Two-Dimensional Photonic Crystals Coupled to One-Dimensional Bragg Mirrors

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***Abstract*—Planar two-dimensional (2-D) photonic crystals can be combined with a one-dimensional (1-D) Bragg mirror to control the quality factor and out-of-plane coupling of optical modes. We have investigated the optical properties of such structures fabricated on silicon. The optical properties are probed by the room-temperature photoluminescence of Ge/Si self-assembled islands as an internal source. We show that the enhancement of the quality factor can be obtained by controlling the thickness of the silicon upper layer in which the 2-D photonic crystal is etched and the air filling factor of the photonic crystal. Quality factors of 2200 around 1100 nm are obtained by this method for bulk photonic crystals with a square lattice pattern. The experimental results are supported by three-dimensional (3-D) finite-difference time-domain calculations of the investigated structures.**

***Index Terms*—Ge/Si self-assembled islands, Si-based photonic crystal structures.**

I. INTRODUCTION

PHOTONIC crystals obtained by a periodical patterning of material dielectric permittivity are artificial structures that allow to control light propagation, optical density of states, and the coupling and extraction of spontaneous emission to specific optical modes. One of the main types of investigated structures consists of two-dimensional (2-D) slab structures [1]. In this case, photonic bandgaps can be obtained for the in-plane propagation. The coupling of light in the vertical direction to the radiative continuum depends on the position of the light line that is associated with the total internal reflection. Optical modes with wave vectors below the light line can be truly guided in the layer plane. Above the light line, the modes can couple to the radiative continuum and are thus leaky. This leakage can be, on one hand, an advantage if one wants to extract light efficiently from the device. On the other hand, it can reduce the quality factor of the optical modes significantly and can, thus, be, for example, detrimental to laser thresholds. One way to circumvent this problem is to fabricate three-dimensional (3-D) photonic crystals that can create a complete photonic bandgap in all crystal directions and, thus, control and inhibit the spontaneous emission. The fabrication of such crystals remains, however, technologically challenging [2]. Another approach can be achieved by adding another degree of freedom to control the light coupling of 2-D photonic crystals. This degree of freedom can be provided by inserting a one-dimensional (1-D) Bragg mirror below the 2-D photonic crystal [3], [4]. By adjusting the thickness of different layers, one can control the overlap of the 1-D and 2-D photonic bandgaps and, thus, control the light coupling and its redistribution toward the vertical direction. The quality factor of the optical modes can be either enhanced or decreased depending on the resonance conditions in the system.

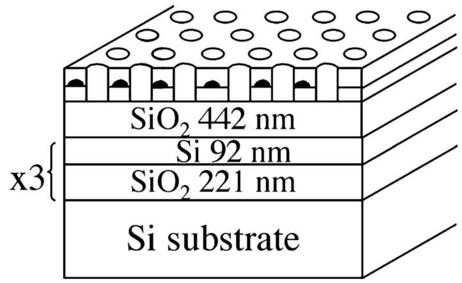

Fig. 1. Schematic description of the investigated sample.

In this paper, we report the optical properties of silicon-based 2-D photonic crystals fabricated on top of a 1-D Bragg mirror. The photonic crystal contains a single layer of Ge/Si self-assembled islands that allows to probe the optical properties as an internal source at room temperature. We show that the quality factor of specific optical modes can be enhanced by finely adjusting the thicknesses of the layer and the air filling factor of the photonic crystal.

II. SAMPLE FABRICATION

A schematic of the investigated structures is shown in Fig. 1. The Bragg mirror was first grown on a silicon substrate and consists of three periods of quarter-wave thick SiO_2 (221 nm)/polycrystalline Si (92 nm) layers with a stop-band centered around 1.3 μm. A 432-nm-thick oxide layer was then deposited on top of this mirror. A silicon-on-insulator substrate with a thin (50 nm) silicon layer covered by a 10-nm-thick oxide was bonded on this wafer. The Bragg mirror is thus separated from the top silicon layer by a $\lambda/2n$ layer, where λ is the wavelength and n the refractive index. Following this wafer-bonding process, silicon and Ge/Si self-assembled islands were deposited

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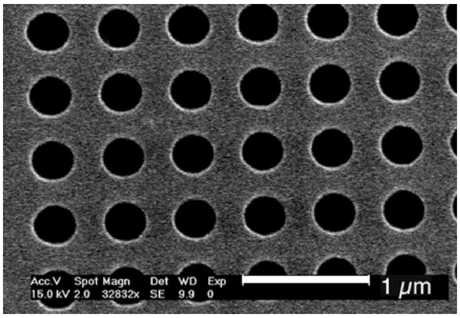

Fig. 2. SEM image of the top surface of the square lattice photonic crystal.

