Multifilament and multidomain stationary states in a hot electron-hole plasma in GaAs

B. S. Kerner and V. F. Sinkevich

(Submitted 21 September 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 10, 359–362 (20 November 1982)

An electron-hole plasma in GaAs which is heated by a field initially stratifies along the direction perpendicular to the field at room temperature. This stratification results in the formation of numerous current filaments. As the voltage across the sample is increased, these filaments become stratified along the field direction into domains (striations), and the sample becomes filled with plasma "droplets."

PACS numbers: 72.30. + q, 72.80.Ey, 71.35. + z

This letter reports experimental observation of an effect predicted theoretically in Refs. 1–4: the formation of stable, steady-state multifilament and multidomain states in an electric-field-heated quasineutral electron-hole plasma. Stratificiation of the plasma was observed at room temperature ($T_0 \cong 300$ K) in homogeneous n-GaAs samples with a thickness $l_z = 0.25 \times 10^{-4}$ cm, a length $l_x = 20 \times 10^{-4}$ cm, and an equilibrium-electron concentration $n_0 = 1.2 \times 10^{17}$ cm^{-3}, produced by gas-phase epitaxy on semi-insulating GaAs ($n < 10^{14}$ cm^{-3}) (Fig. 1). Planar antiblocking contacts were produced by depositing an AuGe-Au film in a vacuum and then brazing it. Before the beginning of impact ionization (at $U < U_i$; Fig. 2), the voltage-current characteristic of the samples had its conventional shape[5]: At $U_H < U < U_i$ there is a region of saturation in the current J, which corresponds to the presence of a strong-field domain near the anode (Fig. 1). An electron-hole plasma appeared in these samples as a result of impact ionization of the carriers in the region of the static domain near the anode. The beginning of impact ionization of the carriers was accompanied by the appearance of a region of weak recombinational emission near the anode. At a certain critical voltage $U = U_c > U_i$ on the part of the characteristic having the positive differential conductivity, the emission near the anode became stratified along the y axis, perpendicular to

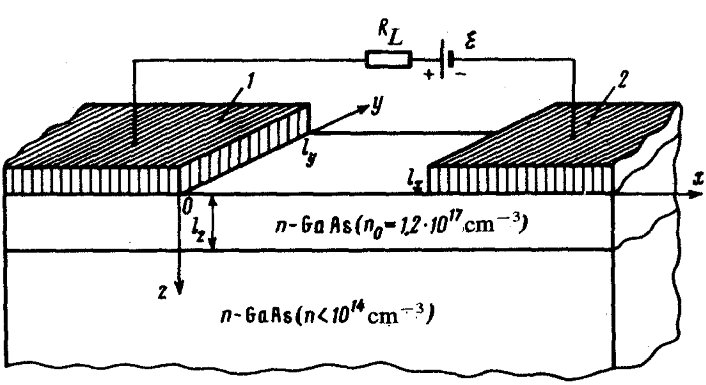


FIG. 1. Sample structure. 1—Anode; 2—cathode.

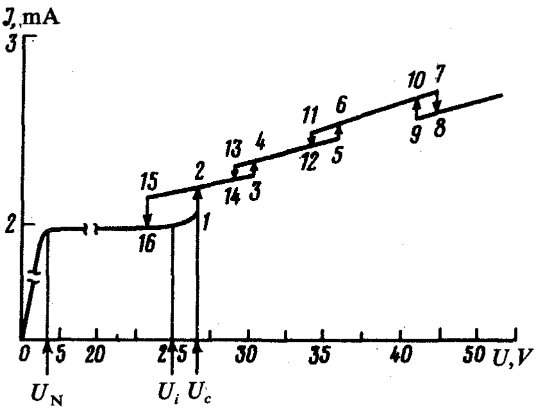
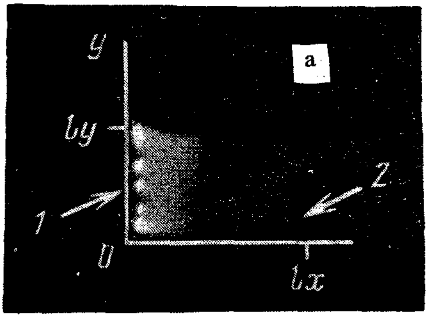


FIG. 2. Voltage-current characteristic of one of the samples. The branch 15-3 corresponds to a state with $N = 3$ filaments; 13-5—$N = 4$; 11-7—$N = 5$; 9-8—$N = 5$ filaments and $M = 2$ domains ($m = 7$ droplets).

