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Citation: Applied Physics Letters 100, 201905 (2012); doi: 10.1063/1.4718524
View online: http://dx.doi.org/10.1063/1.4718524
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Magnitude-tunable sub-THz shear phonons in a non-polar GaN multiple-quantum-well p-i-n diode

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(Received 2 February 2012; accepted 1 May 2012; published online 15 May 2012)

Coherent transverse acoustic phonons are optically generated and detected through the piezoelectric coupling between the build-in electric fields and shear strains of a non-polar GaN multiple quantum wells embedded in a p-n junction. By optical transient transmission change measurement, the phonon frequency is observed to be 0.4 THz which corresponds to a wavelength of 12.5 nm, the periodicity of the multiple quantum wells, and the estimated phonon velocity corresponds to the transverse acoustic phonon velocity in GaN. Moreover, we can magnify the driving amplitude of the generated shear phonons by increasing the reverse bias of the p-i-n diode.

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As the MQWs were excited by femtosecond laser pulses, the static strain would be lunched because of the instantaneous screening of $P_3$ by separately photo-generated electrons and holes.\(^{12}\) The spontaneous polarization field, $P_s$, can only piezoelectrically couple to dilatational strains, $s_1$, $s_2$, and $s_3$. To manifest shear strains, $s_4$, $s_5$, and $s_6$, we have to grow MQWs along some other directions so that $e_{24}$ or $e_{15}$ can be involved in the piezoelectric effect.

A macroscopic load-string model has been presented in Ref. 24 to study the effect of crystal orientation of GaN MQWs on the magnitudes of LA and TA phonons. In wurtzite GaN, piezoelectric effect and deformation potential coupling are the two main mechanisms to generate acoustic phonons. Deformation potential coupling will only contribute to the generation of LA phonons, so we can neglect it in the TA phonon generations. On the other hand, the piezoelectric driving forces for the LA and TA modes can be expressed by\(^{24}\)

$$f_{\lambda\text{-piezo}} = -rac{e}{e_{\lambda}} \rho_{SC},$$

where $\rho_{SC} = \rho_h - \rho_e$ is the space charge defined by the density difference of holes and electrons, $e = \varepsilon_{\lambda} n_l n_i$ is the effective dielectric constant along propagation direction, and $e_{\lambda} = e_{ijk} n_i n_j w_{\lambda,k}$ is the effective piezoelectric constants with $\lambda$ = LA and TA, $e_{ijk}$ is the piezoelectric tensor of GaN, $n$ is the unit vector of phonon propagating direction, and the unit vectors $w_\lambda$ indicate the polarization directions of $\lambda$ modes.

Equation (2) is derived from elastic wave equation and Maxwell’s equation under the assumption that the elastic and dielectric properties of barriers and wells are the same. Also note that the $f_{\lambda\text{-piezo}}$ can only be decomposed into two phonon polarization directions on the plane spanned by $\hat{n}$ and $\hat{x}_3$, because the projection of $f_{\lambda\text{-piezo}}$ into the third polarization direction normal to the plane is always zero. Since wurtzite GaN is uniaxial, it is sufficient to describe phonon propagating direction by an angle $\theta$ between $\hat{n}$ and $\hat{x}_i$. More specifically, with the Cartesian coordinate as shown in Fig. 1(a), the effective piezoelectric constants for LA and TA modes can be expressed as\(^{22,24}\)

$$\bar{e}_{LA} = \frac{1}{\bar{e}_{24}} \sin^2 \theta + e_{33} \cos^2 \theta, \quad (3)

\bar{e}_{TA} = \frac{1}{\bar{e}_{24}} \sin^2 \theta - e_{24} \sin^2 \theta \sin \theta, \quad (4)$$

respectively. Therefore, MQWs grown along the direction with an orientation angle $\theta = 90^\circ$ will be a suitable candidate to achieve pure TA phonon generations by piezoelectric effect.

