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

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The characteristics of a charge-sensitive infrared phototransistor (CSIP) based on a GaAs/AlGaAs multiple quantum-well (QW) structure are studied under a magnetic field. In the CSIP, the upper QWs serve as a floating gate that is charged by photoexcitation. The photoinduced charges are detected using the resistance of the lowest QW conducting channel. The conducting channel exhibits the integer quantum Hall effect (QHE) in a perpendicular high magnetic field, yielding the magnetic field dependence of the terahertz (THz) response $\Delta R$. We found two different features of $\Delta R$. One is that $\Delta R$ switches sign across the QHE plateau, which is explained simply by an increased electron density in the conducting channel. The other feature is observed as an enhanced positive $\Delta R$ when a potential barrier is formed in the conducting channel. The latter mechanism can be interpreted as the promotion of edge/bulk scattering due to photoinduced charges. These findings suggest ways to enhance the THz response by using magnetic fields and potential barriers. © 2018 The Japan Society of Applied Physics

1. Introduction

Sensitive detection of terahertz (THz) waves has attracted considerable attention because of its applications in many scientific fields, such as astrophysics, biochemistry, and material science. Photoexcitation through intersubband transition in semiconductor quantum-well (QW) structures is a fascinating phenomenon for sensitive THz detection. Extensive effort has been made to enhance the photocurrent or photovoltage in THz infrared photodetectors (QWIPs).1-3

In recent years, a different type of QW-based detector has been developed to suit the wavelength range $\lambda_0 = 12 - 45 \mu m$.4,5 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 the UQWs through a tunnel barrier and relaxes into the lowest QW (LQW). A photoinduced positive charge in the UQWs is sensed by the LQW conducting channel through capacitive coupling between QWs. These charge-sensitive infrared phototransistors (CSIPs) provide an extremely low noise-equivalent power (NEP = $10^{-18}$–$10^{-20}$ W/Hz$^{1/2}$) and a high specific detectivity ($D^* \sim 1 \times 10^{16}$ cm$^2$/Hz$^{1/2}$/W). Because the photoexcited states are long-lived, single THz photons can be detected in a small device.5,6

A fascinating application of this sensitive THz detector is for magneto-optical studies of two-dimensional electron systems (2DESs). Extensive studies of magneto-optical phenomena such as cyclotron resonance have been conducted to obtain a better understanding of Landau quantization and its related quantum transport phenomena.7 In particular, measurements of cyclotron emission induced by currents are a powerful tool for investigating nonequilibrium electron dynamics in quantum-Hall-effect (QHE) conductors.8-13 It has proven possible to detect an extremely weak cyclotron emission (photon energy: 10 meV and wavelength: 124 µm at 6 T) in a GaAs/AlGaAs heterojunction by using a quantum-dot far-infrared photon counter.14 However, the far-infrared photon counter is not suitable for cyclotron resonance studies of a new type of 2DES. In particular, atomic layer materials with Dirac-cone dispersion exhibit a huge energy gap between zero-energy Landau level (LL) and the first excited LL (for instance, the energy gap is about 100 meV at 6 T in monolayer graphene).15 Because sensitive detectors are less developed in the corresponding mid-infrared region, cyclotron emission is yet to be observed in Dirac-cone dispersion. If a CSIP could be embedded in a cryogenic optical system subjected to a strong magnetic field, its high sensitivity would open up a new way to study magneto-optical phenomena in graphene and its related atomic layer materials.

In the presence of a perpendicular magnetic field $B$, the 2DES formed in the LQW exhibits the integer QHE. Such a quantum magnetotransport property is usually sensitive to any change in electrostatic potential. Hence, the THz response is strongly affected by magnetic fields and potential barriers.16 Here, we show the characteristics of a CSIP in the QHE regime and provide guidelines for operating the CSIP in a magnetic field.

