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Stimulated emission from semi-polar (11-22) GaN overgrown on sapphire

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(11-22) semi-polar GaN is expected to exhibit major advantages compared with current *c-plane* polar GaN in the fabrication of long wavelength such as green and yellow emitters. However, all the III-nitride based semi-/non- polar laser diodes (LDs) reported so far have been achieved exclusively based on homo-epitaxial growth on extremely expensive free-standing GaN substrates with a very limited size. In this paper, we have observed a stimulated emission at room temperature achieved on our semi-polar (11-22) GaN overgrown on a micro-rod arrayed template with an optimized design on *m-plane* sapphire. This has never been achieved previously on any semi-polar GaN grown on sapphire. Furthermore, an optical gain of $130 cm^{-1}$ has been measured by means of performing a standard laser stripe-length dependent optical measurement. The values of the threshold and the optical gain obtained are comparable to those of the *c-plane* GaN reported so far, further validating the satisfactory crystal quality of our overgrown semi-polar (11-22) GaN on sapphire. This represents a major step towards the development of III-nitride semi-polar based LDs on sapphire, especially in the long wavelength regime. [http://dx.doi.org/10.1063/1.4981137]

The last two decades have seen unprecedented progress in the field of III-nitride optoelectronics, but mainly limited to InGaN based light emitting diodes (LEDs) and laser diodes (LDs) in the blue spectral region. Very recently, a number of emerging technologies based on visible LDs have been developed, such laser color display,[1] smart-phones with pico-projectors, opto-genetics[2] and visible light wireless communication,[3] where long-wavelength green/yellow laser diodes (LDs) are the key missing components. Growth of III-nitrides along a semi-polar direction, in particular the (11-22) orientation, would be a promising solution to achieving long wavelength LDs, as such an orientation is expected to lead to both reducing so-called quantum-confined stark effect (QCSE) and increasing indium incorporation efficiency in InGaN, the two fundamental limitations posed by current *c-plane* III-nitrides.[4] So far, all the III-nitride semi-/non- polar LDs reported have been achieved exclusively by means of growth on extremely expensive GaN substrates with a very limited size (typically $10\times10\ mm^2$).[5,6] The free-standing substrates are typically obtained by slicing a thick *c-plane* GaN layer grown on sapphire along a semi-/non- polar orientation,[5,6] and such homo-epitaxial growth is therefore not very attractive to the optoelectronic industry in terms of mass production.

A practical way forward, which could address the two major challenges, is to grow long wavelength such as green and yellow LDs along the semi-polar (11-22) orientation on sapphire substrates.[4] However, the major issue is due to the unsatisfactory crystal quality of (11-22) semi-polar GaN grown on sapphire. Recently, our team has developed a semi-polar (11-22) GaN overgrowth approach based on regularly arrayed micro-rod templates on *m-plane* sapphire, leading to significant improvement in crystal quality.[7,8] Our approach has demonstrated a number of major advantages compared with other technical routes.[9,10] For details, please refer to a topical review published very recently.[4] As a

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consequence, we have demonstrated (11-22) semi-polar InGaN LEDs from green to amber grown on such high quality semi-polar GaN templates. However, a stimulated emission has never been achieved on any semi-polar GaN on sapphire.

In this paper, we have observed a stimulated emission optically pumped at room temperature on our semi-polar (11-22) GaN overgrown on regularly arrayed micro-rod templates with an optimized design on *m-plane* sapphire. Furthermore, a standard laser stripe-length dependent optical measurement has been performed in order to investigate optical gain characteristics, and an optical gain of 130 cm^{-1} has been measured. The results presented further validate the satisfactory crystal quality of our overgrown semi-polar (11-22) GaN on sapphire, representing a major step towards the development of III-nitride semi-polar LDs on sapphire.

A 5μm overgrown semi-polar (11-22) GaN sample has been used for the optical pumping measurements performed at room temperature. We specifically chose an overgrown (11-22) GaN sample on a template with a micro-rod diameter of 4 μm, exhibiting a dislocation density of $2x10^8/cm^2$ and a basal-stacking-faults (BSF) density of $4x10^4$/cm, respectively. It is worth highlighting that the semi-polar GaN exhibits the lowest dislocation density but not the lowest density of basal stacking faults (BSFs).[11] Details on the fabrication of the regularly arrayed micro-rod template and the subsequent overgrowth procedure can be found elsewhere.[7,8]

A 266 nm diode pumped pulsed Nd: YAG laser with a pulse duration of 9 ns and a repetition frequency of 850 Hz is employed as an excitation source for the optical pumping measurements. Two cylindrical lenses are placed in front of the sample to focus the laser into a stripe-shaped beam incident on the surface of the sample, and the width and length of the laser beam are 0.2 and 1 mm, respectively. A motorized transition stage with an accuracy of 1 μm is employed to control the stripe length of the laser beam incident on the samples accurately. The emission is collected from the edge of the sample, and then detected by a high sensitivity CCD array detector. The stripe-length dependent optical pumping measurements have been carried out as a function of the laser stripe length from 0.3 to 0.9 mm. It has to be highlighted that the non-uniformity in laser beam due to the edge effect can be safely ignored, as a linear increase in emission intensity below the threshold for lasing has been found with increasing the laser stripe length even in a small step. This can allow us to obtain an accurate optical gain.

