Reliability and Output Power Improvement of GaAs Nano-Ridge Lasers Integrated on 300 mm Silicon

Ping-Yi Hsieh[1,*], Peter Swekis[1], Huseyin Sar[1], Davide Colucci[1,2], David Coenen[1], Debi Prasad Panda[1], Alexey Milenin[1], Andualem Ali Yimam[2], Geert Morthier[2], Dries Van Thourhout[2], Maumita Chakrabarti[1], Yoojin Ban[1], Filippo Ferraro[1], Didit Yudistira[1], Bernardette Kunert[1], and Joris Van Campenhout[1]

[1] *IMEC, Kapeldreef 75, 3001 Leuven, Belgium*

[2] *Photonics Research Group, Ghent University-imec, Technologiepark-Zwijnaarde 126, 9052 Gent, Belgium*

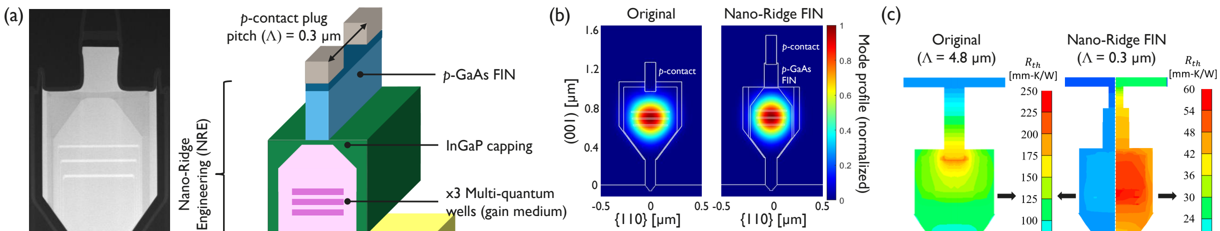
[*]*e-mail: ping-yi.hsieh@imec.be*

Abstract: Reliability-improved GaAs nano-ridge lasers are fabricated on 300 mm silicon. A novel contact-FIN-based design, including an anisotropic InGaP passivation, ensures carrier injection while pulling down the optical modes. Single-facet power exceeding 10 mW is achieved at 25 °C.

1. Introduction

Silicon photonics has revolutionized data communication. Particularly, optical I/O (input/output) interfaces have been moved closer to electrical processing units to address the ever-growing data traffic demand [1], fueled by recent advancements in artificial intelligence and high-performance computing. However, a universal solution of highly integrated on-chip light sources is still missing. The demonstration of GaAs nano-ridge lasers [2], enabled by nano-ridge engineering (NRE) [3], discloses the potential of attaining cost-effective and environmentally friendly light sources fully fabricated in a complementary metal-oxide-semiconductor (CMOS) production line. In the first nano-ridge (NR) laser design, the metal *p*-contacts are placed inside the NR waveguide, with a strong overlap between the tungsten metal plugs and the optical modes, introducing a significant optical loss. This is alleviated by using a 4.8 μm *p*-contact plug pitch (Λ) to trigger optical multimode beating, creating loss dips in the absorption spectrum [4]. Nevertheless, the current density at metal/*p*-GaAs interfaces is two orders of magnitude higher than that in the quantum wells, owing to the sparse pitch design, which results in a *p*-contact-breakdown failure mode [5].

In this work, a novel design, labelled "Nano-Ridge FIN" in Fig. 1, incorporating an anisotropic InGaP passivation layer and a contact-FIN module, is demonstrated. The optical modes are pulled down from the *p*-contacts in the NR waveguide, allowing a much denser plug pitch design. The device concept is justified by optical, electrical, and thermal simulations. In addition, key fabrication processes are discussed. Lastly, a preliminary study of device characteristics and reliability is reported.



Design	Original, ref. [2]	Nano-ridge FIN
Metal plug loss [1/cm]	1519.63*	0.26
p-doping loss [1/cm]	2.21	5.03
n-doping loss [1/cm]	0.81	1.07
Total loss [1/cm]	1522.45	6.36

Fig. 1: Design of the nano-ridge FIN lasers. (a) An HAADF-STEM image of the nano-ridge cross-section, together with a bird's eye view schematic, indicating critical design parameters. (The *p*-GaAs/*n*-GaAs layer is doped by carbon/silicon to create positive/negative charge carriers. The *i*-GaAs is an intrinsic layer with an unintentional doping.) (b) Normalized mode profiles (TE00) comparing the "Original" [2] and the "Nano-Ridge FIN" designs. The table summarizes the loss components of both designs. The contact-FIN design successfully pulls down optical modes from *p*-contacts. *The simulation considers a continuous metal contact in the out-of-plane direction, while lasing is achieved by using a 4.8 μm plug pitch to create loss dips. (c) Thermal simulation shows a much lower R_{th} of the nano-ridge FIN lasers, because of the much lower *p*-contact current density.

