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Acoustoplasma State of Matter

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Abstract. In our experiments it was shown that the modulation of the discharge by the current, which contains constant and variable components, leads to the transition of the plasma to a new state, which was called acoustoplasmic. In this new state, many parameters of acoustoplasma differ from the parameters of the plasma when it is supplied with direct current. In the plasma of the positive glow discharge column the electron concentration is determined by the parameters of the external circuit and the modulation of the discharge current. The modulation of the electron concentration leads not only to the modulation of the level populations, but also to the disturbance of the relative equilibrium of the populations. It becomes possible the inversion of the populations of individual states, which will lead to the appearance of anomalously strong lines in the emission spectra. In a non-equilibrium plasma, due to the multi-level energy structure of atoms and molecules, there are dozens of mutually transforming neutral components with different levels of excitation. The report presents the experimentally obtained results of studies of acoustoplasma states. All the diversity of the research is presented in the form of a nomogram.

Keywords: acoustoplasma, phase transition, discharge parameters, acoustic generation and interaction.

1. Introduction

The concept proposed more than forty years ago by Academician of the National Academy of Sciences of Armenia Alpik Mkrtchyan is as follows: acoustic fields lead to a deformation of the characteristics of the medium and a small amount of acoustic energy due to the collective action of many particles can lead to a significant change in the parameters of the medium and in the parameters of radiation with an energy that is much larger than the energy of an individual phonon. In plasma, an acoustic disturbance forms acoustic parameter superlattices. Plasma with acoustic vibrations excited in it allows this approach to be treated as a new medium - ACOUSTOPLASMA.

The parameters of the acoustoplasma (hereinafter AP) can significantly differ from the parameters of the plasma without acoustic disturbance (hereinafter OP - ordinary plasma). In particular, the behavior of some of the parameters of the AP becomes similar to the behavior of the parameters of a condensed medium.

Most of the experiments correspond to the AP obtained by modulating the discharge current in a long cylindrical tube. The length of the tube is much larger than the diameter. Modulation of the discharge current leads to the generation of an acoustic signal in the tube that interacts with the plasma created by the same discharge current. In addition, it should be taken into account that the discharge tube itself is an acoustic resonator and acoustic modes are possible in it, leading to the appearance of superlattices of parameters [1–4].

Figure 1 shows a diagram of the state of the medium and the main phase transitions (PT). PT can also be in the solid state, for example, topological [5,6]. First, we consider only the basic thermodynamic transitions.

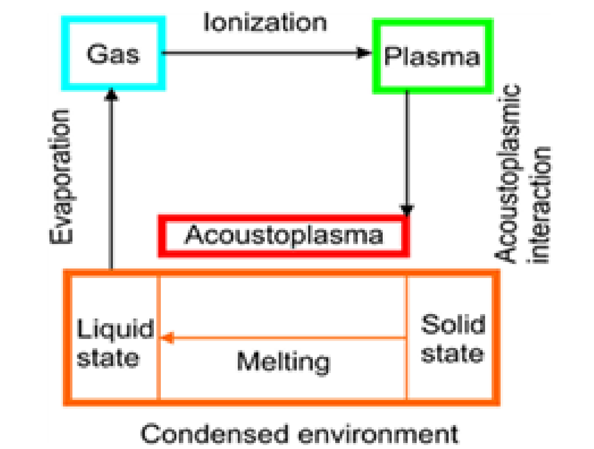

Fig. 1. General diagram of the state of the medium and the main phase transitions (PT).

The first PT is the melting. During melting, there can also be various cascade PT, but only the main thermodynamic can be represented. The second PT is the evaporation, the transition from liquid to gas. The third PT is the ionization - the transition from gas to plasma.

The interaction of acoustic waves with OP creates the state of AP. Standing acoustic waves form parameter gratings, long-range order appears and the acoustoplasma medium becomes similar to a condensed medium. We get the fourth PT - the acoustoplasmic, the transition from plasma without acoustic disturbance to the acoustoplasma state (OP-AP). And then various PT can be realized in acoustoplasma. It is possible to have PT of the OP-AP, and also between various acoustoplasmic states.

