Estimation of Self-Ignited Plasma Density Using Plasma-Based Ion Implantation

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Plasma density is estimated from the target voltage and current characteristics of the pulse modulator circuit in plasma-based ion implantation. The voltage recovery time constant directly reflects the ion sheath characteristics, and the sheath resistance is related to the ion density inside the transient sheath. The stationary current also provides information on the sheath parameters. From these viewpoints, we propose a method to estimate plasma density by equating the circuit. The plasma density can be obtained only by monitoring the voltage-current waveforms on an oscilloscope display, and the obtained ion density can be converted into plasma density using a continuity equation. The conventional method uses the dual structure of RF plasma and self-ignition plasma. In this study, the plasma density is calculated using only self-ignition plasma.

Оценка на плазмената плътност при самозапалване на плазма предназначена за йонна имплантация (Н. Фуджимура, К. Шимоно, Х. Ногучи, Х. Тойота, У. Шираи, Т. Танака). *Плътността на плазмата е оценена от напрежението на мишената и токовите характеристики на импулсната модулаторна верига в базирана на плазма йонна имплантация. Константата за възстановяване на напрежението директно отразява параметрите на йонната обвивка, като съпротивлението е свързано с йонната плътност във временната обвивка. Стационарния ток също предоставя информация за параметрите на обвивката. Ние предлагаме метод за оценка плазмената плътност от уравненията на веригата. . Плазмената плътност може да се получи само от наблюдаваните волт-амперни форми на екрана на осцилоскопа и получената йонна плътност може да се преобразува в плазмена плътност използвайки уравнението за непрекъснатост. Конвенционалният метод използва двойна структура на РЧ плазма и само-запалваща се плазма. В това изследване плазмената плътност се пресмята използвайки само само-запалваща се плазма.*

Introduction

Plasma ion implantation was proposed by J.R. Conrad in the 1980s [1]. Plasma-based ion implantation (PBII) is a recently developed technique which modifies sample surface using sheath formed along sample in a plasma applied negative high pulse voltage. Since sheath was formed along surface structure of sample, ions can be uniformly injected into the sample surface. PBII with good controllability is effective as a surface treatment method for samples with wide variety shapes.

Conventionally, the plasma sterilization process at hospitals uses hydrogen peroxide gas. This method achieves sterilization by the oxidation reaction of high concentration hydrogen peroxide. Currently, plasma ion implantation is used to sterilize surgical instruments. The sterilization process using plasma ion implantation is composed of the following elements.

(1) Generation of ions using plasma
(2) Acceleration of the generated ions
(3) Interaction between samples and ion

Therefore, it is important to control ion sheath at sample surface, the quantity and energy of ions in an ion sheath [2].

In this paper, the density of ions in the sheath formed by self-ignition plasma for PBII was calculated using the basis of modulator circuit. The plasma density and the length of sheath of self-ignition plasma were also calculated.

Estimation of plasma density [3]

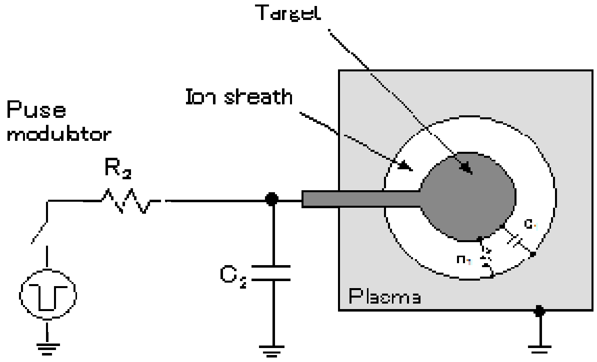


Fig. 1 Equivalent circuit of the modulator voltage

Fig. 1 shows an equivalent circuit representing the pulse modulator circuit used to apply a pulse voltage to a target immersed in plasma. Because the main load of the modulator output is the ion sheath formed around the target, which consists of resistance R_1 and capacitance C_1., the plasma impedance can be ignored. Although R_1 and C_1 are time-varying parameters, they are treated as constant for simplification during the pulsed ion implantation. In other words, R_1 and C_1 are said to be average values during the process. Generally, these are functions of the ion density in the sheath as shown below. In the modulator circuit, modulator output resistance R_2 and circuit stray capacitance C_2 exist in addition to R_1 and C_1, and are not dependent on the plasma parameters. These are constants. C_2 exists between the apparatus and the ground of the system.

