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Characteristics of bistable transition in magnetized plasma by control of voltage biasing

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Abstract

Applying a dc or a pulsed voltage on the end plate in a magnetized plasma, self-excited bistable transitions and back ones in the plasma density and potential had been investigated. During a transition, the bias current and plasma parameters near the electrode changed with a fast time scale of less than a few tens of microseconds, while the bulk plasma transition time ranged from a few hundreds of microseconds to a few milliseconds. The probability distribution function (PDF), staying time probability and its PDF in one of two states of ion saturation current showed the hysteresis characteristics by increasing and decreasing the bias voltage.

Keywords: Magnetized rf plasma; Voltage biasing; Plasma profile; Density transition; Hysteresis

1. Introduction

To generate and sustain plasmas in a controlled manner in time and space is crucial in various fields such as the plasma application as well as the fundamental plasma. If the control of the plasma with good stability is not established, e.g., quantifying plasma parameters for fabricating materials is not reliable. Generally, the spatio-temporal behavior of the plasma is nonlinearly governed by the plasma generation and diffusion mechanisms, which are influenced by instabilities. The intrinsically nonlinear characteristics of the plasma exhibit various interesting phenomena showing the self-organized structural formation during a transition and a bifurcation, e.g., [1–9].

However, there have been few experiments from a basic viewpoint to study these transitions as well as to control the density and rotation profiles by imposing electric fields. In this paper, detailed characteristics of the self-excited bistable transition phenomena [10,11] have been investigated with a final goal to understand the transition mechanism related to the stable plasma operation. Here, we controlled the bias voltage (dc or pulse) applied to an inserted electrode in a rf-produced, magnetized plasma to see the plasma response, including hysteresis characteristics.

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2. Experimental setup

Argon plasma was produced by a four-turn spiral antenna [12,13] at a typical pressure of $P_0=1-3$ mTorr. The continuous rf power and frequency of 160 W and 7 MHz, respectively, were applied to a linear device, 45 cm in outer diameter and 170 cm in axial length, with the magnetic field of 500 G, as shown in Fig. 1(a). Here, $x(z)$ is taken along the radial (axial) direction. In order to control the radial potential profile, we used 10 concentric, segmented rings as biased electrodes [10,11]. Mostly, the no. 3 electrode (radius is 3.7–6 cm) was used in the present experiment.

The spatial plasma parameters were measured by various Langmuir probes. In addition, we installed a 24-channel probe array as well as three-dimensional moving system [14] near the electrode region. The typical target (before biasing) plasma density n_e was in the range of $4\times10^9-2\times10^{10}$ cm^{-3} with the electron temperature $T_e=3-6$ eV, and estimated ion temperature <1 eV.

3. Experimental results

Fig. 2 shows an example of the time evolution of the bias current I_b and the ion saturation current I_{is} measured at $x=9$ cm and $z=60$ cm, on changing bias voltage V_3 (voltage at the no. 3 electrode) with other electrodes being at a floating potential. Here, P_0 was 2.1 mTorr and five traces showed