Figure 1a shows the emission spectra of the overgrown semi-polar GaN sample measured as a function of an optical pumping density from 130 to 1100 kW/cm^2. Under the low optical pumping densities, a broad emission centered at around 363 nm has been observed as expected, corresponding to the spontaneous near-band-edge emission (NBE) of the GaN sample. However, when the optical pumping power density increases, another peak on the long wavelength side at around 374 nm appears. With further increasing the optical pumping power density, this peak becomes narrower and stronger, indicating a stimulated emission process.

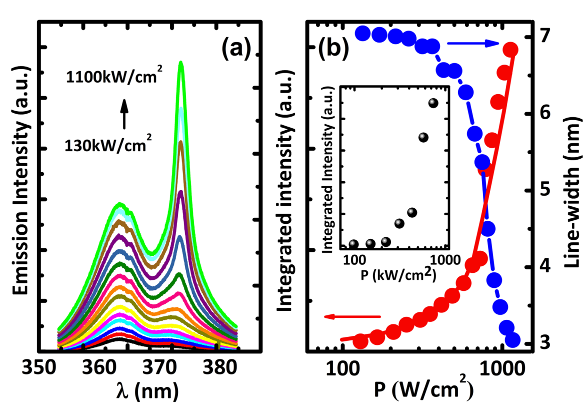

FIG. 1. (a) Emission spectra of the semi-polar overgrown GaN measured as a function of an optical pumping density from 130 to 1100 kW/cm^2; (b) Integrated intensity and line-width of the stimulated emission as a function of an optical pumping density. Inset of (b): Integrated intensity of a stimulated emission as a function of an optical pumping density measured on a standard *c-plane* GaN sample grown on sapphire for comparison.

Figure 1b shows both the integrated intensity and the line-width of the stimulated emission at 374 nm as a function of an excitation power density. Under the low excitation power densities, the integrated intensity increases linearly with increasing an excitation power density. A super-linear increase in integrated intensity has been observed when the excitation power density exceeds 725 kW/cm^2. Simultaneously, the line-width shows a dramatic reduction from around 7.4 to 3 nm. Both this super-linear increase in intensity and the reduction in line-width further confirm the stimulated emission, and the threshold labeled as E_{th} can be estimated to be 725 kW/cm^2. For comparison, optical pumping measurements have been performed on a standard *c-plane* GaN grown on (0001) sapphire under identical conditions, and a stimulated emission at around 374 nm has been observed. The inset of Figure 1b presents the integrated intensity of the stimulated emission from the standard *c-plane* GaN grown on sapphire as a function of an excitation power density, showing a threshold of around 576 kW/cm^2.

Other reports on *c-plane* GaN have also been listed in Table I, where Amano[12] reported a stimulated emission at around 374 nm on *c-plane* GaN with a thickness of ~3.5 µm grown on (0001) sapphire when an optical pumping density exceeds 0.7MW/cm^2. Stimulated emission for GaN grown on SiC[13] or bulk GaN[14] have been reported, and have been provided in Table I as well. As revealed from Table I, the E_{th} obtained for our overgrown semi-polar (11-22) GaN (725 kW/cm^2) is generally comparable to those for *c-plane* GaN, which should be attributed to the significantly improved material quality as a result of our overgrowth technology.

Based on the overgrown (11-22) GaN sample with such high quality, standard stripe-length dependent optical-pumping measurements have been performed in order to measure its optical modal gain. Generally speaking, an optical modal gain can be quantitatively obtained using the well-known equation provided below.[15–17]

$$I(L) = \frac{A}{g} * (e^{g^*L} - 1) \tag{1}$$

where I is the emission intensity as a function of the laser stripe length incident on the sample tested; L is the laser stripe length incident on the sample; g is optical gain and A is a constant.

Figure 2a shows the typical amplified spontaneous emission (ASE) spectra recorded as a function of the laser stripe length incident on the sample from 0.3 to 0.9 mm with an increment step of 0.1 mm. When the laser stripe length incident on the sample is less than 0.7 mm, only a broad peak centered at 363 nm due to a spontaneous emission can be observed. When the laser strip length is increased to 0.7 mm, another peak on the long wavelength side at 374 nm appears. The peak becomes narrower and the emission intensity increases rapidly when the laser stripe length on the sample is further increased, a typical fingerprint for a stimulated emission. This can be clearly observed in Figure 2b, the integrated intensity of the ASE as a function of the laser stripe length incident on the sample. The excitation power density remains constant (namely, above 725 kW/cm^2) during the measurements.

Figure 2a shows that the stimulated emission peak starts to appear when the laser stripe length on the sample is above 0.7 mm. Therefore, the optical gain is calculated based on the data obtained with the laser stripe length on the sample of larger than 0.7 mm, namely, 0.8 mm. Figure 3 shows the gain spectra, exhibiting that the maximal net modal gain is around 130 cm^{-1} at ~374 nm.

