SELF-ORGANIZATION AS THE CAUSE OF DIFFERENT STATES OF dc AND hf DISCHARGE PLASMAS[1]

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Dc and hf gas discharges used in industrial devices are strongly nonlinear media whose characteristics and behavior critically depend on the type of the device and on the way and the amount of energy injected into the system. Consequently, considering a certain industrial device, it is possible to select, by gradually changing the injected energy, the working regimes that offer the most suitable conditions for a certain practical applications. The consideration of the nonlinear behavior of gaseous conductors (plasmas), created in dc and hf electric fields, and implicitly of the self-organizing phenomena at their origin become important for certain applications.

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1 Introduction

Changing in a controllable way the energy injected into a laboratory device where the electric conductor is plasma produced in dc or hf electric field, it is possible to reveal abrupt transitions between different states. The cause of this strongly nonlinear behavior of the plasma is the spontaneous emergence, by self-organization, of complex space charge configurations (CSCC) [1-7]. The CSCC appearance is related to critical values of the energy injected into the system. Usually, the nonlinear behavior of a dc gas discharge plasma is emphasized by the current-voltage characteristic. For the plasma produced by an hf electric field the same phenomena can be emphasized by the dependence of the energy absorbed from the hf electric field on the energy delivered by the oscillator.

Note that nonlinear phenomena related to self-organizing processes are observed in dc gas discharges [1], plasma diodes [2,3], double plasma machines [4,5], Q-machines [6,7] magnetrons [8], hf plasma devices [9] and also in fusion devices [10].

As known, self-organization phenomena appear in a plasma device when an external imposed cause produces a local gradient of the kinetic energy of the electrons [11-13].

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Briefly speaking the self-organization process involves the following sequences: (i) breaking the translation symmetry accompanied by spatial separation of the regions were the excitation and ionization cross section functions sudden increase; (ii) accumulation of electrons and positive ions in adjacent regions where the excitation and ionization cross section functions abruptly increase and consequently appearance of a non-equilibrium state when the electrostatic forces acting between the adjacent net positive and negative space charge reach a critical value; (iii) development of an instability accompanied by bifurcation; (iv) self-assembling of a CSCC characterized by long-range order. As generally accepted, nonequilibrium, instability, bifurcation, symmetry breaking and long-range order are essential characteristics of all systems resulting after self-organization [14].

In this paper we point out that, based on the nonlinear behavior of the plasma, it is possible to adjust the working regime of the device so that the concentration and energy of the charged particles to be the most suitable for a certain practical application. This is possible by varying the amount of the energy injected into the device so that, transiting through instabilities, the characteristics and parameters of the plasma, as well as its stable or unstable behavior can be externally controlled. Additionally, we reveal by experimental results that at the surface of a solid sample exposed to a chemical active plasma, created in an industrial device, patterns are self-assembled. Their similarities to those observed in chemical media suggest the presence of a self-organization process.

2 Nonlinear variations of the working regime of plasma when the injected energy is gradually changed

For proving the possibility to adjust the working regime of a plasma device by changing the energy injected into the system we present the typical characteristics shown in Figs. 1 and 2. In Fig. 1 the static current-voltage characteristic of a device (plasma diode) where the plasma is produced by a dc gas discharge is shown. In Fig. 2 the relationship between the energy absorbed by the hf plasma and the energy delivered by the oscillator that creates the hf plasma is plotted.

Both characteristics reveal the presence of critical values of the injected energy for which the plasma spontaneously transits between different states. Thus, the static $I(V)$-characteristic shown in Fig. 1 proves that, when the voltage of the dc power supply (PS) is gradually increased, a critical value is reached for which the internal resistance of the plasma suddenly decreases so that an abrupt increase of the current extracted from the PS is observed. This experimental result proves that after the instability appearance, revealed by the abrupt increase of I, the concentration of the charged particles in the plasma abruptly becomes greater. The gaseous conductor spontaneously transits into an unstable state when the voltage of the PS reaches another critical value for which de current suddenly increases [3]. Under such conditions the plasma device works as a generator of oscillations [3,4]. A similar phenomenon can be observed when the energy generated by an hf oscillator, used for plasma production, is gradually decreased. The decreasing takes place from the value for which a usual hf discharge is ignited to a value for which, through an instability, another mechanism governs the absorption of the hf energy. The sudden increase of the energy absorbed from the oscillator that creates the hf electric field is shown in Fig. 2. In this figure it is plotted the variation of the

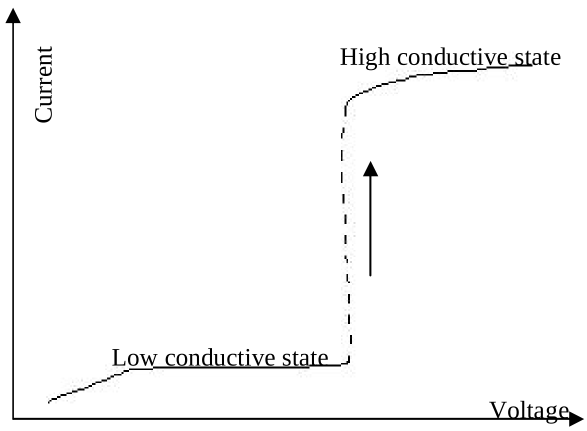

Fig. 1. Typical current-voltage characteristic of a diode in which the gaseous conductor is produced by a dc gas discharge.

current collected by control grid of the electronic tube (that sustains the oscillations) when, by gradually decreasing the screen grid voltage, the energy of the hf electric field is decreased. As known, the variation of the control grid current is directly related to the amount of energy absorbed by a system coupled to an hf oscillator. The sudden increase of the hf energy absorption proves that, after the appearance of the instability produced for a critical value of the oscillator energy, the plasma works at resonance, i.e. in a state potentially favorable for improving the economical performance of the device.

