Experimental observation of drag of 2D electrons by far-IR light

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A fast longitudinal photovoltage has been observed to arise when a 2D electron gas is exposed to far-IR light. The observed photovoltage is shown to be due to photon drag of electrons in the course of indirect optical transitions.

Photon drag of charge carriers has been observed in bulk semiconductors, and it has been studied in detail in that setting.[1] For a 2D electron gas, the effect has been studied theoretically for the case of direct optical transitions between quantum-well bands,[2] and it has been observed in GaAs-based structures.[3]

In this letter we are reporting the experimental observation of a photon drag of 2D electrons in the far-IR region, in which the interaction with the light is governed by indirect optical transitions.

The experiments were carried out at room temperature on structures grown by molecular beam epitaxy[4] on semi-insulating GaAs substrates (Fig. 1). The 2D electrons were localized at the GaAs–AlGaAs heterojunction. The parameters of the potential well formed by the heterojunction were such that the energy gap between the quantum-well subbands was ~ 100 meV. This figure is considerably larger than the energy of the photons used for excitation (< 13.7 meV), so there is no possibility of direct intersubband transitions.

The density of the 2D electrons in the test samples was $\sim 6 \times 10^{11}$ cm^{-2}. At this density, there was a filling of predominantly the zeroth quantum-well subband; there was also a partial filling of the first subband. At room temperature and at liquid-nitrogen temperature, the mobilities of the test samples were ~ 6000 and 100 000 cm^2/(V · s), respectively. The surface of the sample in the plane of the 2D layer had dimensions of 4×4 mm. Electrical contact with the 2D layer was achieved by diffusing indium on the side of the junction near the corners of the samples. The contact region was clad with a material opaque to the light.

The light source was a pulsed NH_3 or D_2O laser with optical pumping by a TEA CO_2 laser. The wavelengths of the radiation were 90, 55, and 385 μm; the pulse length was 40 ns. The intensity of the linearly polarized light was varied from 1 to 200 kW/cm^2. The time resolution of the measurement apparatus was no worse than 10 ns.

When the light was incident normally on the structure with the 2D electrons, no photovoltage was manifested. When light was incident obliquely (Fig. 1), we observed a fast longitudinal photovoltage (i.e., along the x axis), which reproduced the shape of

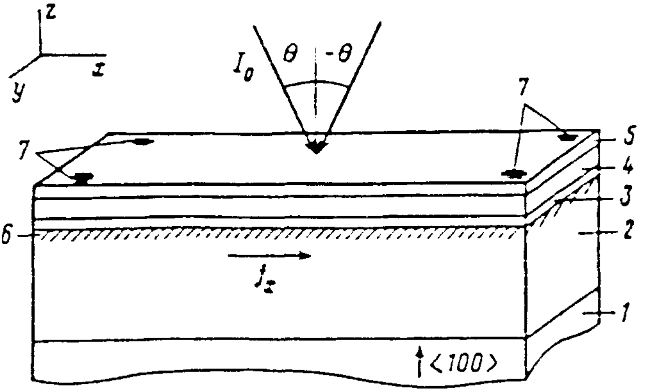

FIG. 1. Schematic diagram of the 2D structure. *1*—Substrate of semi-insulating GaAs oriented in the (100) plane; *2*—buffer layer of p-GaAs with $p \sim 10^{15}$ cm^{-3} and a thickness ~ 1 μm; *3*—layer of pure $Al_{0.25}Ga_{0.75}As$ with a thickness of 100 Å; *4*—layer of silicon-doped n-$Al_{0.25}Ga_{0.75}As$ with a thickness of 400 Å, which furnishes electrons to the 2D layer; *5*—heavily doped GaAs layer with a thickness of 100 Å; *6*—region of spatial localization of the 2D carriers; *7*—indium contacts; I_0—incident wave.

the laser pulse. When the angle of incidence of the light was switched from θ to $-\theta$, the photovoltage also changed sign. Obviously, this change in the light propagation direction would be accompanied by a change in only the direction of the momentum of the light along the plane of the 2D layer. This behavior of the signal as a function of the momentum direction is characteristic of photon drag of electrons.[1] The sign of the observed photovoltage corresponds to a motion of the electrons along the light propagation direction. In samples which did not have a 2D layer, no photosignal was observed.

