論文の内容の要旨

論文題目

Interaction of Electromagnetic Waves with Electrons in Semiconductor Quantum Wells - Development of Ultra-Highly Sensitive THz Detectors

(半導体量子井戸構造中の電子と電磁波の相互作用の研究
- 超高感度テラヘルツ検出器の実現にむけて)

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In this thesis, we discuss the strong resonant coupling due to interaction between electrons and Longitudinal Optical (LO) phonons. Spectral measurement by using charge sensitive infrared phototransistors (CSIP) found evidence of anti-crossing due to interaction of intersubband transition with LO phonons.

1 Motivation

Our aim is to develop CSIP for astronomical applications at the wavelengths of 30 – 60 μm.

Teraherz (THz) or Far-infrared (FIR) region ($\lambda \sim 30 - 300\ \mu$m) offers the opportunity to probe the process of star-, planet-, and galaxy-formation. Star-forming galaxies are heavily obscured by interstellar dust. The energy sources for the star-forming galaxies are so deeply embedded that more than 90% of their total output energy is absorbed and re-radiated in the FIR by interstellar dust. Hence optical and near-infrared observations cannot sufficiently reveal true nature of these galaxies due to heavy dust extinction. On the other hand, FIR observations can reveal the processes happening in these galaxies without much affected by dust extinction. FIR spectroscopy is important tool to reveal physical processes in these galaxies, offering rich lines that probe the characteristics of the interstellar medium in its ionized or neutral atomic and molecular phases. In addition, the wavelength range of 30 – 60 μm is important for the study of protoplanetary disks, which provides the clue to understand the planetary-formation process. However, spectroscopic observations in the wavelength range of 30 – 60 μm, have been very much limited for the lack of sensitive detectors in this range.

Hence, in this thesis, we focus on the application of CSIP for the wavelength range of 30 – 60 μm, which has rich astronomical information yet unexplored. CSIP is a quantum-effect device implemented in a GaAs/AlGaAs double QW structure as shown in Fig.1. The operation mode of CSIP is as follow: The upper quantum-well (QW) in the double QW structure is positively charged up by photo-excitation via intersubband transition. This conduces to increase in the conductance of the lower QW channel. In other words, the electrically isolated upper QW serves as a photo-sensitive gate to the source-drain channel formed by the lower QW. This mechanism gives

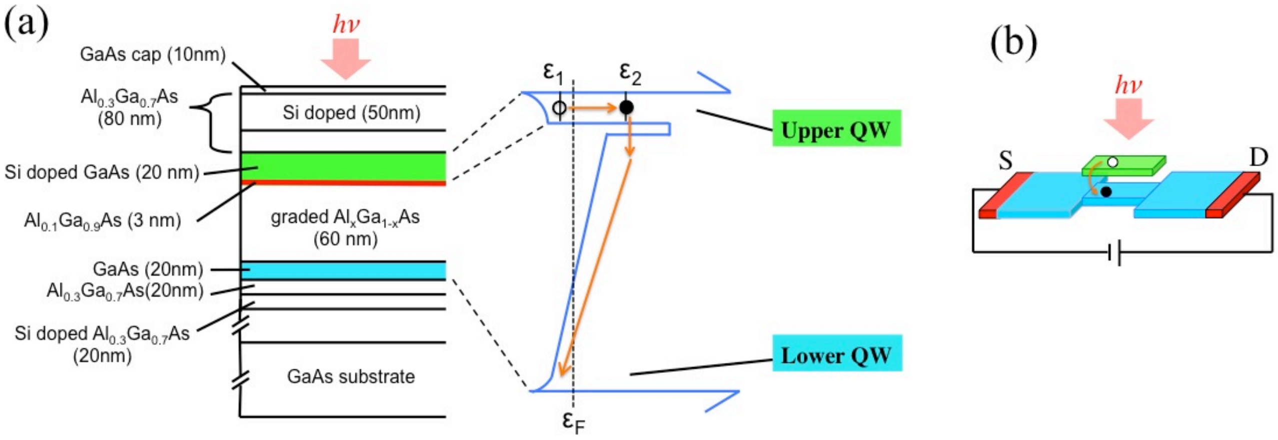

Figure 1: (a) CSIP crystal structure and potential diagram for the target wavelength of 48 μm as an example. The light green layer indicates the upper QW, and the light blue indicates the lower QW. The red line corresponds to the tunnel barrier. The right-hand side figure shows the potential diagram of conduction band. ε_1 and ε_2 are intersubband levels, ε_F is the Fermi energy. (b) Schematic representation of a CSIP device. The light green and the blue layers correspond to the wafer structures shown in (a). The electrically isolated upper QW serves as a photo-sensitive gate to the source-drain channel formed by the lower QW.

extraordinary high photoconductive gain. Hence CSIP is the promising detector with high sensitivity in the FIR. CSIPs have been well established in the mid-infrared region (12 – 20 μm), achieving Noise Equivalent Power (NEP) of 7 $\times 10^{-20}$ W/ $\sqrt{\text{Hz}}$, which is much better than those of conventional semiconductor detectors [1].