In order to know the ion density in the sheath, we need to know R_2 and C_2. To evaluate these parameters, a capacitor or a resistor is set to the modulator output instead of the plasma. R_2 and C_2 can be derived by measuring the rise time τ_r and fall time, i.e., recovery time τ_f. A resistor with a resistance of 10 kΩ and capacitor with a capacitance of 70 pF were used as dummy loads for evaluating the circuit parameters of R_2 and C_2. By observing the voltage and current waveforms for these loads, C_2=220 pF for τ_f=2.2 μs and R_2=2.2 kΩ for τ_r=0.88 μs, respectively, are obtained. C_1 is thought to be approximately 10 pF or less. Thus, $C_2 >> C_1$ is satisfied. As a result, the ion sheath capacitance does not substantially contribute to the time constant in the voltage recovery region after the pulse.

When a planar sheath is formed around the target, the ion current density j at the target surface, the electrical field strength, is expressed as V_p/s,

$$j = \sigma \frac{V_p}{s} \quad (1),$$

where σ is conductivity of the ion sheath, s is sheath thickness and V_p is applied voltage. When $j = en_i v$ is assumed, where n_i is the ion density at the target surface, and the ion velocity v at the target surface is expressed as $v = \sqrt{mV_p/2e}$ under a collisionless field, $R_1 (= s/\sigma A)$ can be expressed as Eq. (2).

$$R_1 = \frac{1}{en_i A}\sqrt{\frac{mV_p}{2e}} \quad (2),$$

where e is electron charge, n_i is ion density at the target surface with a surface area A, and m is ion mass. From Eq. (2), it is seen that R_1 is a function of n_i for the experimental parameters. At the sheath edge, Eq. (3) is satisfied.

$$n_i v = n_0 u_B \quad (3),$$

where n_0 is plasma density and u_B is Bohm velocity. R_1 can be experimentally obtained using τ_f, which is expressed as:

$$\tau_f = C_2 \times R_1 . \quad (4)$$

By obtaining R_1, the ion density can be estimated. This method of estimating the ion density is advantageous because only the voltage waveform need be observed. R_1 can be also obtained by using the target voltage and the current through the target at the end of the pulse.

Experimental

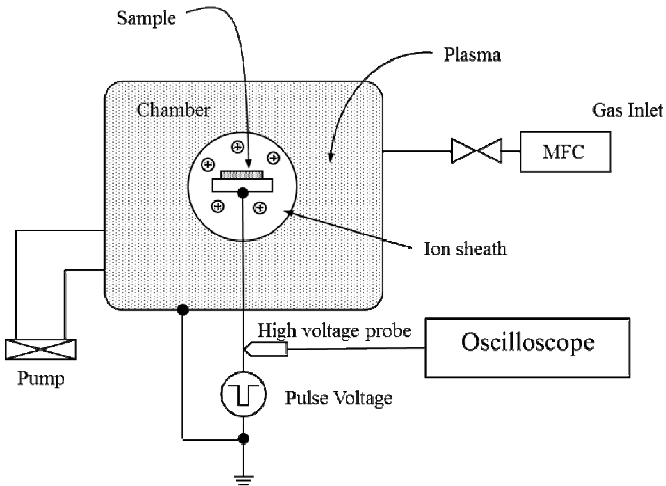
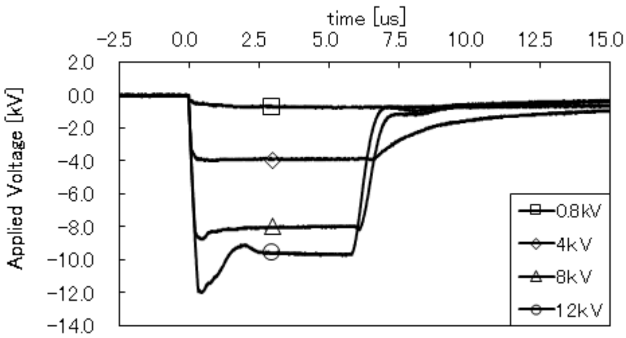


