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UNSTEADY ENERGY TRANSFER BY SOLITON-LIKE WAVES IN A SOLID BODY AFTER EXPOSURE TO A LASER PULSE

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The authors report results of experimental and theoretical studies of the soliton nature of laser-induced nonequilibrium wave processes of energy transfer in solid bodies 1 μsec–10 sec after exposure to pulsed laser radiation. These results can serve as a key to the understanding of a new phenomenon that has been observed in investigation of the effect of IR laser radiation on various classes of solid bodies, namely, a wave of change in the optical reflection and electrical conduction. Investigation of this phenomenon pertains to a fundamental problem of solid-state physics and thermal physics related to investigation of the nonequilibrium process of transfer of energy absorbed in a substance under pulsed action of high-power electromagnetic, heat, or corpuscular fluxes.

Introduction. A possible role of solitons in the process of thermal-energy transfer in a solid body has already been discussed for a long time. The discovery of a soliton was made as early as 1834 by J. S. Russel when he was the first to pay attention to a "solitary" wave on a water surface [1]. However, N. Zabusky and M. Kruskal [2] displayed this variety of wave in a new light precisely in connection with the problem of theoretical explanation of the finite heat conduction in solid bodies, since already in 1965 they discovered that it possesses properties of both a wave and a particle and called it a soliton. The investigation as such was started by E. Fermi, J. P. Pasta, and S. Ulam [3] with the help of a pioneering computer-assisted experiment. A one-dimensional grid, i.e., a set of point masses connected with springs, served as the model of a solid body. These authors [3] tried to find how quickly an initial excitation of the lower mode of a nonlinearly connected oscillator would be distributed uniformly among the entire chain (i.e., when the energy would be distributed equally among all the oscillation modes). The diffusion coefficient could have been measured from the transient time of relaxation. The result of the investigation [3] was unexpected: the energy was not thermalized at all. Hence it followed that the Fourier law of heat diffusion is not derived "from first principles."

A recent extensive survey basically of theoretical works pertaining to the problem under consideration starting in the last century is contained in [4]; a small number of experimental investigations of solitons in a solid body are briefly reviewed in [5]. We would like to note here only the following.

M. Toda specially studied the role of heat transfer by solitons in a one-dimensional chain and arrived at the conclusion that with allowance for the nonlinear interaction of atoms in the lattice of a solid body with distortions (i.e., in an approximation to the case of actual crystal lattices) energy must be transferred mainly by solitons [6]. R. E. Peierls [7] objected to this, considering that in an actual three-dimensional lattice, excitations of the soliton type can be neglected.

However, in the case of condensed media exposed to unsteady high-power electromagnetic or corpuscular pulses, conditions can be created where heat is transferred mainly by solitons if ordinary heat conduction by diffusion is retarded [8]. Precisely such conditions have been implemented in a series of experiments [9-20] that are discussed in the present work, concerned with results of investigation of the wave of change in the optical reflection and electrical conduction (WCRC).

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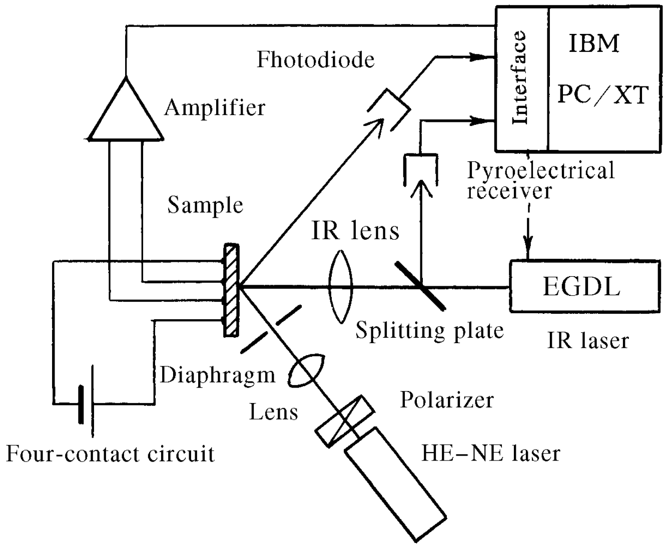

Fig. 1. Scheme of recording changes in reflection and conduction: 1) four-contact circuit; 2) lens; 3) diaphragm; 4) sample; 5) amplifier; 6) photodiode; 7) IR lens; 8) splitting plate; 9) polarizer; 10) He–Ne laser; 11) IR laser; 12) EGDL; 13) pyroelectrical receiver; 14) interface.

