Microwave-induced patterns in *n*-GaAs and their photoluminescence imaging

V. V. Bel'kov
A.F. Ioffe Physico-Technical Institute of the Russian Academy of Sciences, St. Petersburg 194021, Russia

J. Hirschinger, D. Schowalter, F.-J. Niedernostheide,* S. D. Ganichev, and W. Prettl
Institut für Experimentelle und Angewandte Physik, Universität Regensburg, 93040 Regensburg, Germany

D. Mac Mathúna
Physics Department, Trinity College, Dublin 2, Ireland

V. Novák
Institute of Physics AS CR, Cukrovarnická 10, 162 00 Praha 6, Czech Republic
(Received 8 December 1999)

Using the technique of photoluminescence imaging, self-organized patterns of high-electron density in homogeneous *n*-GaAs layers under homogeneous microwave irradiation are studied. The structures are shown to be analogous to current filaments in a static electric field. The symmetry of the microwave induced patterns is not constrained by the current feeding electrodes. It is, however, concluded that a feedback mechanism exists between the formation of high-conducting structures and the homogeneity of the incident microwave irradiation.

I. INTRODUCTION

Open nonlinear systems driven by external forces into a state far from thermal equilibrium may undergo nonequilibrium phase transitions and spontaneously evolve into ordered spatial and temporal structures. In contrast to closed systems, which relax after perturbation to thermal equilibrium with maximum entropy, open dissipative and extended systems may form self-organized patterns of locally reduced entropy that are maintained by a continuous flow of energy through them. The electron system of semiconductors is a model object well suited to the study of self-organized pattern formation because states far from thermal equilibrium are easily accessible by applying external electric fields.[1,2] Furthermore, electrons react rapidly to external perturbations, which allows the investigation of nucleation dynamics on short-time scales. Generic dissipative structures are electric-field domains and current filaments.[3] In both cases the formation of structures is influenced by electric contacts that act as nucleation centers.

At low temperatures the basic nonlinearity in moderately doped semiconductors is associated with the autocatalytic generation of free carriers by impact ionization of shallow impurities. The electric field accelerates free electrons, increasing their energy, which leads to an abrupt free-carrier multiplication at a critical electric-field strength of a few volts per cm. In static electric fields this nonlinearity is known to yield complex filamentary current patterns nucleating at electric contacts.[4–6] In the experiments reported here, electromagnetic waves have been used instead of static fields to apply an electric field to semiconductor samples in a contactless manner. As long as the frequency is low enough for electrons to thermalize, the incident wave is believed to act much like a static electric field. The analogy between the effect of a static electric field and a microwave field is supported by the works of Ashkinadze *et al.*,[7,8] who have shown that the intensity of photoluminescence at excitonic lines decreases substantially in *n*-GaAs samples subjected to microwave irradiation. The same result has been observed previously in static electric fields.[9–11] In addition, as with the nonlinear dynamics characteristic of current filamentation in dc fields,[12] various types of oscillations have been observed in the photoluminescence signal in microwave fields.[8]

Considering the above facts it is reasonable to expect that the absorption of the microwave power by the sample can be accompanied by the formation of spatial structures of enhanced electron density, analogous to the case of static electric fields of supercritical intensity. The formation of such structures has been theoretically treated by Kerner and Osipov who coined the term ''ball lightning in semiconductors''[13] because of strong similarities. In fact, ball lightning has been proposed by Kapitsa to result from electric discharge in the atmosphere by strong electromagnetic fields emerging from thunder clouds.[14] Spatial structures of enhanced electron density have indeed recently been found using the technique of spatially resolved photoluminescence imaging.[15] Here we report their characteristics in detail and discuss the pattern forming mechanism. Attention is payed to the possible role of microwave field inhomogeneities due to wave reflections.

