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Phonon-assisted stimulated emission from pendeoepitaxy GaN stripes grown on 6*H*-SiC substrates

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Phonon-assisted stimulated emission has been demonstrated by photopumping GaN stripes grown via pendeoepitaxy on 6*H*-SiC (0001) substrates. Transverse-electric-polarized emission with well-defined Fabry-Pérot modes located at one longitudinal optical phonon energy (90 meV) below the band gap of GaN was observed at 77 K. An effective refractive index of 8.578 was obtained using a cavity length of 13.3 μm and a mode spacing of 0.6 nm. This value is significantly higher than the value previously reported in the literature using ellipsometry, which indicates that the absorption loss is more severe during lasing when the excess carrier concentration is very high. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2767239]

III-Nitride semiconductors have emerged as the most promising materials in which to fabricate ultraviolet light emitting diodes and laser diodes. As substrates of these materials are not yet readily available, thin film and device structures containing these materials are heteroepitaxially grown on sapphire (Al_2O_3) and SiC. The density of threading dislocations in these as-grown materials ranges from 10^9-10^{11} cm^{-2}; however, it may be reduced by three to five orders of magnitude via the use of various epitaxial lateral overgrowth (ELO) techniques,[1] e.g., pendeoepitaxy.[2,3] The parallel, atomically flat and mirror like sidewalls of the suspended, low dislocation density "wing" regions that are the hallmark of uncoalesced stripes of GaN grown by this technique (PE-GaN) should form a cavity with low scattering loss for stimulated emission.

Photopumped stimulated emission at room-temperature has been observed in GaN layers grown on SiC and sapphire substrates.[4,5] Optically pumped lasing from InGaN/GaN heterojunctions grown on sapphire substrates has been demonstrated at 77 K.[6] Longitudinal modes were observed in the luminescence spectra; however, the lasing cavity was not well defined. Al-Ajmi *et al.*[7] have reported room temperature laser action from cleaved GaN platelets with well-defined Fabry-Pérot modes. The cleaved dielectric interfaces of the platelets forms Fabry-Pérot cavity with a defined length. Exciton and phonon related emission peaks were also observed. Stimulated emission located at one or more longitudinal optical (LO) phonon energies below the allowed quantum-well transition energies was first reported in AlGaAs/GaAs multiple quantum wells.[8] Phonon-assisted recombination processes are stronger and easier to be observed in much polar materials such as GaN and II-VI materials. The purpose of this letter is to report the demonstration of phonon-assisted stimulated emission from a 13.3 μm wide PE-GaN stripe. Transverse-electric-polarized lasing with well-defined Fabry-Pérot modes was observed and located at one LO phonon (90 meV) below the band gap of GaN. The effective refractive index of the GaN was calculated to be 8.578.

The GaN sample investigated in this study was derived from an ~1.5 μm thick GaN thin film that had been grown on a 100 nm AlN buffer layer previously deposited during the same growth run on a polished 6*H*-SiC (0001) substrate, lithography patterned, and etched using an Inductively coupled Cl plasma to form a set of GaN stripes on which was deposited additional GaN material that grew primarily along $[1\bar{1}00]$ but without coalescence. Details of the sample preparation procedures are reported in Refs. 2 and 3. The sample was mounted on a conductive copper plug and placed on the cold finger of liquid nitrogen Dewar. A frequency-quadrupled flash-lamp-pumped Nd doped yttrium aluminum garnet laser having a pulse duration and repetition rate were 6 ns and 15 Hz, respectively, was used to acquire the photoluminescence (PL) spectra. The sample was illuminated at an angle slightly off the [0001] direction and oriented so that emission from the edge of the GaN stripes could be collected. A schematic of a single GaN stripe on the substrate and the excitation arrangement is shown in Fig. 1. The signal was analyzed using a 0.32 m spectrometer equipped with a liquid-nitrogen cooled, color-coupled-detector.

