Reflectivity Modelling of All-Porous-Silicon Distributed Bragg Reflectors and Fabry-Perot Microcavities

N. Samuolienė, E. Šatkovskis

Vilnius Gediminas Technical University
Saulėtekio av. 11, LT-10223 Vilnius, Lithuania
eusat@fm.vtu.lt; eusat@pfi.lt

Received: 04.10.2004
Accepted: 08.11.2004

Abstract. Herein, the problem of nanocrystaline silicon laser and its importance in microelectronics are discussed upon. The features of vertical Fabry-Perot microcavities made on the base of porous silicon are described. The responses of the reflectivity of the distributed reflection Bragg mirrors and Fabry-Perot microcavities were found using transfer matrixes method for this purpose. Inherent optical parameters of porous silicon, deposited by electrochemical etch, were used in the calculations. The calculation of the reflectivity of the distributed reflection Bragg mirrors with front active layer of nanostructural porous silicon had been examined. In the second part, the features of Fabry-Perot microcavities on variation of the number of layers of the front or rear mirrors are described. The impact of the thickness of the active nanocrystaline silicon spacer between two distributed reflection Bragg mirrors upon the spectra of optical reflectivity of Fabry-Perot microcavities in the wavelength range of 0.4–$0.9\,\mu$m had been examined as well. The made conclusions are important for improvement of the thickness of the active porous silicon spacer in front of Bragg mirror and the features of Fabry-Perot microcavities.

Keywords: porous silicon, modelling, Fabry-Perot microcavity.

1 Introduction

A great variety of porous silicon based electronic, optical and optoelectronic devices have been processing intensively in the recent decade [1]. High attention had been concentrated especially upon examination of the problem of silicon laser. Distributed Bragg reflectors (DBR) and Fabry-Perot microcavities are ones of the basic elements involved by exploiting this problem [2]. On the contrary to A_3B_5 semiconductor lasers, the mirrors of the microcavity and the active layer (AL) between them are fabricated of the same material – porous silicon, because diverse effective refraction index n of the unlike porosity silicon layers may be ensured by modulating the current density during electrochemical etching of silicon [3]. Porosity, refraction index and radiation range of layers differ dependently on the AL and DBR mirrors, formed of $\lambda_c/4$ thick porous silicon layers (here λ_c – is the central wavelength of AL radiation spectrum) [4]. The emission for wavelengths $\lambda = \lambda_c$ (or $\lambda \neq \lambda_c$) due to the radiative recombination occurs in the mirror spatial region as well. The efficiency of operation of porous silicon based Fabry-Perot microcavities is very sensitive to selection of DBR and the active layer's parameters [5]. In order to ensure the maximum amplification of radiation, the optimal relations between refractive indexes and porosities of layers of the said elements should be found. On the other hand, the relation of the AL and DBR optical parameters should not disturb the quality factor of Fabry-Perot microcavity. Because of sufficiently complicated experimental processing of high-quality porous silicon based Fabry-Perot structures, we carried out firstly a modeling of reflection properties of theoretical DBR and Fabry-Perot microcavities. The main conclusions concerning permission to vary DBR and AL optical parameters are summarized on the base of the obtained results.

2 Calculation procedure

The basis of the algorithm of the program for the calculation of DBR and Fabry-Perot microcavities reflectivity spectra are the structure consisted layers of given thickness and dielectric functions [6]. For the calculation, only the real part of the effective dielectric function was used

$$\varepsilon = \sin^2\theta \left[1 + \operatorname{tg}^2\theta\left(\frac{1-R}{1+R}\right)^2\right].$$

The imaginary part that describes the light absorption inside the microcavity is considered equal to zero. $R = \operatorname{tg}\Psi e^{i\Delta}$, where Ψ, Δ are ellipsometric parameters that describe polarization of reflected light. So

$$R = \frac{1-\sqrt{\varepsilon - \sin^2\theta}}{1+\sqrt{\varepsilon - \sin^2\theta}}.$$

The structure consisting of substrate and several layers is described using the method of transfer matrixes [7], where each individual layer of a multilayer system is represented by a characteristic matrix, formed of geometrical and optical parameters of the layer. The matrix of the whole multiplayer structure is then expressed by product of characteristic matrixes of separate layers. Two cases are to be singled out: when the electric field vector is perpendicular to the plane of light incidence and when it is parallel to the said plane.

