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Germanium-based nanophotonic devices: Two-dimensional photonic crystals and cavities

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ABSTRACT

Two-dimensional photonic crystals are promising structures for photonic applications. Here, we show that the optical properties of two-dimensional photonic crystal membranes fabricated from silicon-on-insulator substrates can be probed at room temperature by the internal continuous wave photoluminescence of Ge/Si self-assembled islands. Quality factors up to 15 000, limited by the spectrometer resolution, are measured. We also show that two-dimensional photonic crystals can be fabricated as well with germanium-on-insulator substrates by using the same processing techniques. The optical properties of these two-dimensional photonic crystals can be probed by the room-temperature photoluminescence associated with the direct band gap of the bulk Ge layer. Enhanced resonant extraction efficiency can be obtained for wavelengths longer than 1.55 µm. The quality factors of H1 hexagonal cavities are found in good agreement with those obtained by finite-difference time domain calculations.

Very strong progress has been achieved over the past years in the field of silicon photonics either for passive or active devices. Cavities with record quality factors have been demonstrated by using photonic heterostructures fabricated in silicon membranes [1]. Pulsed and continuous wave Raman lasers with silicon as the active medium have also been demonstrated [2,3]. These advances are not limited to pure silicon. A strong interest is also devoted to structures containing Ge since this material is compatible with the standard CMOS processing of the microelectronics industry. Silicon germanium alloys can cover a very large spectral range in the transparency window of silicon. The absorption/emission spectral range depends both on the composition of the alloy and on the strain-induced band gap modification. In the case of Ge/Si self-assembled islands, an additional band gap reduction occurs because of the tensile strain in the surrounding silicon matrix. It leads to a type II band alignment for the self-assembled islands [4]. At room temperature, the luminescence of the inhomogeneous ensemble of islands covers the 1.2 to 1.6 µm spectral range. The Ge/Si self-assembled islands can be used as internal sources to probe the optical properties of two-dimensional photonic crystals [5]. These two-dimensional photonic crystals are adapted to fabricate high quality factor nanocavities with very small mode volumes which can find various applications in the field of silicon photonics (ultrasmall filters, sensors…). Inversely, one expects an enhanced extraction efficiency of the island radiative recombination associated with the change of the electromagnetic density of states.

We have first fabricated two-dimensional photonic crystals from silicon-on-insulator substrates. A single layer of Ge/Si self-assembled islands was grown by chemical vapor deposition on a silicon-on-insulator substrate. The thickness of the buried oxide layer is 2 µm. The whole structure is covered by a thin film of epitaxial silicon. The total thickness of the upper silicon film is 265 nm. Two-dimensional photonic crystals were fabricated by combining electron-beam lithography and plasma etching. After photonic crystal fabrication, the buried oxide is removed by wet etching through the holes using HF diluted in NH_4F, thus leading to the formation of a silicon membrane separated from the substrate by a 2 µm thick air gap. The vertical confinement of the light is obtained by total internal reflection. The intrinsic vertical symmetry of the structure inhibits the coupling between quasi-TE and quasi-TM guided modes which is detrimental to the in-plane confinement since there is no photonic band gap for the TM-polarization. Different type of cavities can be obviously fabricated with this technique. The inset of Fig. 1 shows a scanning electron micrograph of an elongated L3 cavity which is obtained by omitting to drill three holes in one direction of a triangular lattice pattern. The lattice periodicity is 400 nm and the air hole radius is 0.3*a*. The thickness of the membrane is 0.66*a*. Fig. 1 shows the room-temperature photoluminescence of this cavity excited by the 458 nm line of an argon laser. The excitation and collection are provided by an objective with a 0.8 numerical aperture. The luminescence is detected with a multichannel nitrogen-cooled InGaAs photodetector. Despite the fact that

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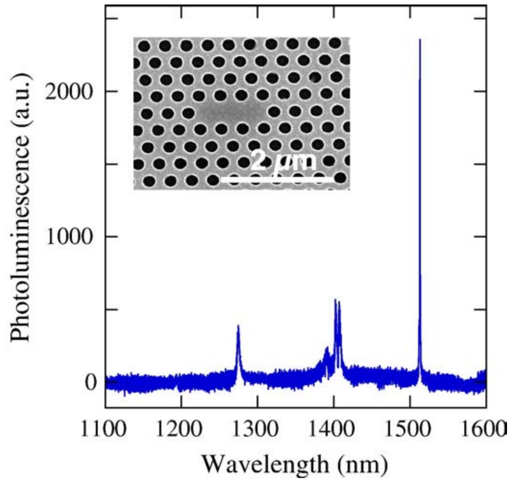

