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A Relation between Current-Driven Ion-Acoustic Instability and Potential-Relaxation Instability Excited by a Positively Biased Electrode in a Plasma

IIZUKA Sotoru*, TAKADA Kenichi and SATO Noriyoshi
Department of Electrical Engineering, Tohoku University, Sendai 980-8579, Japan

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Abstract

Properties of the instabilities excited by a positively biased electrode in a dc-discharge plasma are systematically investigated. There appear two types of the instabilities. The one is so-called current-driven ion-acoustic instability and the other is potential-relaxation instability. We find that the former instability appears at the potential lower than the threshold for the latter one as the potential applied to the electrode is increased. It is also clarified that the phase difference of the electrode current against a grounded mesh-anode current is nearly out of phase. The excitation mechanisms of these instabilities are discussed in detail.

Keywords:
current-driven ion-acoustic instability, potential-relaxation instability, current-carrying plasma, ion-acoustic wave, moving double layer

1. Introduction

Ion-acoustic instabilities in collisionless plasma have received considerable attention theoretically and experimentally [1-5]. It has long been understood that the electron drift in a current carrying plasma can transfer energy to the ion-acoustic mode. This kind of instabilities was observed in a mercury-vapor discharge tube [1,2]. Assuming the wavelength of the n-th harmonic waves to be equal to L/n, where L is distance between the grid and anode, then a dispersion relation with a property of the ion-acoustic wave was obtained. On the other hand, there was also observed an instability (potential-relaxation instability) characterized by a large-amplitude oscillation [6-8] for positively-biased electrode system. This instability was accompanied by a moving space-charge double layer. The period of the instability is almost determined by the transit time of plasma expansion with ion-acoustic velocity. From these comparisons both instabilities have a quite similar property for the excitation condition and wave propagation. Fujita et al. investigated these instabilities in detail under various experimental situations in discharge plasmas and found that the electron current subtracted by the grid was important for distinguishing these instabilities [7,9,10]. However, the excitation mechanism was still unclear in relation with the role of the grid that determined the boundary conditions for the wave propagation.

In this paper we experimentally clarify the detailed relations between the ion-acoustic instability and the potential-relaxation instability, which are excited by a positively biased electrode in a dc discharge plasma. The boundary conditions are also investigated and the excitation mechanisms are discussed.

2. Experimental Apparatus

The experiment is carried out in a dc plasma

*Corresponding author's e-mail: iizuka@ ecei.tohoku.ac.jp

produced by a discharge between hot cathode and mesh anode in weak magnetic field applied in axial direction. The magnetic field employed here is weak, so the property of instabilities is unchanged. The layout of the experimental apparatus is shown in Fig. 1. The mesh anode of 70 mm in diameter, made of 7 mesh/inch stainless wires, is grounded. Working gas is argon at 1.0 $\times 10^{-4}$ Torr. The plasma is produced by applying –50 V to the hot cathode of 60 mm in diameter with respect to the anode. The plasma diffuses out through the mesh anode along the magnetic field of 25 G toward an end plate at floating potential placed at 65 cm from the anode. The experiment is mainly carried out in the diffusion plasma region between the mesh anode and end plate. In order to excite the instabilities, we place a grid of 50 mm in diameter, made of 2 mesh/inch stainless wires, at grounded potential and a collector of 50 mm in diameter, made of 2 mesh/inch stainless wires, to which dc bias voltage V_C is applied externally. Distance L between the grid and collector is changed in the range 10–30 cm.

The plasma parameters are measured by a usual Langmuir probe. Typical electron density and temperature are $n_p \sim 5.0 \times 10^8$/cm^3 and $T_e \sim 2$ eV, respectively. The discharge current is $I_d \sim$ 50–100 mA. The fluctuation signal of the collector current detected through resistance of 500 Ω is analyzed by oscilloscope and spectrum analyzer. The cross-correlation function and phase difference between the grid and collector current signals are analyzed by FFT analyzer.

3. Experimental Results and Discussions

Typical characteristic curve of collector current I_C and potential V_C is shown in Fig. 2. Here, L = 18 cm. As V_C is increased, I_C varies like a usual probe characteristics. However, as shown more clearly in the inserted figure in Fig. 2, a small current depression is observed around $V_C \sim$ 22 V. Here, we define the potential V_{cri} as a critical potential for the current

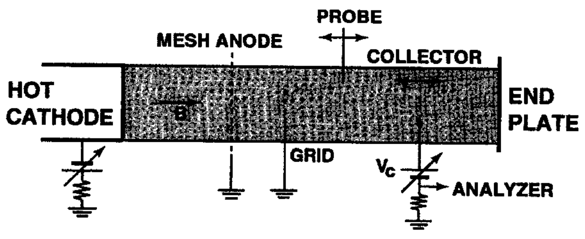

Fig. 1 Schematic of experimental apparatus.