In general case, in a calculation of optical response we find, first of all, the product of transfer matrixes. For the light polarized perpendicularly to the plane of light incidence

$$M^E = \prod_{n=1}^{N} \begin{pmatrix} \cos(cr_n d_n \cos\theta_n) & -i/r_n/\cos\theta \sin(cr_n d_n \cos\theta_n) \\ -ir_n \cos\theta \sin(cr_n d_n \cos\theta_n) & \cos(cr_n d_n \cos\theta_n) \end{pmatrix}$$
$$= \begin{pmatrix} m^E_{1,1} & m^E_{1,2} \\ m^E_{2,1} & m^E_{2,2} \end{pmatrix}.$$

The optical response is calculated according to the following expression:

$$C^E = \frac{\left(m^E_{1,1} + m^E_{1,2} r_s\right)\cos\theta - \left(m^E_{2,1} + m^E_{2,2} r_s c_s\right)}{\left(m^E_{1,1} + m^E_{1,2} r_s\right)\cos\theta + \left(m^E_{2,1} + m^E_{2,2} r_s c_s\right)}.$$

Similarly, for light polarized parallel to the plane of light incidence

$$M^M = \prod_{n=1}^{N} \begin{pmatrix} \cos(cr_n d_n \cos\theta_n) & -ir_n/\cos\theta \sin(cr_n d_n \cos\theta_n) \\ -i/r_n \cos\theta \sin(cr_n d_n \cos\theta_n) & \cos(cr_n d_n \cos\theta_n) \end{pmatrix}$$
$$= \begin{pmatrix} m^M_{1,1} & m^M_{1,2} \\ m^M_{2,1} & m^M_{2,2} \end{pmatrix},$$

and

$$C^M = \frac{\left(m^M_{1,1} + m^M_{1,2}/r_s c_s\right)\cos\theta - \left(m^M_{2,1} + m^M_{2,2} r_s c_s\right)}{\left(m^M_{1,1} + m^M_{1,2}/r_s c_s\right)\cos\theta + \left(m^M_{2,1} + m^M_{2,2} r_s c_s\right)}.$$

In the formulae, c, d_n, r_n, θ_n are constant, thickness, refractive index and angle of incidence for n-th layer, respectively, $r_s = \sqrt{\varepsilon_s}$, $c_s = \sqrt{1 - 1/\varepsilon_s \sin^2\theta}$ and ε_s – parameters of the substrate. The angle of light incidence in n-th layer:

$$\cos\theta_{n+1} = \sqrt{1 - \frac{\varepsilon_n}{\varepsilon_{n+1}}(1 - \cos^2\theta_n)},$$

where $\theta_1 = \theta$.

The ellipsometric angle Ψ, Δ are calculated from the following formulae:

$$\Psi = \operatorname{arctg}\left|\frac{C^M}{C^E}\right|, \quad \Delta = \operatorname{arctg}\frac{\operatorname{Im}\left(\frac{C^E}{C^M}\right)}{\operatorname{Re}\left(\frac{C^E}{C^M}\right)}$$

In the paper, we have studied the case, when the light incidence is perpendicular to the plane of surface of the sample, i.e. $\theta = \theta_n = 0$. In such case, the values of the parallel and the perpendicular components coincide, so the calculation becomes much simpler. Varying the number of layers of DBR mirrors or refractive indexes or the thickness of the AL spacer, we have obtained the results that describe optical response of Fabry-Perot microcavities dependently on selection of their parameters.

3 Results and discussion

Optical response of porous silicon DBR mirrors was calculated for mirrors, involving stack of eight $\lambda_c/4$ layers, because our previous calculations showed, that such number of layers is sufficient to obtain 80% of the incident light [8]. The influence of the active porous layer, involving silicon nanocrystalites, on the refracting index of the mirror had been investigated. Taking into account the earlier results, we placed a supplemental porous silicon AL in front of the mirror, varying its thickness to be multiple to the wavelength λ_c. In most cases, refractive indexes of layers satisfied the condition $n_1 = \sqrt{n_2}$. Porosity of the AL had been chosen corresponding to the refraction index $n_0 = 1.5$ or $n_0 = 1.27$. The calculations showed that the AL does not influence resonantly the refraction coefficient of the mirror, when the number of porous silicon layers in the stack exceeds 15, independently on the thickness of the layer $N\lambda_c$ (Fig. 1). Therefore, following the results of the calculation, it may be concluded that there is no restriction on the thickness of the AL when it is needed, taking into account optical amplification values in silicon nanocrystalites upon radiation of the chosen wavelength.

