Transition from E to H mode discharge in pulse-modulated inductively coupled plasmas

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Abstract

Time-resolved measurements of pulse-modulated inductively coupled plasmas were carried out by using a Langmuir probe. It was found that under a certain set of conditions (a mixture of 20% O_2 and 80% Ar, a pressure of 2.67 Pa, a radio-frequency power of 200 W, a pulse frequency of 500 Hz, and an RF-off time of 100 μs), a plasma transits from E mode (capacitive coupling mode) to H mode (inductive coupling mode) after the RF-off time. With a shorter RF-off time of 50 μs, the plasma returned to H mode without passing through E mode. Whether H mode or E mode appears after the RF-off time depends on the electron density at the end of the afterglow. Namely, the restoration to H mode after the RF-off time occurs if the plasma has an adequate electron density, and E mode occurs if electron density is not enough to sustain H mode. It was also found that electron

temperature decreases and plasma potential increases gradually during E mode because of the change of the electron-energy distribution. The change of the plasma reduces the impedance mismatching gradually and increases the electron density until the transition to H mode occurs. Such mode transition behavior strongly depends on the basic characteristics of the plasma processing apparatus during continuous discharge and also on the condition of the chamber wall.

I. INTRODUCTION

Process windows that can achieve uniform plasma etching have been narrowed from year to year as circuit patterns of semiconductor devices have become finer. Therefore etching apparatus that enables better process control has become essential.[1-3] To meet this demand, it is necessary to develop an etching apparatus with predictable characteristics of plasma generation and higher controllability of plasma distribution, process-gas dissociation, and surface reactions in the reactor. Recently, inductively coupled plasmas (ICPs) have been used extensively because they can linearly generate and control the plasmas with low to high densities under the pressures required for the etching processes, and also because they have a simple plasma generating mechanism and reactor structure. [4,5]

One possibility for widening the process window, pulse-modulated plasmas [6-8], has been studied extensively. They have been used to control the degree of dissociation of the process gas or the wafer charging by turning the plasmas on and off for several tens of microseconds to several milliseconds. Although pulse-modulated plasmas add extra process-control parameters to the conventional process-control parameters (process-gas pressure, source power, bias power, and wafer temperature), the plasma changes dynamically in a pulse period, thus further complicating the system. [9,10] Accordingly, in order to achieve practical utilization of such plasmas in semiconductor manufacturing, it is essential to fundamentally understand the plasma behavior during the pulse period.

In response to the above-described circumstances, we made time-resolved plasma measurements during a pulse period by using a Langmuir probe.

II. EXPERIMENTAL APPARATUS AND METHOD

The experimental apparatus used for this experiment was constructed by replacing an upper electrode of a Gaseous Electronics Conference (GEC) Reference Cell with an inductively coupled plasma source (hereafter referred to as ICP cell).[11] As shown in Fig. 1, a quartz window is mounted below the top flange of the stainless steel vacuum chamber of the ICP cell. A 5 turn spiral induction coil, to which a radio-frequency (RF) power of 13.56 MHz is supplied, is located on the atmosphere side of the quartz window. A lower electrode is mounted opposite the quartz window. Though it was possible to apply an RF bias to the lower electrode,[12] the experiment was performed with the lower electrode electrically grounded. A Langmuir probe (Scientific Systems Ltd., Smart Probe[†]) is mounted through a port at the side of the chamber so that its tip lies vertically 15 mm above the lower electrode and horizontally 20 mm from the center of the chamber. Experimental uncertainties on the order of 20% are typical for this probe. Fig. 2 shows a schematic diagram of measurement setup used for the experiment. A sinusoidal 13.56 MHz wave generated by a signal generator is modulated by a pulse wave generated by a pulse generator in order to produce an RF sinusoidal wave signal that periodically turns off. This signal is amplified by a broadband amplifier and then supplied to the center of the spiral induction coil via a matching circuit. The other end of the induction coil is electrically grounded. A trigger signal from the pulse generator is sent via a delay generator to the controller of the Langmuir probe. Since the computer can capture data in synchronization with the trigger signal, the plasma parameters can be measured at various times within the pulse period by changing the delay time set by the delay generator.

Unless particularly specified, the experiment was performed using a gas mixture of 20% O_2 and 80% Ar under the following conditions: a flow rate of 10 sccm (7.45 μmol/s), a pressure of 2.67 Pa, and an RF power of 200 W. Since the impedance matching of a load could not be tuned completely during the pulse modulation, the experiment was carried out under an impedance-matching condition set before the addition of pulse modulation. The power-off time of the RF supply (hereafter referred to as RF-off time) ranged from zero to 100 μs and the pulse frequency was 500 Hz (a period of 2 ms). For example, the duty cycle is 95% for 100-μs RF-off time and 97.5% for 50 μs. Usually, pulse-modulated plasmas are used with a duty cycle around 50%, but a very large duty cycle was selected for this experiment. Our aim was to ensure that the plasma in a particular pulse period would not be affected by the previous pulse, so we could clarify the behavior of the plasma in a particular pulse period.

III. RESULTS AND DISCUSSION

A. Basic Characteristics of ICP Cell

To understand the fundamental plasma characteristics of the ICP cell before making measurements of the pulse-modulated plasmas, plasma parameters under continuous discharge were investigated by changing the RF power. Fig. 3 shows the relationship between source RF power and electron density and plasma potential. It is clear from this figure that when the power is around 65 W, the electron density increases significantly but the plasma potential decreases. This tendency shows a transition from a capacitively coupled plasma generated by the high voltage of the coil (E mode) to an inductively coupled plasma in which electrons are accelerated by the induction electric field generated by the coil (H mode). The sudden decrease of plasma potential around 65 W indicates that the electron-heating mechanism changes from stochastic heating at the ion sheath to inductive heating. [13]