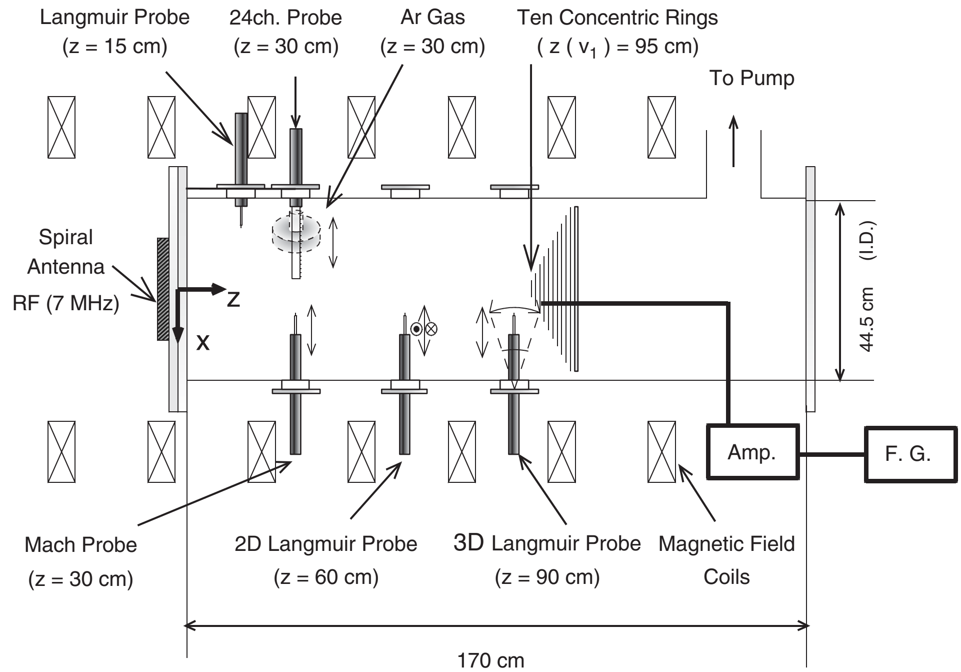

Fig. 1. Schematic view of experimental setup.

different shots. For the case of low bias voltage (less than ~160 V), no n_e change was observed (state I). Here, n_e is considered to be nearly proportional to I_{is} since T_e did not change appreciably, and $I_{is}=1$ corresponded to $n_e=2.8\times10^9$ cm^{-3} for the case of $T_e=5$ eV. From this figure, with the

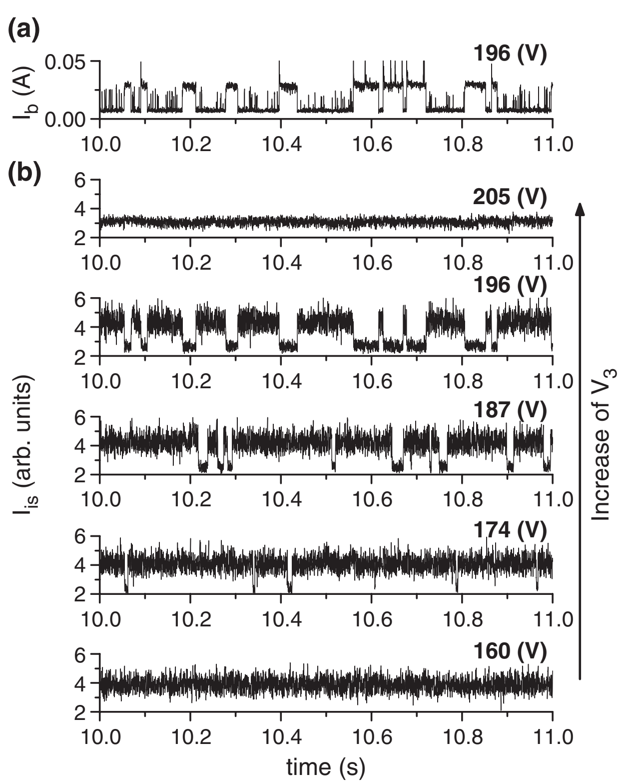

Fig. 2. Time evolution of (a) bias current I_b and (b) ion saturation current I_{is}, changing bias voltage V_3. Here, individual traces have different shots.

increase of V_3, an increased number of transitions from the higher (state I) to the lower (state II) states was found, in addition to back transitions from state II to state I: density oscillation (self-excited transitions) between two states (bistable system). Finally, with a further increase of V_3 ($\geq$205 V), there appeared a lower n_e state, which is stationary with time, i.e., state II only, without back transitions to state I. This bistable system is qualitatively analogous to the double well or the Schmidt trigger, but this model must be modified due to the presence of the hystereses in a stochastic sense [11] which will be described later.

