Solid state streamer lasers

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A new method for generating light in semiconductors and dielectrics is considered. Generation arises behind the ionization front in the streamer in a region with a characteristic dimension ~ 5 μm and moving at $(1\text{–}4)\times 10^8$ cm/sec. Generation of light with an intensity $\sim 10^9$ W/cm^2 and total power up to 300 W is obtained in CdS_xSe_{1-x} and ZnSe crystals.

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1. INTRODUCTION

A general method of obtaining light generation by exciting a homogeneous semiconductor with electric-field pulses was proposed earlier.[1] At sufficiently high electric-field intensity, owing to impact ionization over the tunnel effect, the concentration of the non-equilibrium carriers, which are distributed in a broad energy band, is rapidly increased in the semiconductor. To obtain inverted population and generation of light it is necessary that the applied field be rapidly turned off, within a time τ_E much shorter than the lifetime τ_R of the nonequilibrium carriers ($\tau_E \ll \tau_R \approx 10^{-9}$ sec). Such a situation was realized in several semiconductors of the GaAs type in which Gunn domains propagated.[2] As already reported,[3] these conditions for the generation of light are produced also behind the ionization front in streamer discharges in a large number of semiconductors and dielectrics.

Streamer discharges in the form of luminous filaments are produced as a result of rapid ($\sim 10^8$ cm/sec) motion of the "head" of the streamer along definite crystal-symmetry directions, and produce no damage in the crystal lattice under certain conditions that limit the current strength.[4,5] On the leading front of the streamer a high local electric-field intensity is produced and causes the appearance of a larger number of nonequilibrium carriers as a result of impact ionization or the tunnel effect. The dense highly-conducting electron-hole plasma produced behind the front leads to a rapid decrease of the electric field intensity and to a slowing down and degeneracy of the carriers, as a result of which local conditions for light generation are produced.

We report here a theoretical and experimental investigation of the physical characteristics of lasers based on the crystals CdS, CdS_xSe_{1-x} and at ZnSe, in which the pumping was effected in streamer discharges.

2. EXPERIMENT

The crystal samples used in the study were plane-parallel plates 30–80 μ thick, with dielectric mirrors coated on their surfaces. The reflection coefficients of the mirrors were 100% on one side and 97% on the other.

Light generation was observed in a direction perpendicular to the plane of the plates, both at liquid-nitrogen temperature and at room temperature. The streamer discharges were excited in the samples by two methods. In one case a short pulse of ~100 nsec duration and voltage from 10 to 30 kV was applied to the crystal placed in a liquid dielectric (transformer or castor oil, or else liquid nitrogen) through a small discharge gap from a high-voltage generator (see Fig. 1a). In the second case the crystal sample was mounted on a transparent insulator, placed in vacuum, and charged with an electron beam (Fig. 1b) until a streamer discharge was produced in the sample. The generation spectrum was recorded with an STÉ-1 spectrograph, and the power was measured with a calibrated coaxial photocell. The time characteristics of the radiation were investigated with the aid of an FÉR-2 high-speed camera with a time resolution up to 20 psec, and the near and far radiation zones were recorded on photographic film.

Excitation of CdS and CdSe crystals and their solid solutions, in which the principal symmetry axis of the crystals was in the plane of the plate, produced glowing tracks making an angle 43 ± 3° with this axis. The direction of these tracks was practically independent of the magnitude or polarity of the voltage pulse. In crystal plates cut perpendicular to the principal symmetry axis, the track pattern was in the form of a star with rays making an angle 60°. The track thickness was measured with a microscope and was equal to 1–5 μ.

Experiments on the influence of the pulse voltage on the track length have shown that their average length increases linearly with increasing pulse voltage. The investigations have shown that the initial conductivity of the crystal exerts an appreciable influence on the for-

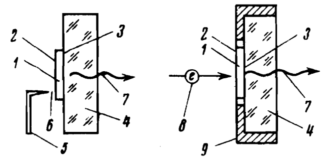

FIG. 1. Excitation of streamer discharges by applying electric-pulses through a discharge gap (a) and by charging the crystals with an electron beam in vacuum (b): 1—investigated crystal, 2, 3—dielectric mirrors, 4—sapphire or glass substrate, 5—high-voltage electrode, 6—gap filled with liquid dielectric, 7—investigated radiation, 8—electron beam, 9—metal frame.