As already shown [1-3, 12-14], the sudden increase of the conductivity when the voltage supported by the plasma column reaches a certain critical value, is related to the emergence of a self-organized space charge configuration in a region where an external constraint produced a local gradient of electrons' kinetic energy. In common plasma devices such phenomena appear in front of the anode [1-6]. When the area of the anode is large, as for example in the most of industrial devices, the self-organization phenomena emerge in the form of anode spots located in different points of the anode surface. Since every anode spot works as a new source of charged particles [11,12] their emergence changes the concentration and the mean energy of the charged particles in the plasma. A similar phenomenon can be observed in hf gas discharges where the sudden increase of the energy absorbed by the plasma is accompanied by the appearance of a plasmoid [9]. It is well established [1-4, 11,12,14], that the anode spots, as well as the plasmoids, are space charge configurations spontaneously emerging after self-organization.

Since during the self-assembling and de-aggregation of the anode spot the gaseous conductor reveals the behavior of a negative differential resistance [1], a plasma device frequently generate instabilities. These instabilities, which usually appear as spontaneous oscillations, modify the quality of the plasma and its interaction with the surface. Therefore, by elucidating the role played by anode glow-like space charge configurations in the

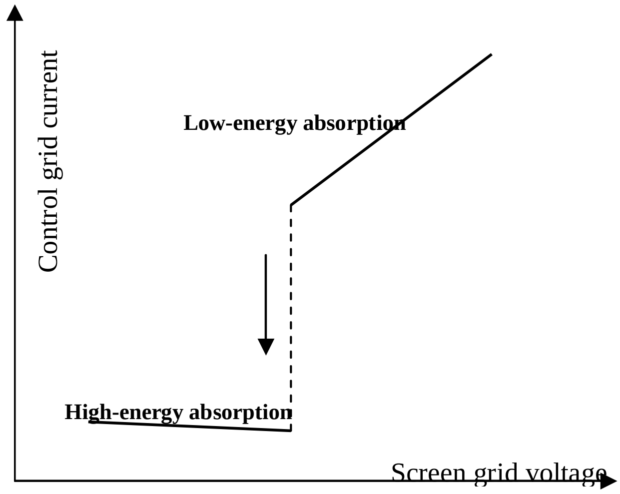

Fig. 2. Graph showing the relationship between the energy generated by the hf oscillator, controlled by the screen grid voltage of the electronic tube that sustain the oscillations, and the energy absorbed by the hf plasma that increase when the control grid current decrease. Resonance is obtained for a minimal value of the control grid current.

stimulation and sustenance of instabilities, it becomes possible to control the stability of a plasma device. Knowing the genuine cause of the negative differential resistance behavior of the gaseous conductor, it becomes possible to control the stability of the system or, if favorable, to make the system working in an intermittent (oscillatory) way by connecting reactive circuit elements to it.

According to the above said, it results that self-organization phenomena taking place in industrial plasma devices are able to strongly influence their working regime. Therefore controlling the presence of self-organization phenomena we can improve the technological applications of a plasma device.

Beside the self-organization phenomena briefly described above, interesting phenomena were observed at the surface of a solid sample subjected to the action of reactive plasma. Thus, in Fig. 3 the photograph of a 10-70 micrometers thick boron layer produced at the surface of a 15% carbon steel cathode deposed in a dc discharge using a BCl_3-H_2 mixture at 600-900°C is shown. The boron deposes as overlapped spiral crystals in conical or columnar shape in cross section. The spiral diameter is 10-20 micrometers. Morphology of the crystals was investigated by metallographic and scanning electron microscopy. At the present date the mechanism by which these ordered patterns emerge is unknown. The similarities with pattern formation in chemical media [13] suggest the presence of a self-organization process.

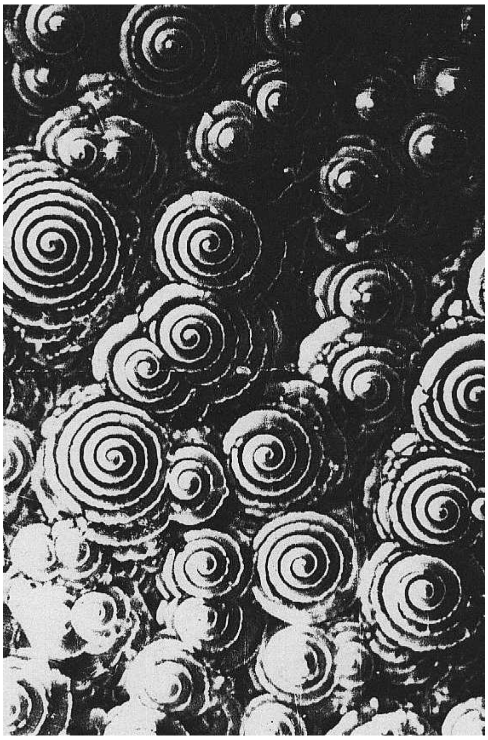

Fig. 3. Ordered spatial pattern obtained by deposition on a metal sample supposed on the action of a chemical reactive plasma.

3 Conclusions

The aim of this paper was to call the attention on the possibility of improving the control of currently used plasma technologies by using the self-organization phenomena frequently appearing in dc and hf gas discharges. This becomes possible by changing the energy injected into the plasma.

Additionally, we presented experimental results that seem to prove that, at the surface of a solid sample subjected to the action of a chemical active plasma, phenomena that potentially involve self-organization take place and therefore can be relevant for mastering and processing intelligent materials.

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