Modulation of laser action in lead telluride by varying the polarization of the pump radiation

I. P. Areshev, A. M. Danishevskiĭ, S. F. Kochegarov, and V. K. Subashiev

A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences
(Submitted September 1, 1975)
Pis'ma Zh. Eksp. Teor. Fiz. 22, No. 9, 437–441 (5 November 1975)

We report observation of the effect of deep modulation of laser action in lead telluride (PbTe) at 20°K. This effect arises following two-photon pumping by CO_2-laser radiation and rotation of the direction of the linear polarization of the radiation aimed at the crystal. An explantion of the obtained effect is proposed.

PACS numbers: 79.20.Ds, 42.60.Nj

Laser action in the cubic multivalley semiconductor PbTe was observed in[1,2]. In[2], the laser action in the lead telluride was effected by two-photon pumping with a pulsed CO_2 laser.

In our present study we observed the effect of modulation of the lasing in PbTe by varying the polarization of the pump radiation.

An n-PbTe sample ($n\sim 10^{17}$ cm^{-3}) in the form of a plane-parallel polished plate cut in the (001) plane of the crystal was glued on a thin sapphire substrate, which in turn was glued to the cold finger of a helium cryostat. Linearly polarized radiation from a CO_2 laser ($\lambda = 10.6\ \mu$) in the form of short pulses ($t_p \sim 120$ nsec) was used for two-photon volume excitation of the crystal in the [001] direction. The luminescence was measured from the front surface of the crystal in a relatively small solid angle, $\sim 20°$ (corresponding to an angle $\sim 4°$ in the crystal). The radiation from the crystal was fed directly to a photoreceiver (Ge:AU at 77 °K) and was then synchronously detected. We measured the total luminescence yield I_L as a function of the pump radiation intensity j_p and of the direction ϕ of its polarization. Figure 1 shows the first of the indicated characteristics. At low intensities of the exciting radiation, there is a quadratic section of the $I_L(j_p)$ plot, and with increasing j_p the yield of the recombination radiation from the crystal increases sharply and I_L then becomes proportional to $\sim j_p^8$. This character of the $I_L(j_p)$ dependence points to a changeover to laser action.[1)]

It was furthermore observed that the contribution of the luminescence and the presence of laser action depend strongly on the direction of the pump-radiation polarization. Figure 2 shows this dependence. We see that the experimental curve consists, as it were, of two periodic functions with period 180°, one superimposed on the other, and shifted 90° in phase. The ratio of the maximal values of the luminescence signals to the minimal ones ranges from 6 to 15. It must be emphasized that the function $I_L(\phi)$ was plotted at a pump intensity only slightly higher (by ~ 1.06 times) than the lasing threshold.

To explain the observed effect, we must examine the rate of change of carrier generation in various valleys of the "c" and "v" bands with changing pump-polarization direction.

Using the expression given in[3] for the probability of two-photon absorption in PbTe, we can show that in the case of linearly-polarized pump radiation, when the laser beam is perpendicular to the (001) plane of the crystal, the rate G of carrier generation is proportional to

$$G \sim \left[1 - \frac{2}{3}\alpha + \frac{1}{6}\alpha^2 \pm \frac{2}{3}\alpha\left(1 - \frac{1}{3}\alpha\right)\sin 2\phi - \frac{\alpha^2}{18}\cos 4\phi\right], \qquad (1)$$

where the sign (–) is for valleys elongated along the directions $\langle 1, 1, 1\rangle$ and $\langle -1, -1, 1\rangle$ while (+) pertains to valleys in the directions $\langle 1, -1, 1\rangle$ and $\langle -1, 1, 1\rangle$. Here $\alpha = (m_\parallel - m_\perp)/m_\parallel \sim 0.9$[4]; $m_\parallel$ and $m_\perp$ are the longitudinal and transverse effective masses of the carriers at the bottom of the conduction band, ϕ is the angle between the pump-radiation polarization vector and the [100] axis of the crystal. It is seen from (1) that, for example at $\phi = \pi/4$, the carrier generation rate in the valleys $\langle 1, -1, 1\rangle$ and $\langle -1, 1, 1\rangle$ is 6.25 times larger than the generation rate in the valleys $\langle 1, 1, 1\rangle$ and $\langle -1, -1, 1\rangle$. The situation is reversed when the polarization vector is rotated through 90°.

Thus, when a certain pump intensity is reached, at $\phi = (\pi/4)(4n+1)$ ($n = 0, 1, 2$) the carrier density in one pair of valleys ($\langle 1, -1, 1\rangle$ and $\langle -1, 1, 1\rangle$) becomes sufficient for the onset of lasing, whereas in the other

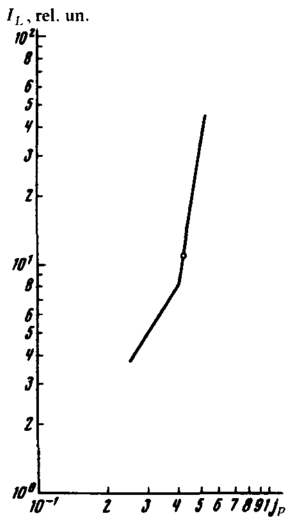

FIG. 1. Dependence of the luminescence yield on the pump intensity. 20 °K, n—PbTe. The small circle marks the value of j_p at which $I_L(\phi)$ was plotted.

