Photonic-crystal surface-emitting laser near 1.55 µm on gold-coated silicon wafer

G. Vecchi, F. Raineri, I. Sagnes, K.-H. Lee, S. Guilet, L. Le Gratiet, F. Van Laere, G. Roelkens, D. Van Thourhout, R. Baets, A. Levenson and R. Raj

An InP/InGaAs-based photonic band-edge laser bonded on silicon operating near 1.55 µm is presented. A gold reflector positioned below the slab containing the active layer reduces the optical losses of the Bloch-mode resonator. As a result, a quality factor exceeding 8000 is obtained at transparency leading to a laser threshold as low as 3.4 µJ/cm^2.

Introduction: Two-dimensional (2D) photonic crystals (PhC) have grabbed the attention of many because, with their lattice dimensions of the order of light wavelength, they enable extensive control of the photonic states inside the matter. Right from the early stages of development in this domain, laser emission has been demonstrated by incorporating III–V active materials within the PhC [1–3]. Laser emission was obtained in two different generic designs: the 'cavity' design, in which the light is trapped in an optical cavity created by introducing a defect in the uniform periodic pattern [1, 2]; and the 'band-edge' design, which consists in using the increase of the density of optical modes at the band edges of a perfectly periodic structure [3]. In this context, the main concern has been and still is the reduction of the threshold through the management of optical losses. Concurrently, hybrid structures integrating III–V-based and silicon-based devices by means of wafer bonding methods were being developed [4, 5]. Bonding assisted by benzocyclobutene (BCB), a polymer transparent at 1.55 µm, is particularly promising for the development of a low-cost silicon-based photonic architecture, incorporating active devices. In this Letter, we report on an InP-based PhC-band edge laser integrated on silicon, emitting at 1.59 µm under pulsed optical excitation, at room temperature. The two-dimensional (2D) PhC structure is bonded by BCB on a gold-coated silicon wafer, whereby the high reflectivity gold layer reduces photon losses, and consequently the threshold of the PhC laser.

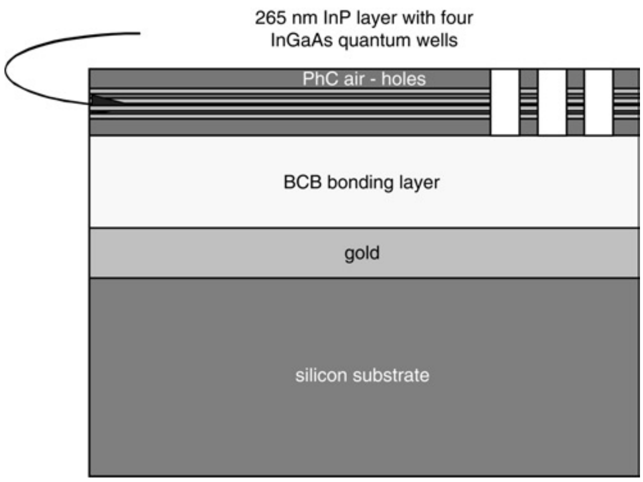

Fig. 1 *Schematic of fabricated heterostructure*

Device design and fabrication: The schematic structure of the device is shown in Fig. 1. The in-plane periodic structure is designed to obtain a slow photonic mode near 1.55 µm at the Γ point of the Brillouin zone, in order to enable surface-normal laser emission [6]. Vertically, the structure consists of the InP-based PhC slab, onto the BCB-bonding layer and the gold mirror. The latter, by controlling the optical losses, introduces a way to improve the performance of PhC band-edge emitters. In this way, by controlling the coupling rate between the resonant lasing mode and radiative modes, resonators with improved Q-factors are achievable. The coupling rate depends on the distance separating the InP slab from the mirror, which, in our case, is defined by the thickness of the BCB layer. The value of ~780 nm chosen here ensures that the light emitted in the vertical direction interferes destructively with the light reflected by the mirror, hence increasing the attainable Q-factor [7, 8]. We preferred to use a gold mirror instead of an Si–SiO$_2$ Bragg mirror as in [7], because it has the advantage of acting as a broadband reflector, and can be easily coated.

The MOCVD-grown InP slab contains four lattice-matched $In_{0.53}Ga_{0.47}As$ QWs, whose photoluminescence peaked near 1.53 µm. Following evaporation of the gold layer onto a silicon wafer, the InP slab was transferred onto it through BCB bonding. The 2D PhC structure is a graphite lattice of air holes drilled into the 265 nm-thick InP slab, by inductive plasma etching through a silicon nitride mask, defined by e-beam lithography and reactive ion etching. Fig. 2 shows a scanning electron micrograph of the fabricated structure. The graphite lattice constant is 750 nm, and the air-hole diameter is 270 nm.

