Side-amorphous-silicon-grating InGaAs/GaAs nano-ridge distributed feedback laser monolithically grown on 300 mm silicon substrate

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***Abstract*—A compact III-V semiconductor laser is regarded as a promising light source for the silicon photonic platform due to its unique advantages of low energy consumption and small footprint. However, the significant lattice mismatch between the III-V material and silicon is a fundamental challenge for the monolithic integration of III-V lasers on silicon substrates and requires specific integration solutions to confined relaxation defects outside the active device region. Here, a distributed feedback GaAs/InGaAs nano-ridge laser directly grown on silicon substrate by nano-ridge engineering is demonstrated. Under pulse pumping, the lasing was achieved with a cavity length as small as 50 μm. This laser establishes a novel route to realize a compact light source for the future high-density and massively scalable silicon photonic integrated circuits.**

Keywords—silicon photonic platform, compact, nano-ridge engineering, III-V laser on Si, high-density, massively-scalable

I. Introduction

The rapid growth of data traffic requires efficient chip-to-chip and on-chip optical interconnection methods with low energy consumption and high density [1-2]. The silicon photonics platform has attracted much attention in the past few decades due to its potential use in such applications. However, the lack of a practical and compact laser directly integrated on this platform is a main roadblock for further development of scalable silicon photonic circuits. Given silicon's indirect bandgap and associated low emission efficiency, the integration of III-V lasers using various approaches has been extensively studied over the last decade, but all have their limitations [3-6]. Recently, we demonstrated a new method for directly growing high-quality III-V material on silicon substrates without introducing any buffer layer. Compared to other methods, this novel nano-ridge engineering technique [7-8] shows advantages in terms of device scalability, integration density and cost.

To reduce power consumption and increase bandwidth-density, footprint reduction and device miniaturization are critical. In our previous work, we realized a laser cavity by defining an etched grating inside or a metal grating on top of the nano-ridge, which results in a low coupling coefficient and hence long cavity (more than 100 micrometers) [9-11]. Therefore, in this work, high-refractive-index amorphous silicon (a-Si) gratings were deposited on the two sides of the nano-ridge as shown in Fig. 1.(a), which enhances the interaction with the guided mode and allows to reduce the cavity length.

II. Laser Design

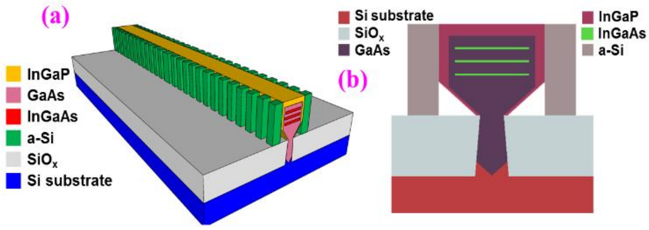
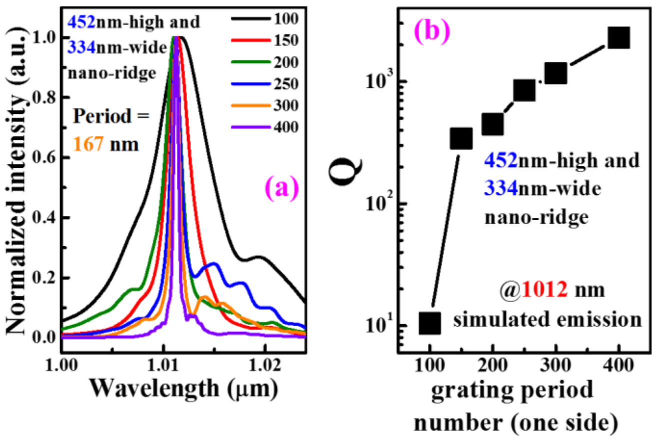


Fig. 1.(a) The 3D structure used for the simulation of 452nm-high and 334nm-wide nano-ridge with 100nm-wide a-Si grating with different number of periods by 3D-finite difference time domain (3D-FDTD) solver. (b) Cross-section view of the simulation model in 3D-FDTD solver.



