Entrainment of electron-hole drops by a strain pulse produced as a result of laser irradiation of germanium

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It is shown experimentally that electron-hole drops (EHD) can be captured by a strain pulse and carried along with it at the velocity of sound.

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The discovery of high mobility of EHD in inhomogeneous external fields[1] resulted in the publication of a large number of papers, which have been reviewed in detail.[2] An EHD velocity of $V \sim 10^3$ m/sec was obtained in experiments with a nonuniform static strain of germanium.[3] This value is only slightly smaller than the velocity of sound S in germanium for the corresponding crystallographic direction. However, the case $V \geqslant S$ is apparently the most interesting one at present. The motion of EHD with velocities $V \gtrsim S$ has been examined theoretically in Refs. 4 and 5. A peculiar "polaron" effect resulting in a dependence of the EHD mass on the velocity, a flattening of the drop in the direction of its motion, and an instability which can break up the drop, are predictable phenomena that make it experimentally interesting to investigate the possibility of achieving EHD velocities $V \geqslant S$. The possibility of EHD entrainment by a sound wave with a sufficiently large amplitude has been pointed out elsewhere.[6]

We can assume that the high strain and the high strain gradient needed to achieve $V \geqslant S$ can be realized if a strain pulse produced as a result of irradiation of solids by a laser flash[7] is introduced into the sample. If we ignore the effects produced at $V = S$, then $S = F\tau/M$, where F is the force acting on a pair of carriers in the drop, τ is the momentum relaxation time of the carriers in the EHD, and M is the effective mass of a carrier pair. In the strain field $S \sim D\epsilon\tau/LM$ or $S \sim DP\tau/ELM$. Here D is the strain potential, E is Young's modulus, ϵ is the strain, and L is the linear dimension of the strained region. It follows from this that $P/L \sim MSE/D\tau \sim M\rho S^3/D$, where P is the pressure and ρ is the density of germanium. Thus, $\frac{P}{L} \sim \frac{10^{-27} \times 10 \times 3 \times 10^{16}}{3 \times 10^{-11} \times 10^{-8}} \sim 2 \times 10^9$ dynes/cm^2 $= 2 \times 10^3$ kg/cm^3.

Our primary goal was to investigate the interaction of EHD, of excitons, and of free carriers with the perturbation produced in a germanium crystal at 1.7–4.2 K as a result of irradiation of germanium with "giant" laser flashes. Special attention was focused on achieving the experimental conditions for which the EHD velocity can reach the value of S.

The measurements were performed on samples of pure germanium with a residual impurity concentration of $\sim 10^{12}$ cm^{-3}. The samples were in the form of a cylinder with a length of $\sim$8–10 mm or an elongated parallelepiped with dimensions of

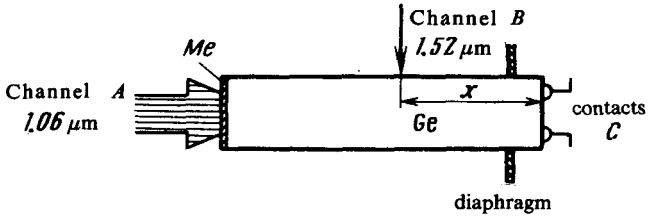

FIG. 1. A scheme for photoexcitation of a germanium sample in the study of the interaction of a strain pulse with a system of nonequilibrium carriers (electron-hole drops and excitons).

$2.5\times2.5\times10$ mm^3(Fig. 1). The laser flash irradiated one end of the sample (channel A), on which either a metal layer (Au or Al) with a thickness of 0.5–3 μm was evaporated or a thin metallic foil was cemented. We used either a fused p–n junction, a thin-film CdS piezotransducer, or a superconducting aluminum bolometer, depending on the perturbation produced by a laser flash in the crystal that had to be analyzed[8]; the detectors were applied to the sample end opposite channel A.

A YAG laser was used as the high-power pulsed light source in channel A. The laser operated in the "giant" flash regime at $\lambda = 1.06$ μm with $\tau_{\text{flash}} \cong 10$ nsec and a repetition rate of 12.5–25 Hz. The maximum energy in a flash, $\sim2\times10^{-3}$ J, could be attenuated in steps. A special optical system made it possible to focus the laser beam within 0.1-mm accuracy on the end of the sample and to monitor the condition of the crystal surface. Nonequilibrium carriers were generated in the bulk of the material by means of a He-Ne laser with $\lambda = 1.52$ μm and up to 8-mW power (channel B in Fig. 1). The perpendicular beams A and B were directed in one plane. The amplitude and shape of the detector signals were measured and analyzed by an S8-2 storage oscilloscope or strobe-integrator using an x-y recorder. The minimum time resolution of the system was 1.5×10^{-8} sec.

