QThI2

Coherent hybrid modes in the THz emission from InAs and InSb

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When confined to a dimension much smaller than their characteristic wavelength, coupled longitudinal modes of polar semiconductors can radiate.[1] We impulsively excite coherent, collective modes of bulk InAs and InSb using 30 fs near-infrared laser pulses and detect the emitted THz frequency radiation by using a bolometer and the broadband interferometric technique of Ref. [2]. All our results are insensitive to excitation power and crystal orientation.

In Fig. 1a we show an interferogram obtained with a slightly n-type ($N = 2.4 \times 10^{16}$ cm^{-3}) InAs (100) sample at room temperature. The strong peak at zero delay corresponds to the near-instantaneous polarization signal caused by screening of the surface field by the photocarriers. At larger absolute delay, we observe two distinct oscillation periods resulting from the coherent, coupled plasmon-phonon system. The Fourier transform of the time-resolved signal is displayed in Fig. 1b, revealing a broad plasma peak at 2.1 THz and a weaker peak at 7.3 THz, which is very close to the bare LO phonon frequency. The location of these spectral peaks corresponds exactly with values calculated assuming a nonparabolic conduction band appropriate for narrow-gap semiconductors.[3] When the electron density is increased to $N = 2.2 \times 10^{17}$ cm^{-3} by donor doping, we obtain the data shown in Figs. 1 c-d. The plasma peak shifts to higher frequency (5.2 THz) due to the higher density donor ion-electron plasma. Comparing Figs. 1b and 1d, we see a spectral shift of the upper hybrid mode (phonon mode) to 8.4 THz (dotted vertical line for reference), in complete agreement with calculations for the longitudinal mode frequencies of this system. We also note the pronounced increase in the spectral weight of the phonon mode as the plasma mode moves into closer proximity, a characteristic of radiation from the coupled electronic-lattice system predicted in Ref. [1].

Data obtained with room temperature (111) InSb is presented in Fig. 2. The time domain signal for an intrinsic sample ($N = 2 \times 10^{16}$ cm^{-3}) is shown in Fig. 2a. The spectrum in Fig. 2b reveals a broad peak at ~2.5 THz due to coherent plasma oscillations and a second peak at 6 THz arising from coherent LO phonons. These measured peaks are in good agreement with the calculated values of 2 THz and 5.6 THz. For InSb donor doped to a density of $N_D \approx 4 \times 10^{17}$ cm^{-3}, the plasma frequency moves above the bare phonon frequency and strongly damped, poorly resolved hybrid modes are found (Fig. 2 c-d). The high frequency peak at 8.3 THz in Fig. 2d corresponds to the plasmon mode of the system.

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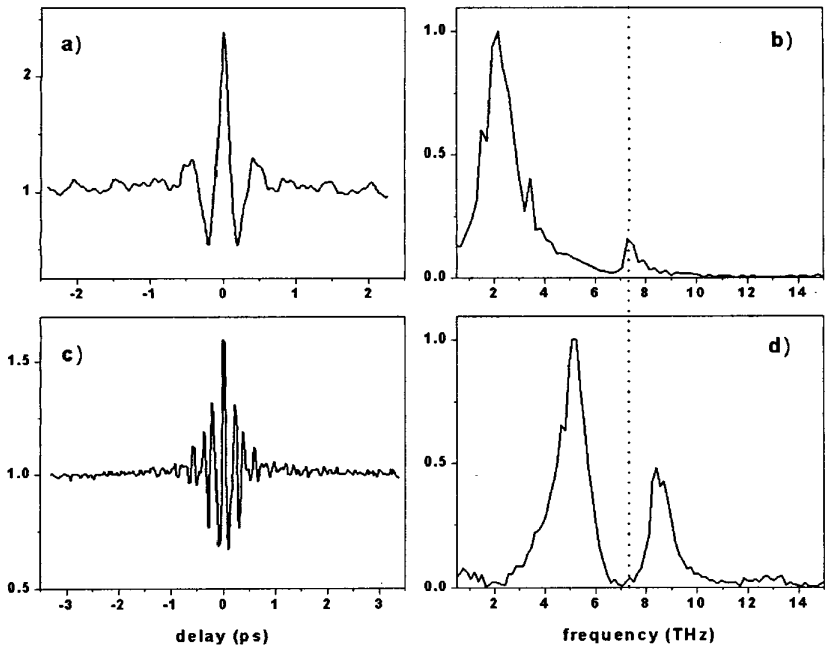

QThI2 Fig. 1. Time-resolved interferometric signal (a) and Fourier transform (b) of terahertz radiation emitted by bulk, intrinsic InAs ($N = 2.4 \times 10^{16}$ cm^{-3}); Data from donor doped sample ($N = 2.2 \times 10^{17}$ cm^{-3}) is shown in (c) and (d). Bare LO phonon frequency indicated by dotted vertical line.