Fig. 3 shows an example of the spatio-temporal behaviors of I_{is} and the floating potential V_f, measured by the 24-channel probe. Near the electrode region, dips of I_{is} and V_f, were observed [11]. The transition time T_{tr} between two states was dependent on the spatial region, and it was typically less than a millisecond and approximately a few milliseconds for I_{is} and for V_f, respectively. On the other hand, T_{tr} was less than a few tens of microseconds for the bias current as well as for V_f and I_{is} near the electrode region. This time was much shorter than those for I_{is} and V_f in the bulk region, which showed the importance of the sheath, electrode region to trigger the transitions: The potential structure changed [15] in this region due to some instabilities, coming from the two-dimensional ion motion and field-aligned electron one.

Pulsed voltage biasing to the electrode was tried to see the dynamic plasma response, as shown in Fig. 4. Here, the bias voltage is 10 times of the function generator voltage. Although I_b could follow change of the short voltage pulse, I_{is} could not change fully from state I to state II with the pulse width less than approximately a millisecond, due to the

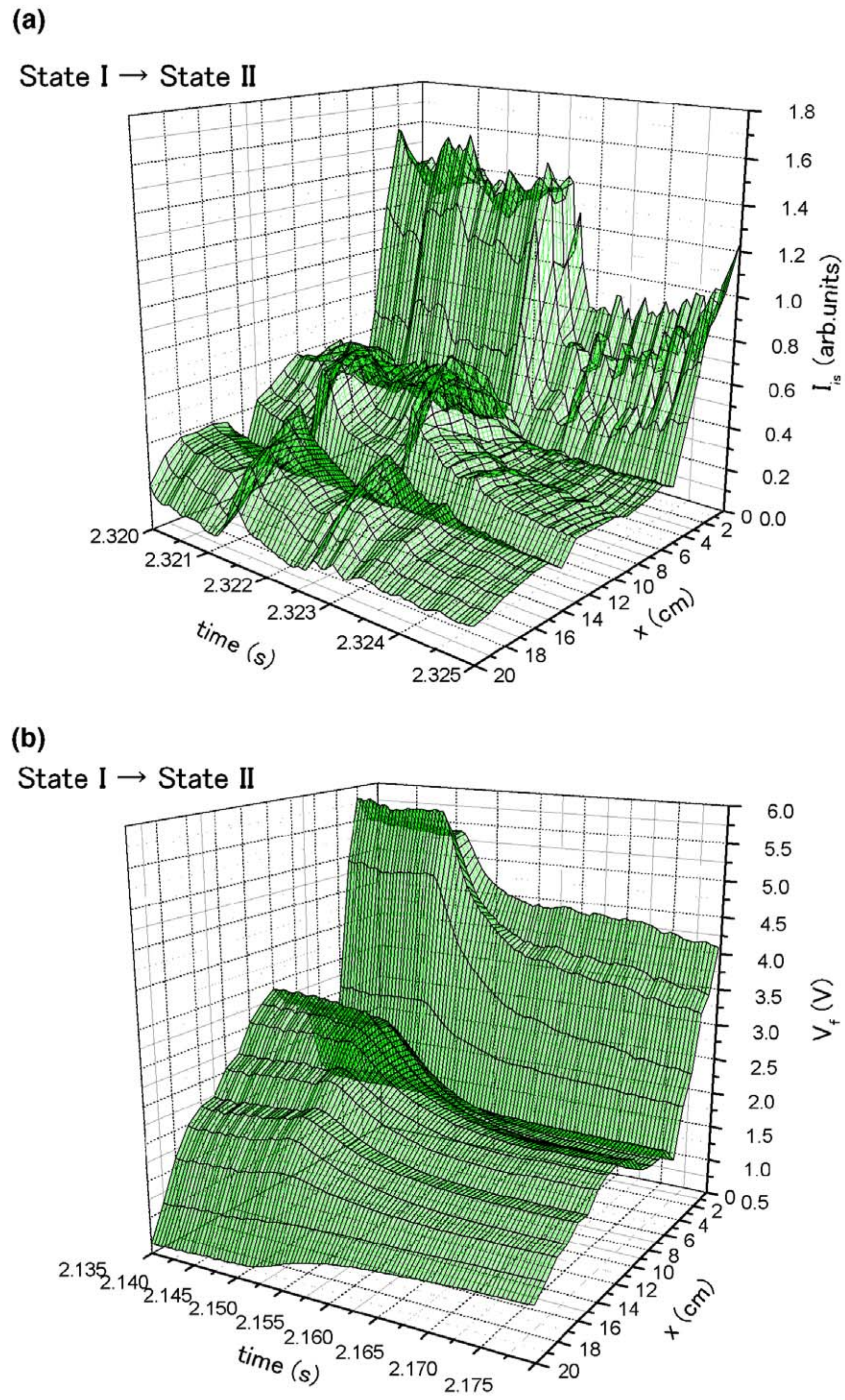

Fig. 3. Spatio-temporal behaviors of (a) ion saturation current I_{is} and (b) floating potential V_f, measured by the 24-channel probe.

different response time represented as T_{tr} described above. Even the pulse width was as short as a few microseconds, I_b could change from the low (high) to high (low) levels. A detailed measurement of I_b showed the fast peak with less than approximately a microsecond followed by a fast decay into the steady state within a few microseconds during the transition from state I to state II, with a single-step function of the bias voltage (not shown).

Next, stochastic hysteresis behaviors were investigated, as was partly described in Ref. [11]. Fig. 5 shows the probability distribution function (PDF) of I_{is} by first increasing and then decreasing V_3. Here, the voltage swing range satisfied the region from the state I only with high I_{is} value [Fig. 5(a) and (i)] to state II only with low I_{is} value [Fig. 5(e)]. In the increasing phase, the probability to have state I (state II) was higher (lower) than that in the decreasing phase. This can also be seen in Fig. 6(a), which showed the higher staying time probability at state II in the decreasing phase than that in the increasing phase. Note that there was no hysteresis in the case of insufficient voltage