By using a CdS piezotransducer we discovered that a strain propagates through the germanium sample when its clean or metallized surface is irradiated (Fig. 2a). The first and second groups of signals corresponded to the arrival at the CdS of a longitudinal strain with $S_l = 5530$ m/sec and a shear strain with $S_t = 3200$ m/sec, i.e., they exactly coincided with the longitudinal and transverse sound velocities for the [111] orientation in germanium.[9]

There are many mechanisms capable of producing a strain pulse in a laser-irradiated crystal. A series of control experiments and estimates made it possible to eliminate: (a) Lebedev light pressure, (b) the strain resulting from a sudden increase in the number of free carriers; and (c) the strain resulting from a sudden blow-out of liquid helium due to heating of the sample surface. Thus, there are apparently two mechanisms in the absorbed-energy interval of 10^{-5}–10^{-1} J/cm^2 responsible for the appearance of a strain pulse in our case: local heating of the crystal surface followed by a nonuniform thermal expansion that is accompanied by stress gradients as high as 10 kbar/cm, and the evaporation of material from the surface due to the action of a laser flash (for energies of 10^{-2}–10^{-1} J/cm^2).

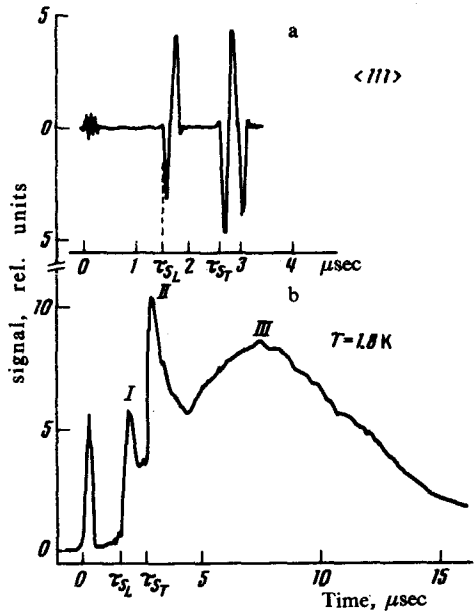

FIG. 2. (a) System of signals appearing at CdS piezotransducer after passage of a strain pulse through the germanium sample. The sample length is 8.3 mm; (b) a signal produced at the p–n junction as a result of interaction of a strain pulse, which is propagating along the [111] direction, with free excitons. The sample length is 8.2 mm.

The complicated signal wave-form in Fig. 2b was recorded using the p–n junction detector when the lasers were operated simultaneously in channel A and B. It is important that the signal completely disappeared when there was no radiation in channel B. Therefore, the signal is apparently associated with the appearance of nonequilibrium carriers in the vicinity of the p–n junction, which are attributable to the perturbation that propagates from the region of interaction of the laser beam in channel A with the crystal surface. We note an important argument in favor of this assumption: signal I in Fig. 2b is delayed by a the transit time of the longitudinal sound through the sample, and signal II is delayed by the transit time of the transverse sound. In other words, the charge carriers generated by the light in channel B are entrained by the longitudinal and transverse strain pulses and arrive at the detector with *exactly* the sound velocities. We note that the channel-B beam can be shifted with respect to the p–n junction and that the distances x at which signals I and II can still be recorded are 4 mm.

This raises a question: in what state are the nonequilibrium carriers entrained by the strain pulse? The steep temperature dependence of the amplitudes of signals I and II near 2 K, shown in Fig. 3, is typical for the conversion of some particles to the liquid phase near the condensation threshold for the excitation level (in channel B) that we used and provides an unambiguous answer to this question.

Signal III in Fig. 2b had no steep temperature dependence and was observable to 4.2 K (Fig. 3). The behavior of signal III (the steepness of the signal build-up, its duration, and the position of the maximum) as a function of the energy in channel A is similar to the behavior of the bolometer signal that appears during the detection of high-frequency acoustic phonons.[8] It may be that both the EHD (since a steep region is also observed on curve 2 in Fig. 3) and the excitons and free carriers (see smooth

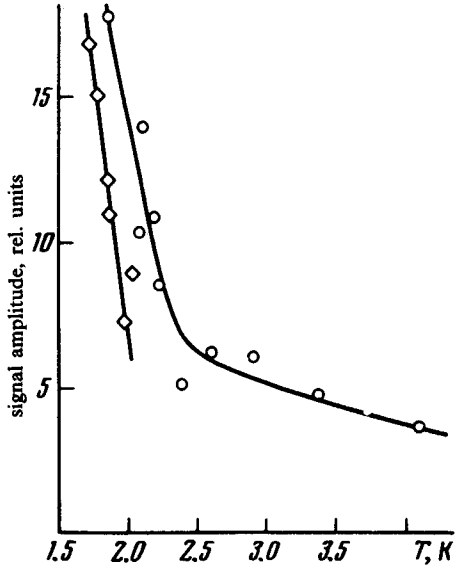

FIG. 3. Temperature dependence of the signal amplitudes at the $p-n$ jucntion: ◇ - (1) for signals I and II, ○ - (2) for signal III. The power in channel B is ~2 mW.

portion of curve 2 in Fig. 3), which are in the immediate vicinity of the p–n junction and which are entrained by the flow of nonequilibrium acoustic phonons with velocities less than the sound velocity ($V \sim 10^4$ cm/sec),[10] are responsible for the appearance of signal III.

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