Plasma experiments with relevance for nano-science

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The mechanism that actually drives self-organization revealed by plasma experiments offers a new insight concerning fundamental knowledge potentially important for nanoscience. It reveals that at the genuine origin of the memory proper to complex space charge configuration emerged by self-organization in plasma is a mechanism based on extraction of matter and thermal energy from the surroundings. This takes place, similar to the mechanism used by living organism, by exploiting collective effects of quantum processes. The informational content of these experiments potentially elucidates one of the fundamental problems concerning the mechanism by which the so-called intelligent materials work.

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1. Introduction

The increasing degree of computer performance has lead to the miniaturization of the individual integrate circuits by simultaneous increasing the speed of operations and decreasing the energy consumption, both under conditions that their size and weight are diminished. However, as recently recognized [1], there are limits in miniaturization imposed by quantum and thermal fluctuations.

One way to avoid these limits, followed by the computer scientist, is to seek inspiration from the living organisms, which actually operate with functional elements at nano-meter scales, extracting matter concomitant with thermal energy from the surroundings by a mechanism exploiting collective effects of the quantum processes [1]. The most important quality of such functional elements is their capability to build themselves their structural components. This takes place following a program "learned" during their emergence by self-organization.

Self-organization is scientifically interesting and technologically important for at least two reasons. The first reason is that it is centrally important for life. The cell contains an astonishing range of complex structures that emerge by self-organization. The second reason is that self-organization seems to offer one of the most general strategies now available for generating nano-structures. Plasma experiments were recently appreciated to be potentially able to offer a new insight concerning both of the aforementioned reasons [2]. Thus, such experiments are considered elucidative for understanding the mechanism by which supramolecular and biochemical assembles emerge by self-organization [3].

In this paper we add significant new information concerning the physical basis of the memory of intelligent systems created in laboratory. Investigating the origin of the hysteresis phenomena revealed by gaseous conductors (plasma), we have discovered the emergence, by self-organization, of a complex space charge configuration (CSCC) endowed with memory. The working mechanism of this memory is based on extraction of matter and thermal energy from the surrounding plasma. This takes place, similar to the mechanism working in biological systems, by exploiting quantum processes. Endowed with memory, the complexity attributes to the gaseous conductor the qualities to act as a bistable circuit element. For nanoscience, the elucidation of the physical processes at the genuine origin of this quality offers new fundamental information. These refer to the way how, by self-organization, structural elements endowed with memory self-assembly in a framework of bistable elements whose presence attribute to a system the ability to work as a multifunctional intelligent material.

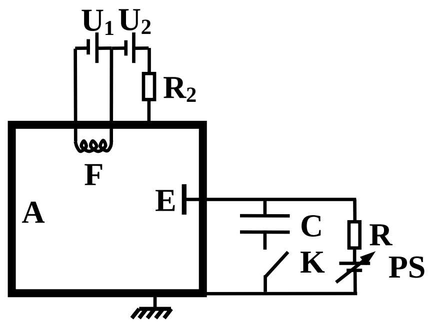

Fig. 1. Schematic of the experimental setup (F – filament, E – electrode, A – anode, PS – power supply, K – switch, U_1 – power supply for heating the filament, U_2 – power supply for discharge, R,R_2 – load resistors).

2. Experimental results and discussion

The experiments were performed in a plasma diode, schematically shown in Fig. 1. Plasma is created by an electrical discharge between a hot filament (marked by F in Fig. 1) as cathode and the grounded vessel (made from non-magnetic stainless steel) as anode. The plasma was driven away from equilibrium by gradually increasing the voltage applied to a supplementary electrode (marked by E in Fig. 1), under the following experimental conditions: argon pressure $p = 10^{-2}$ mbar, plasma density $n = 10^{9}$ cm^{-3}.

