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Terahertz response in the quantum Hall effect regime of a quantum-well based charge sensitive phototransistor

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Abstract

The properties of a charge-sensitive infrared phototransistor (CSIP) based on a GaAs/AlGaAs multiple quantum-well (QW) structure are studied under magnetic field. In the CSIP, the upper QWs serve as a floating gate that is charged up by photoexcitation. The photo-induced charges are detected by the resistance of the lowest QW (LQW) conducting channel. We found two different features of terahertz (THz) response, ΔR, in the quantum Hall effect (QHE) regime. One is simply explained by the increment of electron density in the LQW channel, in which the ΔR switches a sign across the QHE plateau. The other feature is observed as more enhanced ΔR when the potential barrier is formed in the LQW channel. The latter mechanism could be interpreted by the promotion of edge-bulk scattering due to photo-induced charges.

1. Introduction

Sensitive detection of terahertz (THz) waves has attracted considerable attention, due to its applications in many scientific fields such as astrophysics, biochemistry and material science. The photoexcitation through intersubband transition in semiconductor QW structures is a fascinating phenomenon for sensitive THz detection. Extensive efforts have been made on the enhancement of photocurrent or photovoltage in the QW infrared photodetectors (QWIPs) [1,2].

In recent years, a different type of QW based detectors has been developed in a wavelength range of $\lambda_0 = 12-45$ μm [3]. In this new scheme, the upper QWs (UQWs) serve as an isolated photosensitive semiconductor gate. An electron excited in the second quantized electron level escapes out of the UQWs through the tunnel-barrier, and relaxes into the lowest QW (LQW). A photo-induced positive charge in the UQWs is sensed by the LQW conducting channel through a capacitive coupling between QWs. This charge-sensitive infrared phototransistors (CSIPs) provide an extremely low noise equivalent power, $NEP \sim 7 \times 10^{-20}$ W/H$^{1/2}$, and a high specific detectivity, $D^{*} \sim 1 \times 10^{16}$ cmH$^{1/2}$/W.

The two-dimensional electron system (2DES) exhibits Shubnikov-de Haas oscillation and the integer QHE in perpendicular magnetic field B. Since such quantum magnetotransport would be sensitive to the electrostatic potential, an appropriate external magnetic field may provide a possible means to improve the detection performance of the CSIP.

2. Experiments

The CSIP studied is fabricated from a GaAs/AlGaAs triple QW structure (Fig. 1). The detail layer structure has been described in Ref. [4]. The first UQW (UQW1) is formed in a 7 nm thick Si-doped GaAs layer and the energy splitting $\Delta\epsilon$ between the ground-state subband (ϵ_0) and the first excited subband (ϵ_1) is designed to be 135.4 meV. The second UQW (UQW2) is formed in a 9 nm thick Si-doped GaAs layer. The corresponding $\Delta\epsilon$ is designed to be 82.2 meV.

The schematic of the measurement setup is shown in Fig. 2(a). To avoid unintended background infrared radiation, the detector and the radiation source are embedded into a copper box cooled down to 4.2 K. A chip resistor (1 kΩ) suspended in vacuum is used as a thermal radiation source. THz-response measurements are carried out by using the temperature-controlled thermal radiation source (typically at 39 K).

3. Results and discussion

The electron mobility μ of UQW1, UQW2 and LQW at 4.2 K is experimentally estimated to be 6.1×10^{-2} m^2/(Vs), 6.7×10^{-2} m^2/(Vs), and 5.3 m^2/(Vs), respectively. In both UQWs, the 2DES can be deemed to be in the classical low-field regime ($\omega_c\tau = \mu B < 1$, $B < 9$T) where ω_c and τ

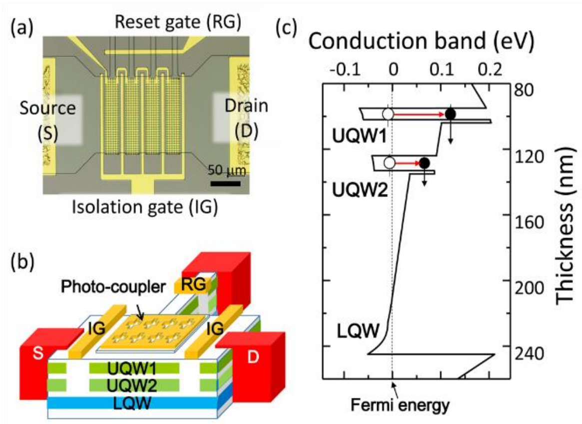

Fig. 1 (a) Optical micrograph and (b) schematic view of the CSIP measured. (c) The conduction band energy diagram of the triple GaAs/AlGaAs quantum wells. The sheet electron density n of UQW1, UQW2 and LQW at 4.2 K is evaluated to be 1.57×10^{15}m^{-2}, 2.87×10^{15}m^{-2} and 2.86×10^{15}m^{-2}, respectively. The electron excited to the ϵ_1 escapes out of UQW1 (UQW2) through a 2 nm thick $Al_{0.3}Ga_{0.7}As$ tunnel barrier (a 2 nm thick $Al_{0.15}Ga_{0.85}As$ layer).

