Hybrid InP-based photonic crystal lasers on silicon on insulator wires

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We report on InP-based photonic crystal lasers operating at 1.585 μm at room temperature, integrated with and evanescently coupled to silicon on insulator (SOI) waveguides. By optically pumping at 1.18 μm through the SOI wires, pulsed laser emission from line defect photonic crystal waveguides accurately aligned (<30 nm) to the silicon circuitry is demonstrated. © *2009 American Institute of Physics*. [doi:10.1063/1.3265743]

Silicon photonics is a major subject of research in optoelectronics because it opens the way to the low cost fabrication of ultracompact optical integrated circuits. Indeed, silicon is an extensively studied material, unsurpassed in quality of fabrication and with high yields due to decades of investment from the microelectronics industry in complementary metal oxide semiconductor (CMOS) processing. Using this technology for integrated optics is a path undertaken by many which has brought interesting solutions to problems encountered in the realization of optical circuits. For example, silicon on insulator (SOI) waveguides have been demonstrated to be excellent at transporting light in a very compact manner with low losses.[1]

However, light emission and amplification, two essential functions in an optical circuit, are not straightforward with silicon because of its indirect electronic bandgap. Despite promising demonstrations on Raman lasers[2] and optical gain[3] using Si, the performance is still not comparable to that of III-V semiconductors based devices. To overcome this lacuna, one solution consists in combining silicon with III-V semiconductors in an unique optical platform. Two possibilities arise: in one, as described in Fang *et al.*,[4] the devices are defined completely within the SOI material and an unstructured III-V epilayer is then directly bonded on top of that SOI structure. In this approach, the light is almost entirely confined within the SOI waveguide. It is the evanescent tail of the optical mode which feels the gain provided by the III-V active layer. This approach was used for demonstrating edge emitters and racetrack lasers.[4] The second option consists in bonding III-V lasers onto silicon wires by the use of a low refractive index bonding material. In this configuration the two levels (III-V material and the silicon wire) independently each possess one transverse mode. When integrated they share a pair of supermodes due to the evanescent coupling which is strongest at the phase matching condition.[5] Microdisk lasers were integrated and coupled to SOI wires using this method.[6] With the view of progressing toward ultimate laser devices in terms of power consumption and compactness, III-V photonic crystals[7] (PhCs) are promising candidates, as part of this hybrid platform.

In this letter, we report the demonstration of room temperature 1.585 μm pulsed laser emission from InP-based two-dimensional (2D) PhCs heterogeneously integrated to SOI wires. The SOI circuitry is used both for collecting the laser emission from, as well as, for channelling the optical pump to, the 2DPhC. Pump threshold energy is measured to be 1 pJ.

The samples explored in this work are schematically represented in Fig. 1(a). They consist of a structure with two optical levels: the lower level is composed of narrow single mode SOI waveguides (width of 300 nm and height of 220 nm) where the light propagates passively, i.e., without any absorption/gain. In specific areas, an upper level is added, which is composed of a 255 nm thick InP-based membrane with four embedded InGaAs/InGaAsP(wavelength band gap=1.2 μm) quantum wells (QWs) emitting around 1.55 μm drilled with a 2DPhC. Here, the light interacts with the matter to achieve laser emission. The two levels are separated by a thin transparent layer (400 nm) of a low refractive index material (n=1.54 for benzocyclobutene) allowing evanescent coupling. The PhCs under consideration are W0.65 line defect waveguides in a triangular lattice of air holes. The width of the line defect is $w=0.65\sqrt{3}a$, where a is the lattice constant, and the ratio of the radius to the period is $r/a=0.3$. For the fabricated sample under study, these parameters are w=501 nm, a=445 nm, and r=133 nm. The band diagram of the PhC in Fig. 2(a) is calculated using the guided mode expansion method.[8] These structures are of particular interest because they enable regimes of slow light

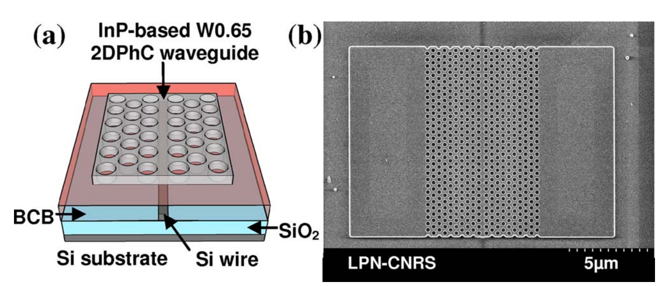

FIG. 1. (Color online) (a) Schematic of the sample. (b) SEM image of the sample.