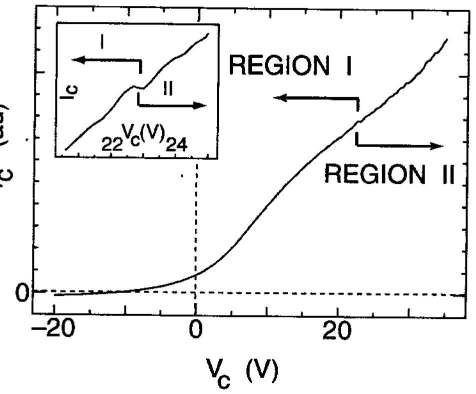

Fig. 2 Dependences of collector current I_C and ratio $\tilde{I}_C/I_C$ on collector potential V_C.

depression. Henceforth, V_C is divided into two regions, i.e. region I for $V_C < V_{cri}$ and region II for $V_C > V_{cri}$. We also measure the amplitude ratio of I_C fluctuation to the dc component $\tilde{I}_C/I_C$ as a function of V_C. It is shown that the current fluctuation level drastically changes around V_{cri}. In region I no remarkable fluctuation is observed when $V_C <$ 5 V. However, when $V_C >$ 5 V we observe a weak fluctuation with a level of 1~2 %. On the other hand, in region II the fluctuation level increases up to more than 10 % and almost saturates for $V_C >$ 30 V. These properties are quite similar to those in previous works [7,10].

The current depression described above is related with the potential variation in front of the collector. In region I, since $V_C < V_S$ (space potential), the electron current is partially suppressed by the potential barrier at the collector. Some part of electrons can pass through this barrier toward the collector. Because the barrier potential becomes small with increasing V_C, I_C increases with V_C. However, when $V_C > V_S$, almost all electrons are subtracted by the collector, leading the plasma column unstable to form a potential dip at the grid, then the current depression takes place [6]. This situation has very close relation with the current-driven ion-cyclotron instability and potential relaxation type of ion-cyclotron instability excited by a small positively-biased electrode in a magnetized plasma [11,12]. Much electron current flowing toward the electrode along the magnetic field breaks two-dimensional potential structure in front of the electrode.

The frequency spectrum of I_C fluctuations is observed at the same time. It turns out that in region I there appears a quite broad spectrum near the onset of the fluctuation at $V_C \sim$ 5V. With further increasing V_C, fine multiple-peaks, super-imposed with the background broad spectrum, are coming out. A typical spectrum at V_C = 25 V is shown in Fig. 3(a), in which we can recognize that the frequency difference between adjacent peaks diminishes with an increase in the frequency. Assuming the wavelength of n-th harmonics to be equal to L/n, then a dispersion relation with a property of the ion-acoustic wave is obtained. Here, the ion plasma frequency is $\omega_{pi}/2\pi \sim 750$ kHz. The phase velocity of the wave in the long wavelength regime is $\sim 2.8 \times 10^5$ cm/s, which is comparable to the ion-acoustic velocity of $C_S \sim 2.2 \times 10^5$ cm/s. This property is well consistent with the previous results [1,7,10].

A typical frequency spectrum in region II is shown in Fig. 3(b) for V_C = 30 V, in which multiple-peaks are clearly observed. Taking account of the similar assumption for the n-th frequency peak, the dispersion relation shows a non-dispersive relation, since the frequency differences between adjacent peaks are constant. The phase velocity of the wave in this case is $\sim 3.1 \times 10^5$ cm/s, which is also comparable to the ion-acoustic velocity.

The frequency of both kind of fluctuations varies almost inversely proportional to L, i.e. $\omega \propto 1/L$. Therefore, the boundaries at the grid and the collector seem to be very important for the wave excitation and propagation. In order to clarify the roles of these boundaries we measure the cross-correlation function (coherence) and the phase difference between I_G and I_C fluctuations under various conditions. Figure 4(a) shows the coherence in region I, where we find broad spectrum just as in Fig. 3(a). The phase difference is shown in Fig. 4(b). Here, we find that the phase shift is nearly ~140 degree, roughly out of phase for $\omega/2\pi > 40$ kHz. This implies that an increasing phase of I_G fluctuation corresponds to a decreasing phase of I_C fluctuation. The cross-correlation function and the phase between I_G and I_C fluctuations are also measured in region II. It is found that the phase shift is also nearly out of phase.

In order to discuss the phase relation between I_G and I_C fluctuations in region I we measure the variation of dc components of those currents as a function of V_C as shown in Fig. 5. As V_C is increased, I_C increases simply and saturates at higher V_C regime. On the other hand, the variation of I_G is completely opposite. Therefore, total current $I_C + I_G$ is kept constant and almost independent of V_C. This means that the electron loss flux flowing behind the anode region, which is restricted mainly in axial direction due to the axial magnetic field, is almost conserved because of the constant plasma-production rate in the cathode and anode region.

