Acoustic phonon pulse generation and detection in GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells

Takehiro Tachizaki[1], **Osamu Matsuda**[1], **Takashi Fukui**[2], **Jeremy J. Baumberg**[3], and **Oliver B. Wright***[1]

[1] Department of Applied Physics, Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan
[2] Research Centre of Integrated Quantum Electronics, Hokkaido University, Sapporo 060-8628, Japan
[3] School of Physics and Astronomy, University of Southampton, SO17 1BJ, Southampton, UK

Received 15 November 2002, revised 30 November 2002, accepted 2 December 2002
Published online 3 December 2002

Key words Semiconductor nanostructure, photoacoustic effect, ultrafast optical measurement.
PACS 78.20.Hp, 78.47.+p, 78.67.De, 78.66.Fd

Acoustic phonon pulse generation and detection are investigated in a sample with three embedded GaAs/AlGaAs quantum wells by an ultrafast optical pump and probe technique at the temperatures 20 K and 300 K. Scanning the pump photon energies around the $hh1$-$e1$ resonances we find a strong variation of the transient reflectance and phase changes. These changes are compared with a numerical simulation based on probe light scattering due to the inhomogeneous photoelastic effect.

1 Introduction

The generation of picosecond acoustic phonon pulses in semiconductor nanostructures with ultrashort light pulses is of practical and theoretical importance because of 1) the possibility of producing high frequency THz acoustic phonons and 2) the close relationship between the phonon pulse shape and the confined electron and hole wavefunctions [1, 2]. We present here a spectroscopic study of acoustic phonon generation and detection in a GaAs/AlGaAs quantum well nanostructure by the use of a two-colour interferometric pump and probe technique for monitoring reflectance and phase changes. The results are analysed by a theory based on light scattering in a multilayer at normal optical incidence perturbed by acoustic waves therein [3].

2 Experiment and Results

2.1 Experimental Setup

A GaAs/$Al_{0.3}Ga_{0.7}As$ quantum well structure was prepared on a GaAs (100) substrate by MOVPE (metalorganic vapour phase epitaxy). GaAs quantum wells of three different thicknesses were incorporated at depths $\sim$ 300 nm, 350 nm and 450 nm respectively. At 20 K their *hh*1-*e*1 transition energies are 1.515 eV, 1.479 eV, and 1.562 eV, corresponding to GaAs thicknesses 4.5 nm, 7.6 nm and 3.1 nm, respectively. A cap layer of GaAs of thickness 10 nm is also deposited.

We use a dual mode-locked pulsed laser system that allows independent control of the pump and probe photon energies. Energy-tunable pump light pulses in the photon energy range 1.43 eV to 1.59 eV, duration

* Corresponding author: e-mail: assp@kino-ap.eng.hokudai.ac.jp, Phone: +81 11 706 6625, Fax: +81 11 716 6175

1.5 ps (at full width at half maximum), and repetition rate 82 MHz were used to generate longitudinal acoustic phonon pulses in the quantum wells. The energy of the probe light pulses was fixed at 3.06 eV for ease of data analysis. The pump light was focused onto the sample surface with a spot radius $\sim$ 20 μm and with fluence $\sim$0.04 mJcm^{-2}. A common-path interferometer was used to probe the transient reflectance changes $\delta r/r$ (a complex quantity)[4]. The temperature of the sample, fixed in a cryostat, was kept at either $\sim$20 K or 300 K. Low temperatures favour phonon propagation because of the lower ultrasonic attenuation is expected. In addition, the isolation of the sample in a vacuum minimizes the degradation of the sample surface, in particular in the irradiated area. The temperature of the sample at 20 K was estimated by photoluminescence measurements of the GaAs substrate when pumped by a continuous wave laser.

In spite of the electronic synchronization of the two lasers used, the measured waveforms exhibit up to $\pm$5 ps of jitter. In order to compensate for this we incorporated a cross-correlator containing a BBO (β-barium borate) crystal and an optical path scanning system. This improved the time resolution to $\sim$ 1.5 ps.