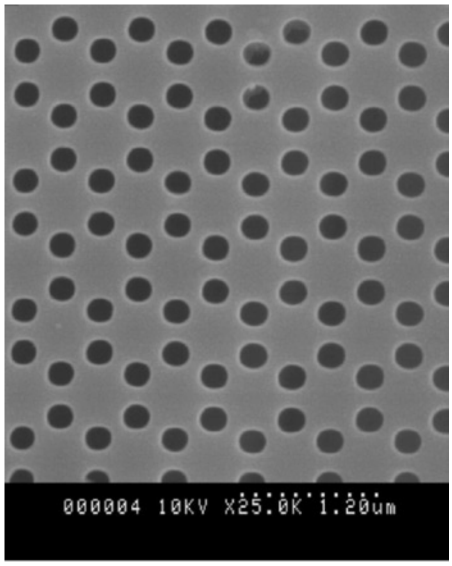

Fig. 2 *Scanning electron micrograph of PhC surface*

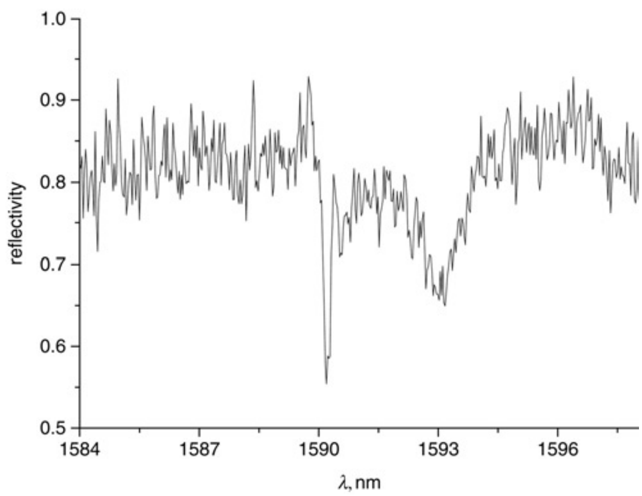

Fig. 3 *Reflectivity spectrum measured at transparency*

Results: To evaluate the performance of the fabricated sample, and in particular the Q-factor of the resonator, the PhC structure is studied through ultrafast pump and probe spectroscopy [9]. Fig. 3 shows the reflectivity spectrum near transparency. In this case, the pump beam at 810 nm, with repetition rate and pulse duration of 82 MHz and 130 fs, respectively, is set to bleach the total material absorption at the resonance wavelength. The central wavelength of the resonance is located at ~1590 nm, and its full width at half maximum is ~190 pm, which corresponds to a very high $Q = \lambda/\Delta\lambda \simeq 8400$. A broader resonance is also present in the spectrum near 1593 nm, which is the signature of another band-edge mode near to the Γ point. Note that the Q-factor we measured here is one of the highest reported for resonators based on slow Bloch modes, attesting the excellent quality of the fabricated structure.

Room temperature laser emission in the vertical direction is then characterised by stopping the probe beam and increasing the pump intensity. Fig. 4 shows the output laser peak power against pump fluence. The laser threshold, obtained from a linear fit, corresponds to an external excitation fluence of about 3.4 μJ/cm^2, a value of the same order of magnitude as the one reported in [7], where the 2D PhC was positioned on top of a dielectric Bragg mirror. As shown in the upper inset of Fig. 4, as the pump is further increased, saturation of the light–light curve is observed. This indicates the onset of a multimode laser regime owing to the presence of the resonance at 1593 nm shown in Fig. 3. The spectrum of emission just above threshold is shown in the lower inset of Fig. 4. The laser peak is at 1589.3 nm, with a linewidth of ~1.2 nm, which is broader than the resonator linewidth at transparency. Indeed, in such a pulsed pumping regime, the carrier density is not constant during the emission, which leads to a frequency chirp and, consequently, to spectral broadening of the laser linewidth.

