Self-consistent circuit model for plasma source ion implantation

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A self-consistent circuit model which can describe the dynamic behavior of the entire pulsed system for plasma source ion implantation has been developed and verified with experiments. In the circuit model, one-dimensional fluid equations of plasma sheath have been numerically solved with self-consistent boundary conditions from the external circuit model including the pulsed power system. Experiments have been conducted by applying negative, high-voltage pulses up to ~10 kV with a capacitor-based pulse modulator to the planar target in contact with low-pressure argon plasma produced by radio-frequency power at 13.56 MHz. The measured pulse voltage and current waveforms as well as the sheath motion have shown good agreements with the simulation results.


I. INTRODUCTION

Plasma source ion implantation (PSII) has drawn great interest as a promising technique to overcome the line-of-sight limitation of a traditional beamline implantation method. In PSII, the ions to be implanted onto a target surface are supplied by the motion of expanding plasma sheath, which varies in time and space by high-voltage pulses applied to the target. When a sudden negative voltage is applied to the target in contact with plasma, electrons near the surface are driven away on the time scale of the inverse electron plasma frequency, leaving the ions behind to form an ion matrix sheath. On the time scale of the inverse ion plasma frequency, ions within the sheath are accelerated into the target. The sheath edge is then driven further away from the target exposing new ions which are extracted from the plasma. For a much longer time scale (typically tens of microseconds), the system evolves toward the steady-state Child law (CL) sheath.

Systematic understanding of the entire pulse system is crucial in PSII processes because all components composing the PSII pulse system directly influence the dynamic motion of plasma sheath, which determines the dose and energy of implanted ions. It gives the accurate dose and energy distribution of implanted ions and also the optimum operating conditions for various processing plasma environments. The PSII system can be characterized by two major categories. One is the high-voltage pulse generator or pulse modulator which consists generally of the high-voltage dc charging power supply, energy-storage system, high-voltage switches, current-limiting resistors, and trigger system. Another is the processing plasma which is usually generated by external dc or rf power sources in the vacuum chamber. During the PSII process, the plasma sheath responds dynamically to the applied pulse bias and draws the electrical current from the pulse modulator. Because this current is relatively large in realistic PSII process, the loading by the dynamic motion of plasma influences the pulse waveform applied to the target as well. The deformed voltage waveform has influence on the dose and energy of the implanted ions in return. In realistic PSII, therefore, the self-consistent analysis of the entire PSII system including the plasma sheath as well as the pulsed power supply is necessary to predict the dose and energy of the implanted ions more precisely.

So far, most previous studies have treated the pulsed power supply (pulse modulator) as an independent source, i.e., the output voltage waveform of the pulse modulator was assumed to be independent to the high-current loading during the sheath expansion. En et al. used the prescribed voltage waveforms obtained from experiments in developing an equivalent circuit model for PSII.1 In their model, the measured voltage waveform was assumed as a piecewise-linear time-varying voltage source. Then, the dynamic motion of the sheath edge and the current flowing into the target were solved with the Lieberman’s analytic model based on the quasistatic CL sheath approximation.2 Barroso et al. have used a set of analytical functions to express approximately the voltage pulse waveform obtained from experiment.3 Qi et al. examined numerically the effects of pulse waveform on plasma sheath expansion under the assumption of the square pulse that rises exponentially with time.4 Recently, Chung et al. have developed a self-consistent circuit model based on the analytic CL sheath approximation for plasma sheath.5 However, their analytic CL sheath approximation for the dynamic sheath is only adequate to the slowly varying pulses.

In this article, a numerical code based on one-dimensional fluid equations is developed to describe the dynamics of plasma sheath. This numerical code is capable to simulate the response of plasma sheath on the pulse voltage more accurately than the analytic model based on the CL sheath approximation. In the self-consistent circuit model of a PSII system, the fluid equations of plasma sheath are nu...
numerically solved with self-consistent boundary conditions from the equivalent circuit model including the pulsed power system. The self-consistent circuit model is verified by comparing the pulse waveform and sheath motion with the experimental measurements.

