

Chapter 8

Summary and conclusions

The work presented in this thesis has dealt with the following subjects:

- Theoretical study and design of dielectric multilayers for different optical applications.
- Establishment and calibration of a porous silicon fabrication system for the formation of multilayers.
- Characterization of porous silicon layers using different methods.
- Design, fabrication and characterization of porous silicon optical components.

Porous silicon has many potential applications. In this work we have focused on the study and design of porous silicon multilayers for optical applications. Porous silicon is a suitable material for the fabrication of multilayers because the refractive index and thickness of the layers can be selected by changing the formation parameters during the fabrication process. Besides, once a porous layer has been formed, no more electrochemical etching occurs for it during the following current density variations. Hence, the

refractive index can be modulated in depth, making porous silicon a suitable dielectric material for the formation of multilayers

By choosing, in an appropriate way, the thicknesses and the refractive indices of the various layers, it is possible to generate different reflectivity spectra and therefore different optical components. In this work, the optical components studied are Distributed Bragg Reflectors (DBR), microcavities, omnidirectional mirrors and waveguides.

The theoretical methods for the study of multilayers have been developed in chapter 3 where different programs realized for the simulation of multilayers have been explained. All these programs are based on the transfer matrix method, a mathematical method that has been already developed in detail in this chapter. These programs have been used for the study of different optical devices, analyzing their design parameters and evaluating the influence of these parameters on the optical response. The performance of these programs has been verified simulating different Distributed Bragg Reflectors (DBR) and microcavities and comparing the results obtained with the ones reported in the literature. This comparison has demonstrated the suitability of the realized programs. From the study of the DBRs, we have observed that porous silicon is a suitable material for the fabrication of filters with a wide bandgap centered at $\lambda=1.55 \mu\text{m}$. Although the difference between the refractive indices of the layers determines the bandgap width, the possibility to easily fabricate porous silicon stacked filters centered at different wavelengths, widening the bandgap, compensates the limitations of the porous silicon refractive index range.

The simulation of different optical devices based on multilayers has been realized in chapter 4 using the different programs presented in the previous chapter. These optical devices are omnidirectional mirrors and waveguides. From the study of omnidirectional mirrors, we have observed that the omnidirectional bandgap of porous silicon mirrors is very narrow due to the limited refractive index range obtainable with porous silicon. In order to widen this bandgap we have proposed three different multilayer structures, the random, the balanced and the unbalanced mirrors, that overcome these material limitations and allow obtaining an enlarged omnidirectional bandgap with a

simple design. Therefore, we can conclude that porous silicon is a suitable material for the fabrication of omnidirectional mirrors although for obtaining wide omnidirectional bandgaps with this material, the structure of the multilayer is decisive. Besides, these omnidirectional mirrors have been designed to work at wavelength $1.55 \mu\text{m}$, a wavelength widely used for telecommunication applications, demonstrating that porous silicon is appropriate for these applications.

Besides, in the same chapter two different types of porous silicon waveguides have been also designed. Firstly, the modal analysis of waveguides based on total internal reflection has been realized for $1.55 \mu\text{m}$ applications. The influence of the refractive indices and the core thickness on the number of modes has been studied. It has been demonstrated that when the thickness increases, the number of modes increases and that the cutoff wavelength of the modes allowed in the waveguide depends on the refractive indices of core and the cladding. It has been demonstrated that, for a fixed core thickness, different refractive indices resulting in the same numerical aperture have the same cutoff wavelength.

However, the most widely analyzed waveguide structure has been the one where the confinement of the light is based on the properties of photonic crystals. In these waveguides, the multilayer is the cladding. In concrete, we have studied the suitability of omnidirectional mirrors and DBR to be used for the cladding. We have obtained the optimal refractive index for the core, that is the refractive index that gives the highest confinement for all the modes. The different modes of this waveguide have been studied and we have demonstrated that the position of the mode in the projected band structure of the multilayer cladding determines the guiding condition of the modes. The influence of different parameters of the waveguide structure on the modes and the modal confinement has been studied. We concluded that when the core thickness increases, the confinement of the modes increases and gets closer to 100 % indicating that the modes closer to the light line have a higher confinement. Besides, the increment of core thickness results in the increment of the number of modes, the same that happened with TIR waveguides. The omnidirectional

mirror cladding has been also compared with a DBR cladding. From this study, we have observed that the DBR cladding can be also an appropriate structure for the cladding and the suitability of the DBR structure can be compared to the one of the omnidirectional mirror.