Fi. 2.(a) The 3D-FDTD simulated spectra from the 452nm-high and 334nm-wide nano-ridge with the 100nm-wide a-Si grating with different number of periods, while fixing the grating period and the duty cycle at 167 nm and 50%. (b) The dependence of the quality factor of the same device on the number of grating periods.

First, we optimized the grating dimensions and size through 3D-finite difference time domain (3D-FDTD) simulations. The model is depicted in Fig. 1.(a) and it consists of a cavity with a λ/4 phase shift section in the middle. In the cross-section view of simulation model shown in Fig. 1.(b), the grating duty cycle and period were fixed at 167 nm and 50%, while the number of periods was varied. Fig. 2.(a) shows the simulated spectra of a 452nm-high and 334nm-width nano-ridge device with increasing number of periods. The resonance peak narrows with increasing number of periods, which is ascribed to the enhanced reflection along the light propagation direction. Fig. 2.(b) plots the quality factor (Q-factor) for different a-Si grating period numbers. The Q-factor increases as the grating period number increases due to the reduction of the light leakage at the end of the cavity. For more than 150 periods on each side, the Q-factor value raises more slowly because leakage and scattering in other directions becomes more important. To ensure sufficient reflection from the grating, a 100nm-wide a-Si grating with 150, 200 and 250 periods on each side of the nano-ridge were included in the final device design. Second-order grating couplers with 200 periods were added at the front and back side of the cavity for device characterization.

III. FABRICATION PROCESS

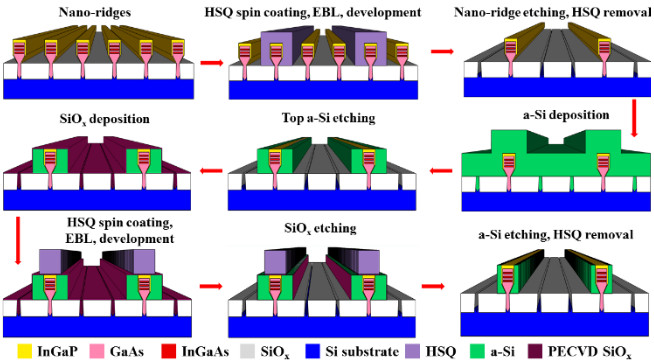


Fig. 3 process flow of nano-ridge distributed feedback laser with a-Si grating on the two sides.

Following the design, the devices were fabricated starting from nano-ridges with a height and a width of 452 nm and 334 nm, containing 3 InGaAs quantum wells and passivated with an InGaP layer. The box-shaped nano-ridges were grown by metal organic vapor phase epitaxy (MOVPE) on a silicon substrate containing a dense array of narrow trenches patterned in a SiO_2 layer. The details of the epitaxy process can be found in previous reports [7-8]. To ensure complete a-Si filling between the nano-ridges, it was necessarily to remove part of them. The fabrication details are shown in Fig. 3. First, hydrogen silsesquioxane (HSQ, Dow Corning) was spin coated, followed by electron-beam lithography (EBL, Voyager, Raith) and development using a developer consisting of AZ400K mixed with DI water at a ratio of 1:3. Second, some of the nano-ridges were etched by inductively coupled plasma reactive ion etching (ICP-RIE, Plasmalab System 100, Oxford) with BCl_3/N_2 to remove the overall filling ratio of the nano-ridge pattern (see Fig. 3). Next, the remaining HSQ resist was removed by a buffered oxide etching solution (BOE) and a ~600 nm a-Si thin film was deposited using plasma-enhanced chemical vapor deposition (Advanced Vacuum Vision 310 PECVD, Plasma-Therm). Then, the a-Si thin film was uniformly etched using a CHF_3/H_2 gas mixture through ICP-RIE (PlasmaPro 100 Cobra, Oxford), leaving only the a-Si on the sidewalls. To protect the a-Si layer from the HSQ-developer used in the next step, ~40 nm SiO_x was added as protection layer using the same PECVD system mentioned above before the second HSQ spin coating, EBL, and development. Finally, the grating pattern forming the laser cavity and the second-order grating coupler structure were transferred from the HSQ resist to the side a-Si layer by ICP-RIE etching of the SiO_x layer and the a-Si layer with CHF_3/O_2 and $CHF_3/SF_6/H_2$, respectively.