II. EXPERIMENTAL SETUP

A PSII system has been constructed using a planar target in contact with low-pressure argon plasma, as shown in Fig. 1. The plasma was generated in a discharge tube made of fused quartz with 7 mm thickness, the dimensions being 295 mm diameter and 200 mm height. Radio-frequency (rf) power at 13.56 MHz was delivered to a single-turn loop antenna surrounding the discharge tube. A simple L-type matching network composed of two variable capacitors was inserted between the antenna and a rf power source for impedance matching. The inductively generated plasma in the discharge tube diffuses towards the region surrounded by a Pyrex tube (185 mm in inner diameter and 100 mm in height) located at the top of the quartz discharge tube. All measurements have been carried out in the diffusion region to avoid the perturbation of the main plasma generated in the quartz discharge tube by high-voltage pulses. A planar stainless-steel disk of 180 mm diameter was used as a target, and it was installed at the top of the Pyrex tube, as shown in Fig. 1. In this configuration, one-dimensional analysis of the sheath motion is possible because the edge effect of sheath evolution can be ignored. Argon was chosen as a working gas because argon plasma is mostly generated with a singly charged ion species, \( \text{Ar}^+ \), under our experimental conditions. This allows us to ignore the ion species ratio effect on sheath formation. To minimize collisional effects and maximize sheath size, the experiments have been carried out under low-pressure and -power conditions. Typically, the operating pressure was 0.4 mTorr (0.05 Pa) with the input rf power of 120 W.

In this study, a relatively low-power pulse modulator based on the solid-state switch was used for driving high-voltage pulses to the target. An equivalent circuit diagram of the pulse modulator is depicted schematically in Fig. 1. A capacitor \( C_1 \) in the figure; Maxwell, 37330) of 100 nF is used for an energy-storage device of the pulse modulator. The internal inductance of \( C_1 \) is as low as 15 nH. The capacitor is charged by a high-voltage dc power supply \( (V_0) \) and its stored energy discharges onto the target in contact with plasma when a solid-state switch \( (S_1) \); Behlke, HTS 651-03-LC). The solid-state switch is triggered by applying +5 V transistor-transistor logic (TTL) pulse signal to the gate of the switch using a delayed pulse generator (BNC, 555-4C). A current-limiting resistor \( (R_f) \) having 2 kΩ is connected between the energy-storage capacitor \( (C_1) \) and the switch \( (S_1) \) for the protection of the switch from overcurrent. Since the internal impedance of the solid-state switch cannot be neglected, three capacitors are introduced in the equivalent circuit of the switch. Here, the \( C_N \) and \( C_C \) are the natural capacitance and coupling capacitance of the switch, respectively. The values of \( C_N \) and \( C_C \) are verified through a short-circuit test as 30 and 48 pF, respectively.

III. SELF-CONSISTENT CIRCUIT MODEL

A. Fluid model for plasma sheath

One-dimensional fluid model for plasma sheath is developed with the assumptions described below. The motion of ions is assumed to be collisionless, that is, valid for low-pressure PSII operation. Because the time scales of sheath expansion and collapse are longer than the inverse of electron plasma frequency \( (\omega_{pe}^{-1}) \), the electron inertia can be neglected so that electrons are assumed to obey the Boltzmann relation. Moreover, the thermal motion of ions is neglected (cold ion; \( T_e=0 \)). The governing fluid equations in one-dimensional planar geometry are as follows:

\[
\frac{\partial n_e}{\partial t} + \frac{\partial (nu_e)}{\partial x} = 0 \quad \text{(continuity equation)},
\]

\[
\frac{\partial u_e}{\partial t} + u_e \frac{\partial u_e}{\partial x} = -\frac{e}{M} \frac{\partial \phi}{\partial x} \quad \text{(equation of motion)},
\]

\[
\frac{\partial^2 \phi}{\partial x^2} = -\frac{e}{\varepsilon_0} (n - n_e) \quad \text{(Poisson’s equation)},
\]

\[
n_e = n_0 \exp \left( \frac{e\phi}{kT_e} \right) \quad \text{(Boltzmann’s relation)},
\]

where \( n \) is the ion density, \( n_e \) is the electron density, \( n_0 \) is the bulk plasma density, \( u \) is the ion velocity, \( \phi \) is the electric potential, \( e \) is the electronic charge, \( \varepsilon_0 \) is the permittivity of free space, \( M \) is the ion mass, \( k \) is the Boltzmann constant, and \( T_e \) is the electron temperature. By assuming the electrons to be in thermal equilibrium, their detailed motions occurring on the time scale of \( \omega_{pe}^{-1} \) are neglected in this approach. Equations (1)–(4) are solved numerically using a finite difference method. The MacCormack’s explicit scheme is employed to solve the equation of motion. The continuity equation is solved using an implicit low-order upwind scheme.
Total current ($I$) flowing into the target is a sum of the ion convection current ($I_i$), the thermal electron current ($I_e$), the secondary electron current ($I_s$), and the displacement current ($I_d$) as follows:

$$I(t) = I_i(t) + I_e(t) + I_s(t) + I_d(t),$$

where

$$I_i(t) = e n_0 |u(0,t)| A,$$

$$I_e(t) = -e \sqrt{\frac{kT_e n_0}{2 \pi m}} \exp \left( \frac{e \phi(0,t)}{kT_e} \right) A,$$

$$I_s(t) = \gamma(E) I_i(t),$$

$$I_d(t) = C_s \frac{dV}{dt},$$

where $A$ is the area of the target located at the position $x=0$, $m$ is the electron mass, $V$ is the target voltage, and $C_s$ is the sheath capacitance. $\gamma(E)$ is the secondary electron emission coefficient by ion impact. Although it varies with ion species, target materials, and surface roughness, the secondary electron emission coefficient for Ar$^+$ bombardment onto dirty metal surfaces can be fitted approximately as a function of ion energy $E$ in eV,

$$\gamma(E_{ion}) = 0.002 \left( \frac{1}{1 + (E/30)^{1.2}} \right) + 1.05 \times 10^{-4} \left( \frac{E - 80}{1 + (E/8000)^{1.5}} \right),$$

where the second term is zero for ion energies below 80 eV.

### B. Self-consistent circuit model

Figure 2 shows the self-consistent circuit model which is developed by including the one-dimensional fluid code described in the previous subsection into the equivalent circuit of the PSII system depicted in Fig. 1. In the circuit model, the one-dimensional fluid code is embedded into the circuit model using an “embedded MATLAB function block” which allows the use of MATLAB function or C language in a SIMULINK module. The fluid code receives time ($t$) and voltage ($V$) from the external circuit at each time step. Time $t$ is used to calculate a time advance ($\Delta t$) in Eqs. (1) and (2). Target voltage $V$ is used as a boundary condition of the Poisson’s equation given in Eq. (3). Then, the block “Fluid Model” solves the set of equations [Eqs. (1)–(4)] numerically and calculates ion, electron, and displacement currents given in Eq. (6) at each time step. These calculated currents are added through a block “Sum” and connected to the external circuit by using a voltage-controlled current source (block “Isum”). Then the block “Isum” converts the calculated total current to a real current, thereby allowing the self-consistent analysis of the pulse system possible.

In the simulation, a variable-step solver “ode23s” is used for solver option. In this case, SIMULINK varies the step size automatically during the simulation. The step size is reduced to increase accuracy when the state of model calculation is changing slowly. In contrast, the step size is increased to avoid taking unnecessary steps when the state of model is changing rapidly. Computing the step size adds to the computational overhead at each step but can reduce the total number of steps, and hence simulation time.

### IV. DIAGNOSTICS

Prior to a high-voltage pulse, initial plasma conditions such as two-dimensional density profile, electron temperature, and one-dimensional ion flow velocity profile have been measured in front of the target by using a Langmuir probe and a Mach probe, respectively. A steady-state solution of Eq. (1) and a quasi-neutrality condition gives the initial plasma properties for the circuit model as following:

$$\frac{\partial}{\partial \kappa} (nu) = 0,$$

$$n = n_e = n_0 \exp \left( \frac{e \phi}{kT_e} \right).$$

Here, we ignore a floating sheath initially formed in front of the target because the thickness is negligibly small (less than a few millimeters) compared to the system size. Once the spatial distribution of initial plasma density is known, the spatial profiles of the initial ion velocity and potential are calculated from Eq. (8). Figure 3 shows the initial plasma properties obtained from the probe measurements as well as the fitting curves using Eq. (8). In the circuit simulation, the
local ion density, i.e., the sheath edge is determined as the position where the density of the sheath edge and rarefaction wave are depicted in Fig. 4 for the charging voltage of −10 kV. Simulation results show good agreements with experimentally measured ones. The pulse fall time after switching off is measured as long as approximately 40 μs. Note that the pulse fall time is determined by the rate at which the electric charge stored in the circuit capacitance is discharged through the load (plasma sheath), provided that there are no external circuits for controlling the fall time such as a pull-down resistor or a parallel switch (tail biter). Therefore, the pulse fall time is greatly affected by the load conditions such as plasma density, electron temperature, and target area. A small hump in the voltage trace at the initiation of the pulse bias is caused by the drawing of large target current during the early stage of the pulse.