II. EXPERIMENTAL SETUP

Pattern formation has been visualized by the method of quenched photoluminescence.[5] A schematic diagram of the experimental setup is shown in Fig. 1. Contactless samples of *n*-GaAs were fixed in a rectangular Ka-band waveguide (frequency range 26.5–40 GHz, inner dimensions 7 $\times 3$ mm). To enable the observation of the sample's photoluminescence, a section of the waveguide was cut away and

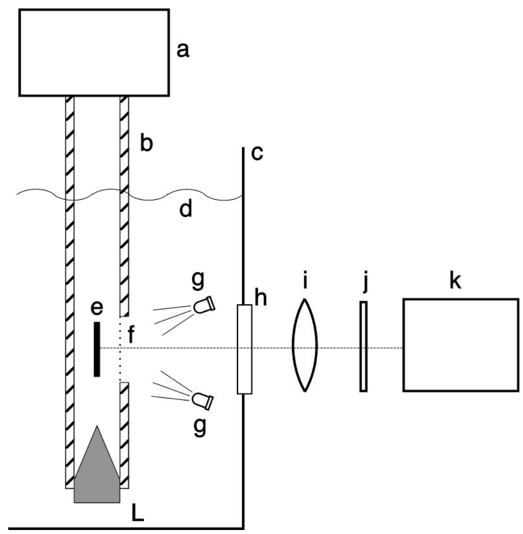

FIG. 1. A schematic diagram of the experimental setup. (a) microwave generator, (b) waveguide, (c) bath cryostat, (d) liquid Helium, (e) sample, (f) metallic mesh window in the waveguide, (g) ring of red LED's, (h) cryostat window, (i) optics, (j) interference filter 820 nm, (k) video camera, and (L) absorber.

either left open or covered with a fine metal mesh (pitch ≈ 20 μm). The sample was then cooled to 4.2 K in a cryostat and illuminated uniformly with nine red light-emitting diodes mounted in a ring around the sample. An infrared sensitive video camera was used to image the sample through an 820-nm filter placed in front of a window in the cryostat. A spatially resolved image of the sample's excitonic recombination photoluminescence, and any quenching of it, could then be obtained using this camera.

Microwaves were introduced into the waveguide by either a klystron source (frequency 36 GHz, maximum power 100 mW) or yttrium-iron-garnet (YIG) variable frequency oscillator (frequency range 26–32 GHz, maximum power 50 mW). At these frequencies, only the TE_{10} mode propagated in the waveguide. An attenuator was used to vary the microwave power reaching the sample, and a relative measure of this power at a fixed frequency was provided by a diode. The waveguide was terminated with either an absorber or a reflector.

Two types of n-GaAs samples have been investigated, one which is medium doped, while the other is ultrapure with a doping level three orders of magnitude lower. The parameters of the ultrapure and the medium doped epitaxial layers are summarized in Table I.

TABLE I. Sample parameters. MBE and VPE stay for molecular beam epitaxy and vapor phase epitaxy, respectively. Electron mobility and density of both PC layers were obtained by standard Hall measurement at 77 K, whereas the parameters of ultrapure V layer were extracted from cyclotron resonance data at 4.2 K (for the details on the latter material and the measurement method see Ref. 16).

Sample	PC00, PC05	V
Growth method	MBE	VPE
Layer thickness (μm)	4.3	20
Sample thickness (mm)	0.4	0.5
Electron density (10^{14} cm^{-3})	19	0.05
Electron mobility (10^3 cm$^2/Vs$)	43	2000
Sample dimensions	3×7 mm	3×7 mm

III. RESULTS AND DISCUSSION

The general behavior of the medium doped n-GaAs sample subject to microwave irradiation is illustrated in Fig. 2. No observable change in the luminescence intensity can be detected as long as the microwave power does not exceed a threshold value, Fig 2(a). Once this critical power is exceeded an approximately circular dark spot of finite diameter and sharp border appears on the luminescence image, Fig. 2(b). As the microwave power is increased further, the spot grows continuously, until another critical-field strength is reached and a second, separate spot is formed, Fig. 2(e). In a similar way, depending on the sample parameters, one or two additional spots arise at a distance of about 3 mm when the power is increased further. Formation of an additional spot does not influence the size of the ones that already exist. The neighboring spots grow and merge smoothly with increasing power, without an observable jump in the evolution of their shape, until finally the entire sample becomes dark, as in Fig. 2(j).