The cross section of a representative uncoalesced PE-GaN stripe obtained using scanning electron microscopy (SEM) is shown in Fig. 2(a). The width and height of the stripe are ~13.3 and ~5.6 μm, respectively, and the top (0001) and side $(1\bar{1}00)$ surfaces are orthogonal. The plan-view SEM image of four of the stripes shown in Fig. 2(b) reveals that the sidewalls of the stripes are parallel; they were

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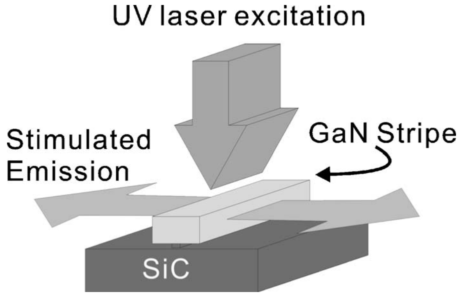

FIG. 1. Schematic showing the UV excitation of one PE-GaN stripe and the resultant photoluminescence emanating from the sidewalls.

also mirrorlike and separated by a 44 μm gap. As such, Fabry-Pérot cavities with minimum reflection loss were obtained between the sidewalls.

The emission spectra from a 13.3-μm-wide stripe at 77 K acquired under different excitation power densities are shown in Fig. 3. A broad spontaneous emission peak was observed at excitation power densities of 2.144 and 11 MW/cm^2. By contrast, a set of Fabry-Pérot modes were observed located at ~90 meV below the band gap energy of GaN at 77 K (~360 nm), when the power density was increased to 38 MW/cm^2. Noted the band-to-band transitions maintain their spectral positions at 360 nm when the excitation power density changes. Therefore, band gap renormalization does not responsible for this below band gap transition. It is proposed that LO-phonon assisted processes are responsible for this transition, since the LO phonon energy in GaN has been reported to be 90 meV.[9] The inset of Fig. 3 is an enlargement of the spectrum acquired at 38 MW/cm^2 and shows that the Fabry-Pérot modes are well defined with a mode spacing of 0.6 nm. Well-defined Fabry-Pérot modes are one of the important characteristics that indicate when the lasing occurs.

Photopumped lasing in an edge-emitting configuration favors transverse electric (TE) polarized emission, since the reflection coefficient is higher than the transverse magnetic (TM) polarization. Therefore, another key criterion that determines the occurrence of stimulated emission is the presence of a TE-polarized signal. A linear polarizer was utilized to analyze the output signal to determine the polarization of the emission signal when the excitation power density was above threshold. Only the TE-polarized emission exhibited a well-defined Fabry-Pérot mode, as shown in Fig. 4. This result verifies that these Fabry-Pérot modes located at one LO-phonon energy below the band gap energy originate from the stimulated emission of the photopumped GaN stripes. In addition to the phonon-assisted Fabry-Pérot modes, another set of modes with a mode spacing of 2 nm is also observed in Fig. 4. The ratio between the two sets of modes (0.6/2) is very similar to the ratio of the thickness to the width of the GaN strip (5.6/13.3). This concludes that the phonon-assisted process occurs across the width of the stripe and the other mode is the results from the cavity effects between the top and bottom interface of the thick GaN stripe.

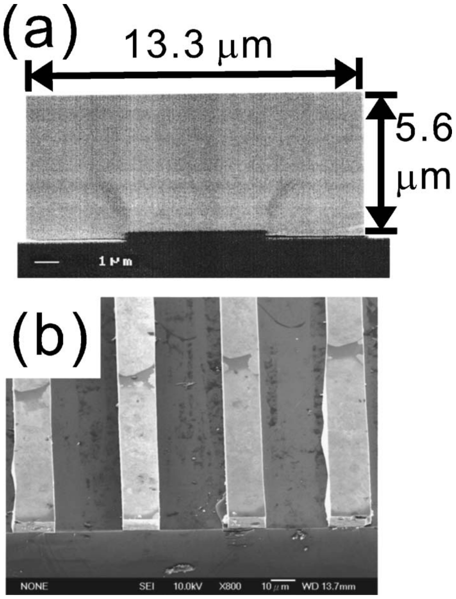

FIG. 2. SEM micrographs of (a) the cross section of one and (b) the plan-view of four uncoalesced PE-GaN stripe(s). The width and thickness of each stripe are 13.3 and 5.6 μm, respectively. The sidewalls of the stripes are flat and mirrorlike.