As known, the presence of a special kind of memory proper to a material used in nano-technology is physically proved by emphasizing the presence of a hysteresis phenomenon in the static current versus voltage (*I*-*V*) characteristic. Following the same way, we emphasize the presence of memory of the plasma "material" by plotting the static *I(V)* characteristic. Such a characteristic is shown in Fig. 2. It was obtained when the voltage V_{PS} delivered by an external dc power supply (marked by PS in Fig. 1) is gradually increased and decreased. Note that, because of the presence of a load resistor (marked by R in Fig. 1) connected between the PS and E, the voltage supported by the gaseous conductor (plasma) differs from the voltage V_{PS} delivered by PS.

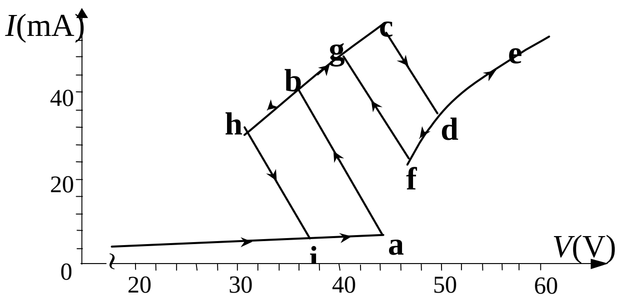

Fig. 2. Static current-voltage characteristic obtained in the condition when a CSCC appears in front of it.

The *I(V)* characteristic shown in Fig. 2 reveals the presence of critical values of V_{PS} for which the current *I* transported by the gaseous conductor abruptly varies. Simultaneously with these jumps of *I*, the voltage *V* supported by the gaseous conductor self-adjusts at values that depends on its electrical conductivity. The most important phenomenon emphasized by this static *I(V)* characteristic is the presence of two kinds of bistabilities. Thus, by increasing V_{PS}, a first instability is observed for a critical value of it. This instability manifests as an abrupt increase of *I*. When V_{PS} reaches a second critical value, other instability, revealed by an abrupt decrease of *I* is observed. The abrupt increase of *I* corresponds to an S-shaped bistability, whereas the abrupt decrease of *I* corresponds to a Z-shaped bistability. Concomitant with the appearance of the first instability, the plasma diode becomes able to sustain electrical oscillations in a resonant circuit suitably connected between E and the grounded metal vessel. In this state the plasma diode behaves as an S-shaped negative differential resistance (S-NDR) [1]. After the second instability, the plasma diode behaves as a system that produce periodic limitations of the current, fact emphasized in the dynamic *I(V)* characteristic shown in Fig. 3. In this state the plasma diode behaves as an N-shaped negative differential resistance (N-NDR) [2]. Every of the revealed instabilities are related to the presence of a hysteresis phenomena. This means that the plasma diode was endowed with memory, *i.e.*, it is able to store information.

Possessing memory, the plasma diode reveals all the qualities of bistable and multistable circuit elements, respectively, used in nanotechnology. Therefore, the knowledge of the physical basis of the mechanism by which this memory works could be of special interest also for nanoscience and nanotechnology. In this context, as recently shown [4], the experimental results the experimental results obtained by the investigation of the nonlinear behaviour of the plasma diode offer new information. This information refers to the presence of a new mechanism that actually drives self-organization in general. As known, structures revealing bistable and multistable properties spontaneously self-assembly when the system is driven, by an external constraint, away from equilibrium. In electronic circuit elements, the external constraint is an electric field applied to the sample. Under such conditions, there are critical values of the applied electric field for which the sample spontaneously transits from a low to a high conducting state and vice versa. The existence of similar phenomena are revealed in the static *I(V)* characteristic of the plasma diode shown in Fig. 2. As already shown [1-3], the abrupt increase of *I*, emphasized in this characteristic, originates in the self-assembling of a CSCC able to work as an additional new internal source of charged particles. For working as an additional source of current, the CSCC extracts matter concomitant with thermal energy by a mechanism based on collective effects of quantum processes [4]. Since these quantum processes involve, besides ionizations (production of new charged particles), also excitations of the atoms, the extraction of matter and thermal energy is accompanied by sending out of entropy. This entropy appears in the form of incoherent radiation energy related to the transition of the excited atoms in the ground state. The sending out of entropy is equivalent to consider that, for surviving, the CSCC produces negative entropy. This means that the CSCC actually represent a new quality of a material system emerged by self-organization that reveals some of the qualities exclusively attributed to primitive organisms [5]. However, unlike to the living organism, the CSCC requires the presence of an external source of current for surviving. This means that the CSCC behaves in a mettastable state, *i.e.*, its "life" is artificially sustained.

