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Preparation of one-dimensional porous silicon photonic quantum-well structures

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ABSTRACT One-dimensional porous silicon (PSi) photonic quantum-well structures have been electrochemically fabricated and spectroscopically characterized. The photonic well in the structure is a photonic crystal (PC) consisting of alternately stacked high- and low-refractive-index PSi layers. Discrete states are observed in both reflectance and transmission spectra. It is found that the number of confined states appearing in the photonic bandgap of the photonic barrier depends on the number of periods adopted in the well PC. Thus, increased confined photonic states can be created simply by increasing the number of periods of the well PC in the structures.

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1 Introduction

Ever since the concepts of superlattices and quantum wells (QWs) [1, 2] in semiconductor crystals were first introduced to photonic-bandgap (PBG) materials in the late-1980s [3], much progress has been achieved and photonic quantum-well structures (PQWSs) have been presented for one-, two- and three-dimensional PBG materials [4–8]. A two- or three-dimensional PQWS can be constructed by inserting a photonic well (a uniform medium photonically different from the surrounding area) into photonic barriers. Theoretical analysis by Y. Jiang et al. [7] has predicted the presence of quantized confined states in such structures due to the photonic confinement effect, similar to that in semiconductor quantum wells. They showed that the transmission coefficient was unity for all the confined states, just like the electronic tunneling in a semiconductor quantum-well system, and the resonant tunneling effect could be used to explain the phenomenon. For one-dimensional (1D) PQWSs, two types have been proposed, with the photonic well being a homogenous dielectric slab [9] or a photonic crystal (PC) [6]. It is difficult to observe PBG and QW effects in the former type; but for the latter, the QW effect has proved to exist and the number of confined photonic states can be tuned by adjusting the number of periods in the photonic well region if the band of the well is within the PBG of the barrier.

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In this letter, we report on realization of the latter type of 1D PQWS with both the barriers and the well in the structure being porous-silicon (PSi)-based PCs. From the viewpoint of the quantum wire model [9, 10], the formation of a PSi structure originates also from some sort of confinement – self-limited etching of the pores in the structure. The commonly used electrochemical etching technique can provide good control of both thickness and porosity of different PSi layers and hence produce periodic PSi structures with varying layer thicknesses and refractive indices, such as superlattices [12, 13] and microcavities [14, 15]. The structures prepared are operable in the wavelength range of visible light, characterized by quantum-well features similar to those of semiconductor quantum-well structures.

2 Experimental

The particular technique adopted for preparation of the PSi PQWSs in the present experiment was pulsed electrochemical etching [16], controlled by a personal computer. The substrates were (001)-oriented, heavily p-doped silicon wafers, anodized by a HF(48%)-C_2H_5OH(99%)-H_2O solution (1:1:2 by volume). The desired porosities or refractive indices were achieved by controlling the current density during etching, with the reported dependence of porosity on current density [11] as a reference, and the thicknesses of the different layers were derived from scanning-electron-microscope micrographs [17]. The validity of the estimated refractive index and thickness values was further checked by fitting the measured reflectance spectra based on the transfer-matrix method [5, 18]. The PSi PCs were obtained by periodically stacking combined high/low-refractive-index PSi bilayers, with the optical thickness being about $\lambda/4$ for each layer. Finally, the 1D PSi PQWS was realized by sandwiching a PC as a well between two photonic barriers consisting also of periodically stacked PSi bilayers, but with different parameters. Such a barrier/well/barrier structure can be labeled as $(AB)_n/(CD)_m/(AB)_n$, as shown in Fig. 1, where n and m represent the periods of AB and CD PCs, respectively. The refractive indices and thicknesses of layer A and layer B in the AB stacking were 2.1, 0.07 μm and 1.45, 0.09 μm, respectively; and those in CD were 2.1, 0.085 μm and 1.45, 0.13 μm. In the case of $n = m = 5$, adopted in the present experiment, reflectivity as high as 90% was attainable.

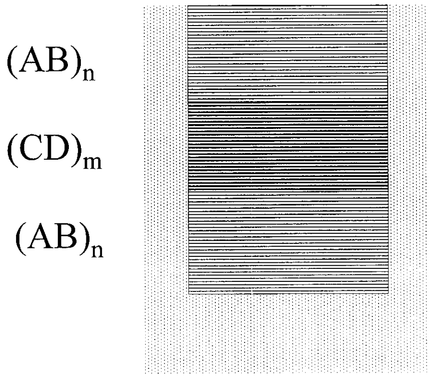

FIGURE 1 Sketch of the one-dimensional photonic quantum-well structure

The reflectance spectra were measured by using a 100-W tungsten iodine lamp as the light source, incident at about 8° off normal. The reflected light was normally detected by a spectrophotometer consisting of a 0.275-m double monochromator, a photomultiplier tube and a lock-in amplifier.

