Self-organized electron density patterns in n-GaAs induced by microwaves

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Abstract Self-organized spatial patterns of enhanced electron density have been observed in a cooled n-GaAs layer under homogeneous microwave irradiation. The common origin of these patterns and the current filaments have been demonstrated. A global coupling between the microwave-field distribution and the power dissipation in the sample has been concluded as the pattern forming mechanism.

1 Introduction

If biased above a certain critical voltage, a moderately doped sample of n-GaAs cooled to 4.2 K exhibits an electric breakdown. The essential mechanism of this non-equilibrium phase transition is the autocatalytic generation of free carriers by the impact ionization of shallow impurities. Under the global constraint of the current supplying circuit the carrier multiplication results in the formation of distinct current channels. The geometry of these filaments inevitably reflects the geometry of the galvanic electrodes [1].

In the microwave field of sufficiently low frequency the carriers gain energy analogously to the case of static electric field, and thus analogous nonlinear effects can be expected to occur [2,3]. However, in contrast to case of the current filaments no external constraints like, e.g., the sample contacts a priori enforce a certain geometry of the possible pattern formation.

2 Experiment

The sample was cut from MBE-grown layer of n-type GaAs. The technological thickness of the layer was 4.3μm, doping was $N_D = 3.1 \times 10^{15}\text{cm}^{-3}$ and $N_A = 5.1 \times 10^{14}\text{cm}^{-3}$, and the electron mobility at 77 K was $\mu = 40800\text{cm}^2/\text{Vs}$. Dimensions of the sample were 3×7 mm, substrate thickness 0.4 mm. The sample was fixed inside a rectangular waveguide for the Ka-band of microwave frequencies, behind a fine-mesh metallic window in the waveguide wall. The waveguide was terminated by an absorber and immersed in the Helium bath. A klystron and a YIG-oscillator were used as microwave sources for frequencies from 26 to 36 GHz.

In order to detect the changes of the electron density in the epitaxial layer the sample was homogeneously illuminated by an interband light and its photoluminescence (PL) was photographed by an infrared-sensitive camera. Using a proper interference filter only the PL-line of excitonic recombination was selected, known to be quenched by the excess free electrons [4].

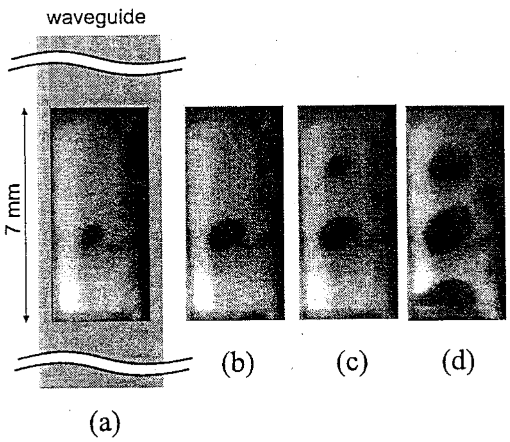

Fig. 1 Photoluminescence images of the sample in the waveguide. In (a) the positioning of the sample behind the window in the waveguide is schematically shown. The microwave power increases from (a) ($P = P_{th} = 15$ mW) to (d) ($P = 28$ mW).

The images in Fig. 1 show the changes of the photoluminescence when increasing the power of the incident microwaves. In the originally homogeneous luminescence a distinct, sharp edged dark spot of a roughly circular shape and a finite diameter abruptly emerges, if a certain critical power (15 mW for the reported sample) is exceeded, Fig. 1(a). Its size grows continuously as the power is further increased, Fig. 1(b), till another critical field strength is reached and a second spot is formed, Fig. 1(c). The scenario is repeated once again at a higher microwave power, Fig. 1(d). At the highest available power of about 50 mW the spots merge together, covering almost the whole area of the sample.

The critical microwave power necessary for the ignition of a particular spot is always higher then that of the spot extinction. Thus, hysteretic loops and intervals of bistability exist. It should be noted, however, that except for the close vicinity of the critical points the dark spot configuration is absolutely stable. The form of the spots does not change on varying the illumination intensity, the current spot configuration persists even after the interruption of the illumination. Any significant role of the light-generated charge carriers and excitons during the spot formation can thus be excluded, similarly as in the case of the current filaments.