Increasing the width of the upper QW can shift the target wavelength to longer region. However, within the wavelength region at 30 – 60 μm, there is a wavelength range, called "Reststrahlen band", in which the light is strongly reflected and absorbed due to strong coupling of photons with phonons. The wavelength range of the Reststrahlen band is bounded by the Longitudinal Optical (LO) phonon frequency, ω_{LO}, and the Transverse Optical (TO) phonon frequency, ω_{TO}. In GaAs, the Reststrahlen band is located in the range between 33.8 μm (LO) and 36.8 μm (TO) at 4K. Since the light does not penetrate substantially into the material, photo-response is completely absent in the Reststrahlen band, as exemplified for widely used Quantum-Well Infrared Photodetctors (QWIP). In the case of CSIP, however, the photo-active upper QW is located close immediately below the GaAs surface (about 100 nm depth). The photo-active region is well within the penetration depth (around a few microns) of radiation in the Reststrahlen band. Hence, CSIP is expected to exhibit finite response to the radiation in the Reststrahlen band: The response is of particular interest because of strong interaction of electrons and LO phonons (Polaron effect). It is important to experimentally clarify how the interaction plays a role in the photo-response mechanism.

2 Anti-crossing due to electron-LO phonon interaction

For this sake, we have designed and fabricated CSIPs especially for the Reststrahlen band in this work. The upper QW width along with the overall crystal structure was so designed that the target wavelength falls in the Reststrahlen band. The target wavelengths of the crystals are designed to be 32, 36, and 48 μm. As a result, we observed photo-response in all of the three devices. Moreover, spectral measurement revealed that photo-response consists of two distinctly separated spectral bands. One of the bands substantially overlaps with the Reststrahlen band, while the other was found in shorter wavelength region than the target wavelength.

In GaAs crystal, conduction electrons strongly couple to LO phonons due to Coulomb interaction. Due to the interaction, an electron excited to the first-excited subband in the upper QW will rapidly emit one LO phonon if a photon of the energy equal to the LO phonon energy, ε_{LO}, is absorbed. The electron, thereby returning to the ground subband, re-absorbs the LO phonon, and, in turn, repeats coherent process of the emission and absorption of LO phonons. This process leads to the formation of hybridized "polaron" state, that is a superposition of the two states; the state with an electron in the excited subband and zero LO phonon $| \mathrm{e}, 0_{LO}\rangle$, and the state with the electron in the ground subband and one LO phonon $| \mathrm{g}, 1_{LO}\rangle$. The polaron states give rise to level anti-crossing as the intersubband energy difference ε_{12} is close to the LO phonon energy ε_{LO}.

The scenario of anti-crossing is justified only when the electron/phonon system is in a quantum-mechanically undisturbed state to assure coherent interaction between electrons and LO phonons. This condition is violated in widely applied QWIP, but is satisfied in the present system of CSIP. This is because excited electrons are preserved coherently in isolated region consisting of the upper and the lower quantum-wells with a lifetime experimentally evaluated to be about 4 ps, which is long enough for the formation of coupled polaron state. It is hence probable that the subband transition in CSIP coherently couples with LO phonons.

In order to quantitatively discuss the experimental results here, we consider a theoretical model. The "dielectric continuum model" describes dielectric constant due to interaction between intersubband transition and LO phonons in a homogeneous medium. The data points representing those experimental values in Fig.2 are substantially reproduced by the theoretical values based on the dielectric continuum model. This definitely indicates the validity of the interpretation described in the above. Theoretical values calculated with different two-dimensional electron density (N_{2DEG}) quantitatively require more than twice for N_{2DEG} than experimentally obtained values. (The experimental values of N_{2DEG} remain in $(2.5 \pm 0.2) \times 10^{11}\mathrm{cm}^{-2}$.)

The coupling strength of polaron states should be weakened if the density of electrons relevant to the intersubband transition decreases. For rigorous test of the interpretation described in the above, dependence of the anti-crossing on the two-dimensional electron density (N_{2DEG}) in the upper QW is studied. The experimental data definitely indicate that the amplitude of energy splitting between the upper and the lower branches is reduced with decreasing N_{2DEG} which is consistent with theoretical prediction. The general trend of experimentally obtained coupled-mode frequencies (ω_+ and ω_-) as a function of N_{2DEG} is reproduced substantially by the theoretical curves derived from the dielectric continuum model. In more detail, however, we notice further that the experimental values of the lower energy branch (ω_-) agree satisfactorily with the corresponding theoretical values, while those of the upper energy branch (ω_+) exhibit a certain deviation towards higher values than the theoretical prediction. This difference suggests that the coupled modes are in stronger resonant regime because energy splitting increase with coupling strength.

