Instabilities in Capacitively Coupled Plasmas Driven by Asymmetric Trapezoidal Voltage Pulses

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***Abstract*—Instabilities in Ar capacitively coupled plasmas driven by asymmetric trapezoidal voltage pulses were observed using particle-in-cell simulations. Despite its geometric symmetry, the discharge was electrically asymmetric. The instabilities were electron plasma waves launched from the sheath edge at the time the voltage pulse was applied and were accompanied by local electric field reversal.**

***Index Terms*—Plasma simulation, plasma waves.**

THE need for high selectivity and low damage in plasma etching used for fabrication of microdevices has sparked an interest in controlling the energy distribution of ions bombarding the substrate. This can be achieved by using tailored voltage waveforms applied to the substrate electrode or to an auxiliary electrode (so-called boundary electrode) in contact with plasma [1], [2]. Ion energy distributions (IEDs) with peaks at desired energies and with small energy spread can thus be achieved. Large area parallel plate capacitively coupled plasma (CCP) reactors are essentially geometrically symmetric, i.e., the powered and grounded electrodes are of equal area. The symmetry can be broken by exploiting the electrical asymmetry effect (EAE) [3]. The EAE provides a way of controlling the IED independently from the ion flux, by applying a tailored plasma generating voltage to one of the electrodes of an otherwise standard CCP reactor. The physics behind plasmas generated by these unconventional waveforms is still unclear. In particular, the mechanisms of electron heating, and the spatiotemporal variation of the sheath structure need to be further investigated. In this paper, images are presented (Fig. 1) generated by a particle-in-cell simulation with Monte Carlo collisions (PIC/MCC) of an Ar (10 mTorr at 500 K) CCP driven by asymmetric trapezoidal voltage pulses.

The simulation code was a purposely modified version of XPDP1 [4] a 1-D PIC/MCC simulator. The CCP was geometrically symmetric (equal electrode areas), with a plate separation of 6 cm. A tailored voltage waveform was applied to one of the electrodes of the CCP through a blocking capacitor, while the other electrode was grounded. A cycle of the applied waveform consisted of a negative dc voltage followed by a brief excursion to a positive dc voltage, with specified ramp-up and ramp-down times (Fig. 2). The negative dc voltage controls the ion energy. During application of this voltage, the electrode is bombarded by positive ions; electrons cannot overcome the large sheath potential to reach the electrode. Thus, positive charge accumulates on the electrode. The brief excursion to positive dc is necessary to attract a burst of electrons and neutralize the accumulated positive charge, so that at steady state there is no net particle charge flowing to the electrode. The applied trapezoidal pulses were asymmetric (i.e., the absolute value of the negative dc voltage was different than the positive dc voltage) with a frequency of 5 MHz. The waveform was characterized by a parameter α, the fraction of the cycle spent at the dc positive voltage. For this paper, the ramp-up and ramp-down times were 4 ns each, the negative dc voltage was -170 V, the positive dc voltage was 130 V (300 V peak-to-peak), the blocking capacitor was 10 nF/m^2, and α was set to 1%. Because of the asymmetry of the applied voltage, the discharge was electrically asymmetric with a dc self-bias of -167 V. The raw data for the images generated by the PIC-MCC simulation were visualized using Origin 8.5 by OriginLab Corporation (Northampton, MA).

Fig. 1(a)–(d) shows the spatiotemporal profile of plasma characteristics of the powered electrode sheath. The figure focuses at the sheath and part of the bulk plasma during application of the positive voltage pulse. When a cycle of the applied voltage pulse starts at $t = 0$, electrons are attracted to the powered electrode and, when the voltage returns to its quasi-dc negative value, a beam of energetic electrons is pushed back into the plasma bulk, thus generating an instability at time $t \sim 10$ ns. Fig. 1(a) shows the formation of double layers (alternating net positive and negative charge) at the sheath edge. As a consequence, modulation of the space potential [Fig. 1(b)], and field reversals [Fig. 1(c)] occur. Compression of the electron fluid during sheath expansion (ramp-down) gives rise to a wave propagating into the bulk plasma. The electron density is also oscillatory, especially at the sheath edge [Fig. 1(d)]. The frequency of the oscillations is 220 MHz almost exactly equal to the electron plasma frequency at the sheath edge (224 MHz). Thus, these oscillations constitute electron plasma waves propagating toward the bulk plasma. Such waves contribute to collisionless electron heating by Landau damping or other electron-wave interactions. Simulations at higher pressures showed that electron-neutral collisions dampen these waves.

Manuscript received November 5, 2013; revised April 29, 2014; accepted July 21, 2014. Date of publication August 11, 2014; date of current version October 21, 2014. This work was supported in part by the National Science Foundation under Grant CMMI 1030620 and Grant CBET 0903426 and in part by the U.S. Department of Energy under Grant DE-SC0001939.