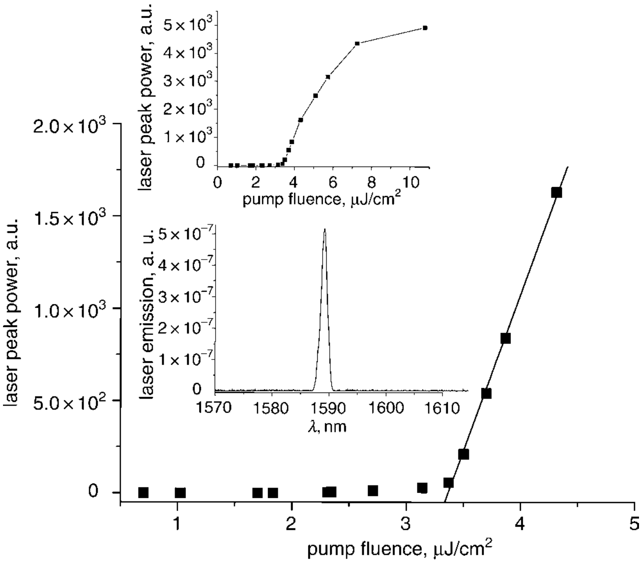

Fig. 4 *Laser peak power against pump fluence*

Straight line fits linear characteristics above threshold
Upper inset: saturation of peak power at high pumping
Lower inset: spectrum of laser emission at 1589.3 nm

Conclusions: We have demonstrated room temperature band-edge laser emission on silicon at 1.59 μm, under pulsed optical excitation. The insertion of a gold layer is an important step towards improvement of the field confinement and control of optical losses in the vertical direction. This results in a Q-factor as high as 8400 and low laser threshold fluence of 3.4 μJ/cm^2.

Acknowledgments: This work was done in the framework of the ePIXnet network.

12 December 2006
Electronics Letters online no: 20073816
doi: 10.1049/el:20073816

G. Vecchi, F. Raineri, I. Sagnes, K.-H. Lee, S. Guilet, L. Le Gratiet, A. Levenson and R. Raj (*Laboratoire de Photonique et de Nanostructures (CNRS UPR20), Route de Nozay, Marcoussis 91460, France*)

E-mail: gabriele.vecchi@lpn.cnrs.fr

F. Van Laere, G. Roelkens, D. Van Thourhout and R. Baets (*Department of Information Technology, Ghent University–IMEC, Sint-Pietersnieuwstraat 41, Ghent 9000, Belgium*)

References

1 Painter, O., Lee, R.K., Scherer, A., Yariv, A., O'Brien, J.D., Dapkus, P.D., and Kim, I.: 'Two-dimensional photonic band-gap defect mode laser', *Science*, 1999, **284**, pp. 1819–1821

2 Lončar, M., Yoshie, T., Scherer, A., Gogna, P., and Qiu, Y.: 'Low-threshold photonic crystal laser', *Appl. Phys. Lett.*, 2002, **81**, pp. 2680–2682

3 Monat, C., Seassal, C., Letartre, X., Viktorovitch, P., Regreny, P., Gendry, P., Rojo-Romeo, P., Hollinger, G., Jalaguier, E., Pocas, S., and Aspar, B.: 'InP two-dimensional photonic crystal on silicon: in-plane Bloch mode laser', *Appl. Phys. Lett.*, 2002, **81**, pp. 5102–5104

4 Hattori, H.T., Seassal, C., Touraille, E., Rojo-Romeo, P., Letartre, X., Hollinger, G., Viktorovitch, P., Di Cioccio, L., Zussy, M., Melhaoui, El, and Fedeli, J.M.: 'Heterogeneous integration of microdisk lasers on silicon strip waveguides for optical interconnects', *IEEE Photonics Technol. Lett.*, 2006, **18**, pp. 223–225

5 Roelkens, G., Van Thourhout, D., Baets, R., Nötzel, R., and Smit, M.: 'Laser emission and photodetection in an InP/InGaAsP layer integrated on and coupled to a Silicon-on-Insulator waveguide circuit', *Opt. Express*, 2006, **14**, pp. 8154–8159

6 Imada, M., Noda, S., Chutinan, A., Tokuda, T., Murata, M., and Sasaki, G.: 'Coherent two-dimensional lasing action in surface-emitting laser with triangular-lattice photonic crystal structure', *Appl. Phys. Lett.*, 1999, **75**, pp. 316–318

7 Ben Bakir, B., Seassal, C., Letartre, X., Viktorovitch, P., Zussy, M., Di Cioccio, L., and Fedeli, J.M.: 'Surface-emitting microlaser combining two-dimensional photonic crystal membrane and vertical Bragg mirror', *Appl. Phys. Lett.*, 2006, **88**, p. 081113

8 Kim, S.-H., Kim, S.-K., and Lee, Y.-H.: 'Vertical beaming of wavelength-scale photonic crystal resonators', *Phys. Rev. B*, 2006, **73**, p. 235117

9 Raineri, F., Cojocaru, C., Raj, R., Monnier, P., Levenson, A., Seassal, C., Letartre, X., and Viktorovitch, P.: 'Tuning a two-dimensional photonic crystal resonance via optical carrier injection', *Opt. Lett.*, 2005, **30**, pp. 64–66