Transfer of electronic-excitation energy of germanium to liquid helium

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A transfer of energy stored in electron-hole droplets during the excitation of germanium to liquid helium has been observed. The release of the energy of the droplets at the surface of the sample causes the liquid helium to boil up, and sound is emitted. Data have been obtained on the formation time and lifetime of a vapor bubble formed during this incipient boiling.

The electron-hole droplets which form in semiconductors pumped intensely at low temperatures[1] may be thought of as stable blobs of excitation energy, and the drift of these droplets which is driven by external forces[1,2] may be thought of as a directed transport of this energy in a crystal. In the experiments described below, electron-hole droplets produced by a light flash move at a velocity near the velocity of sound toward the surface of the sample, where the energy they carry is released in an extremely short time, significantly shorter than the lifetime of the droplets in the interior of the crystal. This intense release of droplet energy causes liquid helium to boil up at the surface of the sample, in a process accompanied by the excitation of a first-sound pulse in the helium.

The experimental geometry is shown in the inset in Fig. 1a. A mechanically polished germanium sample, a disk 10 mm in diameter with a thickness $\xi = 0.72$ mm (the axis of the disk is parallel to the $\langle 111 \rangle$ axis), is held in a special holder in such a way that one surface is bordered by a vacuum, while the other is bordered by superfluid helium ($T = 1.8$ K). Surface pumping of the sample is caused by the beam from an N_2 laser (wavelength $\lambda = 0.34\ \mu$m, pulse length $t_p \cong 10$ ns, maximum energy in the pulse $J_{max} \cong 120$ erg, pulse repetition frequency of 50 Hz, and light-spot diameter $\cong 3$ mm at the sample). The electron-hole droplets are produced during the excitation of the surface of the sample bordered by the vacuum (beam I). They are driven by a phonon wind toward the opposite surface[2,3]; once they reach this opposite surface, they are quickly consumed.[4] As a result of the transport across the surface of the sample into the liquid helium of the energy of the nonequilibrium phonons which are released during the radiationless surface recombination of the electrons and holes making up the droplets, a sound pulse is excited in the helium, and a bubble of helium gas is formed. The sound and the bubble are detected from the scattering of a probing light beam ($\lambda = 0.63\ \mu$m) by these inhomogeneities.[5,6] The scattered light propagating at a small angle from the probing beam is focused by a condenser lens onto the cathode of a photomultiplier.

In the measurement of the time required for the droplets to move across the

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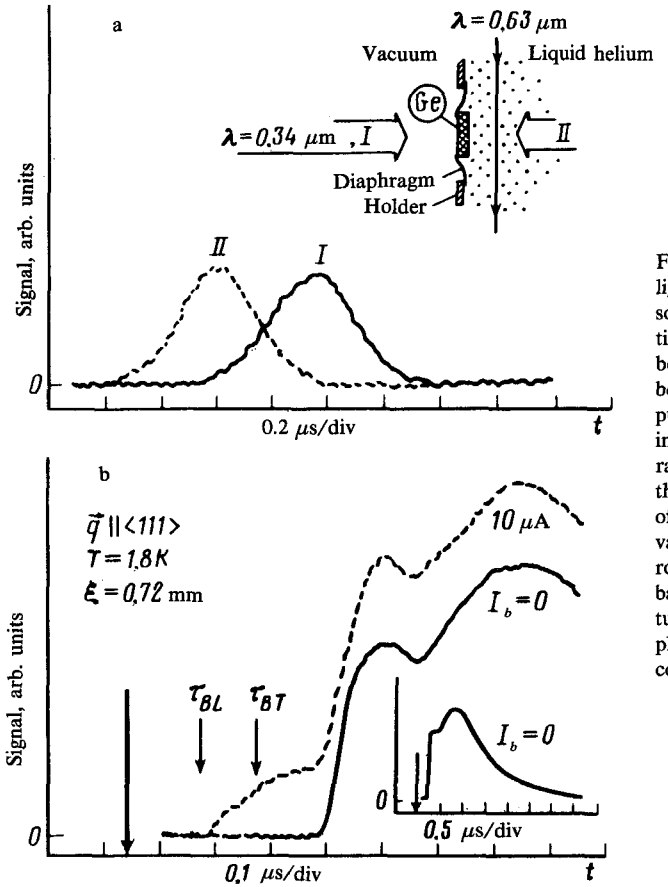

FIG. 1. a: Signals representing the light scattered by the pulses of first sound excited during the illumination of the surface of the sample bordered by liquid helium (II) and bordered by a vacuum (I). For pulse I, the energy J is 120 erg. The inset shows the experimental arrangement. b: Output signals from the bolometer during the excitation of the surface of the sample in a vacuum ($J = 120$ erg). Heavy arrow—Pump pulse; τ_{BL} and τ_{BT}—ballistic propagation times of longitudinal and transverse acoustic phonons, respectively; inset—a complete recording of the signal.

sample, the probing beam propagates from the surface of the sample over a distance significantly larger than the dimensions of the vapor bubble. To measure this time, we excite a reference sound pulse (pulse II in Fig. 1a) by means of laser beam II at the surface of the sample bordered by the helium. The excitation of this reference sound pulse is associated with the emergence into the helium of nonequilibrium phonons released during the thermalization of photoexcited current carriers.[5] The time shift between the reference pulse and the pulse resulting from the release of the energy in the electron-hole droplet (pulse I in Fig. 1a) tells us the transit time of the droplets. The energy in the laser pulse during the excitation of sound pulse II is chosen in such a way that pulses I and II have roughly the same height. Accordingly, the two sound pulses propagate at the same velocity through the helium.[6]

