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Omnidirectional Mirrors for Porous Silicon Multilayer by Electrochemical Etching

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Abstract

The measurements and calculations of monolayer and multilayer reflectance, made of porous silicon films, have been carried out. The multilayer component has been made of porous silicon layers that has refractive indices of n_A=2.16 and n_B= 1.55. The band structure of one dimensional photonic crystal has been calculated using the transfer matrix method which consists of alternative layers of two dielectric materials A and B.
As for the multi layers component which are consist of the periodical repetition of two layers of different refractive indices (n_H and n_L) which has an omnidirectional photonic band gap (PBG), the width of which depends on the incidence medium and on the refractive index ratio n_H/n_L. In porous silicon, this ratio is limited by the material and fabrication characteristics. Theoretical and experimental study has been carried on the wide range of practical fabrication parameters for the formation of omnidirectional PBG. A band width of 400 nm is corresponding to a reflectivity higher than 97% which is suitable for applications of omnidirectional PBG at wavelength 1550 nm.

Keywords: Porous silicon, muli layers, Anodization, Omni directional mirrors

مرآيا متعددة الأتجاهات للسيلكون المسامي متعدد الطبقات بالتنميش الكهروكيمياوي

الخلاصة

اجريت حسابات وقياسات الأنعكاسية لطبقة أحادية ومتعدد الطبقات المصنوعة من أغشية السليكون المسامي .حيث ان تركيب متعدد الطبقات صنعت من طبقات السليكون المسامية التي تمتلك معاملات انكسار n_A=2.16 و n_B=1.55. باستخدام طريقة نقل المصفوفة حيث تم حساب تركيب فجوة الحزمة الضوئية احادية البعد التي تتكون من طبقات متبادلة من مادتين معزولتين A و B.
اما متعددة الطبقات المكونة من الترتيب الدوري من طبقتين لمعاملات انكسار مختلفة عالية وواطئة (n_H و n_L) فان لديها فجوة حزمة ضوئية متعددة الاتجاهات والذي عرضها (PBG) يعتمد على تأثير الوسط والنسبة بين معاملي الانكسار n_H/n_L. في السليكون المسامي هذه النسبة محددة بالخصائص التصنيعية للمادة. وقد اجريت دراسة نظرية وعملية على معدل عرض معلمات تصنيع عملية لتكوين فجوة الحزمة الضوئية متعددة الاتجاهات . وعرض الحزمة 400 نانومتر المقابلة لانعكاسية اعلى من 97% وهي ملائمة لتطبيقات فجوة الحزمة الضوئية (PBG) متعددة الاتجاهات عند الطول الموجي 1550 نانومتر.

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Introduction

Recently, it has been theoretically and experimentally demonstrated that an omni directional mirror (OM) can be realized using one-dimensional photonic crystals [1]. OMs are dielectric mirrors that have the ability to completely reflect the radiation in a particular range of frequencies for all possible angles of incidence and whatever the polarization [2]. Over the last few, an increasing effort has been dedicated to photonic structures because of their wide application in the control of the emission, propagation, and detection of light. The simplest 1D photonic crystal consists of a periodic sequence of two layers with two different n and the same nd. It is usually called Distributed Bragg Reflector (DBR) since for a wavelength range around $\lambda = 4nd$ the structure reflects most of the incoming light. This wavelength range is named stop-band. High reflection is a consequence of the fact that light cannot propagate with a **k** vector in the stop-band since it is a forbidden quantum state. In analogy to the electronic case, the stop-band is also called a *photonic bandgap* and the DBR a 1D photonic crystal [3-5].
One-dimensional photonic crystals can be perfect omnidirectional mirrors (OMs), reflecting light for any incidence angle and any polarization over a range of wavelengths. Omnidirectional mirrors made by periodically repeating two different refractive index layers have been widely studied [6].

For the latter purpose, have to realize optical multilayer having a proper refractive index profile. In case of PS, it can be reached easily applying a programmed anodisation current control. Porous silicon multilayer (PSM) can exhibit a strong modulation of light so they can replace other dielectric layers in interference filters or mirrors. PSMs can be formed essentially in two different ways: (i) by a periodic variation of the etch parameters, such as the current density or the light intensity, during the electrochemical process, or (ii) by the use of periodically doped substrates, while keeping the etch parameters constant [7].
It is known that the porosity of porous silicon (PS) layers is related to the current density applied in the electrochemical process and this porosity is proportional to the refractive index of the material. useful as passive optical elements, such as multilayer Bragg mirrors or Fabry–Perot (FP) multilayer cavities with alternating layers of high and low porosity layers (hence (L)ow and (H)igh refractive indices) [8].
The PS multilayer stacks can be designed as to match the desired optical behavior, since the changes of the reflection and transmission spectra would depend on the variations induced in the effective index of refraction [9]. This dependence opens a new and interesting field in the development of optical filtered mirrors based on PS with selected bands in the visible and infrared spectra. Thus, PS multilayer mirrors are

converted into a new type of PS-based heterostructures that exhibit a periodic variation in depth and porosity [10].

