7. G. B. Lopansteva, A. P. Napartovich, A. F. Pal', et al., Fiz. Plasmy, **8**, No. 6, 1264-1268 (1982).
8. D. A. Mazalov, A. P. Napartovich, A. F. Pal', et al., Pis'ma Zh. Tekh. Fiz., **14**, No. 20, 1865-1870 (1988).
9. A. V. Dem'yanov, I. V. Kochetov, A. P. Napartovich, et al., Pis'ma Zh. Tekh. Fiz., **12**, No. 14, 849-853 (1986).
10. A. V. Dem'yanov, I. V. Kochetov, A. P. Napartovich, et al., Fiz. Plasmy, **15**, No. 4, 487-492 (1989).
11. A. V. Dem'yanov, I. V. Kochetov, A. P. Napartovich, et al., Dokl. Akad. Nauk, **306**, No. 5, 1099-1103 (1989).
12. L. D. Tsendin, Zh. Tekh. Fiz., **35**, No. 11, 1972-1977 11965).
13. J. H. Jacob and S. A. Mani, Appl. Phys. Lett., **26**, No. 2, 53-55 (1975).
14. N. L. Aleksandrov, A. M. Konchakov, A. P. Napartovich, and A. N. Starostin, Zh. Éksp. Teor. Fiz., **95**, No. 5, 1614-1624 (1989).
15. I. V. Kochetov, D. A. Mazalov, A. P. Napartovich, et al., Authors' Abstract, All-Union Scientific Seminar, "Interaction of Acoustic Waves with a Plasma," Mergi (1989), pp. 31-32.

# SHOCK WAVES IN A GAS-DISCHARGE PLASMA

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UDC 533.951

*We experimentally determine the dynamic characteristics, and also the parameters (concentration and temperature of the electrons) and the ionic composition of a plasma before and behind the front of a shock wave which is propagating in the gas-discharge plasma. We show that during shock wave propagation in a nitrogen plasma in the initial stages of the discharge, the shock wave is accelerated and amplified, because of the release behind the shock wave front of energy stored in the gas discharge.*

It is widely known that various elementary processes take place in any medium at the front of a shock wave (SW) and in its relaxation layer, and the characteristic times of these processes can differ significantly. This leads to the appearance of different physical effects, including SW instability. Shock waves in a gas-discharge plasma are of special interest, because in addition to the usual processes in strong SWs (dissociation, ionization, recombination, diffusion, precursers, etc.), there is an electric field and discharge current, which impose additional conditions on the kinetics of the ongoing processes.

The diversity and complexity of the processes which take place during SW propagation in a gas-discharge plasma make a theoretical examination extraordinarily difficult, which places priority on the performance of experimental work. The first works on SWs in a partially ionized gas-discharge plasma were conducted in an electric shock tube (EST) more than 20 years ago [1-3]. However, the broad investigation of this phenomenon was begun much later [4]. At present, a significant number of works have been published on experimental investigations of SWs that are propagating both along and across pulsed and steady discharges, and also in decaying gas-discharge plasmas. In these, various experimental methods were used to measure the SW parameters in the gas-discharge plasma, including probes, mass-spectrometry, interferometry, and the schlieren method. As a result, an entire series of new physical effects has been established, and mechanisms for their realization have been proposed. In our review, we examine the more significant of these effects.

**1. SW Acceleration in a Gas-Discharge Plasma.** Chutov [2] first established experimentally that a SW is sharply accelerated during passage from a neutral gas into a gas-discharge plasma, in an investigation of SWs in a glass EST with Ø of 1.6 cm, filled with hydrogen at a pressure of 67 Pa. In these experiments, a quasisteady gas-discharge plasma was created during discharge of a capacitor bank C through resistance R, so that $\tau = RC \sim 1.6$ msec (Fig. 1b). Fig. 1a, taken from [2], represents the

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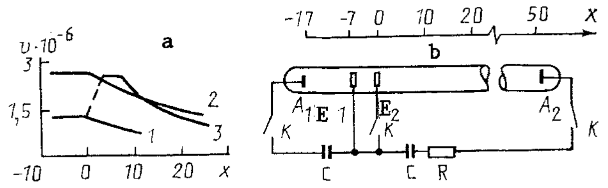


Fig. 1. (a) Shock wave velocity v (cm/sec) as a function of distance x (cm): 1) in a neutral gas; 2) in a gas-discharge plasma; and 3) SW transits from a neutral gas to a plasma at x = 7 cm. (b) Block diagram of the experiment.

