Facet roughness analysis for InGaN/GaN lasers with cleaved facets

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Atomic force microscope images reveal a root-mean-square roughness $\Delta d = 16$ nm for InGaN/GaN double-heterostructure laser structures with cleaved *a*-plane facets. The *c*-plane sapphire substrate cleaves cleanly along both the *a* and *m* planes. A theoretical model is developed which shows that the power reflectivity of the facets decreases with roughness by a factor of $e^{-16\pi^2(n\Delta d/\lambda_0)^2}$, where *n* is the refractive index of the semiconductor and λ_0 is the emission wavelength. Laser emission from the optically pumped cavities shows a TE/TM ratio of 100, an increase in differential quantum efficiency by a factor of 34 above threshold, and an emission line narrowing to 13.5 meV. © *1998 American Institute of Physics.* [S0003-6951(98)00340-4]

In the GaAs and InP material systems, laser facets are formed by cleaving the substrate and epilayers along a mutual cleavage plane. The formation of facets in GaN grown on sapphire, however, has proven to be more difficult, because sapphire does not cleave readily. For this reason, a variety of methods, including dry etching,[1–3] polishing,[4] sawing,[5–7] and cleaving on a variety of substrates[8–12] has been used for fabricating lasers in III–N materials. In this study, we report on facet fabrication and roughness analysis for cleaved-facet InGaN/GaN double-heterostructure laser structures.

The InGaN/GaN double-heterostructure lasers were prepared as follows: After an initial 10-μm-thick buffer layer of GaN was grown on *c*-plane sapphire by hydride vapor phase epitaxy, a 0.5-μm GaN bottom cladding layer, a 1000-Å $In_{0.09}Ga_{0.91}N$:Si active region, and a 2200-Å GaN top cladding layer were deposited by metal–organic vapor phase epitaxy. Waveguide calculations reveal that the double heterostructure is a single-mode waveguide with an active region confinement factor $\Gamma = 0.06$.

Sapphire does not cleave readily, and there has been some disagreement as to whether it cleaves at all. Some reports indicate that sapphire has no cleavage planes, but *parts* along both the (0001) and $(01\overline{1}2)$ planes.[13] Cleavage is the ability of a crystal to break along definite crystallographic directions, while parting is the splitting of a crystal along a plane that does not normally cleave, and can be caused by stress, defects, or other perturbations of the crystal structure.[13] Other reports indicate parting only along the (0001) plane when a layer of defects is present, and no cleavage in any direction.[14] We have observed cleavage along both the *a* $(11\overline{2}0)$ and the *m* $(10\overline{1}0)$ planes. In preparation for cleaving the substrate is thinned to 200 μm, polished, and scribed. After being mounted with wax to a thin piece of flexible metal, the samples are cleaved along the scribes by bending the metal.

Figure 1(a) is a cross-sectional atomic force microscope (AFM) image of a cleaved GaN *a* plane, showing striations with a root-mean-square (rms) facet roughness of 16 nm. These striations may be caused by misalignment of the epilayer *a* planes with the sapphire *m* planes. Figure 1(b) shows a scanning electron microscope (SEM) image of a cleaved *m* plane GaN facet. The surface is very smooth, except for 90-nm steps that occur at 2.2-μm intervals. These steps have

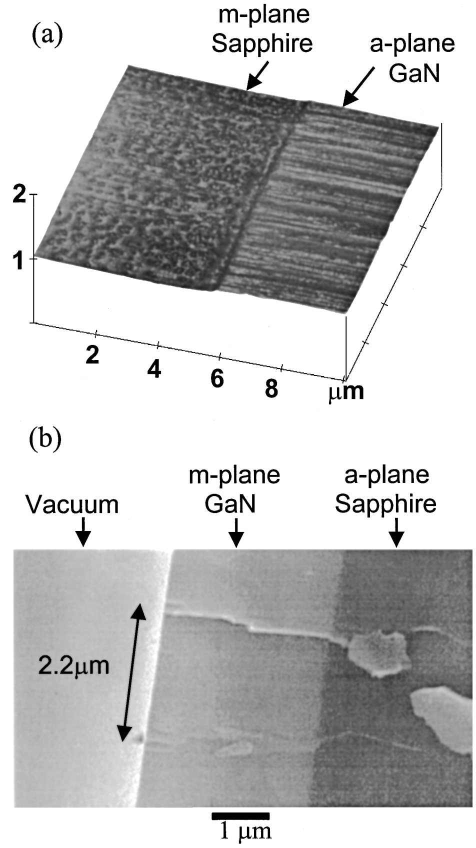

FIG. 1. Images of cleaved GaN on *c*-plane sapphire. (a) AFM image of cleaved *a*-plane GaN, showing striations with a rms roughness of 16 nm. All units are in μm. (b) SEM micrograph of cleaved *m*-plane GaN, showing 90-nm steps occurring every 2.2 μm.