2. Device Concept and Simulations

Figure 1(a) shows a schematic of the nano-ridge FIN laser, jointly with a high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image, revealing the different III-V materials in the NR heterostructure after epitaxy and a FIN etch process. Two critical designs, the anisotropic InGaP capping and the *p*-GaAs contact-FIN, are employed to guarantee sufficient carrier injection and confinement in the gain volume, as well as an adequate surface passivation. Furthermore, Fig. 1(b) discloses normalized optical mode profiles and a summary of loss components, comparing the two designs. The narrow *p*-GaAs FIN (FIN width = 150 nm) pulls down optical modes from p-contacts, tremendously reducing the metal-plug-induced loss; the main loss comes from the p-doped region. This allows using a much denser plug pitch ($\Lambda = 0.3\ \mu$m) to lower the current density at metal/p-GaAs interfaces (J_{p-con}), mitigating the p-contact-breakdown failure mode [5] observed in the original laser design. Finally, it is worth noting that the denser plug pitch also improves thermal properties. Thermal simulation [6] results in Fig. 1(c) suggest that the highest thermal resistance (R_{th}, indicating the temperature hot spot) is 250 mm-K/W at the metal/p-GaAs interface for the original laser, while it decreases to 60 mm-K/W in the center quantum well in the nano-ridge FIN laser (which is still ×2 lower than R_{th} of the original laser at the same location). Based on these analyses, improvements in characteristics and reliability of GaAs nano-ridge FIN lasers are expected.

3. Device Fabrication

The GaAs nano-ridge FIN lasers are fully fabricated in imec's 300 mm CMOS pilot line. Fig. 2(a) illustrates a high-level process flow. It starts with a shallow trench isolation (STI) process standardized in CMOS foundries to fabricate Si trenches along <110> direction. After an ion implantation to form n^+-Si, a subsequent tetramethylammonium hydroxide (TMAH) wet etch creates high-aspect-ratio STI oxide trenches terminated by {111} Si facets. Next, GaAs NR are selectively grown out of the oxide trenches by means of a metal-organic vapor phase epitaxy (MOVPE) growth. Misfit defects are trapped in the high-aspect-ratio trenches, and the NR shape is precisely controlled by the nano-ridge engineering approach [3]. The nano-ridge FIN design improves upon the original design. It realizes a p-i-n diode structure by utilizing NRE to achieve an anisotropic InGaP passivation on top of a truncated GaAs pyramid, terminating the $In_{0.2}Ga_{0.8}As$/GaAs multi-quantum well gain medium. The structure is completed by a p-/p^+-GaAs layer contact-FIN. The NR uniformity is confirmed by the scanning electron microscopy (SEM) images in Fig. 2(b). After oxide coating and planarization, the p-GaAs FIN is patterned using a deep ultraviolet (DUV) lithography and a III-V dry etch selective to the InGaP layer. The wafer is then subjected to a second oxide coating and planarization step, where the process continues with the definition of etched laser mirrors; this process also defines the facet of a monitoring photodiode (PD) in a bid to enable wafer-scale laser characterization [2]. Subsequently, a pre-metal dielectric process is executed, which involves a third oxide deposition and planarization step to isolate devices from metal layers adopted for electrical connections. Lastly, the back-end-of-line process is done by precisely landing tungsten contact plugs onto the p-GaAs FIN, followed by a final metallization using a standard CMOS copper (Cu) damascene and a Cu chemical mechanical planarization.