While the spot merging is a continuous process, the formation and disappearance of a spot corresponds to a first-order phase transition. In Fig. 3 the dependence of the spot diameter on the incident power is plotted. A well-defined interval of bistability can be seen between two critical values of power, depicted as P_h and P_{th}. The metastable state between P_h and P_{th} on the upper branch of the hysteresis has a very long lifetime, and does not disappear during a period of tens of minutes, even if the visible illumination is repeatedly interrupted for some minutes. This experiment reveals that the driving process of nucleation is to be attributed to a self-sustained impact ionization of shallow impurities driven by the microwave field, and that it is not caused by exciton quenching. The lifetime of both the excitons and the photo-excited electron-hole pairs is definitely by many orders of magnitude shorter. Thus the influence of the illumination on the nucleation process can be neglected.

The growth of a spot diameter with increasing microwave power is qualitatively similar to the dependence of the width

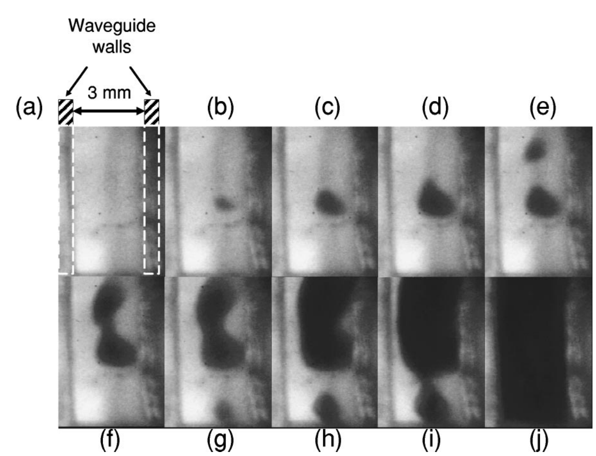

FIG. 2. Formation of dark spots in microwave irradiation of intensity increasing from (a) to (j).

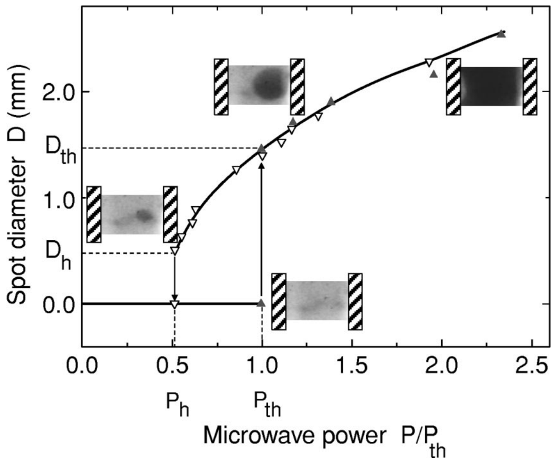

FIG. 3. Spot diameter vs incident microwave power.

of a filament on the applied static voltage. For the latter case the hysteretic behavior[17] and lateral growth[18] has been investigated previously in detail.

The reproducibility of the spot formation process, the spot distances, and their initial positions is surprisingly good with respect to various kinds of external perturbation, such as switching on and off the microwave power, as well as visible illumination, and heating and recooling of the sample. Besides that, a weak inverse dependence between the microwave frequency and the spot distances has been found. Consequently, the question arises of the homogeneity of the field distribution and of a possible standing-wave effect in the waveguide. To prove this, experiments have been carried out on the medium doped sample and the ultrapure sample with different waveguide terminations.

Investigating the medium doped sample, the absorber at the end of the waveguide was replaced by a metallic reflector, forcing a standing-wave regime in the close vicinity of the sample. For a fixed microwave frequency no significant change could be detected either in the spot size or in their distance. However, in contrast to the case of an absorber-terminated waveguide, the spot positions react to a variation in the microwave frequency. They shift towards the reflector as the frequency is increased. This observation indicates some influence of the microwave standing-wave pattern on spot formation.

