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POPULATION INVERSION IN SOLIDS BY IMPACT EXCITATION OF IMPURITIES

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There are two known methods of producing inverted population in semiconductors by direct electric excitation. The first is based on injection of non-equilibrium carriers through a p-n junction in degenerate semiconductors [1]; it is realized in injection lasers. The second method consists of producing inverted population in the conduction (or valence) band of a homogeneous semiconductor by electric-field pulses that cause ionization of the ions of host lattice or of the impurity [2 - 6]. There is still no unequivocal proof that the latter method can produce inverted population.

We propose in this paper a new method of producing inverted population in solids at the excited levels of deep impurity centers, by impact excitation with majority carriers accelerated by an external electric field. A similar method is used successfully in gas lasers.

The proposed method of producing inverted population was realized by us in zinc sulfide doped with manganese. This substance is a broad-band (ε_g = 3.7 eV) high-resistivity semiconductor of n-type ($\rho \sim 10^8 - 10^{10}$ $ohm^{-1}cm^{-1}$). The manganese enters the ZnS lattice in the form of Mn^{2+}, replacing the zinc. The presence of an unfilled 3b shell in Mn^{2+} leads to the appearance of a number of local energy levels connected with electronic transitions in this shell. The ground state (^6S) of the Mn^{2+} ion corresponds to an electron configuration $3d^5$ with parallel spins, and the excited state (^4G) corresponds to spin flip of one of the $3d^5$ electrons. The crystal field of the lattice leads to a splitting of the excited level into several sublevels and to a partial lifting of the hindrance from the transitions under consideration. The luminescence in ZnS:Mn is due to a transition from the lowest excited level $^4T_1(^4G)$ to

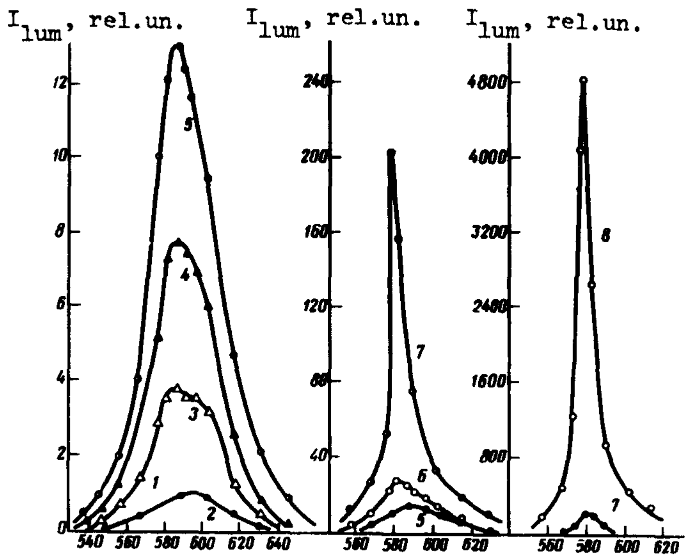

Fig. 1. Emission spectra of ZnS:Mn at different intensities of the exciting electric field: 1 - 0.8 × 10^6, 2 - 1 × 10^6, 3 - 1.1 × 10^6, 4 - 1.2 × 10^6, 5 - 1.3 × 10^6, 6 - 1.46 × 10^6, 7 - 1.62 × 10^6 V/cm.

the ground level ${}^6A_1({}^6S)$ and has a spectrum in the form of a broad band (half-width ∿700 Å) with λ_{max} = 590 nm [7]. The mechanism of electroluminescence excitation in ZnS:Mn is impact excitation of the impurity ions [8, 9].

Figure 1 shows the emission spectra of ZnS:Mn, obtained by us at different electric-field intensities E. Starting with a certain "threshold" value E_{thr} (∿1.4 × 10^6 V/cm), the emission band begins to narrow down strongly, a fact accompanied by a sharp increase in the intensity (by 2 - 3 orders of magnitude). At the same time, the spatial distribution of the radiation is altered, and a clearly pronounced directivity of the radiation appears (see Fig. 2). At E > E_{thr}, the radiation becomes partly coherent, as is evidenced by the presence of an interference picture with visibility 0.2 upon diffraction by two slits placed behind the output mirror (slit width 20 μ, distance between them 30 μ). The current density through the sample at the threshold field intensity was ∿10^{-2} A/cm^2. The internal quantum yield in the generation regime (ratio of the number of photons emitted per second to the number of electrons passing through the sample during this time) greatly exceeds unity. The gain measured by comparing the intensities of the light passing through the sample in the excited and in the unexcited state is (1 - 5) × 10^3 cm^{-1} for $\lambda = \lambda_{max}$.