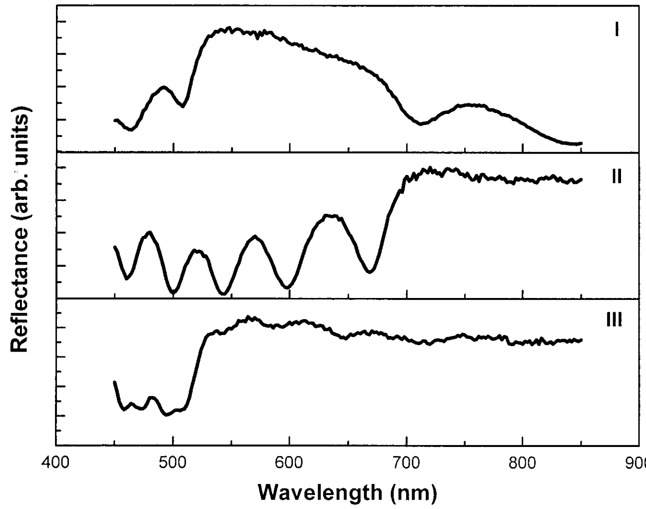

FIGURE 2 Reflectance spectra of $(AB)_5$ PC (I), $(CD)_5$ PC (II) and photonic heterojunction structure $(AB)_5/(CD)_5$ (III)

3 Results and discussion

Figure 2 shows the reflectance spectra measured from (I) $(AB)_5$, (II) $(CD)_5$ and (III) $(AB)_5/(CD)_5$. Here, the subscript '5' means that each PC consists of five AB or CD bilayers. One can see that, whereas the AB and CD PCs are highly reflective to the incident light in the wavelength ranges from 500 nm to 690 nm and from 690 nm onwards, respectively, $(AB)_5/(CD)_5$ exhibits highly reflective behavior in the summed ranges of the two. In other words, the heterojunction-like photonic structure $(AB)_5/(CD)_5$ has a PBG as large as the sum of the two constituent PCs. This is consistent with the theoretical prediction by Zi et al. [5], that an enlarged energy range of the PBG can be achieved by properly choosing the geometric and dielectric parameters of the photonic constituents.

Characteristics of PQWSs are more complicated than those of the photonic heterojunction structure. Shown in Fig. 3(I) are the reflectance spectra of the PQWSs $(AB)_5/(CD)_m/(AB)_5$. Panels a, b and c correspond to $m = 1, 3$ and 5, respectively. The corresponding photonic band structures of the separate AB and CD PCs are shown in Fig. 3(II) [6, 19]. Several features are immediately evident. First, the PBG of the PQWS enlarges with increasing m, the period number of the CD PC. In the case of $m = 1$, insertion of the CD layer brings no enlargement in the PBG, but brings a defect in the AB PC; alternatively, an enlarged PBG appears for m larger than three. The phenomenon can be attributed to the limited period number of the well PC. Secondly, the num-