Fig. 1. Room-temperature photoluminescence spectrum of a membrane L3 elongated cavity containing a single layer of Ge/Si self-assembled islands. The inset shows a scanning electron micrograph image of the cavity.

the materials have an indirect band gap and that the optical recombination of the islands is of type II origin, a strong photoluminescence signal associated with the Ge/Si self-assembled island recombination can be measured at room temperature. Several defect photonic modes can be directly evidenced by this technique. The resonance wavelengths and linewidths can be compared with those obtained using three-dimensional finite-difference time domain calculations. The linewidth of the resonances are directly linked to the quality factor of the resonators which corresponds to the optical energy stored in the cavity divided by the energy loss during one light cycle. It is thus sensitive to the absorption losses of the cavity and to the energy loss by radiative out-of-plane coupling. The resonant mode at 1520 nm, corresponding to a normalized frequency $u=a/\lambda=0.264$ has a quality factor Q of 4300 in agreement with FDTD calculations. The amplitude of the out-of-plane radiation loss of this mode can be inferred from the Fourier transform of the confined electric field. The in-plane components with wavevectors smaller than the wavevector of light in air contribute to the radiative energy loss of the optical mode. One way to decrease the out-of-plane radiative losses is to shift laterally the position of the air holes at the edge of the cavity. A small symmetric shift by a fraction of the lattice parameter can lead to a very strong suppression of the in-plane components in the leaky region, leading in turn to the prediction of ultra high quality factors as large as

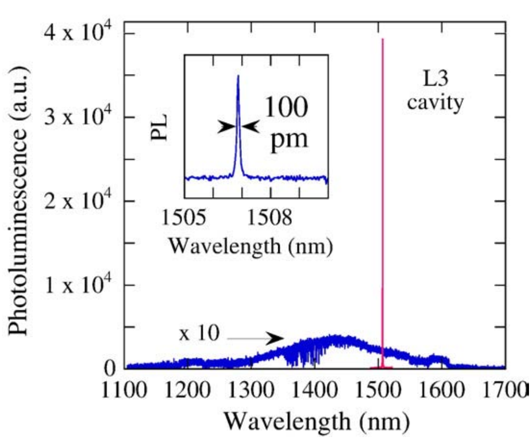

Fig. 2. Comparison between the photoluminescence spectra of the unprocessed sample containing one single layer of Ge/Si self-assembled islands and the photoluminescence spectrum of a L3 cavity with a 0.15a lateral shift of the edge air holes. The experiment is performed at room temperature. The inset shows a zoom on the resonant mode.

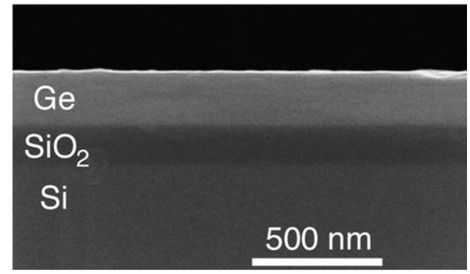

Fig. 3. Scanning electron micrograph cross-section image of the germanium-on-insulator substrate.

300 000 [6]. Fig. 2 shows the photoluminescence properties of an L3 elongated cavity with lateral air holes shifted by 0.15a, i.e. 60 nm. The linewidth of the cavity mode is ≃0.1 nm, corresponding to a quality factor of 15 000. The measurement is in this case limited by the spectrometer resolution. The inset of Fig. 2 shows a zoom on this spectral resonance. Fig. 2 shows a comparison of the amplitude of the mode as compared to the photoluminescence recorded under the same conditions in an unprocessed region of the sample. The peak amplitude between the processed and unprocessed region is modified by a factor ≃200, a signature of an enhanced extraction efficiency and better collection of the luminescence. We emphasize that the amplitude ratio is given for strictly equivalent excitation conditions and does not account for the air filling factor of the structure nor for the modified coupling and diffraction efficiency of the exciting argon laser. By increasing the lateral shift of the air holes, a further increase of the quality factor is observed but above 15 000 the measurement becomes limited by the spectrometer resolution. We note that there is a strong dependence of the measured quality factors as a function of the incident optical density. This dependence is associated with the free-carrier absorption losses generated by the interband optical pumping and thermal heating effects.