In chapter 5 we have explained in detail the fabrication and characterization processes of porous silicon layers. Firstly, the porous silicon fabrication system established at the Department of Electronic, Electric and Automatic Engineering of the University Rovira i Virgili has been presented and the influence of the different elements of the system on the porous silicon characteristics has been discussed. We have designed and fabricated an electrochemical cell that permits the fabrication of homogeneous porous silicon layers. The program realized for the control of the whole fabrication system has been also explained.

The characterization part has been focused on the study of the fabricated porous silicon layers. The different measurement techniques used for the characterization of the porous silicon layers have been explained. These techniques are Scanning Electron Microscopy (SEM), Fourier Transform Infrared spectroscopy (FTIR) and Spectroscopic Ellipsometry (SE). From these measurements the two main characteristics of the porous silicon layers, refractive index and thickness, have been calculated using two different mathematical methods: the interference fringes method and the spectrum analysis fitting. The comparison of the results obtained with both methods indicates that both are equally suitable for the characterization of microporous silicon layers.

These characterization methods have been also used to calibrate the porous silicon fabrication system. The calibration has established the relations between the anodization parameters and the physical characteristics of the porous silicon layers: the current density-refractive index relation and the anodization time-thickness relation. In addition, the porosity has been analyzed. We have concluded that the increase of the current density leads to an increase of the porosity and therefore a decrease of the refractive index. The relations of the current density with porosity and refractive index are both exponential. We

have also concluded that the thickness increases linearly with the anodization time. Moreover, the etch rate has been studied and we have observed that it depends on the current density; in particular it exponentially increases with current density.

The porous silicon layers have also been characterized using spectroscopic ellipsometry during a stage at the Ecole Polytechnique (Palaiseau, France). This characterization has determined the main physical features of these layers, porosity (and therefore refractive index) and thickness; and has allowed the analysis of their anisotropy. From the ellipsometric study of the porous silicon layers we have concluded that low porosity layers can be modelled with a graded index model. However, as porosity of the monolayers increases, the gradient index model is no longer valid, and it must be substituted by another one consisting of an anisotropic uniaxial layer with its optical axis oriented perpendicular to the surface of the sample. This indicates that the anisotropy increases with the porosity. In fact, we could conclude that depth inhomogeneity and anisotropy exist for all porosity layers but for low porosity layers the difference between the extraordinary and the ordinary refractive indices are small and the anisotropy of the layer is masked by the in depth inhomogeneity, and when the porosity increases the anisotropy becomes more important than the inhomogeneity.

The depolarization of light caused by sample thickness non-uniformity has also been measured and used to estimate the quality of measurements as well as the adequacy and goodness of ellipsometric data fits. We have concluded that when the current density increases, that is when the porosity increases, the depolarization of the fabricated porous silicon layer increases making more difficult the characterization of the layer using ellipsometry.

Chapter 7 presents multilayer optical components fabricated with porous silicon. In this chapter the different steps explained in the rest of chapters are used because each component is simulated, fabricated and characterized. Although many different components have been realized during the realization of this thesis, here we have only presented the most representatives.

The reflectivity spectrum of a DBR has been studied for different incidence angles. We have demonstrated that the behavior of the structure can be theoretically predicted and that for any wavelength, the range of incidence angles for which the bandgap exists can be studied with the projected band structure.

The reflectivity spectrum a microcavity has been measured for different humidity levels. We have observed that the reflectivity spectrum not only depends on the humidity level of the ambient medium but also on the presence of a water thin film on its surface due to the condensation of water. In both cases, the reflectivity resonance shifts to higher wavelengths and the reflectivity decreases when the humidity increases, but the relative changes in the reflectivity spectrum are much more significant with the presence of condensed water. This indicates that a porous silicon microcavity could be used for the sensing of humidity variations.

Finally, porous silicon omnidirectional mirrors have been fabricated and characterized. We have demonstrated that although the limited refractive index range of porous silicon does not permit the fabrication of omnidirectional mirrors with a wide omnidirectional bandgap using the typical periodic structure, the fabrication of multilayers consisting of different periodic structures stacked together solves these limitations. We have fabricated a mirror with the unbalanced structure propose in this work, which has demonstrated that a wide omnidirectional bandgap can be obtained using porous silicon and that this width can be enlarged by stacking periodic structures.