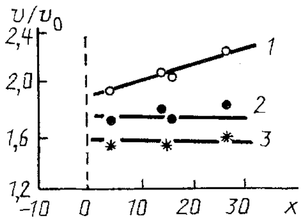


Fig. 2

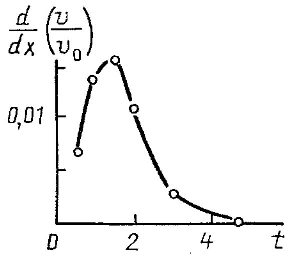


Fig. 3

Fig. 2. Relative shock wave velocity $v/v_0$ in a gas-discharge plasma as a function of distance x: 1) SW in nitrogen plasma at t = 2 msec; 2) in an argon plasma at t = 2 msec; 3) in nitrogen plasma at t = 4 msec.

Fig. 3. Slope of the function $v/v_0 = f(x)$ as a function of discharge burn time t (msec).

SW velocity as a function of the distance x along the axis of the EST when the SW is (1) propagating in a neutral gas, (2) propagating in a gas-discharge plasma, and (3) transitioning at x ~ 7 cm from a gas to a gas-discharge plasma. It is the latter case which makes it very clear that the SW accelerates. Later, SW acceleration was observed in ESTs in longitudinal and transverse steady glow-discharges in air [4], and in argon [5], and also in ordinary diaphragm shock tubes with transverse glow-discharges [6, 7], and RF discharges [8].

There is interest in the acceleration of a SW in a gas-discharge plasma because this effect be induced not only for a trivial reason, that is, change in the SW velocity in a steady thermal inhomogeneity (i.e., SW refraction [9, 10]). It can also be induced as a result of additional energy liberation behind the SW front, as a consequence of V–T relaxation [4, 5, 11-13]; heating of the gas in front of the shock wave by various precursors, including ion-acoustic waves, which are excited in front of the shock [14]; and other causes. Usually the role of these nontrivial mechanisms is clarified by comparing measured and calculated values of the SW velocity. However, the differences turn out to be modest, which makes it impossible to draw unambiguous conclusions concerning the contribution of these mechanisms to the acceleration of the SW. In addition, accounting for radial inhomogeneity of the gas-discharge plasma [6] or two-dimensionality of the flow [7] in a large number of cases in general leads to agreement in practice of experimental results and calculational results, based on the usual hydrodynamic representations.

Comparison of the behavior of SWs in a gas-discharge plasma and a neutral gas with the same conditions is a more promising approach for establishing the role of nontraditional mechanisms of SW acceleration. This was first undertaken in [15, 16]. Figure 2 shows the velocity v of an N-type SW (i.e., an explosive wave (EW)) in a gas-discharge plasma, relative to the velocity $v_0$ of such a wave in a gas with the same conditions, as a function of the distance x along the axis of the discharge. Lines 1 and 3 were obtained for nitrogen, and line 2 for an argon gas-discharge plasma with an initial gas pressure of 133 Pa. The experiments were conducted in a glass EST of ∅ 2 cm. The discharge part and gas-discharge section, in which the gas-discharge plasma is formed, were separated by a formation section of length 20-30 cm in the EST. The SW was created in the developing gas discharge at different moments of time after discharge initiation: lines 1 and 2 were obtained at t = 2 msec, line 3 at t = 4 msec.