2. Experimental methods

The CSIP under investigation was fabricated as a GaAs/AlGaAs triple-QW structure (Fig. 1). The layer structure is described in detail in Ref. 17. The first UQW (UQW1) is formed in a 7-nm-thick Si-doped GaAs layer, and the energy gap $\Delta \epsilon$ between the ground-state subband ($\epsilon_0$) and the first excited subband ($\epsilon_1$) is designed to be 135.4 meV. The second UQW (UQW2) is formed in a 9-nm-thick Si-doped GaAs layer, and the corresponding $\Delta \epsilon$ is designed to be 82.2 meV. In this triple-QW structure, the upper two QW layers serve as photosensitive floating gates when they are isolated electrically by a biasing isolation gate (IG) and a reset gate (RG). The LQW functions as a source–drain (SD) channel. The device was fabricated by standard electron-beam lithography and wet chemical etching. Ohmic contacts for the SD electrodes were formed by alloying them with AuGeNi. The IG and RG were formed by depositing a 120-nm-thick Ti/Au layer. The control gate (CG) for tuning the electron densities of the UQW layers consists of a uniform...
Fig. 1. (Color online) (a) Optical micrograph and (b) schematic view of the CSIP under investigation. (c) Conduction-band energy diagram of the heterostructure of triple GaAs/AlGaAs quantum wells. The sheet electron density $n$ values of UQW1, UQW2, and LQW at 4.2 K are evaluated as $1.57 \times 10^{12}$, $2.87 \times 10^{13}$, and $2.86 \times 10^{15}$ cm$^{-2}$, respectively. The excited electron escapes UQW1 (UQW2) through a 2-nm-thick Al$_{0.15}$Ga$_{0.85}$As tunnel barrier (2-nm-thick Al$_{0.3}$Ga$_{0.7}$As layer). The UQWs are thus positively charged by photoexcitation.

The electron mobility $\mu$ values of UQW1, UQW2, and LQW at 4.2 K are experimentally estimated to be $6.1 \times 10^{2}$, $6.7 \times 10^{2}$, and $5.3 \text{ m}^{2}/(\text{V} \cdot \text{s})$, respectively. In both UQWs, we deem the 2DES to be in the classical low-field regime ($\omega_0 \tau = \mu B < 1$) under the present experimental conditions ($B < 9$ T), where $\omega_0$ and $\tau$ are the cyclotron frequency and relaxation time, respectively. Because we do not expect the well-defined LL splitting in the UQWs, the two spectral bands used for THz detection will not be affected appreciably by the magnetic field. In contrast, the LQW channel satisfies $\omega_0 \tau \gg 1$. It follows that the electron transport should be dominated by quantum-mechanical effects due to the presence of LL splitting. The characteristics of the THz response will make a marked difference in the QHE regime.

The measurement setup is shown schematically in Fig. 2(a). To avoid unintended background infrared radiation, the detector and radiation source are embedded in a copper box that is cooled to 4.2 K. The copper box is placed in a superconducting solenoid with a 2 in cold bore. A chip resistor (1 kΩ) is used as a thermal radiation source. The temperature of the resistor is monitored by a calibrated sensor (Lake Shore Cryotronics Cernox) and set typically to 39 K. The radiation source is suspended in a vacuum between the CSIP under investigation. (c) Conduction-band energy diagram of the semitransparent NiCr layer.

Fig. 2. (Color online) (a) Schematic of measurement setup involving a temperature-controlled thermal radiation source. (b) Conductance $G$ as a function of isolation-gate voltage $V_{IG}$ at zero magnetic field. The solid and dashed lines show the data obtained under photoactive (reset-gate voltage $V_{RG} = -1.0$ V) and photoinactive (reset-gate grounded) conditions, respectively. The inset shows a time trace of the THz response $\Delta G$ during reset operation. (c) Two-terminal resistance $R$ as a function of magnetic field at $I_{SD} = 100$ nA.