It is clear that the E-to-H-mode transition with increasing RF power occurs quite distinctly at relatively high power in the ICP cell used for the experiment. This is because it has a tightly wound induction coil and a lower electrode that lies near the coil. The plasma thus is generated at low powers between the coil (especially the center of the coil where the voltage of the coil is highest) and the lower electrode in E mode (like a parallel-plate plasma processing apparatus). The difference between plasma-generation position in E mode and that in H mode is another reason for the clear E-to-H-mode transition at relatively high power. Since RF power is supplied to the center of the spiral coil in the ICP cell, plasmas are generated just below the center of the quartz window in E mode. On the one hand, in H mode, the plasma is generated where the inductive electric field produced by the coil is the strongest, that is, a ring-shaped region between the center and the outer diameter of the coil. The plasma-generation position varies as the mode changes and this variation is a possible cause of the clear mode transition. On the other hand, in the case of a traditional inductively coupled plasma processing apparatus with a cylindrical chamber and a coil around the chamber, plasmas are generated along the chamber in both E and H modes. The E-to-H-mode transition in a chamber with a cylindrical external coil is thus made smoothly and no clear mode transition is observed. [14]

B. Pulse-modulated Plasmas (H mode only)

Fig. 4 shows behaviors of electron and ion density with time under an RF-off time of 50 μs. Both electron and ion density decrease when the RF-off time begins. However, the electron density does not decrease monotonically, and it tends to increase slightly after 15 μs. This increase indicates that the mechanism of electron loss and generation after the power shut-off is not simple. The slight increase of electron density around 15 μs might be caused by a reaction via Ar metastables. That is, a sudden fall of electron temperature in the afterglow promotes generation of Ar metastables.[15] It is reported that Ar metastable-metastable ionization reaction ($2Ar^* \rightarrow Ar^+ + Ar + e^-$) can produce electrons during an afterglow.[16] The electrons released by this metastable-metastable ionization reaction might be observed significantly around 15 μs with the decrease of the number of electrons generated by Ar ionization reaction ($Ar \rightarrow Ar^+ + e^-$).

As shown in Fig. 5, during the afterglow the electron temperature falls off faster than the electron density and saturates at a value about 0.6 eV. When the power is restored after the RF-off time, the electron temperature reaches a high of about 4.5 eV, and then gradually decreases, reaching a steady state at about 3 eV. The electron temperature is high just after the power is restored because the electron density decreased during the afterglow and thus energy is supplied to a small number of electrons. [9] With the lapse of time, as the electron density increases, the electron temperature settles around 3 eV, a typical value for inductively coupled plasmas under this condition. When RF-off time is 50 μs, the plasma is smoothly restored to a high density on the order of 1×10^{11} cm^{-3}, that is, to H mode, after the RF-off time.

C. Pulse-Modulated Plasmas (E-H Mode Transition)

Fig. 6 shows a transition of electron and ion density when RF-off time is 100 μs. Under this condition, a new phenomenon occurs: electron and ion densities continue to decrease even after the RF power is restored. The decrease in the electron and ion densities just after RF-off time is significantly more than that during the RF-off time. After that, the electron density slightly increases to around 1×10^{9} cm^{-3} and then suddenly increases after 1000 μs, restoring the plasma to H mode with the electron density on the order of 1×10^{11} cm^{-3}. It can thus be said that under this condition, a long E mode with low electron density occurs after the RF-off time.[10] This phenomenon, observed under many conditions, is considered hereafter.

A certain condition was required to return the plasma to H mode after the RF-off time. E mode seemed to occur if there was not enough electron density to sustain the plasma in H mode when the RF power is restored. To verify this supposition, we investigated whether H-mode plasma or E-mode plasma occurs after the RF-off time by varying the RF power, that is, by varying the electron density during the RF-on time. Fig. 7 plots the minimum electron density at the end of the afterglow necessary to avoid the prolonged E mode versus the RF-off time. As shown in Fig.7, in the range of RF-off time of 40 μs or more, H mode just after the RF-off time occurs in the electron-density range of more than 5×10^{10} cm^{-3}. For continuous discharge, an electron density of 2×10^{10} cm^{-3} is necessary to sustain H mode under the same gas and pressure conditions; in other words, the plasma will be lost or fall into E mode if we try to set its density to less than 2×10^{10} cm^{-3}. Therefore a slightly higher electron density is necessary to maintain H mode after the RF-off time for the pulse-modulated plasmas. This is because electron density continues to decrease for a while even after RF power is restored. The difference of plasma distribution between afterglow and continuous discharge is another reason. The electron density near the coil in the afterglow is lower than that in the continuous plasma even if electron densities at the probe position are the same.

The reason the electron density decreases significantly at the beginning of E mode is considered hereafter. The electron density just after RF-off time is about 1×10^{10} cm^{-3}, which is not enough to keep H mode but is much more than the density that can be sustained by E mode. Therefore, at the beginning of E mode, excess electrons are accelerated by the electric field of E-mode plasma and lost to the wall of the chamber. The electron density thus decreases significantly at the beginning of E mode and then increases gradually until the transition from E to H mode occurs.

Fig. 8 shows the behavior of electron temperature and plasma potential under the same experiment as Fig. 6. From 300 μs to 900 μs in E mode, plasma potential increases slightly as electron temperature tends to decrease slightly. Since plasma potential is in proportion to the electron temperature when the electron-energy distribution is Maxwellian, a reverse tendency as shown in Fig. 8 indicates that the electron-energy distribution is varying gradually in E mode. Since plasma potential is sensitive to electrons with high energy, it is clear that average electron temperature decreases and the number of electrons with high-energy increases in E mode.

Fig. 9 shows the transition of electron-energy distribution function (EEDF) in a pulse period. The EEDF was obtained from secondary differential of the electron-current curve against probe-voltage in Langmuir probe measurements. As shown in Fig. 9, it is clear that the EEDF varies gradually in E mode. A low energy peak exists in the first half of E mode. In general, plasmas containing negative ions have such a low energy peak.[17] However, although we have observed negative ions during the beginning of the E mode from a similarly behaving pulsed Ar/CF_4 discharge using a time-resolved mass spectrometer (Hiden EQP†), we could not detect any negative ions from these pulsed Ar/O_2 plasmas. Accordingly, it is considered that this peak is attributed to the residual electrons cooled in the afterglow rather than to the negative ions. As shown in Fig. 9, this peak becomes smaller and then disappears in E mode; then transition to H mode occurs.

