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Roles of Dislocation Density to the Scattering of Nano-acoustic Waves in GaN

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We have investigated how the density of threading dislocations in GaN affects the decay of the intensity of nano-acoustic waves. We carried out measurements using a reflection-type femtosecond pump probe, and thus, we determined the local dislocation density from the lifetime of nano-acoustic waves. We found that for a dislocation density of 10^8 cm^{-2}, defect scattering will surmount other scattering mechanisms and dominate the attenuation of 100GHz acoustic phonons.

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I. INTRODUCTION

In semiconductors without magnetic impurities, phonon scattering is mainly caused by relaxation damping, anharmonic coupling, lattice imperfections, and carrier doping. The scattering processes cause not only energy losses but also dephasing of coherent acoustic phonons. This, in turn, will affect the imaging depth and spatial resolution achieved in nano-acoustic imaging. For GaN-based nano-ultrasonics at sub-THz phonon frequencies [1, 2], the relaxation damping time is on the order of nanoseconds [3]. In contrast, the intrinsic anharmonic decay time of GaN is approximately100 ps for 470-GHz phonons at room temperature, which dominates the decay of nano-ultrasound [3]. However, in our previous study, we found that there occurs a background decay of sub-THz phonons that is comparable to the anharmonic decay, which has a dependence on the phonon frequency [3]. We attributed this background decay to the defect scattering caused by lattice imperfections, which include mass differences, dislocations, stacking faults, and grain boundaries. In GaN material system, the major lattice imperfection is threading dislocation; the density of threading dislocations is strongly anticorrelated to the photoluminescence efficiency of ultraviolet light emitting diodes (LEDs). In general, the phonon lifetime of dislocation scattering can be expressed as [4]

$$\tau_{dislocations}^{-1} = C_1 N_d b^2 \omega, \tag{1}$$

where N_d is the number of dislocation lines per unit area, b is the magnitude of Burger's vector, ω is the phonon frequency, and $C_1$is the proportionality constant that depends on the type of dislocation. Since this defect scattering rate is linearly dependent on the phonon frequency, its contribution will be greater than that of anharmonic decay for phonons with frequencies around 100 GHz. This property of acoustic scattering could be exploited to reveal the density of dislocations in GaN. To investigate the attenuation of nano-ultrasound in this regime, in this study, we exploit the processes of backward Brillouin scattering in order to indirectly determine the intensity of 100-GHz propagating acoustic phonons. We found that the density of threading dislocations in GaN can be investigated by performing a femtosecond pump-probe measurement.

II. SAMPLE STRUCTURE

To demonstrate the abovementioned idea, we used a GaN LED grown on wet-etched stripe-patterned sapphire substrates (PSSs) along the $<$1-100$>_{sapphire}$ direction [5]. We prepared the patterned sapphire substrates with periodic stripe patterns (width: 3 μm; spacing: 5 μm) by photolithography and wet chemical etching using a 500-nm-thick SiO_2 hard mask deposited by plasma-enhanced chemical vapor deposition. To obtain a flat surface for the growth of InGaN/AlGaN multiple-quantum-well LED structures, a 6-μm-thick GaN:Si buffer layer was grown by low-pressure metal-organic chemical vapor epitaxy at a doping density of 2×10^{18} cm^{-3}. The densities of threading dislocations in the lateral growth and heteroepitaxial growth regions, as characterized by scanning electron microscopy, are approximately 10^6 cm^{-2} and 10^8 cm^{-2}, respectively [6]. Over the GaN:Si substrate, 10 periods of 3-nm/14-nm $In_{0.06}GaN$/GaN multiple quantum wells (MQWs) with a 14-nm GaN cap layer were grown (See Fig. 1). Photoluminescence measurement at room temperature shows spectral peaks at 400 nm; these peaks correspond to the MQW transition. By using this sample, we can generate nano-acoustic waves from photo-excited MQWs and observe the decay of their intensity in GaN:Si at different densities of threading dislocations.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental setup comprises a reflection-type femtosecond pump-probe system, which has been widely used in picosecond ultrasonics [7]. By measuring the magnitude of the strain-induced dynamic Fabry-Perot effect (See Fig. 1.), the lifetime of acoustic waves at a backward brillouin scattering frequency can be characterized. The laser source for the pump-probe system is a femtosecond Ti:sapphire laser. In this laser, the frequency is doubled by a BBO crystal; then, optical pulses with a FWHM pulsewidth of 200 fs at a central wavelength of 390 nm are emitted. The pump-probe system splits these blue pulses into pump and probe pulses. The temporal delay between the pulses was controlled by a stepping motor. Both 40-mW pump pulses and 10-mW probe pulses were focused on the

MQW region by a UV-objective lens with NA = 0.85. The diameter of the focused spot was about 1 μm, which is sufficiently small for excitation and observation over different growth regions on the sample.