TABLE I. Comparison of the data for optically pumped stimulated emissions obtained on our semi-polar (11-22) and *c-plane* GaN from other groups and our group.

Reference	E_{th}	Structure
H. Amano, et al[12]	0.7 MW/cm^2	c-plane GaN on sapphire
A. S. Zubrilov, et al[13]	3.4 MW/cm^2	c-plane GaN on SiC
S. Sakai, et al[14]	0.86 MW/cm^2	c-plane GaN on GaN
Present work	0.725 MW/cm^2	Our overgrown semi-polar (11-22) GaN on m-plane sapphire
	0.576 MW/cm^2	c-plane GaN grown on sapphire

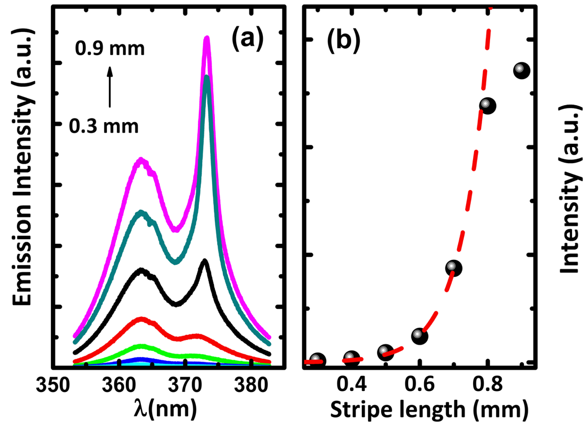

FIG. 2. (a) Typical amplified spontaneous emission (ASE) spectra recorded as a function of the laser stripe length incident on the sample; (b) Integrated intensity of the ASE as a function of the laser stripe length incident on the sample.

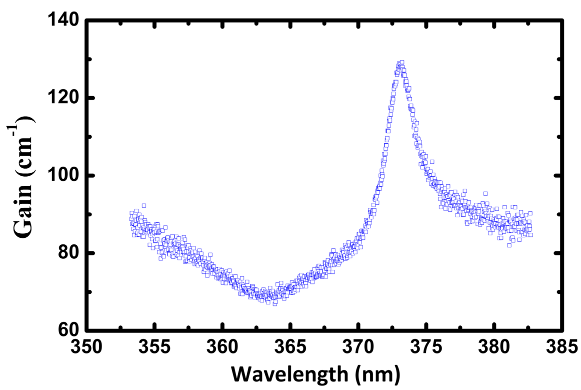

FIG. 3. Typical gain spectrum measured on the semi-polar overgrown GaN sample, showing the maximal net modal gain of around 130 cm^{-1} at ~374 nm.

As stated above, our overgrowth approach has led to a significant reduction in dislocation density, which is crucial for obtaining a stimulated emission. Unlike *c-plane* GaN, there generally exist two kinds of defects, namely, dislocations and BSFs.[4] A systematic micro-structural investigation has been carried out on a number of semi-polar (11-22) GaN samples achieved by our overgrowth on the regularly arrayed micro-rods with different micro-rod diameters, indicating that an increase in micro-rod diameter from 2 to 7 µm can effectively reduce both the dislocation density and the BSF density of the overgrown (11-22) GaN, but in different ways.[11] For example, a 4 µm micro diameter leads to the lowest dislocation density, typically below $2 \times 10^8/cm^2$ (i.e., the sample used for the present study) measured by detailed transmission electron microscopy (TEM) measurements. The TEM data indicate that the crystal quality of our semi-polar GaN approaches or is even better than that of standard *c-plane* GaN on sapphire. The TEM results are also in good agreement with detailed on-axis (11-22) x-ray diffraction rocking curve measurements performed along two typical directions, namely, the [1-100] direction and the [11-2-3] direction, showing the full widths at half maximum (FWHM) are typically 330 and 272 arcsec for the two directions, respectively. However, a 5 µm micro diameter instead of the 4 µm micro-rod diameter gives rise to the lowest BSF dislocation, but not the lowest dislocation density. So far, we have observed a stimulated emission on the sample grown on the regularly arrayed micro-rods with the 4 µm micro-rod diameter. Therefore, the high crystal quality of our overgrown semi-polar GaN, in particular the sample with a low dislocation density, is crucial for achieving the stimulated emission.

In summary, we have reported a simulated emission optically pumped at room temperature on our semi-polar (11-22) GaN overgrown on a micro-rod arrayed template with an optimized design on *m-plane* sapphire, which has never been reported previously on any semi-polar GaN grown on sapphire. This is attributed to the significantly improved crystal quality achieved by the overgrowth approach. Based on the high crystal quality sample, an optical gain of 130cm^{-1} has been measured by means of performing a standard laser stripe length dependent optical measurement. Both the threshold and the optical gain obtained are comparable to those of the c-plane GaN grown on (0001) sapphire reported so far, implying that our cost-effective overgrowth approach pave the way for the development of semi-polar GaN based long wavelength LDs on sapphire substrates with a large size.

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