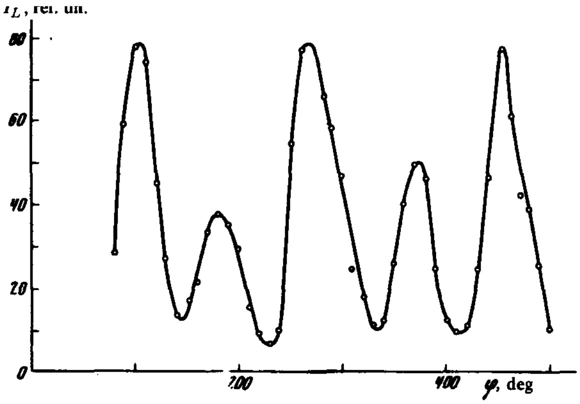

FIG. 2. Dependence of the luminescence yield on the direction of the linear polarization of the pump.

pair of valleys (⟨1, 1, 1⟩ and ⟨−1, −1, 1⟩) the generation threshold is not yet reached. The carrier lifetime τ in the first pair of valleys becomes very small, less than the intervalley relaxation time τ_{ivr},[5] and the carrier exchange between the indicated pairs of valleys is small. Luminescence from the ⟨1, −1, 1⟩ and ⟨−1, 1, 1⟩ valleys takes place. When the polarization vector is rotated through 90°, a similar effect should occur for the second pair of valleys. Thus, the luminescence yield should vary periodically with the direction of the pump-polarization direction, with a period $\pi/2$.

It must be noted, however, that in the experiment the maxima of I_L, which are spaced 90° apart, are unequal in magnitude. It was therefore suggested that the crystal is somewhat deformed at low temperatures, because of its being glued to the substrate. The following experiment was performed to verify this assumption: the luminescence polarization was measured for circular pumping with intensities lower than the lasing threshold. It turned out that the recombination radiation was partially polarized (degree of polarization $\rho = 0.184$). This indicates that the crystal is uniaxially deformed. Uniaxial deformation along the [110] axis causes the valleys in the "c" and "v" bands to shift in energy in the manner shown in Fig. 3. If τ_{ivr} is of the same order as τ, then part of the carriers from valleys 1 and 2 (Fig. 3) of the valence band can go over into valleys[2)] 3 and 4, and the luminescence turns out to be partially polarized.

It follows therefore that if the direction of the linear polarization of the pump is such as to ensure maximum rate of filling the valleys 1 and 2 and an excess above

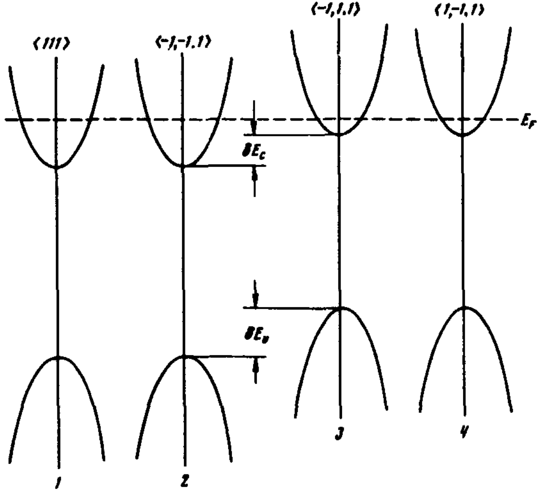

FIG. 3. Band structure in deformed PbTe crystal. Deformation direction [011]. At $p = 200$ kg/cm^2, $\delta E_c = 4.2$ meV, $\delta E_v = 5.3$ meV.

the lasing threshold, the stationary concentration in them will be lower than in the absence of deformation. In the presence of deformation, the concentration in valleys 1 and 2 will be lower than in valleys 3 and 4 in the case when the maximum generation rate is realized in the latter valleys. It is this circumstance which can explain the difference between the amplitudes of the maxima shifted by 00° in Fig. 2.

1)A similar dependence together with a sharp narrowing of the PbTe luminescence spectrum was observed in[2].

2)Intervalley transitions can occur effectively only if the difference between the Fermi quasilevels exceeds ~ 3 meV, since this is the minimal energy of the phonons (002) having a wave vector sufficient for execution of the intervalley transitions.[5]

1. F. A. Junga, K. F. Cuff, I. S. Blakemore, and E. R. Waschwell, Phys. Lett. **13**, 103 (1964).
2. C. K. N. Patel, P. A. Fleury, R. S. Slusher, and H. L. Frish, Phys. Rev. Lett. **16**, 971 (1966).
3. E. L. Ivchenko, Fiz. Tverd. Tela **14**, 3489 (1972) [Sov. Phys.-Solid State **14**, 2942 (1973)].
4. Yu. I. Ravich, B. A. Efimova, I. A. Smirnov, Metody issledovaniya poluprovodnikov v primenenii k khal'kogenidam svintsa PbTe, PbSe, PbS (Methods of Semiconductor Research as Applied to the Lead Chalcogenides PbTe, PbSe, and PbS), Nauka, 1968.
5. G. W. Pratt, I. McMullin, P. G. McMullin, Proc. 10th Internat. Conf. on the Physics of Semiconductors, Cambridge, Mass, 1970, p. 87.