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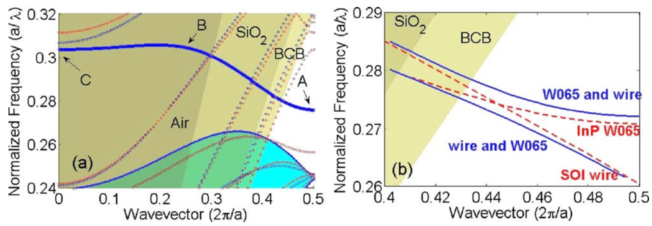

FIG. 2. (Color online) (a) Band structure calculated using guided mode expansion for the W0.65 PhC membrane with a BCB substrate and air upper cladding (with air holes). Laterally odd modes are shown in blue, even in red. The thick blue line corresponds to the odd TE-like defect mode. The odd TE-like band edge modes are shaded in cyan. The odd and even TM-like lattice modes are plotted as fainter dotted lines. Low-vg modes are denoted A, B, and C. The light cones of the various cladding materials, air, SiO_2, and BCB are denoted by progressively darker shading for lower index. (b) Dispersion relation of TE-like modes of the hybrid structure calculated using 3D FDTD for wavevectors around π/a. Both coupled supermodes (solid lines) and uncoupled modes (dashed lines) are represented.

propagation which can lead to laser emission as demonstrated in the work of Kiyota *et al.*[9] Further, in these waveguides narrower than regular W1 waveguides, the even modes are pushed out of the band gap of the PhC and are therefore not confined in the line defect. This renders them completely single mode within the band gap region and avoids supplementary transverse mode competition for the laser emission. The width of the SOI wires is set at 326 nm in order to be close to the phase-matching condition for the modes propagating in the wires and the III-V PhC. The dispersion diagram of the entire structure [Fig. 2(a)] is calculated using three-dimensional finite difference time-domain method (3D FDTD) (Ref. 10) for wavevectors close to π/a. The dispersion curves of the 2DPhC and the SOI wire intersect at $a/\lambda=0.275$ near the edge of the Brillouin zone. A splitting in the dispersion curve of the full structure is observed near this point attesting to the coupling between the two levels. Thus, in this region of the band structure where the group velocity strongly decreases, the power is transferred from one waveguide to the other. A theoretical study on the coupling will be described elsewhere.

The fabrication relies on the adhesive bonding of the metalorganic chemical vapor deposition-grown InP-based heterostructure onto the SOI wires through the use of the planarising polymer BCB. The 300 nm wide SOI waveguides are fabricated in a CMOS fab using 193 nm deep ultra-violet (DUV) lithography. Alignment markers written on the same mask level as the waveguides allow us to align to the Si waveguides, the PhC defined by electron beam lithography. The PhC is patterned in the III-V membrane using reactive ion etching and inductively coupled plasma etching.[11] Scanning electron microscope measurements [see Fig. 1(b)] allow us to show that our 2DPhC structures are aligned right on top of the SOI wires with an accuracy of better than 30 nm. This level of accuracy enables reproducibility in the fabrication and a close control of the evanescent wave coupling.

The samples are explored at room temperature using the experimental set-up depicted in Fig. 3. The pump laser source is an optical parametric oscillator providing 100 fs long pulses at a repetition rate of 80 MHz. The wavelength of operation is set at 1.18 μm where silicon is transparent and where the InGaAsP QW barrier material is absorptive in order to maximize the pumping efficiency. The pump is delivered to the sample via a SMF-28 optical fiber and coupled to the SOI waveguides thanks to gratings etched at their extremities.[12] These gratings couplers are originally optimized for operating at 1.55 μm. But, by using p polarization and by setting the angle between the fiber and the sample at 12°, it is possibly to couple the pump at 1.18 μm into the TM mode of the SOI waveguides. While propagating below the 2DPhC, the pump light is absorbed by the III-V-based layer. Of course, the alignment of the SOI wire with the line defect 2DPhC waveguide is of primary importance to ensure maximum efficiency of the optical pumping. When perfect alignment is assumed, which is not far from reality (30 nm), we calculate, using 3D FDTD, that 33% of the incoming light is absorbed within 100 μm. Then, the light emitted by the 2DPhC and coupled to the TE mode of the SOI wire, is collected at the output of the other grating by a SMF-28 positioned at 10° angle in order to maximize collection at 1.55 μm (s polarization). The emission is analyzed using a spectrometer.

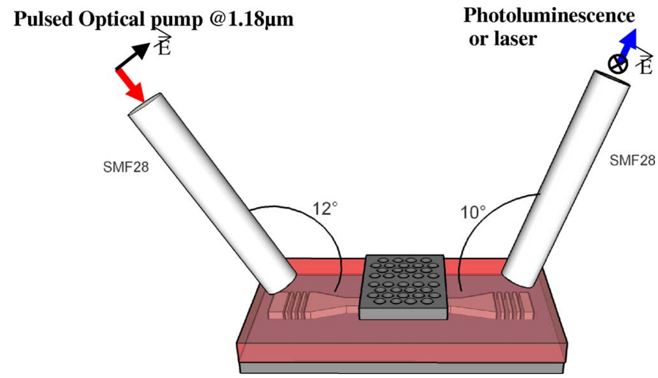

FIG. 3. (Color online) Experimental configuration.

