Quantum Electronics **37** (1) 69 – 73 (2007)

PACS numbers: 42.55.Px; 42.60.Lh
DOI: 10.1070/QE2007v037n01ABEH013316

On increasing the efficiency of a streamer semiconductor laser

K.I. Rusakov, V.V. Parashchuk

***Abstract*. The influence of intense electric and optical fields produced by a streamer discharge in wide-gap semiconductors on their spectroscopic properties is studied. The effect is manifested in the reversible change of the luminescence parameters of the active medium. Methods are proposed for increasing the service life and efficiency of a streamer laser in limiting regimes, which are based on the use of semiconductor protective layers of a certain crystallographic orientation and a crystal microrelief with the size of elements of the order of the wavelength of light. Streamer emission was observed and studied in new promising Eu : $CaGa_2S_4$ and Eu : $Ca_4Ga_2S_7$ materials.**

Keywords: *wide-gap semiconductor, streamer discharge, rare-earth chalcogenide, lamellar crystal, photo- and streamer luminescence, streamer laser, limiting regime, resource.*

1. Introduction

The study of streamer discharges in solids, in particular, wide-gap semiconductors opens up new possibilities for investigations of nonlinear optical, electric, acoustic, and other phenomena in these media [1, 2]. The development of the physics and technology of semiconductor streamer lasers (SSLs) was hindered for a long time by the lack of correct understanding of the role of radiative processes in the formation of a streamer, in particular, by the absence of information on the action of strong optical and electric fields accompanying the discharge on the active medium. In addition, practical applications of streamer technologies were prevented by a number of other reasons such as the degradation of the electrode region, which is considerable in limiting operation regimes and reduces the service life and efficiency of real SSLs. The search for new active media remains of current interest due to the necessity of expanding the spectral range of streamer lasers, the elucidation of the specific features of discharges in these media and the improvement of parameters of these lasers.

The aim of this paper is to study the action of a streamer discharge on the active medium under conditions of intense radiation and a strong electric field, to develop methods for increasing the service life and power (efficiency) of the laser in limiting regimes, in particular, repetitively pulsed regime [3], and to find new promising active media.

2. Development of methods for improving laser parameters in limiting operation regimes

The increase of the resource and improvement of the stability and other basic properties of streamer emission is a problem that has not been completely solved so far. To solve this problem, it is necessary to consider the interaction of the discharge with the medium and to study the action of strong electric and optical fields and other factors involved in the discharge.

A comparison of different excitation methods showed that the maximum intensity of the streamer discharge and, hence, the maximum pump efficiency of the laser are achieved upon excitation through the discharge gap near the working surface of a sample. This gap provides a considerable sharpening of the front of the applied voltage pulse at minimal energy losses, which is one of the necessary conditions for the streamer production. The method for exciting and studying discharges is described in [1 – 3]. The duration of excitation pulses was ~ 100 ns, the effective pulse repetition rate achieved 10 MHz (repetitively pulsed regime), and the pulse peak intensity was 250 kV. To increase the service life of an emitting element in the case under study, it was necessary to protect it from a spark discharge in a dielectric medium. We used for this purpose a buffer material protecting the working crystal from the action of a strong electric field and spark discharge. At the same time, the buffer layer should not prevent the intense lasing of steamers.

The search for materials for fabricating a protective layer was performed among different dielectrics, semiconductors, and metals under different conditions, among which the conditions of transition (energy transfer) of discharges between the layers are most important. We found that a system based on the buffer layer made of the same semiconductor proved to be most efficient in this respect (Fig. 1). In this case, steamer tracks had the maximum length and emission intensity when the spatial orientations of streamers in the protective (a) and working (b) crystals were virtually the same (optimal conditions). This corresponds to the minimal energy losses during the transition and provides the minimal damage of the working crystal surface.

