InGaN/GaN Laser Diodes with High Order Notched Gratings

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Abstract—**We report on InGaN/GaN distributed feedback laser diodes with high order gratings emitting at a single wavelength around 428 nm. The 39th order notched gratings havethe advantage of a simplified fabrication route with no need for overgrowth. The laser ridge and grating were formed by electron beam lithography followed by ICP etching. The as-cleaved lasers emitted in the pulsed regime with a peak single-mode output power if 15 mW. Optimization of the grating design should lead to higher power single wavelength operation.**

Index Terms— **Semiconductor lasers, Distributed feedback laser diodes, InGaN, GaN, sidewall gratings, slotted laser, notched grating.**

I. INTRODUCTION

LASER Diodes based on Gallium Nitride (GaN) have found a wide range of applications ranging from atomic spectroscopy [1] to optical communications [2]. To fully exploit many of these application areas there is a requirement for a GaN laser diode with high spectral purity and wavelength selectivity. For example in atomic clocks, where a narrow line width blue laser source can be used to target the atomic cooling transition [4][5], and in fluorescence spectroscopy for medical diagnostics where one can accurately target the emission wavelength [3],
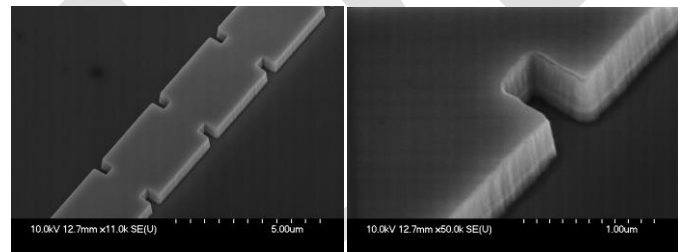
Previously GaN DFB lasers have been realised by one of two approaches, buried [6][7], or surface gratings [8]. Buried gratings require complex overgrowth steps which have the potential to introduce epi-defects. Surface gratings designs, all though simpler to fabricate, can compromise the quality of the p-type contact due to dry etch damage and are also prone to increased optical losses in the electrically un-pumped grating regions. A different approach, where the grating is etched into the sidewall of the ridge is described in [9], advantages include a simpler fabrication route and design freedom over the grating coupling strength. The authors have previously reported third order sidewall gratings in the InGaN/GaN material system [10],[11] with single wavelength emission. In this paper we go on to investigate lasers with higher order gratings, having the advantage of less stringent fabrication tolerances due to the larger grating dimensions. Additionally, these devices could exhibit narrower linewidths than conventional DFB laser diodes [12],[13], and so could be particularly suited to supplications such as atomic cooling.

II. DESIGN

Our chip designs are based on 39th order gratings and are conceptually similar to devices described in [14]. Conventionally for this type of device the grating consists of slots etched into the top of the laser waveguide ridge. However this approach is not suited to GaN laser diodes where the p-type GaN contact layer should remain continuous along the ridge to minimise resistance and avoid optical losses in the p-type GaN. In our design the index perturbations are introduced as regularly spaced notches in the ridge sidewall thus maintaining the continuity of the contact.

With high order gratings of this type the reflectivity is significantly less than can be achieved with 1st or 3rd order gratings. In fact, the dominant source of optical feedback is the cleaved facets. The effect of the grating is to introduce a wavelength selective optical loss for Fabry Perot (FP) modes detuned from the Bragg wavelength. Depending on the reflection bandwidth of the grating, lasing can be in a single or narrow band of FP mode\s.

(a)   (b)

Fig. 1. SEM micrograph of the as etched grating (a), and at higher magnification (b).

The grating bandwidth is a function of the reflectivity of the individual notch pair. The lower the reflectivity the narrower the bandwidth but the larger the number of pairs required to maintain the required total reflectivity. For a GaN laser the effective modal index is low (~2.4) so the FP modes are closely spaced at ~0.05 nm and the grating bandwidth should be of a similar value to give single mode operation. We used the TMM (transmission matrix method) along with effective indices found using a 2D mode solver to calculate the grating bandwidth. This technique is approximate [15] but gives us an estimate of the required grating length. We calculate a bandwidth 0.08 nm using a total 125 notch pairs along the ridge. It was also taken into consideration that the notches introduce scattering losses so there is an optimal notch number to achieve single wavelength operation while minimising the drop in efficiency.

III. FABRICATION

For fabrication, 39th order gratings and ridges with four different periods (spanning 3403 nm to 3486 nm) were defined using electron beam lithography (EBL). Inductively coupled plasma (ICP) etching was then used to form the 500 nm deep grating and ridge. Process chemistry and power settings were optimised to give the vertical and smooth etch profile required for good grating performance. Figure 1 shows electron micrographs of an etched high order grating. Electrical contacting was achieved using Pd/Au on the Mg doped p-GaN cap layer. The processed wafer was then lapped to 100 µm thickness and subsequently cleaved into die of 1000 µm cavity length. Full details of the fabrication process can be found in [11].