3. Results and discussion

The THz response in a transition region between integer QHE plateaus ($B = 2.29$ T; $\nu = 5.17$) is shown in Fig. 3. We measured the $V_{IG}$ dependence of $R$ at $I_{SD} = 100$ nA. Comparing photoactive ($V_{RG} = -1.0$ V) and photoinactive (reset-gate grounded) conditions, we observe a negative response ($\Delta R < 0$) when the two UQWs are isolated electrically and no potential barrier is formed in the conducting channel. We define the condition near $V_{IG}^{th}$ as Region I. We examined the THz response by using its time trace during reset operation [Fig. 3(c)]; the rate at which the photosignal increases, namely, $\alpha_R = \Delta R/\Delta t$, indicates the responsivity of the detector. We consider the negative response in Region I to be simply due to the increased electron density $\Delta n$ observed at zero field [Fig. 2(b)]. By contrast, a larger positive response ($\Delta R > 0$) is observed when we set the LL filling factor beneath the IG, namely, $\nu_{IG}$, to a lower integer value [Region II in Fig. 3(a)]. The rate $\alpha_R$ is higher than its magnitude observed in Region I. A similar
behavior is observed in the other transition region \((B = 3.38 \text{T}; \nu = 3.50)\), whereas there is no THz response in the middle of the QHE plateau \((B = 2.97 \text{T}; \nu = 4.00)\) (Fig. 4).

We begin by discussing the THz response in Region I on the basis of the charge-sensitive detection model proposed for the zero-field condition.\(^{21}\) In this model, the photocurrent signal \(\Delta I\) is expressed as \(\Delta I = (g W/L)\Delta n \sigma V_{SD}\), where \(\Delta n\) is the photoinduced charge density in the photoinsensitive area (length \(L\) \times width \(W\)) of the conducting channel and \(g\) is the geometrical factor of the device considering voltage drops in the photoinsensitive regions. For the photon flux \(\Phi_{\text{inc}}\) incident on the photoactive area, the photocurrent increases at the rate \(\alpha = \Delta I/\Delta t = \eta\Phi_{\text{inc}} \Delta I_e\), where \(\eta\) is the quantum efficiency and \(\Delta I_e\) is the current through the conducting channel by the amount of one additional electron.

The THz response in conductance, namely, \(\Delta G = \Delta I/V_{SD}\), is expressed by \(\Delta G = (\Delta n/\nu)G^{(0)}\), where \(G^{(0)} = (g W/L)\sigma_0\) is the original conductance in the dark (\(\sigma_0\) is the conductivity in the dark). In resistance measurements at a constant \(I_{SD}\), the THz response is expressed as \(\Delta R \approx -\Delta(n/\nu)R^{(0)}\), where \(R^{(0)}\) is the original resistance in the dark. Therefore, the relation

\[
\frac{\Delta G}{G^{(0)}} = \frac{\Delta n}{\nu} \approx \frac{\Delta R}{R^{(0)}}
\]

is expected at zero field. From the time trace at zero field [inset in Fig. 2(b)], we can derive the rate of increase \(\Delta G/\Delta t\) at \(V_{IG} = -0.49\ \text{V}\). Using \(g W/L \approx 0.5\) for this device, we evaluate the photoinduced electron density \(\Delta n\) to be \(2.5 \times 10^{13} \text{m}^{-2}\) with \(\sigma_{G} = \Delta G/\Delta t = 5.3 \mu\text{s}/\text{s}\) and \(\Delta t = 1\ \text{s}\). Hence, we obtain the ratio \(|\Delta G/G^{(0)}| = 4.4 \times 10^{-3}\). We also derive the ratio \(|\Delta R/R^{(0)}| = 4.9 \times 10^{-3}\) with \(\alpha_R = \Delta R/\Delta t = -4.0 \Omega/\text{s}\) at zero field, which agrees reasonably with \(|\Delta G/G^{(0)}|\).

Equation (1) no longer holds in the high-field regime. However, in the absence of an IG-formed potential barrier (Region I), we suppose that the THz response arises simply from an increased electron density \(\Delta n\) in the conducting channel. In that case, we express the rate \(\alpha_R\) as

\[
\alpha_R = \frac{\Delta R}{\Delta t} = -\frac{\partial R}{\partial \nu} \frac{\partial \nu}{\partial n} \frac{\Delta n/\Delta t}{(\Delta n/\Delta t)}
\]

\[
= -\frac{\partial R}{\partial /\nu} \frac{h}{e V} (\Delta n/\Delta t),
\]

where \(h\) is Planck’s constant. Figure 5(a) shows the derivative of resistance with respect to magnetic field, namely, \(-\partial R/\partial \nu\), obtained from the data plotted in Fig. 2(c). This indicates a finite response in the transition region and none in the middle of the QHE plateau. In addition, the behavior of \(-\partial R/\partial \nu\) suggests that the response switches sign across the QHE plateau. The values of \(\alpha_R\) obtained for different magnetic field strengths are plotted in Fig. 5(b). The experimental results qualitatively support the above interpretation.

