Silicon-based photonic crystal nanocavity light emitters

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The authors have demonstrated an up to sevenfold enhancement of photoluminescence from silicon-rich silicon nitride film due to a single photonic crystal cavity. The enhancement is partially attributed to the Purcell effect [Purcell, Phys. Rev. **69**, 681 (1946)], which is predicted to be up to 35-fold by finite difference time-domain calculations for emitters spectrally and spatially aligned with the electric field. Experimentally measured cavity quality factors vary in the range of 200–300, showing excellent agreement with calculations. The emission peak can be tuned to any wavelength in the 600–800 nm range. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2396903]

Silicon-based light sources compatible with the mainstream complementary metal-oxide semiconductor (CMOS) technology are highly desirable because they will have a low manufacturing cost relative to III/V semiconductor diodes, and it will be easier to integrate them with electronic components on the same chip. Photoluminescence (PL) from silicon-rich silicon nitride[1–3] (SRN) and, more commonly, from oxide films,[4,5] with 3–5 nm precipitates of silicon nanocrystals (Si-nc) in the dielectric matrix, has been studied. Two different origins for photoluminescence from SRN films are reported in the literature. In one case the luminescence is attributed to confined exciton recombination in the Si-nc since emission wavelength is correlated to Si-nc size.[3] In another study, observed radiative lifetime from SRN films (on the order of 10 ns) is much shorter than is typical for Si-nc exhibiting quantum confinement (on the order of 10 μs),[5] thus the luminescence is attributed to nitrogen-related surface states in small Si-ncs.[4] Internal quantum efficiencies for Si-ncs can be as high as 59%,[6] and optical gain has been demonstrated.[4]

Confining luminescent material in an optical microcavity enhances the emission by restricting the resonant wavelength to a directed radiation pattern that can be collected effectively and by reducing radiative lifetime of the on-resonance emitters due to the Purcell effect.[7,8] Considerable emission enhancement from Si-ncs in one-dimensional resonant multilayer structures was seen by several groups.[9–11] However, such multilayer structures do not exhibit appreciable Purcell effect due to their large mode volumes.[12] Reduction in radiative lifetime is particularly important for the development of lasers based on Si-ncs because it makes radiative recombination compete more favorably with nonradiative recombination processes which increase at higher pump powers. In fact, lower lasing threshold and faster modulation of a gallium arsenide based laser utilizing the Purcell effect of two-dimensional (2D) photonic crystal (PC) coupled-cavity array were recently demonstrated.[13] In this letter, we demonstrate light emitters based on 2D PC cavities fabricated in SRN membrane. We used 2D PC nanocavities because of their high quality factor (Q) values and small mode volumes (V), since both are necessary for the Purcell effect. Planar geometry of the implementation is well suited for integration with other optical devices on a chip.

The structures were fabricated starting from bare silicon wafers. At the first step, a 500-nm-thick oxide layer was formed by wet oxidation. At the second step, a 250-nm-thick layer of silicon-rich silicon nitride was deposited by a chemical vapor deposition from NH_3 and SiH_2Cl_2 gases at 850 °C. Next, a positive electron beam resist, ZEP, was spun on a wafer piece to form a 380-nm-thick mask layer. Photonic crystal pattern was exposed on the Raith 150 electron beam system. After development, the pattern formed in the resist layer was transferred into the silicon nitride layer by reactive ion etching with NF_3 plasma[14] using ZEP pattern as a mask. Any remaining resist was removed by oxygen plasma. The oxide layer was removed under photonic crystal structures by the 6:1 buffered oxide etch. Fabricated PC cavity membrane with periodicity (a) of 330 nm is shown in the insert on Fig. 1.

