Interaction of Electron-Hole Drops with Ballistic Phonons in Heat Pulses: The Phonon Wind

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We have performed heat-pulse experiments which graphically demonstrate the strong effect of the phonon wind in propelling electron-hole drops. Investigation of the dynamics of droplet motion sheds light on the mechanisms of propulsion and damping.

Recently, Bagaev *et al.*[1] and Keldysh[2] have proposed the novel idea that electron-hole (e-h) drops can be propelled by a "phonon wind," a flux of nonequilibrium phonons. Their treatment and subsequent experiments[1,3,4] considered acoustic phonons generated by optical processes of creation and decay of e-h pairs either directly or by means of down-conversion of optical phonons. In this Letter we report a new approach to the problem employing phonons generated by a heat pulse. This technique has significant advantages: The phonons have a known Planck energy distribution[5]; they can be employed as collimated beams; they can be time resolved; and the peak of their energy distribution falls in the energy range, ~5 to 25 K, almost precisely where the phonon absorption by drops is greatest. These features enable us to study the dynamics of droplet motion directly and to infer the mechanisms giving rise to their propulsion and damping.

The experimental setup is shown in the inset in Fig. 1. We use a crossed-beam geometry wherein the phonon beam intersects a line of e-h drops produced by volume excitation with the focused 1.52-μm cw He-Ne laser beam (~1-mm absorption length). The heat pulses were generated optically be means of Q-switched pulses (~0.3 μsec pulse width) from a Nd-doped yttrium aluminum garnet laser focused on the metallized sample end. Phonons were detected by a thin-film, granular Al superconducting bolometer. Data acquisition equipment consisted of a Biomation 8100 transient recorder (1024 channels, each 20 nsec wide) coupled to a Nicolet multichannel analyzer used to store the data.

There are two separate aspects of the phonon problem to be considered: (1) absorption of nonequilibrium phonons, the origin of the phonon-wind force; (2) emission of phonons, the process damping the droplet motion as described by a scattering time τ_p. Experimentally, these effects are manifested, first, by the attenuation of the phonon flux and, second, by the dynamics of the e-h drops seen via their displacement and drift velocity $\vec{v}_d$. The dynamical situation is particuarly simple if—as typically the case—the force $\vec{F}$ on the drop is slowly varying in time compared to τ_p ($\simeq 10^{-9}$ sec in Ge), so that $\vec{v}_d$ is essentially a terminal velocity. We have then the elementary relationship

$$\vec{v}_d = \vec{F}\tau_p/M \tag{1}$$

between force, drift velocity, and the damping. (M is an appropriate inertial effective mass of the droplet.)

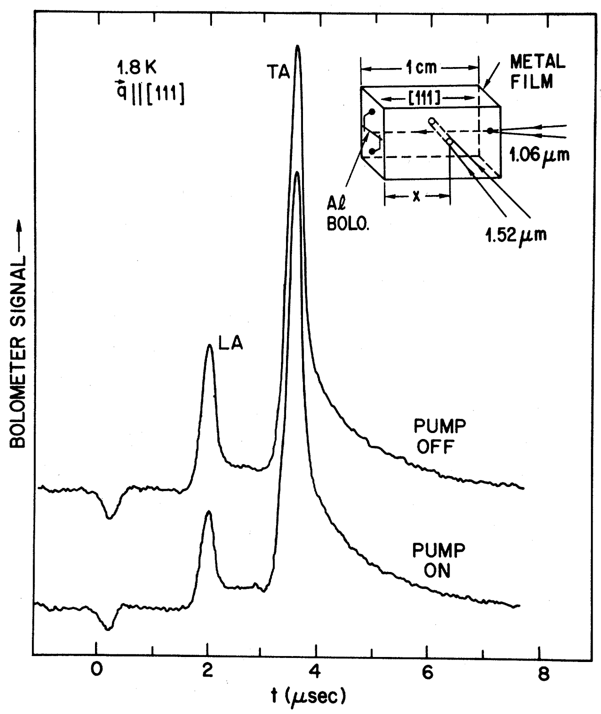

FIG. 1. Absorption of phonons by the e-h liquid in Ge. Traces show phonons time resolved by time of flight across the 1-cm sample length. Excitation: heater, $\lambda = 1.06$ μm, power = 75 mW (0.25 W/mm^2), pulse width = 0.3 msec; pump, $\lambda = 1.52$ μm, power = 6 mW cw. The pulse at zero time arises from the laser pulse. The experimental geometry is shown schematically in the inset.