K.I. Rusakov Brest State Technical University, ul. Moskovskaya 267, 224017 Brest, Belorussia; e-mail: rusakov@bstu.by;
V.V. Parashchuk B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, prosp. Nezavisimosti 68, 220072 Minsk, Belorussia

Received 29 June 2006
Kvantovaya Elektronika **37** (1) 69 – 73 (2007)
Translated by M.N. Sapozhnikov

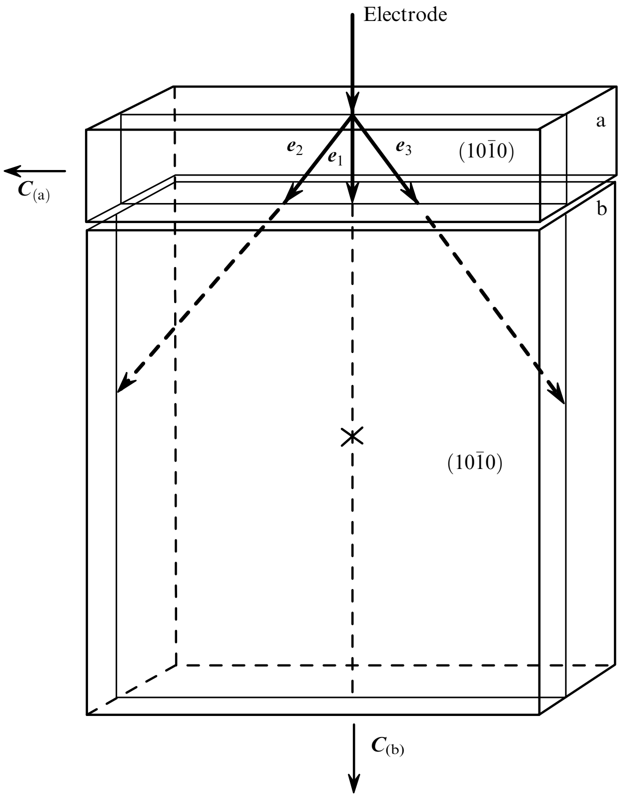

Figure 1. Schemes for discharge excitation and the mutual orientation of the protective (buffer) (a) and working (b) CdS crystals in the repetitively pulsed regime.

This system consists of a working ~ 0.5-mm thick CdS crystal plate oriented in the plane $\{0001\}$ and a protective ~ 1-mm thick CdS crystal layer cut in the plane $\{1\bar{2}10\}$. The projections of streamer tracks form a hexagram in the plane $\{0001\}$ (working crystal), which alleviates observations, while in the buffer layer the discharges propagate at some angles to the normal. Because crystal plates $(10\bar{1}0)$, in which streamers propagate, are parallel, streamers of the types $\boldsymbol{e}_2$ and $\boldsymbol{e}_3$ weakly deviate from the initial streamers in the protective layer. Unlike streamers of these types, the transition of the $\boldsymbol{e}_1$ streamers is hindered because the propagation direction should change considerably by ~ 90°. Such transitions of discharges from one crystal to another are possible because the orientation angles of streamers are close to the angle ±45° with respect to the $\boldsymbol{C}$ axis.

By performing excitation in this geometry by single pulses with a repetition rate up to 50 Hz and amplitude no more than 50 kV, we observed a stable picture of streamer tracks in the working crystal for at least two hours without a noticeable decrease in the emission intensity, which exceeds by one–two orders of magnitude the data reported in the literature and corresponds to the exposure $N \sim 10^6$ pulses. The influence of the protective layer on the intensity of the streamer radiation source and its resource is shown in Fig. 2.

Note that in the limiting regimes, damages appear in the protective materials in the form of a deep, almost a through crater, whereas the damage depth in the working crystal is very small (virtually at the initial stage level). As the number of exciting pulses is increased up to ~ 10^5, the crater size increases, and to recover the initial radiation energy, it is necessary to displace a needle electrode from its initial position by a distance of 1.0–1.5 mm.