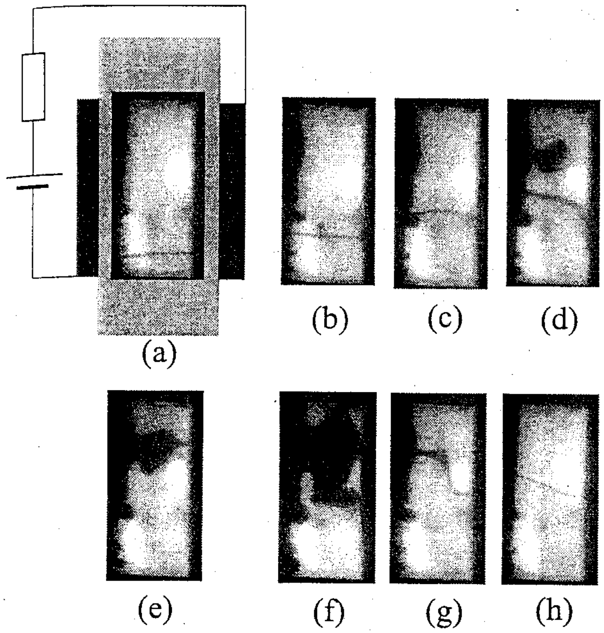

Fig. 2 Coalescence of the microwave-induced spots and the current filaments. In (a) the DC-contacts to the sample are schematically shown, leading through the openings in the side walls of the waveguide. The DC-current is between 110μA in (a) and (h), and 130μA in (f). The microwave power is zero in (a), increases to its maximum of 30 mW in (f), and then decreases again to zero in (h).

A common nature of the microwave-induced dark spots and the current filaments is demonstrated by combining the two effects. Additionally to the microwave irradiation, a static voltage bias is applied to the sample via a pair of stripe-like ohmic contacts, Fig. 2(a). In the solely static field, a thin current filament emerges on some preferred position in the sample, Fig. 2(a). On increasing the microwave power, the filament is apparently attracted to the place in the sample, where the microwave induced spot appears, Fig. 2(d), till the two structures finally coalesce, Fig. 2(e). Upon decreasing the microwave power (Fig. 2(f) to (h)) the DC-current path obviously prefers to cross the dark spots (Fig. 2(g)) till they extinct in a subcritical microwave field, Fig. 2(h).

The role of conductivity in the forming of the microwave induced structures has been studied on a sample with an insulating gap in the middle, Fig. 3. An obvious difference in the behaviour of the two parts of the sample is seen: the upper part (the one closer to the microwave generator) seems to absorb the most of the incident power. Only after this part is saturated with the high electron density, the dark spots emerge also in the bottom of the sample.

The shape and the configuration of the dark structures are influenced by several factors, as e.g. the quality of the sample, its exact positioning in the waveguide and the microwave frequency used. Thus, an equal spacing of the circular spots in Fig. 1 can be shown to coincide approximately with the half-wavelength of a standing wave,

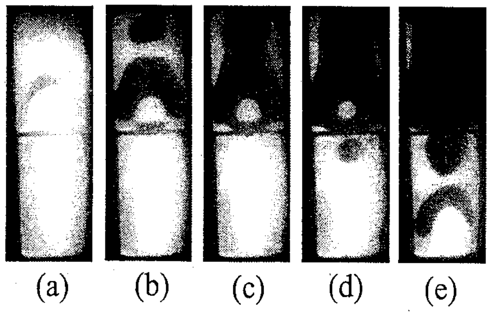

Fig. 3 Complex patterns of quenched PL in a galvanically divided sample. In the half-height of the images a horizontal gap is seen which separates the two parts of the sample. The microwave power increases from (a) to (e).

which arises in the sample acting as a dielectric obstacle inside the waveguide. On the other hand, no such coincidence can be found in the case of more complex patterns observed in the galvanically split sample in Fig. 3.

3 Conclusions

The microwave induced structures correspond to regions of substantially enhanced density of free electrons due to the impact ionization of shallow donors in the microwave field. There exists a relation between the observed spatial form of the structures and the standing wave pattern induced in the waveguide by the presence of the dielectric obstacle. This relation is rather straightforward if the conductivity of the dark spots is low. If, however, a significant power is dissipated in the high-conducting areas, a non-linear coupling between the standing wave pattern and the conductivity distribution sets on, leading to the formation of complex spatial patterns.

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References

1. J. Hirschinger, F.-J. Niedernostheide, W. Prettl, and V. Novák, Phys. Rev. **61**, (2000) 1952.
2. V.V. Bel'kov, J. Hirschinger, V. Novák, F.-J. Niedernostheide, S.D. Ganichev, and W. Prettl, Nature **397**, (1999) 398.
3. V.V. Bel'kov, J. Hirschinger, D. Schowalter, F.-J. Niedernostheide, S.D. Ganichev, W. Prettl, D. Mac Mathúna, and V. Novák, Phys. Rev. **61**, (2000) 13698.
4. W. Eberle, J. Hirschinger, U. Margull, W. Prettl, and V. Novák, Appl. Phys. Lett. **68**, (1996) 3329.

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