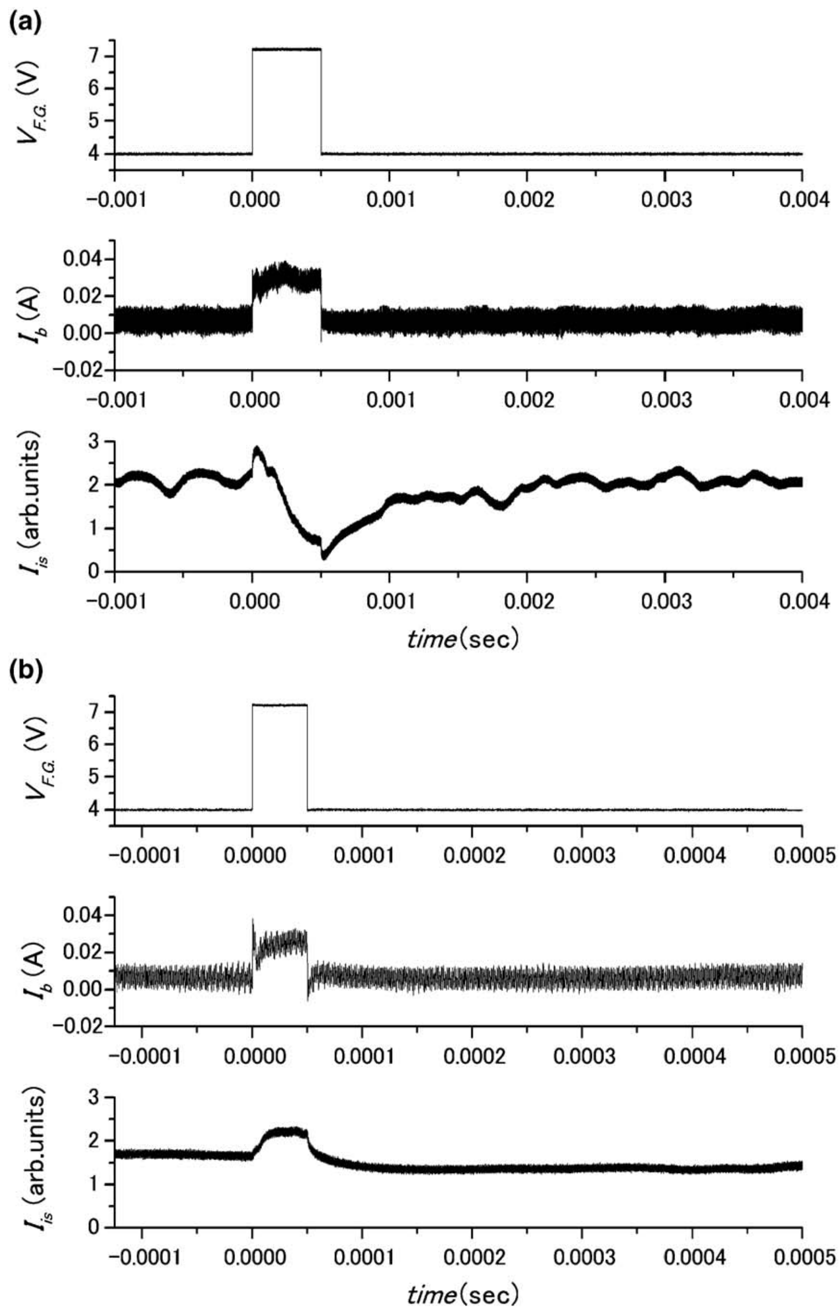

Fig. 4. Time evolutions of (a) function generator voltage for biasing, (b) bias current I_b and (c) ion saturation current I_{is} in the cases of pulse width of (a) 500 μs and (b) 50 μs.

swing as shown in Fig. 6(b), where the highest voltage did not lead the state II only. Fig. 7 shows the PDF as a function of the staying time at state II by increasing and decreasing V_3 (the same condition as Fig. 5). With the increase of V_3, the PDF extended to the longer staying time, whose spread was narrower than that in the decreasing phase. These behaviors are completely different from the hysteresis observed in dc discharges, and these may be understood by, e.g., fine spatial structure changes, hidden parameters or some memory effects.

Finally, in order to check the fine structure change, the PDF as a function of I_{is} was measured from the low bias voltage region, which is well below the typical bias voltage observed at state I only, to the higher voltage region, as shown in Fig. 8. Here, a monotonic increasing voltage was applied. First, as shown in Fig. 8(a), the PDF takes the higher value of I_{is} compared to that at state I only. With increasing the voltage from Fig. 8(a) to (c), the PDF became wider and then there appeared two peaks: One had the value of the typical one at state I and another showed a small peak at the higher value side. Further increase of the voltage, as shown in Fig. 8(e) and (f), showed the same behavior as was described before: transitions between state I and state II.

