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OPTICALLY PUMPED Cd3P2 LASER

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shear waves are synchronous with the charge carriers.

The experimental data are tabulated in Table I and plotted in Fig. 2. For samples of aperture angle ϕ_a less than the null angle of the electromechanical coupling coefficient, the agreement is very good. At larger angles the coupling to off-axis shear waves disappears and the drift velocity becomes constant, indicating longitudinal wave amplification. The value observed here of 7.0×10^5 cm/sec is in good agreement with 7.2×10^5 cm/sec observed for the longitudinal wave-gain crossover of a zinc oxide amplifier.[5] Competition between the longitudinal and shear modes for bunching electrons may account for this velocity being greater than the longitudinal sound velocity.

Acoustoelectric current saturation for electric fields parallel to the c axis is due to amplification of off-axis shear waves whose propagation direction is limited by the sample geometry and not by the gain characteristic as long as shear wave coupling exists.

TABLE I. Aperture angle and saturation velocity for zinc oxide samples.

Crystal	Length (mm)	Width (mm)	ϕ_a (degrees)	V_{sat} ($\times 10^5$ cm/sec)
63	6.2	2.5	22	3.3
80-4*ZA*1	4.8	2.1	23	3.1
80-4*ZA*2	4.5	2.3	27	3.4
80-2*ZA*	3.4	1.75	27	3.6
80-4*ZA*	4.8	4.5	43	4.2
80-2*Z*	3.6	3.9	47	4.8
40-46-4-3	2.5	4.8	63	6.1
40-46-15	2.2	5.5	68	6.9
80-1*Z*	1.1	3.9	75	7.0
80-3*Z*	0.60	3.9	80	6.9

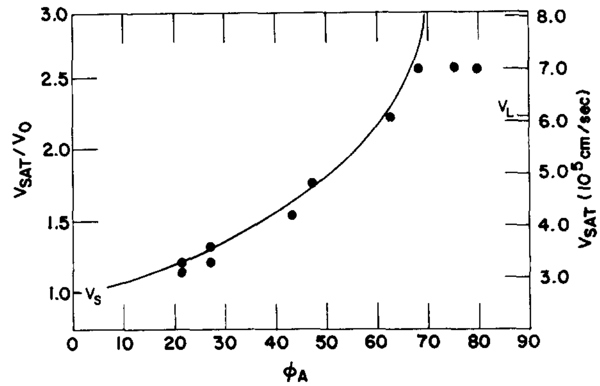

FIG. 2. Drift velocity at saturation for zinc oxide versus sample aperature angle ϕ_a.

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OPTICALLY PUMPED Cd_3P_2 LASER*

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Coherent laser oscillation with wavelength near $2.12\,\mu$ has been achieved in as-grown crystal of Cd_3P_2 at 4.2°K using pulsed optical excitation from a *Q*-switched Nd-doped YAG laser.

Optically pumped coherent laser oscillation has been obtained in as-grown crystals of Cd_3P_2 at wavelengths near $2.12\,\mu$. This represents the first observation of laser action in a II_3-V_2 semiconductor. The Cd_3P_2 samples were mounted on a cold finger which was in contact with a 4.2 °K reservoir. Exciting radiation was provided by a *Q*-switched Nd-doped YAG laser operating at a wavelength of $1.06\,\mu$ with a pulse width of $0.2\,\mu$sec and a repetition rate of 4500 Hz. The observed laser oscillations are distinguished from the superradiant narrowing reported previously[1] by the occurrence of a characteristic laser threshold and the appearance of well-defined geometric mode structure.

The sublimation growth technique[1,2] produces n-type crystals of Cd_3P_2 with $N \approx 1 \times 10^{17}$ cm^{-3} and $\mu \approx 8 \times 10^3$ cm^2/V sec at 77 °K. Crystals of various shapes and sizes and with several different crystallographic growth directions are obtained. Laser action has been achieved in both quasi-hexagonal prism-shaped crystals and in rectangular parallelopipeds. The upper half of Fig. 1 shows the pumping geometry for the quasihexagonal crystals. In this case one of the broad faces of the prism and the two smaller faces adjoining it are in contact with the indium solder. The other faces are illuminated by the pumping radiation, and the active volume (region of inverted population) extends across all three illuminated front surfaces. As indicated in Fig. 1, the 2.1-μ laser emission was observed in a direction very nearly parallel to the direction of incidence of the 1.06-μ exciting radiation. This is also along the c axis which is perpendicular to the broad illuminated surface. A germanium transmission filter excluded the 1.06 μ radiation from the monochromator.