Photonic crystals can also be obtained with pure germanium layers, i.e. not only self-assembled silicon germanium islands. Pure Germanium is characterized by a very large refractive index (~4.1–4.2 in the near infrared as compared to 3.47 for silicon). It also exhibits a direct band gap around 0.8 eV at room temperature not far in energy from the indirect band gap (0.66 eV). This direct band gap results in strong absorption coefficients for wavelengths shorter than 1.5 μm. Pure germanium on silicon photodetectors with very high cut-off frequencies and large responsivities have been demonstrated with this system [7,8]. Quantum confined Stark effects based on excitonic transitions with pure germanium quantum wells grown on relaxed buffer layers on silicon have also been evidenced, opening the route to the development of electro-absorption optical modulators operating around 1.5 μm [9]. In order to enhance the absorption, modulation, or emission properties of germanium based structures, resonant cavities are particularly important. The question arises whether two-dimensional photonic crystals with pure germanium can be fabricated in the same way than silicon photonic crystals.

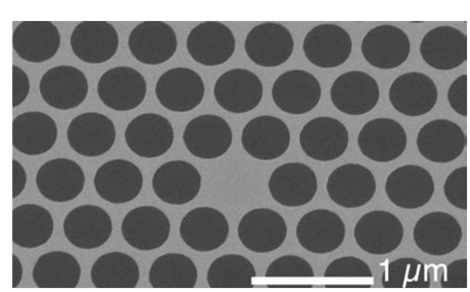

Fig. 4. Scanning electron micrograph image of a H1 cavity fabricated on the germanium-on-insulator substrate.

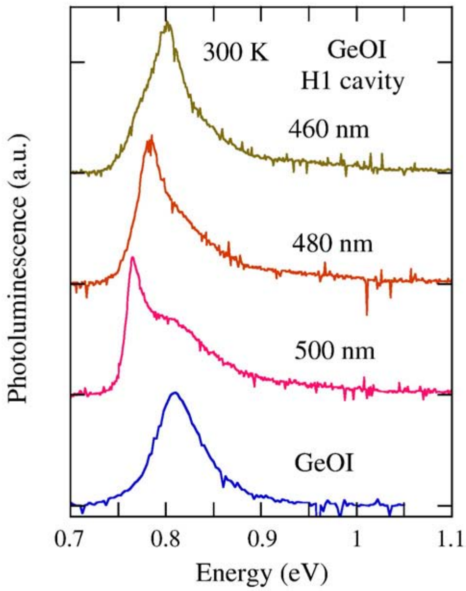

Fig. 5. Room-temperature photoluminescence of the bulk germanium-on-insulator substrate and H1 cavities for different triangular lattice periodicities. The air filling factor is 55%. The curves have been offset for clarity. The lattice periodicities are indicated on the graph. The luminescence is excited with the 458 nm line of an argon ion laser.

We have investigated two-dimensional photonic crystals fabricated on a germanium-on-insulator substrate. The germanium-on-insulator substrate was obtained by wafer bonding using the Smart-Cut™ technology [10]. Hydrogen implantation is used to peel off a very thin layer of a germanium wafer which is later bonded on a silicon wafer covered by an oxide layer. Following this procedure, we obtain a 230 nm thick pure Ge layer separated by a 170 nm thick oxide from a silicon substrate. Fig. 3 shows a cross-section scanning electron micrograph of the vertical stacking before processing. The fabrication of the photonic crystals was performed with the same processing techniques used for the silicon-based photonic crystals. A 300 nm thick photoresist was first deposited on the sample. A triangular lattice pattern and hexagonal cavities were defined by electronic beam lithography. The pattern was then transferred into the germanium layer down to the buried oxide by reactive ion etching using SF_6 and CHF_3 gases. No oxygen was used in the process. Fig. 4 shows a scanning electron micrograph image of a hexagonal H1 cavity obtained by omitting to etch one air hole in a triangular lattice. This type of cavity is known to provide a weak quality factor but a small mode volume. The investigated germanium-on-insulator substrates have a buried oxide with a small thickness. This feature is detrimental to the achievement of large quality factors since the coupling to the substrate is significant. A way to circumvent this effect would be to etch the photonic crystal deeper, i.e. though the oxide layer and through the silicon substrate. This strategy remains however technologically challenging. Moreover, it would only lead to an increase by a factor of 2–3 of the quality factor for a standard H1 cavity. As our objective is to demonstrate that photonic crystals can be obtained with germanium-on-insulator substrates, we did only etch the germanium layer down to the buried oxide, i.e. in a process equivalent to the one used for silicon-on-insulator substrates.

