MECHANISM OF STABILIZATION OF A PLASMA BY HIGH FREQUENCY ELECTROMAGNETIC FIELDS

L. V. DUBOVOĬ and V. F. SHANSKIĬ

Submitted to JETP editor March 19, 1966

J. Exptl. Theoret. Phys. (U.S.S.R.) 51, 412—416 (August, 1966)

The spatial structure of the Kadomtsev-Nedospasov instability in a germanium electron-hole plasma is investigated experimentally. It is shown that, in agreement with theory, zero boundary conditions exist on the sample ends. A mode spectrum with various spatial periods along the sample axis are detected by means of a microwave technique. The relative content of short wave modes increases with growth of the quasistationary electric field strength. This latter circumstance explains qualitatively the increased efficiency of instability suppression by an alternating electric field when the quasistationary electric field strength increases.

IN connection with searches for ways of further improving the methods of magnetic thermal insulation of a plasma, interest has greatly increased recently in systems in which the plasma instability is eliminated by using rapidly alternating electromagnetic fields. Of particular interest is a plasma stabilization principle which is a close analog of strong focusing in accelerators. Such a stabilization method can be used when the interaction of the unstable plasma with the external high-frequency field can be described with the aid of a Mathieu or Hill equation.

Experiments[1] carried out in an electron-hole plasma of a semiconductor have demonstrated that instability of the Kadomtsev-Nedospasov type can be efficiently suppressed by an alternating electric field. On the basis of the experimentally obtained strong dependence of the efficiency of stabilization on the length of the samples on which the measurements were made, Kadomtsev advanced a hypothesis according to which an important role is played in the investigated mechanism by effects connected with reflection of instability waves from the ends of the plasma column. Using this hypothesis as a starting point, Vladimirov has shown[2] that if one assumes zero boundary conditions on the ends of a semiconductor sample, the solution previously obtained[3] for the plasma-parameter perturbations connected with the presence of the instabilities, of the type $n_1 \sim \exp(ikz)$, where $k \sim 2\pi/a$ (a = plasma radius), should be supplemented by allowance for the longer-wave spatial modulation in the form $n_1 \sim \exp(ikz)\sin(\pi nz/L)$, where L is the length of the sample. The presence of a spatial spectrum of harmonics of the instability has made it possible to reduce the problem to the usual method[4] of describing the stabilization process with the aid of the Hill equation. In the resultant modified solution, the presence of terms of the type $\sin(\pi nz/L)$ is fundamental in explaining the effect of stabilization of a helical current-convective instability by means of an alternating electric field. Indeed, for sufficiently long samples with $L \gg a$, the results of the new theory coincide with those obtained earlier[3], where the considered type of instability is described by a differential equation of first order in the time and does not reduce to a Mathieu or Hill equation.

The present investigation, which is a continuation of our earlier work[1], is devoted to an experimental verification of the agreement between the experimental conditions and the theoretically assumed zero boundary conditions on the ends of the plasma column in a semiconductor. We have also checked on the presence (resulting from this assumption) of spatial long-wave harmonics of the instability.

All the experiments were carried out in germanium electron-hole plasma. The semiconductor samples had longitudinal dimensions L from 0.5 to 1.5 cm and transverse dimensions 1×1, 1.5×1.5, and 2×2 mm. The longitudinal spatially-homogeneous magnetic field in the experiment could be varied from 0 to 12 kOe. The procedure for exciting the instability by means of an alternating electric field and the determination of its position were identical to those described in[1]. We used a microwave technique[5] to observe the system-parameter oscillations connected with the presence of instability in the semiconductor plasma. A block diagram of the measurements is shown in Fig. 1. The tested sample was made to pass through the wall of a waveguide, in which TE_{01} modes were excited at

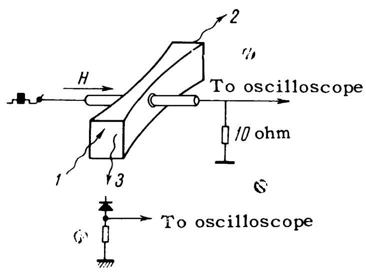

FIG. 1. Block diagram of the microwave method of determining the spatial structure of the instability: 1 – incident wave, 2 – transmitted wave, 3 – reflected wave.

8 mm wavelength. To increase the resolution of the system, the waveguide dimensions parallel to the crystal axis were decreased to 1 mm.

We registered in the experiments the amplitude of the reflected or transmitted microwave signal, which was proportional to the amplitude of variation of the average value of the carrier density in the region where the waveguide was crossed by the semiconductor sample. The maximum deviations of the carrier densities from their equilibrium values served as a measure of the amplitude of the instability in the given section of the sample.