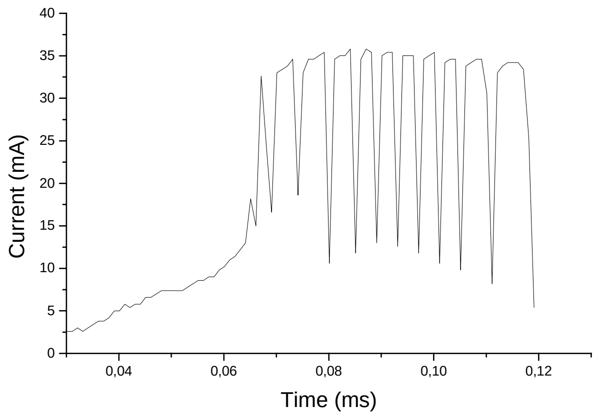

Fig. 3. Dynamic current-voltage characteristic of the electrode emphasizing the current limiting phenomenon.

For explaining the way by which the CSCC acts as a new internal source of current, i.e., to explain the cause of the abrupt increase of I and implicitly the origin of the S-NDR emphasized by the plasma diode, it is necessary to consider the Maxwellian energy distribution of the electrons. A detailed description of the self-enhancing mechanism of the production of positive ions that determines the abrupt increase of I was already published [4]. Here we point out the fact that this mechanism explains the self-assemblage process of a CSCC, i.e., a structure of two adjacent space charges that form an electric double layer. The double layer separates two regions of the conductor that physically differ one from the other. Generally, the shape of the double layer corresponds to the structure of a system characterized by a local minimum of the free energy. Therefore the structure reveals certain "robustness" with respect to random external causes. In the plasma diode, the shape of the double layer is a nearly spherical one. This shape is related to the requirement that the external PS collects the electrons that, after ionizations, ensure the survival of the CSCC. This means that the PS "helps" the CSCC to perform the operations required for ensuring its existence [1]. These operations, "learned" during self-organizations, maintain the high value of the current I after the development of the S-shaped bistability. Implicitly, the mechanism of these operations explains also the genuine origin of the S-NDR. As shown [4], these operations involve continuous conversion of thermal energy of a part of the electrons extracted from the surrounding plasma in electric field energy of the double layer. This takes place, as aforementioned, by a mechanism exploiting collective effects of quantum processes. By this mechanism, the potential drop on the double layer is maintained constant at a value for which a great number of electrons that traverse the double layer arrive the anode surface in spite of the fact that the potential of the ionic side of the double layer is greater than the potential of the anode. This means that the abrupt increase of I, related to the property of the plasma diode to work as an S-NDR, is due to a mechanism by which matter concomitant with thermal energy is extracted from the surroundings. In other words, instead of consumption of power, the plasma diode produces power by consuming thermal energy. In this phase of the CSCC the plasma diode is able to act as a bistable circuit element. Connecting the plasma diode to a circuit able to oscillate naturally, oscillations are sustained in the circuit [1,4]. Sustaining oscillations, the plasma diode works as an engine whose duty cycle corresponds to the hysteresis loop shown in Fig. 2.