2.2 Experimental Results

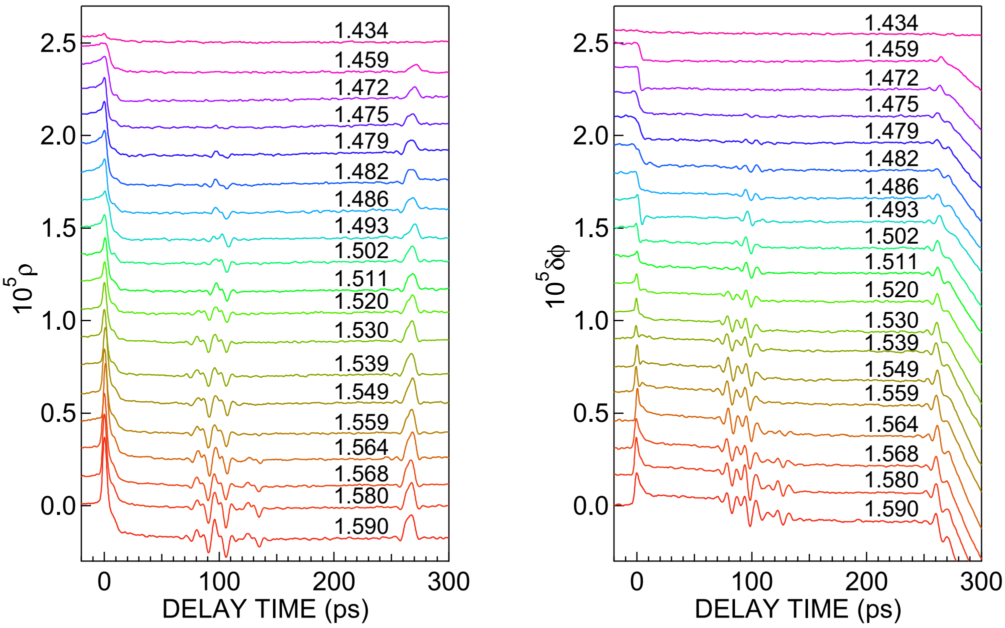

Fig. 1 Real (ρ) and imaginary ($\delta\phi$) parts of the complex reflectance change at pump photon energies from 1.432 to 1.589 eV at 20 K. Waveforms are shifted vertically for clarity.

Experimental results at 20 K for the real (ρ) and the imaginary ($\delta\phi$) parts of the relative reflectance change $\delta r/r$ as a function of delay time are shown in Fig. 1 for various pump photon energies from 1.434 eV to 1.590 eV. The features at around 100 ps and after 250 ps are due to the acoustic phonon pulses arriving at the sample surface from the quantum wells and from the GaAs substrate, respectively. The downward step in the phase change $\delta\phi$ after the reflection of the phonon pulse from the sample surface that takes place between 50 ps and 150 ps is a result of the sample surface bulging out. A change $\sim 10^{-6}$ in $\delta\phi$ is equivalent to a surface displacement of 0.03 pm. For example, the total outward displacement of the sample surface is 0.036 pm when three quantum wells are excited by a 1.590 eV pump light pulse. The excitation-photon energy dependence of the features around 100 ps in ρ and $\delta\phi$ can be explained by the selective excitation of phonon pulses in the quantum wells of different width.

3 Discussion

Numerical simulations were carried out taking account of the longitudinal acoustic phonon generation, propagation, and detection processes in the sample. The phonon pulses are generated in the quantum wells through the deformation potential and the thermal expansion mechanisms. The spatial distribution of the generated acoustic strain in the depth direction depends on the photon-induced distribution of nonequilibrium electrons and holes and on the lattice temperature rise due to carrier energy relaxation.