In the present work, PS-based multilayer structures were developed by the periodic variation of the formation current density during the electrochemical formation process. This formation method provides an excellent control of the porosity and thickness of the individual layers, and the present work is to show practical design rules to obtain omnidirectional photonic band structures (PCs).

Experimental procedure

For fabricating PSM, we have used boron doped, p++ type crystalline silicon wafers with resistivity 0.001–0.005 Ωcm, and (100) oriented substrates, for electrochemical anodization process at room temperature, and the electrolyte is constituted by an ethanoic solution of HF with an HF concentration of 15% in volume. A metal plate was used as anode and a platinum (Pt) mesh as cathode. The Si wafer was put on the anode and sealed by a polytetrafluoroethylene (PTFE) cell O-Ring with an etching area of about $1cm^2$. The backside of the Si wafer was coated with an aluminum layer to get a proper Ohmic contact.

Constant currents between the wafer and the electrolyte are applied to produce the multilayer i.e., $5mA/cm^2$ (49% porosity) for the high refractive index (n=2.16) layer A and $45mA/cm^2$ (70% porosity) for the low refractive index (n=1.55) layer B ones the layer thickness is controlled by the etching time, so in this case t_A = 63s (layer A) and t_B = 12s (layer B) respectively. The reflectance spectra measurements were performed on an UV-vis-NIR recording spectrophotometer (Cary 5000) from 175 to 3300 nm.

Results and discussion

Fig.1a,b Shows an experimental reflectance spectrum as a function of the incident radiation wavelength, obtained for a porous silicon monolayer sample prepared at different anodizing times at current densities $5mA/cm^2$ and $45mA/cm^2$.

The reflectance of PS shows the smallest reflectance with increasing time etching means that most of the incident photons are absorbed into the substrate.

The optical characterization (i.e. reflectance spectrum) of thin-film monolayer data. It consists of a least squares fitting of the simulated spectrum to a measured spectrum by assuming that the optical constants of the film follow a mathematical model. With this method, the refractive index and the thickness of the monolayer are determined. The used program, inspired in this method, is the Cauchy model [11], useful for dielectric materials, far from the absorption band. Cauchy's equation is a semi-empirical relationship of a dispersion curve (refractive index versus wavelength) is known as a Cauchy's equation,

$$n(l) = A + \frac{B}{l^2} + \frac{C}{l^4};$$

These windows allow changing the values of A, B and C and show a plot of these indices against the wavelength [12].

Fig.2 a,b where the dielectric structure has been made by using $5mA/cm^2$ and $45mA/cm^2$ of current density which corresponds to the refractive index of a porous silicon monolayer is represented. It can be observed that the refractive index is higher for wavelength 400nm and decreases until approximately 650nm in this wavelength the decrease of the refractive index is very slow, quite constant.

The time during which a current density is applied is the etching time. It determines the thickness of the porous silicon layers. The anodization time thickness relation for the fabricated porous silicon monolayer can be seen in Fig. 3, the layer thickness of PS monolayer increases with the etching time and current density where the results for two different current densities are represented. From these measurements a linear fit, we can also see that the slope is different for every current density and it increases when the current density increases.

In Fig.4a we can see the relation current density refractive index established from the measurements of the fabricated porous silicon monolayer. These refractive indices have been calculated using the measurement of Cauchy model method. We can observe that the decrease of refractive index is linearly with the current density.

One of the most important characteristics of a porous silicon layer is its porosity, defined as the fraction of air inside the porous layer. In fact, for the purpose of this work, the porosity of a layer is not an essential value but our essential parameter is the refractive index of the layer. As it has been explained before, for the simulation of any optical device the essential data of the layers that form the multilayer are the thickness and the refractive index, whereas the porosity is not used anywhere in the simulation and design process. Of course, we know that the refractive index is determined by the porosity but for the simulation, the concept porosity is completely invisible.