Fig.2 presents a diagram for PT which shows in which areas there are thermodynamic PT and non-thermodynamic PT.

The abscissa represents the values of the internal energy of the substance in relative units. On the ordinate axis: PSM - the phase state of the substance in the standard representation, UST - ultra low temperatures, T-PT - thermodynamic phase transitions, BKT-PT - topological phase transitions (Nobel Prize in 2016), Berezinskiy-Kosterlitz-Thouless phase transitions [5,6], AP-PT -

acoustoplasma phase transitions [7]. In Fig. 2, it is noted that PT are also possible in solids and liquids, and the regions of existence of topological and acoustoplasma PT are also noted.

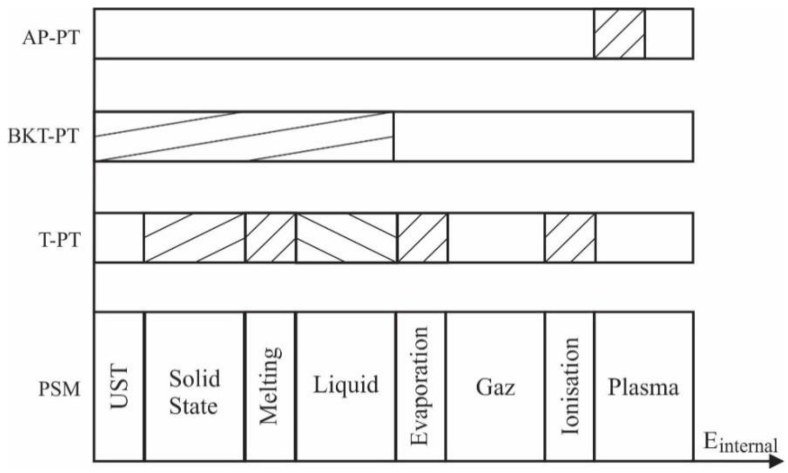

Fig. 2. The hierarchy of PT. The regions of existence of PT are shaded as slanting lines. PSM - the phase state of the matter, UST - ultra low temperatures, T-PT - thermodynamic phase transitions, BKT-PT - topological phase transitions, AP-PT - acoustoplasma phase transitions.

Both AP and OP are self-consistent environments. Adding new control parameters (frequency and depth of modulation of the discharge current, as well as the shape of its variable component) allows one to control almost all the parameters of the AP [3,4]. The depth of modulation is the ratio of the amplitude of the variable component to the value of the constant component. ***This allows to implement new types of devices based on acoustoplasma interaction and to upgrade existing devices***.

It is possible that in the future, AP will indeed be called the 5th state of matter. The fact is that the behavior of some of the parameters of the AP is similar to the behavior of a condensed medium. A further increase in energy in the AP also leads to quasi-melting of AP structures (destruction of long-range order) and a return to gas. The further increasing of the energy will lead to complete ionization. Thus, AP can exist only in the region of low-temperature plasma.

2. Generalities

Below we list the differences of AP differs from OP.

1. In the AP, parameter jumps and PT are possible, so the question arises about the appropriateness of using the continuity formulas and the small increment method that are used for OP;

