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Screening effects of photogenerated carriers on terahertz radiation from coherent GaAs-like longitudinal optical phonons in (11*n*)-oriented GaAs/$In_{0.1}Al_{0.9}As$ strained multiple quantum wells

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Abstract. We investigated terahertz radiation from coherent GaAs-like longitudinal optical (LO) phonons in (11*n*)-oriented GaAs/$In_{0.1}Al_{0.9}As$ strained multiple quantum wells for clarifying the screening effects of photogenerated carriers. We observed the intense quasi-monochromatic terahertz wave from the coherent GaAs-like LO phonon, which originates from the initial polarization enhanced by the strong piezoelectric field. The intensity of the coherent GaAs-like LO-phonon band exhibited a saturation behavior as the pump power was increased. We evaluated the saturation behavior in terms of excitation efficiency of the terahertz wave from the coherent GaAs-like LO phonon using the parameter of unit-power intensity. From the pump-power dependence of the unit-power intensity, we conclude that the screening effect of high density photogenerated carriers on the piezoelectric field causes saturation of the terahertz-wave intensity from the coherent GaAs-like LO phonon.

1. Introduction

Femtosecond pulse-laser technology enables us to directly observe time-domain characteristics of phonons in phase referred as coherent phonons [1]. In polar semiconductors, the carriers generated by laser pulses release the initial amplitude of optical phonons through their instantaneous screening effects on internal electric fields. This starts the oscillation of the coherent optical phonons [2, 3]. There are two major techniques for observing the coherent phonons: pump-probe [1] and terahertz time-domain techniques [1, 4]. The initial amplitude of the coherent longitudinal optical (LO) phonon corresponds to the initial longitudinal polarization [3]. Accordingly, following the release of the initial polarization, the coherent LO phonon emits a terahertz electromagnetic wave. Thus, the dynamically oscillating polarization due to the coherent LO phonon is directly observed in terahertz time-domain spectroscopy. This is advantageous because, in the pump-probe measurement, the motion of the coherent phonon is indirectly observed through the modulation of the dielectric function. In earlier work, we observed that (11*n*)-oriented GaAs/$In_{0.1}Al_{0.9}As$ strained multiple quantum wells (MQWs) emit an intense quasi-monochromatic terahertz wave from the coherent GaAs-like LO phonon through the release of piezoelectric fields in the GaAs well layers by photogenerated carriers [5]. Here, we settle an issue whether the terahertz-wave emission from the coherent GaAs-like LO phonon is affected by screening effects of high density photogenerated carriers.

In the present work, we investigated the screening effect of photogenerated carriers on the terahertz waves from the coherent GaAs-like LO phonons in the (11*n*)-oriented GaAs/$In_{0.1}Al_{0.9}As$ strained MQWs. We found that the amplitude of the terahertz wave from the coherent GaAs-like LO phonon increases as the orientation index approaches $n = 1$, which enhances the piezoelectric field. The Fourier transform spectra of the terahertz waveforms show an intense quasi-monochromatic band of the coherent GaAs-like LO phonon. We found that the integrated intensity of the coherent GaAs-like LO-phonon band tends to saturate with an increase in the pump power. We analyzed the saturation behavior in terms of the unit-power intensity corresponding to excitation efficiency of the terahertz wave.

2. Samples and Experimental Procedure

The present samples, the GaAs/$In_{0.1}Al_{0.9}As$ strained MQWs, were grown on (11*n*)-oriented semi-insulating GaAs substrates by molecular beam epitaxy. The orientation indices *n* were 2, 3, and 4. The MQW structure of each sample consisted of 20 periods of the 10-nm-thick GaAs well layer and 10-nm-thick $In_{0.1}Al_{0.9}As$ barrier layer. We simply refer the (11*n*)-oriented GaAs/$In_{0.1}Al_{0.9}As$ strained MQW as the (11*n*) MQW. We note that an $In_{0.1}Al_{0.9}As$ metamorphic buffer layer with a thickness of 1.0 μm was grown in each sample. Accordingly, only the GaAs layer is influenced by the biaxial stain resulting from the lattice mismatch between GaAs and $In_{0.1}Al_{0.9}As$. This biaxial strain produces the piezoelectric field in the GaAs layer. The lattice constants of GaAs and $In_{0.1}Al_{0.9}As$ are 0.5633 and 0.5701 nm, respectively [6]. Using these values, the biaxial tensile strain ε in the GaAs layer is calculated to be 0.84%. Consequently, the piezoelectric fields in the GaAs layers of the (112), (113), and (114) MQWs were calculated to be 144, 72, and 41 kV/cm, respectively, according to the theory in Ref. 7. We notice that the value of 144 kV/cm is about one-third of the breakdown electric field in GaAs [8]. The calculated piezoelectric field strength increases as the orientation index approaches $n = 1$. This is reasonable because the GaAs crystal has a polar axis along the [111] direction. The terahertz time-domain measurement was performed at room temperature, using a Ti:sapphire femtosecond pulse laser. The duration time and repetition of the laser pulse were about 50 fs and 90 MHz, respectively. The pump beam was focused on the sample with an incidence angle of 45°. The diameter of the beam spot on the sample surface was about 100 μm. The emitted terahertz wave was collected with the use of two off-axis parabolic mirrors, and was detected by an optically gated photoconductive dipole antenna with a gap of 6.0 μm formed on a low-temperature-grown GaAs layer. The peak photon energies of the pump and probe beams were the same value: 1.55 eV. We used a purge of dry nitrogen gas and kept the humidity being ~5% to suppress the noise arising from the absorption of water vapor. The details of the experimental setup are described in Ref. 9.