the electric field, which was applied along the x axis (Figs. 1 and 3a). This stratification of the emission is evidence of a stratification of the electron-hole plasma and of the formation of current filaments. As a rule, this effect is accompanied by a jump in the current J on the voltage-current characteristic (the transition 1→2 in Fig. 2). The brightness and contrast of the emission from the electron-hole plasma in each of the filaments falls off along the x axis because of the recombination of holes as they undergo an ambipolar drift toward the cathode and also because of transverse diffusion. In other words, the filament is comet-shaped, with the head of the comet (the droplet of electron-hole plasma) lying near the anode ($x = 0$) and with its tail stretched out along the direction of the applied field (the x axis; Fig. 3a). The tail unravels along the y axis. With a further increase in U, the number of filaments (N) and, correspondingly, the number of droplets near the anode increase, while if U is reduced these numbers decreases, generally in a process involving many hysteresis regions (Fig. 2). In sufficiently homogeneous samples, there are stationary states with a periodic arrangement of the current filaments (the droplets near the anode) along the entire transverse dimension (l_y) of the sample (Fig. 1). For samples with $l_y = 1.5 \times 10^{-3}$ cm the maximum number of filaments is 6–8, while that for $l_y = 15 \times 10^{-3}$ cm is several tens.

At some voltage U, the emission of the electron-hole plasma (at the tail of the filament) abruptly stratifies along one of the filaments (or, sometimes, simultaneously along several of them). A certain number (M) of plasma droplets appear, positioned along the x axis far from the anode (Fig. 3b, $M = 2$). This effect is evidence of a stratification of the current filament into domains (striations) along the x axis. This effect is accompanied by a jump in J (the jump 7→8; Fig. 2). With increasing U, the number (M) of droplets separated from the anode increases, because of both the appearance of new droplets along the given filament and the stratification of the electron-hole plasma along other current filaments. As a result, the sample becomes filled with plasma droplets, in a number $m = N + M$. The radius of the droplets and the minimum distance between them are $\sim 10^{-4}$ cm. The emission brightness and the radius of



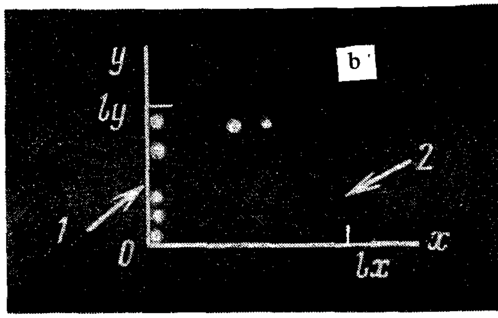


FIG. 3. Photographs of the emission (in the visible part of the spectrum) of an electron-hole plasma which has undergone stratification in the sample whose voltage-current characteristic is shown in Fig. 2. The photographs correspond to two different states with (a) $N=5$ current filaments (branch 11-7 in Fig. 2) and (b) $m=7$ droplets ($N=5$ current filaments and $M=2$ domains; branch 9-8 in Fig. 2). The coordinate axes in parts a and b correspond to the axes in Fig. 1. (For clarity in the image of the droplets, the exposure time for the photograph in part b was chosen eight times shorter than that for the photograph in part a. For this reason, in part b we can see some filament heads near the anode, but the fainter filament tails seen in part a cannot be seen in part b.) Part b corresponds to the case in which only one of the filaments, at $y \cong l_y$ ($l_y = 1.5\times10^{-3}$ cm) stratifies into domains ($M=2$).

the droplets are essentially constant along the y axis, but they decrease slightly with distance from the anode.

At sufficiently high values of U, an irreversible breakdown of the sample results from the overheating of the GaAs lattice. Either narrow channels melt through the sample along the current filaments, or several local regions of damage to the GaAs film form at the positions of the droplets.[1)]

