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1.5 μm Fabry–Perot microcavities based on hydrogenated silicon and related materials

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Abstract. Fabry–Perot a-Si:H/a-Si:O:H microcavities with Er-doped a-Si:H active region were fabricated by plasma-enhanced chemical vapour deposition technique. A metalorganic compound was used to incorporate erbium into the active a-Si:H layer. The room temperature transmission, reflection and spontaneous emission spectra of the microcavities with 2 and 3 pairs of layers in distributed Bragg reflectors are measured. An intensity enhancement by two order of magnitude and selective narrowing of the 1.54 μm erbium emission line was observed as compared to the case of a single a-Si(Er):H film deposed on a quartz substrate. A theoretical analysis of the experimental data presented is given.

Introduction

Hydrogenated amorphous silicon doped with erbium, a-Si(Er):H, is known to exhibit at 1.54 μm (the wavelength of the $^4I_{13/2} \rightarrow\ ^4I_{15/2}$ optical transition in Er^{3+}-ions) stronger room temperature photoluminescence (PL), smaller temperature quenching and shorter radiative lifetime of Er^{3+}-ions than its crystalline counterpart [1]. On the other hand, the 1.54 μm band coincides with the minimum-loss spectral range in optical-fiber-based telecommunications. For this reason, a-Si(Er):H can be considered as a promising optical material for optical communication systems, in particular, for amplifiers, light-emitting and lasing devices operating at 1.54 μm at room temperature. In our work, the transmission, reflection and emission characteristics of a-Si:H/a-Si:O:H Fabry-Perot microcavities (MCs) with a-Si(Er):H active region tuned around 1.54 μm are studied both experimentally and theoretically. Special emphasis is given to an analysis of the PL spectra. Preliminary results of our work were published in Ref. [2].

1. Results and discussion

Figure 1(a) shows schematically the layer sequence in the MC. The distributed Bragg reflectors (DBRs) and active layer of the MC were fabricated by plasma-enhanced chemical vapour deposition (PECVD) in a single technological cycle without exposure to air between the intermediate operations. The active a-Si:H layer was doped with Er during deposition by making use of the metalorganic fluorine containing compound [3]. The top (A) and bottom (B) DBRs consisted of three a-Si:H/a-Si:O:H quarter-wave layer pairs ($\lambda_1/4 \approx 110$ nm for a-Si:H and $\lambda_2/4 \approx 260$ nm for a-Si:O:H, the corresponding refractive indices at 1.54 μm are $n_1 = 3.46$ and $n_2 = 1.46$), the $\lambda_c/2$ a-Si(Er):H active region thickness being around 220 nm.

The transmittance spectrum of the MC is shown in Fig. 1(b). The long-wave cut-off of the spectrum is limited by sensitivity of InGaAs photodiode. A sharp 1.54 μm peak corresponds to a resonant mode of the MC.
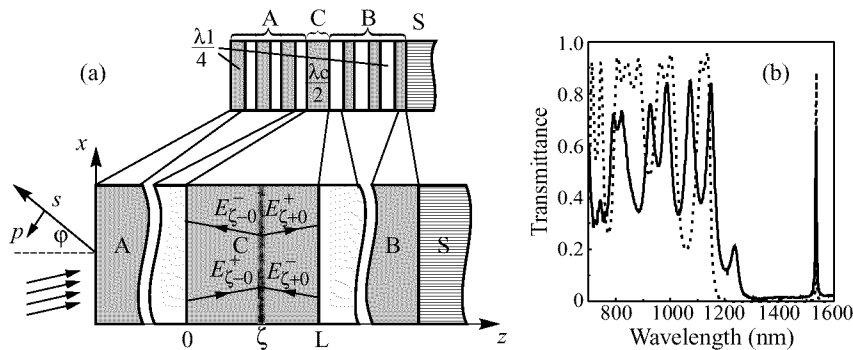
Fig. 1. (a) Schematic diagram of an a-Si:H/a-Si:O:H microcavity consisting of the A- and B-$\lambda/4$ DBRs with the $\lambda/2$ active layer C incide, S being the substrate. Also is shown an elementary emitting layer centered at $z=\zeta$. (b) Experimental (solid) and theoretical (dashed) transmittance spectra of the microcavity structure shown in Fig. 1(a).
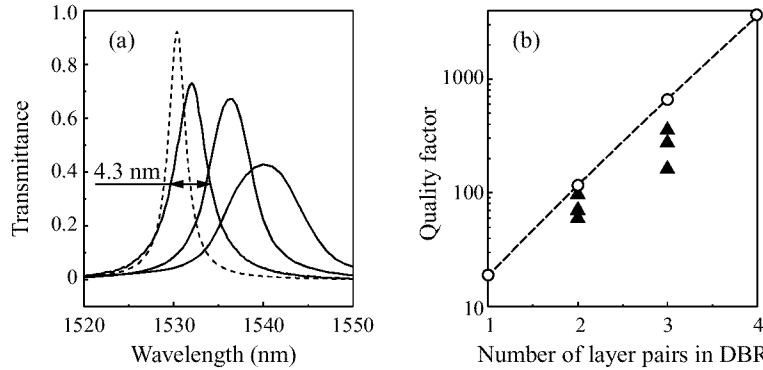

Fig. 2. (a) Experimental (solid) and theoretical (dashed) resonant contours for various micro-cavities with DBRs consisting of three pairs of layers. (b) Theoretical (circles) and experimental (triangles) values of the quality factor.

