Amorphous Si Side-wall Grating DFB InGaAs/GaAs Nano-ridge Laser Epitaxially Grown on a Si Wafer

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Epitaxial growth of InGaAs/GaAs nano-ridges allows monolithic integration of laser sources on silicon wafers [1]. This opens up the possibility for integrated silicon photonics applications on a single chip. In this paper, we study the possibility of improving the design of DFB nano-ridge lasers, by adding a silicon grating on the side walls of the nano-ridge structure. The fundamental TE mode of the nano-ridge extends to the side walls of the structure, resulting in a stronger interaction with a side wall grating, compared to the top grating used in previous work [1]. The mode simulations show a bigger overlap of the electric field with the side-wall grating resulting in an increased mode effective index and hence, higher reflectivity from the grating, allowing for a smaller device.

Introduction

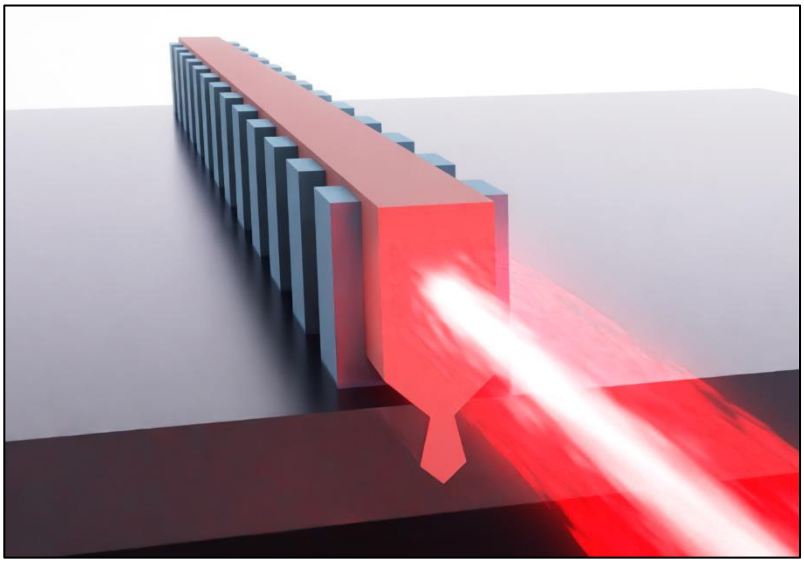

Figure 1: An illustration of the proposed nano-ridge laser with side-wall gratings.

To make full use of the potential offered by silicon photonic ICs, we need a method to integrate lasers on the same silicon platform. This can be achieved through heterogenous integration. An example is transfer printing [2], where the active material is fabricated on a different wafer in the form of coupons, that are then transferred and bonded on a silicon chip.

Monolithic integration on the other hand offers an advantage as the active material is directly grown on the Si wafer. But comes with a challenge, the lattice mismatch between the active material and silicon causes crystal dislocations and defects, resulting in no-radiative recombination. One way to solve this issue is by using aspect ratio trapping (ART) and nano-ridge engineering (NRE). In this approach, the dislocations are trapped

in narrow trenches, allowing the growth of defect-free active material in the form of nano-ridges [1].
Here, we introduce an improvement on the design of the nano-ridge DFB lasers reported earlier [3]. We show that introducing an amorphous Si side-wall grating to the nano-ridge structure, instead of the previously used top grating, allows for higher interaction of the DFB grating with the fundamental TE mode of the device. A single nano-ridge device (figure 1) comprises a GaAs waveguide with InGaAs quantum wells embedded in the middle of the device, providing the gain medium needed for lasing (figure 2b). The waveguide can support multiple modes with different mode profiles. The fundamental TE mode has a higher overlap with the quantum wells and lower losses [3]. Additionally, the electric field is parallel to the quantum wells plane, making it the dominant lasing mode (figure 2a). To achieve lasing, A form of resonator structure is needed. In a Fabry-Perot laser, the resonator is formed using two mirrors at both ends of the gain medium to provide the feedback, in this case, reflection between the two mirrors [4]. Another way to achieve the necessary feedback is by using a periodic structure along the length of the device. The modulation of the mode effective index due to the grating causes Bragg scattering at the designed wavelength [4].