Similarly, to simulation for the fabrication the porosity is also “invisible” because the different methods used for the characterization of the porous silicon layers (interference fringes method and spectrum analysis fitting) calculate the refractive index and the thickness of the layers, not the porosity. However, here we present the relation between porosity and current density because it could be interesting for future applications of the porous silicon layers.

Fig.4b the porosity-current density relation. We can observe that the porosity increases linearly with the current density.

In this paper, we describe the theoretical and experimental results of the light propagation through asymmetric multilayer. We use the transfer matrix formalism to calculate reflectance spectra and PS multilayers as experimental samples.

Using the transfer-matrix method (TMM) [13] numerical calculations of R spectrum have been carried out to fit the experimental data. In these simulations, linear drifts in porosity and thickness of the layers could be considered. As the optical thickness depends on both porosity and thickness (*n* and *d*) and as the thickness can be easily controlled by simply varying the duration of the etching, we allow only variation in the thickness.

Fig.5 shows the calculated and experimentally measured reflectance of PSM. The periods forming of the randomized sequence multilayered structures are the 4^{th} (14 constituent layers), 8^{th} (28 layers) and 16^{th} (56 layers). Theoretical spectra result from a simplified numerical simulation along the lines of the transfer matrix method without including any kind of losses, and assuming normal incidence. It can be seen that the fabricated samples show high reflectivity with increasing layers. The partially randomized structures were found to have many features (many narrow resonances localized inside the sample) relevant for its application in optical interferometric biosensors and can be concluded as promising photonic structures [14].

It is an interesting fact that in these heterostructures their reflectance spectra exhibit a good agreement between the simulated and experimental spectra, in spite of the limitations of the theoretical model. As expected higher generations, lead more directly to the appearance of pseudo-photonic band gap (PBG) regions because of the increasing dielectric contrast in the system. One detects that, although they are high indeed, the experimental reflectance signals in the PBG regions fall short to achieve the unity [15]. This can be explained by assuming the presence of optical losses in the system attributed to partial absorption and scattering, as a consequence of the structure of PS, mainly composed of Si nanocrystals [9].

These dielectric multilayer films act as a perfect mirror for light with a frequency within a sharply-defined gap. For a fixed number of periods, the PBG increases as the ratio of the refractive indices of the two layers [n_H /n_L , high (H) and low (L) refractive index n] increases and, for a fixed ratio of refractive indices, up to a certain limit, the PBG increases with the number of periods [16].

It is important to stress that *Pavesi group*, too, has developed photonic structures with wide PBG using aperiodic porous-silicon layers [3].

The simplest type of a multilayer thin film interference filter is a Bragg reflector or a Bragg stack. It is based on a stack of paired layers, where each layer satisfies the Bragg condition $nd = \lambda_0/4$, with one layer having a low refractive index, n_L, and the other layer having a high refractive index, n_H. A compact way of denoting the design is

HLHLHL . . . HL = $(HL)^i$

with i being the number of pairs. The thickness of the layer is *d* while λ_0 is the wavelength of the incident electromagnetic (EM) wave in vacuum for which the maximum reflection will occur (design wavelength). Plane waves are assumed. This condition results in the reflected EM wave at the design wavelength constructively interfering in each layer and one may reflect up to 97% of the incident energy.

Fig.6. shows the measured reflectivity spectrum of a dielectric Bragg mirror designed for a maximum reflectance at a

wavelength of 1550nm (ABABABAB…. the stack consists of 25 periods Here “A” and “B” represent the low porosity (49%) and high porosity (70%) layer respectively.
The dielectric structure has been made by using 5mA/cm^2 and 45mA/cm^2 of current density which corresponds to the refractive index contrast of n_B/n_A = 1.55/2.16. Here n_A and n_B correspond to low porosity and high porosity layer. The photonic bandgap of around 400nm wide is observed.

Conclusions

In this work, we have studied the optical properties of periodic multilayers structure in the reflectance spectrum, when the optical path length of the layers is considered constant. This periodic pattern is sensitive to small variations in the optical path length of the layers or in the refractive index. The numerical results were compared with those obtained from samples of PSM, and a good agreement is observed.
We have reported a theoretical approach to photonic bandgap analysis of porous silicon multilayer. The multilayers exploit a high quality optical response and a good agreement between theoretical and experimental results has been obtained. We have found the splitting of the PBG on increasing of the layers. The width of the omnidirectional bandgap of the mirror reflectivity 97% and the photonic bandgap of around 400nm at a wavelength 1550nm.