Absorption of phonons occurs[6] in e-h drops by the scattering of electrons (and holes) across the Fermi surface with the transfer of the absorbed phonon's crystal momentum q to the drop resulting in a force. The transition probability for absorption increases linearly with q up to a cutoff at $q \approx 2k_F$, where $\vec{k}_F$ is the Fermi wave vector along $\vec{q}$. For a given phonon distribution the force peaks when $\vec{q}$ is oriented along the major axis of the Fermi surface maximizing the momentum transfer ($\propto q$), the phonon density of states ($\propto q^2$), the transition probability ($\propto q$), and, finally, the electronic density of states. For Ge this case for electrons corresponds to $\vec{q} \parallel [111]$ with the LA-phonon absorption predominantly from the [111] ellipsoid.[7] The TA-phonon absorption by electrons is insignificant for $\vec{q} \parallel [111]$. Also the hole contribution can be ignored because of the relatively smaller deformation potentials of the valence bands.

These predictions are borne out by the data in Fig. 1. Two time-resolved traces of the bolometer output are shown, one with drops present and one without. One sees that the LA phonons are attenuated (on the order of 35%) through absorption by droplets. The TA heat pulse is virtually unaffected. We estimate that the thickness of e-h liquid in the phonon beam path is $\sim 8\ \mu$m, on the order of a drop diameter. This thickness is simply dv where $d = 0.7$ mm is the droplet cloud diameter ($\gg$diameter of the focused 1.52-μm pump beam) ascertained from the spatial profile of the absorption and where $v = 0.012$ is the fractional volume of condensate defined by the pumping power and cloud volume. For phonons having q's near $2k_F$ (absorption maximum) the calculated phonon mean free path is $\sim 5\ \mu$m, so that for these phonons the absorber is essentially "black." However, because we are dealing with a Planck distribution there will be transmission for q's greater[8] than $2k_F$ as well as some for small q's, which may in part account for the ~65% transmitted signal in Fig. 1. Another possible contribution is the phonons reemiited from the moving drop. The data demonstrate directly for the first time the strong absorption of LA phonons, so strong in fact that a measurement of the absorption coefficient is not possible (for $\vec{q} \parallel [111]$) inasmuch as *each* drop is essentially a thick abosrber.

Because of the very strong nature of the absorption it is appropriate to ask, how rapidly is the droplet moving as a result of the phonon force? To address this question we have conducted an experiment at a much higher level of pulsed heater excitation to produce a readily observable drift of drops. These excitation conditions, as we shall discuss later, lead to formation of a "hot spot" from which emanates a more or less steady flux of phonons for times long compared to the droplet time of flight. We have monitored the droplet motion by registering the elasped time for arrival at the bolometer of drops produced (as a steady-state cylindrical cloud of ~0.5 mm diam) at a distance x from the sample end (see inset in Fig. 1). The bolometer serves in the dual capacity as detector of drops as well as phonons. Traces showing "droplet" pulses superimposed on the heat pulses are given in Fig. 2. One observes that the droplet pulse "advances" in time as the position x of injection is moved toward the bolometer end of the sample. Concurrently there is an increase in the signal intensity, presumably resulting from the widening solid angle subtended by the bolometer stripe