The ultrapure n-GaAs was investigated in the same manner. At first the microwave power was applied using the absorber-terminated waveguide. Upon increasing the power, the intensity of sample luminescence decreased continuously, leading to homogeneous darkening of the sample, Figs. 4(a)–4(e). Next, the waveguide was terminated by a reflector. In this case, weak extrema can be identified in the photoluminescence of the ultrapure sample, which again clearly shift with varying frequency, Figs. 4(f)–4(h). The behavior of the ultrapure sample confirms the effect of the standing wave in the case of the reflector-terminated waveguide. The diffuse bright areas in the photoluminescence image correspond to nodes of the standing wave, and they are absent in the case of the absorber termination. In contrast to this result, the sharp bordered luminescence patterns on a moderately doped sample are almost independent of the kind of termination.

Thus, in absorber-terminated waveguides with free propagating microwaves, pattern formation is observed only in the case of moderately doped material. Standing waves in the reflector-terminated waveguide affect the spatial distribution of luminescence quenching. However, even in this case the sharp borders of the spots in medium doped n-GaAs give strong evidence for self-organization. In contrast, the smooth spatial variation of luminescence quenching in the ultrapure sample shows the absence of self-organization processes.

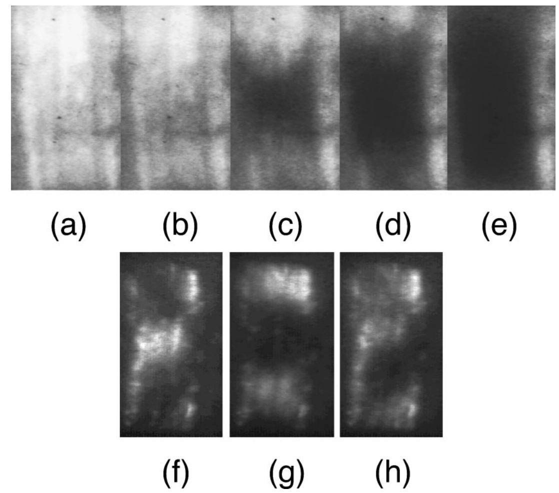

FIG. 4. Diffuse darkening of ultrapure sample. (a)–(e) Waveguide with absorber and increasing microwave power; (f)–(h) waveguide with reflector and varying microwave frequency.

The equivalent nature of microwave induced spots and current filaments, which has been concluded from the similarity of their characteristics, can further be confirmed by the nature of their interference. In Fig. 5, images of a moderately doped sample are shown, which were simultaneously subjected to microwave irradiation and a static electric field; the galvanic contacts were placed on the sample edges outside the waveguide. In Figs. 5(a)–5(e) an experiment is shown in which at first the microwave induced spot is formed without an applied static voltage. Under an increasing additional voltage bias, a current filament ignites without exception through the dark spot, and remains pinned at this position for higher static biases, growing only in width. If, on the other

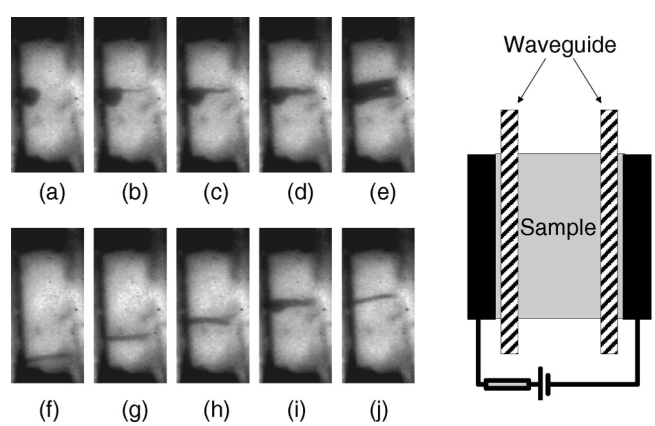

FIG. 5. Coexistence of the dark spots and current filaments. (a)–(e) Increasing dc bias in state with already existing microwave induced spot; (f)–(j) increasing microwave power in state with already existing current filament.

