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Formation of nitride laser cavities with cleaved facets on transferred laser diodes on GaAs substrates

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Smoothly cleaved facets with high reflectivities have been demonstrated on GaN laser diodes after the devices were transferred onto GaAs substrates. The GaN based laser diode structure was first fabricated by metal organic chemical vapor deposition (MOCVD) on c-plane sapphire substrates. The samples were then mounted onto thin GaAs substrates using wafer-bonding technology. Laser lift-off (LLO) technique was applied to remove the original sapphire substrate and transfer the GaN laser structure onto GaAs substrates. Since the cubic substrates have well-defined laser cavity cleavage facet, the GaN structures bonded onto the substrates also formed smooth facets after cleavage. The cleaved facets of GaN laser diodes have been characterized using atomic force microscopy (AFM) with less than 2 nm roughness. The present study demonstrated the feasibility of transferring GaN laser structures onto other more appealing substrates for formation of laser cavities.

1 Introduction Several research groups have demonstrated nitride based laser diodes [1–8]. This device is desirable for optical storage systems (e.g., high-density digital versatile disk, HD-DVD), printing, display technology, medical surgery and chemical monitoring (such as pollution). The lifetime estimate of 10000 h from Nakamura at Nichia Chemicals, Inc., demonstrates the viability of these devices for commercial products [9].

Various approaches have been explored for fabricating nitride laser diodes. Sapphire substrates are used primarily due to the availability of low-cost high-quality wafers [1–3, 6–8]. C-plane sapphire is the primary orientation employed and has been used to fabricate devices with dry etched facets [1, 6, 7] as well as cleaved facets [2, 8]. A-plane sapphire has been employed for fabricating cleaved facet laser diodes [1, 10]. Silicon carbide substrates, employing cleaved facets, are favored due to a closer lattice match and higher thermal conductivity [4, 5]. Their use is limited by the high cost of this substrate. In this paper, we report on the properties of laser diodes fabricated using cleaved facets after the devices were transferred onto GaAs substrates.

2 Experimental The InGaN multi-quantum-well (MQW) laser diode structure was grown on the 2” c-plane (0001) sapphire substrates by metal organic chemical vapor deposition (MOCVD). The chemical precursors used were trimethylgallium (TMGa), trimethylaluminum (TMAl), trimethylindium (TMIn), bis(cyclopentadienyl) magnesium Cp_2Mg, disilane (Si_2H_6), and ammonia (NH_3) .

The general laser structure is shown in Fig. 1. The InGaN MQW LD structure consisted of a 3-µm *n*-type GaN:Si n-contact layer, a 0.1-µm *n*-type $In_{0.05}Ga_{0.95}N$:Si strain release layer, a $Al_{0.2}Ga_{0.8}N$/GaN MD-SLS cladding layer consisting of forty 2.5-nm Si-doped GaN layers separated by forty 2.5-nm Si-doped $Al_{0.2}Ga_{0.8}N$ layers, an $In_{0.12}Ga_{0.88}N$/GaN MQW structure consisting of five 4-nm Si-doped $In_{0.12}Ga_{0.88}N$ well layers forming a gain medium separated by 10-nm undoped GaN barrier layers, a $Al_{0.2}Ga_{0.8}N$/GaN MD-SLS cladding layer consisting of twenty 2.5-nm Mg-doped GaN layers separated by 2.5-nm undoped $Al_{0.2}Ga_{0.8}N$ layers, and a 0.1-µm *p*-type GaN:Mg p-contact layer. A laser cavity was formed by cleaving the facets along [1–100] of the LD grown on the c-sapphire

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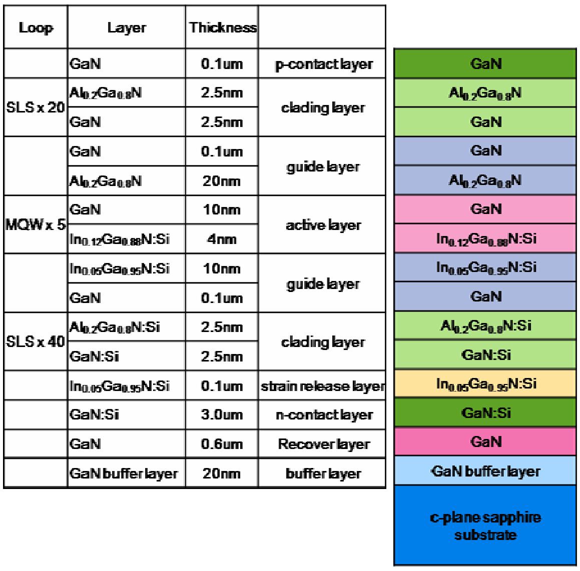