Fig. 2. Schematic diagram of experimental setup

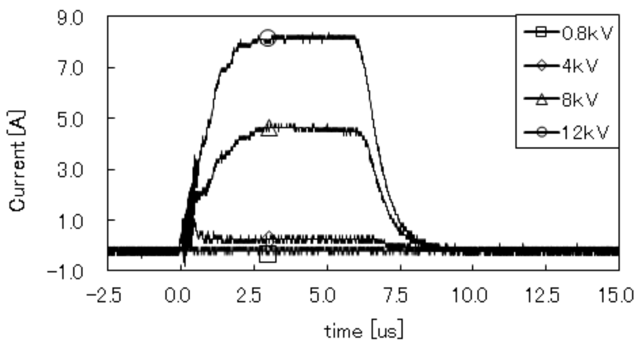
Figure 2 shows a schematic diagram of the self-ignited plasma (SIP) PBII apparatus. The treatment chamber in the experiments measured 450 mm in height, 590 mm in width and 470 mm in depth. The electrode made of stainless steel (SUS) which is insulated for the treatment chamber was set at the center of treatment chamber. This charge is performed by applying a pulsed negative dc voltage of up to –12 kV to the target. The pulse width of the voltage waveform is about 6.3 μs and its repetition rate is 1000 pulses/s. The maximum current supplied by a high-voltage pulse modulator is approximately 8 A. A pulsed dc voltage is employed to simplify the sterilization apparatus. A diffusion pump was used to evacuate the chamber to a base pressure of 1.0×10^{-3} Pa, and the nitrogen gas pressure during plasma generation was maintained at 3 Pa.

Result and discussion

The applied voltage is varied from 0.8 to 12 kV at 3 Pa. The applied voltage and current waveform is shown in Fig. 3. Then the generation of plasma is not observed at 0.8 kV. At more than 4 kV, generation of plasma was observed. It is impossible to observe a clear current waveform of less than 4 kV. The current waveform clearly appears at more than 8kV. The voltage waveforms shown in Fig. 3(a) have nearly rectangular forms. The steady current is about 4.4A for applied voltage of 8kV.



(a) Applied Voltage



(b) Current

Fig. 3 Self-ignition plasma discharging characteristic for N_2

For metal materials, secondary electron emission coefficient is about 0.1 (less than 1 keV). For high ion energy (more than 1 keV), secondary electron emission coefficient become large. At 20 keV, the secondary electron emission coefficient of stainless steel is 4.8.[4]

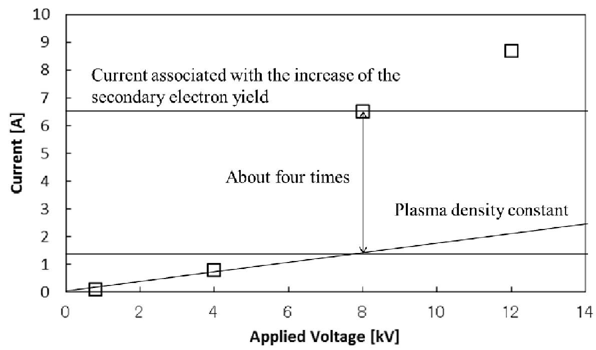


Fig. 4 Currnet – applied voltage characteristic

Figure 4 shows the relation of current and applied voltage. When the plasma density is constant, the current is proportional to the applied voltage. However, the current drastically increases at more than 8 kV. At 8kV, measured current is approximately 4 times compared with current of plasma density constant. This suggested that the measured current increase with secondary emission electron coefficient. The secondary electron emission coefficient obtained by current as shown in Fig.4 is shown in Fig.5.

