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OPTIMIZATION OF LIMITING MODES OF STREAMER SEMICONDUCTOR LASER

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The influence of intensive electric and optical fields produced by streamer discharge in wide-gap semiconductor on their spectroscopic properties has been studied. The given effect is developed at appearance of reversed reconstruction of active environment luminescent characteristics. The methods of sufficient increase in durability and efficiency of streamer laser at limiting modes based on application of semiconductor protecting layers of a definite crystallographic orientation and crystal microrelief with element size of light wave length order. Streamer luminescence in new perspective $CaGa_2S_4$:Eu, $Ca_4Ga_2S_7$:Eu compounds is found and studied.

Introduction

Steamer discharge in semiconductors is a highly effective method of producing laser action in homogeneous media when excited by short pulses of electric field [1]. Investigation of steamer discharge properties gives new possibilities in study of nonlinear optical, electric, acoustic, and other phenomena in solid bodies [1, 2]. For a long time development of research in semiconductor streamer laser (SSL) physics and technique was blocked by the absence of unique understanding of the part of emitting processes on streamer formation including the action of strong optical and electric fields accompanying discharge in active medium. Besides, practical application of streamer technology was retarded by a number of other reasons, among which degradation of near-electrode region sufficient in the case of maximum permissible operation conditions and conditions relatively low resource and efficiency of SSL should be noted.

The purpose of the present work is to reveal the regularities of streamer discharge action on active medium as a complex phenomenon under the conditions of strong radiation and strong electric field, to develop the methods of sufficient increasing in efficiency of laser in maximum conditions including packet-pulse one [3], as well as to search for new perspectives of active media.

Development of methods of improving laser characteristics under maximum permissible operation conditions

Increasing resource, stability and some other main characteristics of streamer radiation is one of the problems that has not been solved completely to the present day and requires consideration of interaction of charge with medium (feedback) and complex character of interaction due to strong electric and optical fields as well as other intensive factors accompanying discharge.

Experiment shows that the maximum efficiency of streamer excitation is achieved when using additional discharge gap directly in the surroundings (dielectric liquid) sharpening the edge of applied voltage pulse [1–3]. *Procedure of discharge excitation and investigation* is presented in the same works: the voltage pulser duration amounted ~100 ns, the efficient repetition frequency varied up to 10 MHz (packet-pulse condition), the amplitude was up to 250 kV. In this case in order to increase life time of radiating element it is necessary to perform special protective measures from direct action spark discharge in a liquid. One of such measures is application of protective (buffer) material against the action of strong electric field and spark discharge on operating crystal. Simultaneously the buffer layer should not prevent from intensive generation of streamer radiation. Search for the materials suitable for protective layer was performed among different solid dielectrics, semiconductors and metals under different conditions, among which the most important are the conditions of discharge transition (energy transfer) between the layers. As a result, it was stated that the most effective from this point of view is a system consisting of operating crystal – a CdS plate of ~0,5 mm thick, oriented in the plane of {0001} type and protective layer from the same crystal of ~1 mm thick, cut in $\{1\bar{2}10\}$ plane, fig. 1.

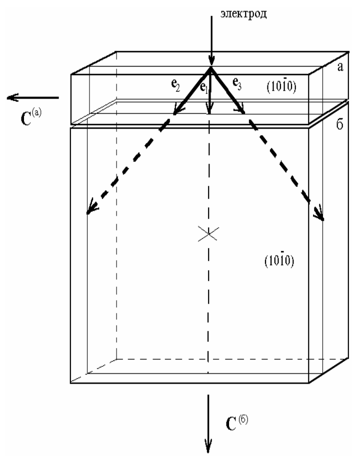

Fig. 1. *Scheme of discharge excitation and mutual orientation of protective (buffer) (a) and operating (b) CdS crystals in pulse-periodic conditions*

