SELF-FOCUSING OF RUBY LASER RADIATION IN A CdS *CRYSTAL AND ITS INFLUENCE ON TWO-PHOTON PHOTOCONDUCTIVITY*

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Submitted June 9, 1969

Zh. Eksp. Teor. Fiz. 58, 26–30 (January, 1970)

An investigation was made of the characteristic features of the photoconductivity of a CdS crystal in the case of two-photon excitation by ruby-laser radiation. At certain values of the excitation power an additional photocurrent peak was found to be superimposed on the background of the photocurrent pulse and this peak was attributed to the thermal effects of current in the crystal. The generation of a high concentration of free carriers and the localization of these carriers in a narrow current channel was ascribed to the self-focusing of the laser radiation in CdS.

INTRODUCTION

THE problems of formation and investigation of plasmas in semiconductors, i.e., of states associated with the presence of large concentrations of free carriers, have attracted increasing interest of research workers. The establishment of high concentrations of nonequilibrium carriers is particularly interesting in connection with the use of semiconductors as active media in lasers.

The present paper reports an investigation of the special features of the photoconductivity of a CdS crystal at high free-carrier concentrations established by two-photon excitation with radiation of a ruby laser. The results obtained indicate that self-focusing plays an important role in the formation of a photocurrent pulse and these results are used to suggest an effective method for the establishment and investigation of the self-focusing in photosensitive crystals.

EXPERIMENTAL PROCEDURE AND RESULTS

A ruby laser working under Q-switching conditions, was used as the photocurrent excitation source. The duration of laser pulses was 3×10^{-8} sec and the total initial power was 30 MW. The density of the radiation power incident on a crystal was varied by means of neutral filters. The power was measured by splitting the laser beam and directing the split-off component to a calibrated system consisting of a photocell, an expander, an amplifier, and a pulse voltmeter.

The measurements were carried out on a bulk high-resistivity photosensitive crystal of CdS cut in the shape of a parallelepiped with $0.4 \times 0.4 \times 1.2$ cm dimensions. Indium contacts were deposited on the ends of the parallelepiped and these contacts were used to apply a voltage to the sample. One of these contacts had a circular aperture (d ~ 1 mm) which was used for admission of a stop-limited (d_1 = 1.2 mm) cylindrical beam of laser radiation which was made slightly convergent by a long-focus lens. Thus, the electric field E was parallel to the axis of the laser beam. A photocurrent pulse generated by laser radiation was recorded using a fast-response oscillograph of the S1-11 type. All measurements were carried out at room temperature. A block diagram of the apparatus is shown in Fig. 1.

A typical oscillograph of a photocurrent pulse generated in a crystal of CdS is shown in Fig. 2. This oscillogram shows a sharp photocurrent peak corresponding to the laser pulse and two regions of photocurrent decay: a fast region, representing recombination of free carriers at fast recombination centers, and a slow region, representing recombination at slow recombination centers.[1,2] The photocurrent pulse amplitude is a quadratic function of the excitation intensity.[3,4] This pulse

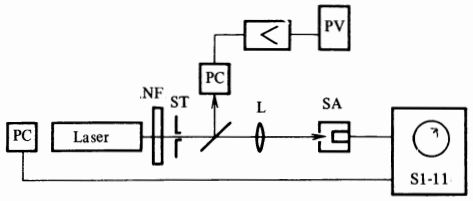

FIG. 1. Block diagram of the apparatus. PC are photocells, NF is a neutral filter, ST is a stop, L is a lens, SA is a sample, PV is a pulse voltmeter, and S1-11 is an oscilloscope.

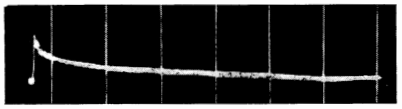

FIG. 2

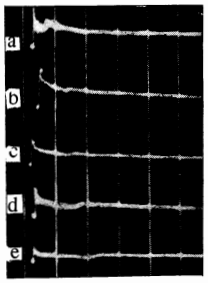

FIG. 3

FIG. 2. Oscillogram of a photocurrent pulse in a CdS crystal excited with laser radiation (P < 0.2 MW; E ~ 300 V/cm parallel to the laser beam axis). Scanning rate 0.25 μsec/division.

