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GaN-based lasers on SiC: influence of mirror reflectivity on L–I characteristics

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Abstract

The influence of the mirror reflectivity on the *L–I* characteristics of GaN-based lasers has been studied. A cleaved, Al-coated fiber is used as an external micro-mirror to control the reflectance of the end facets allowing for a continuous adjustment of mirror losses of a particular laser. In contrast to other methods, this eliminates all ambiguities usually arising from the comparison of different or differently coated devices. An increase in the single facet external quantum efficiency by 45% is observed for uncoated lasers and simultaneously, the threshold current is reduced by 12%. Internal losses of approximately 20–30 cm^{-1} are derived from the differential quantum efficiency variation depending on the particular device under investigation. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

GaN-based ultra-violet-emitting laser diodes are of huge importance for optical data storage and spectroscopic applications [1,2]. Beside rigid requirements on epitaxial growth, process technology, etc. the quality (i.e., the reflectivity) of the laser mirrors is of significant importance. At 410 nm wavelength, the refractive index of GaN is approximately 2.5 resulting in a reflectance of perfect GaN/air interfaces of merely 0.18 according to Fresnel equations. The facet reflectivity is further reduced by any roughness of the interface [3]. Whereas laser cavities on sapphire substrates are usually made by dry chemical etching [4], resonators on SiC substrates benefit from the feasibility of cleaving facets usually yielding superior (i.e., smoother) surfaces and thus higher reflectivity mirrors. We investigate the influence of mirror reflectivity on the $L-I$ characteristics of a GaN/SiC-based laser by changing the reflectance of cleaved facets using an Al-coated fiber as an external micro-mirror. This allows for mirror-loss variation of a particular laser diode avoiding all ambiguities usually arising from the comparison of different and/or differently coated devices. Epitaxial and technological variations among different

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lasers can be excluded by this method. The influence of mirror quality on the output characteristics of the laser diode can be examined by a variation of the effective mirror reflectance. The low dependence of the refractive index on the Al content together with epitaxial limits on Al content and AlGaN thickness yield a comparably weak optical confinement making the waveguide susceptible to absorption losses. Thus, it is important to determine the waveguide losses occurring in the structure under investigation.

2. Experimental procedure

The experimental setup is shown in Fig. 1. A cleaved fiber facet with 100 μm diameter, coated with 200 nm thick Al was used, as an external micro-mirror. The coated fiber with an estimated reflectance of about 0.92 (at $\lambda = 410$ nm) [5] is mounted on a piezo-controlled *xyz*-stage to align the micro-mirror in front of one of the laser facets (resolution approximately 20 nm). The light output is collected from the opposite facet by a microscope objective and imaged on a photodiode. The sample itself is mounted on a 4-axis waveguide manipulator, which allows for the additional correction of tilt errors. Short-pulsed excitation with pulse lengths between 50 and 200 ns at pulse repetition rate of few kHz is applied to obtain a typical $L - I$ characteristic of the devices.

The laser diodes under investigation are separate confinement double heterostructure (SCH) devices grown by MOVPE on SiC substrates. Oxide stripe lasers with a 600 μm × 5 μm geometry have been fabricated from those structures, and the details are reported elsewhere [6]. The facets are formed by cleaving the thinned substrate. Within the study we concentrate on laser diodes with two uncoated facets.

3. Results and discussion

At constant current the output power obtained from one laser facet depends strongly on the distance between the opposite facet and the micro-mirror. Fig. 2 depicts the output power of a single-side HR coated laser at constant current with a micro-mirror approaching the uncoated facet. Strong oscillations enveloped by an exponential decay are observed. Divergence of the laser beam decreases the feedback with increasing distance and accounts for the exponential decay. The oscillations arise from coupling a second external resonator formed by the micro-mirror, the air gap

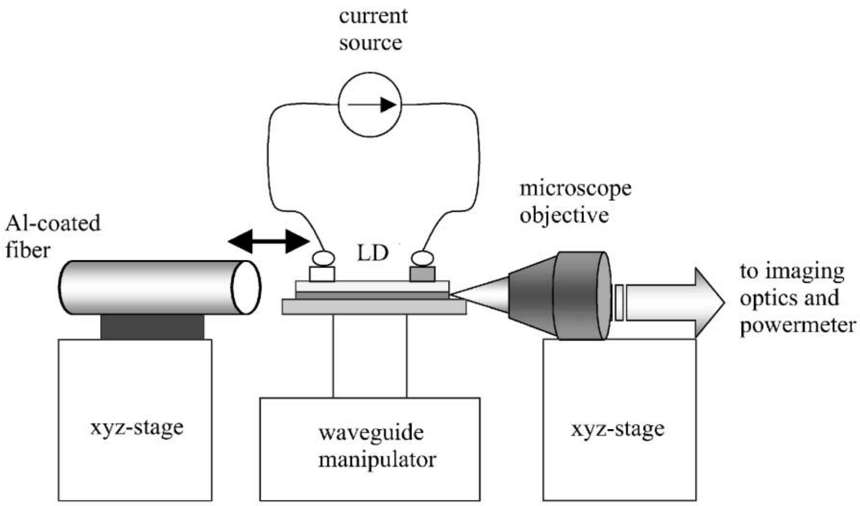

Fig. 1. Experimental setup.