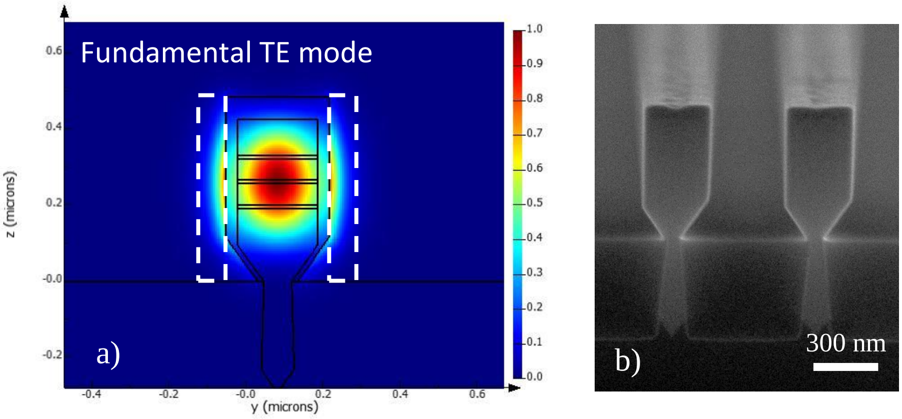

Figure 2: a) The fundamental TE mode is extending outside the sides of the structure. b) SEM image of Nano-ridge structure.

Designing a smaller device

Making a smaller device required two modifications. First, the grating was added on the two sides of the nano-ridge, allowing for higher interaction with the TE mode. For a nano-ridge of 220 nm width, 70 nm trench width, and 485 nm height, a side grating of 50 nm width results in a mode power overlap of 7.035% per side (~14% total). This can be compared to a top grating of 50 nm, for which the overlap is only 1.8%. Increasing the top grating thickness to 100 nm, improved the overlap to 6.1%, but it is still less than half of that found for the side grating.

Secondly, the nano-ridge width needed to be reduced to increase the index contrast of the grating even more. An FDTD simulation for different nano-ridge widths shows the change in the frequency of the fundamental TE mode (Figure 3). The simulations show that at smaller nano-ridge widths (<300 nm) the change in the resonance frequency is higher and the bandgap strongly increases. Using this information we can choose a width, which is still possible to fabricate, and maximizes the difference between the mode supported in the grating region and the mode in the waveguide region (figure 4 a, b). The grating period (Λ) is then calculated according to the Bragg formula, $\Lambda = \lambda_0/2n_{avg}$. A $\lambda\backslash 4$ phase shift section is used to force single longitudinal mode operation.

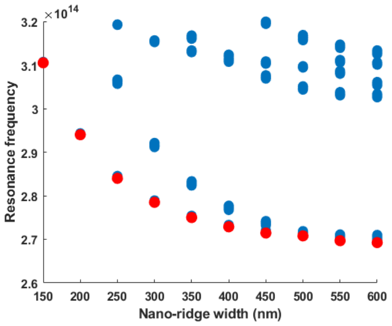

Figure 3: A band-edge (vertical slice of the bandstructure) simulation sweep showing the fundamental TE mode (red) frequency changing rapidly at smaller nano-ridge width and the increasing bandgap.