A WCRC has been discovered in the study of the effect of pulsed IR laser radiation on high-temperature ceramic superconductors [9]. In these experiments, a reversible change in the reflection of visible light was recorded using the procedure of observation of reflection changes in Brewster geometry [10] (see Fig. 1). A procedure for recording the change in the sample's conduction under the action of this wave is presented in [11]. In [12], the authors have suggested and implemented a procedure for recording changes in the pressure as a third independently measured parameter on passage of the investigated wave. Later, to record a WCRC, the change in the transmission of samples in the visible or IR spectrum and the thermal radiation of a sample have also been employed (with the aid of a thermovideocamera).

A number of calculations and experiments [13] have been undertaken to assure oneself that the WCRC observed is not merely the propagation of heat released on the sample surface as a result of absorption of the laser pulse. A calculation of heat transfer by diffusion using the thermal diffusivity measured for our sample has shown that the times of wave propagation judged from the arrival of pulses of reflection ΔR and conduction $\Delta\rho$ at distances of up to 0.3–0.4 cm are 10–100-fold smaller than the calculated diffusion time of arrival of heat. Moreover, the calculated temperature growth due to diffusion is small (less than 0.1^o) at these distances and cannot lead to the observed changes $\Delta R > 0.4\%$, for which $\Delta T > 4^o$ is required [10].

A WCRC has been detected very reliably in several thousand experiments. All the results obtained are in quite good agreement even though measurements by various methods have been carried out in laboratories in Russia, France, and Japan.

Experimental Results. Figure 1 provides a scheme for recording changes in reflection and conduction. Figure 2 shows typical oscillograms obtained in one experiment by the scheme of Fig. 1 for the changes in the reflection and conduction. The dashed lines indicate the noise levels for the two oscillograms.

In order to obtain information on WCRC propagation by the scheme (see Fig. 1), measurements must be repeated for different distances on the sample surface between the focal spot of the laser exciting the wave and the spot of the Ne–He recording laser. Here, on oscillograms similar to those of Fig. 2 the maxima of the changes in the reflection and voltage (or conduction) are displaced along the time axis proportionally to the indicated distance. Hence the WCRC velocity can be calculated.

In investigations of the wave under consideration, the following main special features, along with others, have been established, which allow us to consider it as a soliton-like wave:

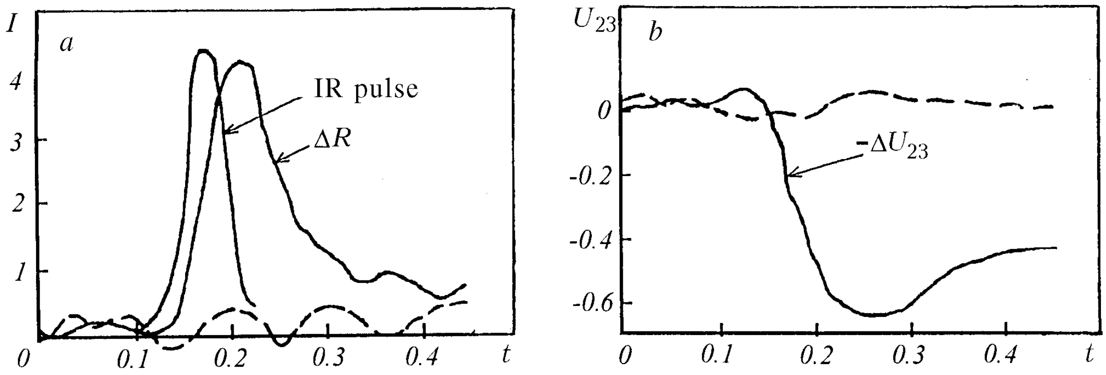

Fig. 2. Typical oscillograms obtained in one experiment using the scheme (see Fig. 1) for changes in reflection and conduction. I, U_{23}, arbitrary units; t, sec.