Microphotoluminescence setup was used to measure radiation spectra from the fabricated structures. A single 100× objective lens with numerical aperture=0.5 was used to image the sample with white light for alignment, to focus the pump beam, and to collect luminescence in the vertical direction (perpendicular to photonic crystal membrane). A 5 mW, 532 nm green laser was used as the excitation source. The beam was spatially filtered though a pinhole to achieve the small spot diameter of about 1 μm necessary for selective excitation on the sample. The total incident pump power was about 0.3 mW.

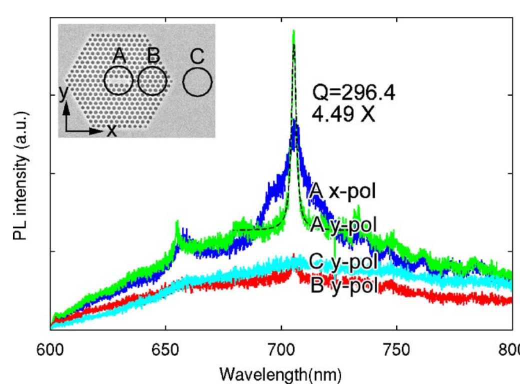

FIG. 1. (Color online) Polarized PL spectra from the areas shown in the insert: cavity region (A), PC region (B), and unpatterned film (C). Dashed line shows Lorentzian fit to y-polarized cavity resonance with Q=296.4. The emission with y polarization from region A is enhanced 4.49 times relative to region C at resonant wavelength of 705.2 nm.

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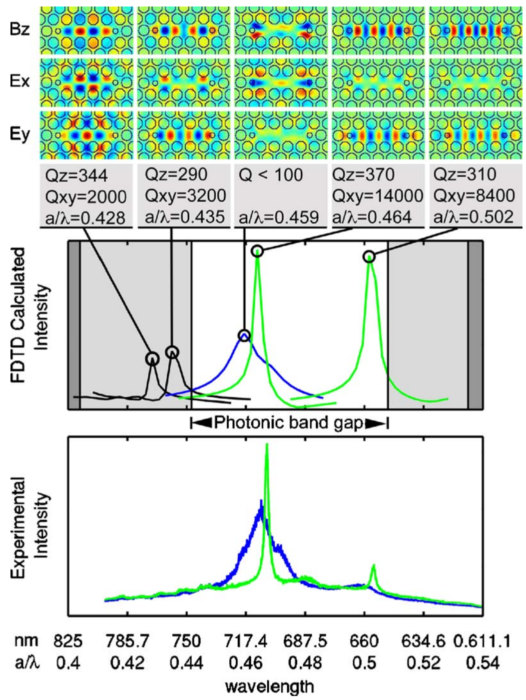

FIG. 2. (Color online) Electromagnetic field distributions for TE cavity modes and their Q factors in-plane (Q_{xy}) and out-of-plane (Q_z) calculated by FDTD together with calculated and measured spectra plotted on the same wavelength scale. The axes are z (perpendicular to the membrane), x (along the cavity axis), and y (perpendicular to x and to z). Photonic band gap for TE modes is indicated (white region). The region shaded in light gray indicates the span of the photonic band edges in frequency from X point to J point.

Polarized PL spectra from a single PC cavity structure with periodicity of 330 nm are shown in Fig. 1. The spectra were taken from three locations on the structure marked by circles in the insert on Fig. 1 by selectively exciting the regions and spatially filtering the signal so that only PL coming from the region of interest was detected. For the cavity region (A) emission with polarizations along the cavity length (x-pol) and perpendicular to it (y-pol) were measured. For the PC region (B) and unpatented region (C) only the y polarization is plotted for comparison with the stronger y-polarized resonance of the cavity. The intensity at the resonant wavelength of 705.2 nm is increased 4.5 times relative to that of the unpatterned film for the electric field polarized along the y direction. Sevenfold intensity enhancement was observed without polarization selection. Lorentzian fit, shown as a dashed line, gave $Q=296$ for the y polarization.