FIG. 3. Oscillograms of photocurrent pulses in a CdS crystal excited with laser radiation (P > 0.2 MW: E ~ 300 V/cm parallel to the laser beam axis; scanning rate 0.25 μsec/division): a) P = 0.35 MW, I = 2.8 A; b) P = 0.4 MW, I = 2.2 A; c) P = 0.25 MW, I = 4.1 A; d) P = 0.38 MW, I = 1.6 A; e) P = 0.35 MW, I = 1.8 A.

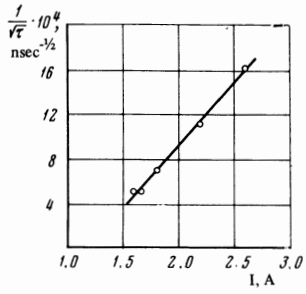

FIG. 4. Dependence of the delay time of an additional photocurrent pulse on the amplitude of the current through a crystal. P = 0.45 MW.

shape is observed at moderately high excitation intensities ($P < 0.2$ MW, $E \sim 300$ V/cm). When the laser radiation power is of the order of 0.25—0.30 MW and the applied electric field is E = 300 V/cm, the main peak is followed by an additional photocurrent peak superimposed on the background of the photocurrent pulse (Fig. 3). Measurements show that the time interval between the beginning of the pulse and the additional peak is a function of the laser radiation intensity and of the applied electric field, as demonstrated by the oscillograms in Fig. 3.

Figure 4 gives the dependence of $1/\sqrt{\tau}$ on I for a constant laser radiation intensity (~ 0.45 MW). Here τ is the time interval between the beginning of the photocurrent pulse and the additional photocurrent peak; I is the amplitude of the current through a crystal. The dependence is linear.

DISCUSSION OF RESULTS

We shall now discuss the nature of the additional photocurrent peak. This peak indicates that the conductivity of a crystal σ increases abruptly. If n, e, and μ are, respectively, the concentration, charge, and mobility of the photocarriers, it follows that the value of the photocurrent in an applied field E is $I = ne\mu E = \sigma E$.[3] On the other hand the quadratic dependence of $1/\tau$ on I^2 suggests that the additional photocurrent peak is due to the thermal effects of the current. Consequently, an increase in the conductivity may be explained by an increase in the free-carrier concentration since the mobility of carriers in CdS decreases with increasing temperature.[5] More precisely, we may assume that at a given value of the current through a crystal the Joule heat is dissipated in the current channel more rapidly than it can be lost from the crystal by heat conduction, i.e., the generation of heat predominates over the conduction heat losses. This gives rise to a rapid local heating of the crystal and an increase of its electrical conductivity due to, for example, thermal liberation of carriers from some levels (possibly s-centers) i.e., due to a "thermally-induced conductivity". Moreover, the lattice can melt locally in the current channel and this would also increase the electrical conductivity. Estimates show that the amount of heat evolved in the postulated current channel may be sufficient to melt the lattice.

A similar thermal effect of the current has been reported for InSb.[6] It is called the thermal pinch. The necessary critical condition for the appearance of such a pinch is that the power in the current channel should exceed the heat losses. Thus, we shall attribute the additional photocurrent peak to an increase of the electrical conductivity caused by the thermal effect of the current in a CdS crystal.

