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Photomagnetic effect in bilayer two-dimensional electron–hole systems

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Abstract

In tilted magnetic fields a bilayer electron–hole system is found to generate a photocurrent under terahertz radiation as the system is tuned to electron cyclotron resonance conditions. The photoinduced current amplitude oscillates with the magnetic field in correlation with Shubnikov–de Haas oscillations for electrons. The phenomenon is accounted for by a photomagnetic effect in electron–hole systems in the quantum Hall regime and has potentialities for terahertz detection and spectroscopy.

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Keywords: Bilayer electron–hole system; Photocurrent; Terahertz radiation; Cyclotron resonance; Quantum Hall regime

A bilayer two-dimensional electron–hole system is a very interesting physical object revealing a number of fascinating effects (for review see Ref. [1]). Here we report the observation of photocurrent induced by terahertz (THz) emission in a bilayer two-dimensional electron–hole system in tilted magnetic field. As the system is tuned to electron cyclotron resonance condition, THz radiation induces an in-plane current flowing in the direction perpendicular to the magnetic field without any external bias. The effect in the bilayer electron–hole system described below is similar to that observed in an asymmetric InAs quantum well (QW) [2]. The photoinduced current in bilayer systems can be understood as a consequence of a spatial separation of photo-exited carriers which can be considered as an effective current in the direction normal to the sample plane. At these conditions in-plane component of the magnetic field produces in-plane Hall current in the direction normal to the magnetic field. The photocurrent is an oscillatory function of the external magnetic field and the oscillations correlate with the electron filling factor.

Our samples consist of a single InAs QW separated from adjacent GaSb layers by AlSb barriers (see the inset in Fig. 1). Several undoped samples were cleaved from different wafers grown by molecular-beam epitaxy under the same conditions. The wafers have the same sequence of layers and differ only in the widths of the layers. The existence of the electron and hole layers in our samples was directly proved by observation of corresponding cyclotron resonance peaks [3]. A tunable far-infrared cyclotron resonance laser was used to deliver 0.5-μs pulses with power less or around 1 W per pulse at any desired wavelength between 110 μm and 180 μm. The photocurrent I generated in the unbiased devices was measured through the voltage drop across a load resistor in a closed circuit configuration. The signal was registered without amplification just using an averaging mode of a digital oscilloscope.

The effect appears under unpolarized THz emission in sufficiently strong tilted magnetic fields, as in our experiments at tilt angle of 45°, and vanishes at small in-plane component of magnetic field (at tilt angle of 8°). The ratio of signal to noise exceeds 20 as shown in Fig. 1 where we plot an oscilloscope trace of a photoinduced current obtained under illumination by the radiation with photon energy of $\varepsilon = 9.46$ meV and in magnetic field of 4.59 T. The photocurrent is generated only in the direction perpendicular to the in-plane magnetic field. No signal even at the tilt angle of 45° was registered in the direction along the

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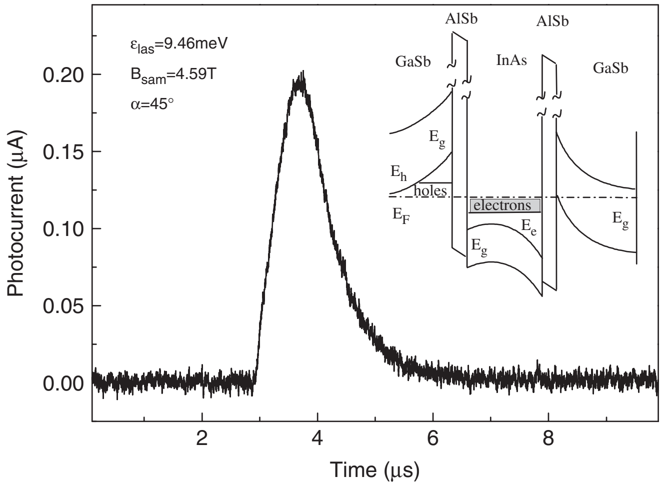

Fig. 1. An oscilloscope trace of the photoinduced current obtained at $\varepsilon = 9.46$ meV ($\lambda = 131$ μm) and in magnetic field of 4.59 T tilted at angle of 45° with respect to the structure normal. The inset presents the structure scheme.