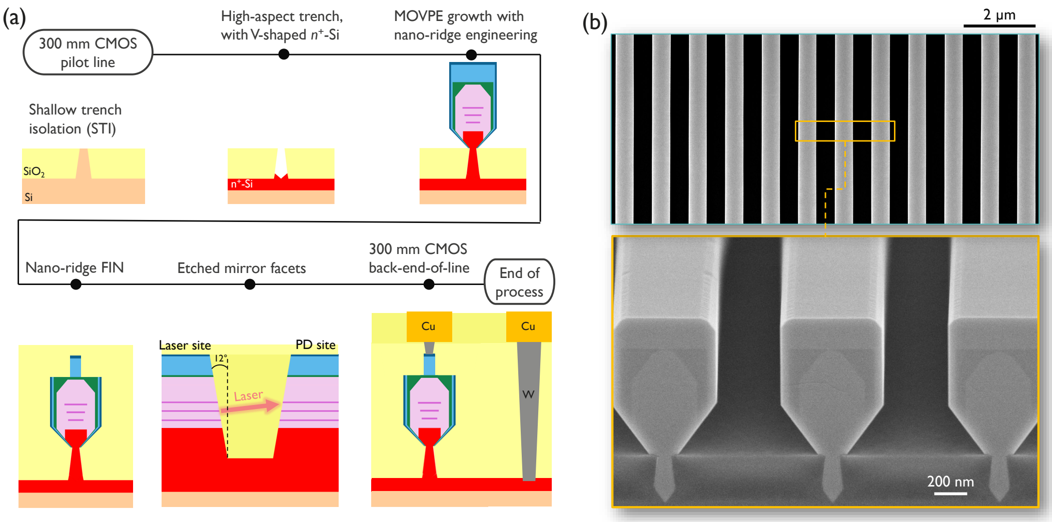


Fig. 2: (a) Key process steps of the GaAs nano-ridge FIN lasers fully fabricated in imec's 300 mm CMOS pilot line. (b) The top-view (top) and 20° tilted cross-section (bottom) SEM images demonstrate a uniform MOVPE process.

4. Characteristics and Reliability

The light–current–voltage (L–I–V) characteristic and the optical output spectrum are shown in Fig. 3(a) and (b), respectively. The L–I plot is measured by a monitoring nano-ridge photodiode, and the spectrum is obtained by collecting the out-of-plane optical emission from the 12° etched mirror using a multimode optical fiber (MMF). The GaAs nano-ridge FIN laser achieves continuous-wave lasing at 25 °C; the threshold current (I_{th}) is 13 mA and the wavelength is around 1048 nm. Although I_{th} is higher when comparing to the original lasers, a three-times greater slope efficiency (SE) is attributed to the lower optical loss and the reduced junction heating in the nano-ridge FIN lasers (Fig. 3(c)). Accordingly, a single facet output power exceeding 10 mW is demonstrated. On the other hand, the operating voltage of nano-ridge FIN lasers is higher than the original design, because carriers need to inject through a InGaP capping layer (around 10 nm on the (001) plane), which has a wider bandgap than the adjacent GaAs layers. This work presents the first demonstration of the GaAs nano-ridge FIN laser, and the process can be further optimized to enhance laser properties.

A preliminary reliability study discloses an improved lifetime of the GaAs nano-ridge FIN lasers. First, the p-contact-breakdown failure mode, which is detrimental in the original design, is alleviated. Fig. 3(d) benchmarks the time to breakdown (TTB) of the original lasers, extrapolating it to J_{p-con} of nano-ridge FIN laser suggests a TTB longer than 10 years at 25 °C. Next, constant current aging tests are performed at 25 °C for three current densities in the quantum wells (J_{QW}); results are plotted in Fig. 3(e). The p-contact-breakdown is not observed, whereas a gradual degradation in the output power is still witnessed in nano-ridge FIN lasers. The degradation manifests a square root time dependence ($\Delta P/P_0 \propto t^{0.5}$), which is likely linked to an impurity diffusion process [5]. More reliability study will be followed to thoroughly understand the failure mechanism.

