF system with the RF sensor.

power of the RF generator with respect to the RF sensor. From this figure, it can be observed that the averaged phase difference (between voltage and current waveforms) for the RF sensor is 1.32° , and that for ENI probe (VIP1004) is 24.78° . As a result of this experiment, the phase difference for the RF sensor is greatly close to that for the ideal case, compared with that of the ENI probe. On the basis of the electric-

Figure 6. (Color online) Phase differences between the voltage and current waveforms with respect to the RF sensor.

and magnetic-field distribution at 13.56 MHz in the inductive detector, which is not included in this paper, the electric field is shielded only within the NDWs. The CEF, however, is blocked by the NDWs. Therefore, low phase difference for the RF sensor results from successful blocking of the CEF by the NDWs in the inductive detector.

From this result, we can expect that the interference between the capacitive detector and the inductive detector is considerably reduced to be able to perform high-precision measurement of voltage and current waveforms, in contrast to that of the ENI probe.

IV. Supplementary Study

The RF sensor is conventionally connected between the matcher and the plasma chamber. Under this configuration, the characteristic impedance of the RF sensor is as close to $50\ \Omega$ as possible. If the characteristic impedance exceeds $50\ \Omega$, the RF generator can be damaged by the reflected power from the load. Therefore, we computed the transmission coefficient of the RF sensor in 3D-EM simulation as the information of the characteristic impedance [1].

Figure 7 depicts the transmission coefficient (S_{21}) of the RF sensor and the error (in %) ($=100 \times (1 - S_{21})$), versus frequency. In Fig. 8, S_{21} is very close to 1 under the frequency of 100 MHz with the error under 2 %. The result means that the characteristic impedance of the RF sensor is very close to $50\ \Omega$.

Subsequently, the input impedance of the inductive detector was computed in 3D-EM simulation to confirm the bandwidth frequency of the RF sensor. The bandwidth depends on the self-resonance frequency

Figure 7. (Color online) Transmission coefficient and error of the RF sensor against frequency.

Figure 8. Input impedance of the inductive detector versus frequency.

(SRF) that comes from stray capacitance in the detector [11].

Figure 8 depicts the input impedance versus frequency for the inductive detector. In Fig. 8, the SRF is shown as 176 MHz, and the impedance is linearly proportional to the frequency under 100 MHz; the 0–100 MHz range can be defined as bandwidth because the stray capacitance in this range is negligible and hence can be ignored. Therefore, we expect that this inductive detector works suitably as an inductor in the bandwidth of 100 MHz. From this result, it can be noted that this RF sensor operates precisely with the bandwidth of 100 MHz.

V. Conclusions

As a result of this research, we developed a high-precision RF sensor by minimizing the interference between the two detectors by using NDWs in 3D-EM simulation. The bandwidth (100 MHz) and the characteristic impedance ($50\ \Omega$) were analyzed in the 3D-EM simulation as supplementary study. The RF sensor's phase difference measured between the voltage and current waveforms was observed to be 1.32° for a matched load. This small value of phase difference means that the RF sensor is much more superior to another commercial sensor (VIP1004: 24.78°) for performing high-precision measurement of voltage and current waveforms.

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