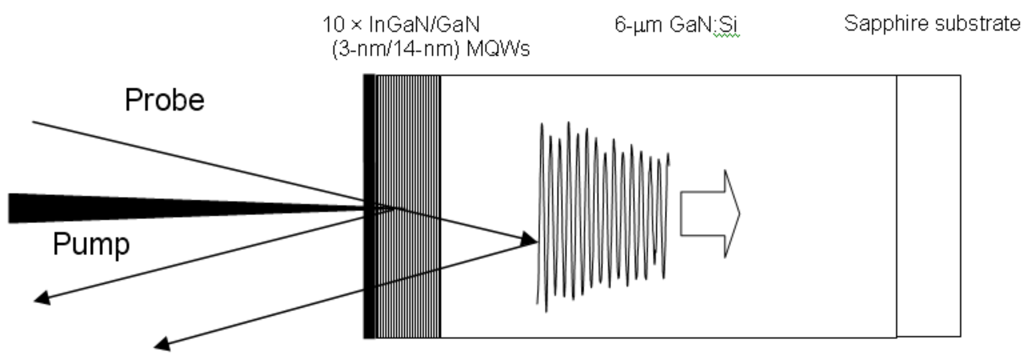

FIG. 1: Sample structures of the GaN MQW sample. Nano-acoustic waves can be generated by the pump of blue femtosecond pulses. The phonon lifetime can then be monitored by the probe pulse with Fabry-Perot type interference.

When the pump pulses excite carriers in MQWs through the piezoelectric effect, longitudinal acoustic waves with a wavelength of 17 nm are generated; this wavelength is identical to the period of MQW. Since the speed of sound for longitudinal modes in GaN is approximately 8200 m/s [7], the corresponding acoustic frequency is approximately 0.48 THz. Figure 2(a) shows the normalized differential reflection pump-probe trace for the region of heteroepitaxial growth. As the nano-acoustic waves propagated, the thickness of etalon changed and the differential reflection signal was modulated because of the change in the etalon thickness. The oscillation period of the differential pump probe trace is approximately 10 ps; this indicates the presence of phonons with a frequency of approximately 100 GHz. At this frequency, according our previous results, the anharmonic decay time of GaN will increase to 2.2 ns. However, the modulation amplitudes show an approximately 200-ps exponential decay (fitting dotted curve in Fig. 2(a)). We attribute this decay to the defect scattering of nano-acoustic waves. Then, the focal spot was moved to the lateral growth region, where the dislocation density is reduced by a factor of 100 on the surface of the GaN cap layer. Using Eq. (1) and assuming homogenous Burger's vectors and C_l for the same sample, the lifetime is estimated to be 20 ns. As we expected, the pump-probe trace shows almost no decay during the initial 150 ps (See Fig. 2(b)), which corresponds to a depth of 1.23 μm below the surface of sample. Thereafter, a decay is observed for 250 ps (between 150 ps and 400 ps), and there is no further decrease after 400 ps. Because the temporal delay is limited, we cannot analyze the propagation of 100-GHz phonons through the entire GaN:Si layer. This result indicates that dislocations with a greater density exist between the depths of 1.23 and 3.28gμm, and at depths greater than 3.28gμm, there is a recovery and the dislocation density is low. This result agrees with the fact that even though most of the threading dislocations are guided and suppressed in a region close to the sapphire interface, there are still a non-negligible number of threading dislocations stretching laterally in the middle of the GaN:Si layer.

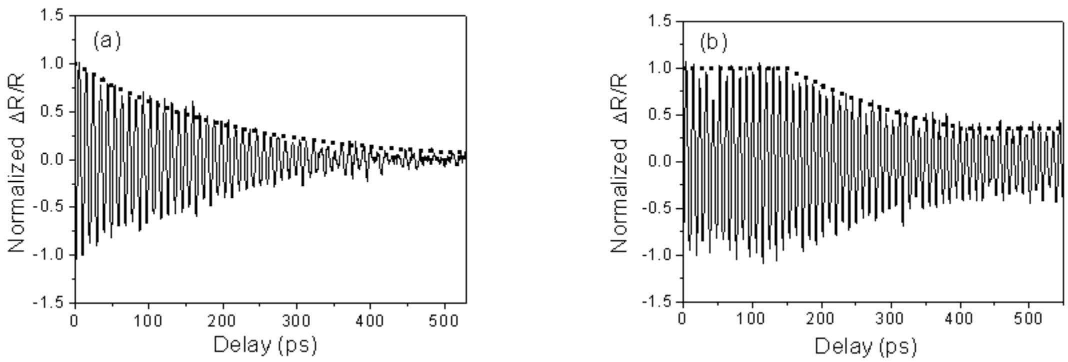

FIG. 2: The measured changes in differential reflection as a function of time delay (a) for heteroepitaxial growth and (b) in the region of lateral growth. The dotted curve in (a) is the curve used for fitting the lifetime of nano-acoustic waves, and it shows a 200-ps exponential decay.

IV. CONCLUSIONS

In conclusion, we have demonstrated that the density of threading dislocations in GaN can be determined by calculating the decay lifetime of nano-ultrasound. The lifetime was calculated by using a reflection-type femtosecond pump-probe system for measurement. Probed by the 100GHz acoustic phonons, dislocation density of $10^8 \mathrm{cm}^{-2}$ will dominate the attenuation over other mechanisms in GaN. For an even lower dislocation density in the lateral overgrowth sample, the acoustic intensity did not decay. The technique adopted in this study can serve as a tool for detecting the structural defects in LED devices.

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