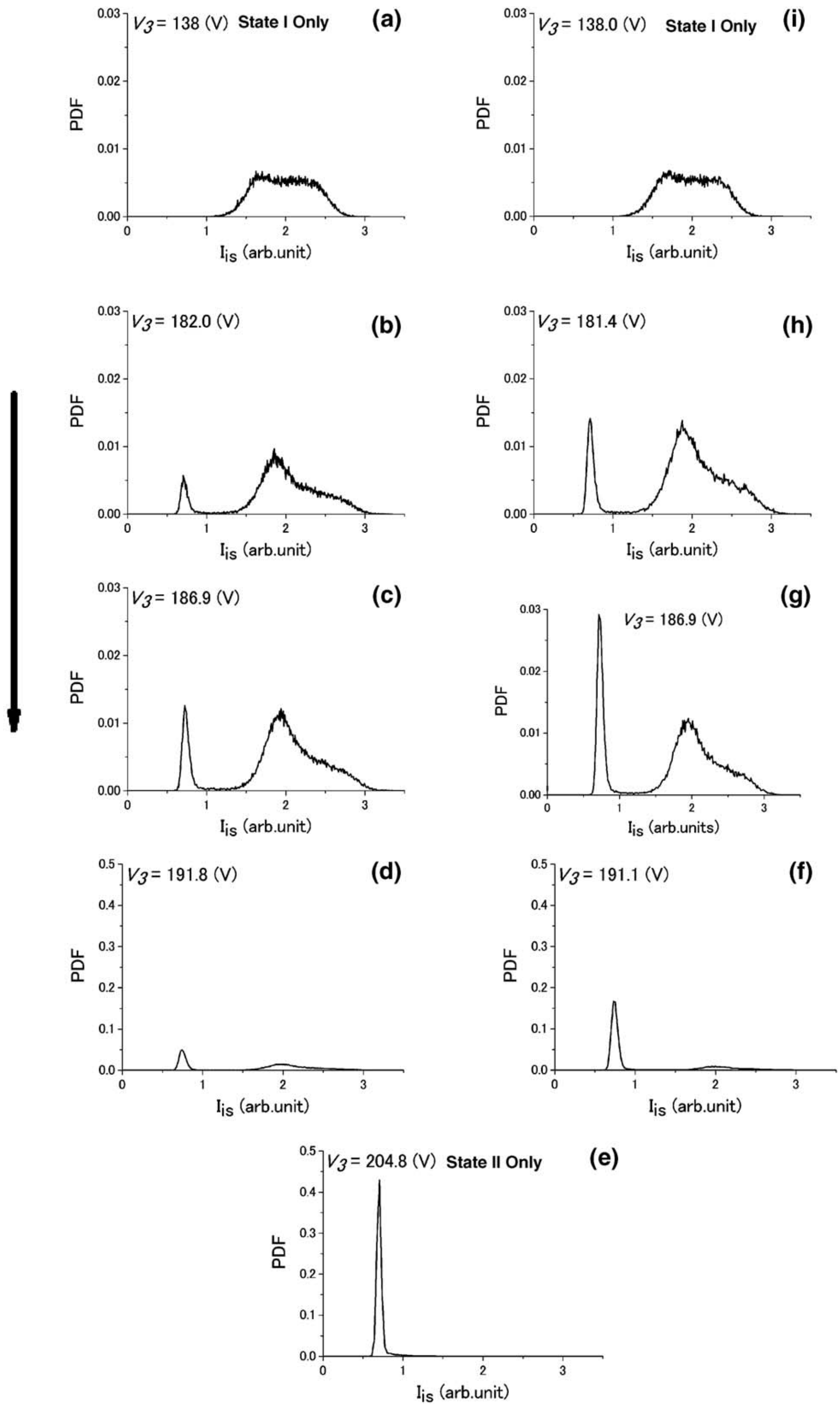

Fig. 5. Probability distribution function of ion saturation current I_{is} by increasing and decreasing bias voltage V_3.

4. Conclusions

Applying a dc or a pulsed voltage on one of the segmented end plates in a magnetized rf-produced plasma, detailed characteristics of bistable transitions have been investigated. During a transition, the bulk plasma transition time ranged from few hundreds of microseconds to few milliseconds, while the bias current and plasma parameters near the electrode changed with a fast time scale of less than a few tens of microseconds, which showed the important role of the sheath