This effect can be explained by the theory of Refs. 1–4 for the stratification of an electron-hole plasma. For n-GaAs at $T_0 = 300$ K the carrier energy is dissipated on polar optical phonons, while the momentum is dissipated on the same phonons and also on donors ($n_0 \gtrsim 10^{17}$ cm^{-3}). In the case of a dense plasma, the electron-hole dissipation of the momentum is predominant. The momentum and energy relaxation times, $\tilde{\tau}_{e,h} \propto T^a_{e,h}$ and $\tau_{e,h} \propto T^s_{e,h}$, respectively, are thus increasing functions of the average energy of the hot electrons (T_e) and holes (T_h); i.e., $\alpha, s>0$ (Ref. 6). At $n \cong 10^{17}$ cm^{-3}, the scale time for electron-electron collisions is $\tau_{ee} \cong 2\times10^{-13}s\ll\tau_{e,h} \sim 10^{-12}$ s (Ref. 6). The relaxation length for the carrier energy is $l_\epsilon \cong 2\times10^{-5}$ cm, the ambipolar diffusion length is $L\sim10^{-4}$ cm, and the screening length is $l_D \sim 10^{-5}$ cm. We thus have $l_D < l_\epsilon \ll L \ll l_x, l_y$. All the necessary conditions for stratification of a hot electron-hole plasma are thus satisfied.[3,4] The hole concentration p is at a maximum near the anode and falls off as the holes drift toward the cathode. Near the anode, the plasma is therefore dense ($\tau_{ee} < \tilde{\tau} \ll \tau$), and it is in this region that all the conditions for current stratification are met,[3] and the numerous filaments form. The density of the electron-hole plasma falls off with distance from the anode toward the cathode; i.e., the current stratification conditions are satisfied only in a relatively small region of the sample (near the anode in Fig. 3a; "small" refers to the dimension along the x axis). The filaments are thus comet-shaped (Fig. 3a). For the less dense electron-hole plasma

($\tilde{\tau} < \tau_{ee} \ll \tau$) far from the anode, however, where the curent filamentation conditions do not hold,[3] conditions are satisfied for a stratification of the plasma along the field direction.[4] As a result, the plasma in the filaments stratifies into striations (or domains).[4] In the region in which the striations form, the electron-hole plasma becomes dense again. The plasma density (or the current density) in each striation thus undergoes an additional stratification (contraction) along the y axis, and plasma droplets of essentially uniform size form in the sample.[2)]

Each state with N filaments and M striations ($m = N + M$ droplets) observed experimentally exists only in a certain voltage interval $U^m_{\min} \leqslant U \leqslant U^m_{\max}$. At $U > U^m_{\max}$, the number of filaments or striations increases (e.g., 3→4 in Fig. 2), while at $U < U^m_{\min}$ this number decreases (Fig. 2). We find $U^m_{\max} > U^n_{\max}$ and $U^m_{\min} > U^n_{\min}$ at $m > n$. This evolution of the number of filaments and domains (striations) as U is changed is consistent with the nonlinear theory of inhomogeneous states in nonequilibrium systems.[1,2] According to the theory of Refs. 2–4, the minimum distance between the filaments and striations for these GaAs samples should be on the order of $L \cong 10^{-4}$ cm, again in agreement with the experimental observations.

We wish to thank N. A. Kozlov for participation in planning and carrying out the experiments, and we thank V. V. Osipov for some useful comments offered in a discussion of this study.

[1)]If the sample contains inhomogeneities, the multifilament and, correspondingly, multidomain periodic states do not occur. As U is increased, the local thermal breakdown, which occurs in the sample in the vicinity of a current filament localized at an inhomogeneity, occurs sooner.

[2)]The density of the electron-hole plasma in the droplets tends toward saturation because of the decrease in the carrier lifetime with increasing carrier concentration. The energy released during recombination causes a pronounced local heating of the GaAs, and at high values of U this heating evaporates the arsenic at the positions of the plasma droplets, i.e., causes spotty damage to the sample.

[1]B. S. Kerner and V. V. Osipov, Zh. Eksp. Teor. Fiz. **74**, 1675 (1978) [Sov. Phys. JETP **47**, 874 (1978)].
[2]B. S. Kerner and V. V. Osipov, Zh. Eksp. Teor. Fiz. **79**, 2218 (1980) [Sov. Phys. JETP **52**, 1122 (1980)]; Fiz. Tekh. Poluprovodn. **13**, 721 (1979) [Sov. Phys. Semicond. **13**, 424 (1979)].
[3]B. S. Kerner and V. V. Osipov, Zh. Eksp. Teor. Fiz. **71**, 1542 (1976) [Sov. Phys. JETP **44**, 807 (1976)]; Fiz. Tekh. Poluprovodn. **13**, 891 (1979) [Sov. Phys. Semicond. **13**, 523 (1979)].
[4]B. S. Kerner and V. V. Osipov, Fiz. Tverd. Tela (Leningrad) **21**, 2342 (1979) [Sov. Phys. Solid State **21**, 1348 (1979)].
[5]V. L. Bonch-Bruevich, A. G. Mironov, and I. P. Zvyagin, Domennaya élektricheskaya neustoĭchivost' v poluprovodnikakh (Domain Electrical Instability in Semiconductors), Nauka, Moscow, 1972.
[6]E. M. Conwell, High Field Transport in Semiconductors, Academic Press, New York, 1967.

Translated by Dave Parsons
Edited by S. J. Amoretty