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1.5 µm Photonic Crystal Surface Emitting Laser Diode

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Abstract

We present a 1.5 µm InP-based epitaxially regrown photonic crystal surface emitting laser diode operating at room temperature.

1. Introduction

Photonic crystal surface emitting lasers (PCSELs) are a novel class of laser, incorporating a photonic crystal (PC) layer in the semiconductor structure. When placed within a semiconductor laser structure, the PC scatters light out of plane forming a surface emitting laser. PCSELs have shown ability to operate single mode [1] with high power [2]. While traditionally realized by wafer fusion, recently epitaxial re-growth has become the *de facto* standard PCSEL device fabrication [3,4]. 5G roll-out requires larger data-centers to satisfy the growing demand for data. Longer link lengths will be required to connect distributed data-centers, requiring low-cost, high-speed laser sources at wavelengths suitable for silica-fibers. Several LiDAR, free-space communication, and range-finding systems operate at 1.5 µm for eye-safety. PCSELs can achieve high powers, with production costs similar to VCSELs. Here we present an epitaxially re-grown InP-based all semiconductor PCSEL operating at 1.5 µm at room temperature.

2. Design and Fabrication

Device simulations were made using LaserMOD. Fig. 1a) shows a schematic of the PCSEL device considered in this paper. Five 6 nm AlGaInAs quantum wells provide a room-temperature spontaneous emission peak at 1.53 µm. A p-doped 243 nm PC Layer (GaInAsP and InP with air containing voids) is 100 nm above active layer. The PC and active layers are further sandwiched between 3.3 µm of n-doped InP and a 1.8 µm p-doped InP layer. The device is capped with a p+InGaAs contact layer. The PC is patterned with a circular atom in a square lattice. The period and r/a are 470 nm and 0.17, respectively. Fig. 1b) shows a cross section of the same structure with simulated mode profile overlaid. The average refractive index of PC layer is assumed to be 3.24, providing a mode overlap of 12.9% and 16.4% with the active and PC layers respectively.

The devices were fabricated on InP epitaxial wafers, topped with a 245 nm GaInAsP layer forming the basis for the PC structure. The PC pattern was defined by electron-beam lithography, and a CHF_3/Ar - based reactive ion etch was used to imprint the pattern into a 200 nm-thick SiO_2 hard mask. Through this hard mask, the underlying semicon

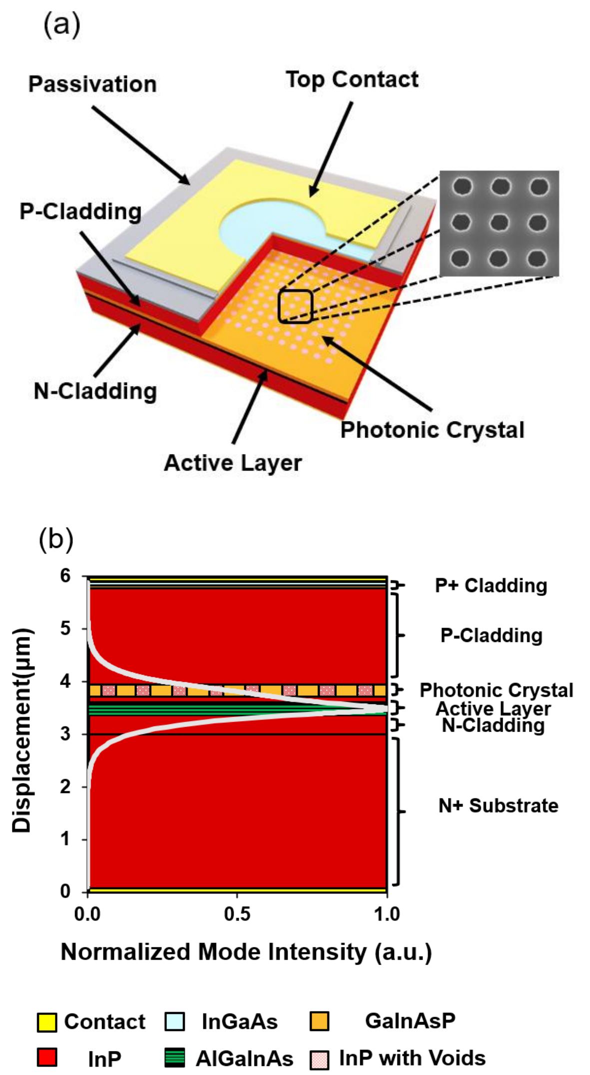

Fig. 1: a) A 3D schematic of the device, with cut-out area showing an SEM image of the photonic crystal pattern. b) A schematic of the corresponding mode distribution inside the device structure.