Taking account of these facts, the following model is considered. When the positive potential is applied to

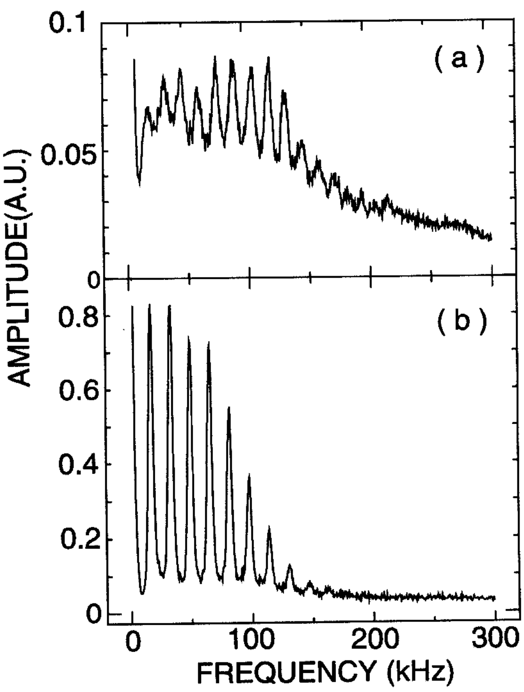

Fig. 3 Frequency spectra at (a) V_C = 20 V and (b) V_C = 30 V.

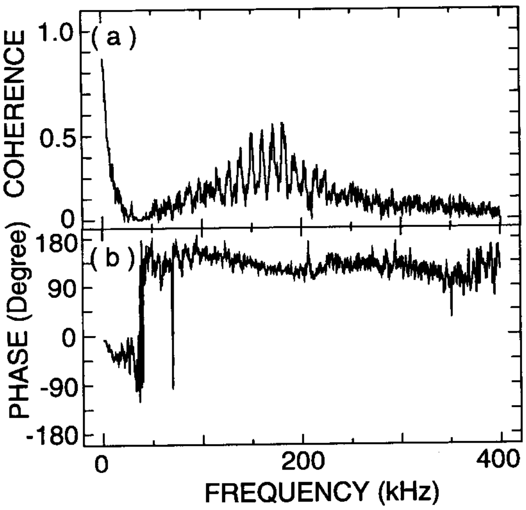

Fig. 4 (a) Cross-correlation function (Coherence) and (b) phase between grid and collector current fluctuations in region I.

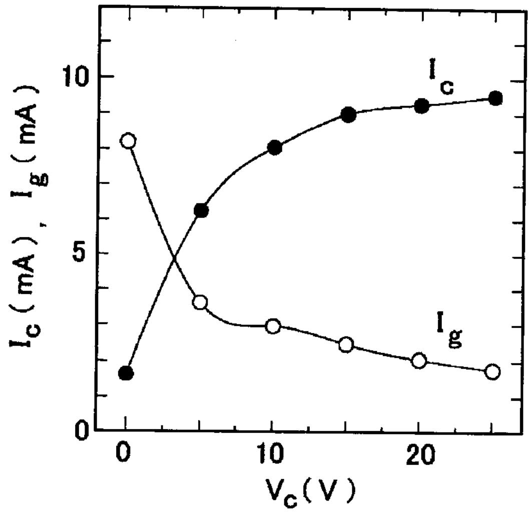

Fig. 5 Dependence of grid I_G and collector I_C currents on collector potential V_C.

the collector, the plasma potential near the collector starts increasing. Then, it is followed by the increase in I_C, which in turn causes a decrease in I_G by the total current conservation. This current suppression at the grid means physically an increase in the sheath and/or plasma potential in front of the grid, which conversely enhances the electron current passing through the grid toward the collector. From this model, since the potential fluctuations at the grid and the collector are in phase, it is reasonable to consider that the wavelength of the fundamental mode is L as assumed in the previous works [1,7,10]. In similar way, the wavelength of the n-th harmonic waves is given by L/n. This is a kind of feed back mechanism between grid and collector, conserving the electron current flux constant within a time scale of electron response.

The phase relation between I_G and I_C in region II for the potential-relaxation instability is also explained as follows. The subtraction of I_C above some threshold due to the positively biased collector results in the disruption of the plasma column between the grid and the collector. Then, immediately the plasma potential is increased in the whole plasma column, and eventually an electron sheath is created in front of the grid with a negative potential dip (a kind of virtual cathode) to suppress the current toward the grid. Therefore, I_G varies in time almost out of phase with respect to I_C [6].

5. Conclusions

Two kind of instabilities are excited by simply applying positive potential to the collector with respect to the grounded grid immersed in the diffusion plasma region, produced by a hot cathode dc discharge. One of them is so-called current-driven ion-acoustic instability and the other is potential-relaxation instability.

The current that is controlled by the potential applied to the collector externally classifies these instabilities. Phase relation between the grid and collector current fluctuations in region I show that the potential fluctuations at the grid and collector are almost in phase. Therefore, the wavelength with the fundamental frequency corresponds to the distance L between the grid and collector. This phase relation is well coincident with the static relation of the grid and collector currents against the collector potential variation.

Acknowledgements

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