Next, we attempt to analyze the magnitude of the response signals quantitatively. Using \(\partial R/\partial \nu = -5.5 \text{k}\Omega/\text{s}\) at 3.38 T and \(\Delta n/\Delta t = 2.5 \times 10^{13} \text{m}^{-2}\) for 39 K thermal radiation, we estimate \(\alpha_R\) to be roughly \(-160 \Omega/\text{s}\) from Eq. (2). However, as shown in Fig. 5(b), the experimental value of \(-12.6 \Omega/\text{s}\) at 3.38 T is one order of magnitude smaller than the calculated value. One possibility is that the magnetic field modifies the detectable spectrum considerably. However,
recent efforts have revealed no such change in the CSIP spectrum.19) Another possibility is that heating due to the 39 K thermal radiation reduces the sensitivity of the detector. Indeed, the CSIP temperature increases to 7 K when the thermal radiation source is activated. However, according to earlier studies of the temperature dependence of the performance,20) the sensitivity is not affected markedly up to 10 K. A more likely reason for this is the geometrical structure of the conducting channel. As shown in Fig. 1(a), the photosensitive regions in the actual device are separated into four areas by the comblike IGs. The measured response signals correspond to changes in the two-terminal resistance of the conducting channel biased partially by photoinduced charges. In particular, in the photoexcited states, the conducting channel comprises four gated and five ungated regions. In the presence of Hall voltages, the inhomogeneity of the electron density causes a potential drop at the corners of the boundary between the gated and ungated regions.21-25) Detailed consideration is required of these energy-dissipating corners. Using potential probes to measure the four-terminal resistance in the photosensitive region might clarify the difference between the measured $\alpha R$ and that expected from Eq. (2).

Next, we discuss the THz response in Region II. The $B$ dependence of $\alpha R$ in Region II is shown in Fig. 5(c). The notable features are that (i) a THz response is observed only in the transition regions between QHE plateaus, (ii) the response signal is restricted to an increase in resistance (i.e., $\Delta R > 0$ or $\alpha R > 0$), and (iii) the response signal is larger than that in Region I.

Because potential barriers are formed in the QHE conductor, we should consider the THz response mechanism from the viewpoint of scattering in quantum transport channels. Our interpretation is as follows. Because of the suppressed inter-LL tunneling in a smooth edge potential, a nonequilibrium electron distribution between the edge and bulk states usually forms on a macroscopic scale (Fig. 6).10,26) With the present device geometry, a nonequilibrium electron distribution will form in the photosensitive area when $\nu_{IG}$ is set to an integer value. For such adiabatic transport, the two-terminal resistance in a transition region between $\nu$ and $\nu + 2$ can be expressed as $R = \nu\hbar/(2e^2)\left[1 + \text{exp}(-2x/l_{eq})\right]^{-1}$, where $x$ is the length of the scattering region and $l_{eq}$ is the equilibration length.27) In the $2 < \nu < 4$ transition region, for instance, the resistance is $R = \hbar/(2e^2)$ in the no-scattering limit ($l_{eq} \to \infty$) and $R = \hbar/e^2$ in the equilibrium limit ($l_{eq} \to 0$). Because the probability of edge/bulk scattering through the inter-LL tunneling depends on the overlap integral of electronic wave functions between the edge and bulk states, $l_{eq}$ decreases exponentially in the case of a decrease in the distance $\Delta Y_{IG}$ between the edge and bulk states as described by $l_{eq} \propto \text{exp}[\frac{1}{2}((\Delta Y_{01}/l_{B})^2)]$.22,28) In the photoexcited state, an additional electron density $\Delta n$ is induced in the photosensitive area of the first excited $N = 1$ LL (Fig. 6(d)). An increase in electron density decreases the distance $Y_{01}$, indicating an appreciable decrease in $l_{eq}$. Thus, the above interpretation based on edge/bulk scattering can explain both why the resistance is very sensitive to $\Delta n$ and the reason for the positive response.