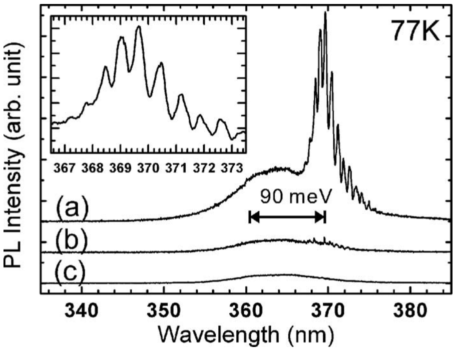

FIG. 3. Spectra of Phonon-assisted stimulated emission with Fabry-Pérot modes from a 13.3 μm wide PE-GaN stripe acquired at 77 K using UV excitation power densities of (a) 38 MW/cm^2, (b) 11 MW/cm^2, and (a) 2.144 MW/cm^2. Inset shows enlargement of the spectrum (a). The mode spacing is estimated to be 0.6 nm at the center wavelength of 370 nm.

The threshold gain g_{th} necessary for laser oscillation along the cavity length L may be calculated using

$$g_{\mathrm{th}} = \alpha + \frac{1}{L}\ln\left(\frac{1}{R_1 R_2}\right),$$

where R_1 and R_2 denote the dielectric mirror reflectivity and α is the absorption coefficient of the material. The threshold gain must overcome both the loss from the absorption of the material and the reflection of the cavity mirrors. It should be noted that the GaN stripe is uniformly illuminated across the stripe surface and high concentration of excess carriers are

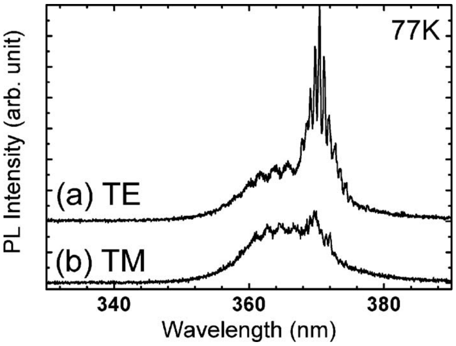

FIG. 4. (a) TE- and (b) TM-polarized emission spectra acquired at 77 K using UV excitation power density of 38 MW/cm^2. Phonon-assisted stimulated emission was only observed in the TE-polarization spectrum.

uniformly generated. However, the photogenerated carriers are not uniformly distributed in the vertical direction and are concentrated within the 1 μm thick region from the sample surface for a thick 5.6 μm GaN film. Band-to-band recombination suffers a higher distributed absorption loss compared to the phonon-assisted processes and required a higher threshold gain for stimulated emission. Therefore, the threshold gain for the phonon-assisted stimulated emission (PASE) is lower than the band-to-band stimulated emission, which explains why only PASE is observed in the stimulated emission spectra.

The Fabry-Pérot mode spacing in the lasing spectra from a 13.3-μm-wide cavity has been estimated from the inset of the Fig. 3 to be 0.6 nm at the center wavelength of $\lambda_0=370$ nm. These data were analyzed using the following formula:[10]