QThI3

Observation of Coherent Acoustic Phonon Oscillations in Bulk Gallium Nitride

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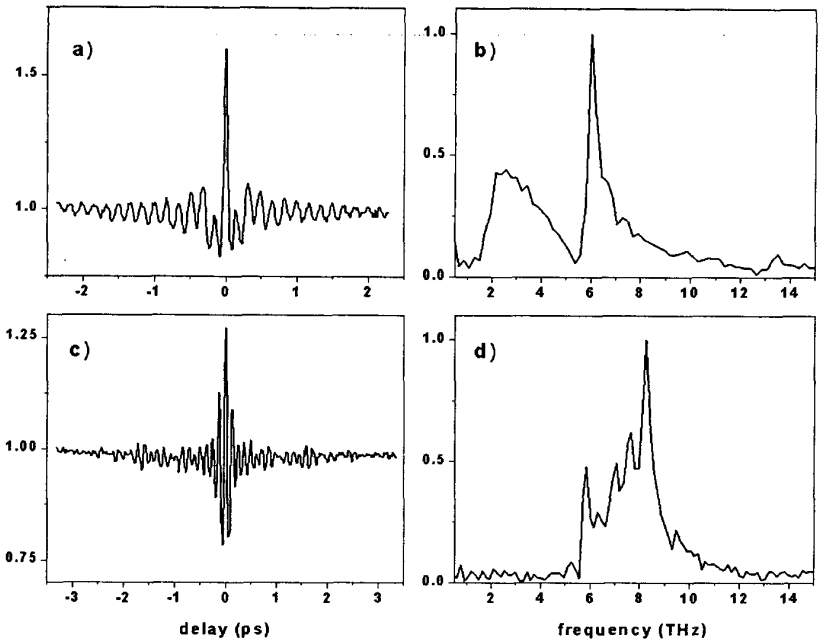
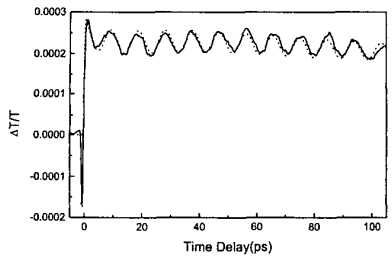
Progress in femtosecond lasers and ultrafast spectroscopy technology has enabled us to generate and directly observe the coherent oscillation of phonon modes. Coherent optical phonon oscillations have been observed in bulk GaAs,[1] bulk Ge, and a number of other bulk materials.[2] For *acoustic* phonons, it is much harder to selectively excite a specific coherent acoustic phonon mode in bulk materials. Higher frequency coherent acoustic phonon oscillations were recently observed in AlAs/GaAs superlattices,[3] InGaN/GaN multiple-quantum-wells,[4] and PbTe/PbS quantum dots.[5] In this presentation, we report our observation of high frequency coherent acoustic phonon oscillations in a bulk material, a highly strained bulk GaN film. The longitudinal interference of an ultraviolet femtosecond pump pulse was used to create periodic carrier distribution in the bulk GaN thin film. The periodic carrier distribution screened out the strain-induced piezoelectric field and initiated the coherent acoustic phonon oscillations corresponding to the carrier periods. The decay time of the initiated coherent phonon oscillation is longer than 250 ps. This long decay time and the traveling wave nature of the generated acoustic phonons provide the hope for the realization of the first phonon laser.

The experiments were performed at room temperature on a 0.45 μm-thick strained GaN thin film on top of an 1.4 μm-thick $Al_{0.05}GaN$ substrate. Room temperature PL measurements indicated 3.42 eV (362 nm) bandgap energy for the GaN layer and 3.53 eV bandgap energy for the AlGaN substrate. Femtosecond pulses were generated using a Ti:sapphire laser. The pulse was then frequency doubled by a BBO crystal of 0.5mm thick to reach an energy level that is close to the band gap energy of the bulk GaN sample, which is in the UV wavelength range. The measurements were performed with a standard transmission type pump-probe technique. A series of measurements with different below bandgap wavelengths, from 362nm to 390nm, were recorded. A typical transient transmission response at 390 nm was shown in Fig. 1. Large coherent acoustic phonon oscillation was observed. With spacing between interference patterns of 75 nm, the observed oscillation frequency of 106 GHz corresponds to a longitudinal sound velocity in bulk GaN of ~ 7980 m/s. The comparison experiment in a bulk GaN thin film without AlGaN substrate shows no obvious acoustic phonon oscillation, indicating the important of the strain-induced piezoelectric field in the initiation of the coherent oscillation. According to our fitting (dotted line in Fig. 1), the decay time of the acoustic oscillation in Fig. 1 is ~ 270 ps. This increase of decay time supports our previous hypothesis[4] that the coherent phonon oscillation decay time is not only dominated by phonon lifetime but is also strongly affected by dephasing be-