Fig. 5 shows the room-temperature photoluminescence of several H1 cavities with different lattice parameters (460, 480 and 500 nm). The air filling factor of the photonic crystal is 55% corresponding to a radius over periodicity $r/a = 0.39$ for the 500 nm lattice. The photonic band gap for TE polarization covers the spectral range from 0.6 eV to 1 eV, i.e. 50% around its central energy. The photoluminescence is compared to the photoluminescence of the bulk germanium-on-insulator substrate. At room temperature, the recombination associated with the indirect band gap of germanium at 0.67 eV and the direct band gap at 0.8 eV contribute to the signal. The amplitude of the direct band gap recombination is about 4 times larger than the amplitude of the indirect band gap recombination at 300 K. This ratio can be modified by the reabsorption of the direct band gap emission. In the case of the germanium-on-insulator substrate, the emission peaked around 0.81 eV stems from the direct band gap recombination. The indirect band gap is not observed because of the cut-off of the nitrogen-cooled germanium photodetector used for the experiment. In the case of the H1 cavities, an enhanced extraction efficiency is observed at low energy (0.765 eV in the case of the sample with a 500 nm lattice parameter). This resonant emission shifts as expected towards high energy as the lattice parameter is decreased. It shows that we can tailor and reinforce the emission properties of the germanium layer at long wavelength, i.e. above 1.5 µm. This feature is of prime importance since the absorption of Ge can be too weak at the telecommunication wavelength of 1.55 µm to fabricate small detectors which can be operated at very high frequency. Meanwhile, we do observe a broadening of the resonant emission as the lattice parameter is decreased, i.e. as the emission shifts towards the direct band gap of the germanium. This decrease of quality factor is associated with the increased absorption of the material as we move closer to the band gap edge. The quality factor is given by the relation $1/Q = 1/Q_{int} + 1/Q_{abs}$ where Q_{int} is the intrinsic quality factor of the cavity and $Q_{abs} = 2\pi n/\alpha\lambda$ the quality factor resulting from the absorption α at the resonant wavelength λ. The inverse of the quality factor varies thus linearly with the absorption coefficient amplitude. We have reported in Fig. 6 the dependence of the inverse of the quality factor as a function of the bulk germanium absorption coefficient at the peak wavelengths corresponding to the different lattice parameters. We observe as expected a linear dependence [11]. The extrapolation of this curve to zero absorption gives an intrinsic quality factor of the H1 cavity of 85. This value corresponds to the one calculated for the H1 cavity by 3D-FDTD.

We have calculated by two-dimensional plane wave expansion and 3D-FDTD the resonance energy, quality factor and spatial profiles of the confined modes in the H1 cavity. Several defect modes, including dipolar, quadrupolar modes…, appear in the photonic band gap for this cavity. The dipolar fundamental mode is predicted at a normalized frequency $u = 0.287$ corresponding to an energy of 0.712 eV for the cavity with a 500 nm lattice parameter. The dipolar mode exhibits strong radiation losses and has the largest amplitude coupled to the radiative continuum. We attribute the resonance observed for the H1 cavity to this fundamental dipolar mode. The discrepancy between the

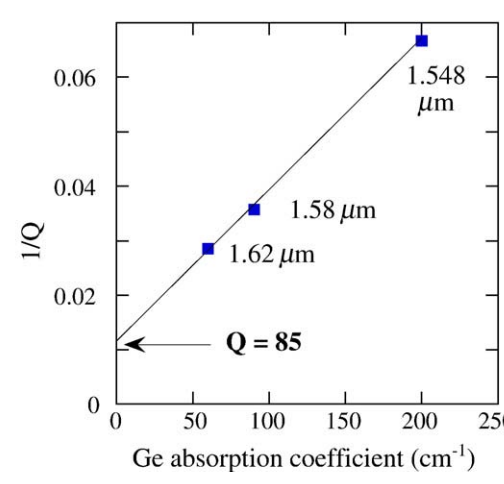

Fig. 6. Inverse of the quality factor of the H1 cavity as a function of the bulk germanium absorption coefficient. The absorption coefficient is taken at the resonance wavelengths of the H1 cavity modes for different lattice parameters.

calculated resonance energy and the experimentally measured resonance energy is attributed to the uncertainty on the values of germanium refractive index and its dependence as a function of the excitation density and to a possible small deviation from the nominal parameters. We note that resonant emission of the photonic crystals can also be tuned by varying the air filling factors of the photonic crystals.

In conclusion, we have reported on the fabrication and optical characterization of two-dimensional photonic crystals. We have shown that silicon air-bridge structures can be probed by the room-temperature photoluminescence of a single layer of Ge/Si self-assembled island. Quality factors up to 15 000, limited by spectrometer resolution, have been measured by this technique. We have also shown that a new class of two-dimensional photonic crystal can be obtained with germanium-on-insulator substrates. The photonic crystals are fabricated with the same processing techniques as those used for silicon. The photonic crystal properties can be probed by the room-temperature photoluminescence of the bulk germanium layer. Resonant emission and enhanced extraction efficiency have been observed at wavelengths above 1.53 μm These results open the route to the development of germanium photonics.

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