Coherent phonons in a doped GaAs/AlAs superlattice

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Abstract. In this paper we report the excitation and detection of coherent zone-folded longitudinal phonons in a \textit{n}-doped AlAs/GaAs superlattice using femtosecond pump-probe measurements. Oscillations in the probe reflectance were observed at a frequency of about 440 GHz, which is the frequency of the first mini-zone centre phonon mode. By applying an electrical bias across the superlattice, the intensity of the oscillations was increased when the energy drop per period of the superlattice was approximately equal to the energy of the first mini-zone centre mode. We attribute this observation to phonon amplification occurring in the superlattice.

1. Introduction

Previously, a resonance in the acoustic phonon emission from a weakly-coupled AlAs/GaAs superlattice (SL) was observed when the applied bias was such that the energy drop per period of the SL, $\Delta$, was the same as the energy of the first mini-zone centre folded phonon mode [1]. This resonance was attributed to phonon amplification by stimulated emission occurring in the hopping electron transport regime, as predicted theoretically [2, 3], see figure 1. As well as providing the gain, the SL also acts as an acoustic cavity for mini-zone boundary modes of frequency $\nu = n c_s / d_{SL}$, where $c_s$ is the velocity of sound in the SL; $d_{SL}$ is the superlattice period and $n$ is an integer. In effect, the device

![](image)

\textbf{Figure 1.} (a) Schematic representation of phonon amplification by stimulated emission in a weakly-coupled SL in the phonon-assisted hopping conduction regime. (b) Electron energy dispersion for two neighbouring wells showing the phonon-assisted (stimulated emission) transition that is characterised by population inversion [2].
appeared to be operating like a distributed feedback saser. However, in that experiment, bolometers were used to detect the emitted phonons and so it was not possible to determine conclusively that *coherent* phonon amplification was occurring in the SL.

Femtosecond pump-probe measurements are ideal for studying coherent phonons in SLs [4 – 6]. In the reported experiments, coherent zone-folded longitudinal acoustic (LA) phonons were excited by an intense femtosecond pump pulse and detected by measurement of the reflectance of a time-delayed probe pulse. Phonon-induced oscillations of the probe reflectance as a function of the delay time were observed. The period of the oscillations corresponded to the first mini-Brillouin zone centre mode for longitudinal phonons at $\nu \approx c/s_{SL}$.

In this paper we use femtosecond pump-probe measurements to study coherent phonons in a doped SL with the same structure as the one used in Ref. [1], and also investigate the effect of applying a DC bias to the SL.

2. Experimental details

The experimental device, figure 2, was based on a 50-period GaAs/AlAs SL grown by molecular beam epitaxy on a 0.4 mm-thick semi-insulating GaAs substrate. Each period consisted of a nominally 5.9 nm-thick GaAs well and a 3.9 nm-thick AlAs barrier, uniformly $n$-doped with Si to a density of $2 \times 10^{22}$ m$^{-3}$. The SL was separated from the $n^+$ ($2 \times 10^{24}$ m$^{-3}$) contact regions by 20 nm-thick undoped GaAs spacer layers. A 400 $\mu$m-diameter optical device mesa was formed by etching and contacts with the emitter and collector layers made using GeAuNiAu, alloyed at 360 C. The device was characterized at temperature $T = 4.2$ K by measuring its DC current-voltage characteristics, shown in figure 3. The device turns on at the threshold bias voltage, $V_T \approx 35$ mV which is the bias required to align the Fermi energy of the emitter and the nearest well. After that, the current increases monotonically for biases up to about 240 mV. Fluctuations of the current with applied bias larger than 240 mV indicate the formation and growth of electric field domains within the sample [7]. For measurements made at bias voltages, $V_b$, between $V_T$ and 240 mV it is reasonable to assume the variation of electric field along the structure is uniform. In this case, the electron energy drop per period of the SL is given by $\Delta \approx e(V_b - V_T)/50$.