A number of cavities of the same design were fabricated on the same chip. The measured quality factors fell in the range from 200 to 306. To tune the resonance location, structures with slightly different hole radii were produced by varying electron beam exposure dose. The resonance wavelength shifted from 680 to 720 nm as the hole radius changed from 132 to 122 nm.

The optical properties of the photonic crystal cavities were analyzed using three-dimensional finite difference time-domain (FDTD) calculation method.[15] The modeling parameters were chosen to closely resemble fabricated structures with refractive index of 2.11, as measured by spectroscopic ellipsometry at 700 nm, photonic crystal slab thickness of $0.75a$, and hole radius of $0.4a$. Figure 2 shows the electromagnetic field distributions for TE cavity modes and their in-plane (Q_{xy}) and out-of-plane (Q_z) Q factors calculated by FDTD, and both, calculated and measured spectra, which are plotted in the same wavelength scale. The axes are z (perpendicular to the membrane), x (along the cavity axis), and y (perpendicular to x and to z). PC exhibits a 19% band gap for TE modes, from 0.4416 to $0.535a/\lambda$, as indicated in Fig. 2. Generally, the high Q mode observed for the three-hole defect PC cavities in high refractive index materials has four lobes of magnetic field.[16] Here, this mode is at $0.428a/\lambda$ and is outside the complete photonic band gap as it falls below the band edge at J point. The next order mode with five lobes of magnetic field is also below the band edge. There are only slight hints of these modes in the measured spectra. Experimentally observed frequency and polarization for the three modes that fall into the complete photonic band gap are in excellent agreement with theoretical calculations. The broad mode at $0.459a/\lambda$ is primarily polarized in the x direction as evident from its electric field distribution and matched by experimental measurement. The next two modes at $0.464a/\lambda$ and $0.502a/\lambda$ are polarized along the y axis according to their electric field distribution and are observed with this polarization experimentally at $0.467a/\lambda$ and $0.503a/\lambda$, respectively. The slight discrepancy in frequency may be attributed to the slight deviation between the fabricated structure and the model. The most prominent mode in the measured spectrum is the highest Q mode at $0.467a/\lambda$ which has six lobes of B_z in the cavity, calculated mode volume of $0.785(\lambda/n)^3$, calculated Q of 360, and maximum radiative rate enhancement of 35, as given by the Purcell factor, $F=3/(4\pi^2)\ (\lambda/n)^3 Q/V$.[7,8] Using experimentally measured Q of 296 the Purcell factor becomes 28.5. The actual observed enhancement depends on how many emitters fall into the electric field maxima and within the cavity resonance, on how well their dipole moments are aligned with the electric field, and on collection efficiency of the cavity mode relative to the unpatterned film. The experimentally observed PL enhancement is 4.5 times at the resonant wavelength, a factor of 6.3 lower than the theoretical maximum possible. This is expected, because the experimentally observed value is an averaged value of the Purcell factor for all emitters, and majority of them are spectrally and spatially detuned from the cavity resonance, and therefore do not exhibit a maximum Purcell factor.

In summary, we have demonstrated an enhancement of PL from silicon-rich silicon nitride film with a single PC cavity. The use of silicon nitride film rather than more commonly employed silicon oxide film with Si-ncs allows higher index contrast necessary for stronger optical confinement in PC cavities. Studied cavities show excellent agreement with theory. The observed PL enhancement is especially important because it results from the strong Purcell effect, as supported by the FDTD simulations. Thus the radiative lifetime of emitters can be shortened considerably, which could be crucial for making a laser based on Si-ncs. Theoretically much higher Q-factor cavities can be realized in the material system reported here, so even stronger enhancement of PL can be achieved. We would like to emphasize that the processing used to fabricate these light sources is fully compatible with CMOS fabrication technology, so optical and electronic components could be seamlessly integrated on a single chip at low cost. This may open the door to a variety of applications ranging from optoelectronics to biophotonics, especially since the emission wavelength can be chosen anywhere from around 600–850 nm.

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