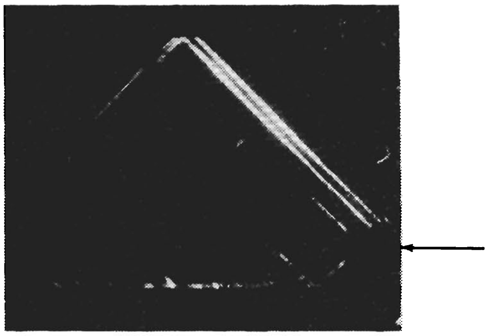

FIG. 2. Generation of light in streamer discharges in CdS plates at $T = 80\,°K$. The arrow shows the point where the pulse voltage was applied. The length of the double track is 0.8 cm.

mation of the streamer discharges when they are excited by an electric field.

We have investigated cadmium-sulfide crystals doped with indium, with a resistivity from 10^2 to 10^{12} Ω-cm. The largest radiation power was obtained in the samples with the highest resistivity. With decreasing resistivity, the length of the tracks decreased, their structure became more branched, and no tracks were observed at a resistivity lower than $\sim 10^4$ Ω-cm.

Measurement of the power of the generated light has shown that in the better crystals the power reaches ~ 300 W if the crystals are placed in liquid nitrogen and ~ 70 W at room temperature. The duration of the radiation in one pulse was 0.5–2 nsec. By regulating the voltage of the applied pulses it was possible to produce generation in one or two tracks following the same path in the crystal (see Fig. 2). At a pulse repetition frequency 5 Hz, the generation could last for an hour without noticeable attenuation. The generated radiation was

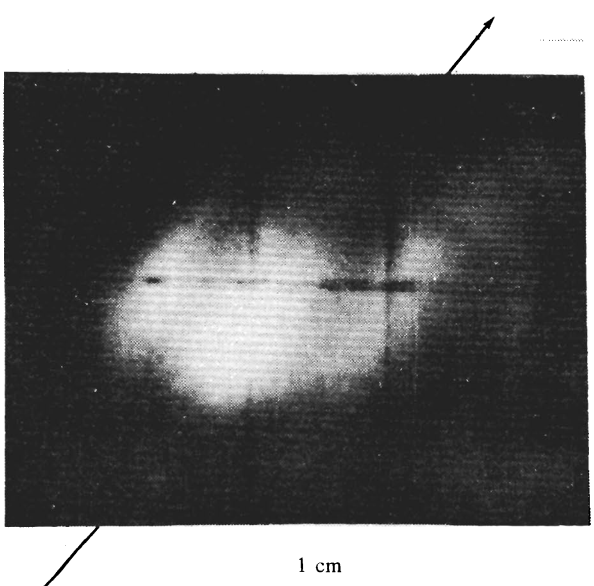

FIG. 3. Photograph of the angular divergence of the radiation generated by an individual track at a distance of 3 cm from the CdS plate. The arrow indicates the direction along the track axis.

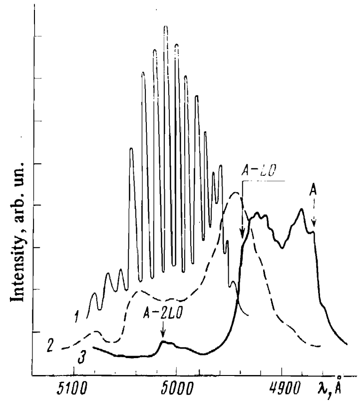

FIG. 4. Generation (1) and spontaneous emission (2) spectra of a streamer discharge in CdS at $T = 80\,°K$. The photoluminescent spectrum of the same sample (3) is shown for comparison.

directed perpendicular to the plane of the crystal plate with an average angle divergence 20° (see Fig. 3).

The spectrum of the light excited in the streamer discharges agreed with the spectrum observed when the samples were excited with a beam of fast electrons, and consisted of individual modes corresponding to the plate thickness with total width of the spectrum from 1 to 7 nm (see Fig. 4).

The investigation of the time characteristics of the radiation with the aid of the FÉR-2 high-speed camera has shown that the generation region moves through the crystal at a velocity from 1×10^8 to 5×10^8 cm/sec (Fig. 5), the duration of the glow of each individual point not exceeding 20 psec (the time resolution of the instrument). The velocity of the generation region, in the indicated range, was practically independent of the polarity of the applied high-voltage pulse.

