Silicon Microcavity based on 1-D Photonic Bandgap Structure

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ABSTRACT

In this paper, we report on the design, modeling, fabrication, and characterization of an amorphous silicon microcavity. The microcavity is fabricated using a one-dimensional photonic bandgap structure. The structure was grown by plasma deposition method. Quarter wavelength thick stacks of hydrogenated amorphous silicon nitride and hydrogenated amorphous silicon oxide were consecutively deposited using low temperature plasma enhanced chemical vapor deposition. For the characterization of the dielectric microcavities the intrinsic photoluminescence of the amorphous silicon is used. Bulk amorphous silicon has a luminescence bandwidth of 250 nm. Due to the presence of the microcavity, the luminescence is enhanced by at least an order of magnitude at the resonance wavelength of 700 nm. Additionally, the luminescence is inhibited in the photonic bandgap occupying a spectral band of 150 nm. The microcavity resonance has a quality factor of 120 corresponding to a luminescence linewidth of 6 nm. The enhancement of the photoluminescence is understood by the modified photon density of states of the dielectric microcavity.

Keywords: microcavity, amorphous silicon, photoluminescence, thin films.

1. INTRODUCTION

The possibility to control the emission properties of materials with the use of optical microcavities is continuing to attract the attention of the photonics community.^{1,2} Optical microcavities can now be realized in solid state systems such as organic materials³ and semiconductors.⁴ Semiconductor microcavities are used in resonant cavity enhanced (RCE) optoelectronic devices, which are wavelength selective and ideal for wavelength division multiplexing (WDM) applications.⁵ The simple planar Fabry-Perot resonator is the most widely used geometry in semiconductor microcavities.^{6,7} As they alter the optoelectronic properties of photonic gain media, semiconductor microcavities can be used in very low threshold lasers and very efficient light emitting diodes (LED's).⁸ Semiconductor microcavities have been used in the realization of the low threshold vertical cavity surface emitting lasers,^{9,10} external-cavity surface emitting lasers,¹¹ microdisk,¹² and microwire¹³ lasers. Semiconductor microcavities have also been used in efficient RCE LED's.¹⁴ The cavity alteration of the spontaneous emission was first proposed for radio waves.¹⁵ Afterwards, the microcavity alteration of the spontaneous emission was proposed¹⁶ and observed in organic microcavities,¹⁷ in the optical part of the electromagnetic spectrum. In addition, alteration of the spontaneous emission in semiconductor microcavities was observed¹⁸ and calculated.¹⁹ In this weak coupling (of the photon and exciton modes) regime, the interaction (Rabi coupling) strength is smaller than the microcavity mode damping (linewidth) and the exciton mode damping (linewidth). The spontaneous emission spectrum is altered due to a redistribution of the density of optical modes by the presence of the microcavity. However, in the strong coupling (of the photon and exciton modes) regime, the interaction (Rabi coupling) strength is bigger than the microcavity mode damping (linewidth) and exciton mode damping (linewidth), and Rabi splitting of the microcavity and exciton modes occurs.²⁰ The proposition of strong coupling in optical microcavities,²¹ was followed by its observation²² and theory.²³

2. PROPERTIES OF AMORPHOUS SILICON

2.1. Luminescence of amorphous silicon

Planar waveguides are already being realized from hydrogenated amorphous silicon (a-Si:H).²⁴ An advantage of a-Si:H is that, it can be deposited by plasma enhanced chemical vapor deposition (PECVD) on almost any substrate at temperatures below 500 K, which makes it compatible with the microelectronic technology. This property justifies the renewed interest in silicon as a potential optoelectronic material.

