Quality factor control of Si-based two-dimensional photonic crystals with a Bragg mirror

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We have investigated the coupling between two-dimensional photonic crystals and a distributed Bragg reflector by fabricating silicon-based photonic crystals on top of a one-dimensional Bragg mirror. The two-dimensional photonic crystals contain Ge/Si self-assembled islands as an internal source covering the 1.1–1.6 μm spectral range. We show that we can control the quality factor of Bloch modes by varying the thickness of the silicon layer on top of the Bragg mirror. Quality factors up to 2200 are obtained for optical radiative modes collected from the surface for a photonic crystal with a square lattice pattern. The variation of the quality factor as a function of the thickness of the upper layer is confirmed by three-dimensional finite-difference time domain calculations of the investigated structures. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2181633]

Photonic crystals are promising candidates to develop nanophotonic devices operating in the near infrared spectral range. Several approaches have been developed to date to selectively and strongly confine light and to obtain high quality factors with small modal volumes. The main activity on photonic crystals is devoted to two-dimensional photonic crystals following a membrane type approach where the permittivity is periodically patterned in the layer plane and the light is vertically confined by a strong variation of the index of refraction. Very high quality factors can be obtained with these photonic crystals as recently reported with small volume microcavities[1] or coupled waveguides.[2] In membrane type photonic crystals, the optical modes below the light line are guided along the photonic crystal slab and are not coupled to the radiative continuum. For emission normal to the surface, it is interesting to control the leaky optical modes at the zone center of the Brillouin zone, i.e. above the light line, which can couple to free space out of the slab.[3] In bulk membrane type photonic crystals without intentional defects, lasing can be either observed at the Brillouin zone edge[4,5] or near the Γ point of the band structure.[6] The threshold of lasing for these Bloch modes is enhanced by the reduced group velocity at the band edges.[7] In the case of surface-emitting diodes or lasers, the normal incidence coupling relies on multidirectional distributed feedback with a Bragg diffraction condition satisfied for wave vectors at zone center after zone folding.[8,9] All the performances of these devices are dependent on the values of the quality factor of the optical modes. It is thus highly desirable to be able to control this parameter.

One-dimensional Bragg reflector can provide an additional degree of freedom to control the light coupling from two-dimensional photonic crystals to the radiative continuum.[10] The constraints on these 2.5 dimensional structures are less stringent than for three-dimensional (3D) photonic structures. Theoretically, the patterning of a distributed Bragg reflector by a triangular lattice of air holes was investigated in Ref. 11. As the two-dimensional and one-dimensional photonic gaps overlap, a strong variation of the photonic density of states is calculated with corresponding changes of spontaneous emission rates and radiation patterns for a local emitter. In this work, we have investigated the combination of silicon-based two-dimensional photonic crystals with a one-dimensional Bragg reflector. Square lattice photonic crystals were fabricated on top of a one-dimensional Bragg reflector, i.e., the Bragg reflector was not etched. The patterned active region on the top surface contains one layer of Ge/Si self-assembled islands as an internal probe source covering the 1–1.6 μm spectral range.[12] We show that the coupling to the radiative continuum strongly depends on the thickness of the top layer. High quality factors can be obtained for optimized thicknesses and air filling factors of the square lattice photonic crystals. The quality factors are significantly larger than those obtained on an equivalent planar photonic crystal slab on silicon-on-insulator. The experimentally observed quality factor variation is supported by three-dimensional finite-difference time-domain (FDTD) calculations of the investigated structures.

Figure 1 shows a schematic cross-section diagram of the vertical stacking. All the wafers have 8 in. diameter, and wafer bonding is achieved on the full surface of the wafers. The Bragg mirror was fabricated with a stop band centered around 1.3 μm. It consists of three periods of quarter-wave thick SiO_2 (221 nm)/polycrystalline Si (92 nm) layers for 1.3 μm wavelength. A 432 nm thick oxide layer was then deposited on top of the mirror (wafer A). A silicon-on-insulator wafer with a 100 nm thick buried oxide, a 50 nm thick crystalline silicon upper layer covered by a 10 nm thick oxide was bonded on wafer A. The 50 nm thick silicon layer

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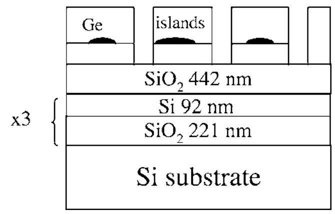

FIG. 1. Schematic diagram of the investigated structure. Photonic crystals with a square lattice pattern are realized in the upper slab layer.