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Digital Object Identifier 10.1109/TPS.2014.2343639

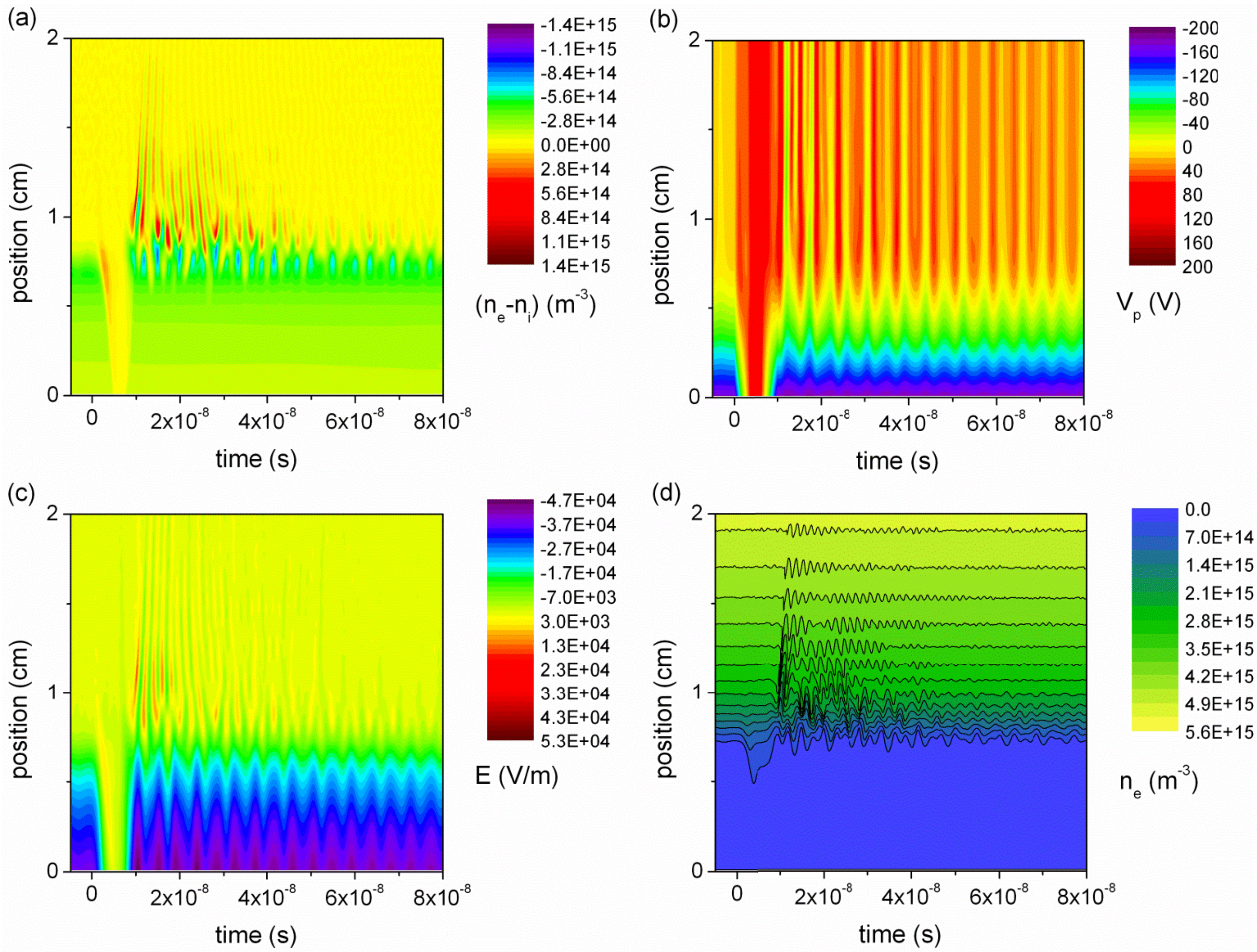

Fig. 1. Spatiotemporal profile of plasma characteristics at the powered electrode sheath of a CCP driven by asymmetric trapezoidal voltage pulses for times around the onset of the instability. (a) Net charge density ($n_e - n_i$). (b) Electric potential. (c) Electric field. (d) Electron number density.

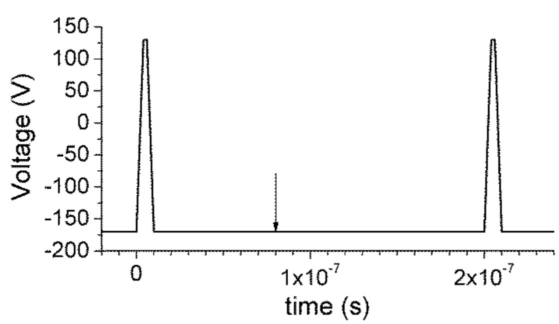

Fig. 2. Applied voltage waveform with a frequency of 5 MHz. The time window shown in Fig. 1 starts at $t = 0$ and ends at the time indicated by the vertical arrow.

Electron plasma waves were also observed in [5] in a traditional CCP with an applied sinusoidal current, for relatively high current densities. Such waves appear to be of the same origin as those reported here. The authors also observed field reversal and periodic double layers at the sheath edge and attributed the emission of waves to trapping and release of electrons from the potential wells formed by the electric field reversal.

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