In the plane {0001} projections of streamer tracks form a six-ray star, that makes observation easy, but in the second (buffer) sample the discharges are distributed at some angles to the normal. The longest streamer track and intensity of their luminescence are observed at such transition geometry (optimal conditions), when spatial orientation of streamers in the protective (buffer *a*) and operating (*b*) crystals is almost the same. It corresponds to the least energy losses at transition and provides minimal distortion of working medium surface. As the $(10\bar{1}0)$ planes of crystals, where the streamers are distributed, are parallel, insufficient streamer deviation of $\mathbf{e}_2$ and $\mathbf{e}_3$ types from the initial ones in the protective layer is achieved in operating crystal. In contrast to the streamer of the mentioned type $\mathbf{e}_1$ transition is difficult due to necessity of sufficient change of motion direction at ~90°. Such discharge transition from one crystal to another is possible owing to closeness of streamer orientation angels to the value ±45° with respect to the **C** axis.

In the described excitation geometry a stable pattern of streamer tracks without noticeable decrease in luminescence intensity was observed by single pulse with repetition frequency up to 50 Hz and amplitude not more than 50 kV in the operating crystal at the minimum 2 hours, which is under other equal conditions 1–2 orders more than the data in the works and corresponds to N~10^6 pulses. Influence of the protective layer on intensivity of streamer emitter and its resource is shown in fig. 2.

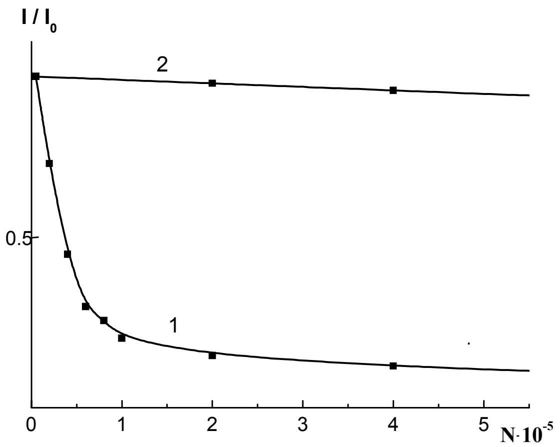

Fig. 2. *Comparative intensity of streamer discharge luminescence depending on exposition in the absence (1) or in the presence of buffer layer (2)*

It should be noted that in maximum conditions there appear distortions in the form of deep, nearly through crater in the protective material, whereas in the operating crystal they have insignificant penetration depth (nearly at the level of initial stage of distortions). Increasing the number of excitation pulses up to ~10^5 the crater size increases and in order to restore the initial energy of radiation one should shift needle electrode from the initial position to the distance ~1,0...1,5 mm.

Influence of crystal microrelief on efficiency of emitter at streamer excitation

To increase intensity and efficiency of SSL the conditions of discharge transition among the crystals for the case when a sample in the form of plate of not more than 100 mkm thick having one polish surface with sprayed mirror coating or without it, but the other one is etched, with microrelief, the elements of which are compared with the light wave length is used [4]. In this case the microrelief surface serves as that of streamer transition, but the sample with two polish surfaces of 1...2 mm thick oriented by the sample mentioned above (fig. 3) serves as a buffer crystal. Laser resonator is formed by the microrelief surface and its opposite surface of the operating crystal. The experiments have been carried out in the absence of buffer crystal.

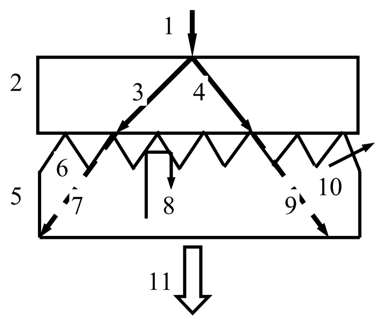

Fig. 3. *Scheme of excitation of light generation in laser system at the presence of microrelief: 1) electrode, 2, 5) buffer and working crystals, 6) microrelief, 3, 4) discharges in protective layer, 7, 9) streamers in working crystal, 8, 10) reflected and refracted rays on the edges of microrelief elements, 11) generated light beam*