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With modern process techniques, it will be possible to integrate lasers, photodetectors, and waveguides into Si motherboards^{25,26} for WDM applications.²⁷ Recently, we have observed room temperature visible PL from Si rich hydrogenated amorphous silicon nitride (a-SiN_x:H).²⁸ While the exact mechanism of the occurrence of the PL in bulk a-SiN_x:H is still under discussion, we have suggested the use of a quantum confinement model.²⁹ There, it was proposed that, our samples consist of small a-Si clusters in a matrix of a-SiN_x:H. The regions with Si-H and Si-N, having larger energy gaps due to strong Si-H and Si-N bonds, isolate these a-Si clusters, and form barrier regions around them. The PL originates from the a-Si clusters. a-SiN_x:H can be grown both with and without ammonia (NH₃). The samples grown without NH₃ are referred to as the Si rich samples. The luminescence of these samples is in the red-near-infrared part of the optical spectrum. The samples grown with NH₃ and annealed at 800° C are referred to as the nitrogen rich samples. The luminescence of these samples is in the blue-green part of the optical spectrum.³⁰ Figure 1 shows the room temperature photoluminescence (PL) of a-SiN_x:H grown without NH₃. The spectrum has a linewidth of 250 nm and the peak of the PL is at 700 nm.

Fig. 1: Room temperature photoluminescence of a-SiN_x:H.

Fig. 2: Low resolution AFM of the a-SiN_x:H surface.

2.2. Morphology of amorphous silicon

Moreover, the surface of the a-SiN_x:H is optically flat and thus amenable for the growth of multiple layers. This is necessary condition for the realization of the 1-D PBG microcavity. In order to study the origin of the luminescence as well as the roughness of the surface, we have used atomic force microscopy (AFM). Figure 2 shows low resolution AFM of the a-SiN_x:H surface. The surface morphology of the a-SiN_x:H is quite uniform. The bulk of the material is composed of globules of a-SiN_x:H and looks like porous Silicon (π-Si), which has very similar luminescence properties. Figure 3 and 4 show medium and high resolution AFM pictures of the a-SiN_x:H surface. The similarity to π-Si can be observed better in Fig. 3 and 4. Additionally, although the surface is flat optically, it is quite rough in the 100 nm range, which corresponds to the average globule size.

2.3. Similarity to porous silicon

Similar to hydrogenated amorphous silicon (a-Si:H), π-Si also exhibits room temperature visible PL.³¹ Semiconductor microcavity effects (in the weak coupling regime) have been applied to π-Si, after the observation of room temperature visible photoluminescence (PL)³² made π-Si a potential optical gain medium.³³ Steady state^{34,35,36} and temporally resolved,³⁷ single and multiple³⁸ microcavity controlled PL in π-Si has been observed experimentally^{39,40,41} and

calculated theoretically.⁴² The possibility of using π -Si microcavities as chemical sensors has been investigated.⁴³ In addition, microcavity controlled PL has been observed in π -Si inorganic-organic structures,⁴⁴ as well as Si/SiO_x superlattices.^{45,46,47} SiO₂/TiO₂ microcavities,⁴⁸ SiO_x/WO_y, and SiO_x/MO_y multilayers⁴⁹ have been fabricated. Microcavity controlled electroluminescence (EL) of π -Si has been reported.^{50,51} Interference filters⁵² and optical waveguides⁵³ have also formed from π -Si. Two-dimensional (2-D) photonic crystals have been fabricated in π -Si⁵⁴ and silicon nitride (Si₃N₄)⁵⁵ waveguides.

Fig. 3: Medium resolution AFM of the a-SiN_x:H surface.

Fig. 4: High resolution AFM of the a-SiN_x:H surface.

3. AMORPHOUS SILICON MICROCAVITY

We have previously observed the enhancement of PL in a planar a-SiN_x:H microcavity realized with metallic mirrors.^{56,57} In this paper, we report the alteration of photoluminescence (PL) in an all dielectric a-SiN_x:H microcavity, and the measured and calculated reflectance of the all dielectric a-SiN_x:H microcavity. The microcavity is realized by sandwiching an active a-SiN_x:H defect layer in a 1-D PBG. The microcavity resonance wavelength was designed to be at the peak (700 nm) of the bulk a-SiN_x:H PL spectrum.

