Generation of light in semiconductors and dielectrics excited by an electric field

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We consider a new method of electrically exciting generation of light in semiconductors and dielectrics. Light of intensity $\sim 10^9$ W/cm^2 was generated in CdS_xSe_{1-x} and ZnSe crystals from radiation regions having characteristic dimensions ~ 5 μ and moving with velocities $(1–4)\times 10^8$ cm/sec.

A method of generating light by exciting a homogeneous semiconductor with electric-field pulses was proposed in[1]. At a sufficiently high electric-field intensity, owing to impact ionization or the tunnel effect, the concentration of nonequilibrium carriers distributed in a wide energy band is strongly increased in the semiconductor. To obtain population inversion and to generate light it is necessary to turn off rapidly the applied field within a time much shorter than the lifetime of the nonequilibrium carriers. This situation is realized in certain semiconductors when Gunn domains propagate in them.[2]

In the present paper we consider a new method of electric excitation of a large class of semiconductors and dielectrics, in which the onset of a large concentration of nonequilibrium carriers as a result of the strong field leads by itself to a rapid decrease of the electric-field intensity, to a slowing down and degeneracy of the carriers, and to intense generation of light. In an earlier investigation of generation in single-crystal CdS plates bombarded by an electron beam,[3] electric discharges were observed in the form of brightly glowing filaments produced in the plate interior as a result of accumulation of space charge. Generation of light was observed in[4] following excitation of such filamentary discharges, and was attributed to the acoustoelectric effect.

We report here an investigation of generation of light from filamentary discharges in CdS, CdSe, CdS_xSe_{1-x} and ZnSe crystals excited by a high-voltage (up to ~30 kV) generator of short electric pulses, and explain the observed phenomena.

The crystal samples were plane-parallel plates 30–50 μ thick, on the surfaces of which dielectric mirrors with reflectivities 100 and 97% were deposited. Generation of light was observed both at liquid-nitrogen temperature and at room temperature. The samples were excited by applying, via a metallic needle, an electric voltage pulse to a crystal secured to a glass or sapphire plate, through a discharge gap in transformer oil or in liquid nitrogen.

The generation took place in a direction perpendicular to the surface of the crystal plate, with an angular divergence ~20°, from filamentary regions several millimeters long with filament diameters $d = 3–5$ μ (see Fig. 1). The generation spectrum corresponded to the spectrum observed when the indicated crystals with a beam of fast electrons, and consisted of individual modes corresponding to the plate thickness, with total spectral width from 1 to 7 nm. The generation power in CdS at liquid-nitrogen temperature, measured with the aid of a coaxial photocell, reached 300 W at a total generation pulse duration 0.5–2 nsec. The temporal characteristics of the generation process were investigated with the aid of a high-speed FÉR-2 photographic camera. A comparison of the photographs of the emission of the samples, with and without time scanning (see Fig. 2) shows that the region where light is generated moves through the crystal with velocity $v = (1-4) \times 10^8$ cm/sec, and the time of glow of each individual point does not exceed ~30 psec (the temporal resolution of the instrument). A much weaker afterglow was ob-

FIG. 1. Generation bands in CdS at $T = 80$ °K. The arrow shows the application of the voltage pulse. The length of the double band was 0.8 cm.

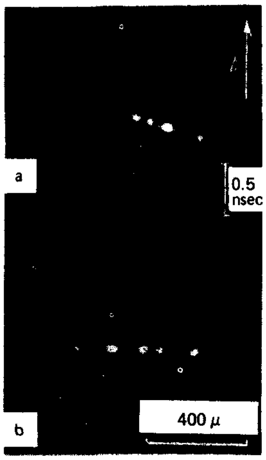

FIG. 2. Time scan of the emission from the generation region without time sweep (a) and with time sweep (b).

served for several dozen nanoseconds after the termination of the generation pulse.

It follows from the angular divergence of the radiation that the generation region constitutes a volume with characteristic dimension $d \approx 5\ \mu$, moving with velocity $v \approx 3\times10^{8}$ cm/sec. From this, and also from the measurements of the generation power of an individual filament (~100 W), it follows that the intensity and the pair-unit power of the light radiation reaches values ~10^{9} W/cm^{2} and ~3×10^{12} W/cm^{3}, respectively, and the generation duration of each individual volume element of the crystal amounts to ~2×10^{-12} sec. Such a high generation intensity and a corresponding density nonequilibrium carrier ~10^{20} cm^{-3} produced within ~10^{-12} sec can be obtained only from impact ionization or the tunnel effect in a strong electric field. The rather high rate of production of the nonequilibrium carriers in the strong electric field and the rapid turning off of this field can be attributed to the streamer mechanism of partial breakdown of solids. It is known that in partial breakdown the streamer develops in definite crystal-symmetry directions with velocities ~10^{8} cm/sec, without causing macroscopic lattice disturbances.[5]

Near the "head" of the streamer, the local electric-field intensity gives rise to the appearance of nonequilibrium carriers as a result of impact ionization or the tunnel effect. At the employed electrode voltages ~10^{4} V, the local field intensity in front of the streamer head reaches ~10^{7} V/cm, and in accordance with the formulas[6] for the probabilities of the impact ionization or the tunnel effect, it produces within a time ~10^{-12} sec a nonequilibrium carrier density ~10^{21} cm^{-3}. At such densities, the conductivity σ of the crystal increases sharply and reaches a value $\sigma \approx 10^{14}$ sec^{-1}. In a conducting medium, the electric field decreases within a time $\tau = \epsilon/4\pi\sigma$, where ϵ is the dielectric constant of the crystal, so that $\tau \approx 10^{-14}$ sec for CdS. Thus, the distribution of the electric field intensity along the streamer axis (see Fig. 3) shows that the conditions considered in[1] for population inversion and generation of light are satisfied in the streamer directly behind the ionization front. We note that when the experiments are repeated many times on one and the same sample, the positions of the generation filaments remain practically unchanged. The motion of a generation region of small dimensions makes it easy to obtain a controlled sequence of ultrashort light pulses. Such a mechanism of intense pumping with rapid motion of the excitation region can be used to produce laser emission in a large class of substances.

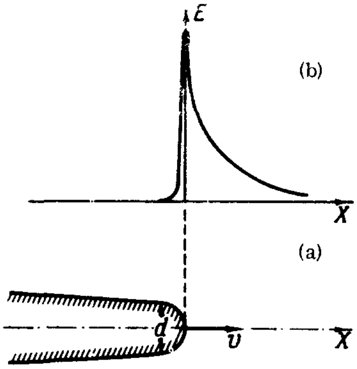

FIG. 3. Form of streamer moving in the direction of the x axis (a) and distribution of the electric field intensity along the streamer axis (b).

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