IV. RESULTS & DISCUSSION

Lasers were characterised under pulsed drive conditions. LIV measurements were carried out using a Keithly 2520 automated test system.
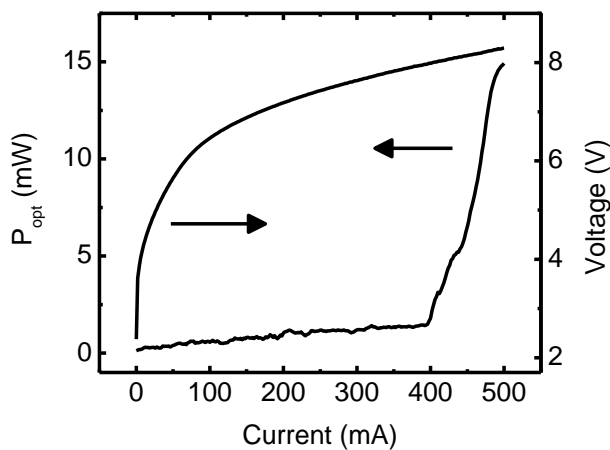
Fig. 2. Optical power and voltage as a function of pulsed drive current for device A.

For spectral measurements we used an Ocean Optics spectrometer with 0.1 nm resolution and for higher resolution measurements a Horiba iHR550 with spectral resolution of 0.025 nm. Note that there was a difference in measured wavelength of around 0.5 nm between the two spectrometers.
A range of devices (A to D) with different grating pitches and emission wavelengths were tested (table 1). All devices had a ridge width of 2.5 µm (1.5 µm at the notches) and etch depth of 520nm. Fig 2 shows the voltage and optical power as a function of drive current for device A. Peak power is 15 mW measured at a drive current of 500 mA.
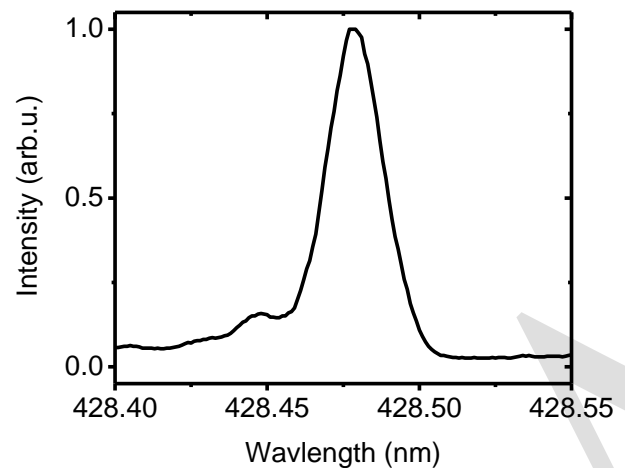

Fig.3. Emission spectra of device A at drive current of 500 mA.

From fig 3 we can see that the device is lasing in a single FP mode up to drive currents of 500 mA before becoming multimode at higher drive currents (fig 4). This is due to detuned FP modes reaching threshold as wavelength dependent losses [14] are overcome. Introducing more slot pairs with weaker index contrast would decrease the bandwidth of the grating and potentially improve single mode performance at higher drive currents.

By varying the temperature of the heatsink between 10 C and 25 C we were able to temperature tune the single mode emission wavelength over a range of 0.2 nm (a temperature tuning coefficient of 0.012 nm/K).
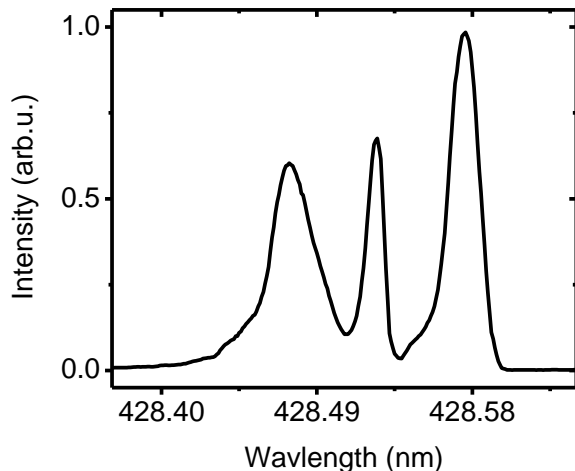
Fig.4. Emission spectra of device A at drive current of 600 mA.

Fig.5. Effective index versus wavelength for chips A to D. Fitted with polynomial function $n_{eff} = 11.041 - 0.0380x + 4.213 * 10^{-5}x^2$

TABLE I
WAVELENGTH, GRATING PITCH & EFFECTIVE INDEX FOR CHIPS A TO D

Device	Grating Pitch (nm)	Emission wavelength (nm)	Grating order	Effective Index
A	3548	328.01	40	2.475
B	3486	430.61	40	2.471
C	3403	431.04	39	2.470
D	3430	433.69	39	2.466

From table 1 we can see that grating pitches of 3458 nm and 3486 nm gave emission at 428.0 nm and 430.6 nm, around 10 nm shorter than would have been expected given the modal index. This is explained by the fact that the grating has an FSR (free spectral range) of ~10 nm and lasing is in the next lowest allowed wavelength to the Bragg wavelength. In fact in this case the grating is operating in the 40th order rather than the 39th.

$$n_{eff,g} = n_{eff} - \lambda \frac{dn}{d\lambda} \qquad (1)$$

$$\Delta\lambda = \frac{\lambda^2}{n_{eff,g}L_{cav}} \qquad (2)$$

From the measured dependence of effective index on wavelength, and using (1) we calculate an effective group index of 3.5. Using (2) we calculate an FSR of 0.052 nm which agrees well with the mode spacing of 0.051 nm observed in fig 4.

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