is thus separated from the Bragg mirror by a half-wave thick oxide layer (432+10 nm). After removal of the bulk substrate silicon coming from the silicon-on-insulator wafer and after surface oxide removal, silicon and a single layer of Ge/Si self-assembled islands were deposited on top of the structure by chemical vapor deposition. The final thickness of the top surface layer is 90 nm (sample A608), 170 nm (A609), and 225 nm (A610). These thicknesses were measured using scanning electron micrograph images or by normal incidence reflectivity. The photonic crystals were further processed on this top crystalline layer by electron beam lithography and reactive ion etching.[13] Different types of geometry patterns were realized. In the following, we will focus on square lattice patterns with lattice periodicities a of 585 nm. The air holes were etched down to the half-wave thick oxide layer. The air hole radius r is around $r/a=0.26$. The surface of the patterned region was around 100 μm^2. The photonic structures were probed at room temperature with a microphotoluminescence setup. The excitation was provided by an argon ion laser. The luminescence is excited from the surface and collected with the same objective with a numerical aperture of 0.6. The optical power incident on the sample is around 5 mW.

Figure 2 shows the room temperature photoluminescence spectrum of a square lattice pattern $(r/a=0.31)$ processed on a standard silicon-on-insulator substrate. The patterned surface is $30\times 30\ \mu m^2$. The investigated spectral range goes from 1550 to 900 nm, i.e., from 0.38 to 0.65 in normalized frequency (a/λ). The upper crystalline silicon layer containing one Ge/Si self-assembled island layer is 280 nm thick and the buried oxide layer is 400 nm thick. The observed resonances are associated with the surface band edge emission near the Γ point of the band structure. This is confirmed by calculating the band structure using a two-dimensional plane wave expansion method. The resonances at 1286 and 988 nm (normalized frequencies $u=a/\lambda=0.46$

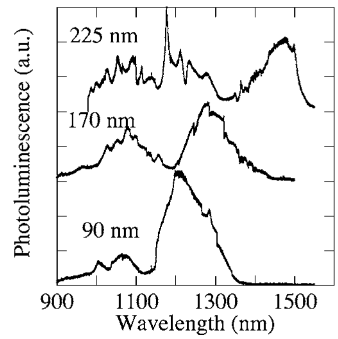

FIG. 3. Room temperature photoluminescence of square lattice photonic crystals fabricated on top of a Bragg miror. The thickness of the upper slab layer is a varying parameter (from bottom to top: 90, 170, 225 nm). The excitation wavelength is 458 nm.

and $u=0.58$) are associated with TE polarization while the resonances between 1050 and 1100 nm $(u=0.53-0.56)$ are associated with TM polarization. Note that because of the vertical asymmetry of the structure, one expects to observe mixing between TE and TM photonic modes. The resonances are quite broad with quality factors Q around 100. These assignments are further confirmed by 3D-FDTD calculation of the optical modes radiated above the surface of the photonic crystal. We have calculated by 3D-FDTD the quality factors of the optical modes for structures with a finite size. The calculated Q values in the investigated spectral range (normalized frequencies between 0.4 and 0.65) are around 130 $(u\sim 0.47)$ and 270 $(u\sim 0.55)$.

We now turn to the structures containing the Bragg mirror. The Bragg mirror that exhibits a stop band between 1 and 1.6 μm exhibits also a very high reflectivity between 400 and 460 nm. The most efficient pumping of the island luminescence is obtained for an excitation wavelength around 488 nm, which corresponds to a trade-off between the reflectivity and the pump absorption in the silicon upper layer. Figure 3 shows the photoluminescence spectra of the three samples with a varying upper layer thickness. The spectrum of sample A608 is dominated by a broad emission between 1150 and 1350 nm which shifts to longer wavelength as the thickness of the upper layer is increased. Additionally we observe that sample A610 exhibits a larger number of resonances between 1000 and 1300 nm. We have investigated in more details sample A610, which exhibits a larger number of narrow resonances. Figure 4 shows the photoluminescence spectra of sample A610 for a square lattice pattern with different air hole radius ($r/a=0.247$, 0.265, and

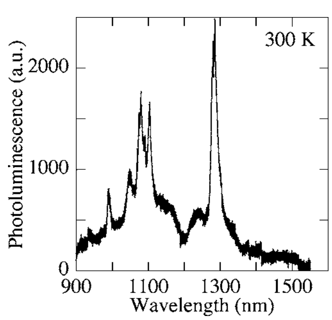

FIG. 2. Room temperature photoluminescence of a square lattice photonic crystal slab on silicon-on-insulator. The luminescence is excited and collected from the surface of the structure. One single layer of Ge/Si self-assembled islands is embedded in the photonic crystal. The excitation wavelength is 488 nm.