As shown in Fig. 6 or Fig. 8, E mode continues as long as 1000 μs and returns to H mode suddenly. The plasma state gradually changes in E mode as shown in Fig. 9. The reason why the E-to-H-mode transition occurs suddenly is discussed hereafter.

The impedance matching circuit was optimized for the continuous discharge prior to the pulse modulation. Therefore, a certain amount of mismatching occurs when the power is restored after the afterglow because the plasma, that is, the load impedance, varies during the afterglow. Consequently, a certain amount of reflected power occurs at this time, so net power is reduced from 200 W by the mismatching. If this power provides enough electron density to sustain H mode, the plasma reverts to H mode. If the electron density is low, however, the plasma falls into E mode. Consequently, mismatching further increases and the net power further decreases. During E mode, for example, due to a change of plasma states like that of electron energy described above, mismatching is gradually reduced and, accordingly, the density increases gradually. And it seems that when the density reaches a high enough value to make the plasma jump up to H mode, the transition occurs. In the ICP cell, even in normal continuous discharges, the density is low in E mode and the E-to-H-mode transition is clear and the mode transition occurs at relatively high power. Such plasma characteristics are the reasons that the ICP cell has a long E mode after the RF-off time.

Though such an E-to-H-mode transition occurs under many conditions, the duration of the E mode could not be reproduced with the same experimental conditions. Since the chamber is used not only for Ar and O_2 but also for plasma experiments with perfluoro-carbon (PFC) gases, which are easy to deposit on the chamber wall, we considered the surface condition of the chamber has an influence on the time of E mode. Accordingly, the time of E mode was compared with three cases: (a) the chamber was badly contaminated due to deposition of PFC plasmas; (b) the deposit on the lower electrode is removed; and (c) the whole chamber was cleaned and the deposit was completely removed from the entire chamber. Fig. 10 plots the zero-to-peak voltage of the coil against time. The higher voltage corresponds to E mode. Since absorption of power by the plasmas in E mode is difficult, actual resistance of the load decreases and both current and voltage increase under the same RF power. As shown in Fig. 10, the cleaner the chamber is, the longer E mode continues. This is because, a cleaner chamber loses more electrons to its surface in the afterglow.

Thus, a lower electron density in E mode makes the E-to-H-mode transition later, because it takes a longer time to increase the electron density in E mode. Since the balance of charged particles in the chamber varies dramatically during the pulse period, the surface condition of the chamber has an extremely great influence on the E-to-H mode transitions.

IV. CONCLUSIONS

Pulse-modulated inductively coupled plasmas during a pulse period were measured using a Langmuir probe. The ICP cell used for the experiment shows a very clear E-to-H-mode transition with an increase of RF power during continuous discharge. By adding pulse modulation under a certain discharge condition (a mixture of 20% O_2 and 80% Ar, a pressure of 2.67 Pa, an RF power of 200 W, a pulse frequency of 500 Hz, and an RF-off time of 100 μs), a very long E-mode discharge of 1000 μs after the RF-off time and an E-to-H-mode transition was observed. In a shorter RF-off time of 50 μs, the plasma reverted to H mode without passing through E mode. Whether H mode or E mode occurs depends on the electron density at the end of the afterglow; that is, when the power is restored after the RF-off time. It was found that the restoration to H mode after the RF-off time occurs if there is an adequate electron density and that E mode occurs if electron density is not high enough to sustain H mode.

It was also found that electron temperature decreases and plasma potential increases gradually in E mode because of the change of the EEDF. A slight change of the plasma density reduces the impedance mismatching gradually, and when the electron density is high enough, transition to H mode occurs.

The time of E mode strongly depends on the wall condition of the chamber: the cleaner the chamber the longer time of E mode. Because a clean chamber loses more electrons from its surface in the afterglow; consequently, the electron density becomes low in the beginning of E mode, and longer time is necessary to increase the electron density in E mode.

An inductively coupled plasma processing apparatus is usually designed only for operation in H mode. However, pulse modulation requires plasma processing apparatus that can discharge smoothly from low to high power. Accordingly, designing plasma processing apparatus for pulse-modulated plasmas is more difficult than designing that for continuous plasmas. Besides, in the pulse-modulated plasmas, the balance of charged particles in the reactor varies greatly during the pulse period, and the surface condition of the reactor has a great influence on the pulse-modulated plasmas. Therefore, they are more sensitive to the surface condition of the reactor as compared with continuous plasmas. In addition, there is a high possibility that process reproducibility will become an issue in the actual processes for manufacturing large scale integrated circuits (LSIs) in which the wall condition varies as the wafer processing is carried out repetitively.

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† Certain commercial equipment, instruments or materials are identified in this paper to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Figure Captions

FIG. 1. Schematic diagram of the ICP cell.

FIG. 2. Schematic diagram of the experimental setup for measurement of pulse-modulated plasma by using a Langmuir probe.

FIG. 3. Plasma characteristics of the ICP cell in a continuous discharge (20% O_2:80%Ar at 2.67 Pa).

FIG. 4. Electron (Ne) and ion density (Ni) in a pulse period with only H mode (RF-off time = 50 μs).

FIG. 5. Electron temperature (Te) and plasma potential (Vp) in a pulse period with only H mode (RF-off time = 50 μs).

FIG. 6. Electron (Ne) and ion density (Ni) in a pulse period with E-to-H-mode transition (RF-off time = 100 μs).

FIG. 7. Minimum electron density at the end of the afterglow in order to avoid the prolonged E mode versus the RF-off time.

FIG. 8. Electron temperature (Te) and plasma potential (Vp) in a pulse period with E-to-H-mode transition (RF-off time = 100 μs).

FIG. 9. Transition of electron-energy distribution function (EEDF) in a pulse period (RF-off time = 100 μs).