The pulse packets are passed to the system with the amplitude to 200 kV. It is stated that if microrelief is present at the surface of emitter, the contact between the crystals is worse than it is between polish surfaces, which makes it difficult streamer transition. However, the disadvantage involved is compensated by significant strengthening of streamer luminescence (2...3 times). If the buffer crystal is absent, the intensity of emitter increases in addition. A sharp reduction of spectrum (close to one-mode condition) and appearance of characteristic radiation direction log with angular divergence ~30°, typical for transverse geometry of streamer excitation in the samples with strayed mirrors (without microrelief) indicates the attainment of light generation mode in the system involved. On the basis of the data [4] one can assume that microstructure on the emitter surface results in sufficient increase of losses for angular modes and rise in radiation reflection efficiency (fig. 3, rays 8) in the active medium, hence, generation efficiency increases. In this case not only refraction of angular modes (10), but also dispersion of corresponding rays on the edges of microstructure elements plays a positive role. Increase in intensity of output radiation is conditioned also by rise in homogeneity degree of light beam in the active region due to its dispersion on the relief. Distortions appeared on the natural surfaces of microrelief etch figures progress slower than in the case with smooth surface. In these conditions radiation strength of such emitter and its efficiency in general increases. The mechanism of the mentioned phenomenon is examined in details by the example of semiconductor laser with two-photon pumping [4]. The results of these examinations have been used as the basis for development of powerful semiconductor lasers of radiating mirror type, pumped by electron jet [5], and have appeared to be useful (as it follows from the mentioned above) for increasing intensity (efficiency) and resource of streamer laser.

Interaction of streamer discharge with laser active medium

In the connection with complex influence of streamer discharges their affect on spectroscopic (luminescent) characteristics of active medium in different conditions is of great interest. The samples in the form of flat-parallel plates of 0,5...1,1 mm thick, oriented in the $(10\bar{1}0)$ planes in such a way that polar axis is directed along the long side of the plate were used. Photoluminescence spectra (PL) were registered from the sample edge, through which radiation of streamer discharges induces by voltage pulses of ~50 kV amplitude with repetition frequency up to 5 Hz came out. In this case the influence of spark acting on the opposite crystal edge was eliminated. Luminescence was excited by radiation of continuous helium-cadmium laser at $T\approx300$ K (at room temperature to be exact) and at the temperature of liquid nitrogen ($T\approx80$ K).

It was stated that in the conditions of aviation kerosene used as a dielectric medium at 300 K the impact in the crystal (exposure) $N\sim5\cdot10^3$ of discharges results in decrease of PL intensity nearly 2 times in comparison with initial intensity, similar to the data in [6]. The care of eliminating direct influence of laser radiation was taken. Further exposition at $N\sim5\cdot10^3$ was also accompanied by decrease in PL intensivity. Then the experiments were repeated at 80 K to control the behaviour of exciton lines. The peculiarities of the line behaviour consists in dependence of their intensity on exposition, in particular in its gradual ~10 times increase at $N=1,5\cdot10^4$ and sharp decrease after $N=2,5\cdot10^4$. The given effect of PL intensification-extinction has a reversed character, as it is reproduced after exposure during $\tau\sim24$ h at 300 K. Corresponding changes of PL spectrum with exposition growth are shown in fig. 4.