The phonon propagation is calculated from the one-dimensional elastic wave equation taking into account multiple acoustic reflections, although their effect is not significant (the strain reflectance at each interface is ∼6 %). Frequency-dependent ultrasonic attenuation is taken into account in the model using $\alpha = bf^2$, where α is the ultrasonic absorption coefficient, f is the ultrasonic frequency, and b is a constant coefficient. A value of b=35 $m^{-1}GHz^{-2}$ is adopted for the $Al_{0.3}Ga_{0.7}As$ barrier layer. This value is essentially the same at 20 K as at 300 K because α is dominated by alloy scattering rather than by phonon-phonon scattering. We took $b = 0$ for the ultrasonic absorption coefficient of GaAs because the quantum wells are too thin to attenuate acoustic phonon pulses significantly.

The theory of the detection process we adopt is based on light scattering through the photoelastic effect in the top two layers as well as on transient surface and interface displacements [3]. Defining the dielectric constant of the GaAs cap layer (of thickness defined here as d) as ε_1 and that of the top AlGaAs barrier layer as ε_2, the relative reflectance change, $\delta r(t)/r$, can be written as follows:

$$\frac{\delta r(t)}{r} = \frac{ik_0}{2a_0b_0}\left\{\int_0^d \Delta\varepsilon_1(z',t)\left[a_1e^{ik_1z'} + b_1e^{-ik_1z'}\right]^2 dz' + \int_0^\infty \Delta\varepsilon_2(z'+d,t)a_2^2e^{i2k_2z'}dz' \right.$$
$$\left. + (a_1+b_1)^2\left[1-\epsilon_1\right]u(0,t) + a_2^2\left[\epsilon_1-\epsilon_2\right]u(d,t)\right\}, \tag{1}$$

where a_i, b_i are given by the transfer matrix method:

$$a_0 = (k_0+k_1)(k_1+k_2) + (k_0-k_1)(k_1-k_2)e^{i2k_1d} \tag{2}$$
$$b_0 = (k_0-k_1)(k_1+k_2) + (k_0+k_1)(k_1-k_2)e^{i2k_1d} \tag{3}$$
$$a_1 = 2k_0(k_1-k_2) \tag{4}$$
$$b_1 = 2k_0(k_1-k_2)e^{i2k_1d} \tag{5}$$
$$a_2 = 4k_0k_1e^{ik_1d} \tag{6}$$

Here k_0, $k_1 = \sqrt{\varepsilon_1}k_0$ and $k_2 = \sqrt{\varepsilon_2}k_0$ are the wave numbers in vacuum, in the GaAs cap layer, and in the top AlGaAs barrier layer, respectively, $u(0,t)$ is the surface displacement, and $u(d,t)$ is the cap-barrier interface displacement. The changes in dielectric constants in the GaAs cap or AlGaAs barrier layer in Eq. (1) are related to the strain η_{zz} through $\Delta\varepsilon_i = 2\tilde{n}_i(d\tilde{n}_i/d\eta_{zz})\eta_{zz}$, with refractive indices $\tilde{n}_i$, where $i = 1$ is for GaAs and $i = 2$ is for AlGaAs.

The numerical simulation together with representative experimental results are shown in Fig. 2. Figure 2(a) shows the results for a pump energy of 1.590 eV at 20 K and Fig. 2(b) shows those for 1.674 eV at 300 K. The solid and dashed lines correspond to experiment and simulation, respectively. The agreement between these is very good except for the sharp signal around 0 ps and the decay immediately following this time. This disagreement is due to the initial ultrafast electron relaxation and subsequent temperature rise not taken into account in the model. Important fitting parameters are the photoelastic constants $d\tilde{n}/d\eta_{zz}$ of GaAs and AlGaAs at the probe wavelength and the effective extinction coefficients [Im($\tilde{n}$)] of each quantum well at the pump wavelength. These fitted extinction coefficients are plotted in Fig. 3(a) as a function of excitation photon energy for 20 K. Figure 3(b) shows the corresponding effective extinction coefficients derived for 300 K.

The spectra of effective extinction coefficients plotted in Fig. 3(b) indicate that one can control the phonon generation in the quantum wells by tuning the excitation photon energy. The blue shift of the spectra at 20 K compared to those at 300 K (shown in Fig. 3) can be qualitatively explained by the temperature dependence of the band gap of GaAs. The absence of exciton peaks may be due to interface roughness in the sample or to an insufficient experimental energy resolution.