FIG. 10. E-to-H mode transitions for three conditions of the chamber and the lower electrode: (a) the chamber and the lower electrode were badly contaminated due to deposition of PFC plasmas (RF-off time = 100 μs, pulse frequency = 500 Hz); (b) the chamber was contaminated and the deposit on the lower electrode was removed (RF-off time = 100 μs, pulse frequency = 500 Hz); and (c) the chamber and the lower electrode were completely cleaned (RF-off time = 100 μs, pulse frequency = 200 Hz).

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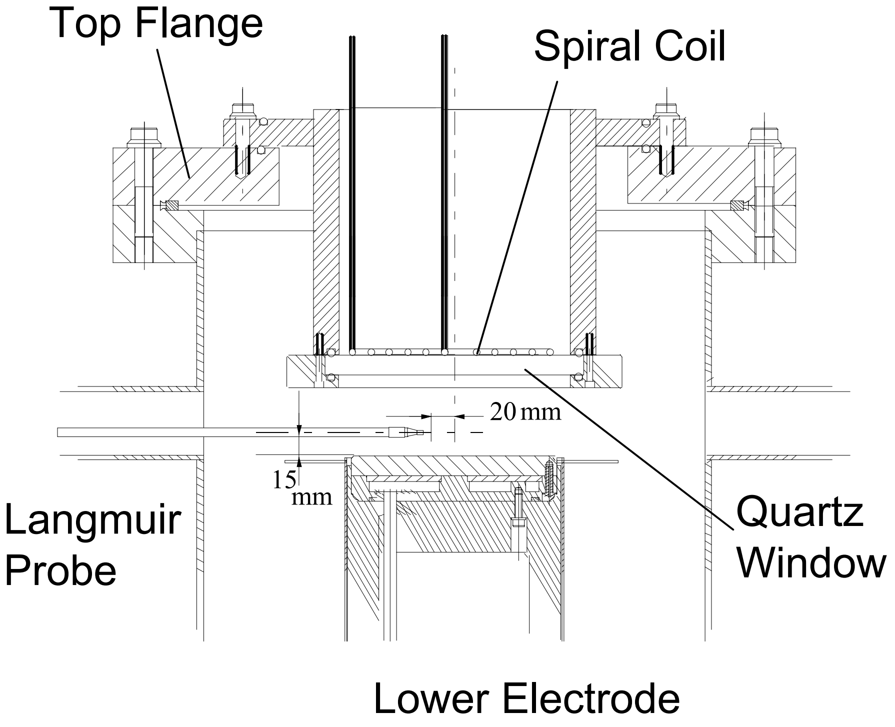
Top Flange
Spiral Coil
20 mm
15 mm
Langmuir Probe
Quartz Window
Lower Electrode

Fig. 1

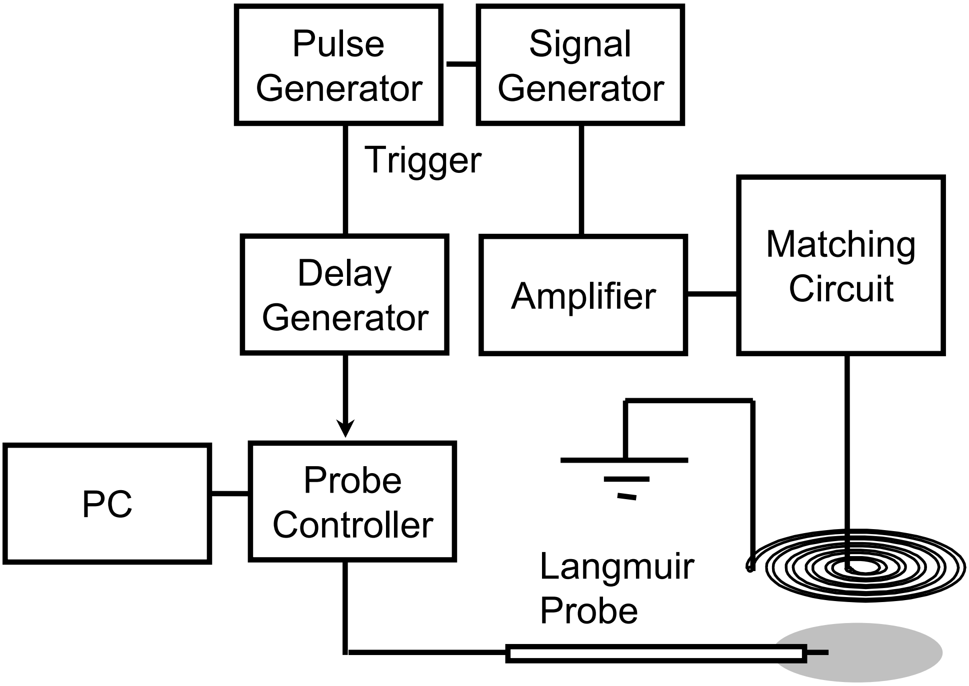
Pulse Generator
Signal Generator
Trigger
Delay Generator
Amplifier
Matching Circuit
PC
Probe Controller
Langmuir Probe