Because the deformation of the voltage waveform caused by the high-current loading alters the energy distribution of implanted ions, the influence of the plasma sheath on the pulse waveform needs to be considered in real PSII processes. Note that this phenomenon cannot be observed in other approaches carried out previously because the prescribed voltage shapes are used there.

After turning off the pulse bias at 10 μs, the sheath edge overshoots a little and then collapses with a nearly constant speed. During the overshoot of the sheath edge, it is observed from the numerical simulations that the ion density inside the expanded sheath is further depleted so as to satisfy the Poisson’s equation. The position of the sheath edge is closely related to the amplitude of the target voltage because the electrons respond instantaneously to the target voltage varying much slowly than the inverse of electron plasma frequency. The rarefaction wave (rarefying disturbance wave) produced by the external high-voltage perturbation is also observed. The waveform of the rarefaction wave propagates into the bulk plasma with a velocity \( u_B - |u_d(x)| \), where \( u_B \) and \( u_d(x) \) are the Bohm velocity and the ion drift velocity at the position of the wavefront, respectively.

FIG. 3. Initial plasma properties considered in the circuit simulation (solid curves), compared to the measured ones by various diagnostic methods.

FIG. 4. Comparison between experiment and simulation for charging voltage of −10 kV: (a) the pulse voltage and current waveforms, (b) the motions of sheath edge and rarefaction wave. Two vertical dashed lines indicate switch-on and -off times, respectively.

V. COMPARISON OF EXPERIMENTS WITH SIMULATIONS

A single high-voltage pulse with a finite duration is applied to the target plate to investigate the behaviors of the plasma sheath and rarefaction wave as well as the pulse waveforms on the target during and after the pulse. In the experiments, the pulse duration (pulse width) is fixed to be 10 μs and all plasma properties are equivalent to those described in the previous section. Both expansion and collapse of the sheath edge during or after the pulse are determined. In the numerical simulations, the switch-off time is set to be 10.3 μs because the pulse switch is found to have a turn-off delay time of approximately 0.3 μs from the experimental data.

Comparisons between experiment and simulation for the pulse voltage and current waveforms as well as the motions of the sheath edge and rarefaction wave are depicted in Fig. 4 for the charging voltage of −10 kV. Simulation results show good agreements with experimentally measured ones. The pulse fall time after switching off is measured as long as approximately 40 μs. Note that the pulse fall time is determined by the rate at which the electric charge stored in the circuit capacitance is discharged through the load (plasma sheath), provided that there are no external circuits for controlling the fall time such as a pull-down resistor or a parallel switch (tail biter). Therefore, the pulse fall time is greatly affected by the load conditions such as plasma density, electron temperature, and target area. A small hump in the voltage trace at the initiation of the pulse bias is caused by the drawing of large target current during the early stage of the pulse.

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The experiment and simulation results for the repetitive pulse operation are compared in Fig. 5 in case of the charging voltage of \(-5\) kV. The repetition period is up to \(20\) μs, which gives 50% duty cycle for 10 μs pulse width. In this case, the pulse-off time keeps as 10 μs so that the pulse fall time is much longer than the pulse-off time, as shown in Fig. 5(a). It is clearly observed that there is no sufficient time for the plasma as well as the sheath edge to recover to its initial state. Figure 5(b) shows that the extents of sheath edges for the second and third pulses are slightly greater than that of the first pulse due to the incomplete sheath collapses during the pulse-off times. The propagation of rarefaction waves into the plasma is observed even for the second and third pulses even though the sheath may not be recovered completely during the preceding pulse-off times [Note that the rarefaction wave generated by the first pulse is only calculated in the circuit simulation so that the simulation results after the second pulse are not depicted in Fig. 5(b)].

VI. DISCUSSION

A self-consistent circuit model based on the fluid description for dynamic plasma sheath has been developed to describe the PSII system more precisely. In the present circuit model, the pulse waveform applied to the target in contact with plasma can be determined by the inter-related characteristics of the pulse modulator and dynamic plasma sheath. The model has explained well the experimental measurements of pulse waveforms and sheath motions for a single or the repetitive pulse operations. This self-consistent circuit model is expected to be used to predict the pulse waveform and the energy distribution of implanted ions in realistic PSII processes.

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10 MATLAB, version 7.0, with SIMULINK, version 6.0 (Available at http://www.mathworks.com). The solver ode23s is based on a modified Rosenbrock formula of order 2. Because it is a one-step solver, it can be more efficient for some kinds of stiff problems than other solvers at crude tolerances.