3 Highlights and Prospective toward THz-CSIP

This paper reports detailed experimental evidence that intersubband transition and LO phonons are resonant in the strong coupling regime by using the novel detecter, CSIP. Anti-crossing has been clearly seen in our spectral measurement in the vicinity of the Reststrahlen band. The experimental values for frequency splitting are substantially reproduced by the theoretical values based on the dielectric continuum model. The LO phonon-like mode (the mode with frequency nearer ω_{LO}) is expected to have smaller photo-response compared to that of the intersubband transition-like mode, since the energy of LO phonon-like mode is spent for lattice scattering rather than intersubband transition. Previous experiments on Quantum-well detectors showed small anti-crossing, showing photo-response only for intersubband transition-like mode [2]. The current result is the first experimental results to show the two polaron states in the strong coupling regime. This is partly because the lifetime of the resonant coupled modes is long enough to observe the response. This long lifetime is caused by the fact that CSIP can read photo-current keeping coupled quantum states in the double QW. Thanks to high sensitivity and the unique structure of CSIP, we observed the strong coupling in the both $\varepsilon_\pm$ modes.

In order to develop CSIPs for the wavelengths of 30 – 60 μm, we have to pay careful attention to the strong coupling between intersubband transition and LO phonons. It is crucial for THz-CSIP to enhance photo-signal in the lower energy spectral band suppressing photo-signal in the higher spectral band. The one approach to realize this condition is the reduction of the height of the graded and the tunnel potential barrier of CSIP, which can soften the strong coupling.

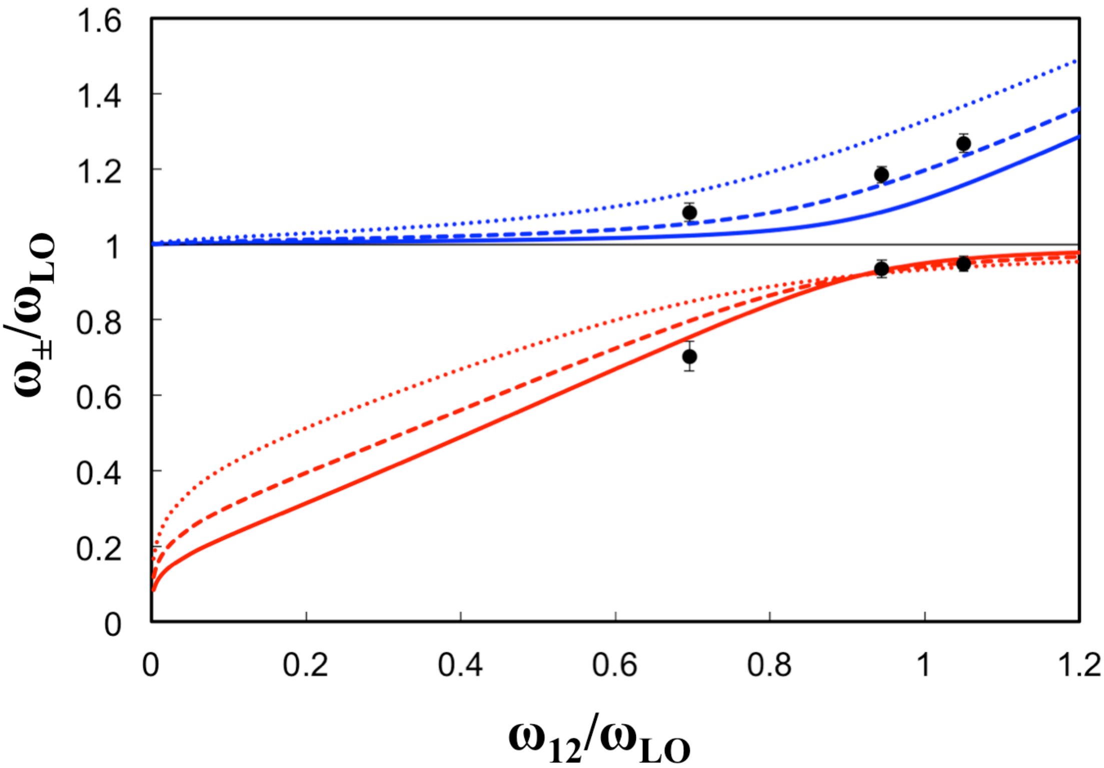

Figure 2: Normalized polaron frequencies $\omega_{\pm}$ as a function of the non-interacting intersubband energy ω_{12} in GaAs. The dielectric continuum model is calculated for $N_{2DEG} = 2.5 \times 10^{11}\text{cm}^{-2}$ (solid), $5.0 \times 10^{11}\text{cm}^{-2}$ (dashed), and $1.0 \times 10^{12}\text{cm}^{-2}$ (dotted). The horizontal line indicates the position of the LO phonons. The top (red) and the bottom (blue) curves are the upper (ω_+) and the lower (ω_-) branches obtained from the dielectric continuum model. The data points are the experimental results for $N_{2DEG} = (2.5 \pm 0.2) \times 10^{11}\text{cm}^{-2}$.

This thesis is organized as follows: Chapter 1 describes that our interests in THz astronomy and characteristics of CSIP. In Chapter 2, we indicate experimental methods and experimental results for spectral measurement at the wavelengths close to that of the Reststrahlen band. Chapter 3 discusses the cause of the spectral splitting with the comparison with theoretical models. Finally, conclusion is drawn in Chapter 4.

References

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