2. Even the OP, as a self-consistent medium, is non-linear, but some equations can be linearized. AP is a fundamentally non-linear medium and the linearization will always lead to errors;
3. A direct current discharge creates a stationary plasma, which manages to reach its equilibrium state. A high-frequency discharge creates a dynamic plasma in which the characteristic times are much smaller than those for ionization-recombination processes. The quasi-stationary low-frequency discharge creates an AP. A relatively slow restructuring of the regimes leads to the fact that the equilibrium point is restored, but in different coordinate parameters. This is the meaning of PT from the state of OP to state of AP. This is a necessary but not sufficient condition for the existence of the AP.
4. The Maxwell distribution is valid only for a homogeneous and isotropic medium. In OP the Maxwell distribution can be applied with reservations. In AP, because the strong anisotropy of the acoustic field in the plasma, the Maxwell distribution is not appropriate.
5. In OP usually pair collisions are considered. In a highly nonequilibrium plasma, like AP, the collective effects dominate the effect of pair collisions. Multiple collisions are treated as waves in a plasma.
6. In both OP and AP, ionization nonlinearly depends on the concentration, but governing laws can be different due to different relaxation times and inertia of processes.
7. At time scales larger than the period of plasma oscillations, the Debye screening has sufficient time to be established. But with low-frequency modulation, the Debye screening receives low-frequency modulation along the screening radius.
8. At low modulation frequencies, $\sim 0.1\,kHz$, almost all the processes are quasi-stationary. At frequencies larger than $0.5-1\,kHz$, the standing acoustic waves may form along the length of the discharge tube. The mechanical displacement is different and it is not simultaneously changed in phase at all points of the discharge tube. Thus, in the AP, a situation arises when there is quasistationarity in electrical parameters and not in terms of the acoustic parameters of the tube.
9. In AP, the mobility of ions depends more strongly on the mechanical vibrations than on the modulation of the electric field strength.
10. In OP and AP instead of the van der Waals forces, the main role is played by the Coulomb forces. This can lead to the consideration of Coulomb acoustics and Coulomb thermodynamics.
11. The velocity anisotropy in the OP leads to instabilities. The AP discharge stabilizes some instabilities since it reduces the fluctuations of anisotropy.
12. In the positive column of AP glow discharge, the current modulation leads to the modulation of the electron concentration. Collisions of electrons with atoms in this case lead not only to the modulation of the level populations, but also to a violation of the relative equilibrium of the populations. The inversion of the populations of individual states is possible, which will lead to the appearance of abnormally strong lines in the emission spectra.
13. In a nonequilibrium low-temperature AP, due to the multilevel energy structure of atoms and molecules, there are dozens of mutually transforming neutral components with different levels of excitation. This property gives rise to various phase transitions (including cascade) and the selection of some individual states of atoms (including optical transitions).

14. In a conventional mechanical system, forced oscillations of large amplitude with a frequency different from the natural frequency of the system can lead to the suppression of own vibrations or to the complex form of their interaction. In the case of AP, an external force can provoke oscillations on frequencies different from the exciting ones, and the further parametric self-amplification can support these oscillations.

15. In our experiments, acoustic fields in the discharge tube were formed upon modulation of the discharge current, which leads to the modulation of heat generation and of the momentum simultaneously along the entire axis of the discharge. An acoustic wave is excited that is orthogonal to the axis of the discharge. In the general case, this is a spiral wave, but if the modulation frequency is lower than the frequency of the existence of spiral waves, then only a longitudinal acoustic wave is excited [8]. Thus, in a tube with an AP discharge, acoustic fields orthogonal to the axis of the discharge are much stronger than the acoustic fields along the discharge. This leads to the strong anisotropy of acoustic fields in the AP during modulation of the discharge current.

From all this chaos of states, the self-consistency of processes in AP leads to the formation of acoustoplasma structures.

Below the experimental results are given that were obtained under the direction of A.R. Mkrtchyan at the Laboratory of Applied Problems of Cold Plasma at the Institute of Applied Problems of Physics over the past 22 years.

The whole variety of studies (40 phenomena, 80 experiments) is presented in the form of a diagram in Fig. 3.