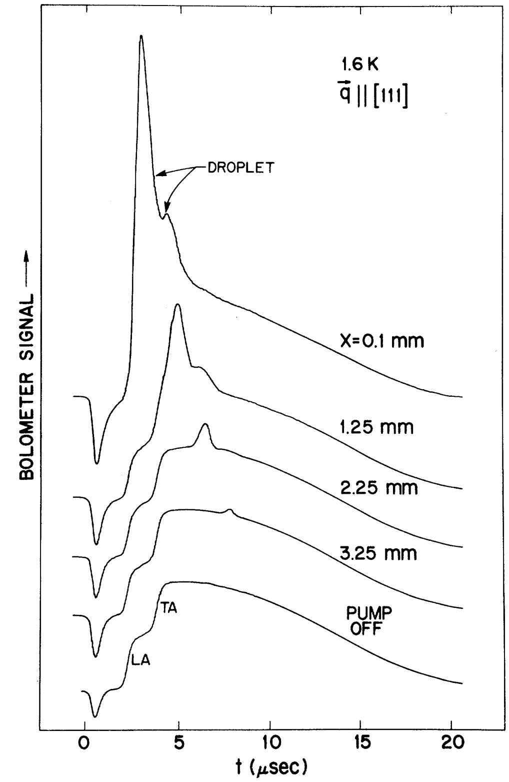

FIG. 2. Drift of e-h drops in the phonon wind. Traces show pulses marking the arrival of drops at the bolometer. The x values specify the position of injection (see inset in Fig. 1). Excitation: heater, $\lambda = 1.06\ \mu$m, power = 190 W, area = 0.5×0.7 mm^2, pulse width = 0.5 μsec; pump, $\lambda = 1.52\ \mu$m, power = 1.5 mW cw.

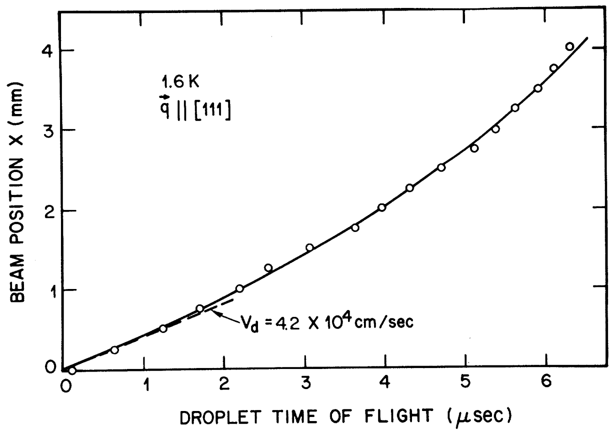

FIG. 3. Dynamics of drops in a phonon wind. Experimental conditions the same as in Fig. 2.

with decreasing x. The double peak seen at small x may indicate spatial structure in the droplet cloud.

In Fig. 3 we plot drift distance x vs time of flight[9] of the drops. The slope at $x=0$ gives 4.2×10^4 cm/sec as a "final" drift velocity. Elsewhere the interpretation is more complicated, the time of flight being an integral $\int_x^0 d\zeta/v_d(\zeta)$ inasmuch as v_d varies spatially. Three factors are involved: First, there is the inverse square law governing the falloff in intensity of the phonon flux with distance from the heater. Second, the force is proportional to $1-v_d/v_s$ where v_s is the sound velocity of the longitudinal modes with $\vec{q} \parallel [111]$. The third factor, which we shall neglect, is the "backwind" of phonons diffusely scattered from the sample end which tends to retard the droplet drift. Considering the first two effects we write from Eq. (1) the velocity

$$v_d(x) = \frac{K}{(l-x)^2}\left[1 - \frac{K}{v_s(l-x)^2}\right], \qquad (2)$$

to lowest order in v_d/v_s, where $l=1$ cm is the sample length. Using this expression we obtain upon integration the fit in Fig. 3 and evaluate the constant of proportionality, $K=4.6\times 10^4$ cm^3/sec. As a point of interest we note that v_d has a maximum value (at $x=4$ mm) of 1.0×10^5 cm/sec as compared with $v_s = 5.62\times 10^5$ cm/sec.