QThI2 Fig. 2. Terahertz emission data for intrinsic (a-b) and n-doped InSb (c-d). The intrinsic electron-hole plasma density is $N = 2 \times 10^{16}$ cm^{-3} and for the doped sample $N = 4 \times 10^{17}$ cm^{-3}.



QThI3 Fig. 1. Observed acoustic phonon oscillation in a bulk GaN sample.

tween different oscillators. In bulk GaN, the photoexcited carriers occupy a much larger area longitudinally compared with our previous MQW samples and a smaller uncertainty in wavevector was thus achieved, which induces acoustic phonons within a narrow frequency distribution. This narrower phonon distribution results in less dephasing and a long decay time is thus achieved. Due to the nature of the bulk sample, the generated coherent acoustic phonons in the bulk GaN sample are hypersonic traveling phonons, which are the key components for hypersonic SASER (sound amplification by stimulation emissions of radiation). With a long decay time, our demonstration thus provides a possible direction toward the realization of the first ever SASER.

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QThI4

Coherent bulk and folded acoustic phonon oscillations in InGaN light-emitting diodes structure

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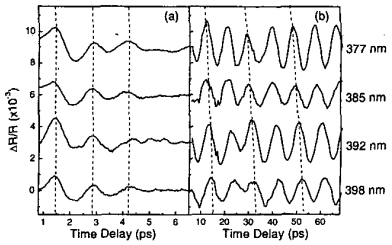
Recently, there has been much interests in InGaN/GaN multiple-quantum-well (MQW) structures due to their applicability as optoelectronic devices such as light-emitting diodes. (LEDs) and laser diodes.[1] Their ultrafast and physical properties are also of significant interests. Anomalously large acoustic phonon oscillations have been observed using ultrafast lasers in InGaN MQW's.[2]

In this study, we have performed femtosecond pump-probe experiments in the reflection geometry on 5 periods InGaN/GaN MQW LED structure with well width of 20 Å and barrier width of 100 Å.

Figure 1 shows the pump-probe signal as a function of probe delay for various pump wavelengths. Two types of oscillations exist: (a) short



QThI4 Fig. 1. Measured reflection changes as a function of probe time delay for InGaN/GaN MQW LED structure for various pump wavelengths. Acoustic folded phonon oscillations are observed in short time delay (a) and bulk phonon oscillations are observed in long time delay (b). Dashed lines are guide to the eye.

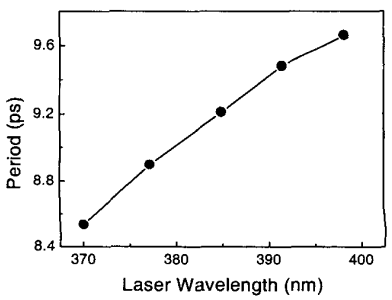
period oscillations which quickly disappear with time (Fig. 1a), and (b) long period oscillations with very long lifetime (Fig. 1b). It is very interesting to note that, for the short period oscillation, the period is independent of the pump wavelength. In contrast, the long period oscillations show a significant change in period: the longer the wavelength, the longer the oscillation period.

The short period oscillation has already been observed by Sun *et al.*, attributed to the folded acoustic phonon oscillation enhanced by strong piezoelectric field in this class of materials. The observed oscillation period of about 1.4 ps at pump wavelength of 398 nm roughly agrees with what is expected from the phonon velocity in InGaN.[2]

On the other hand, the long period oscillation, which is even stronger in amplitude than the short period oscillation, has never been observed in InGaN MQW. We note that the period of long oscillations are proportional to the pump beam wavelength (Fig. 2), which is consistent with the equation: $\tau = \lambda/2vn$, where λ is the pump beam wavelength, v the sound velocity, and n the refractive index.[3] We, therefore, attribute this strong, long period oscillation to the coherent phonons generated by the impulsive Brillouin backscattering.

We will also discuss electric-field dependence of these phonon oscillations.

In conclusion, we have observed folded acoustic phonon and bulk acoustic phonon simultaneously in InGaN/GaN MQW LED structure. The folded phonon oscillation is independent of pump beam wavelength but the bulk



QThI4 Fig. 2. Bulk phonon oscillation periods as a function of laser wavelength.