Photoluminescence spectra obtained from a hexagonal sample 38 μ by 376 μ in cross section and several millimeters long are displayed in Fig. 2. Curve (a) represents the spontaneous spectrum obtained at pumping intensities below laser threshold, while curves (b) and (c) show the development of the laser mode structure as the threshold is exceeded. Since there exist no well-established values of the refractive index n and the dispersion correction term $dn/d\lambda$ for Cd_3P_2 near 2 μ, it is not possible to calculate a predicted value for the laser mode spacing. Moreover, because of the hexagonal shape of the sample it is difficult to determine the exact geometry of the resonant cavity; there can be many resonant cavities in a polygonal structure.[3] The peak of the spontaneous luminescence spectrum in Cd_3P_2 occurs about 20 meV below the 0.6-eV optical band edge,[4] in a spectral range for which the crystal is reasonably transparent. This transparency of the crystal to its own laser emission makes possible complicated resonant modes in the hexagonal sample, since the emitted radiation can pass through inactive regions of the crystal (where the population is not inverted) without severe attenuation.[3] It is possible to eliminate from consideration the Fabry-Perot cavity formed by the parallel front and back surfaces of the hexagon. Their 38-μ separation would require an effective refractive index n_{eff} of nearly 50 to produce the observed 12 Å mode spacing. Some variation of the "around the hexagon" mode reported by Benoit à la Guillaume[5] for hexagonal tellurium crystals is more likely.[6] For such a mode, the resonant cavity length would have to be of the order of the long cross-sectional dimension of the crystal which is 367 μ. This number reduces the effective refractive index to the more reasonable value of 5. The emitted radiation was linearly polarized with $E \parallel [1\bar{1}0]$. However, due to the uncertain mode geometry the direction of polarization inside the crystal is unknown.

The most favorable geometry with which to achieve optically pumped laser action[3] requires

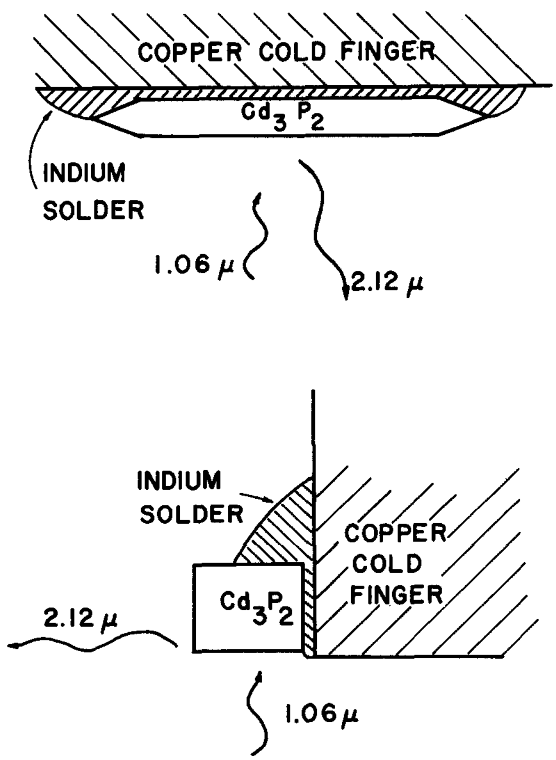

FIG. 1. Experimental configurations for pumping Cd_3P_2 crystals with a Nd-doped YAG laser.

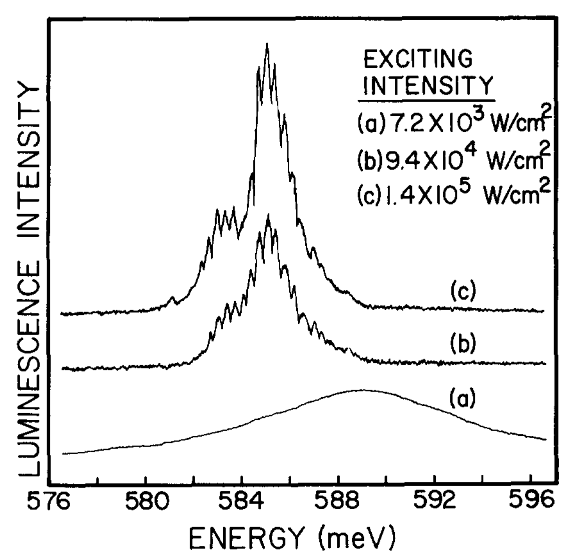

FIG. 2. Spontaneous and laser emission spectra of a $38\,\mu \times 376\,\mu$ quasihexagonal Cd_3P_2 crystal. Curve (a) is the spontaneous spectrum obtained at a pumping intensity below laser threshold; curves (b) and (c) exhibit laser mode structure which occurs at pumping intensities in excess of the threshold.