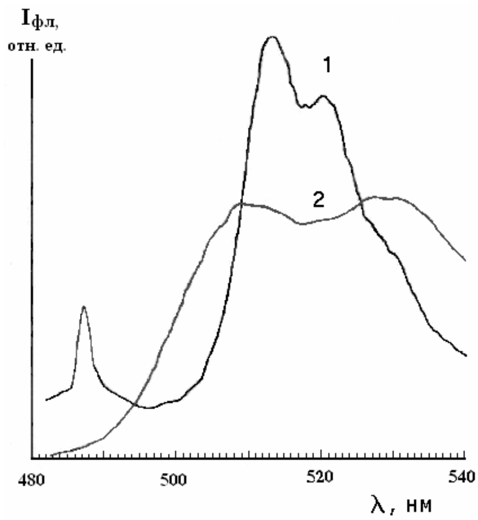

Fig. 4. *PL spectrum of CdS monocrystals in the region of streamer discharge action at the exposition N =2,5·10⁴(1) and 3·10⁴ (2); T=80 K; excitation by continuous laser radiation ЛГН-409, λ=325 nm, P=3 mW*

«Green band» intensivity is nearly 2 times less as in the case $N=2,5\cdot10^4$, its half-width increases, but the exciton lines disappears, that indicates strong changes of crystal surface. The observed spectrum transformation in terms of the data [6] one can explain by intensive decomposition of near-surface layer with formation of emissionless defects and complexes. Owing to mutual action of strong electric field and powerful discharge radiation in the near-surface layer destruction of crystal lattice beginning at different kinds of defects probably takes place. Their formation is provided by mechanical deformations and residual stresses. In this case ionized (due to high levels of excitation) atoms of initial crystal and impurity components appearing on the lattice surface can react with dielectric surrounding the crystal and create different complexes resulting in changes of PL spectrum.

When using aviation kerosene as a dielectric medium the impact of spark discharge and strong electric field results in decomposition of large organic molecules into small parts and formation of different associates with defects on the surface of crystal lattice. Decomposition of CdS monocrystals is stimulated by hexane, ethyl acetate and ethanol [7]. The experiments in streamer pumping in hexane and sulphur ether revealed the absence of spectrum reconstruction even at the exposition $N=3\cdot10^4$, that indicates less intensivity of decomposition processes of cadmium sulphide surface in these liquids in comparison with kerosene in the conditions involved. Thus, by means of selection of surrounding dielectric medium it becomes possible to minimize the influence of the mentioned factors in order to improve the characteristics of streamer laser.

Search for new perspective active media. Streamer luminescence has been obtained and studied by participating the authors in production of a number of binary, triple and more complex compounds both well investigated and new ones (see review [2]): ZnS (radiation wavelength $\lambda\sim345...355$ nm), ZnO (~400 nm), ZnSe (447...470 nm), ZnTe, CdSe and CdS_xSe_{1-x} (610...630 nm), GaAs (~830 nm); $AgGaS_2$ (~550 nm), $CuGaS_2$, $CuGaSe_2$ (820...960 nm), $CuGaS_{2x}Se_{2(1-x)}$ (700...960 nm). The overall results of these investigations are the facts that streamer discharges as a quick-proceeding phenomenon have a property of cooperative self-organized processes [8], in which optical phenomena play an important part. In this case the investigation results of semiconductor laser efficiency using microrelief at optical pumping [4] appeared to be useful, as it was mentioned above, for increasing the output and streamer laser resource.

Let us dwell on the results of studying the excitation conditions, spatial and optical properties of the discharges in two more interesting media – $CaGa_2S_4$ and $Ca_4Ga_2S_7$ crystals, activated by europium ions (representatives of wide-gap compounds of $A_m^{II}B_2^{III}C_n^{VI}$ ($m=n-3$, n=4,5,6,...) type [9]. These are monocrystals of orthorhombic symmetry of D_{2h}^{24} category and cubic syngony correspondingly. $CaGa_2S_4$ compounds are characterised by layer crystal lattice at thickness of layer packet ~30...100 mkm and are model objects for investigation of streamer discharge regularities in quazi-two-dimensional media. Using non-destructive discharges extends the capabilities of studying real crystal structure, its electrical and optical properties. Besides, the crystal of the given kind activated by rare-earth ions are perspective for creation if high-effective sources of day light, screens of X-ray devices, multicolour displays and other systems of reflecting information.