IV. RESULT AND DISCUSSION

Fig. 4(a) and (b) present zoomed-in tilted scanning electron microscope (SEM) images of the DFB laser and the a-Si grating on the side of the nano-ridge, which demonstrates the process flow worked. A device with 150 periods and cavity length as small as 50 µm was excited by a Nd:YAG 532-nm nanosecond pulsed laser at room temperature and the emission from the device was collected and detected with a monochromator (KYMERA-328I-D2-SIL, Oxford instruments, Andor) and a water-cooled InGaAs detector (iDus, DU490A-1.7 Model, Oxford instruments, Andor). Fig. 4.(c) shows the photoluminescence spectrum of this device under different 532nm pump power densities. A lasing peak at 1012 nm becomes apparent when the pumping density reaches 4 kW/cm^2 and the peak intensity increases strongly with a further increase of the pump density. The linewidth of the laser is 1.32 nm from the Gaussian function fitting of the photoluminescence spectrum under 12.5 kW/cm^2 pumping density, as presented in the top-right inset, and is believed to be limited by carrier dispersion during the pump pulse. Fig. 4.(d) shows light in (pump power density) - light out (integrated photoluminescence intensity) curve on linear scale from the same measured device. A clear change of slope indicates strongly the lasing turn-on behavior.

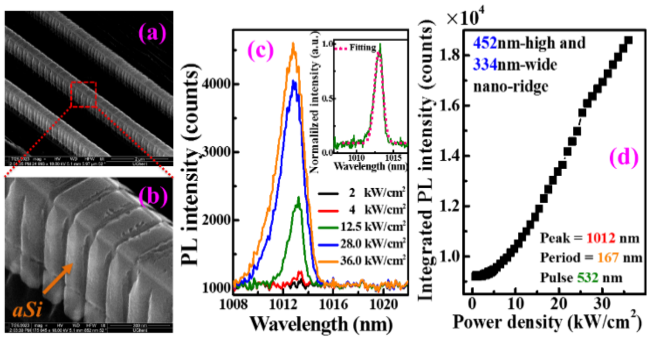


Fig. 4.(a) Tilted SEM image of a 452nm-high and 334nm-wide nano-ridge DFB laser. (b) Zoomed-in tilted SEM image of the a-Si grating on the side of the same nano-ridge laser. (c) Photoluminescence spectra from the same 452nm-high and 334nm-wide nano-ridge DFB laser under different 532 nm pulsed pump power densities. Inset: Photoluminescence spectrum from the same DFB laser under 12.5 kW/cm^2 pump power density and a Gaussian fitting applied to this photoluminescence spectrum (d) Light in (pump power density) -Light out (integrated photoluminescence intensity) curve on linear scale from the same DFB laser.

V. CONCLUSION

We realized compact and small-footprint DFB-like lasers by integrating an a-Si based grating on both sides of InGaAs/GaAs nano-ridges monolithically grown on a standard 300-mm Si wafer. The a-Si gratings were 100 nm wide, had a 167 nm period and included 150 periods on each side. The enhanced light interaction with the side a-Si grating allowed to achieve laser operation for a device with a total cavity length as short as 50 µm, with a threshold pump power density of 4 kW/cm^2. This DFB laser with small footprint opens up a promising path towards developing ultra-compact electrically-driven devices [12] for future high-density and massively scalable silicon photonic integrated circuits.

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