Fig. 2

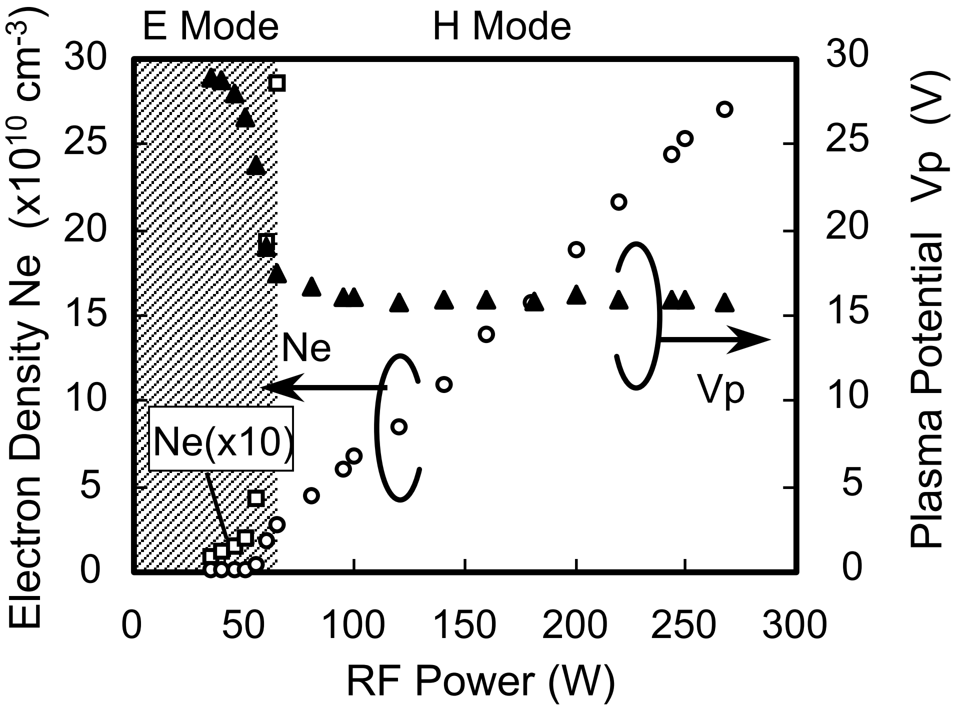
E Mode
H Mode
Electron Density Ne (x10^{10} cm^{-3})
Plasma Potential Vp (V)
RF Power (W)
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Ne
Vp
Ne(x10)

Fig. 3

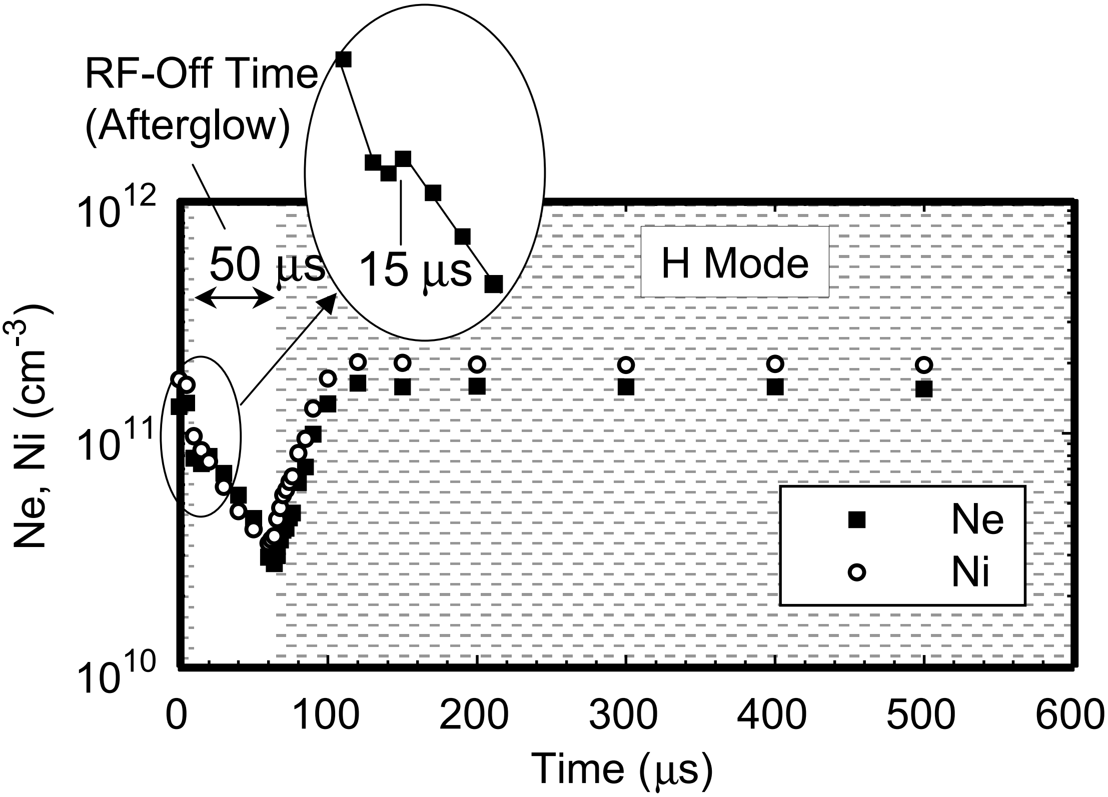
RF-Off Time
(Afterglow)
50 μs
15 μs
H Mode
10^{12}
10^{11}
10^{10}
Ne, Ni (cm^{-3})
0
100
200
300
400
500
600
Time (μs)
Ne
Ni