There was no transverse photovoltage (along the y axis) at any angle of incidence.

Since there is no transverse drag current, we write the longitudinal component of the drag photovoltage as follows:[1]

$$V_x \sim TI\left(\frac{\boldsymbol{\kappa}}{|\boldsymbol{\kappa}|} \cdot \mathbf{n}\right)\kappa_x \sim TI \sin\theta \cos\theta, \qquad (1)$$

where T is the constant of the drag effect, which depends on the position of the polarization plane of the light, I is the light intensity, $\boldsymbol{\kappa}$ is the momentum of the photon, the factor $\cos\theta$ allows for the change in the light intensity incident on the sample as the angle of incidence changes, and the factor $\sin\theta$ allows for the change in the projection of the momentum of the light onto the plane of the 2D layer.

Since the depth of the 2D layer ($d \sim 600$ Å) is small in comparison with the wavelength in the material ($\lambda/n \sim 20$ μm), refracted and reflected waves cannot form at these depths. The 2D electrons are thus acted upon by the incident wave and also the reflected wave formed in the substrate. In this case, expression (1) becomes

$$V_x \sim TI_0[1+R(\theta)]\sin\theta\cos\theta = TI^*, \qquad (2)$$

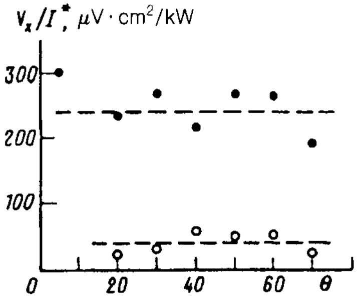

FIG. 2. Normalized drag photovoltage versus the angle of incidence of light polarized in the plane of incidence (●) and perpendicular to this plane (○).

where I_0 is the intensity at which the light strikes the sample, and $R(\theta)$ is the reflection coefficient of the substrate, as calculated from the Fresnel formulas.

Figure 2 shows the drag photovoltage normalized to I^* for various angles of incidence. The normalized voltage is seen to be very sensitive to the polarization of the light and insensitive to the angle of incidence. As the polarization is changed, the orientation of the electric vector of the wave with respect to the 2D layer changes.

The intensity dependence of the photovoltage is also greatly different in the two cases in which the light is polarized in the plane of incidence (this is the s polarization) and perpendicular to this plane (the p polarization; Fig. 3). In the former case, the dependence on the light intensity is stronger than linear. In the latter case, the photosignal is linear in the intensity and is much smaller.

We also carried out a preliminary study of the photoconductivity and the spectrum of the photovoltage.

In the heterostructures described above, we detected a fast, positive photoconductivity in addition to the photovoltage. This photoconductivity is apparently due to a change in the mobility of the 2D carriers as they are heated by the light. The magnitude of the photoconductivity is a linear function of the intensity for any polarization of the light.

The spectral study showed that as the wavelength of the light is increased by a factor ~4 ($\lambda = 385$ μm), the photovoltage in the case of the p polarization increases

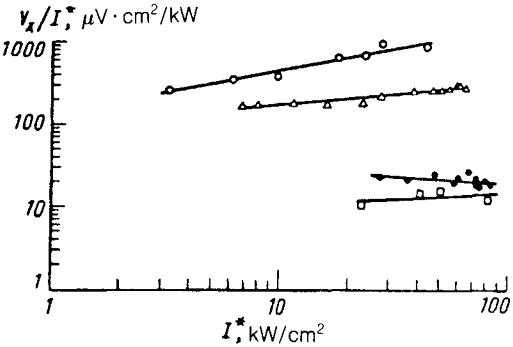

FIG. 3. Normalized drag photovoltage versus the light intensity. ○,△—The light is polarized in the plane of incidence, with $\theta = 70°$ and 50°, respectively; □,●—the light is polaried perpendicular to the plane of incidence, with $\theta = 70°$ and 50°, respectively.

by two orders of magnitude, while that for the *s* polarization increases by less than one order magnitude. The increase in the photoresponse with increasing wavelength is further evidence that the drag photovoltage which arises is due to indirect optical transitions.

In summary, a drag of 2D electrons by light in the far-IR region has been observed in this study. It has been shown that this carrier drag is due to indirect optical transitions.

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