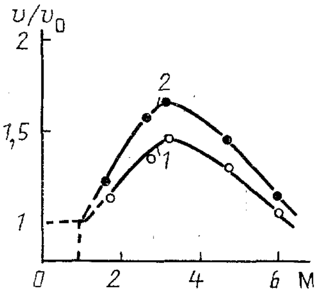


Fig. 4

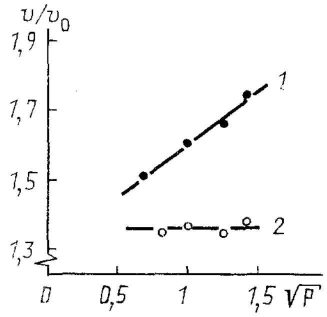


Fig. 5

Fig. 4. Relative SW velocity as a function of Mach number M: 1) $j = 0.25$ A/cm$^2$; 2) $j = 0.5$ A/cm$^2$.

Fig. 5. Relative SW velocity $v/v_0$ in a gas-discharge plasma as a function of gas pressure for $j = 0.5$ A/cm$^2$ and $t = 2$ msec: 1) SW in nitrogen plasma; 2) SW in argon plasma.

The difference between lines 1 and 2 is very clear in Fig. 2, which indicates the difference between the argon and the nitrogen plasmas. In the argon plasma, the SW velocity initially grows rapidly, and then drops off at the same rate as in the neutral gas. In the nitrogen plasma, there is not only a sharp increase in the SW velocity, but also its subsequent uninterrupted amplification, caused by the continuous liberation of energy during the motion of the SW along the discharge axis. This amplification is realized only in the initial stages of the development of the discharge, which indicates the dependence of the slope $d(v/v_0)/dx$ of the lines, similar to line 1 in Fig. 2, on the discharge development time t, shown in Fig. 3. This is probably related to the kinetic population of the excited vibrational levels of the nitrogen molecules, which decreases exponentially with growth of the translational temperature of the gas. In the later stages of discharge development, when the gas is quite strongly heated, the population of the excited vibrational molecular levels drops sharply, which is also reflected in line 3 in Fig. 2, and in the value of $d(v/v_0)/dx \sim 0$ for $t \geq 4$ msec, in Fig. 3.

The relative amplification of the SW depends on the Mach number M (Fig. 4). The maximum in this dependence is due to the fact that at small Mach numbers, the translational temperature behind the SW front is insufficient for intensive V–T relaxation, while for large M, the relative contribution of energy liberated during V–T relaxation becomes less.

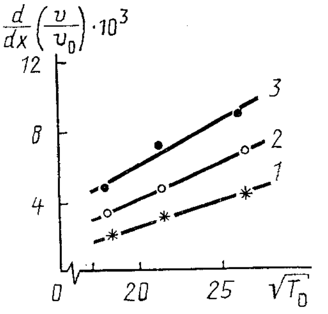
Amplification of the SW in a gas-discharge plasma also depends on the pressure P of the nitrogen (line 1 in Fig. 5), unlike argon (line 2 in Fig. 5). This corresponds to the representation of the liberation of additional energy from the discharge during the passage of the shock wave.

This representation also corresponds to the dependence of the relative amplification of the SW $v/v_0$ on the initial temperature $T_0$ of the nitrogen, in which discharges of different intensities are formed. This is shown by the results, given in Fig. 6, for $j = 40$, 60, and 125 mA/cm$^2$ (lines 1, 2, 3).

Thus, we have established that the SW amplification effect in a nitrogen gas-discharge plasma can take place not only because of the heating of the gas and the resultant SW refraction, but also as a consequence of the release of energy behind the SW front, that has been stored in the gas discharge.

**2. Ionization of Gas at a SW Front.** Unlike the ionization of gas behind the front of strong shock waves, which is caused by strong heating of the gas, a shock wave in a gas-discharge plasma changes the degree of its ionization at any intensity. In this case, it is significant that there is a bipolar electric field at the shock wave front, as a consequence of the steep gradient in the concentration of charged particles. Because of this field, these is a jump in the potential, across which flows an electric current. When the direction of the bipolar electric field coincides with that of the electric field in the discharge, then additional energy is released in the region of the bipolar potential jump, which leads to additional ionization at the front. This increase in ionization manifests itself as a peculiar "electric detonation."