and the GaN facet to the laser. The behavior of this external cavity depends on the effective reflectance R_{eff} being a yet unknown function of the mode shape, emission wavelength, micro-mirror distance, and reflectances of the uncoated GaN-facet (R_2) and micro-mirror (R_{mm}). The output power oscillates according to this effective reflectance comparable to the situation of butt coupling a Fabry–Perot laser into an optical fiber [7]. Detailed modeling of the effective mirror reflectance is currently under investigation. In the following the boundary cases (micro-mirror far away and in contact with facet) are taken to estimate the internal losses $\langle\alpha_i\rangle$. Atomic force microscopy (AFM) reveals that the cleaved facets of the GaN/SiC lasers are extremely smooth with a root mean square (rms) roughness of about 1 nm (Fig. 3). Thus according to Stocker et al. [3] we can assume the reflectance R of the uncoated facet to be 0.18. With the micro-mirror being in contact with the facet a reflectance of 0.92 is estimated (i.e., the reflectivity of the Al mirror at 410 nm). From this the distributed mirror losses α_m of the laser structure can be calculated according to

$$\alpha_m = \frac{1}{2l}\ln\left(\frac{1}{R_1 R_2}\right) \quad (1)$$

with l being the cavity length and R_1, R_2 the reflectivities of the facets. For an uncoated laser we

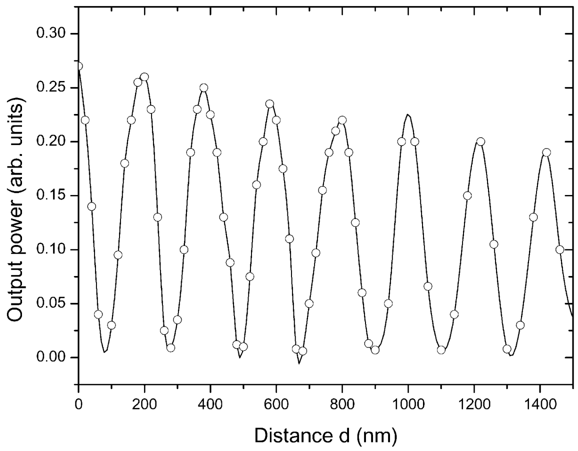

Fig. 2. Optical output power as function of micro-mirror distance from laser facet. Oscillations of the output according to the effective reflectance are observed. The exponential decay of the envelope is caused by reducing the overall feedback into the laser mode with increasing distance.

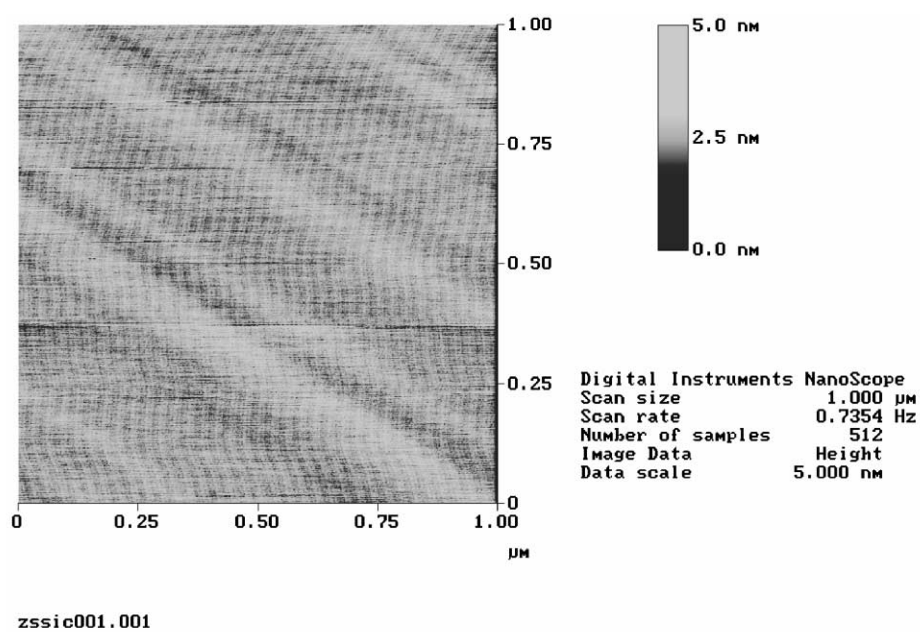

Fig. 3. Atomic force micrograph of a cleaved GaN/SiC laser facets revealing a root mean square (rms) roughness of about 1 nm.

assume $R_1 = R_2 = 0.18$ without and $R_1 = 0.18$, $R_2 \approx 0.92$ with the micro-mirror in contact with one facet, respectively. Thus, for a 600 μm long device the distributed mirror losses are without and with micro-mirror 28.6 and $15\,\text{cm}^{-1}$, respectively.