3. DISTRIBUTION OF ELECTRIC FIELD AND OF THE NONEQUILIBRIUM CARRIERS IN THE STREAMER

The high density of the nonequilibrium carriers, which is needed for intense light generation, is produced by

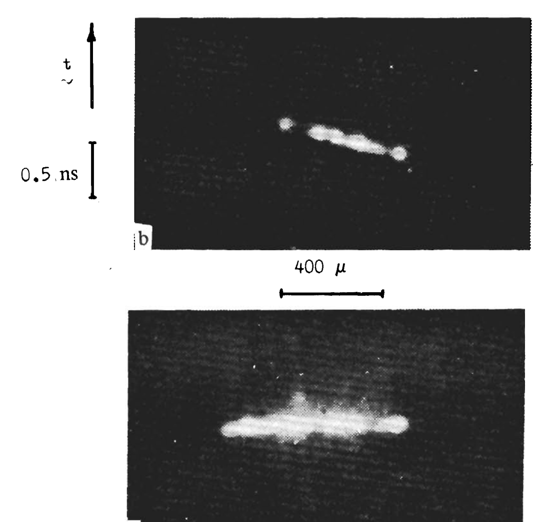

FIG. 5. Streak photograph of the light-generation region in a streamer without a time scan (a) and with a time scan (b).

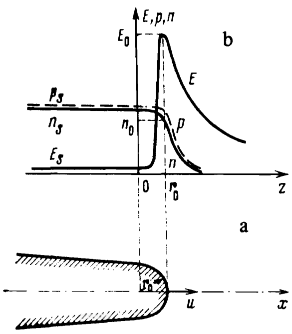

FIG. 6. Picture of streamer moving in the direction of the X axis (a) and the distribution of the nonequilibrium-carrier density and of the electric-field intensity along the streamer axis (b).

impact ionization or by the tunnel effect near the "head" of the streamer, where the electric field intensity is equal, in first approximation, to the electric field intensity of the charged metallic tip, and can reach very high values.

Let us examine the distribution of the electron and hole densities n and p, and also of the electric field intensity E in this region. The strong-field region on the leading front of the streamer (Fig. 6) is the analog of the region of multiplication of carriers in avalanche diodes and can be described by the following system of equations

$$\frac{\partial n}{\partial t}=\frac{1}{e}\operatorname{div}\mathbf{j}+\alpha v n+w, \tag{1}$$

$$\frac{\partial p}{\partial t}=\alpha v n+w, \tag{2}$$

$$\operatorname{div}\mathbf{E}=\frac{4\pi e}{\varepsilon}(p-n), \tag{3}$$

where

$$\mathbf{j}=en\mu\mathbf{E}+eD\nabla n \tag{4}$$

is the electron current density, and where we neglect, for simplicity, the hole current density in the considered broad-band materials. In Eqs. (1)–(4), D is the electron diffusion coefficient, ε is the dielectric constant of the crystal, e is the electron charge, α is the impact-ionization coefficient, w is the rate of formation of electron-hole pairs as a result of the tunnel effect and as a result of ionization by photons emerging from the streamer, μ is the mobility, and $v=\mu E$ is the drift velocity of the electrons, which in the strong-field region is approximation equal to its saturation value

$$v_0=\left(\frac{\hbar\omega_0}{m_e}\operatorname{th}\frac{\hbar\omega_0}{2kT}\right)^{1/2}, \tag{5}$$

where $\hbar\omega_0$ is the optical-phonon quantum energy, m_e is the electron effective mass, and T is the crystal-lattice temperature.

Assuming for simplicity that the distribution of the nonequilibrium carriers and of the electric field on the axis behind the leading front of the streamer is one-dimensional, we obtain from (1)–(4), after a single integration, the following relation

$$\frac{\varepsilon}{4\pi}\frac{\partial E}{\partial t}+env+eD\frac{\partial n}{\partial x}=j_s, \tag{6}$$

which represents the conservation law of the density of the total current j_s flowing along the streamer. To obtain from this equation an explicit expression for the electric field intensity, we neglect diffusion and change over to a system of coordinates moving with the velocity of the leading front of the streamer u, for which purpose we make the substitution $z=x-ut$, $\partial/\partial x=d/dz$, $\partial/\partial t=-u d/dz$. In this coordinate system Eq. (6) takes the form