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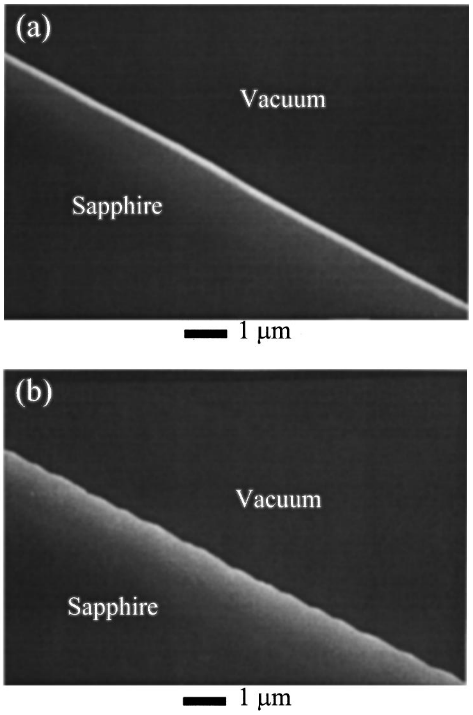

FIG. 2. SEM images of cleaved sapphire. (a) Sapphire cleaved smoothly along its *a* plane. (b) An attempt to cleave sapphire 2° off of its *a* plane, showing a rough edge.

been observed previously and have been attributed to a 2.4° rotation of the GaN *m* plane with respect to the sapphire *a* plane.[15] The rotation of the epilayers with respect to the sapphire substrate is further supported by crystallographic wet etching of GaN,[16] in which the crystal planes formed in the GaN are misaligned by approximately 2° with the cleavage planes of sapphire. Because of the hardness of the GaN epilayers, the steps can propagate several microns into the sapphire substrate, as seen in Fig. 1(b). The steps disqualify the GaN *m* plane from use in fabricating laser facets,[17] unless the sapphire substrate could be cleaved at an angle 2.4° off of the *a* plane.

Typical results of cleaving sapphire are shown in Fig. 2. Figure 2(a) shows an edge cleaved exactly along the *a* plane. Figure 2(b) shows a jagged edge of the same piece of sapphire, this time broken 2° off of the *a* plane. The two distinct results show that the *a* plane is a cleavage plane of sapphire. It also cleaves cleanly along the *m* plane, but cleaving along other crystal planes perpendicular to the *c* plane was not successful.

The method used to analyze laser facets in Ref. 17 assumes a step-like surface like that observed in cleaved *m* plane GaN. The striations in the *a*-plane GaN facets are not step-like, so we have developed a model, which gives the reflectivity of facets with Gaussian roughness distributions. We take the reflected wave to be a superposition of Huygens elementary waves generated at the surface of the laser facet. Because we are applying the model to a laser cavity, only the specular, normal-incidence reflection is considered. We assume a facet with a rms roughness Δd that follows a Gaussian distribution. The roughness of the facet causes phase differences in the elementary waves generated at the surface, broadening the phase of the reflected wave by

$$\Delta\phi = \frac{4\pi n \Delta d}{\lambda_0}, \tag{1}$$

where n is the refractive index of the semiconductor and λ_0 is the emission wavelength in vacuum. For an incident wave with a magnitude U_0, the reflected wave is a superposition of all of the reflected elementary waves, which have a Gaussian phase shift distribution. The magnitude U of the reflected wave as a function of phase shift ϕ has a standard deviation $\Delta\phi$ and is dependent upon the incident magnitude U_0, the amplitude reflection coefficient r, and the phase broadening $\Delta\phi$:

$$U(\phi) = \frac{U_0 r}{\sqrt{2\pi}\Delta\phi} e^{-\phi^2/2\Delta\phi^2}. \tag{2}$$

Because the wave is monochromatic, the superposition of all of the waves in this distribution of phase shifts results in a wave with a magnitude U_f given by

$$U_f = \int_{-\infty}^{\infty} U(\phi) e^{i\phi} d\phi = U_0 r e^{-\Delta\phi^2/2}. \tag{3}$$

The exponential factor is interpreted as a decrease in the amplitude reflectivity r. Substituting Eq. (1) into Eq. (3), we find that the ratio of the actual power reflectivity to the power reflectivity for a perfectly smooth facet is given by

$$\frac{R(\Delta d)}{R_0} = e^{-16\pi^2 (n\Delta d/\lambda_0)^2}, \tag{4}$$

where R_0 is the reflectivity of a perfectly smooth facet. For an uncoated facet, $R_0 = r^2 = (n_1 - n_2)^2/(n_1 + n_2)^2$.

The model was verified by examining the intensity of a HeNe laser ($\lambda_0 = 633$ nm) reflected off of a roughened silica surface. The results of this test are shown in Fig. 3(a), along with the theoretical curve. The values in Fig. 3(a) are normalized so that 1.0 corresponds to the maximum signal observed for a smooth surface. The theory is next applied to the InGaN/GaN laser structure with an emission wavelength of 395 nm. The GaN refractive index at 395 nm, 2.54,[18] is used, since the confinement factor for the guided mode is 0.94 in the GaN cladding layers. The normalized reflectivity of a GaN surface as a function of surface roughness is shown in Fig. 3(b), along with published roughness measurements on GaN-based laser structures. The 16-nm roughness of our facets corresponds to a decrease in reflectivity to 20% of R_0, or 4%. 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.