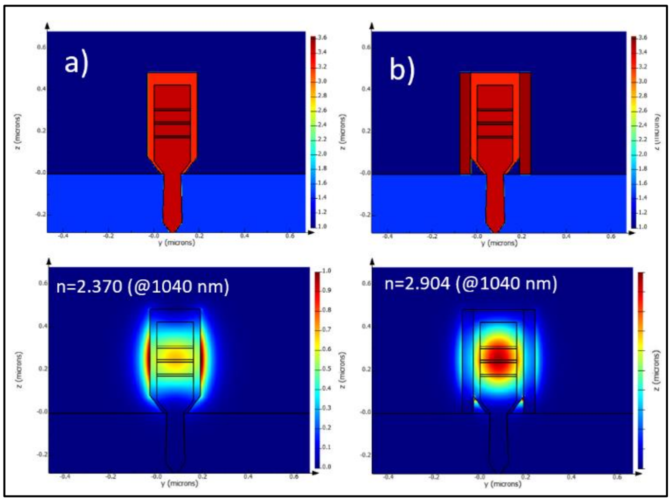

Figure 4: Mode profiles in the region without a) and with b) a-Si sidewall.

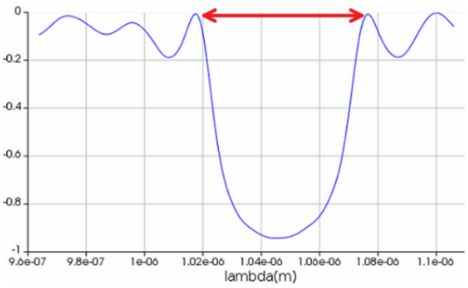

Figure 5: Reflection spectrum for 25 grating periods (one side of the device).

These modifications result in high reflectivity of 94% (figure 5) over a bandwidth of 59 nm for a side-grating of 25 periods (Λ= 200 nm). In previous work [4], a reflectivity of 90% was achieved for a top grating with 300 periods. This is a one order of magnitude reduction in the device length.

The reflectivity isn't the only factor that will dictate the device length, but also the material gain volume. The reduction of the nano-ridge width reduces the amount of gain material (quantum wells) available, which adds a limit on the minimum device length. Further investigation is needed in that regard.

The quality factor of the proposed device was also calculated. The Q-factor shows a significant improvement for a smaller number of grating periods (figure 6) compared to the top grating.

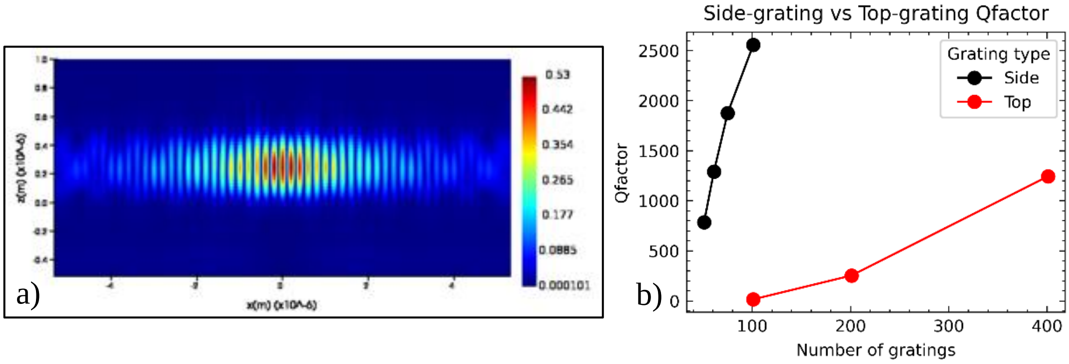

Figure 6: a) Calculated mode profile along the device at 1044 nm, showing the electric field localized at the $\lambda/4$ phase shift section in the center of the device (25 grating periods at both sides). b) Q-factor calculations show a significant improvement for a side-grating (Λ= 200 nm, nano-ridge width of 220 nm, 485 nm height and a grating thickness of 50 nm) vs. a top grating (Λ= 164 nm, nano-ridge width of 410 nm, 485 nm height and a grating thickness of 100 nm).

Conclusion

We demonstrated a significant improvement in the device miniaturization by using a higher index contrast side gratings on both sides of the nano-ridge structure.

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