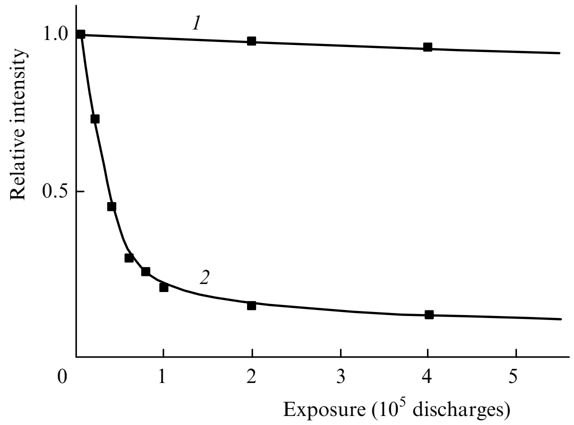

Figure 2. Relative emission intensity of streamer discharges as a function of exposure in the presence (*1*) and absence (*2*) of a buffer layer.

3. Study of the influence of a crystal microrelief on the efficiency of a radiator upon streamer excitation

To increase the power and efficiency of the SSL, we studied the conditions of discharge transitions between crystals when the working crystal was a plate of thickness no more than 100 μm having one polished surface with a mirror deposited on it or without a mirror and another surface with an etched microrelief whose elements were comparable with the wavelength of light. The method of producing such a microstructure is described in [4]. In this case, the streamer transition surface was the microstructure surface, while the buffer crystal was a sample with two polished surfaces of thickness 1–2 mm oriented as shown in Fig. 3. The laser resonator is formed by the microrelief surface and the opposite surface of the working crystal. Experiments were also performed in the absence of the buffer crystal.

Packets of pulses with amplitudes up to 200 kV were

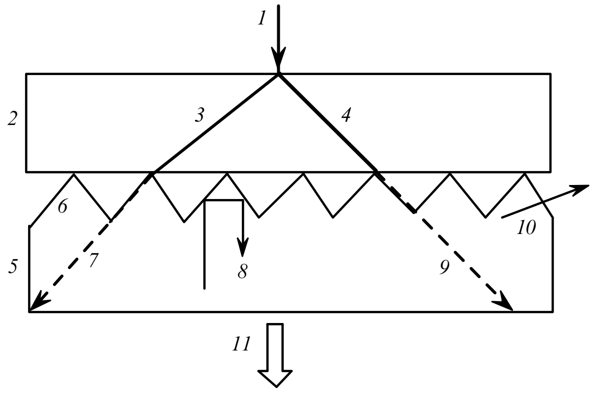

Figure 3. Scheme of lasing excitation in a laser system with a microrelief: (*1*) electrode; (*2*), (*5*) buffer and working crystals; (*6*) microrelief; (*3*), (*4*) discharges in the protective layer; (*7*), (*9*) streamers in the working crystal; (*8*), (*10*) beams reflected and refracted from the faces of microrelief elements; (*11*) generated light beam.

applied to the system. It was found that in the presence of a microrelief on the radiator surface, a contact between crystals was worse than between polished surfaces, which somewhat hinders the streamer transition. However, this disadvantage is compensated by a strong increase (by 2–3 times) of the streamer emission. The emission intensity further increases in the absence of the buffer crystal. The appearance of lasing in the system under study was confirmed by a drastic narrowing of the emission spectrum (nearly single-mode regime) and the characteristic radiation pattern with the angular divergence ~ 30°, which is typical for the transverse geometry of streamer excitation in samples with deposited mirrors (without a microrelief) [1].

Based on the data [4], we can assume that the presence of a microstructure on the radiator surface considerably increases losses for non-axial modes and reflection (returning) of radiation [beams (*8*) in Fig. 3] to the active medium, resulting in the increase in the lasing efficiency. In this case, not only the extraction (refraction) of non-axial modes [beams (*10*)] plays a positive role, but also scattering of the corresponding beams on the faces of microstructure elements. The increase in the output radiation power is also caused by the increase in the homogeneity of the light beam in the active region due to its scattering by the relief. Damages appearing on the natural surfaces of etched microrelief elements develop slower than in the case of a smooth surface. In this case, the radiation resistance and efficiency of the radiator increase as a whole. The mechanism of this effect was studied in detail for a two-photon-pumped semiconductor laser [4]. The results of these studies were used in the development of high-power electron-beam-pumped semiconductor lasers of the emitting mirror type [5] and provided the increase in the power (efficiency) and service life of the streamer laser, as follows from the above discussion.