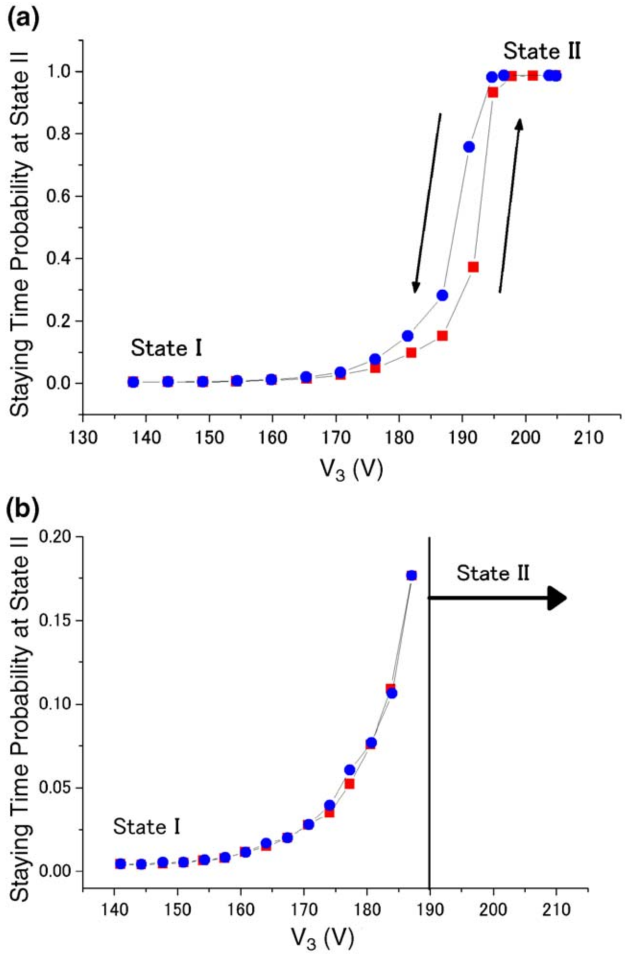

Fig. 6. Hysteresis curves of staying time probability at state II as a function of bias voltage.

region. The PDF, staying time probability and its PDF in one of two states of ion saturation current showed the hysteresis characteristics by swinging the bias voltage. This PDF was also investigated from the low bias voltage.

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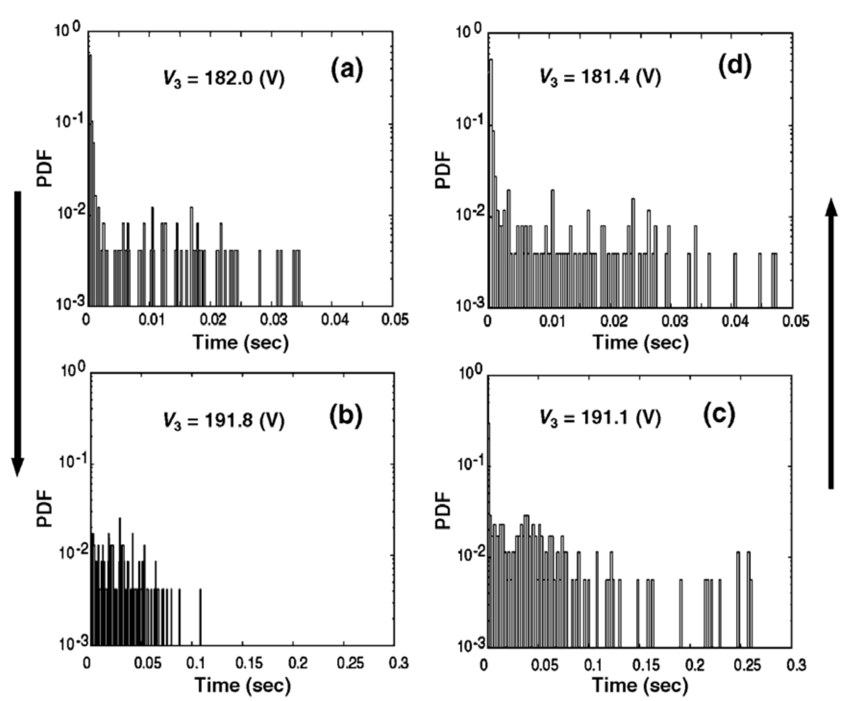

Fig. 7. Probability distribution function of staying time at state II by increasing and decreasing bias voltage V_3.