3.1. One-dimensional photonic bandgap microcavity design

The transfer matrix model (TMM) was used for the calculations.⁵⁸ In this model, we used the structure of the microcavity shown in Fig. 6. Figure 5 shows the calculated room temperature reflectance spectrum of the a-SiN_x:H microcavity. The calculated spectrum of Fig. 5 is in good agreement with the experimentally observed reflectance spectrum of Fig. 7. The resonance linewidth $\Delta\lambda$ and the quality factor Q can also be estimated using the multiplication of the electric field amplitude reflectivity coefficients r_1 and r_2 :

$$r_1 r_2 = \frac{\left(\frac{n_s}{n_{si}} \left(\frac{n_o}{n_n} \right)^{2q} - 1 \right) \left(\frac{n_s}{n_a} \left(\frac{n_o}{n_n} \right)^{2q} - 1 \right)}{\left(\frac{n_s}{n_{si}} \left(\frac{n_o}{n_n} \right)^{2q} + 1 \right) \left(\frac{n_s}{n_a} \left(\frac{n_o}{n_n} \right)^{2q} + 1 \right)} \quad (1),$$

$$Q = \frac{2\pi \left(1 + \frac{n}{\Delta n}\right)}{\ln(1/r_1 r_2)} = \frac{\lambda}{\Delta\lambda} \quad (2),$$

where $\lambda = 700$ nm is the resonant wavelength, $n_s = 2.03$ the refractive index of the silicon rich a-SiN_x:H, $n_{si} = 3.77$ the refractive index of the silicon substrate, $n_a = 1.0$ the refractive index of air, $n_n = 1.72$ the refractive index of the nitrogen rich a-SiN_x:H, $n_o = 1.45$ the refractive index of a-SiO_x:H, $n = 1.59$ the average refractive index of a-SiN_x:H and a-SiO_x:H, $\Delta n = 0.27$ the refractive index difference of a-SiN_x:H and a-SiO_x:H, and $q = 10$ the number of pairs in each side of the 1-D PBG. The estimated quality factor of $Q = 260$ and linewidth $\Delta\lambda = 3$ nm are close to the experimentally observed values.

Fig. 5: The calculated reflectance spectrum of the microcavity.

Fig. 6: Schematic of the 1-D PBG microcavity.

3.2. One-dimensional photonic bandgap microcavity fabrication

The microcavity was realized by a $\lambda/2$ active layer of a-SiN_x:H sandwiched in a passive 1-D PBG. First, the bottom part of the PBG was deposited by PECVD on the silicon substrate using pairs of $\lambda/4$ alternating layers of a-SiN_x:H (with refractive index = 1.72 and metric thickness = 104 ± 5 nm) and a-SiO_x:H (with refractive index = 1.45 and metric thickness = 124 ± 6 nm). Figure 6 shows the schematic of the all dielectric a-SiN_x:H microcavity. For the nitrogen rich a-SiN_x:H deposition, ammonia (NH₃) with a flow rate of 10 sccm, and 2% silane (SiH₄) in nitrogen (N₂) with a flow rate of 180 sccm were used. For the a-SiO_x:H deposition, nitrous oxide (N₂O) with a flow rate of 25 sccm, and 2% SiH₄ in N₂ with a flow rate of 180 sccm were used. After the deposition of the bottom part of the PBG, a $\lambda/2$ defect layer of silicon rich a-SiN_x:H (with refractive index = 2.03 and metric thickness = 163 ± 8 nm) was deposited. For the silicon rich a-SiN_x:H deposition, only 2% SiH₄ in N₂ with a flow rate of 180 sccm was used. Afterwards, the top part of the PBG was deposited, using 10 pairs of $\lambda/4$ alternating layers of a-SiO_x:H and a-SiN_x:H. The radio frequency (RF) power was 20 W, and the deposition chamber pressure 1 Torr during the continuous deposition process. The $\lambda/4$ passive nitrogen rich a-SiN_x:H layers are shown in black, while the $\lambda/4$ passive a-SiO_x:H layers are shown in white. The active $\lambda/2$ central layer of silicon rich a-SiN_x:H is shown in gray. Figure 8 shows a scanning electron microgram (SEM) of the a-SiN_x:H microcavity.

Fig. 7: The measured reflectance spectrum of the microcavity.

Fig. 8: SEM of the 1-D PBG microcavity.