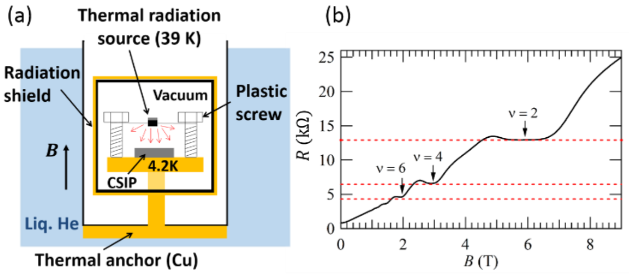

Fig. 2 (a) Schematic of the measurement setup using a temperature-controlled thermal radiation source. (b) Two-terminal resistance R as a function of magnetic field.

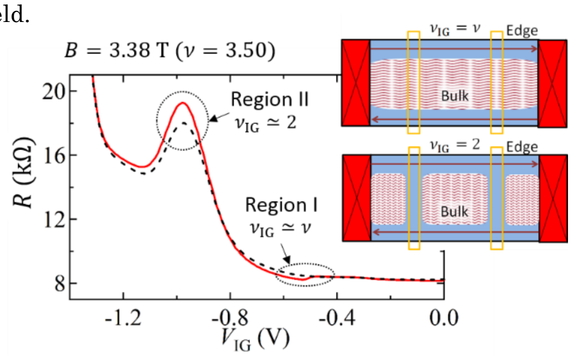

Fig. 3 Resistance as a function of the isolation-gate voltage V_{IG} at a LL filling factor $\upsilon = 3.50$. The solid and dashed curves show the data at a photoactive condition (reset-gate voltage, $V_{RG} = -1.0$ V) and a photoinactive condition ($V_{RG} = 0$ V), respectively. The inset shows the schematic views of conducting channels in Region I and Region II.

are the cyclotron frequency and the relaxation time, respectively. On the other hand, the LQW channel satisfies $\omega_c\tau \gg 1$. It follows that electron transport is dominated by quantum-mechanical effects due to the presence of LL splitting (Fig. 2(b)).

Figure 3 shows the two-terminal resistance R versus isolation-gate (IG) voltage V_{IG} at $B = 3.38$ T (LL filling factor $\upsilon = 3.50$). Negative response ($\Delta R < 0$) is observed when the upper two QWs are isolated at a negatively biased gate voltage (Region I). In addition, positive response ($\Delta R > 0$) is also found when the LL filling factor beneath the IG υ_{IG} is set to a less integer number (Region II in Fig. 3).

Under constant radiation intensity, the rate of THz response $\Delta R/\Delta t = \eta\Phi_{inc}\Delta R_e$ corresponds to an index of the sensitivity, where Φ_{inc} and η are the photon flux incident on the photoactive area and the quantum efficiency, respectively, and ΔR_e is the unit photoresponse induced by a single photon. Figures 4(b) and 4(c) display $\Delta R/\Delta t$ versus magnetic field in the conditions of Region I and Region II, respectively. In the condition of Region I (no potential barrier is formed in the LQW channel), $\Delta R/\Delta t$ will be proportional to $-(\partial R/\partial B)(\partial B/\partial n)(\Delta n/\Delta t)$ where Δn is the increment of electron density in the LQW due to photo-induced positive charges in the UQWs. The derivative dependence of resistance $-\partial R/\partial B$ well explain why the ΔR switches a sign across the QHE plateau (Fig. 4(a)). On the other hand,

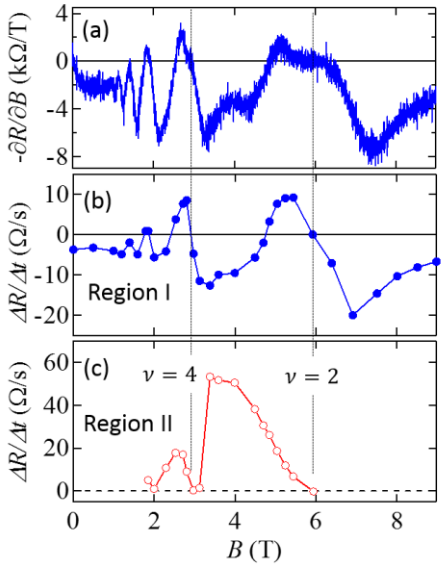

Fig. 4 THz response in magnetic field. (a) Derivative dependence of resistance $-\partial R/\partial B$. (b), (c) the rate of THz response $\Delta R/\Delta t$ obtained in Region I and in Region II, respectively.

larger positive THz response is observed in the Region II. Since the deviation of resistance from the quantized value is attributed to the backscattering in the edge channel, the mechanism of THz response could be interpreted by the promotion of edge-bulk scattering due to photo-induced charges.

4. Conclusion

In the QHE regime, we found two different features of the THz response in the CSIP. One is simply explained by the increment of electron density due to the photo-induced charges when no potential barrier is formed in the LQW channel. Another type of the THz response is observed when the LL filling factor beneath the isolation gate is set to a less integer number. Larger positive THz response is obtained, suggesting the promotion of edge-bulk scattering due to photo-induced charges. These findings may provide a hint for enhancing the THz response by magnetic field and potential barrier. In addition, the availability of ultra-highly sensitive CSIP under strong magnetic field will allow us to study magneto-optical phenomena in semiconductor quantum structures or two-dimensional materials.

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