4. Interaction of a streamer discharge with the laser active medium

Due to the complex action of streamer discharges, it was interesting to elucidate their influence on the spectroscopic (luminescence) parameters of the active medium under various conditions. We studied samples in the form of 0.5–1.1-mm thick plane–parallel plates oriented in planes $(10\bar{1}0)$ so that the polar axis was directed along the long side of a plate. Photoluminescence spectra were detected from the sample face emitting radiation of streamer discharges excited by ~ 50-kV pulses with a pulse repetition rate up to 5 Hz. In this case, the influence of the spark acting on the opposite face of the crystal was eliminated. Luminescence was excited by a cw helium–cadmium laser at room temperature (~ 300 K) and liquid nitrogen temperature (~ 80 K).

We found that, similarly to the results obtained in [6], when the aviation kerosene was used as a dielectric medium at 300 K, the action of $N \sim 5 \times 10^3$ discharges on the crystal reduced the luminescence intensity approximately by half compared to its initial intensity. Precautions were taken to eliminate the direct influence of laser radiation. Further exposure to $N \sim 5 \times 10^3$ discharges was also accompanied by a decrease in the luminescence intensity. Then, experiments were repeated at $T = 80$ K to study the behaviour of the exciton lines. The intensity of these lines depends on exposure. In particular, the line intensity increases gradually approximately by an order of magnitude with increasing N up to 1.5×10^4 and then drastically decreases when N exceeds 2.5×10^4. This effect of luminescence enhancement–quenching is reversible and can be reproduced after keeping the crystal for ~ 24 hours at 300 K. Figure 4 shows the change in the luminescence spectrum with increasing exposure up to 3×10^4.

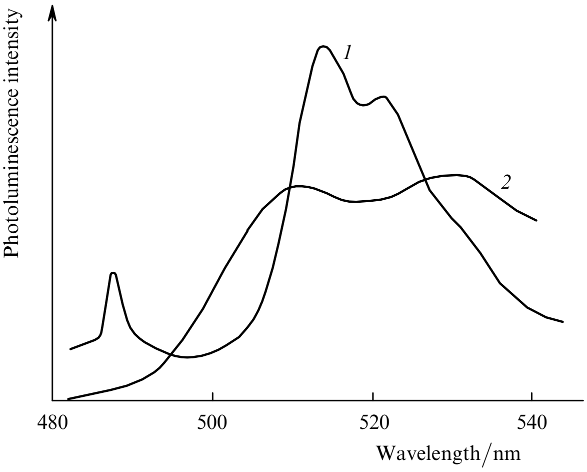

Figure 4. Photoluminescence spectra of CdS single crystals in the region subjected to the action of a streamer discharge at exposures $N = 2.5 \times 10^4$ (*1*) and 3×10^4 (*2*); $T = 80$ K. Excitation was performed by a 325-nm, 3-mW LGN-409 helium–cadmium laser.

The intensity of the 'green band' decreases approximately by half compared to the exposure $N \sim 2.5 \times 10^4$, its half-width increases and exciton lines disappear, which suggests that the surface state of the crystal changes considerably. Taking into account data [6], the observed transformation of the luminescence spectrum can be explained by the efficient decomposition of the surface layer accompanied by the formation of non-emitting defects and complexes. The combined action of a strong electric field and high-power radiation of discharges causes probably the damage of a crystalline lattice in the surface layer, which starts at various defects produced due to mechanical deformations and residual stress. In this case, the ionised (due to high excitation levels) atoms of the initial components of the crystal and impurities can enter into chemical reactions with a dielectric liquid surrounding the crystal and produce various complexes, resulting in the change in the luminescence spectrum.