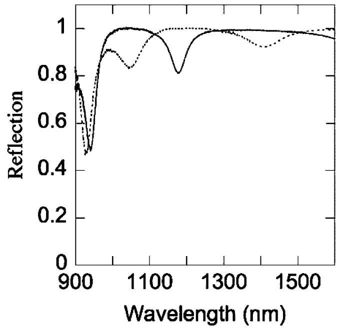

Fig. 3. Reflection spectra of sample A (*dotted line*) and sample B (*solid line*). The upper layer thickness is 170 nm (sample A) and 225 nm (sample B).

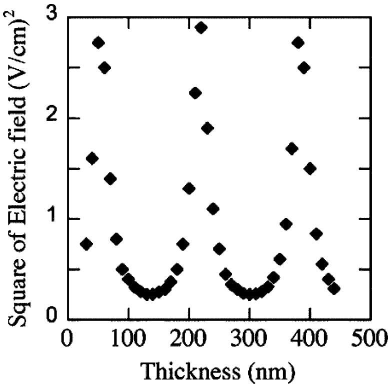

Fig. 4. Square of local electric field amplitude in the upper silicon layer as a function of its thickness. The calculation is performed for a wavelength of 1150 nm.

by ultrahigh vacuum chemical vapor deposition (CVD) [5]. This step allows to control the final thickness of the upper layer. In the following, samples with two different thicknesses are studied and identified as sample A and sample B. Two-dimensional photonic crystals were fabricated on this upper layer by e-beam lithography and reactive ion etching [6]. The holes were drilled down to the $\lambda/2n$ thick oxide layer. Different photonic crystal patternings were realized. Now, we will focus on square lattice patterns with a lattice periodicity a of 585 nm. The air hole radius r is around $r/a = 0.26$, with values ranging from 0.24 to 0.31. Fig. 2 shows a scanning electron microscopy (SEM) image of the sample after processing. The surface of the patterned region was around 100 μm^2. The photonic structures were probed at room temperature with the photoluminescence of Ge islands. The excitation was provided by a tunable 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. Bragg reflections due to vertical stacking also occur at the excitation wavelength. Different excitation wavelengths were thus experimentally used in order to maximize the photoluminescence signals.

III. RESULT

Fig. 3 shows the reflectivity spectra of samples A and B measured with a microscope coupled to a Fourier transform infrared spectrometer. The modeling of the reflectivity of the structure allows to estimate the thickness of the upper layer grown by CVD. Thicknesses of 170 and 225 nm are deduced for samples A and B, respectively. These thicknesses are found in good agreement with those measured by SEM of the cleaved edge of the sample.

The control and enhancement of the quality factor of optical modes depends on the achievement of a double resonance condition between the 2-D photonic crystal and the 1-D Bragg mirror. The resonance frequencies of the 2-D photonic crystals must correspond to resonances set by the total structure (upper silicon layer, quarter-wave thick oxide, and Bragg mirror). At a fixed wavelength, the vertical periodical stacking exhibits constructive interference effects associated with multiple reflections at the interfaces. The amplitude of the local electric field in the silicon upper layer is governed by these interference effects and depends on the thickness of the upper layer. Locally, the optical intensity is proportional to the density of states at a given frequency, i.e., strongly enhanced as the group velocity gets close to zero [7]. A strong local electric field will correspond to a weak group velocity and a large transmission of the multistack layer. The quality factor of an optical mode can be written following $1/Q = 1/Q_{//} + 1/Q_{\perp}$, where $Q_{//}$ is the in-plane quality factor and $Q_{\perp}$ is the vertical quality factor. The enhancement of $Q_{\perp}$ and consequently of Q will, thus, correspond to a strong local electric field at a given wavelength. Fig. 4 shows the variation of the square amplitude of the local electric field in the silicon upper layer without photonic crystal as a function of its thickness. The calculation is performed for a wavelength of 1150 nm. The electric field amplitude exhibits a periodical variation, with sharp resonances observed with a periodicity of $\lambda/2n$. In this case, a strong resonance is observed at 225 nm, which corresponds to a weak group velocity at 1150 nm. This feature is associated with the reflection peak observed for sample B. The thickness of the upper layer is, thus, a critical parameter to adjust the resonance conditions in the structure. Obviously, the thicknesses where a resonance is observed will depend on the thickness of the oxide layer separating the photonic crystal and the Bragg mirror. The periodicity of $\lambda/2n$ would, however, remain the same.