Fig. 4

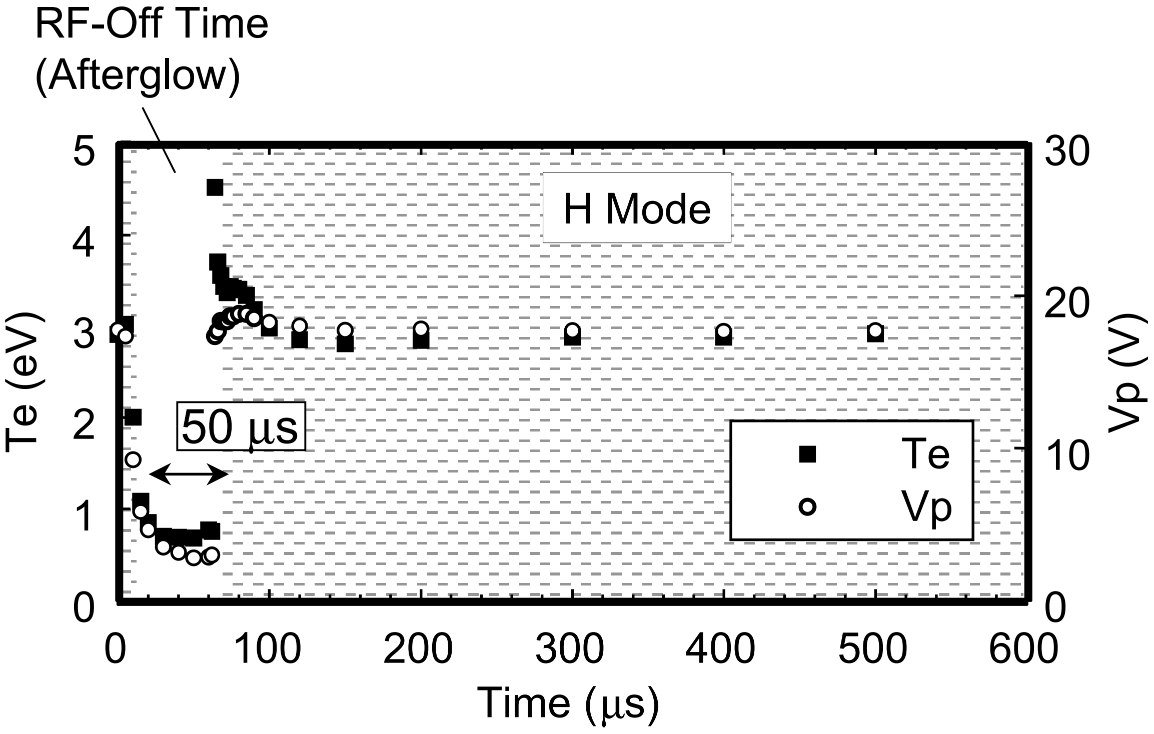
RF-Off Time
(Afterglow)
H Mode
50 μs
Te
Vp
Te (eV)
Vp (V)
Time (μs)
0
1
2
3
4
5
10
20
30
100
200
300
400
500
600

Fig. 5

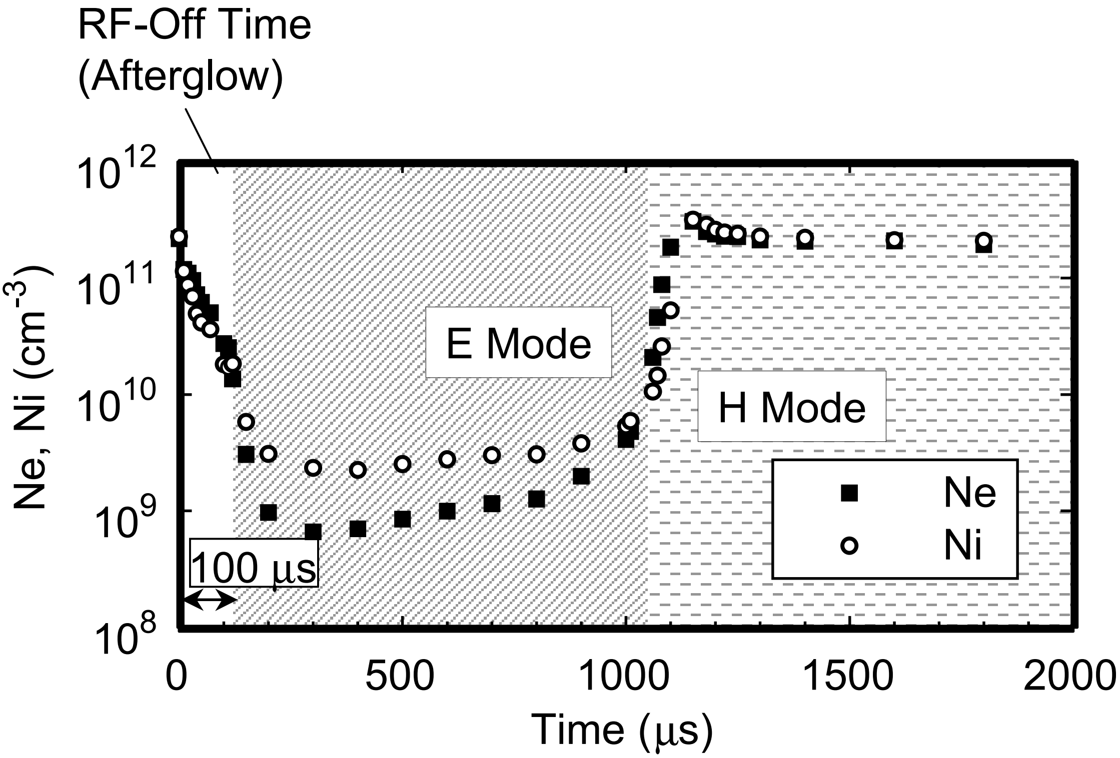
RF-Off Time
(Afterglow)
E Mode
H Mode
100 μs
Ne
Ni
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
Ne, Ni (cm^{-3})
0
500
1000
1500
2000
Time (μs)