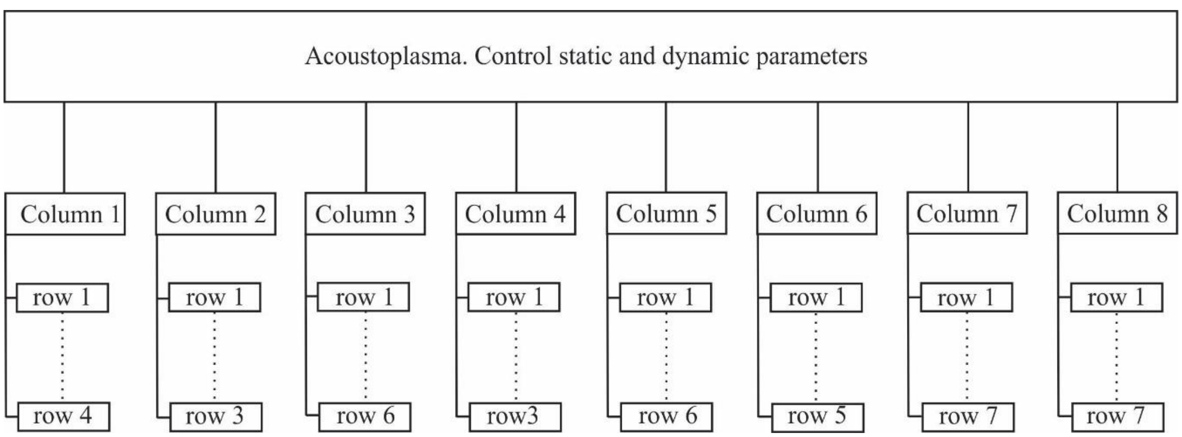

Fig. 3. Diagram of the laboratory studies of the control of parameters and processes of AP states.

For almost every element of this diagram, there is at least one publication.

In this diagram, one more column could be added for magnetized AP. But the work in this direction has begun recently.

Column 1. Change of geometric parameters (sizes and trajectories).
row 1 - changing the trajectory of discharges;
2 - changing of contraction;
3 - acoustic turbulence;
4 - soliton stopping;
Column 2. Change of optical parameters.
1 - integrated brightness;
2 - change of spectrum lines and bands;
3 - generation of strong spectrum lines;
Column 3. Change of electrical parameters.
1 - direct component of voltage and current;
2 - alternate component of voltage and current;
3 - phase shift between voltage and current;
4 - resistance and conductivity;
5 - distribution of charges in space and time;
6 - change in time RCL-parameters of an equivalent circuit modeling the discharge;
Column 4. Change of acoustic parameters in the acoustoplasma medium.
1 - amplification and attenuation of sound;
2 - generation of sound;
3 - change the speed of sound;
Column 5. Change the thermodynamic parameters.
1 - temperature;
2 - thermodynamic phase transition;
3 - non-thermodynamic phase transition;
4 - speed control of the plasma components;
5 - control of acoustic streaming;
6 - memory relaxation;
Column 6. Change in energy parameters.
1 - efficiency;
2 – energy investigation;
3 - energy capacity;
4 - luminous efficiency of light sources;
5 - stabilization and variation of lasers and light sources;
Column 7. Implementation of new types of devices and processes based on AP.
1 - development and manufacture of measuring equipment and modernization of the existing one;
2 - new power sources for AP devices;
3 - AP light sources;
4 - AP lasers;
5 - AP magnetrons;
6 - AP accelerators;
7 - AP controlling in plasma chemistry;

Column 8. Methods of processing the results that were used in the measurements..

1 - creation of an online laboratory;

2 - creation of a multi-channel measuring complex;

3 - waveform processing techniques;

4 - use of catastrophe theory to determine the presence of phase transitions and catastrophic parameter jumps use of the catastrophe theory to determine the presence of phase transitions and catastrophic parameter jumps;

5 - use of the catastrophe theory in solving incorrectly posed inverse problems;

6 -use of rectangular matrices containing several columns (according to the number of measured parameters) and 120 rows for working with the obtained oscillograms;

7 - new software products.

According to the results of the studies, more than 50 works were published, and 7 PhD theses were defended by young laboratory staff and graduate students from 2005 to 2014. Some of the results obtained on the basis of the fundamental research are listed below.