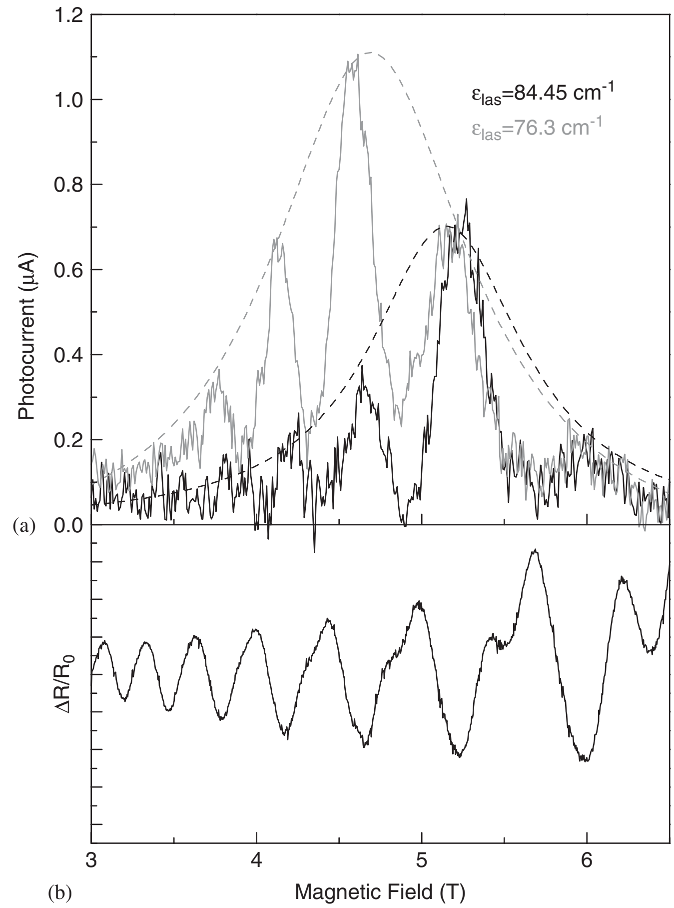

Fig. 2. (a) The photoinduced current as a function of the magnetic field tilted at 45° with respect to the QW layer, measured with 9.46 and 10.48 meV illumination. The broad peaks shown by short-dashed lines with the maximum around 4.7 and 5.2 T, are envelopes as guide to the eyes, attributed to the cyclotron resonance condition for electrons. (b) The bottom plot shows the SdHOs after subtracting the non-oscillating background.

in-plane magnetic field. The photocurrent depends on the normal component of the magnetic field. In Fig. 2(a) we present the magnetic field (B) dependences of the photoinduced current measured at a tilt angle of 45° for two laser energies of 9.46 and 10.48 meV. The signal appears at the normal component of the magnetic field corresponding to the cyclotron resonance conditions and increases monotonically with the radiation power. Broad peaks shown by short lines with the maximum around 4.7 and 5.2 T are envelope curves attributed to the cyclotron resonance peaks for electrons with $m_{CR} = 0.0406m_o$ and $m_{CR} = 0.0402m_o$, respectively [4]. These data indicate that the signal is related to the two-dimensional electron gas. The signal disappears as the normal component of the magnetic field deviates sufficiently from the cyclotron resonant field. The amplitude of the photocurrent oscillates with magnetic field showing $1/B$-periodic oscillations independent on the radiation frequency. Fig. 2(b) shows B dependence of the normalized magnetoresistance measured with a constant bias current of 1 μA. To make the Shubnikov–de Haas oscillations (SdHOs) better resolved, the background resistance was subtracted out. The period of the photocurrent and SdHO is the same (Figs. 2(a) and (b)) that points to the Landau quantization as a reason for the photocurrent oscillations.

Figs. 3(a) and (b) present the B dependence of photocurrents measured at different connection schemes under the same radiation intensity and energy and at the same range of magnetic fields. The currents on the opposite edges of the sample have different directions as seen from Fig. 3(a). At the same time, magnetic fields corresponding to the extremum points of the photocurrent oscillations do not change. Different contact connections produce different phase shift of the photocurrent oscillatory dependence on the magnetic field. The connection scheme shown in Fig. 3 (a) corresponds to a phase shift of π. The case with $1/2\pi$-phase shift is demonstrated in Fig. 3(b). The shift is caused by just grounding the second pair of contacts which are not used in measurements. The $1/B$ periodicity is the same for all three connections.