To verify that the incipient boiling of the helium during the excitation of the surface of the sample bordered by the vacuum is in fact caused by a transport of the energy of electron-hole droplets, rather than a transport of energy by nonequilibrium phonons propagating away from the excitation region, we deposited a granular alumi-

num bolometer on the surface of the sample in the helium during the experiment.[7] If no electric current is passed through the bolometer, it does not respond to a flux of phonons. The bolometer signal in the absence of a current ($I_b = 0$) is shown by the solid curve in Fig. 1b (the inset shows the complete pulse). This signal is the superposition of two pulses: the narrow pulse which occurs first is due to the detection of electron-hole droplets which are moving toward the bolometer under the influence of the phonon wind emitted in the final stage of the thermalization of the photoproduced current carriers. The second pulse results from an entrainment of the droplets by phonons emitted during the relaxation of the hot spot.[2,3] In the working regime ($I_b = 10$ μA), the superconducting bolometer detects, in addition to electron-hole droplets, a flux of nonequilibrium phonons created in the excitation region. The broken line in Fig. 1b shows the bolometer signal. Comparison of the results in Figs. 1a and 1b shows that the time required for the electron-hole droplets to move to the bolometer is essentially the same as the time shift of pulse I with respect to pulse II. In other words, the excitation of sound at the unilluminated surface of the sample is indeed a consequence of the release of energy stored in electron-hole droplets during the pumping of the crystal.

These results show that the velocity at which electronic-excitation energy is transported through a crystal can be measured by a method involving the detection of the sound pulses which propagate away from the surface of the excited sample through liquid helium. We are thus interested in the time required to form the sound pulse. To measure this time, we carried out an experiment using the arrangement shown in the inset in Fig. 2. The idea here is to detect that light which is scattered by the sound pulse and the vapor bubble and which propagates at a small angle from the probing beam which is reflected from the excited surface of the sample. It can be seen from Fig. 2 that the sound pulse in the helium (the solid curve) begins to develop without any apparent delay with respect to the pump pulse. The growth of the scattering signal after the end of the sound pulse is caused by an increase in the dimensions of the vapor bubble at the excited surface. Figure 3 shows some complete recordings of the scattered pulses at two pump intensities. Also shown here is a plot of the total "lifetime" of the vapor bubble (the duration of the scattering pulse) versus the energy in the pump pulse. At small values of J, this dependence is linear, as we might expect for a plane vapor bubble if its volume is proportional to the energy of the exciting pulse.

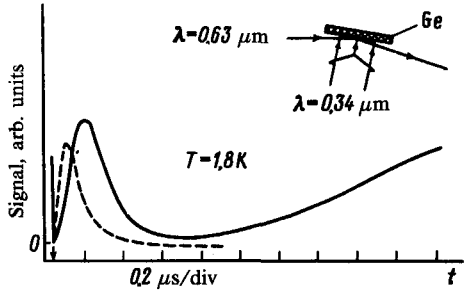

FIG. 2. Solid curve—Time evolution of the intensity of the scattered light ($J = 50$ erg); Arrow—the pump pulse; dashed line—the pulse at the photomultiplier during its illumination with the exciting light; inset—the experimental geometry.

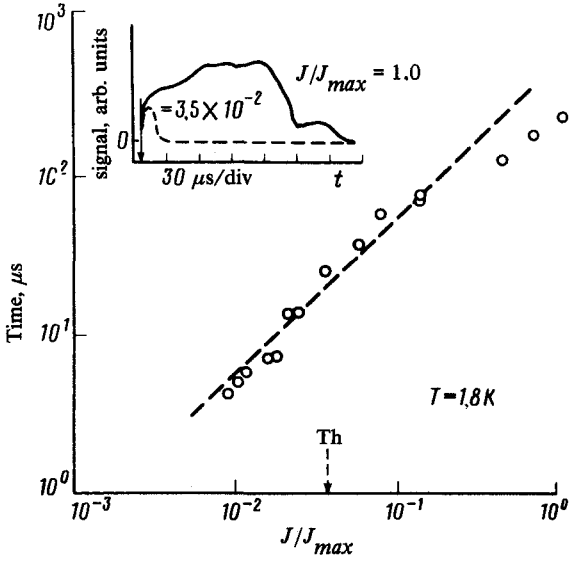

FIG. 3. Length of the light pulse scattered by the vapor bubble versus the energy in the pump pulse. The dashed arrow shows the threshold for the excitation of first-sound pulses. The inset shows recordings of the scattered pulses.

The first sound is excited as a consequence of the boiling up of the helium at the surface of the sample.[8–10] It can thus be concluded from the data in Fig. 2 that at the pump level used the surface of the sample becomes separated from the liquid helium by a vapor film as early as 0.1–0.2 μs after the excitation pulse. This film prevents the transfer of phonons from the sample to the liquid helium.[1)] Consequently, if the excitation consists of intense pulses of length $\gtrsim 0.1$ μs, the efficiency of the entrainment of electron-hole droplets by the phonon wind in the direction away from the excited surface into the interior of the crystal should be roughly the same in samples immersed in liquid helium and samples in a vacuum. Several experiments on the dynamics of a cloud of electron-hole droplets support this conclusion.[2]

We should point out in conclusion that the appearance of a vapor bubble at the surface of the sample has an important effect on the behavior of the nonequilibrium phonons and the current carriers in the excited crystal. The boiling up of the helium is accompanied by the appearance of a photocurrent noise and by the absorption of microwave radiation by the nonequilibrium electron-hole plasma,[12] an increase in the dimensions of the cloud of electron-hole droplets,[13,14] and other effects. The increase in the lifetime of the hot spot[16,17] observed in Ref. 15 during an increase in the pump intensity is apparently also related to the formation of a vapor film.

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