1. A video clip has been created that clearly demonstrates the ability to control plasma using acoustic fields .

2. Specialized power supplies for gas-discharge devices for operation in the AP mode were designed and manufactured.

3. AP fluorescent lamps with high efficiency have been developed. In 2009, Philips, with its Tornado lamp, achieved a luminous efficiency of $90\,Lm/W$. In our laboratory, in small series (several hundred lamps) in 1999, a luminous efficiency of $100\,Lm/W$ was obtained. At the same time, the advantage of the bispiral design of fluorescent lamps during their operation in the AP mode was substantiated. Today, almost all fluorescent lamps operate in AP mode, but no one takes this into account.

4. The possibility of increasing the power of a serial CO_2 laser during transition to the AP mode instead of supplying with direct current (by $25-30\%$) is shown. When developing special AP lasers, the energy input into the discharge can be increased several fold and the efficiency of converting the electric pump power to optical power is almost 2 times higher.

5. The effect of one laser module on another in multimodular structures is investigated. It is shown that it is possible to control the magnitude of the mutual influence of the modules.

6. It is shown that in the AP mode of discharge power, it is necessary to measure the current at the input to the anode of the discharge tube and at the exit from the cathode of the discharge tube at the same time. If the current is measured at only one point then the average values will be correct, and the dynamics of the current will be erroneous. The dynamics of charge variations in the tube will not be taken into account.

7. AP magnetrons were designed, manufactured and patented for sputtering.

8. It was experimentally shown that after switching off the external acoustic exposure (only the direct component of the current from the source remains), the AP remains, i.e. it keeps the memory of his condition. It retains a small modulation of the current, although there is no external

modulation of the current. After a certain time (relaxation time, which can reach several minutes), the AP returns to the OP state, i.e. current modulation disappears completely.

9. It has been experimentally shown that the energy intensity of AP significantly (hundreds of times) exceeds the corresponding quantity for OP. When the AP state is destroyed, this energy can be released in the form of an explosion.

10. The possibility of the existence of phase transitions in the states of various parameters in the AP is shown experimentally. In particular, for some values of the parameters of AP, the medium after the phase transition becomes similar to a condensed medium.

11. The possibility of accelerating charged particles in AP discharge is experimentally shown. A mechanism is proposed for the formation of negative conductivity due to the acceleration.

12. It has been experimentally shown that during the modulation period in the AP in addition to the magnitude of the negative charge in the tube, the electric capacity of the discharge is changed. During the period of modulation in the AP discharge, the electroneutrality of the positive column is almost always violated.

13. The possibility of acoustically controlling of the current–voltage characteristics of the AP discharge is experimentally shown.

14. The possibility of significant (tens and hundreds of times) increase in the intensity of individual spectral lines in the AP regime was shown experimentally in molecular gases. Moreover, these lines are highly monochromatic. Monochromatic sources were developed on these strong lines.

15. The dependence of the generated acoustic pressure in the AP on the magnitude of the discharge current, modulation frequency, pressure and type of gas or gas mixture is investigated. A convenient empirical formula is obtained for determining the magnitude of the generated acoustic pressure from the "specific generated acoustic pressure". For different gases and gas mixtures, the specific generated acoustic pressures $(3-23\,Pa/A\,torr)$ were obtained at the frequency of the first acoustic resonance of the discharge tube. With increasing frequency of modulation of the discharge current, the value of the generated acoustic pressure increases.

16. In AP, both the amplification and attenuation of sound are possible. Acoustic amplifiers and acoustic screens that attenuate sound can be created on this principle.

17. It was experimentally shown that the AP discharge can be modeled by a parallel oscillatory circuit. One branch is represented by resistance and part of the inductance, the other branch is series-connected by capacitance, inductance and resistance. The resonant frequency of the AP discharge does not coincide with the lower acoustic resonances of the discharge tube or with the electric resonance of the equivalent circuit.

18. A technique has been developed to study the possibility of phase transitions and jumps in the parameters of an AP discharge using the mathematical theory of catastrophes and solving incorrectly posed inverse problems.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The authors equally contributed to all steps of the paper preparation.

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