Although there is no clear microscopic picture of the effect, several possible explanations could be discussed. Here we suggest a mechanism based on the presence of closely spaced, but separated electron–hole layers producing nonzero dipole moment of the system [5]. There are two essential conditions for the observation of the photoinduced currents. The first is a strong in-plane magnetic field, which is realized in the experiments. The second is a strong built-in electric field, which is an intrinsic property of structures used in the experiments. Excitation of electrons and holes by the THz emission and their subsequent interlayer transitions in a built-in electric field can be considered as an internal current perpendicular to the structure. The tilt of the magnetic field leads to

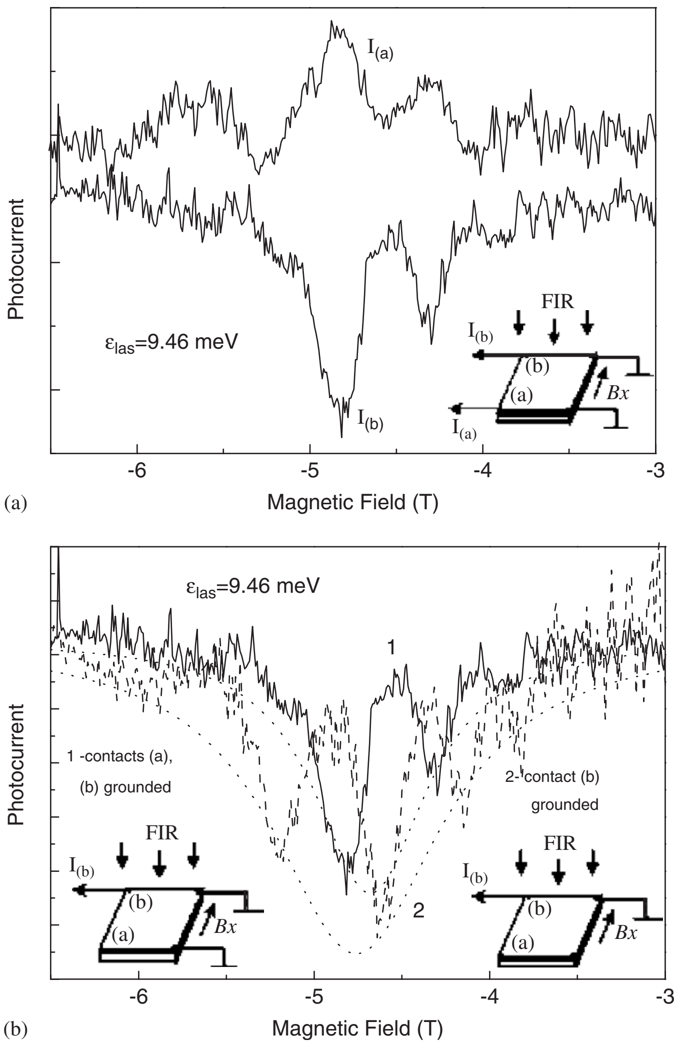

Fig. 3. A phase shift of the photocurrent oscillations measured at different contact configurations. (a) a π-period phase shift for currents on the opposite edges of the sample. (b) a $\pi/2$-period phase shift caused by grounding the pair of contacts unused in measurements. In the insets the measurement arrangement is sketched.

appearance of the in-plane current component which is perpendicular to the magnetic field. We classify this effect as photomagnetic, although it is not related to inhomogeneous carrier distribution, but caused by the built-in electric field. In addition, the features of the induced current are defined by the presence of quantized magnetic field that results in the QHE with photoinduced currents. First of all, this is quantum oscillations of the current magnitude related to the filling factor. Then, opposite directions of the edge currents (Fig. 3a) may be explained as a consequence of a Hall current, circulating along the sample boundaries. And finally, the current distribution in the sample depends on the details of the electrostatic potential, which is strongly influenced by the geometry of contacts (Fig. 3b).

In conclusion, we found that unpolarized terahertz radiation may generate a current in a bilayer electron–hole system in tilted magnetic fields. The phenomenon is described as a photo-magnetic effect in an electron–hole system. The photoinduced current properties are determined by quantized magnetic field that opens a way to a new spectroscopic method of studying QHE.

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References

[1] L.V. Butov, Solid State Commun. 127 (2003) 89.
[2] S.A. Emelyanov, Solid State Commun. 133 (2005) 675.
[3] Y.B. Vasilyev, et al., Phys. Rev. B 60 (1999) 10636.
[4] The increased value of the defined electron mass in InAs is attributed to the deviation of the real tilt angle from the expected angle of 45°.
[5] L.V. Kulik, et al., Rev. B 61 (2000) 1712;
L.V. Kulik, et al., Rev. B 66 (2002) 073306.