The first of these facts was observed in [3] during experimental investigation of SWs in an argon gas-discharge Plasma for $j \sim 80$ A/cm$^2$. Figure 7, which was taken from this work, shows the ratio of the concentration of charged particles behind the front n to the charged-particle concentration before the front $n_0$ for a weak shock wave in an argon gas-discharge plasma for various discharge currents $J_d$. The points in Fig. 7 are experimental results, while the crosses are for an approximate calculation, assuming that all energy released at the front is expended on additional ionization, so that



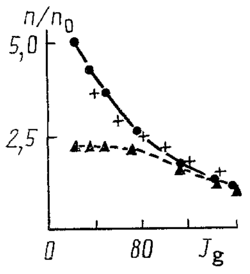


Fig. 6

Fig. 7

Fig. 6. Slope of the function $v/v_0 = f(x)$ in a nitrogen plasma as a function of initial gas temperature $T_0$ at $t = 2$ msec: 1) $j = 40$ mA/cm$^2$; 2) $j = 60$ mA/cm$^2$; 3) $j = 125$ mA/cm.

Fig. 7. Relative concentration $n/n_0$ of charged particles behind a SW front in an argon gas-discharge plasma, as a function of the magnitude of the gas-discharge current $J_d$.

$$\Delta n = n - n_0 = \frac{j\Delta V}{\varepsilon_i v}.$$

In cases where the direction of the electric field in the discharge is opposite in direction to that of the SW front, the change in the concentration of charged particles at the front (triangles in Fig. 7) is practically the same as for the compression of the plasma at the front (dashed curve in Fig. 7) for a weak shock wave. Subsequently, [17] substantiated this effect for nitrogen gas-discharge plasmas as well.

For higher SW intensities, i.e., for larger Mach numbers, additional ionization at the SW front due to the passage of current across the self-consistent jump in the potential does not play a significant role against the background of strong ionization caused by heating of the gas-discharge plasma at the SW front.

Thus, ionization of the gas-phase discharge at the SW front is possible both as a consequence of ordinary ionization in strong SWs, and as the result of the particular effect of "electric detonation." It should be noted that to date detailed study of the state of the gas-discharge plasma behind a shock front has not been done. In particular, it is not known if equilibrium is established behind the front, especially in the case of explosive waves.

**3. Relaxation of the Gas-Discharge Plasma behind the Shock Front.** It is now known [18, 19] that when certain elementary inelastic processes with different characteristic times take place behind the shock front, there can arise a nonmonotonic relaxation layer, which in some cases can be unstable, leading to instability of the SW as a whole. Behind a SW front in a gas-discharge plasma, an electric field and discharge current are added to the various elementary processes; these additionally influence the behavior of the relaxation layer and the shock heating of the plasma.

Figure 8 shows the results of probe measurements of the concentration n and electron temperature $T_e$ before and behind a strong SW front in an argon plasma for $P = 67$ Pa and $j = 10$ A/cm$^2$, when a significant increase in the concentration of charged particles occurs at the front, with a simultaneous decrease in the electron temperature, caused by the balance in the discharge. Indeed, when there is a larger increase in electron concentration at the SW front than there is compression of the plasma as a whole, then the electrical conductivity grows behind the front. Because of the continuity of the gas-discharge current, this growth in conductivity leads to a decrease in the electric field strength behind the front, and thus to a decrease in the electron temperature.

The change in electron concentration behind the front of weak explosive waves in a gas-discharge plasma corresponds to the density profile behind the explosive wave. However, as for strong waves, the increase in the concentration behind the front is accompanied by a decrease in electron temperature, which is shown by the results of measuring n and T behind the SW front in a nitrogen gas-discharge plasma at $P = 133$ Pa and $j = 0.5$ A/cm$^2$ (Fig. 9).