To measure the oscillation amplitude u(z) of the semiconductor parameters in different sections, the waveguide could be moved smoothly along the crystal axis. As before[1], the measurements were made in a pulsed mode to prevent heating of the semiconductor. The duration of the current pulse exciting the instability was 10^{-3} sec. The frequency of the stabilizing alternating electric field was 3 Mcs. The electric field intensities used in the experiments were of the order of 50—100 V/cm.

Figure 2 shows the experimentally obtained oscillograms, which demonstrate the stabilizing role of the high frequency electric field for the case of a waveguide placed in the center of a semiconductor sample. The oscillograms coincide with those obtained in[1] by a probe technique.

Figure 3 shows a normalized plot of e(z) for the most typical experimental conditions: L = 10 mm, a = 0.5 mm, E_0 = 30 V/cm, $\widetilde{E}$ = 0, and H_0 = 8.5 kOe. We see from the obtained dependence that the theoretically assumed [2] vanishing of the current perturbations on the ends of the sample is satisfied with a high degree of accuracy. The correctness of this main premise of the theory is very important evidence in favor of further conclusions of the theory.

Let us dwell in greater detail on the obtained variation of u(z) for $0 \leq z \leq L$. Vladimirov has shown[2] that the stability criterion does not depend in practice on the number of the mode so long

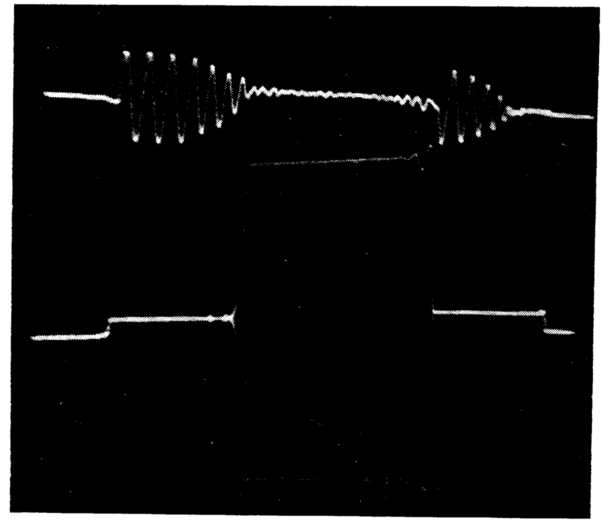

FIG. 2. Effect of alternating electric field on the instability. Upper trace – detected reflected microwave signal; lower trace – intensity of electric field (H_0 = 8.5 kOe, E_0 = 30 V/cm, L = 10 mm, a = 0.5 mm).

as the inequality $\pi na/L \ll 0.8$—3 is satisfied when the surface recombination rate varies from S = 2×10^2 to 10^4 cm/sec. (Thus, for example, in a sample with L/a = 20 and S $\sim 2 \times 10^2$ cm/sec, spatial submodes of the instability, up to the fifth, should be simultaneously excited when the critical values of the fields E_c and H_c are reached.) The plot in Fig. 3 is the amplitude of the resultant signal, consisting of a superposition of correlating modes of spatial harmonics shifted in time phase. However, the very fact that the obtained distribution envelope has an irregular shape is unambiguous evidence in favor of a broad spectrum of spatial harmonics, bounded on the side of the longest wavelengths by the longitudinal dimensions of the sample. In the general case of a strongly developed instability, with $E_0 \gg E_c$, the situation is complica-

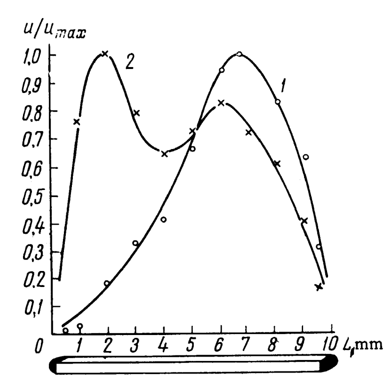

FIG. 3. Normalized dependence of the amplitude of the oscillations of the carrier density along the sample, L/a = 20. Curve 1 – H_0 = 8.5 kOe, E_0 = 25 V/cm; curve 2 – H_0 = 8.5 kOe, E_0 = 80 V/cm.

ted by the presence of higher temporal harmonics of the oscillations, but when $E_0 \gtrsim E_c$ their contribution is small. When working in the range of fields $E_0 \gtrsim E_c$, the first temporal harmonic, having the largest growth increment, was separated by means of filters. No influence of higher temporal harmonics of the instability on the stabilization mechanism was observed in the experiments.

Returning to the plot of u(z), we note that, owing to purely mathematical difficulties, no rigorous expression was obtained for it in the theory [2]. A theoretical value for u(z) was obtained only for the case of the first two spatial modes, which have the form

$$\Phi_1(z,t) \sim b_1 \sin\frac{\pi}{L} z \sin(\omega t + \varphi),\ \Phi_2(z,t) \sim b_2 \sin\frac{2\pi}{L} z \sin \omega t,$$

where the function $b_n(z)$ depends in a complicated manner on the parameters of the semiconductor and leads (as already noted) to the presence of additional small-scale oscillations of the parameters of the instability in a space with longitudinal dimensions on the order of a. These oscillations were not resolved by our apparatus.