In the second part of the paper, we carried out calculation of the reflectivity spectra of Fabry-Perot microcavity involving two porous silicon DBR mirrors

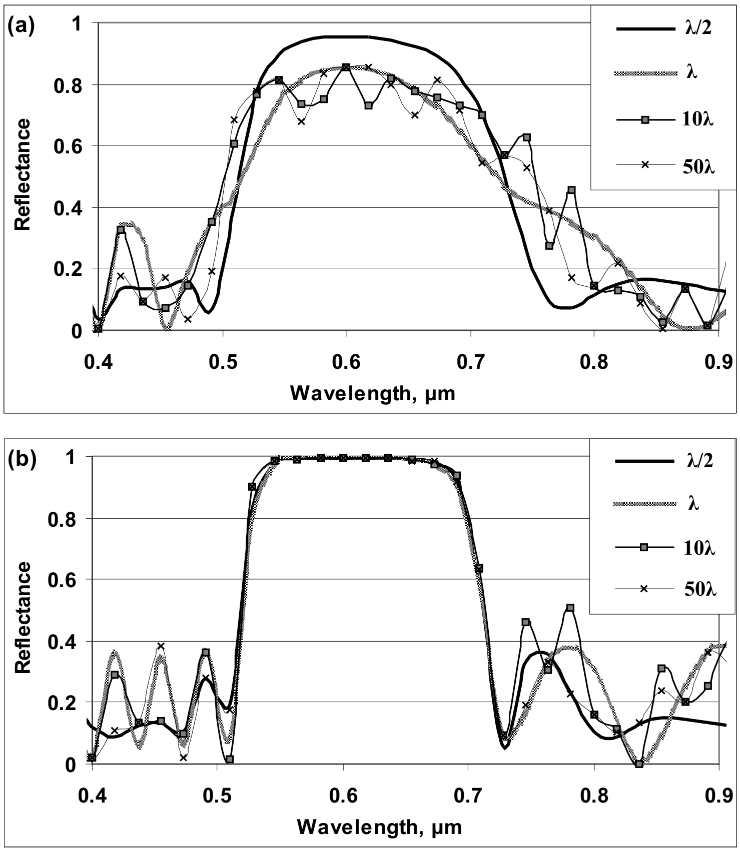

Fig. 1. Reflectivity spectra of DBR mirror, when thickness of the AL is $\lambda/2,\ \lambda,\ 5\lambda,\ 10\lambda,\ 50\lambda$ and its refraction index is $n_0 = 1.5$. Refraction indexes of Bragg mirrors $\lambda_c/4$ layers are $n_1 = 2.25$ and $n_2 = 1.5$ and the number of layers: (a) $i_p = 0,\ i_g = 8$; (b) $i_p = 0,\ i_g = 15,\ \lambda = \lambda_c = 600\,$nm.

with nanocrystaline porous silicon AL spacer between them in spectral ambient of λ_c. A part of the calculation results is presented in Fig. 2. Thickness of the AL spacer was λ_c. The closing Bragg mirror of the microcavity was formed of eight layers and the reflectivity of the front mirror was changed by varying the number of its layers from 3 to 15.

It may be seen from the figure that until the number i_p of the front mirror $\lambda_c/4$ layers (refraction index) is less than the number i_g of the closing mirror layers, the reflectivity of the microcavity at λ_c is less than 1 and decreases on growing of the number of layers added. When the number of layers is the same in both mirrors, the reflectivity of the microcavity becomes equal to zero. On further

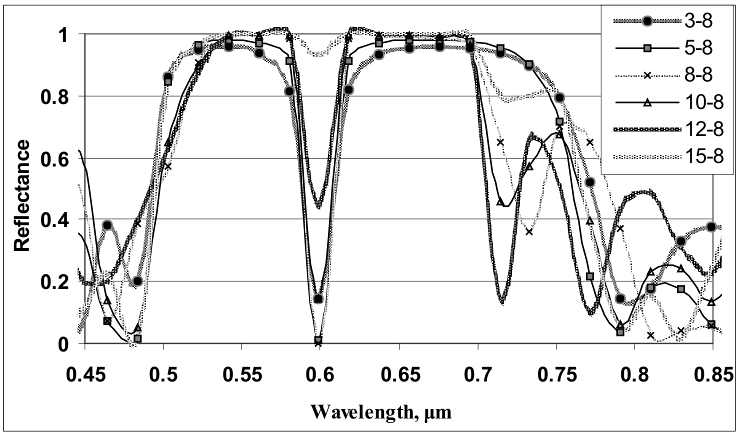

Fig. 2. Fabry-Perot microcavity reflectivity spectra, when the thickness of AL is λ and its refraction index $n_0 = 1.27$. Refraction indexes of layers of DBR mirrors are $n_1 = 2.25$ and $n_2 = 1.5$. The number of layers – $i_p = 3,\ 5,\ 8,\ 10,\ 12,\ 15,\ i_g = 8,\ \lambda_c = 600\,\text{nm}$.