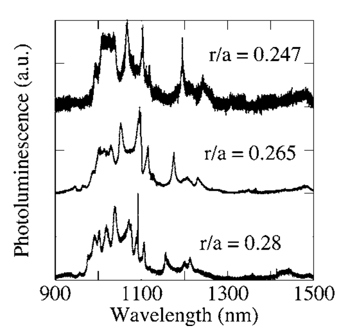

FIG. 4. Room temperature photoluminescence of the square lattice photonic crystal with a 225 nm thick uuper layer slab as a function of the air hole radius. From top to bottom: $r/a=0.247$, 0.265, 0.28. The excitation wavelength is 488 nm.

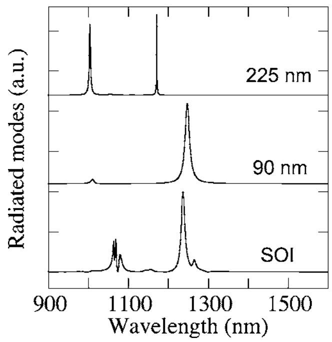

FIG. 5. 3D-FDTD calculation of the square amplitude of the optical modes coupled to the radiative continuum above the surface for three different structures. The curves have been normalized and offset for comparison. Bottom plot: 2D photonic crystal on silicon-on-insulator substrate. Middle and top plots: 2D photonic crystal on a Bragg mirror—upper layer thickness of crystalline silicon 90 nm (middle) and 225 nm (Top curve). The r/a factor is 0.31. The pulsed excitation source has components in the layer plane and along the growth axis.

0.28). The amplitude of the spectra have been normalized for comparison. As seen on the spectra, the quality factors of the optical modes coupled to the radiative continuum depends strongly on the air filling factor of the photonic crystal. Such a feature has already been observed by different groups for standard membrane-type photonic crystals, in particular for the defect resonant cavities.[1] Here we show that we can obtain high quality factors by adjusting the thickness of the upper layer on the Bragg mirror and the air filling factor of the photonic crystals. The thickness of the upper layer film determines the periodical resonance conditions for the amplitude of the local electric field in the layer, as a result of interference effects in the multilayer slab (period of $\lambda/2n$). The 225 nm thickness corresponds for example to constructive interferences and maximum local electric field for a wavelength around1150 nm. The variation of the air filling factor provides a fine tuning of the photonic crystal properties allowing to match resonance conditions between the one-dimensional (1D) layer and the two-dimensional (2D) photonic crystal. For a 225 nm upper layer thickness, resonances with a linewidth of 0.5 nm are obtained around 1100 nm, corresponding to a quality factor of 2200. This value has to be compared to the ~100 quality factor obtained with the same photonic crystal pattern on standard silicon-on-insulator substrates. The same quality factors were measured by pumping the active area with an objective with a lower numerical aperture (NA=0.3), i.e., a larger spot size excitation. We have observed that the change of the excitation wavelength can modify the amplitude ratio between the different resonances as a consequence of the varying carrier density profile and index as well as luminescence source position in the structure. At 458 nm, a narrow resonance (~0.6 nm linewidth) is also observed around 1150 nm.

The structures consisting of the photonic crystal and Bragg mirror were modeled using 3D-FDTD. Figure 5 shows the FDTD spectra for three different structures. The bottom curve corresponds to the standard silicon-on-insulator structure (experimental spectrum shown in Fig. 2); the middle curve corresponds to the structure with a 90 nm thick silicon upper layer (experimental spectrum shown in Fig. 3); the top curve corresponds to the structure with a 225 nm thick silicon upper layer (experimental spectrum shown in Fig. 4). The quality factors are lower than 270 for the first two structures, the main peaks having a quality factor around 100. High quality factors are only observed for the structure with a 225 nm thick silicon upper layer, as observed experimentally, and confirms that the quality factor can be controlled by the thickness of the upper layer. We calculate a quality factor around 900 at 1166 nm for a r/a factor of 0.31. The calculated quality factor exhibits a resonance as a function of the air filling factor and is maximum for $r/a=0.31$. This value is slightly different from those investigated experimentally ($r/a \leq 0.28$). For $r/a=0.28$, the resonance peak is calculated at 1193 nm, i.e., at longer wavelength as compared to the experiment. The observation of a maximum for the quality factor as a function of the air filling factor indicates that the system constituted by the photonic crystal and the Bragg mirror is very sensitive to the resonance conditions. We attribute the difference between the calculated and measured quality factors to the reduced size of the computation area.

In conclusion, we have shown that the quality factor of modes coupled to the radiative continuum can be tailored by combining two-dimensional photonic crystals and one-dimensional Bragg mirrors. This feature is illustrated in the case of silicon-based photonic crystals with a square lattice pattern. The adjustement is achieved by varying the thickness of the upper slab layer where the photonic crystal is etched. Another route to control the quality factor would consist in varying the thickness of the buried oxide layer while maintaining a fixed photonic crystal slab layer thickness.

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