3.3. One-dimensional photonic bandgap microcavity luminescence measurements

Fig. 9: The photoluminescence spectrum of the microcavity.

Fig. 10: The photoluminescence spectrum of the bulk a-SiN_x:H.

Figure 7 shows the measured room temperature reflectance spectrum of the a-SiN_x:H microcavity. The room temperature reflectance measurements were made at $0 \pm 5^\circ$ with respect to the surface normal with a resolution of 0.1 nm. The measured reflectance spectra of Fig. 7 shows a microcavity resonance at a wavelength of 700 nm. This resonance has a linewidth of $\Delta\lambda = 6$ nm and a quality factor of $Q = 120$. The room temperature PL spectra were measured with a resolution of 0.1 nm. The PL spectra were later corrected for the responsivity of the spectrometer and the photomultiplier tube. The PL spectra were taken at $0 \pm 5^\circ$ with respect to the surface normal. During the PL measurements the temperature of the sample is not controlled and there might be local heating, which reduces the PL efficiency, and broadens the PL linewidth.⁵⁹ However, local heating would not considerably affect the general shape

and features of the a-SiN_x:H gain spectrum. As seen in the PL spectra of Fig. 9, even though there might be local heating, we are observing strong PL from the sample. There is good agreement between the reflectance and the PL spectra. Both the reflectance and the PL spectra of Fig. 7 and 9 show a microcavity resonance at a wavelength of 700 nm. This resonance has a linewidth of $\Delta\lambda = 6$ nm and a quality factor of $Q = 120$. The PL is enhanced by the microcavity resonance, which correlates well with the minimum of the reflectance spectrum. In order to clarify the effect of the microcavity and to demonstrate its advantages with respect to the bulk a-SiN_x:H, we also show the PL of a $\lambda/2$ thick layer of bulk a-SiN_x:H in Fig. 10, obtained under the same experimental conditions as the PL of the a-SiN_x:H microcavity shown in Fig. 9. The red-near-infrared PL of the bulk a-SiN_x:H has a broad linewidth of 250 nm. This broad linewidth shows that, a-SiN_x:H has potential as a novel photonic gain medium. A comparison of the spectra in Fig. 9 and 10 shows that the effect of the microcavity is twofold: first, the wide emission band (250 nm) is strongly narrowed to 6 nm; second, the resonant enhancement of the peak PL intensity is more than one order of magnitude with respect to the emission of the $\lambda/2$ thick layer of bulk a-SiN_x:H. In addition by choosing the appropriate width of the a-SiN_x:H active layer and PBG's, it is possible to select the emission wavelength of the microcavity by taking advantage of the broad spectral emission of the a-SiN_x:H active layer.

4. CONCLUSIONS

In conclusion, we have demonstrated that 1-D PBG based a-SiN_x:H microcavity can be successfully realized by PECVD, and can be used for the control of the PL in a-SiN_x:H. The PL of the a-SiN_x:H is both narrowed and enhanced at the microcavity resonance with respect to the PL of the bulk a-SiN_x:H. This narrowing and enhancement of the PL can be understood by the redistribution of the density of optical modes due to the presence of the microcavity. The microcavity narrowing and enhancement of luminescence in a-SiN_x:H opens up a variety of possibilities for optoelectronic applications such as resonant cavity enhanced light emitting diodes and color flat panel displays.