The InGaN/GaN lasers that we have fabricated[8] are 1-mm long with facets produced by cleaving along the *a* plane of the double heterostructure. The transverse electric (TE) modes are enhanced due to the lower reflection of transverse magnetic (TM) modes at the facets of the lasers, confirming feedback from the facets. Figure 4 shows that the TE/TM ratio is 100 at an incident optical pumping power density of 3.1 MW/cm^2. The emission linewidth decreases from 115 meV in the spontaneous emission regime to 13.5 meV in the lasing regime. A large change in differential

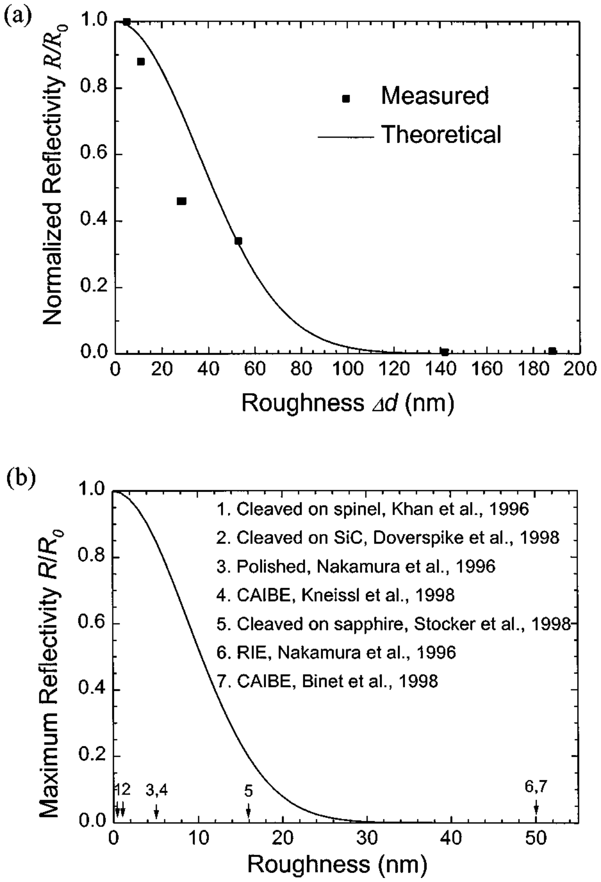

FIG. 3. Power reflectivity of facets as a function of surface roughness. R_0 is the roughness for a perfectly smooth facet, as given by the Fresnel equations. (a) Silica for $\lambda_0 = 633$ nm. (b) InGaN/GaN laser structure for $\lambda_0 = 395$ nm.

quantum efficiency occurs in the lasing regime, as shown in the inset of Fig. 4, where the slope of each curve is normalized to 1 below threshold. The differential quantum efficiency increases by a factor of 34 above threshold, and the differential change in peak intensity increases by a factor of 210.

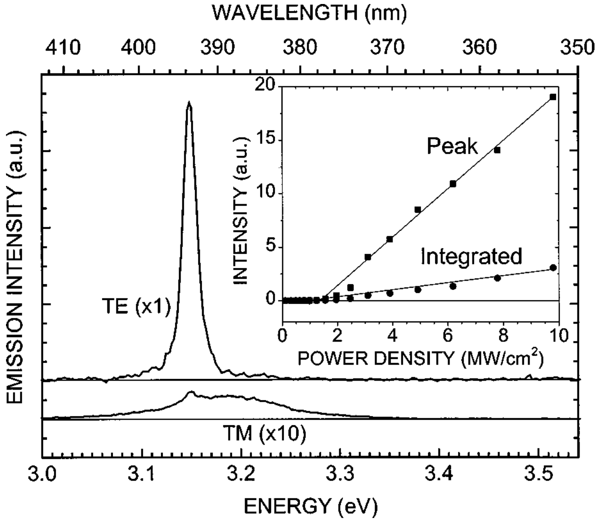

FIG. 4. Polarized spectra of an optically pumped InGaN/GaN laser at $2.4I_{\text{threshold}}$, showing a TE/TM ratio of 100. Inset shows peak and integrated emission intensity as a function of incident pumping power density, revealing a 34-fold increase in differential quantum efficiency upon lasing.

In conclusion, we have demonstrated a method for fabricating III–N lasers with cleaved facets. A model has been developed which shows that the power reflectivity of laser facets decreases as a result of facet roughness Δd by a factor of $e^{-16\pi^2(n\Delta d/\lambda_0)^2}$. Uncoated cleaved *a*-plane GaN facets on *c*-plane sapphire are shown to have a rms roughness of 16 nm, which corresponds to a reflectivity of only 4%. Misalignment of the GaN *m* plane with the cleavage planes of sapphire prevented it from being used for laser facets, and the *c*-plane sapphire did not break smoothly in any direction other than the *a* and *m* planes. The laser emission from our optically pumped cavities shows a TE/TM ratio of 100, an increase in differential quantum efficiency by a factor of 34 at threshold, and a line narrowing to 13.5 meV.

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