Fig. 6

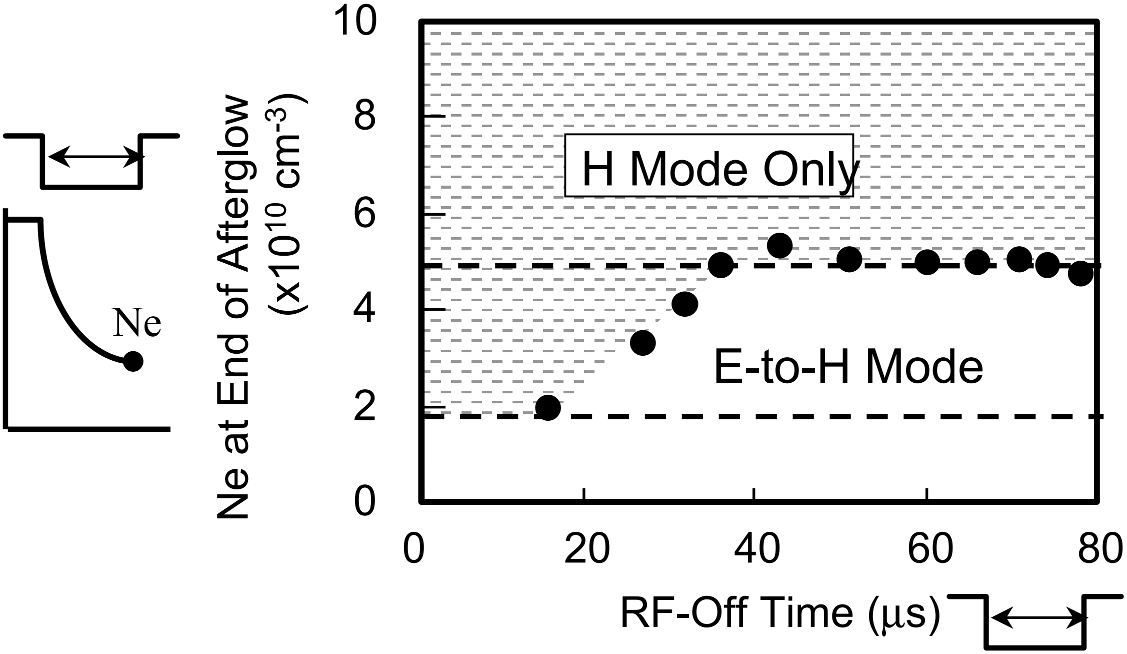
Ne
Ne at End of Afterglow (x10^10 cm^-3)
10
8
6
4
2
0
H Mode Only
E-to-H Mode
0
20
40
60
80
RF-Off Time (μs)

Fig. 7

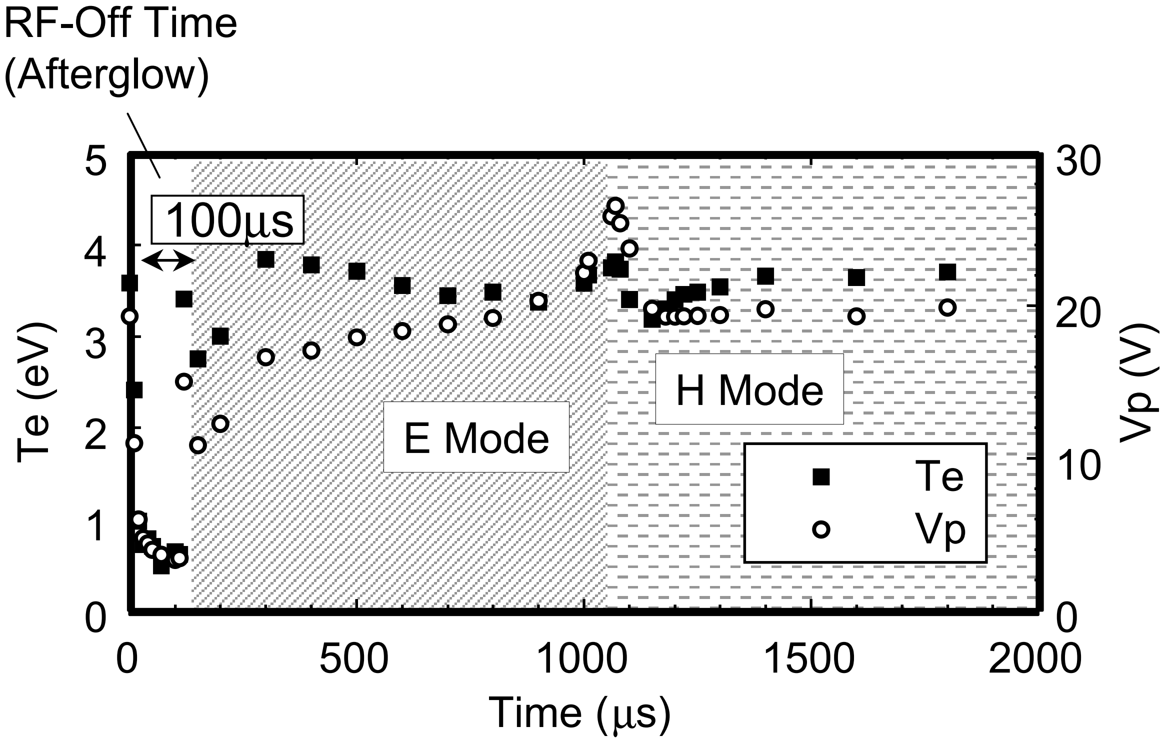
RF-Off Time
(Afterglow)
100μs
E Mode
H Mode
Te
Vp
Te (eV)
Vp (V)
Time (μs)
0
1
2
3
4
5
0
10
20
30
0
500
1000
1500
2000