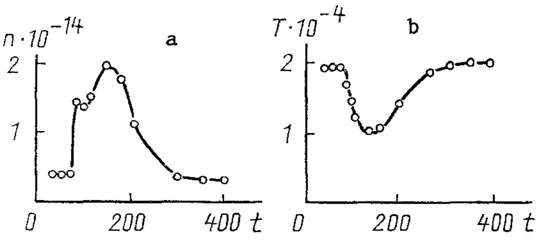


Fig. 8. Profiles of (a) charged particle concentration n and (b) electron temperature $T_e$ in a SW propagating in an argon plasma. n is in $cm^{-3}$, T in K, t in μsec.

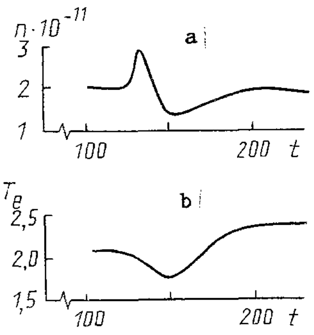


Fig. 9

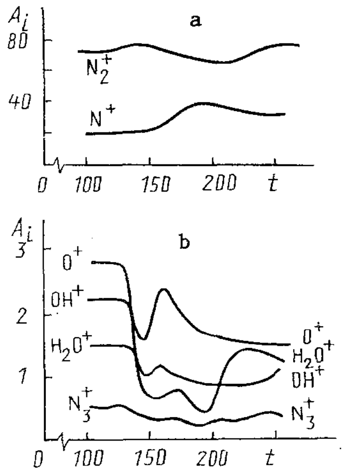


Fig. 10

Fig. 9. Profiles of (a) charged particle concentration n and (b) electron temperature $T_e$ in a shock wave propagating in a nitrogen plasma. $T_e$ in eV.

Fig. 10. Profiles of relative concentrations of various types of ions before and behind a shock wave front in a nitrogen gas-discharge plasma. $A_i$ in %.

Relaxation of the plasma behind the front of an explosive wave in a gas-discharge plasma is associated with not only a change in the electron and ion concentrations, but also with a change in the ion content of the plasma, as indicated by the results of mass-spectrometer analysis done behind the front in nitrogen gas-discharge plasma at $P = 133$ Pa and $j = 0.5$ A/cm$^2$, shown in Fig. 10. As is evident from this figure, not only does the relative ionic composition of the basic ions change (Fig. 10a), but also that of the trace ions as well (Fig. 10b). This opens up the possibility of additional control over the ionic composition of the gas-discharge plasma, which may have practical significance.

The gas-discharge plasma behind an SW front is in practice represented by a gas discharge in special conditions, which cannot be created in the usual way. The characteristics of this discharge differ in an advantageous way from those of an ordinary discharge, primarily in the increased stability with increased energy deposition. In particular, significant amplification of the laser effect was attained in such discharges in [20, 21].

The effects considered here do not by any means cover all properties of the behavior of shock waves in a gas-discharge plasma, which is a subject that is being intensively studied at present. For example, we can mention the structure of the shock front, determined by precursors [22, 23], or the possibility of forming solitons in a weakly ionized plasma [24, 25].

## NOTATION

v, velocity of the shock wave; t, time of entry of the SW into the plasma, after the instant of discharge initiation; M, Mach number; P, gas pressure; T, gas temperature; $T_e$, electron temperature; j, gas-discharge current density; n, electron concentration; $\varepsilon_i$, ionization energy; $\Delta V$, jump in potential at the SW front; $J_d$, magnitude of the gas-discharge current.