Loop	Layer	Thickness	
	GaN	0.1um	p-contact layer
SLS x 20	$Al_{0.2}Ga_{0.8}N$	2.5nm	clading layer
	GaN	2.5nm	
	GaN	0.1um	guide layer
	$Al_{0.2}Ga_{0.8}N$	20nm	
MQW x 5	GaN	10nm	active layer
	$In_{0.12}Ga_{0.88}N$:Si	4nm	
	$In_{0.05}Ga_{0.95}N$:Si	10nm	guide layer
	GaN	0.1um	
SLS x 40	$Al_{0.2}Ga_{0.8}N$:Si	2.5nm	clading layer
	GaN:Si	2.5nm	
	$In_{0.05}Ga_{0.95}N$:Si	0.1um	strain release layer
	GaN:Si	3.0um	n-contact layer
	GaN	0.6um	Recover layer
	GaN buffer layer	20nm	buffer layer

Figure 1 The details and schematic diagram of the InGaN based laser diode structure.

substrate. The details and structure of the sample are shown in Fig. 1.

Inductively coupled plasma (ICP) etch was applied to define GaN laser stripe patterns. The samples were then mounted onto thin GaAs substrates using wafer-bonding technology. Various types of bonding metals, bonding pressures, and bonding temperatures have been attempted in the process. Figure 2 illustrates the cross sectional SEM images of the bonding area under different bonding pressures. Laser lift-off (LLO) technique was applied to remove the original sapphire substrate and hence transfer the GaN laser structure onto GaAs substrates [11, 12]. Since the cubic substrates have well-defined laser cavity cleavage facet, the GaN structures bonded onto the substrates also formed smooth facets after cleavage.

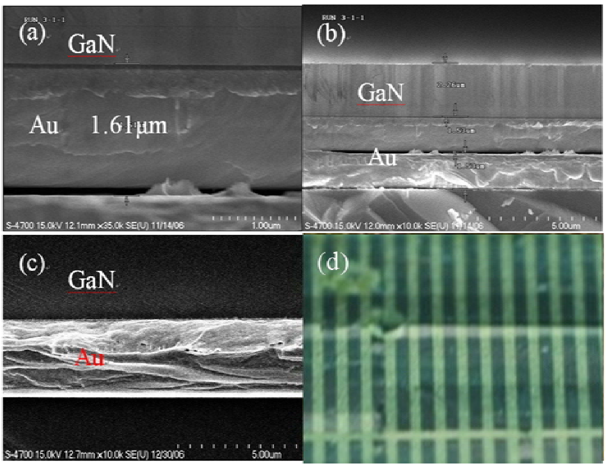

Figure 2 (a) (b) Cross sectional SEM images of the bonding zone with Cr/Pt/Au bonding metal at 400 °C and 2.2 MPa bonding pressure. (c) Cross sectional SEM images of the sample bonded with 11 MPa bonding pressure. (d) Top view OM image of the LD structure transferred onto GaAs.

The InGaN/GaN lasers that we have fabricated are 1-mm long with facets produced by cleaving along the *m* plane of the GaN structures. Figure 3 shows the OM and SEM images of the GaN-based LDs bonded onto the GaAs substrates.

