Demonstration of a novel type of tapered laser based on lateral selective wet oxidation

Kurt De Mesel, Carl Sys, Steven Verstuyft, Ingrid Moerman, Peter Van Daele and Roel Baets
Department of Information Technology, Gent University – IMEC, St.-Pietersnieuwstr. 41, Gent, Belgium
tel.: +32 9 264 8933 / fax: +32 9 264 3593 / e-mail: kurt.demesel@intec.rug.ac.be

A new technique for the monolithic integration of a laser with a spot size converter is presented. The introduction of the wet thermal selective oxidation of an $Al_xGa_{1-x}As$ layer with a high Al-composition simplifies the fabrication to one planar epitaxial growth step and one non-critical conventional etch. We report on the design, fabrication and performance of a 980nm InGaAs/GaAs strained quantum well tapered oxide confined laser with CW threshold currents of 25mA and differential quantum efficiencies of 21%/facet. The integrated spot size converter effectively reduced the horizontal and vertical FWHM to 7.5° and 13.5°, respectively.

1. Introduction

Single-mode fiber coupling is a challenging task in laser diode packaging. The coupling problem arises from the shape and size difference between the small asymmetric laser mode and the large circular fiber mode. Coupling losses of 8-10 dB and submicron alignment tolerances are common values for directly butt-coupled devices. There are several approaches to improve the fiber-chip coupling efficiency, such as the use of microlenses or tapered/lensed fibers [1] [2]. However, these approaches still suffer from the field mismatch problem, since only the size and not the shape of the optical mode is converted. The reduction of the coupling loss is also at the expense of the alignment tolerance, resulting in high packaging costs, which can amount up to 90 % of the total cost. During the past years, many research groups have therefore focused on the monolithic integration of mode size converters with III-V semiconductor components, in order to achieve a larger and more symmetric field profile at the device facet. This monolithic integration, however, often requires complex (re)growth and processing techniques, which all seriously complicate the fabrication process [3]. In this paper we present a novel type of short wavelength tapered laser which only requires one planar growth and one non-critical standard etch step. The key to this simple fabrication scheme is the introduction of a thin $Al_xGa_{1-x}As$-layer with a high Al composition (typ. >90%), which is selectively oxidized in a steam environment.

The high selectivity of the oxidation process and the properties of the oxide - low refractive index and electrical isolation – can be used to define current windows that are at the same time optical apertures. Recently, some research groups reported on the use of oxide layers for optical and current confinement in ridge lasers [4]. This offers the ability to create a self-aligned waveguide with a current aperture in one single epitaxial growth step. Current spreading in these devices is strongly reduced because of the placement of one or more thin oxide layers adjacent to the active layer. The tapered laser we describe here is a 980nm InGaAs/GaAs strained quantum well laser with an oxide window above the active layer. For the first time, however, the layer structure and position of the oxide are chosen such that a simple lateral tapering of the broad ridge adiabatically transforms the strongly confined laser mode in both lateral and transversal direction into a fiber adapted mode at the output facet.

2. Design, fabrication and performance

The design of the tapered oxide confined laser is inspired by the more conventional approach as reported in [5] where a small rib is placed on top of a broad fiber-adapted waveguide. In that design the optical mode is concentrated in the upper waveguide when the upper rib is broad. A gradual narrowing of this rib expands the tightly confined mode into the underlying mesa. The fabrication of this device requires one planar epitaxial growth and two etch steps (and hence also two masks which have to be carefully aligned) to define both mesas. The mode transformation has to be completed before the taper tip reaches a certain minimum width to avoid the problems that arise with the lithography and contacting of thin ridges.

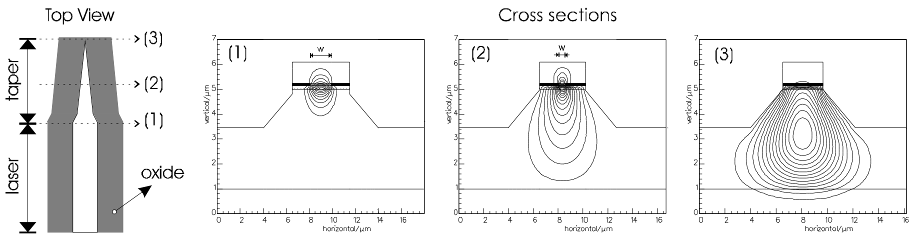

Fig. 1: Design of the tapered laser: top view and different cross sections with the evolution of the optical field along the taper.