$$\frac{dE}{dz}-\frac{4\pi\sigma(z)}{\varepsilon u}E+\frac{4\pi j_s}{\varepsilon u}=0, \tag{7}$$

from which we obtain after integration

$$E(z)=E_0\mathscr{E}(z;r_0)+\frac{4\pi j_s}{\varepsilon u}\mathscr{E}(z;r_0)\int_z^{r_0}\frac{1}{\mathscr{E}(x;r_0)}dx, \tag{8}$$

$$\mathscr{E}(a;b)=\exp\left\{-\frac{4\pi}{\varepsilon u}\int_a^b\sigma(x)dx\right\}, \tag{9}$$

where $\sigma(z)=env/E$ is the electric conductivity of the electron-hole plasma inside the streamer, and the solution (8) itself is determined on the streamer axis in the region $z<r_0$ (Fig. 6b).

In the calculation of the electric field on the leading front of the streamer it is necessary to take into account the geometric shape of the streamer. Assuming that the streamer boundary is a paraboloid of revolution, the Poisson Eq. (3) in parabolic coordinates assumes on the axis the form

$$\frac{1}{z}\frac{d}{dz}(zE)=\frac{4\pi e}{\varepsilon}(p-n),\qquad z\geqslant r_0. \tag{10}$$

Neglecting diffusion and assuming, as before, that the distribution of the nonequilibrium carriers is one-dimensional, we obtain from Eqs. (1) and (2), in the coordinate system moving with the leading front, the following equations:

$$-u\frac{dn}{dz}=v_0\frac{dn}{dz}+\alpha v_0 n+w, \tag{11}$$

$$-u\frac{dp}{dz}=\alpha v_0 n+w, \tag{12}$$

in which we have used the equality $v=v_0$, which is valid in the strong-field region.

From Eqs. (10)–(11) and the chosen boundary conditions $z\to\infty$, $p\to p_i$, $n\to n_i$, $p_i=n_i$, and $E\to E_0 r_0/z$ we obtain for the electric-field distribution and for the concentration of the nonequilibrium electrons at $z\geqslant r_0$ the expressions:

$$E(z)=E_0\frac{r_0}{z}-\frac{4\pi e}{\varepsilon u}\frac{v_0}{z}\int_z^\infty xn(x)dx, \tag{13}$$

$$n(z)=n_0e^{-g(z)}-\frac{1}{v_0+u}e^{-g(z)}\int_{r_0}^z w(x)e^{g(x)}dx, \tag{14}$$

$$g(z)=\frac{v_0}{v_0+u}\int_{r_0}^z\alpha(x)dx, \tag{15}$$

E_0 is the electric field intensity, and n_0 is the concentration of the electrons at the point $z=r_0$.

4. CONDITIONS FOR THE ONSET OF GENERATION OF LIGHT

For light to be generated in a streamer discharge it is necessary that the impact ionization or the tunnel effect during the time of action of the strong electric field on the leading front of the streamer ~ 10^{-12} sec have time to form a sufficiently high density of electron-hole pairs ~ 10^{19} cm^{-3}, and furthermore that the electric field intensity behind the front decrease rapidly to field values at which no significant carrier heating takes place.

We consider first the condition for the formation of a dense electron-hole plasma on the leading front of the streamer, when the principal mechanism of carrier multiplication is impact ionization. In this case the distribution of the electron density is determined by relation (14), in which w should be taken to mean the rate of formation of the electron hole pairs on account of photoionization.

The dependence of the coefficient of impact ionization on the electric field intensity was calculated analytically in[6,7] and has in the general case a complicated form. In this paper we use the simple approximation

$$\alpha(E)=\frac{a}{l}\exp\left\{-\frac{b\varepsilon_i}{elE}\right\}, \qquad (16)$$

where l is the electron mean free path, and the coefficients a and b are obtained from a comparison of (16) with the results of numerical calculations carried out in[8]. Confining ourselves in (13) to the first term, i.e., assuming that the electric field of the streamer coincides in first order with the electric field from the charged metallic tip, we obtain after substituting (13) in (16)

$$\alpha(z)=\alpha_0\exp\left\{-\frac{E_i}{E_0}\frac{z-r_0}{r_0}\right\}, \qquad (17)$$

where

$$\alpha_0=\frac{a}{l}\exp\left\{-\frac{E_i}{E_0}\right\},\quad E_i=\frac{b\varepsilon_i}{el}.$$

Recognizing that the most probable source of the photoionization in streamer discharges is the bremsstrahlung of an electron-hole plasma, we represent the rate of formation of nonequilibrium carriers by photoionization, at a distance z from the leading front of the streamer, in the form

$$W_f(z)=W_0e^{-\varkappa z}, \qquad (18)$$

where $\varkappa$ is the effective absorption coefficient of the bremsstrahlung photons, the energy of which exceeds the width of the forbidden band, and W_0 is connected with the current density I_0 of these photons by the equation $W_0=\varkappa I_0$.