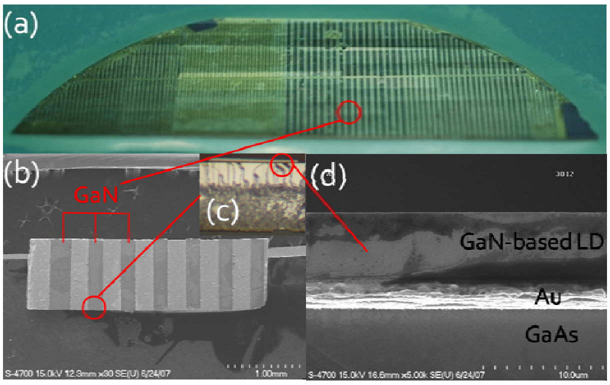

Figure 3 (a) The image of the LD structures after cleavage. (b) The SEM image of cleaving LDs. (c) Cross sectional OM images of the sample. (d) Cross sectional SEM images of the sample.

3 Results and discussion The cleaved facets of GaN laser diodes have been characterized using atomic force microscopy (AFM). The results of AFM analysis are shown in Fig. 4.

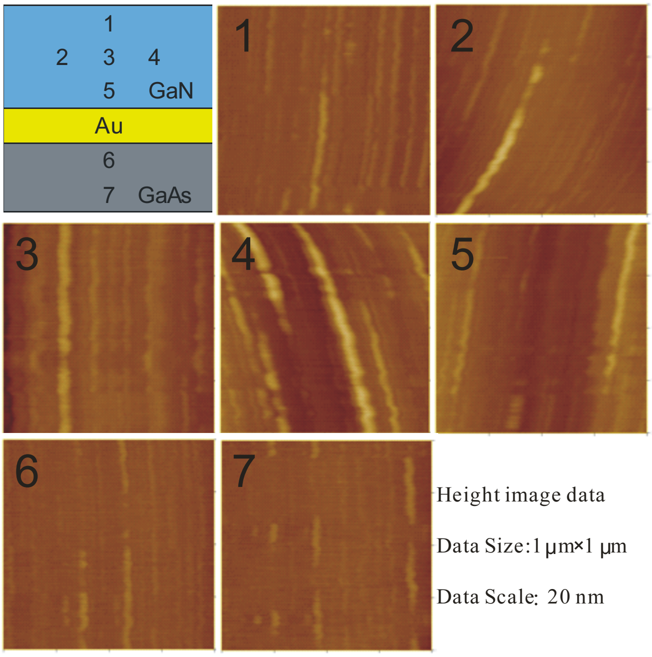

Figure 4 AFM images of cleaved facets of the GaN.

D. A. Stocker has developed a theory that the ratio of the actual power reflectivity to the power reflectivity for a perfectly smooth facet is given by

$$\frac{R(\Delta d)}{R_0} = e^{-16\pi^2 (n\Delta d/\lambda_0)^2} \qquad (1)$$

where R_0 is the reflectivity of a perfectly smooth facet and Δ d is the rms roughness. For an uncoated facet, $R_0 = r^2 = (n_1 - n_2)^2 / (n_1 + n_2)^2$ [13].

Theoretical calculations indicated that a rms roughness of less than 4 nm is required to obtain the reflectivity of greater than 90% for the laser cavity. The results of AFM analysis and the reflectivity of theoretical calculations are shown in Table 1.

Table 1 The ratio between actual reflectivity and the reflectivity for a perfectly smooth facet by theoretical calculations.

Point	Roughness (rms)	Reflectivity
1	0.58±0.05 nm	99.8%
2	1.20±0.05 nm	99.2%
3	1.27±0.05 nm	99.0%
4	1.89±0.05 nm	97.9%
5	1.60±0.05 nm	98.5%
6	0.64±0.05 nm	-
7	0.56±0.05 nm	-

There is no minimum reflectivity required for laser action, since the round-trip gain can be increased by lengthening the cavity or coating the facets, but the performance of the laser is strongly degraded by facet roughness. In order to achieve reflectivities of greater than 90%, facets with a rms roughness of less than 4 nm are required.

4 Conclusion The cleaved facets of GaN laser diodes have been characterized using atomic force microscopy (AFM) with less than 2 nm roughness. The present study demonstrated the feasibility of transferring GaN laser structures onto other more appealing substrates for formation of laser cavities. Theoretical calculations indicated that a rms roughness of less than 2 nm obtain the reflectivity of greater than 95% for the laser cavity.

We have demonstrated a method for fabricating III–N lasers with cleaved facets. A model has been used which shows that the power reflectivity of laser facets.

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