The oxide-confined device operates in a similar way but benefits from the selective wet oxidation to further simplify the processing and improve the device characteristics. The small upper rib is now replaced by an oxide-confined waveguide, which is self-aligned with the broad mesa (Fig. 1). Now only one non-critical standard etch step is required in addition to the planar epitaxial growth. Table 1 summarizes the layer structure. The upper waveguide is formed by wet oxidation (45' at 410°C) of the thin $Al_{0.9}Ga_{0.1}As$-layer, which is sandwiched between the upper core and cladding. The SEM-image in Fig. 2 clearly shows the dark oxide that creates a 1.8µm wide oxide window in the center. The layer stack is designed so that the light resides in the upper core when the $Al_{0.9}Ga_{0.1}As$ is not oxidized (central slab in the laser section) and in the thick lower core layer when the $Al_{0.9}Ga_{0.1}As$ is oxidized (central slab in the output section). This ensures the expansion into the lower waveguide as the oxide window is closed by narrowing the broad ridge. It should be noted that very sharp taper tips can now easily be achieved. The layer stack is found as a trade-off between enhancing the confinement in the quantum well for the unoxidized slab and switching of the mode to the lower waveguide for the oxidized slab.

A standard wet etch in a H_2SO_4:H_2O_2:H_2O (1:1:18) solution was used to fabricate the device, creating the typical waveguide shape as shown in Fig. 1. The slanted edges help to push the expanded mode deeper into the underlying core, but are not essential for a good taper operation.

The spot size converter was modeled with a 3D eigenmode expansion algorithm, where the optical properties are fully characterized by the local modes of the structure and the coupling matrices that link them [6]. Fig. 1 illustrates the evolution of the mode as the width w of the oxide window decreases. In the beginning the mode changes only slightly and a rapid tapering is allowed. Below w=1.1µm the mode begins to change shape more rapidly and starts to expand into the underlying mesa. The taper angle must be kept small enough to ensure an adiabatic mode transformation. This critical taper angle depends on the thickness of the lower core layer and should be smaller for thicker guides because the overall mode change is larger.

Special attention was paid to obtaining a good control of the exact oxide depth. This resulted in a reduction of the Al-content of the to-be-oxidized layer to 90% and lowered oxidation temperature of 410°C.

Table 1: Epitaxial structure.

Material	Thickness [nm]	Doping [cm^{-3}]
GaAs	50	p=1e19
$Al_{12.5}Ga_{87.5}As$	50	p=5e17
$Al_{25}Ga_{75}As$	50	p=5e17
$Al_{37.5}Ga_{62.5}As$	50	p=5e17
$Al_{50}Ga_{50}As$	1000	p=5e17
$Al_{90}Ga_{10}As$	100	p=5e17
$Al_{15}Ga_{85}As$	97	uid
GaAs	1.5	uid
InGaAs	6	uid
GaAs	1.5	uid
$Al_{15}Ga_{85}As$	40	uid
$Al_{50}Ga_{50}As$	4000	n=5e17
$Al_{55}Ga_{45}As$	1000	n=5e17

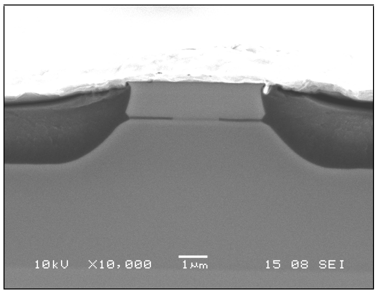

Fig. 2: SEM-image of the laser cross-section.

A mask set has been designed to demonstrate the operation of this new taper. Spot size converters consisting of two linear sections were implemented: an initial 90μm long rapid tapering reducing the oxide window from 1.8μm to 1.1μm width, followed by the slowly tapered section where the actual mode transformation takes place. A narrowing of 100nm per 55μm propagation yields a safe design for the 4um thick guide of the device we report here. The evolution of the power fraction in the fundamental mode is shown in Fig. 3 and confirms the adiabaticity of this design. A lateral view on the expanding optical field is presented in Fig. 4. Apart from this design other tapers with steeper (100nm/35μm, 100nm/45μm) and flatter (100nm/75μm) critical sections were defined for comparison. These four types of tapered lasers were repeated on the mask with a slight variation of their width to account for a possible deviation of the oxidation depth: devices that were 400nm and 200nm wider and narrower were included.

It is important to notice that the processing complexity is significantly reduced as compared to other taper designs, since no submicron features have to be defined (minimum rib width of 8um). These broad ridges also avoid problems with the electrical contacting of the device.

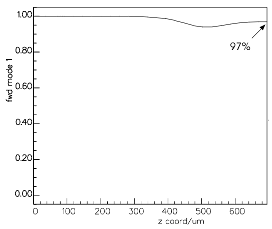

Fig. 3: Power fraction in the fundamental mode as function of propagation distance.

