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Short Communication

Broadband terahertz ultrasonic transducer based on a laser-driven piezoelectric semiconductor superlattice

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ABSTRACT

Spectral characteristics of laser-generated acoustic waves in an InGaN/GaN superlattice structure are studied at room temperature. Acoustic vibrations in the structure are excited with a femtosecond laser pulse and detected via transmission of a delayed probe pulse. Seven acoustic modes of the superlattice are detected, with frequencies spanning a range from 0.36 to 2.5 THz. Acoustic waves up to ~2 THz in frequency are not significantly attenuated within the transducer which indicates excellent interface quality of the superlattice. The findings hold promise for broadband THz acoustic spectroscopy.

1. Introduction

Ultrasound is generally defined as acoustic waves at frequencies larger than ~20 kHz. The upper limit corresponds to phonon frequencies at the edge of the Brillouin zone, which, in most crystalline solids, lies in the THz range. Over the years, steady progress toward generating higher and higher frequencies has been made. Nowadays, piezoelectric thin film resonators generating acoustic waves at frequencies of a few GHz are ubiquitous in wireless communication devices, and frequencies up to 20 GHz have been achieved with this technology [1]. Piezoelectric generation in microwave cavities yielded frequencies up to ~100 GHz at cryogenic temperatures [2]. The use of femtosecond lasers for generation and detection of acoustic waves in thin films [3] extended the frequency range into hundreds of GHz and greatly expanded experimental capabilities due to the noncontact nature of laser-based measurements.

Semiconductor quantum well structures yielded a further expansion of the frequency range of laser-generated ultrasound [4–10], with frequencies over 1 THz becoming accessible. At these frequencies, the acoustic wavelength is typically in the single-digit nanometer range, and thus nanometer-scale interface roughness may significantly attenuate acoustic waves via diffuse scattering [7]. The key advantage of epitaxial semiconductor structures in accessing THz frequencies is excellent quality of single crystal layers and interfaces. While single quantum wells have been used to produce broadband acoustic pulses [8], superlattice (SL) structures comprising multiple quantum wells yield higher signal levels at well defined frequencies. The frequency of acoustic waves generated in a SL is determined by the periodicity of the structure, with the fundamental eigenmode frequency approximately equal to v/d, where d is the SL period and v speed of sound. Thus one way to achieve high acoustic frequencies is to reduce the SL period. For example, 1–1.2 THz acoustic waves were generated by InGaN/GaN [6] and GaAs/AlAs [10] SLs with period of ~5 nm.

In many cases, SL structures yield higher order acoustic modes at frequencies near harmonics of the fundamental frequency [5,9,10]. The amplitudes of higher harmonics were found to increase with a more asymmetric well:barrier width ratio [9]. If a large enough number of harmonics are generated, that will enable broadband spectroscopy with a single transducer structure. In acoustic spectroscopy, one rarely encounters sharp resonances, broad relaxation-type features being by far more common. Thus even a sparse coverage of a wide range by harmonic frequencies would suffice, for example, for studying the frequency-dependent phonon mean free path in most materials.

In this report, we will show that a GaN/InGaN multiple quantum well structure with a strongly asymmetric well-barrier width ratio can generate up to seven harmonics covering an extremely broad spectral range. We will also show that for frequencies up to ~2 THz, acoustic losses within the SL transducer structure are insignificant. The results hold promise for broadband acoustic spectroscopy covering a significant fraction of the Brillouin zone.

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2. Experiment

The sample, schematically shown in Fig. 1a, comprised 10 periods of 3 nm $In_{0.1}Ga_{0.9}N$/19 nm GaN quantum wells/barriers grown on a 2-μm-thick wurtzite GaN buffer layer on a sapphire substrate via metal organic chemical vapor deposition (MOCVD). The SL structure was capped with 150 nm of GaN deposited by the same method and 100 nm of amorphous silica (unrelated to the current study) deposited by sputtering.

Fig. 1b schematically shows the experimental arrangement. To generate and detect acoustic waves, we used frequency-doubled output of an amplified Ti:Sapphire system (wavelength 395 nm, pulse duration 300 fs, repetition rate 250 kHz), which was split into excitation and variably delayed probe pulses. The excitation beam (pulse energy 0.1 μJ) was modulated by an acousto-optic modulator at 93 kHz frequency to facilitate lock-in detection and focused to a spot of 90 μm diameter (at 1/e intensity level) at the sample. The probe beam (pulse energy 3.6 nJ) was focused to a 25 μm diameter spot at the center of the excitation spot. After passing through the sample, the probe beam was directed to a photodiode, whose output was fed into a lock-in amplifier. In order to spatially separate the transmitted beams, the angle of incidence was set to ~20° for the excitation beam and to normal incidence for the probe beam. This angle had no measurable effect on the measurement: the tilt of the excitation pulse corresponded to about 25 fs time difference across the probe spot diameter, which was insignificant compared to both the laser pulse duration and the period of the highest frequency acoustic mode observed.