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6. REFERENCES

1. J. Rarity and C. Weisbuch, Eds., *Microcavities and Photonic Bandgaps: Physics and Applications*, (Kluwer, Dordrecht, 1996).
2. R. K. Chang and A. J. Campillo, Eds., *Optical Processes in Microcavities* (World Scientific, Singapore, 1996).
3. D. G. Lidzey, D. D. C. Bradley, S. J. Martin, and M. A. Pate, "Pixelated multicolor microcavity displays," *IEEE J. Select. Topics Quantum Electron.* 4, 113 (1998).
4. H. Yokoyama and K. Ujihara, Eds., *Spontaneous emission and laser oscillation in microcavities*, (CRC Press, Boca Raton, 1995).
5. M. S. Ünlü and S. Strite, "Resonant Cavity Enhanced Photonic Devices," *J. Appl. Phys.* 78, 607 (1995).
6. H. Benisty, H. De Neve, and C. Weisbuch, "Impact of Planar Microcavity Effects on Light Extraction - Part I: Basic Concepts and Analytical Trends," *IEEE J. Select. Topics Quantum Electron.* 34, 1612 (1998).
7. H. Benisty, H. De Neve, and C. Weisbuch, "Impact of Planar Microcavity Effects on Light Extraction - Part II: Selected Exact Simulations and Role of Photon Recycling," *IEEE J. Select. Topics Quantum Electron.* 34, 1632 (1998).
8. R. E. Slusher and C. Weisbuch, "Optical microcavities in condensed matter systems," *Solid State Commun.* 92, 149 (1994).
9. H. Yokoyama, K. Nishi, T. Anan, Y. Nambu, S. D. Brorson, E. P. Ippen, and M. Suzuki, "Controlling spontaneous emission and threshold-less laser oscillation with optical microcavities," *Opt. Quantum Electron.*, 24, S245 (1992).

10. Y. Yamamoto, S. Machida, and G. Björk, "Microcavity semiconductor laser with enhanced spontaneous emission," *Phys. Rev A* 44 657 (1991).
11. J.V. Sandusky and S. R. J. Brueck, "Observation of spontaneous emission microcavity effects in an external-cavity surface emitting laser structure," *Appl. Phys. Lett.* 69, 3993 (1996).
12. S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, "Whispering Gallery Mode Microdisk Lasers," *Appl. Phys. Lett.* 60, 289 (1992).
13. J. P. Zhang, D. Y. Chu, S. L. Wu, S. T. Ho, W. G. Bi, C. W. Tu, and R. C. Tiberio, "Photonic Wire Laser," *Phys. Rev. Lett.* 75, 2678 (1995).
14. E. F. Schubert, Y.-H. Wang, A. Y. Cho, I. W. Tu, and G. J. Zydzik, "Resonant Cavity Light Emitting Diode," *Appl. Phys. Lett.* 60, 921 (1992).
15. E. M. Purcell, "Spontaneous Emission Probabilities at Radio Frequencies," *Phys. Rev.* 69, 681 (1946).
16. P. W. Milloni and P. L. Knight, "Spontaneous emission between mirrors," *Opt. Commun.* 9, 119 - 122 (1973).
17. F. De Martini, G. Innocenti, G. R. Jacobowitz, and P. Mataloni, "Anomalous Spontaneous Emission Time in a Microscopic Optical Cavity," *Phys. Rev. Lett.* 59, 2955 - 2958 (1987).
18. H. Yokoyama, K. Nishi, T. Anan, H. Yamada, S. D. Brorson, and E. P. Ippen, "Enhanced Spontaneous Emission from GaAs quantum Wells in Monolithic Microcavities," *Appl. Phys. Lett.* 57, 2814 - 2816 (1990).
19. G. Björk, S. Machida, Y. Yamamoto, and K. Igeta, "Modification of spontaneous emission rate in planar dielectric microstructures," *Phys. Rev. A* 44, 669 - 681 (1991).