3. Experimental Results and Discussion

Figure 1 shows the terahertz waveform of each sample at a pump power of 70 mW. The bipolar pulse, which originates from the ultrafast current of the photogenerated carriers [10], appears around the time delay of 0 ps. The bipolar pulse accompanies with the long-lived oscillating pattern with a period of 115 fs. Note that the oscillation amplitude increases with the change in the orientation index toward to $n = 1$. In order to analyze the terahertz waveform, we applied the Fourier transform to the terahertz waveform. The Fourier power spectrum of each sample is shown in Fig. 2. The negligibly weak signal in the frequency range from 0 to 5 THz originates from the bipolar pulse around the time delay of 0 ps. In the frequency range from 8 to 10 THz, the intense sharp band, which has a peak at the frequency of 8.7 THz, appears in each sample. This band is attributed to the coherent GaAs-like LO phonon. The peak frequency of the GaAs-like LO phonon band is about 0.1 THz lower than the LO-phonon frequency (8.8 THz) in a GaAs single crystal. The value of the 0.1 THz corresponds to the biaxial strain of about -0.9% because the strain-induced frequency shift $\Delta\omega$ of the GaAs-like LO phonon is in the following relation with ε: $\Delta\omega \cong -11\varepsilon$ (THz) [11]. This phenomenon indicates the presence of the biaxial tensile strain in the GaAs layer. The intensity of the coherent GaAs-like LO-phonon band is markedly increased as the orientation index approaches $n = 1$. Since the approach of *n*

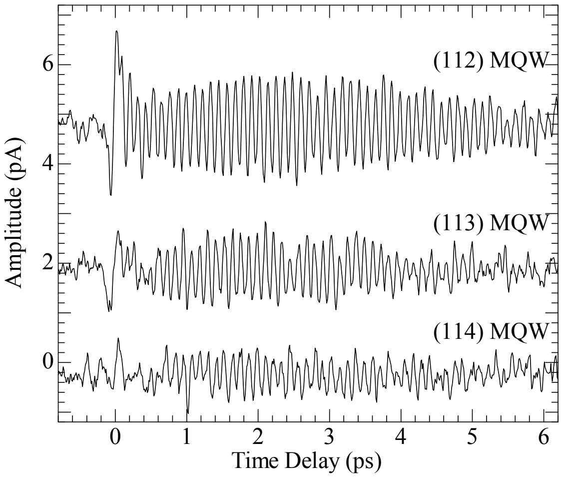

Figure 1: Amplitudes of the terahertz waveforms of the (114), (113), and (112) MQWs as a function of time delay at room temperature. For clarity, each waveform is vertically shifted.

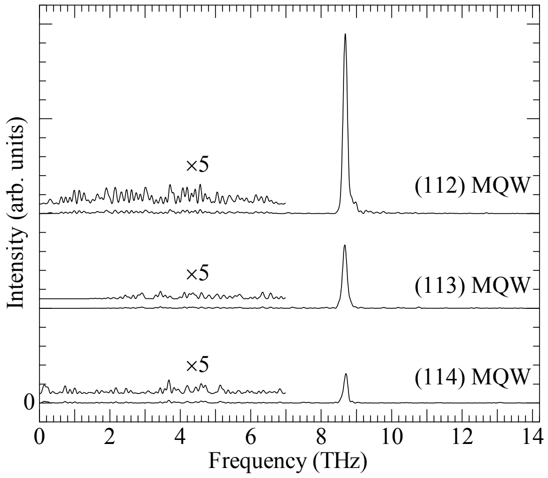

Figure 2: Fourier power spectra of the terahertz waveforms shown in Fig.1.

to 1 causes the enhancement of the piezoelectric field, the increase in the intensity of the coherent GaAs-like LO-phonon band originates from the piezoelectric field enhancement, which enlarges the initial polarization of the coherent GaAs-like LO phonon.