increasing of the number of layers of the front mirror, the general reflectivity approaches zero again. Reflectivity of the mirror with 15 layers achieves 95%. So, it is possible to change effectively the optical parameters of the microcavity from complete reflectivity to total disappearance of it in the ambient of the chosen wavelength by variation of the number of layers in the front Bragg mirror. The similar reflectivity behavior also was found for other numbers of $\lambda_c/4$ layers in the stack of the closing DBR mirror. In both cases, a disappearance of reflectivity is achieved, when the number of layers in both mirrors is the same. In such case, the microcavity demonstrates the properties of a certain photonic crystal or interference filter, according to the earlier terminology.

Similar calculations on Fabry-Perot microcavity reflection have been performed by variation of reflectivity of the closing mirror, while keeping the number of layers of the front mirror constant. Just like as in the second case, it was shown that the microcavity demonstrates properties of interference filter at the chosen wavelength of radiation λ_c, if the number of layers in the stacks of both mirrors is the same. The filter's spectral width $\Delta\lambda$ is equal to $\sim 20\,\text{nm}$. Full reflectivity for wavelength λ_c was reached at $i_g = 20$, if $i_p = 8$ (Fig. 3). Outside the transmission range, at $\sim\ 100\,\mathrm{nm}$ to both sides from λ_c position, the reflectivity of the microcavity was equal to 1. So, the overall optical parameters of the porous silicon Fabry-Perot microcavity may be changed by variation of layer number in the stacks of the front and closing Bragg mirrors, with a simultaneous impact on the ratio of the powers of output radiation and feedback radiation.

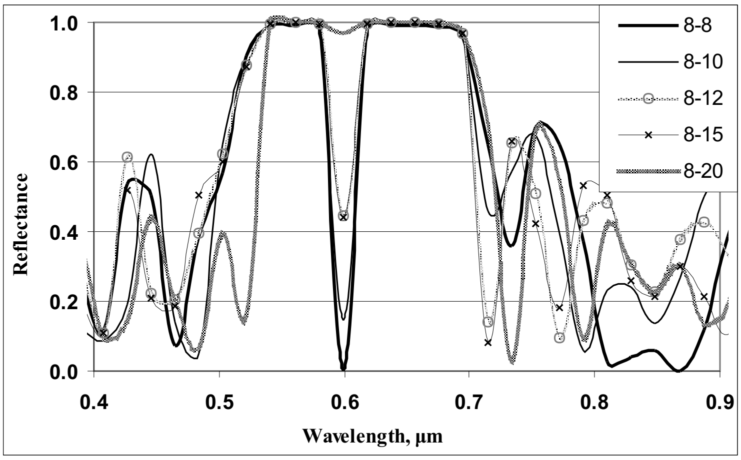

Fig. 3. Fabry-Perot microcavity reflectivity spectra, when the AL spacer thickness is λ and its refraction index $n_0 = 1.27$. Refraction indexes of layers of DBR mirrors are $n_1 = 2.25$ and $n_2 = 1.5$. The number of layers – $i_p = 8,\ i_g = 8,\ 10,\ 12,\ 15,\ 20,\ \lambda_c = 600\,\mathrm{nm}$.

Because the optical amplification coefficient is not high in porous silicon [9], it is reasonable to expect that it will be necessary to expand the thickness of AL in order to ensure laser's effect in silicon. Therefore, it is interesting to investigate how such increasing of thickness of the AL impacts the optical parameters of Fabry-Perot microcavity, including the reflectivity in the vicinity of λ_c. The results of optical reflectivity calculation for interference filter configuration by different thicknesses of AL d are provided in Fig. 4. Like in previous calculations, it was assumed that $\lambda_c = 600\,\mathrm{nm}$, and d changes from $\lambda_c/2$ to $10\,\lambda_c$. It may be seen from the figure that reflectivity changes are inconsiderable in the vicinity of λ_c, when $d \leq 5\lambda$. However, the additional transmission bands turn up in the spectral range in vicinity of λ_c. Reflectivity increases up to ~80% when $d = 10\lambda_c$. This shows that Fabry-Perot microcavity gradually loses the inherent properties of interference filter either photonic crystal on increasing the thickness of the AL. Such circumstance can serve as a positive factor by getting the laser radiation effect in porous silicon nanocrystals.