A standard pump-probe setup, based on an 82 MHz tuneable femtosecond oscillator emitting 70 fs pulses, was used for the measurements. The beam was split, with 90% of the intensity going to the pump and 10% to the probe. An optical chopper disc was used to modulate the pump beam which was then focussed to a spot on the mesa of diameter $\approx 200 \mu$m, and fluence of approximately $2 \times 10^{-2}$ mJ.

![Figure 2](image-url) **Figure 2.** Sample arrangement for pump-probe measurements on a doped SL under bias.

![Figure 3](image-url) **Figure 3.** DC current-voltage characteristics of device
cm$^2$. The probe was passed through an optical delay line and then focused onto the mesa. A photodiode was used to detect the reflected probe beam. Using a lock-in amplifier referenced to the chopper frequency (~ 700Hz), changes in the probe reflectance due to the pump could be measured. Measurements were made with the sample in an optical cryostat at $T \approx 10$ K and the laser was tuned to resonance with the fundamental gap of the SL, $h\nu = 1.63$ eV ($\lambda = 763$ nm).

3. Results and discussion

Figure 4 shows the pump-induced change in the probe reflectance as a function of the pump to probe delay time for zero bias applied to the SL. Clear phonon-induced oscillations are observed superimposed on the decaying tail (see inset) of the dominant signal due to the photoexcited carriers. The period of the oscillation is about 2.3 ps, which corresponds to a phonon frequency of 440 GHz. This agrees well with the calculated frequency of the first mini-zone centre mode of the SL. The characteristic time for the oscillations to decay can be estimated from the data as about 30 ps. This is shorter than typically found for similar undoped SLs [4 - 6], which is probably due to increased phonon scattering by free electrons and ionized donor impurities.

Figure 5 shows the Fourier power spectrum of the pump-probe signal at zero bias shown in Figure 4, and for an applied bias of 123 mV. Before taking the Fourier transform, the signals were low-pass filtered to remove the strong components below 100 GHz. The component due to the coherent phonons at about 440 GHz is increased when the bias is applied. No such increase was seen at biases of 140 mV and 110 mV. At a bias of 123 mV, the energy drop per SL period is 1.8 meV, which is almost exactly equal to the energy of the 440 GHz SL phonon mode. This increase in the magnitude of the coherent phonon oscillations would appear to be evidence for coherent phonon amplification occurring in the biased SL. Qualitatively, we can understand this as follows: the coherent phonons excited in the SL by the femtosecond light pulse stimulate the interwell electron hopping processes, as shown in Figure 1 (a). In order to conserve energy in the transitions, phonons are emitted. The emitted phonons are in phase with the original laser-excited modes and so add coherently to the amplitude of the acoustic oscillations in the probe reflectance. As shown in Figure 1 (b), the necessary population inversion with respect to phonon-induced interwell transitions is achieved when a current is flowing in the device and the energy drop per period of the SL is nearly equal to the phonon energy.

We should also consider the possibility that the application of bias modifies the carrier dynamics in the SL in a way which affects the probe reflectance. This could change the sensitivity of the measurement and lead to the increased intensity of the oscillations. It is certainly the case that the height of the step at zero pump-probe time delay is slightly increased when bias is applied to the device. However, the height of the step depends monotonically on the applied bias, and, if the increase of the acoustic oscillations was due to the same process, we might expect them to depend on bias in the same way. However, we can dismiss this possibility because the acoustic oscillations only show a significant increase of intensity at the “resonant” bias of 123 mV.
4. Conclusions
Using femtosecond pump-probe measurements we have observed 440 GHz coherent zone-folded LA phonons in a doped GaAs/AlAs superlattice. The phonon-induced oscillations in the probe reflectance decayed more rapidly than is typical in undoped SLs, and this is probably due to increased phonon scattering in the doped structure. Application of a DC bias, such that the energy drop per period of the SL was equal to the energy of the coherent phonons led to an increase in the magnitude of the phonon-induced oscillations. We attribute this to coherent phonon amplification occurring in the SL under resonant bias.

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