Until now we have skirted what seems to be a serious paradox having to do with the long flight times (up to ~6 μsec) observed for the drops. They are indeed surprising because once the LA ballistic pulse (moving at v_s) has passed by the droplet the motion of the latter should stop abruptly (in a damping time of $\tau_p \sim 10^{-9}$ sec). The time for passage cannot be much longer than the pulse width (~0.5 μsec). Nor can we expect any help from the TA pulse which does not produce a force on drops for $\vec{q} \parallel [111]$.

We propose the following explanation: Consider the process of energy transfer from the heater. Under strong pumping (as used in Figs. 2 and 3) the local temperature at the heater rises so high that the phonons generated are unable to propagate ballistically as a heat pulse; they can only diffuse. In other words, there is an entrapment of phonons creating a localized "hot spot." To get a crude idea of its size and temperature we note that the distance traveled by ballistic phonons during a pulse width is ~1 mm; if we assume that this roughly represents a limit for the phonon's mean free path λ, then inspection of thermal conductivity data[10] shows the corresponding temperature to be ~8 K. Heat-pulse experiments (to be published) yield more refined values of 8.5 K and $\lambda_{8.5\,\mathrm{K}} = 0.6$ mm. Thus, under strong pumping the hot spot acts as a phonon source with a surface temperature of 8.5 K and a size defined by $\lambda_{8.5\,\mathrm{K}} = 0.6$ mm—values, we feel, that are characteristic mostly of the system rather than the level of excitation.

As the internal energy transfer is by diffusion we can expect the hot spot to have a rather long lifetime and, thus, provide a sustained and relatively constant flux of phonons necessary to propel the drops. The good fit in Fig. 3 is testimony to this fact. Indeed, quite recently we have resolved a broad "diffusion" tail on the LA heat pulse confirming this point directly. We might add that the concept of the hot spot will have broad ramifications in all low-temperature work where strong excitation is used.

To avoid the hot spot we have experimented with an electrical heater (evaporated Constantan film) driven by a long, low-power pulse (~20 μsec or longer) as a source of phonons and succeeded in drifting drops at velocities as low as $\sim 5\times 10^3$ cm/sec and over distances up to 8 mm.

As a final step in the analysis one would like to combine measurements of drift velocity and force (as determined from absorption) with the help of Eq. (1) deduce τ_p. This is as yet incomplete and we must appeal to theory. Detwiler and Rice[6] have calculated the phonon driving force $\vec{F}$ and the damping force $M v_d \tau_p^{-1}$. Substituting into Eq. (1) their $\vec{F}$ (3×10^{-14} dyn/e-h pair) evaluated for the experimental conditions at $x=0$, and $v_d = 4.2\times 10^4$ cm/sec from experiment, we obtain $\tau_p(1.6\ \mathrm{K}) \approx 1.2\times 10^{-9}$ sec assuming an inertial mass[6] per e-h pair of $0.97m$.

This result resolves an interesting controversy. There is an amazing spread of damping strengths quoted in the literature ranging from droplets immobilized[11] on defects to very weak damping, $\tau_p \sim 10^{-4}$ sec, attributed to exciton drag.[4,12] Our work clearly shows that the damping is strong, not inconsistent with some earlier work[13-15] and in good accord with theory,[16,17] e.g., the Detwiler-Rice result[6] $\tau_p(1.6\text{ K}) = 2.2\times10^{-9}$ sec. This leaves little doubt that the electron-phonon interaction is the predominant mechanism responsible for the damping of the droplet motion.

In conclusion, our experiments—the first having capability to see *both* phonons and e-h drops time resolved—demonstrate unequivocally the powerful propulsive effect of the phonon wind on e-h drops and define in some detail the role of the electron-phonon interaction in the propulsion and damping mechanisms. All observations can be understood in terms of the concepts of the phonon wind and phonon damping plus a new concept —the hot spot, which forms under strong pumping conditions and serves as a source of phonons long after cutoff of excitation.

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