Spectral sign inversion of photon drag at far-IR wavelengths

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The sign of the drag current in *p*-type germanium has been observed to change twice when the sample is subjected to intense laser pulses with a wavelength between 10.6 μm and 385 μm. The sign inversion in the short-wave region occurs because the current is carried predominantly by light holes. The inversion in the long-wave region occurs because the drag current results primarily from intraband "indirect" transitions in the light and heavy subbands.

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The recent discovery of the drag of electrons by photons in semiconductors (see Ref. 1, for example) has been studied primarily in the spectral region near 10.6 μm. Kimmitt *et al.*[2] have stated only that there is a drag of charge carriers by photons at wavelengths 337 and 385 μm.

In this letter we are reporting observation of a double sign inversion of the drag current in the far-IR (submillimeter) range (10.6–400 μm) in *p*-type germanium at $T = 300$ K.

1. The apparatus used for these measurements of the drag effect in the far-IR region is shown in Fig. 1. The source of the radiation is a high-power, tunable, pulsed far-IR D_2O laser with optical pumping provided by a CO_2 laser. The wavelength of the D_2O laser is tuned by varying the wavelength of the CO_2 laser. The output wavelength is measured with a Michelson interferometer, and the output energy is measured with an IMO-2 calorimeter.

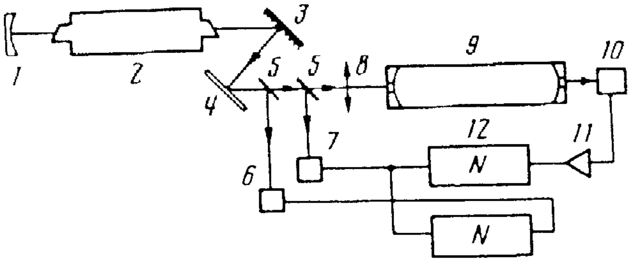

FIG. 1. Block diagram of the apparatus used to measure the drag effect in the far-IR region. 1–Mirror; 2–CO_2 laser cell; 3–echelette grating; 4–rotating mirror; 5–NaCl beam splitters; 6–FPU-50 photodetector[4] (this detector operates through the drag of electrons by photons); 7–Ge + Au photodetector for triggering the oscilloscopes; 8–lens; 9–laser; 10–sample; 11–amplifier; 12–oscilloscope.

2. The p-Ge samples used in these experiments had a concentration $p = 3 \times 10^{14}$ cm^{-3} at $T = 300$ K. It can be seen from the results (Fig. 2) that the sign of the resultant drag current changes twice as the wavelength is raised above 10 μm. To study the nature of this effect, we carried out experiments with n-Ge samples for comparison. We found that the sign inversion occurred only in the p-Ge samples, implying that the reason for the inversion lies in the complicated valence-band structure of the p-type germanium.

3. The model proposed by Danishevskiĭ *et al.*[3] can explain the observations. According to this model, the drag current forms as the sum of two currents, in the heavy and light subbands of the p-Ge valence band, with direct optical transitions between these subbands. Another drag mechanism which may play an important role involves transitions within each of the subbands (the indirect-transition drag current).

Near 10 μm at $T = 300$ K, the resultant drag current directed along the light propagation direction is primarily the direct-transition current of heavy holes, because of the short momentum relaxation times of the carriers in the light subband.

As the energy of the exciting photons is reduced, and light holes are produced with energies near the energy of an optical photon, the momentum relaxation times of the carriers in the light and heavy subbands become comparable. Under these conditions, the direct-transition light-hole current may exceed the heavy-hole current because of the lower effective mass of the carriers. The result will be a change in the sign of the resultant

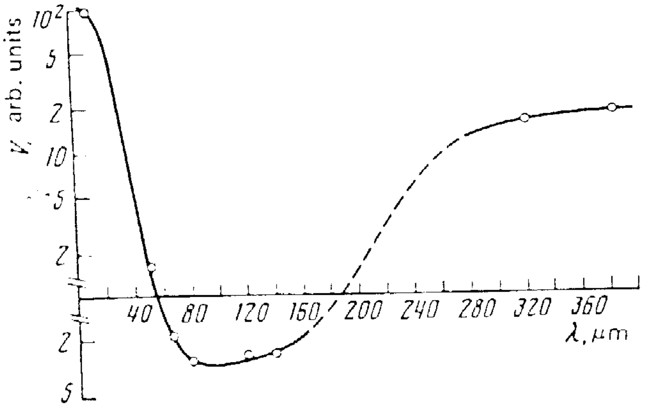

FIG. 2. Spectrum of the drag voltage, normalized to a unit power, in p-Ge with $p = 3 \times 10^{14}$ cm^{-3} at $T = 300$ K.

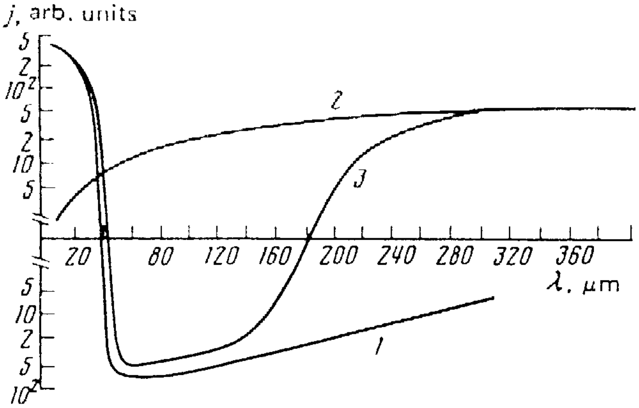

FIG. 3. Calculated spectrum of the drag current for various mechanisms for this current (normalized to a unit light intensity). 1–The drag current which results from "direct" transitions; 2–that which results from "indirect" transitions; 3–the resultant drag current.

drag current if the indirect-transition part of the drag current is small. As the energy of the exciting phonons is reduced further, the absorption cross section for indirect transitions increases significantly, and the drag current begins to be dominated by intraband indirect transitions in the light and heavy subbands. A further result is a second inversion of the sign of the resultant drag current.

We have carried out calculations to find the spectrum of the drag current over the wavelength range from 10 to 400 μm. The direct-transition drag current was calculated from the corresponding equations given in Ref. 3 for the drag currents of heavy and light holes. The calculations for the indirect-transition drag current were carried out on the basis of the theory derived by Brynskikh *et al.*[5] for the case in which scattering by acoustic phonons is predominant; both subbands are taken into account. The absorption coefficients for direct transitions are calculated from Ref. 6. Figure 3 shows the curves calculated for each of these mechanisms for the drag current, along with the spectrum of the resultant drag current. It is clear that the experimental and theoretical results are in qualitative agreement.

In summary, these experiments have revealed a double spectral inversion of the sign of the drag current and have yielded the first observation of a predominant contribution of light holes to the resultant drag current.

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