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Porte, Henrik; van Capel, P.J.S.; Turchinovich, Dmitry; Dijkhuis, J.I.

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High-amplitude THz and GHz Strain Waves, Generated by Ultrafast Screening of Piezoelectric Fields in InGaN/GaN Multiple Quantum Wells

H.P. Porte¹, P.J.S. van Capel², D. Turchinovich¹, and J.I. Dijkhuis²

¹DTU Fotonik - Department of Photonics Engineering, Technical University of Denmark, Ørstedts Plads 343, DK 2800 Kongens Lyngby, Denmark

²Debye Institute for Nanomaterials Science, Utrecht University, P.O. Box 80.000, 3508 TA Utrecht, the Netherlands
hpor@fotonik.dtu.dk

Abstract: Screening of large built-in piezoelectric fields in InGaN/GaN quantum wells leads to high-amplitude acoustic emission. We will compare acoustic emission by quantum wells with different thicknesses with photoluminescence; indicating screening.

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1. Introduction

Ultrafast screening of built-in piezoelectric fields in InGaN/GaN quantum well (QW) structures has been studied by THz optical [1] and strain [2] emission spectroscopy. In this work we will compare the generation of strain between samples with different QW thickness and photoluminescence (PL) measurements, providing information on the presence of an electric field in the QW.

2. Experiment and Results

For the generation of high amplitude strain, InGaN/GaN multiple quantum wells (MQW) with different QW thicknesses of 1.8, 2.7 and 3.6 nm were used. The MQWs represented 10 QWs separated by 7.2-nm thick GaN barriers. The MQW is sandwiched between a 180 nm GaN cap-layer and a 2 μm GaN buffer layer. This structure is grown on a sapphire substrate (Fig. 1(a)). A large strain-induced built-in piezoelectric field of 3.1 MV/cm in the QWs causes modification of the bandstructure via the quantum confined Stark effect. Upon excitation of carriers inside the QWs at 400 nm, with a frequency doubled Ti:Sapphire amplifier, ultrafast screening of the built-in piezoelectric field leads to the emission of THz radiation [1, 3]. Furthermore, the fast removal of the piezoelectric field results in a rearrangement of the atoms, giving rise to the generation of large strain waves. Due to symmetry two acoustic waves will be launched into the sample, traveling initially in opposite directions until one of the waves reflects at the surface. Pump-probe spectroscopy, where both the reflection and the transmission of a 400 nm probe is monitored for various pump-probe delay times is used to detect the strain waves in the material. The pump and probe beams are orthogonally polarized to allow for filtering out the pump light before the detectors.

Fig. 1: (a) Schematic picture of the multiple quantum well (MQW) sample. (b) Modulation of the absorption due to coherent vibration of the superlattice for the 1.8 nm MQW and a pump fluence of 25 mJ/cm^2 . (c) Spectrum of the oscillations shown in (b).

A decrease of the transient absorption for higher pump fluence is observed, which suggests that bleaching of the QWs takes place. The absorption change starts to saturate around a pump fluence of 2 mJ/cm^2 . At high fluences in the saturation regime, we observe fast oscillations in the transient absorption. The result for the 1.8 nm thick QW is shown in Fig. 1(b). These oscillations are caused by the high frequency vibration of the QW structure. A complicated beating pattern between different zone-folded acoustic phonon modes of the superlattice with a decay time of $\sim 15 \text{ ps}$ is observed. A Fourier transform of the trace in Fig. 1(b) shows the presence of zone-folded acoustic phonons with frequencies up to 1 THz (Fig. 1(c)).

For longer pump-probe delays, 100 GHz Brillouin oscillations are observed as the launched strain waves travel through the sample. Fig. 2(a) shows the Brillouin oscillations for the 3.6 nm thick QW. The Brillouin oscillation in the reflection (red line) and the transmission (blue line) are exactly 180° out of phase (i.e. no change in absorption (black line)). Three different regimes can be distinguished. Until $\sim 135 \text{ ps}$, the two generated strain waves travel both in the GaN. After $\sim 180 \text{ ps}$ a strong decrease of the Brillouin amplitude is observed as both waves travel in the sapphire, where the elasto-optic coupling is much smaller than in GaN. In between there is a transition between the two regions, where there are strain waves traveling in both materials.

Fig. 2: (a) Brillouin oscillation in reflection (red) and transmission (blue) for the 3.6 nm thick MQW and a pump fluence of 15 mJ/cm^2 . The black line is the change in absorption, calculated from the reflection and transmission data. For clarity the absorption is displaced by $8 \cdot 10^4$. (b) Amplitude of the Brillouin oscillations divided by the pump fluence as a function of pump fluence for three different quantum well thicknesses. (c) Stark shift as a function of pump fluence obtained from photoluminescence measurements.

The amplitude of the Brillouin oscillations is a measure for the generated strain because the spectrum of the strain pulse is mainly determined by the width of the MQW structure. To show the saturation of the strain generation, the amplitude of the Brillouin oscillations is divided by the pump fluence and shown as a function of pump fluences (Fig. 2(b)). The strain generation begins to saturate around 0.6 mJ/cm^2 . This is in good agreement with calculations, PL, and THz optical emission measurements on the same samples [1, 3]. Fig. 2(c) shows the Stark shift in the PL - a measure of the presence of an electric field in the QW - as function of fluence for the three different quantum wells. It can be seen that complete screening of the piezoelectric field occurs at comparable fluences as the acoustic emission begins to saturate.

In conclusion, we observe the generation of high amplitude strain waves by ultrafast screening of the built-in piezoelectric fields in InGaN/GaN MQW with different thicknesses. At short pump-probe delay times, fast oscillations with frequencies between 0.6 and 1 THz in the transient absorption are observed due to the vibration of the QW acoustic superlattice. At longer pump-probe delay times, Brillouin oscillation showing the traveling of strain pulses through the sample are observed. A saturation of the strain generation at around 0.6 mJ/cm^2 is observed, in good agreement with calculated and measured saturation of the screening of the built-in piezoelectric field.

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