Fig. 8

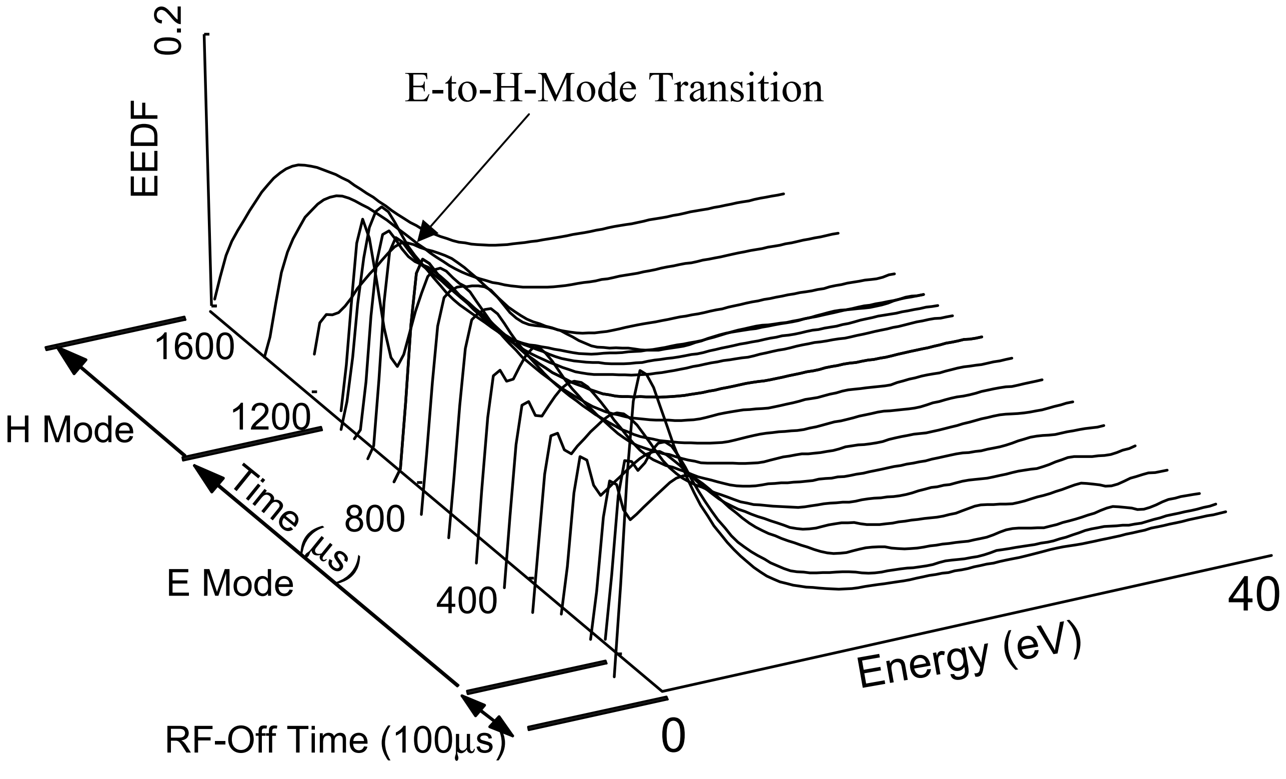
0.2
EEDF
E-to-H-Mode Transition
1600
1200
800
400
H Mode
Time (μs)
E Mode
RF-Off Time (100μs)
0
40
Energy (eV)

Fig. 9

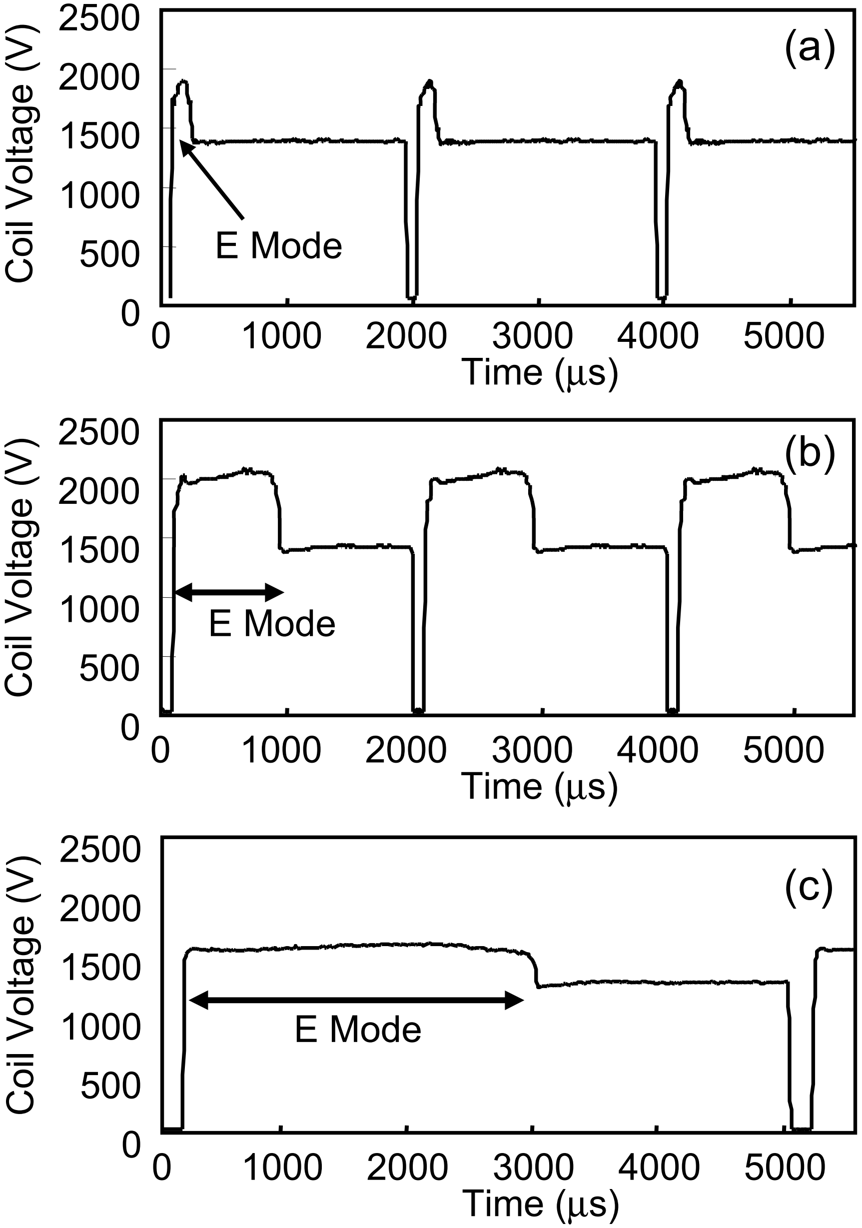
(a)
Coil Voltage (V)
2500
2000
1500
1000
500
0
E Mode
0
1000
2000
3000
4000
5000
Time (μs)
(b)
Coil Voltage (V)
2500
2000
1500
1000
500
0
E Mode
0
1000
2000
3000
4000
5000
Time (μs)
(c)
Coil Voltage (V)
2500
2000
1500
1000
500
0
E Mode
0
1000
2000
3000
4000
5000
Time (μs)

Fig. 10