Mechanisms of laser generation and detection of acoustic waves in InGaN/GaN SL structures have been described in detail previously [11]. The excitation pulse generates free carriers which screen the electric field associated with the static stress in the piezoelectric SL structure. The rapid change in stress yields a driving force that initiates coherent phonon oscillations. The oscillations modulate the effective optical constants of the SL structure, resulting in the observed changes in the transmission of the probe beam [11].

3. Results and discussion

The signal waveform shown in Fig. 2a is dominated by the step-like response due to electronic excitation of InGaN quantum wells. Subtracting the slowly varying background reveals acoustic oscillations dominated by the fundamental frequency of 365 GHz. The non-sinusoidal shape of the signal immediately indicates the presence of higher harmonics. We note the qualitative agreement of the signal waveform, with sharp maxima and smooth minima, with theoretical calculations for a similar asymmetric InGaN/GaN SL [11]. The oscillations decay as coherent phonon wavepackets leave the SL structure; if the acoustic impedance mismatch between quantum wells and barriers is small, the number of oscillations at the fundamental frequency is expected to be equal to the number of quantum wells in the structure, in agreement with the data.

The Fourier spectrum of the signal presented in Fig. 2b contains seven peaks spanning the frequency range up to 2.5 THz. Since the speed of light is much greater than the speed of sound, the excited phonon modes correspond to zero reduced wave number $q = 0$ in the reduced mini-Brillouin zone scheme shown in the inset in Fig. 2b. In modeling coherent phonon generation in InGaN/GaN superlattices with a low In content, it is normally assumed that acoustic impedances and velocities in quantum well and barrier layers are closely matched [11], which leads to a simple expression for the frequencies of the zone-center eigenmodes,

$$f_n = \frac{nv}{d}. \quad (1)$$

Given the acoustic velocity along the c-axis of GaN, $v = 8020$ m/s [12], and the period $d = 22$ nm, we obtain $f_1 = 365$ GHz which accurately matches the experimentally measured value. However, as

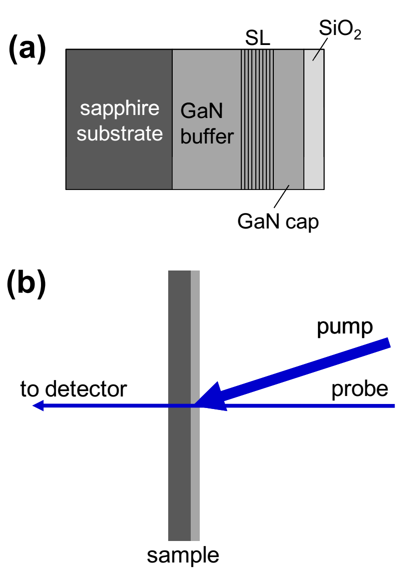

Fig. 1. (a) Schematic diagram of the SL structure (not to scale); (b) experimental arrangement.

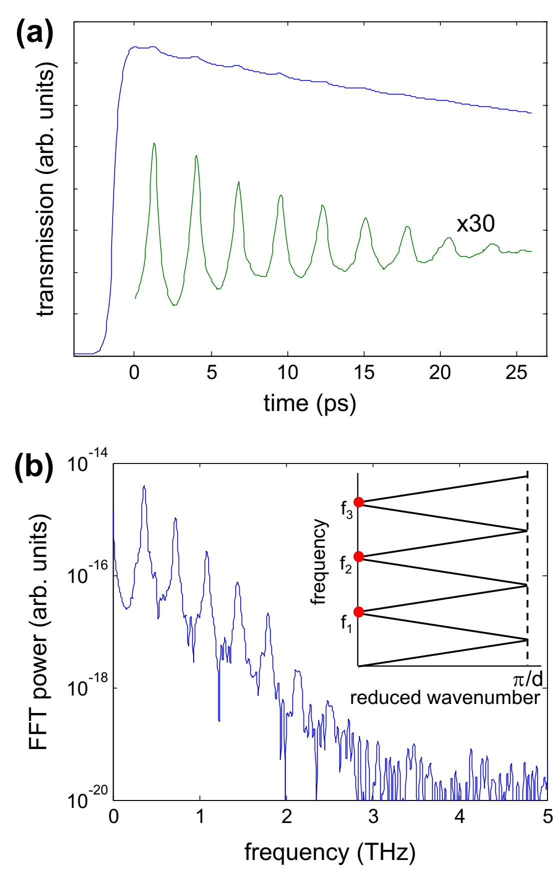

Fig. 2. (a) Measured signal waveform and acoustic oscillation trace obtained by multiplying the signal by a factor of 30 and subtracting the slowly varying background; (b) Fourier spectrum of the acoustic oscillations. The inset schematically shows dispersion curves of the periodic structure within the first mini-Brillouin zone; the first several laser-excited modes are shown by filled circles.