## LITERATURE CITED

1. Yu. I. Chutov, Ukr. Fiz. Zh., **14**, No. 3, 514-517 (1969).
2. Yu. I. Chutov, Ukr. Fiz. Zh., **15**, No. 4, 682-685 (1970).
3. Yu. I. Chutov, Zh. Prikl. Mekh. Tekh. Fiz., No. 1, 124-130 (1970).
4. A. I. Klimov, A. N. Koblov, G. I. Mishin, et al., Pis'ma Zh. Tekh. Fiz., **8**, No. 7, 439-443 (1982).
5. I. V. Basargin, and G. I. Mishin, Pis'ma Zh. Tekh. Fiz., **11**, No. 4, 209-215 (1985).
6. N. V. Evtyukhin, A. D. Margolin, and V. N. Shmelev, Khim. Fiz., **3**, No. 9, 1322-1327 (1984).
7. A. E. Kim and D. K. Raevskii, Propagation of a Shock Wave Through a Region of Heated Gas [in Russian], Preprint of the Institute of High Temperatures No. 2-250, Moscow (1988).
8. S. A. Bystrov, V. I. Ivanov, and F. V. Shugaev, Fiz. Plazmy, **15**, No. 5, 558-562 (1988).
9. J. Uizem, Linear and Nonlinear Waves [Russian translation], Moscow (1977).
10. B. L. Rozhdestvenskii and N. N. Yanenko, Systems of Quasilinear Equations and Their Application to Gasdynamics [in Russian], Moscow (1978).
11. A. Kh. Mnatsakanyan, G. V. Naidis, and S. V. Rumyantsev, "Shock wave propagation through nonuniform and non-equilibrium gas regions," in Proc. XVII International Symposium on Shock Tubes and Waves (Aachen, FRG, July 1987), VCH, Aachen (1987), pp. 201-205.
12. A. A. Rukhadze, V. P. Silakov, and A. V. Chebotarev, Kratkie Soob. Fiz., No. 6, 18-23 (1983).
13. F. G. Baksht and G. I. Mishin, Zh. Tekh. Fiz., **53**, No. 5, 854-857 (1983).
14. R. F. Avramenko, A. A. Rukhadze, and S. F. Teselkin, Pis'ma Zh. Éksp. Teor. Fiz., **34**, No. 9, 485-488 (1981).
15. Yu. I. Chutov, V. N. Podol'skii, and D. A. Braion, Abstracts of Papers from the Vth All-Union Conference on the Physics of Gaseous Discharges (Omsk, June, 1990) [in Russian], Omsk (1990), Part II, pp. 87-88.
16. Yu. I. Chutov, V. N. Podol'skii, and D. A. Braion, Pis'ma Zh. Tekh. Fiz., **17**, No. 3, 59-62 (1991).
17. Yu. I. Chutov, V. N. Podol'skii, and V. Yu. Palkin, III All-Union Conference on the Physics of Gaseous Discharges: Abstracts of Papers (Kiev, October 1986), Kiev (1986), Part III, pp. 466-468.
18. G. I. Mishin, A. A. Bedin, and M. I. Yushchenkova, Zh. Tekh. Fiz., **51**, 2315-2324 (1981).
19. A. F. P. Houwing, T. J. McIntyre, P. A. Taloni, and R. J. Sandeman, J. Fluid. Mech., **170**, 319-337 (1986).
20. E. Wasserstrom, Y. Crispin, J. Rom, and J. Shwartz, J. Appl. Phys., **49**, No. 1, 81-86 (1978).
21. S. Miyashire, Zeitsh. Naturforsch., **39a**, 626-629 (1984).
22. A. A. Filyukov, Dokl. Akad. Nauk SSSR, **302**, No. 5, 1082-1085 (1988).
23. I. V. Basargin, and G. I. Mishin, Pis'ma Zh. Tekh. Fiz., **15**, No. 8, 55-60 (1989).
24. Yu. P. Bliokh, A. V. Tur, and V. V. Yakovskii, Acoustic Waves in a Weakly Ionized Gas [in Russian], Preprint 88-4 of the Khar'kov Institute of Technical Physics (1988).
25. L. Stenfle, N. L. Tsintsadse, and T. D. Buadse, Phys. Lett. A, **135**, No. 1, 37-38 (1989).