Substituting (17) and (18) in (14), in which we go over in the limit as $z\to\infty$, we obtain the following expression for the electron density at the streamer boundary:

$$n_0=n_ie^{g_0}+\frac{\xi I_0}{v_0+u}\gamma(\xi,g_0)g_0^{-\xi}e^{g_0}, \qquad (19)$$

where

$$g_0=\frac{v_0}{v_0+u}\frac{E_0}{E_i}\alpha_0r_0,\quad \xi=\frac{E_0}{E_i}\varkappa r_0,$$

$$\gamma(\xi,g_0)=\int_0 e^{-t}t^{\xi-1}\,dt,$$

and the incomplete gamma function $\gamma(\xi,g_0)$ goes over, in the case of a large value of the multiplication, into the gamma function: $\gamma(\xi,g_0)\approx\Gamma(\xi)$.

On the basis of the obtained relation (19), let us estimate the conditions for impact multiplication of the carriers in CdS. Assuming that the density of the free or of the weakly-bound electrons in the considered samples is not less than $n_i=10^{14}$ cm^{-3}, and also using for CdS at $T=80$ °K the following parameter values: $a=0.6$, $b=0.3$, $\varepsilon_i=3$ eV, $m_e=0.2\,m$, $\hbar\omega_0=0.04$ eV, $l=10^{-6}$ cm, $r_0=1\cdot10^{-4}$ cm, $u=3\cdot10^8$ cm/sec, we obtain $v_0=1\times10^7$ cm/sec and $E_i=1\times10^6$ V/cm. The electric field intensity at which an electron density $n_0=10^{19}$ cm^{-3} is reached in the streamer as a result of multiplication of the priming electrons is therefore $E_0=7\times10^6$ V/cm.

The field values required to attain this density by initiating the avalanche with bremsstrahlung are somewhat higher: $E_0\gtrsim10^7$ V/cm.

In the case when the principal mechanism of formation of the nonequilibrium carriers is the tunnel effect, the distribution of the electron density on the streamer axis is given by formula (14), in which it is necessary to put $g(z)=0$, and w should be taken to mean the rate of formation of the electron-hole pairs by tunneling of the electrons from the valence band[9]:

$$w_t=AN_vE^{10/3}e^{-E_c/E},\quad E_c=\frac{\pi}{4}\left(\frac{m_e}{m}\frac{\varepsilon_g}{I_H}\right)^{1/2}\frac{\varepsilon_g}{ea_H}, \qquad (20)$$

where $A=10^{-7}$ sec^{-1} (V/cm)$^{-10/3}$, N_v is the electron density in the variance band, ε_g is the width of the forbidden band, a_H is the radius of the first Bohr orbit, and I_H is the ionization potential of the hydrogen atom. Assuming, as before, that in the first-order approximation the dependence of the electric field on the coordinate is of the form $E=E_0r_0/z$, we obtain after substituting (20) in (14) and going to the limit as $z\to\infty$ the following relation:

$$n_0=\frac{r_0}{v_0+u}N_vAE_0E_c^{7/3}\Gamma\left(-\frac{7}{3},\frac{E_c}{E_0}\right), \qquad (21)$$

where the incomplete gamma function

$$\Gamma(\alpha,x)=\int_x^\infty e^{-t}t^{\alpha-1}\,dt$$

is equal at large x to $\Gamma(\alpha,x)\approx x^{\alpha-1}e^{-x}$.

Substituting the numerical parameters used above for CdS, and also $e_g=2.57$ eV and $N_v=2\times10^{22}$ cm^{-3}, we obtain $E_c=7.4\times10^7$ V/cm, while the value of the electric field needed to reach a density $n_0=10^{19}$ cm^{-3} is $E_0=5.5\times10^6$ V/cm.