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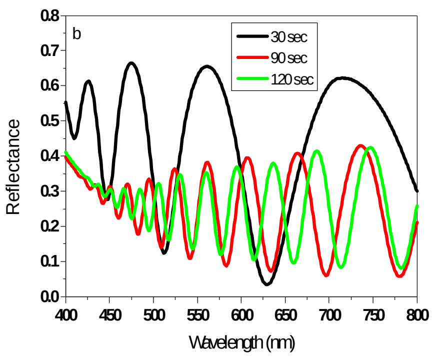

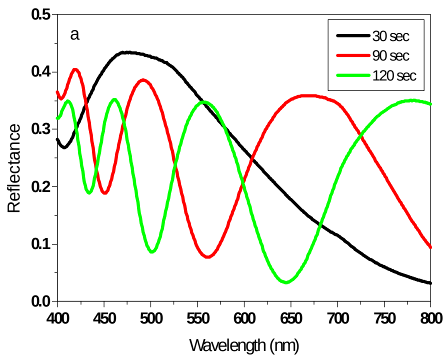

Figure (1) Experimental and reflectance vs. wavelength for different time etching and different current density a) 5mA/cm^2 b) 45mA/cm^2

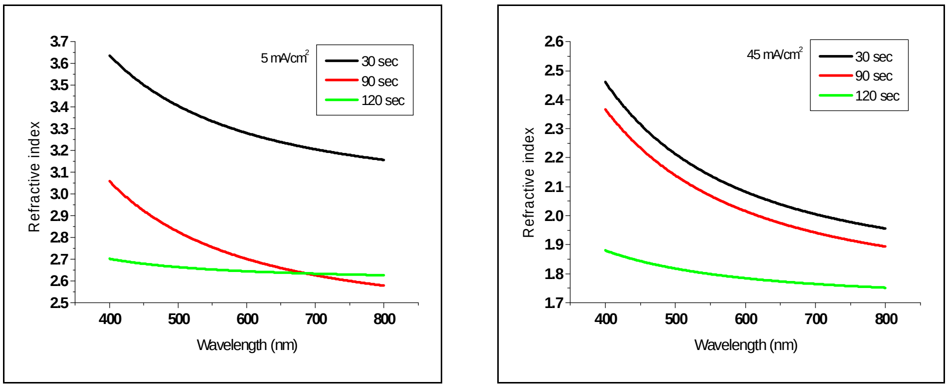

Figure (2) Refractive index of a porous silicon layer simulated with a thin film Cauchy model for different Current densities. a) 5mA/cm^2 b) 45mA/cm^2

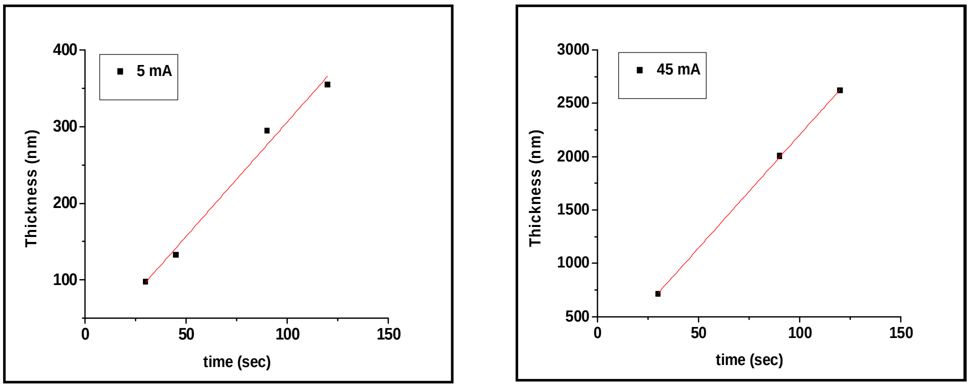

Figure (3) Relation between the applied anodization time and the thickness of the Monolayer, obtained for two different current densities a) 5mA/cm^2 b) 45mA/cm^2