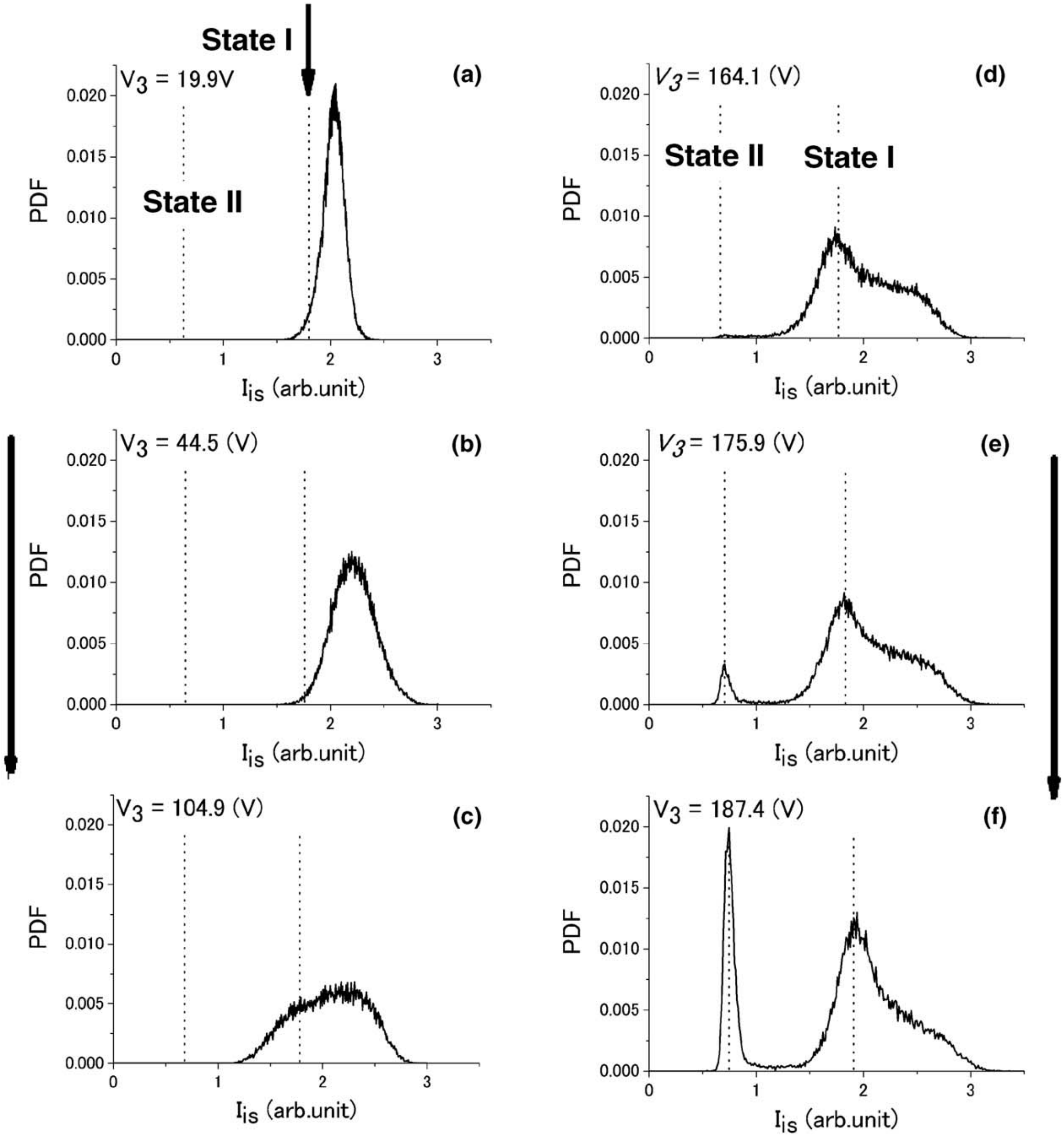

Fig. 8. Probability distribution function of ion saturation current I_{is} by increasing bias voltage from the low voltage V_3.