Thus, in the case of CdS, the more probable mechanism of formation of nonequilibrium carriers in streamer discharges is the tunnel effect, in agreement with the data on static breakdown.[10] The decrease of the electric field intensity behind the leading front of the streamer is determined by expression (8). By way of estimate we assume that the electric conductivity of the plasma behind the front is everywhere approximately equal to its quasistationary value σ_s; then we obtain in place of (8) the following expression for the electric field intensity:

$$E(z)=E_0\exp\left\{-\frac{r_0-z}{u\tau_M}\right\}+E_s, \tag{22}$$

where $\tau_M=\varepsilon/4\pi\sigma_s$ is the Maxwellian relaxation time of the electric field in the conducting medium, and $E_s=j_s/\sigma_s$ is the intensity of the residual electric field inside the streamer.

Thus, the characteristic time during which the strong electric field falls off behind the leading front of the streamer is equal to the Maxwellian time τ_M, and for CdS at a free-carrier density $n_s\approx 10^{19}$ cm^{-3} inside the streamer it amounts to $\tau_M\approx 10^{-12}$ sec, which is much shorter than the lifetime of the nonequilibrium carriers $\tau_R\approx 10^{-9}$ sec.

To determine the density of the current flowing through the streamer we use the current conservation equation (6). Considering this equation at the point $z=r_0$, where the electric field intensity reaches a maximum, and assuming that at this point $\partial n/\partial x\approx -n_0/r_0$, we obtain

$$j_s\approx en_0v_0-eD\,n_0/r_0. \tag{23}$$

Substituting in this expression the previously employed values $n_0\approx\frac{1}{2}n_s\approx 10^{19}$ cm^{-3}, $r_0=10^{-4}$ cm, $v_0=10^7$ cm/sec, and also the quantity $D\approx 10^3$ cm^2/sec, we obtain $j_s\lesssim 10^6$ A/cm^2. Hence, using the electron mobility $\mu_s=200$ cm^2/V-sec, we obtain the following estimate for the residual electric-field intensity in the streamer:

$$E_s=\frac{j_s}{e\mu_s n_s}\leqslant 10^3\ \text{V/cm}.$$

Thus, in a solid, just as in a gas (see[11]), the electric field intensity inside the streamer is a small quantity compared with the external field. In such an electric field, the distance between the electron temperature and the lattice temperature is of the order of the lattice picture, which leads to the possibility of degeneracy of the nonequilibrium carriers and to the onset of conditions for light generation.

5. DISCUSSION OF RESULTS

From the angular divergence and the streak photograph of the radiation, and also from microphotometry, it follows that the generation constitutes a volume with the characteristic dimension ~ 5 μ, moving with a velocity 3×10^8 cm/sec. From this, and also from measurements of the generation power of an individual filament (~ 100 W in the case of CdS) it follows that the intensity and the specific power of the light radiation reach respectively the values ~ 10^9 W/cm^2 and ~ 3×10^{12} W/cm^3, with the duration of the generation from a selected element of the crystal volume amounting to 2×10^{-12} sec, while the specific energy yield of the laser radiation is 6 J/cm^3. In the case of generation at a wavelength λ = 500 nm and a quantum yield equal to unity, the specific radiation energy corresponds to a density $n_s\approx 10^{19}$ cm^{-3} of the nonequilibrium carriers in the active region. The same value of the charged carrier density causes the observed long-wave shift of the bands in the streamer emission spectrum (see Fig. 4), which is a characteristic feature of the emission from a dense electron-hole plasma.[12] The length of the streamer increases so long as the external field is capable of maintaining on its leading front a field intensity exceeding the critical value $E_0\approx 5\times 10^6$ V/cm. This circumstance, with allowance for the decrease of the potential over the length of the streamer, owing to its finite conductivity, explains the observed linear dependence of the average streamer length on the applied voltage.