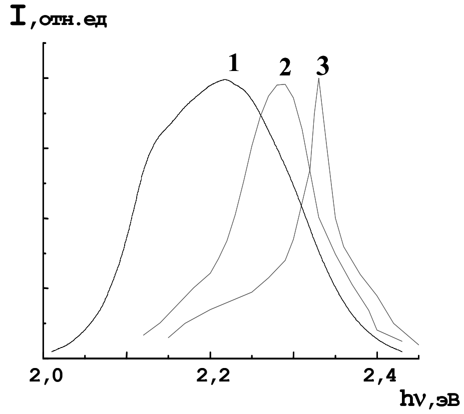

Fig. 5. *Spectra: 1) photo- and 2, 3) streamer luminescence of crystals $CaGa_2S_4$:Eu at T≈300 (1, 2) and 80 K (3); excitation by nitrogen laser radiation (ГИ-21, λ=337,1 nm, $\tau_и$≈10 ns)*

Monocrystals of ~5×3×1 mm size with specific resistance ~10^9...10^{10} Om·sm, grown by the diffusive method of gas-transport reaction and by the Bridgman method were used. Working surface of samples was obtained by chipping; discharges were excited by voltage pulses of ~50 kV amplitude of ~100 ns duration through discharge gap in dielectric liquid by the standard technique and in packet-pulse mode. The optimal conditions of appearing discharges at the room temperature and the temperature of liquid nitrogen depending on experiment geometry, amplitude and polarity of exciting pulses were determined. Single direct discharges of definite crystallographic orientation were observed; in the case with $CaGa_2S_4$ streamers were localized in the plane of layer packet with outlet of the main part of the light flux along the channel. Transition from *T*≈300 to 80 K resulted in significant increase in discharge intensivity. Formation of single discharges, decrease in total number of streamers and their types has been observed by us before in rod-shaped and plate crystals of cadmium sulphide [10], as well as independently by other authors in alkali-haloid crystals [11]. This fact is interpreted in the course of conceptions on interaction of electromagnet waves of microwave and visual range, initiated by streamer [10], and on self-organized processes at discharge [8].

Alloying $CaGa_2S_4$ ($Ca_4Ga_2S_7$) crystals by Eu multicharge deep impurity results in sharp increase in intensivity of streamer radiation in yellow-green spectra region (fig. 5), which is explained by contribution of proper and impure recombination channels (including impure jitter radiation). In doing so the presence of luminescence in the region of absorption edge and straight-energy-band crystal structure are the necessary conditions of streamer formation in semiconductors – in agreement with existing concepts. Similar energy structure provides high quantum output of radiation, taking (according to [10]) active part in discharge formation. It should be noted that layer compounds have some features conditioned by the difference of media properties in the layer plane (two-dimension, layer interaction, etc.) and are perpendicular to it, which can influence the streamer formation.

Conclusion

The method of increasing streamer laser resources more than an order (up to ~10^6 pulses) at maximum operation conditions, based on application of protective layer from semiconductors of the same type with orientation, corresponding to minimal changes in directions of streamer spreading at the transition «protective layer-emitter» boundary has been developed. It is stated that microrelief in the forms of etch figures of the order of light wavelength on the transition surface between crystal and active element raises the emitter efficiency on the whole.

The influence of streamer discharges on luminescent properties of semiconductor forming in appearance of reversed has been found. Spectral changes indicate the appearance in near-surface complex region connected with defects, the presence of chemical decomposition processes of the crystal under the discharge influence. The conditions of minimizing the given phenomenon for greater resources and characteristic stability were determined. Streamer luminescence in new perspective compounds $CaGa_2S_4$:Eu, $Ca_4Ga_2S_7$:Eu are found and studied. The regularities of discharges in layer crystals are shown to be similar to that for quazi-two-dimensional media.

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