When aviation kerosene is used as a dielectric medium, the action of a spark discharge and strong electric field leads to the decomposition of large organic molecules into small fragments and the formation of various associates with defects on the crystal lattice surface. It is known that the decomposition of CdS single crystals is not stimulated by hexane, ethyl acetate, and ethanol [7]. Experiments on streamer pumping in hexane and sulphur ether showed that the luminescence spectrum did not change even for $N = 3 \times 10^4$, which indicates that the decomposition of the cadmium sulphide surface in these liquids occurs less efficiently than in kerosene. Thus, the proper choice of a surrounding dielectric medium allows one to minimise the influence of these factors for improving the parameters of a streamer laser.

5. Search for new promising active media

Streamer emission was obtained and studied in a number of binary, triple, and more complex compounds, both well studied and new (see [1] and review [2]). These are ZnS (emitting at 345 – 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 general result of these studies is that streamer discharges as a rapidly proceeding phenomenon have the nature of cooperative self-organised processes [8], in which optical effects play a very important role. The results of the study of the efficiency of a semiconductor laser by using a microrelief upon optical pumping [4] proved to be useful, as mentioned above, to increase the efficiency and service life of the streamer laser.

We consider below the study of the excitation conditions and spatial and optical properties of discharges in two other interesting media – $CaGa_2S_4$ and $Ca_4Ga_2S_7$ crystals doped with europium ions. These crystals belong to wide-gap II–III–VI compounds ($m = n - 3$, $n = 4, 5, 6,...$) – single crystals of the orthorhombic symmetry of class D_{2h}^{24} and cubic syngony, respectively [9]. The $CaGa_2S_4$ compounds are characterised by the lamellar crystal structure with the layer packet thickness 30–100 μm and are a model object for studying streamer discharges in quasi-two-dimensional media. The use of non-damaging discharges expands the possibilities for studying the real structure of a crystal and its electric and optical properties. In addition, crystals of this class doped with rare-earth ions are promising for the development of highly efficient daylight sources, X-ray screens, colour displays, and other data display systems.

We used single crystals of size ~ 5 × 3 × 1 mm with the specific resistance $10^9 - 10^{10}$ Ω cm grown by the diffusion method of gas-transport reaction and Bridgman method. The working surface of samples was obtained by cleavage, discharges were excited by ~ 50-kV, 100-ns voltage pulses through the discharge gap in a dielectric liquid by the standard method and in the repetitively pulsed regime. The optimal conditions for producing discharges at room and liquid nitrogen temperatures were determined depending on the experimental geometry, amplitude and polarity of exciting pulses. Single direct discharges of a certain crystallographic orientation were observed. In the case of $CaGa_2S_4$, streamers were localised in the layer packet plane and the main part of streamer emission emerged along the channel and had stable spatiotemporal characteristics. As temperature was changed from 300 to 80 K, the discharge intensity noticeably increased. We observed earlier stable single discharges and a decrease in the total number of streamers and their types in columnar and ductile cadmium sulphide crystals [10]. This was also observed by other authors in alkali halide crystals [11]. These observations were interpreted within the framework of the interaction of electromagnetic waves in the microwave and visible regions initiated by a streamer [10] and of self-organised processes during the discharge [8].

The doping of $CaGa_2S_4$ ($Ca_4Ga_2S_7$) crystals with a multi-charge deep Eu impurities leads to a drastic increase in the streamer emission intensity in the yellow–green spectral region (Fig. 5), which is caused by the contribution of the intrinsic and impurity recombination channels (including impurity edge absorption). In this case, according to the existing concepts, the presence of luminescence in the absorption edge region and the direct-gap energy level diagram of the crystal are the necessary conditions for the appearance of streamers in semiconductors. Such an energy level diagram provides a high quantum yield of emission directly involved [10] in the discharge formation. Note that lamellar compounds have specific features caused by the difference in the properties of the medium in the layer plane (two-dimensionality, interaction of layers, etc.) and perpendicular to it, which can affect the formation of streamers.