An m-plane ($\theta = 90^\circ$) In$_{0.22}$Ga$_{0.78}$N/GaN p-i-n diode similar to the one investigated in Ref. 25 was fabricated to generate coherent TA phonons in this work. As depicted in Fig. 1(b), the 6-pair MQWs were sandwiched by a p- and a n-doped GaN to form a p-i-n structure. The spatial period $D$ of the MQWs was determined by the high-resolution x-ray diffraction, as displayed in Fig. 1(c). Through the formula $D = \lambda/2\Delta\Theta$, where $\lambda$ is the wavelength of the x-ray and $\Delta\Theta$ is the angle difference between the diffraction peaks, the period $D$ of MQWs was found to be 12.2 nm with $\lambda = 0.154$ nm and $\Delta\Theta = 6.3 \times 10^{-3}$ rad. The doping densities of p-doped and n-doped GaN are $1 \times 10^{18} \text{ cm}^{-3}$ and $5 \times 10^{18} \text{ cm}^{-3}$, respectively. The resulting built-in voltage is around 2.1 V and the depletion region is 179-nm thick. The p-i-n structure provides a built-in electric field along $x_2$-axis, $P_2$, within the depletion region and induces an in-plane static shear stress, $s_2$. According to the doping densities, the built-in electric field was estimated to be 120 kV/cm, and the induced shear strain is around $10^{-5}$. This shear strain can be launched as soon as the built-in electric field was screened by the photocarriers excited by femtosecond laser pulses. In this scheme the acoustic wave will have the same periodicity as the MQWs,\(^{12,24}\) so the wavelength of the phonons, $\lambda_{\text{phonon}}$, will equal to $D$. As propagating through the quantum wells, the generated shear waves will affect the electric field along the epitaxial direction inside and induce variations in the optical transmission. The frequency of the induced oscillation in the optical transmission change will then equal to the inverse of the travelling time of the strain pulse from one quantum well to the adjacent one.\(^{12,24}\)

Optical transient transmission change measurement\(^{12}\) was used to observe the phonon oscillation. The output beam emitted from mode-locked Ti:Sapphire laser (Coherent, Mira 900F) was first frequency-doubled by a beta barium borate (BBO) crystal to a wavelength of 455 nm to selectively excite the In$_{0.22}$Ga$_{0.78}$N. After second harmonic generation, the laser beam passed through a blue colour filter and a half-wave plate to selectively block the remaining 800 nm-wavelength component and to control the polarization direction, respectively. The laser beam was then separated by a polarizing beam splitter into the excitation and

![Figure 1](attachment:image.png)

**Fig. 1.** (a) Coordinate adopted to express the effective piezoelectric constants in Eqs. (1)-(4). (b) Schematic diagram of the m-plane p-i-n structure. The epitaxial direction is along [1100]. (c) X-ray diffraction measurement of the MQWs. The spatial period of the MQWs is estimated to be 12.5 nm.
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The optical detection sensitivity of TA phonons has been proposed to enhance the detection of TA phonons. In polar GaN MQWs, the transient transmission change $\Delta T/T$ induced by LA phonons with a strain amplitude of $10^{-4}$ is around $10^{-3}$; meanwhile, the $10^{-5}$ shear strain caused a transient transmission change of $10^{-5}$ in this work. Hence, the piezoelectric detection sensitivity of TA phonons in nonpolar GaN MQWs is one order smaller than that of LA phonons in polar GaN MQWs. In most experiments, the generations of TA phonons were accompanied with the generations of LA phonons. In non-polar GaN, LA phonons have also been shown to be generated through deformation potential coupling. In the theoretical analysis, it has also been shown that there will be deformation-potential-coupled LA phonons with amplitude 5 times lower than that of the piezoelectrically coupled TA phonons in the non-polar GaN MQWs excited by a saturated pump fluence. Although LA phonons cannot be piezoelectrically detected in non-polar GaN, they have chances to be detected through deformation potential coupling.

In this investigation, the initial shear strains were provided by the built-in electric field of the p-i-n structure. We could thus magnify the amplitude of the observed TA phonon signal by increasing the reverse bias across the junction. The red circles, blue triangles, and olive squares in Fig. 3(a) show the Fourier spectra of the corresponding phonon oscillations shown in Fig. 2(b), which are observed with different biases under the same pump fluence. It can be clearly seen that the TA phonon signal is enhanced as the reverse bias increases. This result not only further validates that the TA phonon...
masses of electrons and holes. As the voltage jump increases, the electrons and holes gradually separate, and the space charge becomes stronger and stronger. The inset of Fig. 3(a) shows the comparisons of the measured phonon signals and the calculated driving forces for different voltage jumps. The error bars of the experimental signals are estimated from the magnitudes of the 400 GHz component of the background error bars of the experimental signals are estimated from the calculated driving forces for different voltage jumps. The deviation of the experimental and calculated results may be resulted from the suppression of detection sensitivity owing to the applied reverse bias.

In summary, 0.4 THz TA phonons in m-plane GaN MQWs have been generated and detected through piezoelectric coupling. The phonon signals have been shown to be magnified by means of increasing the reverse bias, despite the suppression of detection sensitivity. Our result demonstrated the great application potential of non-polar GaN MQWs in THz shear acoustics.

The authors would like to thank Dr. Yu-Chieh Wen and Professor Vitalyi Gusev for stimulating discussions. This work was sponsored by National Science Council of Taiwan under Grant No. 100-2120-M-002-009.