1) the amplitude of the WCRC propagating over the sample does not change in sign (all the time it is higher or lower than the abscissa axis so that its form differs drastically from sinusoidal) and it changes substantially more slowly with distance than in the case of thermal diffusion;

2) under certain conditions of propagation the WCRC turns out to be very stable and its velocity, which is about 1 cm/sec, changes slightly at distances of about 0.5 cm;

3) meeting with the wall of the sample, the WCRC is reflected without changing the sign of the pulse amplitude and without noticeable losses in its velocity.

In the investigations, the wave was excited mainly by a CO_2–Ar electrogasdynamic laser (EGDL) with an energy of 100 mJ in a pulse of duration about 0.1 sec [14]. With change in the wavelength of the IR radiation of this laser within the limits of 5–10–20 μm, the excitation efficiency of the WCRC and its velocity change slightly (at least for a YBaCuO ceramic sample). However, special experiments have shown that on exposure to 100-mJ laser radiation of the ultraviolet and vacuum- ultraviolet ranges with a pulse duration of $4\cdot10^{-8}$ sec no wave of reflection and conduction occurs in the same samples [15]. With decrease in the power density of the exciting IR radiation, a threshold value (~1 kW/cm^2) is observed below which the WCRC damps rapidly [5].

The investigated wave has been detected by the method of recording the change in the reflection for solid samples that belong to all four major types of crystals (molecular crystals, those of synthetic metals, covalent crystals, and ionic crystals) and for amorphous bodies [5, 16]. For further investigations of the diagnostics of this new and insufficiently investigated phenomenon it is important that the WCRC be easily excited in optically perfect crystals transparent in the visible spectrum.

Using as an example the investigation of Plexiglas and a number of other polymers, results of a direct comparison of two components of the heat-transfer process, namely, the ordinary diffusional component and the investigated soliton component, have been obtained [17].

It has been found that an electric field exerts an influence on WCRC propagation in conducting solid samples [18]. It turned out that an electric field violates the conditions of stability and existence of the investigated wave.

Measurements of the temperature dependence of the WCRC velocity $U(T)$ in the temperature range (300 ± 100) K have shown [19, 20] that for YBaCuO, NdCeCuO, and Ge samples $U \sim T$, while for LaSrCuO, $U \sim 1/T$. This fact is of interest and, apparently, of importance for working out the mechanism of the investigated phenomenon. The matter is that the temperature dependence of the longitudinal velocity of sound $v_L(T)$ for the same substances qualitatively differs as well in the indicated temperature range (for the first three substances $v_L \sim 1/T$ and for the last one $v_L \sim T$).

Significant results have been obtained in experiments on WCRC excitation using a CO_2 laser with the same energy of 100 mJ but with a pulse duration of about $5\cdot10^{-6}$ sec, i.e., five orders of magnitude shorter than in the experiments described above. Use of a pressure gauge with a resolution of $5\cdot10^{-6}$ sec as the detector and development of a procedure for recording the pressure using samples of different thickness made it possible to observe in this case a sequence of the waves formed after exposure of a molecular sugar crystal to a laser pulse [12]. It turned out that upon passage of shock waves in the sample, a whole sequence of more than six waves similar to a WCRC propagated, but with velocities that gradually decreased to a magnitude of about 1 cm/sec. Here their amplitude increased gradually, while the velocity decreased each time by approximately a factor of two [12].

Further investigations revealed that the detected special property of the WCRC is one of the fundamental features of the phenomenon investigated [5]. In response to one exciting laser pulse a whole sequence of components of a soliton wave is generated; these components differ in that the velocity of each latter one of two components undergoes an approximately twofold decrease (from the velocity of sound of about 10^5 cm/sec to velocities of about 10^{-3} cm/sec). This property of the WCRC is also of importance from the viewpoint of an increase in the total energy transferred by such a sequence of wave components [17].

One recent result obtained independently and, in our opinion, pertaining to manifestations of a WCRC is reported in [21]. Additional experiments [22] have confirmed that with a high-power quasistationary electron beam (250 MV/m^2) applied to a 0.3-cm-thick layer of pure copper, several components of a WCRC are excited. The main one of these components moves with a velocity of $7.5 \cdot 10^{-3}$ cm/sec and is repeatedly reflected from the sample walls; the arrival of a wave at the wall is recorded in these experiments by an ordinary thermocouple.

Theoretical Results. As far as we know, works on investigating heat transfer related to waves of the WCRC type are not available, with the exception of ours, in the literature.