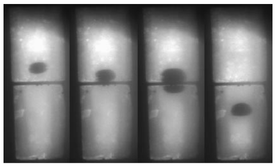

FIG. 6. Dark spot moving through a gap with the frequency increasing from (a) to (d) in the range of 26.2–27.2 GHz. The waveguide is closed by the reflector.

hand, the static current filament is ignited first, its preferred initial position lies elsewhere, only moving to the location of the dark spot after the microwave power is switched on, as can be seen in Figs. 5(f)–5(j).

The same experimental arrangement has been used to estimate the nucleation time of the microwave induced spots. The system was switched from the stable branch of the hysteresis to the metastable branch applying a short electric voltage pulse to the contacts in addition to the microwave field. The voltage pulse increases electron energy for a short time analogous to a temporary increase of oversaturation for a phase transition like the gas-liquid system. The shortest voltage pulses applied were 300 ns and were long enough to nucleate a spot on the metastable branch giving an upper limit of the nucleation time.

The effect of the mobility on the formation of the present patterns has been demonstrated with the doped samples applying a magnetic field perpendicular to the plane of the semiconductor film. Increasing the magnetic field strength shifts the threshold power of spot formation to higher values. At constant microwave power the radius of a spot decreases and finally the spot disappears. This is caused by the lowering of the electron mobility that results in a drop of the microwave absorption by nonequilibrium carriers and therefore in a reduction of the energy of free electrons.

In order to assess the role of conductivity in forming the microwave induced spots the moderately doped sample was cut perpendicularly into two identical pieces. These pieces were then placed back in the waveguide with a gap of less than 0.2 mm between them. Thus the original form of the dielectric obstacle in the waveguide was retained, but an insulating slit was introduced into the active layer. The waveguide was closed with a reflector in order to enable a controlled shift of the spot position by frequency variation. First, at a frequency of 26.2 GHz a single spot ignites in the upper part of the cut sample, Fig. 6(a). Upon increasing the frequency the spot starts to move downwards, but its movement gets slower as the spot reaches the gap, and its size shrinks, Fig. 6(b). Increasing the frequency further, a new spot of a smaller but finite size emerges abruptly near the gap in the bottom part of the sample, creating together with the first section a spot of approximately the original size but with the gap inside it, Fig. 6(c). Later on, the upper part of the spot abruptly vanishes, and finally the spot separates from the gap and drifts towards the reflector, Fig. 6(d).

The approximately circular form of the dark structures is the most frequent shape. On the other hand, depending on the positioning of the sample in the waveguide, and weakly, also on the microwave frequency, more complex shapes can also be observed. In Fig. 7 the cut sample is shown at a frequency of 36 GHz. With either a reflector or an absorber in the waveguide, a bananalike shape gradually formed from the initial spot in the top section as the power was increased from zero, Fig. 7(a). At higher powers this bananastructure was joined by two more usual spots above and below it, Fig. 7(b). Increasing the power further caused all three regions to grow and merge together. A pattern was only seen in the lower half of the sample at powers high enough to cause the top half of the sample to be significantly occupied by the dark pattern, Figs. 7(d) and 7(e). This behavior remained the same if the two parts of the sample were interchanged.

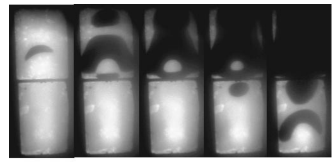

FIG. 7. Dark structures formed in the sample with the gap. Microwave power increases from (a) to (e) at frequency 36 GHz.

The stop effect of a gap in the sample is quite obvious in this case. The spreading of the dark structure is constrained by the insulating slit, and the structures in the separated parts of the sample evolve apparently independently.