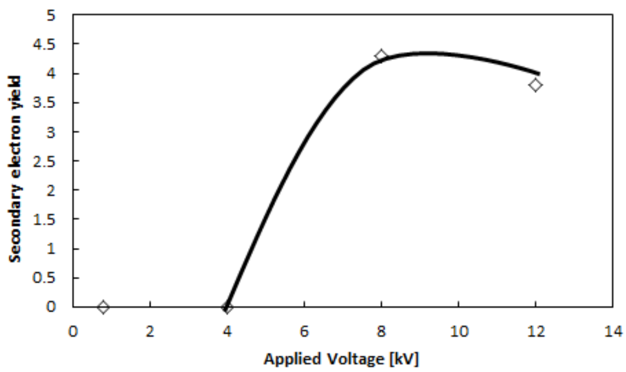


Fig. 5 Secondary electron yield

Using the time constant and C_2, R_1 is calculated by Eq.(4). Moreover, using calculated R1, the value of plasma density was calculated $4.4 \times 10^9 cm^{-3}$ at 8kV.

It suggests that the 2/3 of measured current at 8kV is due to secondary electron emission coefficient. The correction value and the calculation value of the plasma density are shown in Fig.6.

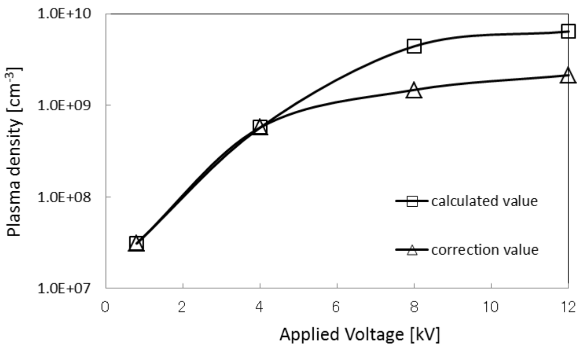


Fig. 6 Plasma density calculation for N_2

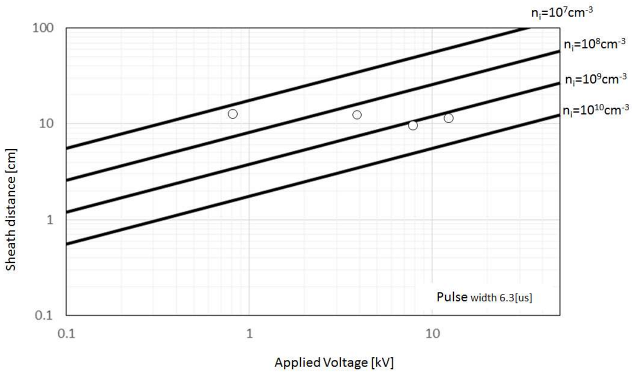


Fig. 7 Sheath distance as a function of applied voltage

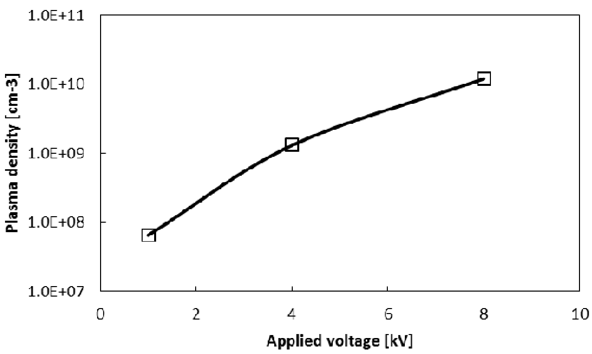


Fig. 8 Plasma density calculation for Ar

Fig.7 shows sheath length as a function of applied voltage. The sheath length was calculated by using Eq.(5).

$$s = \left(\frac{4}{3}\varepsilon_0\right)^{\frac{1}{3}} \left(\frac{2e}{m}\right)^{\frac{1}{6}} \frac{V_p^{\frac{1}{2}}}{(en_i)^{\frac{1}{3}}} t^{\frac{1}{3}} \qquad (5)$$

Similary the calculated plasma density for Argon gas is shown in Fig. 8.

Finally, we concluded plasma density was estimated using only SIP.

Conclusion

The plasma density in the ion sheath was able to calculate using modulation equivalent circuit for PBII. The plasma density and sheath length was calculated by this method. The plasma density and length of sheath is important parameter to manufacture the apparatus. In the future, it is useful to a device design to calculated plasma density and sheath length.

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