We observe the photoluminescence (PL) spectrum of the samples in order to identify the slow modes of interest by comparing the results with the modeling. The PL spectrum of the sample is shown in Fig. 4(a). three peaks, noted A, B, and C, clearly appear in the spectrum at the normalized frequencies corresponding to the low v_g modes of the PhC waveguides also noted A, B, and C in Fig. 2(a).

As the pump energy is increased, laser emission is observed only at 1586 nm in mode A. Indeed, mode A is the only one out of the three observed modes that is situated below the BCB light line [see Fig. 2(a)], which renders it theoretically lossless in the absence of disorder. We plot on Fig. 4(b), in log-log scale, the laser emission energy as a function of the pump pulse energy effectively coupled into the SOI waveguide. The obtained curve has a "classical" S-shape[13] from which a threshold of about 1 pJ is deduced (5.93×10^6 photons). We then plot the spectral position of

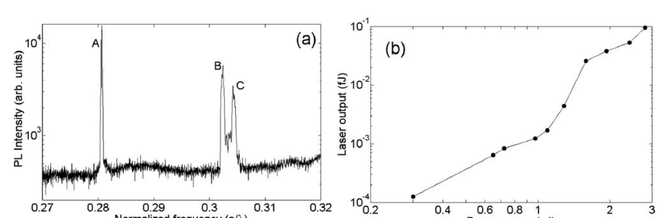

FIG. 4. (a) PL spectrum of the hybrid structure. The three peaks, A, B, and C correspond to the low-v_g modes of Figs. 2(a) and 2(b) Laser emission intensity observed in mode A vs pump pulse energy.

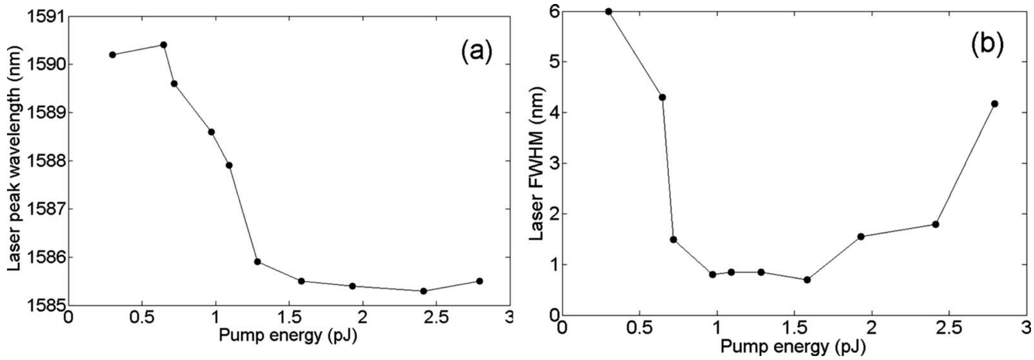

FIG. 5. (a) Peak emission wavelength vs pump energy; (b) FWHM vs pump energy.

the emission peak as a function of the pumping energy in Fig. 5(a). This gives an indication of the level of the carriers inside the structure as the refractive index of the material depends on their density. This carrier induced change in the refractive index results in a blue shift until laser emission occurs at which point the carrier level gets clamped and with it the emission wavelength at a value of 1585.5 nm. The FWHM versus pump energy clearly shows, on Fig. 5(b), the diminishing of the linewidth from the spontaneous emission regime to laser emission where it attains a value of 0.7 nm. For higher pumping energies (2 pJ onwards) the emission linewith broadens due to chirping arising from comparable carrier and photon lifetimes.[14] In this experiment, the maximum measured laser output pulse energy is 1.7 fJ corresponding to an average power of 20 nW.

In conclusion, pulsed laser emission at 1585 nm is obtained in a SOI wire at room temperature through the heterogeneous integration of an InP-based active PhC. The laser emission is due to the efficient light-matter interaction occurring at the low v_g modes of 2D PhC W0.65 waveguides. The particularity of this hybrid system lies in the fact that not only does it permit light collection by the SOI wires but it also enables optical pumping through the very same wire. This allows to decrease the pumping energies due to the tight confinement of the optical pump in the SOI waveguide, as well as to foresee an alternative to electrical injection which is extremely difficult to achieve for lasers based on PhC membrane.[15] Moreover, the use of laser diodes for pumping may be envisaged as it has been done for vertical extended cavity surface emitting lasers, where optical pumping shows better performance.[16] Our particular configuration offers the possibility to optically pump with a single laser source, several PhC lasers atop a SOI optical circuit. Of course, it is an open question whether it is more difficult to contact electrically a PhC laser or bring an optical pump using waveguides connected to optical fibers.

Thus, we believe avenues may open up in the domain of compact photonic circuits with this integration of 2DPhC onto SOI wire. Combining these two powerful elements permits us to derive the benefits of both worlds-Si and III-V systems, allowing us envisage photonic platforms which are both efficient and capable of evolving into multifunctional photonic circuits.

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