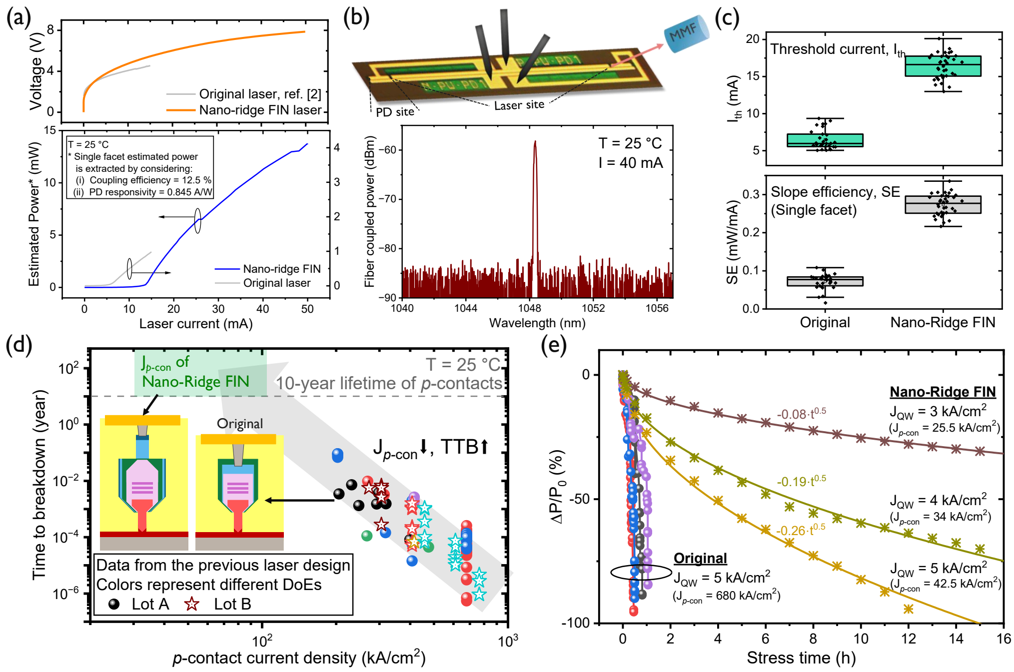


Fig. 3: Wafer-scale laser and reliability measurements. (a) L–I–V plots are measured by a monitoring nano-ridge photodiode. *The estimated output power is obtained by: (i) The laser-to-PD coupling efficiency is 12.5 %, identical to that of the original lasers [2]. (ii) The PD responsivity is 0.845 A/W, which is the theoretical limit for λ = 1049 nm. (b) The optical output spectrum is measured using a multimode optical fiber. (c) Threshold current (I_{th}) and slope efficiency (SE) comparison. The GaAs nano-ridge FIN laser shows a higher I_{th} and a higher SE than the lasers with the original design. (d) The time to breakdown (TTB) as a function of the p-contact current density (J_{p-con}). Extrapolating the TTB using data obtained from the original lasers suggests that the p-contact-breakdown failure mode is circumvented in nano-ridge FIN lasers. (e) Relative change in the output power ($\Delta P/P_0$), plotted with the stress time. Constant current aging tests reveal an improved laser lifetime in nano-ridge FIN lasers, where the degradation is linked to a diffusion-driven mechanism.

5. Conclusions

This work presents a novel GaAs nano-ridge FIN laser design. The anisotropic InGaP passivation and the p-GaAs FIN ensure a good carrier confinement. Optical modes are pulled down from p-contacts so that a much denser metal plug pitch ($\Lambda = 0.3\ \mu$m) can be implemented to improve laser thermal properties and reliability. Leveraging these designs, room-temperature continuous-wave lasing is achieved, showing a single-facet output power beyond 10 mW. The p-contact-breakdown failure mode in the original design is circumvented, leading to an approximately ×10 lifetime improvement at J_{QW} = 5 kA/cm^2, T = 25 °C.

Acknowledgements

This work was carried out as part of imec's industry-affiliation R&D program on "Optical I/O".

References

[1] N. Margalit *et al.*, "Perspective on the future of silicon photonics and electronics," *Appl. Phys. Lett.*, vol. 118, no. 22, 2021.

[2] Y. De Koninck *et al.*, "GaAs nano-ridge laser diodes fully fabricated in a 300-mm CMOS pilot line," *Nature*, vol. 637, pp. 63–69,2025.

[3] D. Van Thourhout *et al.*, "Nano-ridge laser monolithically grown on (001) Si," *Future Directions in Silicon Photonics*, vol. 101, pp. 283–304, 2019.

[4] A. A. Yimam *et al.*, "Semi-analytical model for electrically injected GaAs nano-ridge laser diodes monolithically integrated on silicon," *Opt. Express.*, vol. 33, pp. 2101–2114, 2025.

[5] P.-Y. Hsieh *et al.*, "Degradation mechanisms of monolithic GaAs-on-Si nano-ridge quantum well lasers," *J. Light. Technol.*, vol. 43, no. 12, pp. 5811-5819, 2025.

[6] D. Coenen *et al.*, "Electrothermal modeling of GaAs nanoridge laser diodes," *IEEE T-ED*, vol. 72, pp. 5038–5044, 2025.