The differential quantum efficiency η_d is given by [8]

$$\eta_d = \frac{\eta_i \alpha_m}{\langle \alpha_i \rangle + \alpha_m} \propto \frac{\partial L}{\partial I}, \quad (I > I_{th}), \tag{2}$$

η_i being the internal quantum efficiency, $\langle \alpha_i \rangle$ and α_m the internal and the distributed mirror losses, L the output power, and I, I_{th} the forward and threshold currents, respectively. In the following discussion, we use the differential quantum efficiency in its single-facet definition, i.e., output power L being measured from one facet and external quantum efficiency derived from this. Experimentally we observe the expected dependence of η_d and I_{th} on the change in mirror reflectivity (Fig. 4). As the micro-mirror approaches the end facet, both η_d and I_{th} improves. When the micro-mirror is in contact with the facet corresponding to the highest output power at constant current, the single-facet external quantum efficiency is improved by approximately 45%

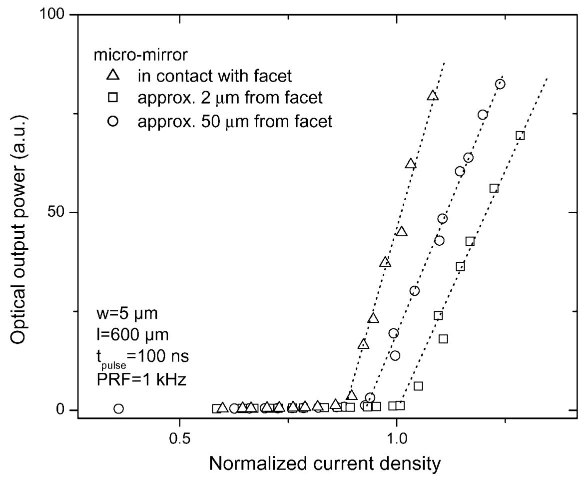

Fig. 4. $L-I$ characteristics of an uncoated laser in dependence of the micro-mirror position. Output power L as measured from the uncoated facet. Threshold current reduction and increasing slope efficiency are achieved by increasing the effective reflectance of the opposite facet by means of a micro-mirror.

and the threshold current is reduced by 12% as compared to the device with the micro-mirror 50 μm away from the facet. Since only very faint oscillations in output power are observed for distances larger than 40 μm this configuration can be treated equivalent to no micro-mirror. From the increase in single-facet external quantum efficiency the internal absorption losses $\langle \alpha_i \rangle$ of the laser can be calculated using Eqs. (1) and (2). Taking the ratio of the measured differential quantum efficiency η_{d1} (micro-mirror far away) and η_{d2} (micro-mirror in contact) and using the above-estimated mirror losses according to Eq. (1), values between 20 and $30\,\text{cm}^{-1}$ are obtained as internal losses depending on the particular examined device. This number agrees reasonably well to data previously reported by Nakamura [9].

4. Summary

We showed that external micro-mirror can reduce current threshold significantly while improving the single-facet differential quantum efficiency. This can be either due to by increasing the effective mirror reflectance or adjusting large-scale striations of the cleaved facets thus homogenizing the rms mirror roughness. A reduction of threshold up to 12% and a 45% increase of differential quantum efficiency are achieved. The estimated internal losses for the SCH-laser diodes derived from change in differential quantum efficiency are approximately 20–30 cm^{-1}.

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References

[1] S. Nakamura, G. Fasol, The Blue Laser Diode — GaN based Light Emitters and Lasers, Springer, Heidelberg, 1997.
[2] S. Nakamura, Phys. Stat. Sol. A 176 (1) (1999) 15.
[3] D.A. Stocker, E.F. Schubert, W. Grieshaber, K.S. Boutros, J.M. Redwing, Appl. Phys. Lett. 73 (14) (1998) 1925.
[4] M. Scherer, V. Schwegler, M. Seyboth, F. Eberhard, C. Kirchner, M. Kamp, G. Ulu, M.S. Ünlü, R. Gruhler, O. Hollricher, J. Crystal Growth, to be published.
[5] E.D. Palik, Handbook of Optical Constants of Solids, Academic Press, New York, 1985.
[6] V. Härle, A. Lell, S. Bader, B. Hahn, H.J. Lugauer, F. Kühn, A. Weimar, Phys. Stat. Sol., to be published.
[7] Y. Sidorin, D. Howe, Appl. Opt. 37 (15) (1998) 3256.
[8] L.A. Coldren, S.W. Corzine, Diode Lasers and Photonic Integrated Circuits, Wiley, New York, 1995.
[9] S. Nakamura, MRS Internet J. Nitride Semicond. Res. 2 (1997) 5.