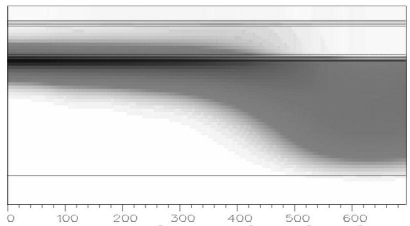

Fig. 4: Lateral view on the mode evolution in the spot size converter.

The metallisation covers the spot size converters over their entire length. The choice of a completely active taper has its influence on the threshold current and efficiency, but on the other hand it avoids the risk of high absorption losses in the passive section of the taper. Untapered reference lasers (L=800μm, w=1.8μm) exhibit threshold currents of 15mA and external differential quantum efficiencies of 21%/facet. All tapered structures contain an 800μm long laser section. The threshold current of these devices ranges from 25mA (shortest tapers) to 34mA (longest tapers). The external differential quantum efficiency amounts up to 23% (shortest tapers) and 16% (longest tapers). This surprisingly high value can be explained by a lower reflection coefficient for the tapered facet and indicates that the radiation losses from the tapered region are very low. Both measured and simulated farfield emission patterns are shown in Fig. 5 and a good agreement is observed. The horizontal and vertical full widths at half maximum (FWHM) are drastically reduced from 21° and 23° for the untapered lasers to 7.5° and 13.5° respectively for the tapered devices, in close agreement with the calculated values.

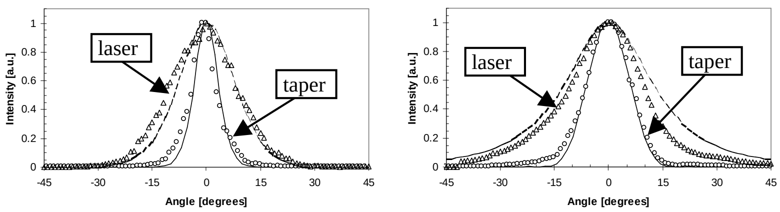

Fig. 5: Horizontal (left) and vertical (right) farfield emission patterns of tapered and untapered lasers. (solid lines: simulation; dots: measurement)

After this successful demonstration of the tapered oxide confined laser a second set of devices has been fabricated from the same wafer to check the robustness of the design and the reproducibility of the fabrication process. The same fabrication procedure (etching, oxidizing and contacting) was followed and a comparison of the characteristics of this new set of devices shows a nearly identical behavior (Fig. 6).

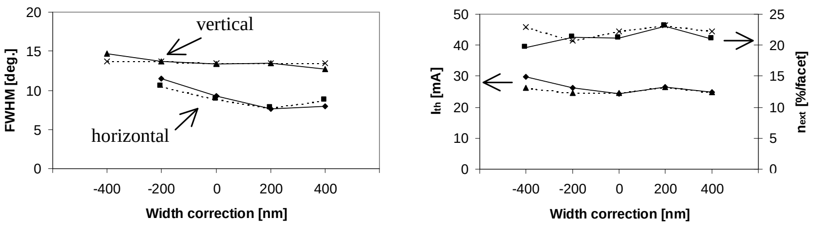

Fig. 6: Characteristics of tapered lasers from different batches (first fabrication: solid lines, second fabrication: dashed): horizontal and vertical FWHM (left); threshold current and external efficiency (right). The width indicates the extra width with respect to the design (cf. the different versions that are implemented on the mask).

3. Conclusion

We have demonstrated a novel technique for the monolithic integration of a laser with a spot size converter. The selective wet oxidation of a thin AlGaAs layer simplifies the fabrication and enhances the device performance. The tapered laser shows very low transformation loss and efficiently reduces the farfield FWHM. The reproducibility of the fabrication process and robustness of the design were shown.

4. References

[1] N.Kalonji and J.Semo, "High efficiency, long working distance laser diode to single mode fiber coupling", *Electron. Lett.* **30**, pp.892-894, (1994).

[2] H.Presby and C.Edwards, "Near 100% efficient fiber microlenses", *Electron. Lett.* **28**, pp.582-584 (1992).

[3] I.Moerman, P.Vandaele and P.Demeester, "A review on fabrication technologies for the monolithic integration of tapers with III-V semiconductor devices", *IEEE J. Sel. Top. Quant. Electron.* **3**, pp.1308-1320 (1997).

[4] J. Heerlein, M. Grabherr, R. Jäger and p. Unger, "Single-mode AlGaAs-GaAs lasers using lateral confinement by native-oxide layers", IEEE Phot. Technol. Lett. **10**, pp.498-500 (1998).

[5] G. Vawter, R. Smith, H. Hou and R. Wendt, "Semiconductor laser with tapered-rib adiabatic-following fiber coupler for expanded output-mode diameter", IEEE Phot. Technol. Lett. **9**, pp. 425-427 (1997).

[6] Fimmprop-3D propagation tool from Photon Design; http://www.photond.com.