20. M. S. Skolnick, T. A. Fisher, and D. M. Whittaker, "Strong Coupling Phenomena in Quantum Microcavity Structures," *Semiconductor Science Technol.* 13, 645 - 669 (1998).
21. Y. Zhu, J. Gauthier, S. E. Morin, Q. Wu, H.J. Carmichael, and T.W. Mossberg, "Vacuum Rabi splitting as a feature of linear dispersion theory: analysis and experimental observations," *Phys Rev. Lett.* 64, 2499 - 2502 (1990).
22. C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, "Observation of coupled exciton-photon mode splitting in a semiconductor quantum microcavity," *Phys. Rev. Lett.* 69, 3314 - 3317 (1992).
23. S. Pau, G. Björk, J. Jacobson, H. Cao, and Y. Yamamoto, "Microcavity exciton-polariton splitting in the linear regime," *Phys. Rev. B* 51, 14437 - 14447 (1995).
24. A. M. Agarwal, L. Liao, J. S. Foresi, M. R. Black, X. Duan, and L.C. Kimerling, "Low-loss Polycrystalline Silicon Waveguides for Silicon Photonics," *J. Appl. Phys.* 80, 6120 (1996).
25. B. Jalali, S. Yegnanarayanan, T. Yoon, T. Yoshimoto, I. Rendina, and F. Coppinger, "Advances in Silicon on insulator Optoelectronics," *IEEE J. Select. Topics in Quantum Electron.* 4, 938 (1998).
26. A. Kaneko, T. Goh, H. Yamada, T. Tanaka, and I. Ogawa "Design and applications of silica-based planar lightwave circuits," *IEEE J. Select. Topics in Quantum Electron.* 5, 1227 (1999).
27. B. J. Offrein, R. Germann, F. Horst, H.W.M. Salemink, R. Beyerl, and G. L. Bona, "Resonant coupler-based tunable add-after-drop filter in silicon-oxynitride technology for WDM networks," *IEEE J. Select. Topics in Quantum Electron.* 5, 1400 (1999).
28. A. Aydinli, A. Serpengüzel, and D. Vardar, "Visible Photoluminescence from Low Temperature Deposited Hydrogenated Amorphous Silicon Nitride," *Solid State Commun.* 98, 273 (1996).
29. M. H. Brodsky, "Quantum Well Model of the Hydrogenated Amorphous Silicon," *Solid State Commun.* 36, 55 (1980).
30. A. Serpengüzel, A. Aydinli, A. Bek, and M. Güre, "Visible photoluminescence from planar amorphous silicon nitride microcavities," *J. Opt. Soc. Am. B.* 15, 2706 (1998).
31. D. J. Wolford, B. A. Scoot, J. A. Reimer and J. A. Bradley, "Efficient visible luminescence from hydrogenated amorphous silicon," *Physica B* 117, 920 (1983).
32. T. Canham, "Silicon Quantum Wire Array Fabrication by Electrochemical and Chemical Dissolution of Wafers," *Appl. Phys. Lett.* 57, 1046 (1990).
33. D. J. Lockwood, "Optical Properties of Porous Silicon," *Solid State Commun.* 92, 101 (1994).
34. L. Pavesi, C. Mazolleni, A. Tredicucci, and V. Pellegrini, "Controlled photon emission in porous silicon microcavities," *Appl. Phys. Lett.* 67, 3280 (1995).
35. L. Pavesi and V. Mulloni, "All porous silicon microcavities: growth and physics," *J. Lumin.* 80, 43 (1999).
36. M. Araki, H. Koyama, and N. Koshida, "Precisely tuned emission from porous silicon vertical optical cavity in the visible region," *J. Appl. Phys.* 80, 4841 (1996).