Figure 2(a) shows resonant transmission peaks for MCs with DBRs consisting of three pairs of layers. The full width at half maximum (FWHM) of the resonant peak as low as $\Delta\lambda$=4.3 nm is achieved. Corresponding cavity quality factor, $Q=\lambda_{res}/\Delta\lambda$, was estimated from the transmission resonance line width as 350. In Figure 2(b), a comparison of the experimental (triangles) and theoretical (circles) values of the Q for two types of MCs with DBRs consisting of 2 and 3 pairs of layers are given. The experimental values approach to the theoretical ones.

The theoretical spectrum of transmittance plotted in Fig. 2(a) as dashed line shows a difference as compared to measured ones. To our opinion, such a difference is due to deviations of the cavity thickness within the illuminated area.

Figure 3 shows the room temperature PL spectrum (curve 1) of the MC (Fig. 1(a)) measured for light propagation along the normal to the surface. For comparison, the PL spectrum (curve 2) of a 220 nm thick a-Si(Er):H film deposed on a quartz substrate (without DBRs) is plotted. The PL peak intensity in the MC structure is seen to be two
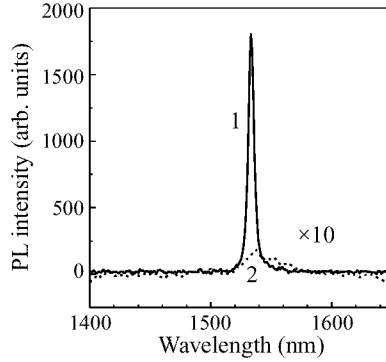
Fig. 3. Room temperature PL spectra: 1 — a-Si:H/a-Si:O:H microcavity structure; 2 — a-Si(Er):H single film without a cavity.

orders of magnitude higher, the PL line FWHM being reduced from 20 nm to 4.3 nm. The enhancement and narrowing of the PL peak are entirely due to the frequency of electronic transitions being resonant with the optical mode of the MC.

The emission problem was considered in terms of field amplitudes generated by stochastic excitation sources [4]. Figure 1a shows schematically the emission process from a MC structure. An elementary layer located at $z=\zeta$ inside the MC, $0<z<L$, emits two plane outgoing waves with the amplitudes $E_{\zeta-0}^{-}$ and $E_{\zeta+0}^{+}$ which are related to the amplitudes $E_{\zeta-0}^{+}$ and $E_{\zeta+0}^{-}$ of the incoming (reflected from the DBRs) waves by the boundary conditions. Direct solution of Maxwell's equations allows one to express field amplitudes at the outer boundary of the top DBR in terms of the induced singular polarization currents. After integrating bilinear combinations of the amplitudes over the thickness of the MC and statistical averaging the result over the ensemble of random-current realizations we obtain the following expression for the outer radiation intensity I in p-polarization of light:

$$I \propto I_0(\omega) \left| \frac{\tilde{t}_{AA}\Phi}{D\,\varepsilon\cos\varphi} \right|^2 \left\{ \left(|n_z|^2 + n_x^2 \right)\left(I_1 + |r_B|^2\, I_2 \right) + 2\left(|n_z|^2 - n_x^2 \right) |r_B|\, I_3 \right\} \qquad (1)$$

where $I_0(\omega)$ is the intrinsic spectral density of emission inside the infinite medium of the dielectric constant ε of the cavity, $D=1-\tilde{r}_A r_B \Phi^2$, $\Phi=\exp(ik_0 n_z L)$, $I_1=\left[\exp(\kappa L)-1\right]/\kappa$, $I_2=\left[1-\exp(-\kappa L)\right]/\kappa$, $I_3=\left[\sin(qL+\Delta_B)-\sin\Delta_B\right]/q$, $\Delta_B=\arg r_B$, $\kappa=2k_0\,\mathrm{Im}(n_z)$, $q=2k_0\,\mathrm{Re}(n_z)$, $k_0=\omega/c$; $\tilde{r}_A$ and r_B are the reflection coefficients on A- and B- DBRs, respectively, for light propagating from the inside of the cavity, $\tilde{t}_{AA}$ is the transmission coefficient for light passing through the A - DBR to outer medium, $n_z=\sqrt{\varepsilon-n_x^2}$, $n_x=\sqrt{\varepsilon_v}\sin\varphi$; φ is the emission angle, ε_v is the dielectric constant of the outer medium.

The transmittance T for the whole structure can be written in the form

$$T = |t_{AA}t_{BB}\Phi/D|^2 \qquad (2)$$

where t_{AA} and t_{BB} are the transmission coefficients for the A- and B- DBRs, respectively, for the light incident from the left outer space. It should be noted that the above expressions for transmittance (2) and luminescence intensity (1) contain the same resonant denominator $|D|^2$ which mainly governs the spectral shape of both transmission and emission lines. The shapes of the PL and transmission spectra are found to be close to each other in agreement with our theoretical analysis.

2. Conclusions

In summary, by making use of the plasma-enhanced chemical vapour deposition technique we have fabricated a-Si:H/a-Si:O:H microcavities with Er-doped a-Si:H active region. A drastic enhancement of the erbium photoluminescence in a microcavity, by two orders of magnitude as compared to a single a-Si(Er):H film, was observed. The cavity quality factor as high as 350 was achieved in the microcavity with only 3 pairs of layers in distributed Bragg reflectors.

References

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