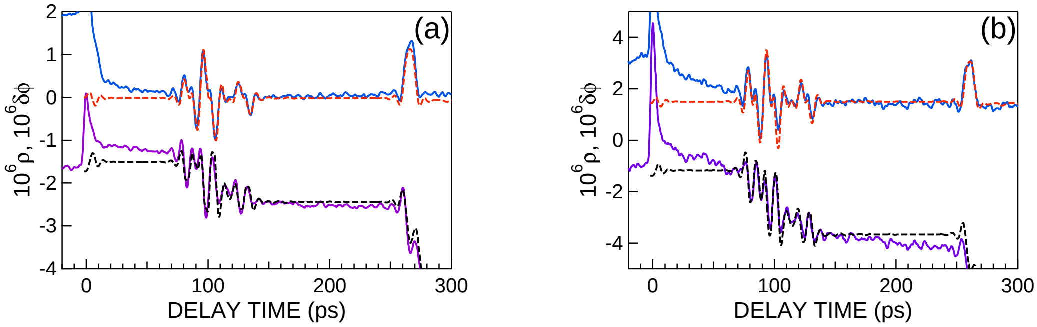

Fig. 2 Typical experimental results compared with numerical simulations. The solid and dashed lines are experiment and simulation, respectively. (a) is for 1.590 eV pump at 20 K and (b) is for 1.674 eV pump at 300 K.

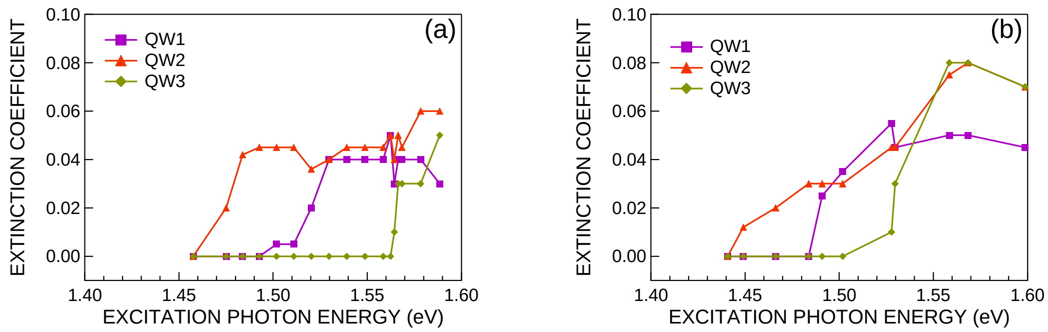

Fig. 3 Fitted effective extinction coefficients for each quantum well as a function of excitation photon energy. (a) is for 20 K (b) is for 300 K.

4 Conclusion

In conclusion, we have investigated picosecond acoustic phonon pulse generation and detection in semiconductor quantum wells at 300 K and 20 K. Good agreement is obtained between experiment and theory for the detected pulse shapes at both these temperatures. The pump photon energy dependence of the generated acoustic phonon pulses indicates that one can control the acoustic phonon generation in such samples. Tailored electronic band structures such as the one used here should in future allow the flexible design of high frequency acoustic transducers.

References

[1] J. J. Baumberg, D. A. Williams, and K. Köhler, Phys. Rev. Lett. **78**, 3358 (1997).
[2] O. Matsuda, I. Ishii, T. Fukui, J. J. Baumberg, and O. B. Wright, Physica B **316-317**, 205 (2002).
[3] O. Matsuda and O. B. Wright, J. Opt. Soc. Am. B **19**, 3028 (2002).

[4] D. H. Hurley and O. B. Wright, Opt. Lett. **24**, 1305 (1999).
[5] W. Chen, H. J. Maris, Z. R. Wasilewski, and S. Tamura, Philos. Mag. B **70**, 687 (1994).