ductor is etched to a depth of approximately 170 nm to form holes with an ~80° side wall angle by inductively coupled plasma etch using a CHF_4/H_2 chemistry. The top view of the PC after etching is shown in Fig.1. After removing the hard mask and cleaning the wafer with uv/ozone and 10:1 buffed HF, epitaxial regrowth was performed. Growth conditions were chosen to form voids during the regrowth inside each of the patterned features within the PC layer. Fig 2a) shows a

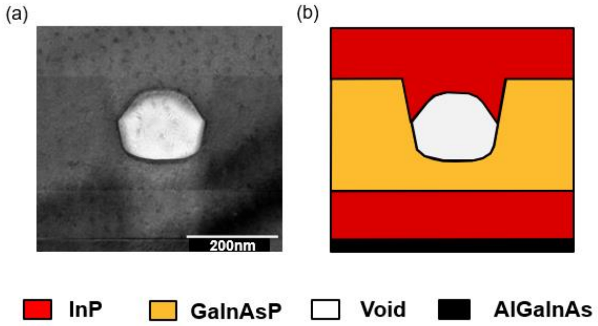

Fig. 2: a) A TEM image and b) a schematic of a single re-grown circular etched feature in the PC Layer. A void is located at the bottom of the hole.

TEM bright field image of an overgrown PCSEL where the void can clearly be seen. Fig 2b) shows a schematic of the imaged structure which provided an input to waveguide simulation and plane-wave expansion simulation of the PCSEL.

Following regrowth, the PCSEL fabrication is completed by etching a 200 μm x 200 μm square device mesa into the regrown material to a depth of 100 nm. Contacts and bond pads were then added using standard fabrication techniques. The PC region is 200 μm x 200 μm.

3. Results

Fig.3 a) shows the LI-characteristics of the PCSEL, measured under pulsed conditions (10% duty cycle, 10 μs pulse width). The threshold current is 640 mA (J=1.6 kA/cm^{-2}). An average slope efficiency of ~0.002 W/A is obtained, which is low due to the circular symmetry of the PC and the masking of the PCSEL emission by the contacts. Higher powers are expected by utilizing asymmetric PC structures [2], developing our processes to realize a height of the void closer to half the PC period, and inducing vertical asymmetry of the re-grown void [5].

The EL spectrum obtained at 1A is shown in Fig. 3b). Lasing is observed at 1523 nm in good agreement with simulated mode-index and a PC period of 470 nm. An SMSR of 17 dB is measured. Fig. 3c) shows the simulated optical density of states (ODOS) for the PCSEL device. Each peak corresponds to the band edge of the photonic crystal. Only the range of k-vectors with NA = 0.34 was considered, matching the collection angle of the experimental setup used in fig. 3a. The simulated features show good agreement with the measured lasing peak, and indicated a second peak at 1519 nm (the leaky non-lasing mode).

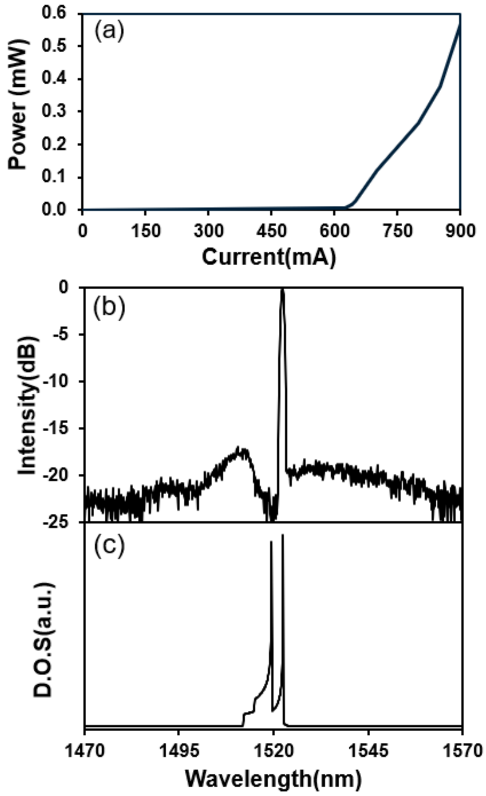

Fig. 3: a) The LI characteristics of the device. b) The emission spectrum and c) corresponding simulated optical density of states.

4. Conclusion

The realization of an InP-based 1.5 μm PCSEL was reported. By controlling PC definition and regrowth parameters, a void is formed inside the PC during the epitaxial regrowth process. This opens a route to a surface emitting laser operating at a key wavelength for a range of applications.

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