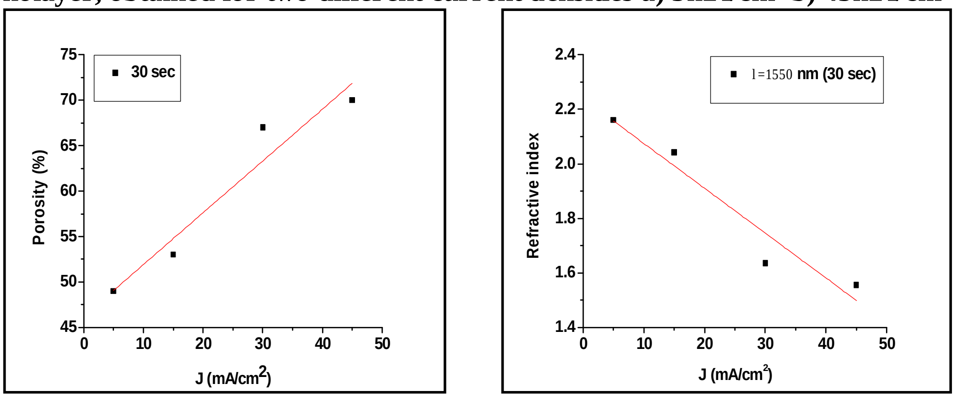

Figure (4) a) Relation between current density and refractive index of porous silicon Monolayers; b) Relation between porosity and current density.

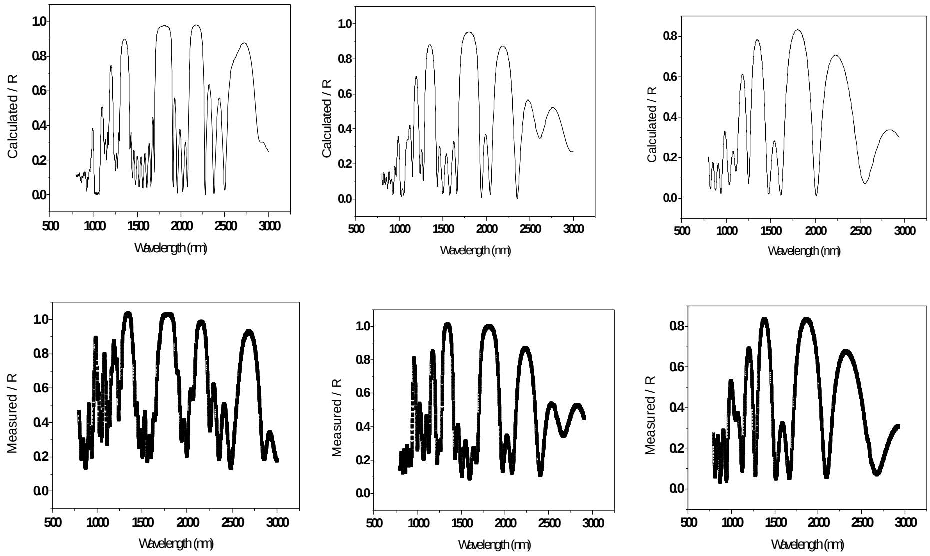

Figure (5) Reflectance spectrum of a randomized structures (a) Calculated and (b) measured reflectance spectra of samples:

i) ABAABAAABAAAAB formed with the 14 layers.
ii) ABAABAAABAAAABABAABAAABAAAAB formed with the 28 layers
iii)ABAABAAABAAAABABAABAAABAAAABABAABAAABAAAABABAABAAABAAAAB formed with the 56 layers.

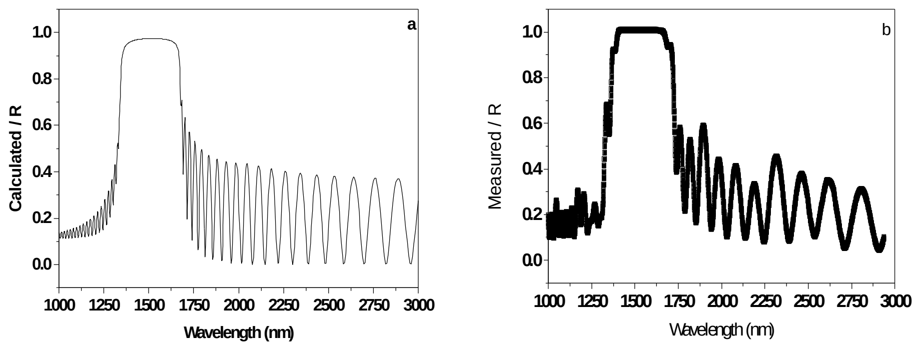

Figure (6) Reflectivity spectrum of a porous silicon of a λ/4-DBR spectra of samples. Sequence: ABABABABABABABABABABABABABABABABABABABABABABABABAB (a) Calculated and (b) measured reflectance