$$\Delta\lambda = \frac{\lambda_0^2}{2L(n - \lambda_0(dn/d\lambda))},$$

where L is the cavity length, λ_0 is the wavelength of the center mode, $\Delta\lambda$ is the spacing between adjacent modes, n is the refractive index at λ_0, and $dn/d\lambda$ is the variation of the refractive index with wavelength. The effective refractive index $[n-\lambda_0(dn/d\lambda)]$ was calculated to be 8.578. According to the result reported by Yu *et al.*,[11] the effective refractive index becomes larger near the band gap of GaN. The values of n and $dn/d\lambda$ at 370 nm were estimated by spectroscopic ellipsometry measurements to be 2.8 and −0.0050, respectively.[11] This leads to an effective refractive index of 4.65, i.e., a much smaller value than that extracted from the mode spacing fitting in the present study. The abnormal high value of effective refractive index can be partly explained by the strong distributed loss for a thick sample. In addition, it should be noted that the carrier concentration inside a material is significantly higher when stimulated emission occurs. New absorption channels related to a high carrier concentration can lead to a higher loss, which increases the value of both n and $dn/d\lambda$. As such, the value of the effective refractive index obtained from this study reflects the loss mechanisms when the carrier concentration inside an unintentionally doped GaN sample is very high. This information regarding loss mechanisms is especially important for laser diodes, since they are operating under high carrier concentrations. Understanding the loss mechanism is crucial for enhancing the efficiency of operation of a laser diode.

In conclusion, GaN stripes with mirrorlike sidewalls have been grown using pendeoepitaxial technique. Stimulated emission with well-defined Fabry-Pérot modes has been demonstrated when these PE-GaN stripes were photopumped at 77 K. The center wavelength of the stimulated emission was located at one LO-phonon below the GaN band gap energy, which indicates the participation of LO phonons during the stimulated emission. This emission exhibits a preferred TE-polarization direction. An effective refractive index of 8.578 was calculated from the stimulated emission based on the cavity length and mode spacing. The high effective index refraction indicates that the absorption loss is more severe during lasing action when the excess carrier concentration is very high. Further understanding of the lasing process and phonon-assisted stimulated emission can catalyze future new developments in semiconductor laser diodes.

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[1] B. Beaumont, P. Vennegues, and P. Gibart, Phys. Status Solidi B **227**, 1 (2001).

[2] T. Zheleva, S. Smith, D. Thomson, K. Linthicum, P. Rajagopal, and R. F. Davis, J. Electron. Mater. **28**, L5 (1999).

[3] A. M. Roskowski, E. A. Preble, S. Einfeldt, P. M. Miraglia, and R. F. Davis, J. Electron. Mater. **31**, 421 (2002).

[4] A. S. Zubrilov, V. I. Nikolaev, D. V. Tsvetkov, V. A. Dmitriev, K. G. Irvine, J. A. Edmond, and C. H. Carter, Jr., Appl. Phys. Lett. **67**, 533 (1995).

[5] X. H. Yang, T. J. Schmidt, W. Shan, J. J. Song, and B. Goldenberg, Appl. Phys. Lett. **66**, 1 (1995).

[6] I. K. Shmagin, J. F. Muth, R. M. Kolbas, S. Krishnankutty, S. Keller, U. K. Mishra, and S. P. DenBaars, J. Appl. Phys. **81**, 2021 (1997).

[7] F. S. Al-Ajmi, R. M. Kolbas, J. C. Roberts, P. Rajagopal, J. W. Cook, Jr., E. L. Piner, and K. J. Linthicum, Appl. Phys. Lett. **90**, 151116 (2007).

[8] R. M. Kolbas, N. Holonyak, Jr., B. A. Vojak, K. Hess, M. Altarelli, R. D. Dupuis, and P. D. Dapkus, Solid State Commun. **31**, 1033 (1979).

[9] M. E. Levinshtein, S. L. Rumyantsev, and M. S. Shur, *Properties of Advanced Semiconductor Materials* (Wiley, New York, 2001), p. 2.

[10] M. I. Nathan, A. B. Fowler, and G. Burns, Phys. Rev. Lett. **11**, 152 (1963).

[11] G. Yu, G. Wang, H. Ishikawa, M. Umeno, T. Soga, T. Egawa, J. Watanabe, and T. Jimbo, Appl. Phys. Lett. **70**, 3209 (1997).