In order to investigate how the screening effect influences the coherent GaAs-like LO phonon, we measured the terahertz waves from the (11*n*) MQWs at various pump powers. Figure 3 shows the integrated intensity of the coherent GaAs-like LO-phonon band as a function of pump power P_{pump}. The integrated intensity monotonically increases with an increase in the pump power; however the pump-power dependence exhibits a saturation behavior. We evaluated the saturation behavior as follows. The intensity of the coherent GaAs-like LO-phonon band I_{LO} is proportional to the square of pump power in principal [12]. Thus, we introduce the parameter of the unit-power density defined as $I_{\mathrm{LO}}^{\mathrm{unit}} = I_{\mathrm{LO}}/P_{\mathrm{pump}}^2$. The unit-power intensity corresponds to the excitation efficiency of the terahertz wave from the coherent LO phonon. In Fig. 4, we plotted the unit-power intensity of each sample as a function of pump power. The unit-power intensity monotonically decreases with an increase in the pump power in each sample. The increase in the pump power leads to an increase in photogenerated

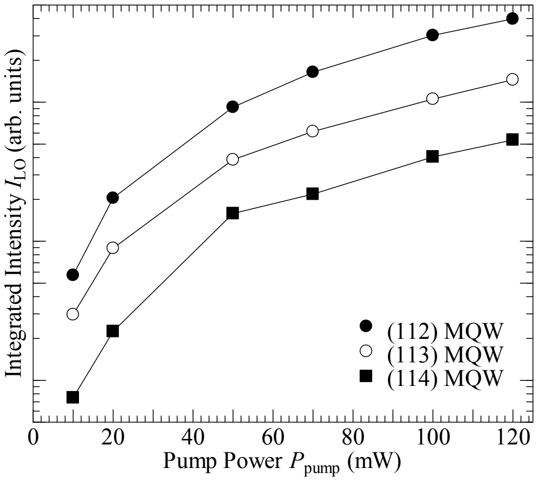

Figure 3: Integrated intensity of the coherent GaAs-like LO-phonon band as a function of pump power. The solid lines are the guides for eyes.

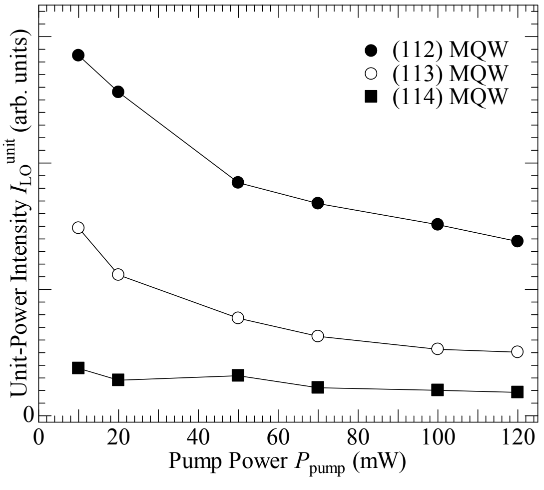

Figure 4: Unit-power intensity of the coherent GaAs-like LO-phonon band as a function of pump power. The solid lines are the guides for eyes.

carriers the GaAs layer, which results in enhancement of the Coulomb screening effect on the piezoelectric field. In other words, the Coulomb screening effect lowers the piezoelectric field, which reduces the initial polarization of the coherent GaAs-like LO phonon. Consequently, the Coulomb screening is attributed to the origin of the saturation behavior of the pump-power dependence of the coherent GaAs-like LO-phonon intensity in the $(11n)$ MQWs.

4. Summary

We have investigated the screening effect of photogenerated carriers on the terahertz radiation from coherent GaAs-like LO phonons in the $(11n)$-oriented GaAs/$In_{0.1}Al_{0.9}As$ strained MQWs. We have observed the intense quasi-monochromatic terahertz wave from the coherent GaAs-like LO phonon, the initial polarization of which is enhanced by the strong piezoelectric field. The intensity of the coherent GaAs-like LO-phonon band exhibits a saturation behavior with an increase in the pump power. We have evaluated the excitation efficiency of the terahertz wave from the coherent GaAs-like LO phonon with the use of the unit-power intensity. From the pump-power dependence of the unit-power intensity, we conclude that the considerable screening effects of high-density photogenerated carriers on the piezoelectric field cause the saturation of the intensity of the terahertz wave from the coherent GaAs-like LO phonon.

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