The observed rate of displacement of the region where light is generated, ~ 3×10^8 cm/sec, greatly exceeds the drift velocity of the carriers in a strong electric field, and is equal to the velocity of the leading front of the streamer, which in turn is none other than the velocity of the density profile of the nonequilibrium carriers:

$$u=\frac{\partial n}{\partial t}\Big/\frac{\partial n}{\partial x}. \tag{24}$$

Substituting here the value of the time derivative from (1), taken at the point at which the electric field intensity is maximal, and also using an estimate of the derivative at this point $\partial n/\partial x\approx n_0/r_0$, we obtain, neglecting diffusion, the following expression for the velocity:

$$u\approx v_0+v_0\alpha_0r_0+w_0r_0/n_0. \tag{25}$$

We see therefore that the rate of motion of the leading front of the streamer greatly exceeds the drift velocity of the electrons in the case of the intense multiplication of the carriers, i.e., when, depending on the multiplication mechanism, inequality $\alpha_0r_0\gg 1$ or $w_0r_0/v_0n_0\gg 1$ is satisfied. More accurate expressions for the velocity are implicitly contained in Eqs. (19) and (21) above, if the parameters n_0, E_0, and r_0 are assumed given.

At a nonequilibrium carrier density the active region $n\sim 10^{19}$ cm^{-3}, the gain of the light in CdS can reach values ~ 10^3 cm^{-1}.[12] Owing to the large gain, generation has time to develop after several passes of the light beam between the resonator mirrors. In individual cases, we observed generation without coating the mirrors, as a result of the Fresnel reflection of the light from the faces of the crystal.

6. CONCLUSION

Intense pumping on the leading front of the extrema can be used to excite a light generation in a large class of semiconductors and dielectrics, particularly in alkali-halide crystals in which, as is well known, individual sharply pronounced streamer discharges are observed.[4,5] The rapid motion of the generation region in the streamer protects the crystal against optical breakdown and makes it possible to attain radiation intensities higher by several orders of order than in ordinary semiconductor lasers. In addition, high speed motion of a generation region of small size makes it easy to obtain, using different masks on the resonator mirrors, a controlled sequence of ultrashort light pulses.

We note in conclusion that under certain operating conditions of avalanche diodes with $p-n$ junctions, ionization impact fronts are observed in which the intensity of the electric field falls off rapidly behind the front.[13] In this case, under suitable conditions, one can also expect light generation of the type considered above.

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Inelastic scattering of gamma quanta by hydrogen-like atoms

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The differential and total cross sections for inelastic scattering of γ quanta by hydrogen-like atoms that involves electron transitions from the $1s$ state to the $2s$ or $2p$ state are analytically calculated with allowance for terms of the order of α^2Z^2 inclusive. The differential cross section formulas obtained with such an accuracy are valid for small angle scattering. The results are applicable in the photon-energy region $\omega \gg m\alpha Z$ (m is the electron mass) and overlap with the results obtained by Gorshkov, Mikhaĭlov, and Sherman {Zh. Eksp. Teor. Fiz. 66, 2020 (1974) [Sov. Phys. JETP 39, 995 (1974)]} for energies $m\alpha Z \ll \omega \ll m$.

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1. INTRODUCTION

The derivation of the nonrelativistic Coulomb Green function stimulated the theoretical study of two-photon processes involving bound electrons. Computations on elastic and inelastic scattering of photons by hydrogen atoms were carried out in the dipole approximation[1–6] and without the use of this approximation,[7,8] which allowed the consideration of the entire nonrelativistic photon-energy region $\omega \ll m$ (m is the electron mass) and the processes forbidden in the dipole approximation.[8] The cross sections for elastic and Compton scattering in the relativistic photon-energy region have been obtained in a number of papers.[9–12] In these papers the cross sections for scattering processes with the transfer to the nucleus of any momentum q, including $q \sim m$, are computed. In[9,10] numerical computations of elastic scattering from the K shell of mercury[9] and of Compton scattering from the K shell of lead[10] are carried out. Analytic calculations in the first approximation in the Coulomb field have been carried out for elastic[11] and Compton[12] scattering.

In the present paper we consider the inelastic scattering of γ quanta by hydrogen-like atoms, accompanied by atomic-electron transitions from the K- to the L-shell (Raman scattering). In the photon-energy region $\omega \sim I$ (I is the ionization energy of the atom), where the dipole approximation is valid, transitions are allowed not to the entire L shell, but only to the $2s$ state. The scattering process involving transitions to the $2p$ states is forbidden. In the relativistic energy region $\omega \sim m$, both processes occur at the same rate. Simple formulas are obtained for the differential and total cross sections for the indicated processes up to terms of the order of α^2Z^2 inclusive in the entire photon-energy region $\omega \gg \eta$, where $\eta = m\alpha Z$ is the mean K-electron momentum. The formulas for the differential cross