37. M. Cazzanelli and L. Pavesi, "Time-resolved photoluminescence of all porous silicon microcavities," *Phys. Rev. B* 56, 15264 (1997).
38. E. K. Squire, P. A. Snow, P. St. J. Russell, L. T. Canham, A. J. Simmons, and C. L. Reeves, "Light emission from porous silicon single and multiple cavities," *J. Lumin.* 80, 125 (1999).
39. M. Takahashi, Y. Toriumi, T. Matsumoto, Y. Masumoto, N. Koshida, "Significant photorefractive index change observed in porous silicon Fabry-Perot resonators," *Appl. Phys. Lett.* 76, 1990 (2000).
40. S. Setzu, S. Letant, P. Solsona, R. Romestain, and J. C. Vial, "Improvement of luminescence in p-type as-prepared or dye impregnated porous silicon microcavities," *J. Lumin.* 80, 129 (1999).
41. Z. H. Xiong, S. Yuan, Z. M. Jiang, J. Qin, C. W. Pei, L. S. Liao, X. M. Ding, X. Y. Hou, and X. Wang, "Photoluminescence studies of porous silicon microcavities," *J. Lumin.* 80, 137 (1999).
42. E. K. Squire, P. St. J. Russell, and P. A. Snow, "Optimized light emission from layered porous silicon structures," *Appl. Opt.* 37, 7107 (1998).
43. V. Mulloni and L. Pavesi, "Porous silicon microcavities as optical chemical sensors," *Appl. Phys. Lett.* 76, 2523 (1999).
44. A. Arena, S. Patane, G. Saitta, S. Savasta, R. Girlanda, and R. Rinaldi, "Silicon based organic-inorganic microcavity and its dispersion curve from angle resolved photoluminescence," *Appl. Phys. Lett.* 72, 2571 (1998).
45. B. T. Sullivan, D. J. Lockwood, H. J. Labbe, and Z.-H. Lu, "Photoluminescence in Amorphous Si/SiO_x Superlattices Fabricated by Magnetron Sputtering," *Appl. Phys. Lett.* 69, 3149 (1996).
46. D. J. Lockwood, J.M. Baribeau, and B. T. Sullivan, "Visible light from Si/SiO_x superlattices in planar microcavities," *J. Vac. Sci. Technol. B* 16, 1707 (1998).
47. D. J. Lockwood, B. T. Sullivan, and H. J. Labbe, "Visible light emission from Si/SiO_x superlattices in optical microcavities," *J. Lumin.* 80, 75 (1999).
48. K. M. Cheng, A. W. Sparks, H.-C. Luan, D. R. Lim, K. Wada, and L. C. Kimerling, "SiO₂/TiO₂ omnidirectional reflector and resonator with sol-gel method," *Appl. Phys. Lett.* 75, 3805 (1999).
49. F. Hamelmann, G. Haindl, J. Schmalhorst, A. Aschentrup, E. Majkova, U. Kleineberg, U. Heinzmann, A. Klipp, P. Jutzi, A. Anopchenko, M. Jergel, and S. Luby, "Metal oxide / silicon oxide multilayer with smooth interfaces produced by in situ controlled plasma enhanced MOCVD," *Thin Solid Films* 358, 90 (2000).
50. L. Pavesi, R. Guardini, and C. Mazolleni, "Porous Silicon Resonant Cavity Light Emitting Diodes," *Solid State Commun.* 97, 1051 (1996).
51. M. Araki, H. Koyama, and N. Koshida, "Controlled electroluminescence spectra of porous silicon diodes with vertical optical cavity," *Appl. Phys. Lett.* 69, 2956 (1996).
52. D. Hunkel, R. Butz, R. Ares-Fisher, M. Marso, and H. Lüth, "Interference filters from porous silicon with laterally varying wavelength of reflection," *J. Lumin.* 80, 133 (1999).
53. H. F. Arrand, T. M. Benson, P. Sewell, and A. Loni, "Optical waveguides in porous silicon pre-patterned by localized nitrogen implantation," *J. Lumin.* 80, 199 (1999).
54. S. W. Leonard, H. M. van Driel, K. Busch, S. John, A. Birner, A.-P. Li, F. Müller, U. Gösele, and V. Lehmann, "Attenuation of optical transmission within the band gap of thin two-dimensional macroporous silicon photonic crystals," *Appl. Phys. Lett.* 75, 3063 (1999).
55. M. C. Netti, M. D. B. Charlton, G. J. Parker, and J. J. Baumberg, "Visible photonic band gap engineering in silicon nitride waveguides," *Appl. Phys. Lett.* 76, 991 (2000).
56. A. Serpengüzel, A. Aydinli, and A. Bek, "Enhancement and inhibition of photoluminescence in hydrogenated amorphous silicon nitride microcavities," *Opt. Express* 1, 108 (1997).
57. A. Serpengüzel, A. Aydinli, and A. Bek, "Alteration of Spontaneous Emission in Hydrogenated Amorphous Silicon Nitride Microcavities," *J. Non-Cryst. Solids* 227-230, 1142 (1998).
58. M. Born and E. Wolf, *Principles of Optics*, (Cambridge University Press, Cambridge, 1998) p. 51
59. R. Fisher, in *Amorphous Semiconductors*, M. H. Brodsky, Ed. (Springer-Verlag, Berlin, 1985). pp.159-187.