A more rigorous expression for u(z) is

$$u(z,t) \sim \sum_n \Phi_n(z,t) \sim \sum_n b_n \sin\frac{\pi n}{L} z \sin(\omega t + \varphi_n),$$

or, confining ourselves only to maximum values,

$$u(z) \sim \sum_n b_n \sin\frac{\pi n}{L} z.$$

In accordance with the general character of the theory, we should expect the absence of high spatial harmonics of the components of the current oscillations, or a small contribution from them to the overall balance, to reduce the efficiency of the stabilization process. This theoretical premise was verified qualitatively by experimentally studying the dependence of the efficiency of the stabilization process on E_0, characterized by the relation $\eta = \tilde{E}/E_0$, at a point where the amplitude of the instability was reduced to one half under the influence of the field $\tilde{E}$. The obtained plots of $\eta(E_0)$ are shown in Fig. 4. Figure 5 shows the spectrum of b_n calculated from the experimental relation

$$u(z) \sim \sum_n b_n \sin\frac{\pi n}{L} z = f(E_0).$$

We see from Fig. 4 that with increasing E_0 the efficiency of the stabilization increases (η decreases), which should lead, in accordance with the theoretical predictions, to an increase in b_n. Figure 5 shows the measured dependence of the relative content of the spatial submodes in the instability spectrum on the value of E_0. We see that the efficiency of the high frequency stabilization increases with increasing amplitude of the higher spatial harmonics of the semiconductor current plasma instability, in qualitative agreement with the calculations.

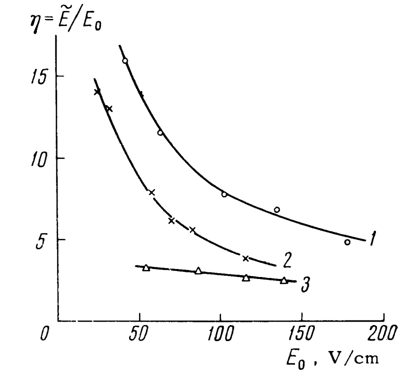

FIG. 4. Efficiency of stabilization vs. the electric field E_0. Curve 1 – for sample L/a = 10; curve 2 – for sample with L/a = 20; curve 3 – for sample L/a = 6; $\beta = \tilde{u}/u_0 = 0.5$; H = 8.5 kOe.

To conclude the discussion of our data, we can state that the experiments confirm the correctness of the main premise of the theory, namely the choice of the zero boundary conditions on the ends of the system. Experiment confirms directly the process of spatial long-wave harmonics of the instability, as predicted by the calculations, and also shows that the stabilization efficiency depends strongly on the spectrum of the spatial harmonics in the current plasma in the unstable state.

The qualitative character of the theory does not permit at present an exact quantitative comparison

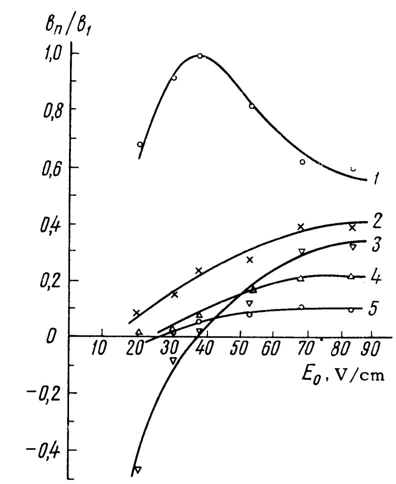

FIG. 5. Relative content of spatial modes of the instability vs. the electric field. Curve 1 – content of mode, with spatial period equal to π/L, reduced to unity. Curves 2, 3, 4, 5 – relative contents of mode with spatial period $2\pi/L$, $3\pi/L$, $4\pi/L$, $5\pi/L$, respectively.

of the data of the experiment with the calculations. It is desirable to refine further the theory proposed by Vladimirov, in connection with the importance of the high frequency method of stabilization of instability in a plasma, which is now being developed in a large number of laboratories.

[1] L. V. Dubovoĭ and V. F. Shanskiĭ, JETP 48, 800 (1965), Soviet Phys. JETP 21, 530 (1965).

[2] V. V. Vladimirov, JETP 49, 1562 (1965), Soviet Phys. JETP 22, 1071 (1966).

[3] M. Glicksman, Phys. Rev. 124, 1655 (1961).

[4] S. M. Osovets, JETP 39, 311 (1960), Soviet Phys. JETP 12, 221 (1961).

[5] I. Misawa and I. Jamada, J. Appl. Phys. Japan 2, 1 (1963).

Translated by J. G. Adashko
47