In order to reach the state when the generation of heat is faster than the losses, it is necessary to localize a high concentration of carriers in a narrow current channel. In a crystal of InSb such localization has been achieved by a "magnetic" pinch.[7-10] The question now arises whether the localization of carriers in a CdS crystal is also due to this magnetic pinch. In order to answer this question we shall estimate the time necessary for the appearance of the magnetic pinch in a CdS crystal. We shall use the formula given in[11]:

$$\tau_p = c^2 R_0^2 / 4 b_n v_d I,$$

where c is the velocity of light; R_0 is the radius of the magnetic pinch channel; b_n is the carrier mobility; v_d is the drift velocity of carriers; I is the current in the pinch channel. Even in the most favorable case for the appearance of a magnetic pinch our calculation gives the value $\tau_p \geq 10^{-2}$ sec, which is several orders of magnitude greater than the values of τ obtained in our experiments. Thus, the localization of carriers in a narrow current channel cannot be explained by the magnetic pinch.

The most probable mechanism of the localization of carriers in a CdS crystal is the establishment of a high concentration of free carriers in a narrow channel by self-narrowing of the laser excitation beam. In the case of such self-narrowing the nonequilibrium carrier concentration should rise because of an increase in the two-photon absorption resulting from narrowing of the beam radius and increase of the power density. When an electric field is applied parallel to the channel axis, these nonequilibrium free carriers can give rise to a high current density in a narrow channel and the thermal effect of this current increases the electrical conductivity of a crystal. Thus, the localization of a high concentration of free carriers in a crystal is caused not by the magnetic field of the current but by reduction of the radius of the excitation channel resulting from self-narrowing of the laser beam in the CdS crystal.

The possibility of self-focusing of a laser beam in a crystal of CdS follows from measurements, carried out by one of the present authors and Kamuz,[12] of a change in the nonlinear refractive index, which is positive and fairly large.

Self-narrowing of the exciting radiation in a CdS crystal is supported by the following additional data. We measured τ as a function of the intensity of excitation under such conditions that the amplitude of the current

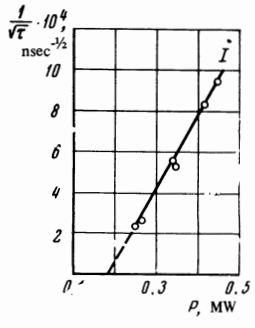

FIG. 5. Dependence of the delay time of an additional photocurrent pulse on the power density in the laser beam. I = 3.6 A.

flowing through a crystal remained constant (this was achieved by an appropriate variation of the applied electric field). In the absence of self-narrowing of the laser beam the position of the additional photocurrent peak, which is attributed to the thermal effect of the current, should be independent of the excitation intensity. In this case the channel diameter and, consequently, the density of the current in the channel should not vary with the excitation intensity. In fact, Fig. 5 shows that τ depends on the excitation intensity. This observation demonstrates that the radius of the current channel depends on the intensity of the laser beam, i.e., it demonstrates that the exciting beam becomes narrower when its intensity is increased. Thus, the dependence $\tau = f(P)$ for $I = \text{const}$ indicates that self-focusing takes place in the investigated crystal.

We estimated the critical power for self-focusing of ruby laser radiation in a CdS crystal. We used the dependence of $1/\sqrt{\tau}$ on P (Fig. 5) which can be approximated by a straight line. Extrapolation of this line to infinite time $\tau = \infty$ gives an estimate of the critical self-focusing power: $P_{cr} \approx 0.2$ MW. Using this estimate, we can find the effective coefficient of nonlinear variation in the refractive index using the formulas for the critical self-focusing power given in[13]:

$$P_{cr} = (1.22\lambda)^2 c / 256\, n_2.$$

We thus find that $n_2 \approx 4.2 \times 10^{-13}$ cgs esu. This value seems reasonable if we bear in mind that strong laser radiation produces a fairly strong long-wavelength shift of the exciton bands of a CdS crystal[12] and if we recall that CdS exhibits a fairly strong two-photon absorption of ruby laser radiation.[14,15]

Thus, the results obtained demonstrate that, above a certain critical intensity of laser radiation, a laser beam experiences self-narrowing in a CdS crystal, which affects the nature of the photocurrent pulses, and that a study of the special features of the photoconductivity excited with a laser provides an effective method for investigating the self-focusing in photosensitive crystals.

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Translated by A. Tybulewicz
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