IV. CONCLUSIONS

We have shown in several experiments that the sharp-bordered dark structures observed in the photoluminescence images of samples in microwave fields are formed essentially by the same mechanism as the stationary current filaments in the same material. Apart from the arguments based on analogies in behavior, such as the hysteretic shift between the spot ignition and extinction, this conclusion is primarily supported by the preferred form of coexistence—namely, coalescence—of the microwave induced patterns and the current filaments.

The probable relation between the microwave induced structures and the standing-wave pattern can be concluded from the experiments with varying frequency and different waveguide terminations. On the other hand, the behavior of the structures in a split sample indicates that it is not only the dielectrics of the sample that controls the standing-wave regime. There is definitely an interplay between the standing-wave pattern and the variable conductivity distribution of the sample. The formation of the patterns are influenced by microwave standing waves but the structures are formed by self-organization processes due to the nonlinear conductivity. This conclusion is also supported by the qualitatively different behavior of the ultrapure sample.

ACKNOWLEDGMENTS

The authors are indebted to E. Schöll and H. Kostial for helpful discussions. Financial support by the Deutsche Forschungsgemeinschaft and the NATO linkage program is gratefully acknowledged. Support of V.N. by the Alexander von Humboldt Foundation is also gratefully acknowledged.

*Present address: Siemens AG, 81730 München, Germany.

[1] P. T. Landsberg, E. Schöll, J. Phys. C **9**, 1243 (1976).
[2] E. Schöll, *Nonequilibrium Phase Transitions in Semiconductors* (Springer, Berlin, 1987).
[3] B. K. Ridley, Proc. Phys. Soc. London **82**, 954 (1963).
[4] K. M. Mayer, R. Gross, J. Parisi, J. Peinke, and R. P. Huebener, Solid State Commun. **63**, 55 (1987).
[5] W. Eberle, J. Hirschinger, U. Margull, W. Prettl, V. Novák, and H. Kostial, Appl. Phys. Lett. **68**, 3329 (1996).
[6] J. Hirschinger, F.-J. Niedernostheide, W. Prettl, and V. Novák, Phys. Rev. B **61**, 1952 (2000).
[7] B. M. Ashkinadze, V. V. Bel'kov, and A. G. Krasinskaya, Fiz. Tekh. Poluprovodn. **24**, 883 (1990) [Sov. Phys. Semicond. **24**, 555 (1990)].
[8] M. Kozhevnikov, B. M. Ashkinadze, E. Cohen, and Arza Ron, Phys. Rev. B **52**, 4855 (1995).
[9] W. Bludau and E. Wagner, Phys. Rev. B **13**, 5410 (1976).
[10] O. A. Ryabushkin and V. A. Bader, Proc. SPIE **13**, 756 (1998).
[11] F. Karel, J. Oswald, J. Pastrňák, and O. Petříček, Semicond. Sci. Technol. **7**, 203 (1992).
[12] K. Aoki, T. Kobayashi, and K. Yamamoto, J. Phys. Soc. Jpn. **51**, 2373 (1982).
[13] B. S. Kerner and V. V. Ossipov, *Autosolitons* (Kluwer, Dordrecht, 1994).
[14] P. L. Kapitsa, in *Ball Lightning*, edited by D. J. Ritchie (Consultants Bureau, New York, 1961).
[15] V. V. Bel'kov, J. Hirschinger, V. Novák, F.-J. Niedernostheide, S. D. Ganichev, and W. Prettl, Nature (London) **397**, 398 (1999).
[16] M. Kozhevnikov, B. M. Ashkinadze, E. Cohen, and Arza Ron, Phys. Rev. B **52**, 17 165 (1995).
[17] J. Hirschinger, W. Eberle, W. Prettl, F.-J. Niedernostheide, and H. Kostial, Phys. Lett. A **236**, 249 (1997).
[18] V. Novák, J. Hirschinger, W. Prettl, and F.-J. Niedernostheide, Semicond. Sci. Technol. **13**, 756 (1998).