To prove the existence of soliton-like heat transfer in actual solid bodies would be of importance for both fundamental and applied science. For this purpose, it is necessary to relate experimental data to results of theoretical developments; however no reliable and comprehensive mechanism of a WCRC has been elaborated as yet (one such attempt was undertaken in [8]). In this respect, the theory developed in [23, 24] for laser-induced diffusion-deformation instabilities in solid bodies that lead to self-organization of defects that interact via elastic fields is of interest. Within the framework of this theory the concept of a soliton wave of defects and deformation under the action of laser radiation on a solid body has been suggested and developed [25]. Laser-induced generation and propagation of a slow steady pulse (soliton) of deformation has been considered. Conditions for such a soliton to occur and its form and velocity of propagation have been determined. It has been established [26] that the model of a wave of defect recombination in solid bodies [27] fits experiments in a number of parameters of the investigated wave.

According to the theory [27], a slow wave of defect (vacancy) recombination propagates in a medium "prepared" as a result of the action of a short-duration (of about a microsecond) high-power laser pulse. The latter generates locally a pulse of expansion of the medium that propagates with the velocity of sound and creates vacancy-interstice pairs in the cold medium. The nonequilibrium concentration of vacancies turns out to be "frozen" since their mobility is low. Recombination of these vacancies is accompanied by heat release that promotes further recombination. As follows from the solution of the corresponding nonlinear differential equation, to maintain a wave of change of vacancy concentration that propagates in a medium with a constant velocity (similarly to a flame front), it is required that the nonequilibrium vacancy concentration exceed a critical value of $\sim 10^{18}$ cm^{-3}. Thermal diffusion decreases the temperature behind the wave front, thus leading to initiation of an asymmetric pulse of elevated temperature that propagates in the medium with a constant velocity.

The suggested mechanism of a soliton is novel and has no analogs in the world literature.

Numerical estimates and a comparison of the indicated theory with results of experimental studies published previously have shown the following [26]. Owing to the suggested physical mechanism a number of important characteristics of the observed waves can be explained: the small velocity (of about 1 cm/sec) that remains constant during motion of the wave; constancy of the sign of the wave amplitude (absence of signal oscillations); a slower, as compared to diffusional, change in the amplitude with increase in the distance traversed.

The developed and improved theory of a slow wave of recombination of defects induced by a laser pulse has been used to interpret experimental results on the temperature dependence $U_i(T)$ of the velocity of WCRC propagation in different materials. It has been shown that the analytical formula for the velocity of a wave of defect recombination predicts passage from an increasing temperature dependence to a decreasing one with decrease in the migration energy of the laser-induced defects. A comparison of experimental and calculated data for a number of particular materials (a high-temperature superconducting (HTSC) LaSrCuO ceramics, on the one hand, and a Ge single crystal and HTSC YBaCuO and NdCeCuO ceramics, on the other hand) has shown [19, 20] that the two different $U_i(T)$ dependences (decreasing and increasing, respectively) found experimentally for the indicated materials in the temperature range $\sim(300 \pm 100)$ K are described qualitatively by this model [27].

Conclusion. We have determined characteristics of a WCRC by several independent methods: 1) by an optical method based on investigation of reflection or absorption; 2) by an optical method based on thermal radiation; 3) using pressure gauges; 4) by measuring the conductivity (in the case of current-conducting samples). The changes in the corresponding parameters (reflection, surface temperature, pressure, conduction) in passage of a WCRC through the measurement region were about $10^{-4} - 10^{-5}$.

The above changes in the corresponding parameters of a solid body found up to now are not great. However, it is possible that the energy transferred by the indicated wave can increase with change in the experimental conditions. Moreover, it should be noted that for a certain time after exposure to an exciting pulse and at certain distances from the site where this pulse is acting, the indicated changes determine practically completely the unsteady-state heat transfer (until the heat flux caused by diffusion arrives there).

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NOTATION

ΔR, change in the reflection coefficient of light; $\Delta\rho$, change in the electrical conduction; ΔU_{23}, change in the voltage between central contacts 2 and 3 (see Fig. 1) used for calculation of $\Delta\rho$; T, temperature; $U_i(T)$, velocity of the wave of defect recombination, cm/sec; $v_L(T)$, longitudinal velocity of sound, cm/sec; t, time, sec; I, intensity, arbitrary units.

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