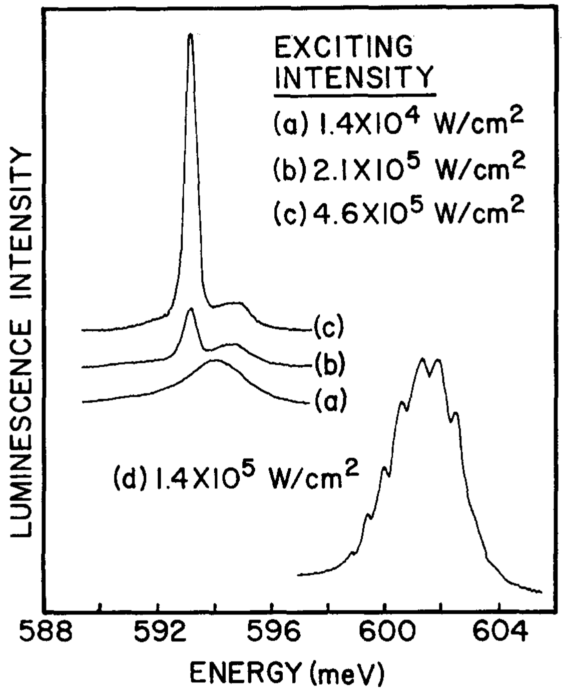

FIG. 3. Curves (a), (b), and (c) show the development of a single laser mode in the luminescence spectrum of a rectangular sample of Cd_3P_2. Curve (d) exhibits laser mode structure in the spectrum obtained from another rectangular crystal with a cavity dimension of 175μ.

two plane parallel surfaces to establish the Fabry-Perot cavity, and a third surface, perpendicular to these two, which is illuminated by the pumping radiation. The area covered by the exciting laser beam is made greater than the separation of the parallel faces, so that the active region extends throughout the length of the resonant cavity. The laser emission is observed in a direction perpendicular to the incident direction of the exciting light (see the lower part of Fig. 1), but parallel to the direction in which the laser oscillation is established. However, certain difficulties are encountered in the case of a tetragonal material. One cannot readily polish suitable parallel faces or cleave a cavity as is done in the case of cubic materials. Fortunately, a certain number of the sublimation-grown crystals grow in the form of rectangular parallelopipeds and are suitable for use in the experimental configuration just described. Microscopic examination reveals that the surfaces of these rectangular crystals have tiny striations or ripples which tend to reduce the Q of the resonant cavities which they form. Nevertheless these crystals are able to support laser oscillations. Curves (a), (b), and (c) of Fig. 3 show the development, with increasing pump intensity, of a single laser mode in photoluminescence spectra obtained from a rectangular Cd_3P_2 crystal. Curve (d) represents a laser emission spectrum obtained from another rectangular crystal; this one exhibits laser mode structure whose 21 Å mode spacing yields $n_{eff} \approx 5.9$ for the 175-μ-thick sample. The modes are not as sharp or well resolved as in the case of hexagonal crystal (Fig. 2).

Since the region of inverted population extends throughout the length of the resonant cavity in the case of the rectangular sample, the laser action is not restricted to the spectral range of crystal transparency, but can and does occur at somewhat higher energies than those observed for the hexagonal crystals. The only real requirement is that the laser emission occur somewhere within the spontaneous emission spectrum of the sample.[3]

The approximate threshold for laser action in terms of power density incident on the Cd_3P_2 is ~ 10^4 W cm^{-2}. If it is assumed that one electron-hole pair is created per absorbed photon,[7] this threshold corresponds to an effective current density of about 4000 A cm^{-2}, after an approximate correction for the reflection from the Cd_3P_2 surface. This result is of the same order of magnitude as the thresholds for optically pumped laser action reported for III-V [7] and II-VI [3] semiconductors.

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