When the voltage of the PS is increased so that V reaches the critical value marked by **c** in Fig. 2, another kind of bistability appears. As shown [2,4], this bistability correspond to a higher phase of self-organization emphasized by the transition of the CSCC into a steady (ordered in behaviour) state in which its survival is ensured by a rhythmic exchange of matter and energy with the surrounding plasma. Because a new hysteresis phenomenon is revealed in the static I(V) characteristic after this transition, this state is also characterized by a new type of memory, so that the plasma diode is able to store information. In the steady state of the CSCC, electrical double layers are periodically shelling off from its surface [2]. These double layers move away from the anode reaching a distance for which they de-aggregate. The periodicity of the phenomenon is ensured by an internal feedback mechanism by which every de-aggregation controls the shelling off process of a new double layer meantime formed at the border of the CSCC. The periodic shelling off process of double layers from the border of the CSCC determines the appearance in the plasma conductors of barriers for the current, so that a current limiting phenomenon is emphasized by the plasma diode. Its presence can be experimentally proved by plotting the dynamic I(V) characteristic (Fig. 3).

In context with the above-described physical basis of the two kinds of bistabilities, we remark that similar phenomena are observed in semiconductors. However, as recently remarked [6], there is a lack of investigations concerning the role played by self-organization in the appearance of these bistabilities. Thus, the most prominent type of S-NDR that appears, for example in pnpn diodes, is usually explained by impact-ionization breakdown. The Z-shaped bistability (that appears in the static I(V) characteristic as an N-NDR [2]) is currently discussed for the double barrier tunnelling diode. It also appears in the post-breakdown regime of p-germanium [7]. Starting from the astonishing similarities between the nonlinear phenomena observed in plasma diodes and in semiconductors, we tentatively proposed [8] to consider at their genuine origin the same self-organization mechanism.

In agreement with the above said, a plasma diode in which a single CSCC emerged by self-organization is able to store information related to two kinds of instabilities. However, as revealed by plasma experiments, there are conditions for emergence by self-organization in the diode plasma of multiple structures bordered by electric double layers. Each of the structures behaves as an S-shaped and Z-shaped bistable system, respectively, so that the plasma diode can work as a multistable circuit element. For proving this fact, we present in Fig. 4 the static I(V) characteristic obtained when two CSCCs appear in front of the anode. By further increasing the voltage from the external dc PS, networks of CSCCs self-assembly attached to the anode surface. Under such conditions, the plasma diode actually works as a multifunctional circuit element.

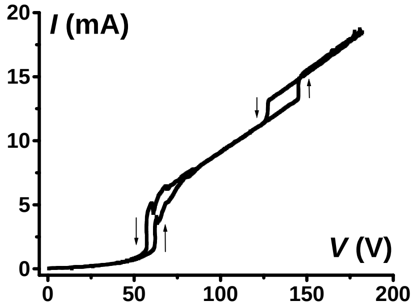

Fig. 4. Static current-voltage characteristic plotted in the condition when a multiple double layers structure is obtained in front of it.

In context with the above-presented experimental results it is interesting to mention that the sizes of the CSCCs formed in plasma devices depend on the gas pressure. When the gas pressure reaches the range of the normal atmospheric pressure, the size of the CSCCs reaches the range of nano-meters [9-11]. For higher gas pressures the concentration of matter and energy in the CSCC could be very high. This suggests that by self-organization produced under controllable laboratory conditions a new route appears for confining matter. Such interesting phenomena for fusion science were observed by creating CSCCs in gases at pressures in range of the normal atmosphere in interrupted z-pinch [12].

3. Conclusion

Self-assemblage phenomena, as above described, provide routes to a range of complexities formed in gaseous conductors with regular structures having sizes larger than that of the molecules. Potentially, the physical basis at the origin of these structures presents a great interest for explaining the emergence of similar structure in condensed matter conductors. Emphasizing as driving mechanism of self-organization a mechanism by which matter concomitant with thermal energy is extracted from the surroundings, we prove that every complexity included in the structure of an intelligent material continuously performs operations learned during self-organization. These operations by which "negative entropy" is produced are similar to that performed by living organisms. Unlike to living organisms that perform these operations in an autonomous self-consistent state, the complexities included in intelligent materials perform these operations when the material are maintained, by an external constraint, at a critical distance from equilibrium. For engines with sizes in the range of nano-meters [13], the informational content of this paper potentially adds significant new information.

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