Fig. 5 shows the calculated 2-D band diagram of a square lattice photonic crystal for the odd (TM-like polarization) and even modes (TE-like polarization). The thickness of the layer is 225 nm, and the r/a ratio is 0.28. The spectral positions of the odd and even modes at the zone center depend on the thickness

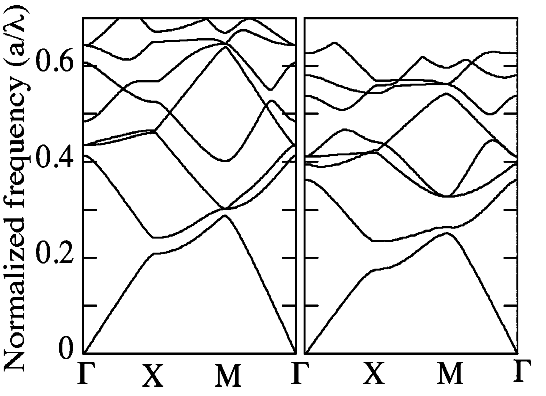

Fig. 5. Calculated band diagram for the odd mode (*left*) and even mode (*right*) for a square lattice photonic crystal ($r/a = 0.28$).

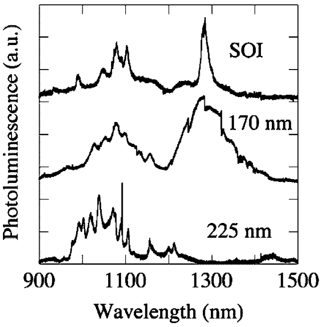

Fig. 6. Room-temperature photoluminescence spectra of sample B (*bottom curve*), sample A (*middle curve*), and a reference silicon-on-insulator sample with a square lattice pattern (*top curve*). The r/a factors are 0.28, 0.28, 0.31 from bottom to top. The excitation wavelength is 488 nm (*top* and *bottom curves*) and 458 nm (*middle curve*). The curves have been normalized and offset for clarity.

of the layers and on the air filling factor of the photonic crystal. By varying these parameters, one expects to achieve resonance conditions between the confinement of the optical modes at the zone center and the vertical confinement provided with the Bragg mirror. For the TM-like polarization, the fifth mode at the zone center has a normalized frequency of 0.49 ($\lambda = 1170$ nm). As will be shown later, this mode has a resonance frequency in the range of the reflection peak of the vertical stacking of sample B.

Fig. 6 shows a comparison between the photoluminescence spectra of samples A, B, and a square lattice photonic crystal fabricated on a standard silicon-on-insulator structure. The buried oxide layer is 400 nm and the upper silicon thickness is 280 nm. A single layer of Ge islands is also inserted in the structure. The observed resonances are associated with band edge emission near the Γ-point of the band structure. Mixing between TE and TM photonic modes is expected because of the asymmetry of the structure. The resonances at 1286 and 988 nm (normalized frequencies $u = a/\lambda = 0.46$ and $u = 0.58$) are associated with TE-like polarization while the resonances between 1050 and 1100 nm ($u = 0.53$–0.56) are associated with TM-like polarization. The resonances are quite broad with quality factors Q around 100. In the case of sample A (170-nm-thick silicon upper layer), the emission exhibits very broad resonances with maxima around 1100 and 1300 nm. The striking feature is the observation of a narrow resonance around 1100 nm for sample B that has an upper layer thickness of 225 nm. Narrow resonances are only observed for this sample, thus confirming that the upper layer thickness is a critical parameter to control the quality factor. The linewidth is around 0.5 nm, corresponding to a quality factor $Q = \omega/\Delta\omega \sim 2200$. The 225-nm thickness effectively corresponds to a weak group velocity condition for wavelengths around 1100 nm, as explained earlier. This wavelength fits in the spectral range of the reflection peak observed at normal incidence for sample B. Meanwhile, this resonance corresponds to an optical mode of the photonic crystal at the zone center. Note that the position of the resonances depends on the refractive index of the materials, and is, thus, modified at high carrier densities because of the refractive index change. This quality factor also depends on the air filling factor of the photonic crystal. It rapidly decreases as the r/a ratio varies from 0.28 to 0.25.