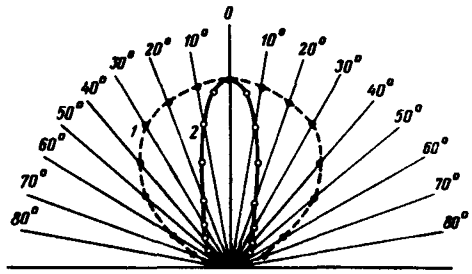

Fig. 2. Directivity pattern of radiation with λ = 580 nm at a field intensity lower (curve 1, E = 1.2 × 10^6 V/cm) and higher (curve 2, E = 1.5 × 10^6 V/cm) than the threshold value.

The foregoing facts indicate that when a field of intensity larger than 1.4 × 10^6 V/cm is applied to ZnS:Mn, inverted population of the excited levels of the Mn^{2+} ions is produced and leads to the appearance of stimulated emission. The mechanism of producing the inverted population is the impact excitation of the Mn^{2+} ion. This is evidenced by the following facts: an emission spectrum typical of the transition ${}^4T_1({}^4G) \rightarrow {}^6A_1({}^6S)$ in the Mn^{2+} ion, a low density of the threshold current, absence of noticeable heating of the sample, and a large internal quantum yield of the generation (>> 1).

The proposed method of producing inverted population has a number of advantages: 1) it admits of excitation in the continuous regime without special cooling of the sample, 2) it ensures high efficiency of conversion of electric energy into light, 3) it produces a large excess population and yields high gains.

In conclusion, we are grateful to Academician S.I. Pekar of the Ukrainian Academy of Sciences, to Prof. M.P. Lisitsa, to Prof. M.V. Fok, and to Doctor of Physical and Mathematical Sciences M.S. Soskin for discussions.

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NEW EXPERIMENTS ON THE FORMATION OF A SELF-FOCUSING FILAMENT FROM THE FOCUS OF THE BEAM ON THE SURFACE OF A MEDIUM

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One of the modifications of self-focusing [1 - 4] is the formation of filaments from the focus of laser radiation in a medium, and was observed first in [5]. However, the conditions and mechanism of the formation of the filaments and their nature and properties have not yet been investigated, in spite of the attractive prospects of obtaining a narrow concentrated beam by focusing a broad one.

We describe here new results on the formation of filaments from the focus of a laser beam in a liquid; these results demonstrate the important role played in the formation of the filaments by the proximity of the focus to the surface of the medium.

The experimental setup is shown in Fig. 1. The beam from a Q-switched ruby laser (1) rated 20 - 30 MW was focused by a lens (2) inside a special vertical cell (3) filled with nitrobenzene. The cell had a large diameter (6 cm) and was lined on the outside with a dull-surface bent sheet of teflon to eliminate false images on the axis by specular reflection of light scattered and radiated from the region near the focus from the glass walls of the cell. An open gap was left between the edges of the teflon sheet to permit lateral observation and photography. By incompletely filling the vertical cell we were able to place the focus very close to the surface of the liquid without the danger of damaging the end window of the cell. (Such experiments are impossible with the horizontal cells previously used by others.) The investigations revealed the important role played in the formation of the filaments by the proximity of the focus to the surface of the medium.

Figures 2(a, b, c, d, e) show side-view photographs of the cell, taken with the lens (focal length 5 cm) successively shifted to the left. As the lens was moved, the focus passed through the surface of the liquid. We see that the drawing process is the most effective when the focus is located ~5 mm from the surface inside the liquid (d).

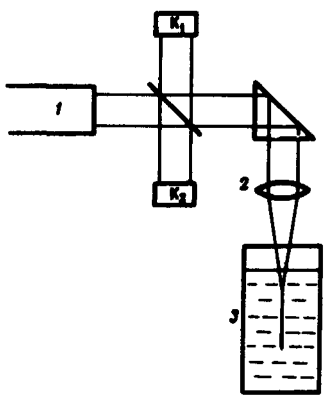

Fig. 1. Experimental setup.

The filament diameter was 100 - 150 μ (determined from a comparison with a standard wire placed on the axis of the filled cell. The length of the wave guide filaments exceeded 10 cm, i.e., filaments in which the divergence was smaller by a factor of 10 than the diffraction value were observed.

By bringing the focus close to the surface, it is possible to obtain consistently long filaments with the aid of lenses having different focal lengths (under ordinary conditions,