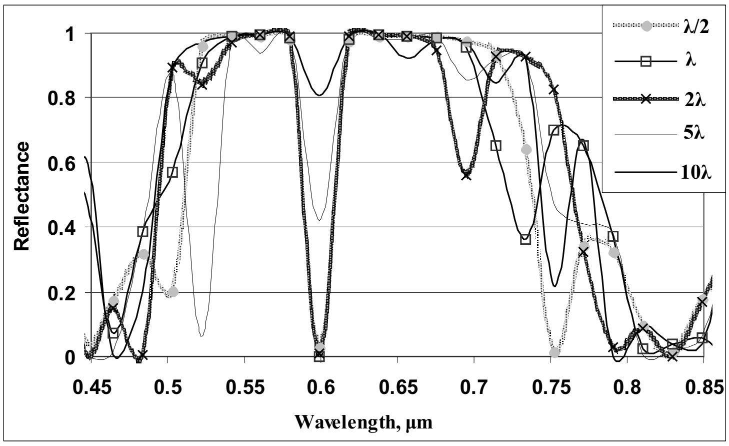

Fig. 4. Fabry-Perot microcavity reflectivity spectra, when $\lambda_c = 600\,\mathrm{nm}$, the thickness of AL spacer is $d = \lambda/2,\ \lambda,\ 2\lambda,\ 5\lambda,\ 10\lambda$, and its refraction index $n_0 = 1.27$. The layer number in stacks of Bragg mirrors is $i_p = i_g = 8$, and their refraction indexes $n_1 = 2.25$ and $n_2 = 1.5$.

4 Conclusions

Calculations of the reflectivity for DBR mirrors with porous silicon nanocrystaline AL in the front of the mirror and Fabry-Perot microcavity had been performed using transfer matrixes method. Inherent optical parameters of porous silicon, deposited by electrochemical etch, were used in the calculation. It was shown that there is no restriction on the thickness of porous silicon layer in front of the mirror when needed to expand it outgoing from the radiation gain or optical amplification values. It is also showed that Fabry-Perot microcavity made of porous silicon posses properties of photonic crystal, when thickness of the AL d does not exceed $10\,\lambda_c$. In such case, the feedback in the microcavity may be changed by any of the mirrors. When thickness of the AL d exceeds $10\,\lambda_c$, the quality of the microcavity is predetermined individually by each mirror.

References

1. P.M. Fauchet. The integration of nanoscale porous silicon light emitters: materials science, properties and integration with electronic circuitry, *J. Lumin.*, **80**, pp. 53–64, 1999.
2. S. Frohnohoff, M.G. Berger. *Adv. Mater.*, **6**, pp. 963–965, 1994.
3. L. Pavesi. Porous silicon dielectric multilayers and microcavities, *Riv. Nuovo Cimento,* **20**, pp. 1–78, 1997.
4. C. Mazzoleni, L. Pavesi. Application to optical components of dielectric porous silicon multilayers, *Appl. Phys. Lett.*, **67**, pp. 2983–2985, 1995.
5. S. Chan, P.M. Fauchet. Tunable, narrow, and directional luminescence from porous silicon light emitting devices, *Appl. Phys. Lett.,* **75**, pp. 274–276, 1999.
6. A. Galickas, G. Krivaitė. Modeling of optical response from layered structure, in: *Scientific reports of semiconductor optics laboratory,* PFI, Vilnius, pp. 47–48, 2001.
7. M. Born, E. Volf. *Principles of Optics,* Pergamon Press, Oxford, 1964.
8. N. Samuolienė, A. Galickas, E. Šatkovskis. Vertical Fabry-Perot microcavities from porous silicon layers of different porosity, in: *International scientific conference of PhD students "Youth seeks progress'2003",* Kaunas, Akademija, pp. 285–289, 2003.
9. L. Pavesi, L. Dal Negro, C. Mazzoleni, G. Franzo, F. Priolo. Optical gain in silicon nanocrystals, *Nature,* **408**, pp. 440–444, 2000.