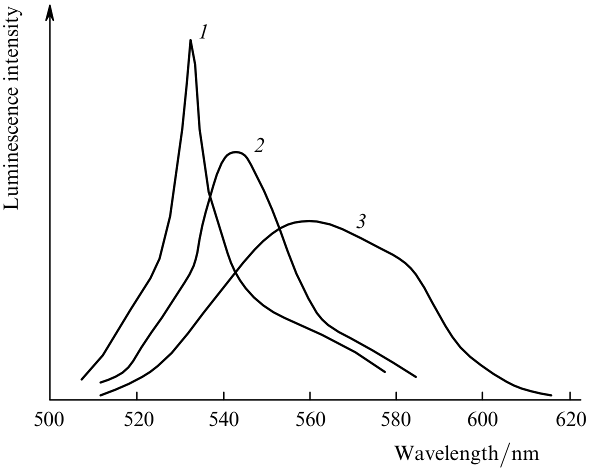

Figure 5. Streamer luminescence (*1*), (*2*) and photoluminescence (*3*) spectra of Eu : $CaGa_2S_4$ crystals at 80 (*1*), (*2*) and 300 K (*3*). Excitation was performed by 337.1-nm, 10-ns, 3-mW pulses of an LGI-21 nitrogen laser.

6. Conclusions

We have developed the method for increasing the service life of a streamer laser in limiting operation regime by more than an order of magnitude (up to ~ 10^6 pulses).The method is based on the use of a protective layer made of the same semiconductor with the orientation corresponding to minimal changes in the propagation directions of streamers on the protective layer-radiator interface. It has been found that a microrelief in the form of etching figures of size of the order of the wavelength of light on the protective layer–active element interface enhances the radiator efficiency as a whole.

We have found that streamer discharges can cause reversible changes in the luminescence spectra of semiconductors. These changes demonstrate the appearance of complexes in the surface region, which are related to defects, and the chemical decomposition of the crystal produced by discharges. The conditions for minimisation of this effect to increase the service life and stability of the streamer laser have been found. Streamer emission has been observed in new promising compounds $CaGa_2S_4$: Eu, and $Ca_4Ga_2S_7$: Eu and it has been shown that the properties of discharges in lamellar crystals are similar to those in quasi-two-dimensional media.

Acknowledgements. The authors thank R.B. Dzhabbarov for placing crystal samples at our disposal and discussion of the results.

References

1. Basov N.G., Molchanov A.G., Nasibov A.S., Obidin A.Z., Pechenov A.N., Popov Yu.M. *Zh. Eksp. Teor. Fiz.*, **70**, 1751 (1976).
2. Gribkovskii V.P. *Zh. Prikl. Spektrosk.*, **40**, 709 (1984).
3. Gribkovskii V.P., Parashchuk V.V., Yablonskii G.P. *Kvantovaya Elektron.*, **16**, 1145 (1989) [*Sov. J. Quantum Electron.*, **19**, 742 (1989)].
4. Gribkovskii V.P., Parashchuk V.V., Yablonskii G.P., in *Kvantovaya elektronika* (Quantum Electronics) (Kiev: Naukova Dumka, 1990) No. 38, p. 1.
5. Gurskii A.L. *Zh. Prikl. Spektrosk.*, **66**, 601 (1999).
6. Yablonskii G.P. *Fiz. Tverd. Tela*, **26**, 995 (1984).
7. Yablonskii G.P., Belyaeva A.K. *Fiz. Khim. Obrab. Mater.*, **4**, 30 (1989).
8. Gribkovskii V.P. *Dokl. Akad. Nauk BSSR*, **29**, 896 (1985).
9. Tagiev B.G., Abdullaev A.B., Tagiev O.B., et al. *Zh. Prikl. Spektrosk.*, **62**, 145 (1995).
10. Gribkovskii V.P., Parashchuk V.V., Rusakov K.I. *Zh. Tekh. Fiz.*, **64**, 169 (1994).
11. Mironov A.L., Zubarev A.I., Shpak V.G., Bykov V.V. *Zh. Tekh. Fiz.*, **60**, 203 (1990).