We have performed 3-D finite-difference time-domain (FDTD) calculations in order to evaluate the quality factors of the optical modes of the structures. The electromagnetic field is recorded at 1 μm above the surface. A pulsed source with an electric field polarized in the layer plane is inserted in the photonic crystal layer. The calculation takes into account the total structure (photonic crystal + Bragg mirror) and a 6.5×6.5 μm^2 surface patterning. The whole structure is surrounded by perfectly matched layers. Fig. 7 shows the calculated spectral dependence of the optical radiated modes, as given by the square of the electric field, as a function of the upper layer thickness. For this calculation, the r/a ratio of the photonic crystal is 0.32, a value larger than the experimental value but close to the value that provides the largest quality factors. One clearly observes, in the spectral range of interest, an enhancement of the quality factor at a wavelength of 1170 nm (normalized frequency $u = a/\lambda \sim 0.5$) for an upper layer thickness around 225 nm. Lower quality factor values are observed for other thicknesses.

Fig. 8 shows the result of the FDTD calculation for different hole radii of the photonic crystal. The upper layer thickness is again 225 nm. As mentioned earlier, the quality factor is dependent on the air filling factor. The quality factor is maximum for $r/a = 0.31$ with a maximum calculated value ~ 900. We attribute the difference between the calculated and experimental values to the reduced size of the computation area.

The resonant mode with the largest quality factor that dominates the spectrum is an odd mode, as evidenced by its spatial cross section perpendicular to the vertical stacking. It corresponds to the fifth mode seen in Fig. 5 at the zone center and a normalized frequency of 0.49. The resonance wavelengths of even TE-like modes occur at longer wavelengths, i.e., not in the spectral range of the reflection minima of sample B (see Fig. 3), which explains that only the odd TM-like mode benefits of the constructive interferences of the vertical stacking. The discrepancy between the experimental values and the calculated values for the wavelength of the resonant modes is attributed to deviations from nominal parameters.

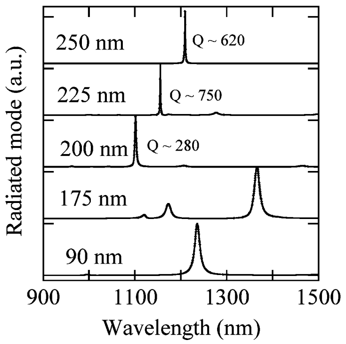

Fig. 7. FDTD calculation of optical modes radiated above the surface as a function of the thickness of the silicon upper layer. The square lattice pattern has a periodicity of 585 nm, the r/a factor is 0.32. The excitation source has an electric field polarized along the layer plane. The curves have been normalized and offset for clarity.

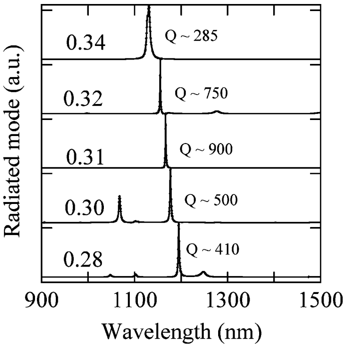

Fig. 8. FDTD calculation of optical modes radiated above the surface as a function of the r/a factor of the photonic crystal. The thickness of the silicon upper layer is 225 nm. The excitation source has an electric field polarized along the layer plane. The curves have been normalized and offset for clarity.

IV. CONCLUSION

In conclusion, we have shown that it is possible to control the quality factor of the optical modes by combining 2-D photonic crystals and 1-D Bragg mirror. Quality factors up to 2200 are obtained for the bulk square lattice patterns. The enhancement is predicted to depend periodically on the thickness of the upper silicon layer in which the photonic crystal is etched. Enhanced quality factors are observed at wavelengths where the local electric field amplitude is strong. A similar enhancement should be obtained by varying the thickness of the oxide layer separating the Bragg mirror and the 2-D photonic crystal slab layer.

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