To estimate the NEP precisely with no heating effect from the thermal radiation source, we measured the background radiation straying from a small aperture in the copper box.29) The sensitivity of this detector at zero field is well characterized by $\alpha = \Delta I/\Delta \tau = \eta \Delta I_{F\text{ave}}/(h\nu)$, where the photon energy $h\nu = 85.5$ meV, the detection efficiency $\eta = 0.17$, and $\Delta I_{F} = 1.5$ pA.17) Hence, we estimate the incident background radiation $P_0$ to be $1.9$ W from the experimental value of $\alpha = 35.5$ nA/s (3.55 mS/s in conductance) obtained from the time trace of the reset operation at zero field. We evaluate the signal-to-noise ratio (SNR) by measuring the noise using $\sqrt{(\alpha - \bar{\alpha})^2}$, where $\bar{\alpha}$ is the average slope of each curve over $\Delta \tau = 1$ s in the time trace.30) We derive SNR = 300 and NEP = $6.4 \times 10^{-18}$ W/\sqrt{Hz} at zero field. For the same background radiation, we derive SNR = 34 and 250 at 3.38 T for $\alpha R$ in Regions I and II, respectively. We thus
obtain \( \text{NEP} = 5.6 \times 10^{-17} \text{ and } 7.6 \times 10^{-18} \text{ W}/\sqrt{\text{Hz}} \) in Regions I and II, respectively. The CSIP sensitivity is thus comparable to that at zero field if the magnetic field and IG voltage are established appropriately.

These findings suggest how to improve the performance of this type of detector further. We can improve its sensitivity by using potential probes to measure the response signal in the longitudinal resistance \( R_{\text{xx}} \) in the photosensitive area. As with a QHE far-infrared detector,\(^{31–33} \) the response signal will be much larger near either end of a QHE plateau because of the large derivative \( \partial R_{\text{xx}}/\partial B \). Furthermore, in the vicinity of such a QHE plateau, the noise power arising from \( R_{\text{xx}} \) remains small regardless of arbitrarily large \( L/W \) values. Hence, the response signal can be amplified by increasing \( L/W \) without the cost of increased noise. Next, to use the THz response in Region II, there may be an optimal distance between IGs. The equilibrium length \( L_{\text{eq}} \) has been reported to reach \( 1–10 \text{ mm} \) at \( B \sim 7 \text{T} \).\(^ {26} \) Controlling the edge potential with a side gate would be an effective way to tune the probability of edge/bulk scattering for a given \( \Delta n \).

4. Conclusions

We studied the characteristics of a CSIP in a magnetic field. The conducting channel exhibits the integer QHE and the THz response is affected strongly by the magnetic field. We found two different features of the THz response \( \Delta R \). In the absence of a potential barrier formed by the IGs (Region I), the THz response can be explained qualitatively by an increase in the electron density in the conducting channel due to photoinduced positive charges in the floating gates. The derivative \( \partial R/\partial B \) is predominant in characterizing the field dependence of the THz response. It follows that there is no THz response in the middle of the QHE plateau and that \( \Delta R \) switches sign across the plateau. By contrast, a larger positive THz response is observed in the transition regions when the filling factor beneath the IGs is set to a lower integer value (Region II). Under this condition, a nonequilibrium electron distribution between the edge and bulk states usually forms in the photosensitive area. Accordingly, the resistance is affected considerably by edge/bulk scattering through the inter-LL tunneling. Thus, the mechanism for a positive response can be understood as the promotion of backscattering in the edge channel due to photoinduced charges. These findings suggest ways to enhance the THz response by using magnetic fields and potential barriers.

Placing the CSIP in a strong magnetic field does not reduce its sensitivity appreciably even though it increases the output impedance of the detector by more than one order of magnitude. The guidelines for operating a CSIP in a magnetic field are summarized as follows. (i) The CSIP is feasible in the transition region between QHE plateaus. No THz response is expected in the middle of the plateau. (ii) Operating in Region I is useful in the classical low-field regime (less than 2 T for this device), whereas a larger THz response can be expected in Region II if the QHE plateau is observed explicitly. The ability of CSIPs to operate in high magnetic fields allows us to study magneto-optical phenomena in atomic layer materials with Dirac-cone dispersion.

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29) The sensitivity is estimated from the response for all the detectable bands of the two-color CSIP.