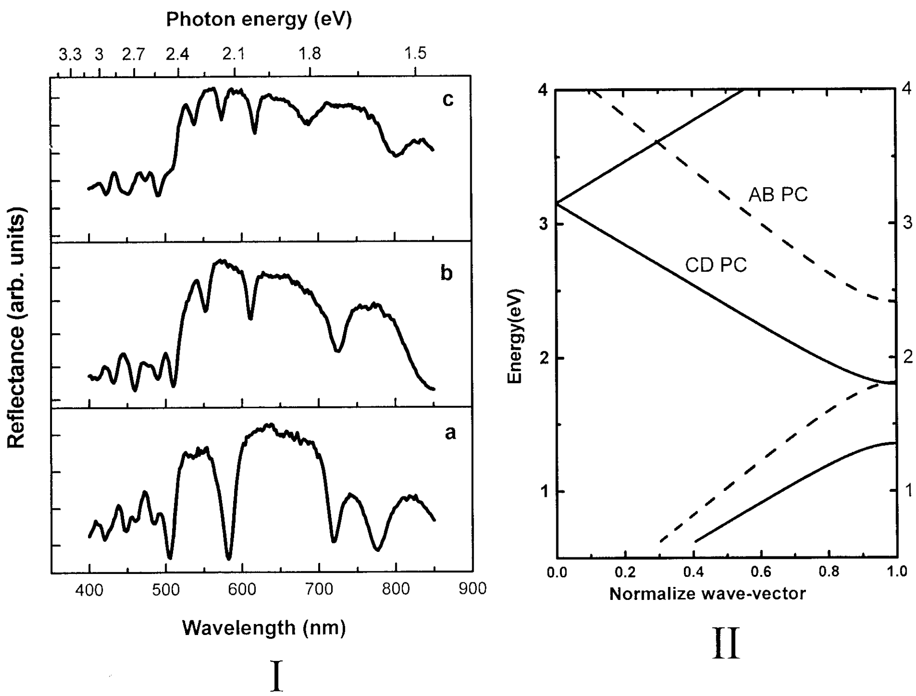

FIGURE 3 Reflectivity spectra of $(AB)_5/(CD)_m/(AB)_5$ ($m = 1$, 3, 5) photonic quantum-well structures (I), with m equal to 1 (a), 3 (b) and 5 (c); and the photonic band structures of the AB and CD photonic crystals (II)

ber of dips in the PBG, or maxima in transmission, is just equal to the number of CD PC. The dips can be further divided into two categories depending on their sharpness, and the number of the sharp dips is 1, 2 and 3 for $m = 1$, 3 and 5, respectively. Thirdly, the transmission coefficient can reach unity at the sharp dip for the sample of $m = 1$, and reduce with increasing m.

To acquire a more thorough understanding of the transfer behaviors of the PSi-based photonic structures fabricated, transmissive measurements have also been performed for the photonic heterojunction $(AB)_5/(CD)_5$ and PQWS $(AB)_5/(CD)_5/(AB)_5$, with the spectra obtained shown in Fig. 4. In this case, the PSi layers were peeled off in several seconds using a high constant current density ($\sim 500\,\mathrm{mA/cm^2}$) after the PSi heterojunction and PQWS structures had been constructed. The peeled films were then stuck on to a glass substrate to enable the measurements to be taken. The spectra measured are quite complementary to those from the reflective measurements, as one may see from the related figures: the spectrum in Fig. 4(I) also exhibits an enlarged PBG, the same as in Fig. 2(III), for the photonic heterojunction structure; and for the sample of PQWS, the transmission peaks appear in the PBG and can be divided into two categories too, depending on their sharpness (Fig. 4(II)), the same as the dips in Fig. 3(Ic). The deviation that the PBGs derived from the two sorts of measurements do not exactly coincide with each other, which can be attributed to the influence induced during peeling off the films. It is possible that the thickness and/or refractive index has been somewhat changed during the procedure. Even the slightly changed sharp peak positions, in comparison with the reflectance spectrum, can be attributed to the influence of the peeling procedure.

The above results can be further clarified by analyzing the photonic band structures of the AB and CD PCs shown in Fig. 3(II). One may see there that the PBGs of the two PCs meet at the energy of 1.8 eV (~ 690 nm), so it should be possible to obtain an enlarged PBG experimentally by constructing the heterojunction structure $(AB)_5/(CD)_5$. However, the photonic band of the well PC (CD PC) is not fully inside the PBG of the photonic barrier (AB PC) in the visible light range. In that case, although the allowed states in the PQWS can be increased by increasing the period number of the CD PC, only those located in the PBG of the photonic barrier are confined states and the rest are unconfined defect states. Experimentally, the confined states correspond to the sharp dips (peaks) in the reflectance (transmission) spectra. Analysis of the distribution of the electric field within the structure shows that the field is confined in the photonic well (CD PC) for the confined states and in the top AB PC for the unconfined defect states [19]. It is thus understandable that the allowed states lie partly in the photonic well corresponding to confined states (sharp dips or peaks), and partly in the photonic well corresponding to unconfined defect states (broad dips or peaks). The number of the confined states is not equal to the number of periods of the photonic well, as mentioned in [6]. This is because the photonic band of the CD PC is not fully inside the PBG of the AB PC, and hence the barriers do not confine all the allowed states completely. The unconfined states overflow the photonic quantum well, and are submerged in the low-wavelength region of the PBG of the photonic quantum well.

As predicted in the theoretical analysis, the transmission coefficient is unity for all the confined states, which can be explained by the resonant tunneling effect. But the experimentally measured values deviate from this, and decrease when the period number of the CD PC increases, though the value is very close to unity in the case of $m = 1$. The discrepancy can be ascribed to the loss of electromagnetic energy during the traveling of the light in a thick sample. As the thickness of the porous silicon and the number of interfaces increase, absorption by porous silicon and scattering at the interfaces would result in a reduction in reflectance [20]; thus the transmission coefficients for confined states cannot reach unity. But this does not influence the exhibition of the characteristics of the PQWSs.

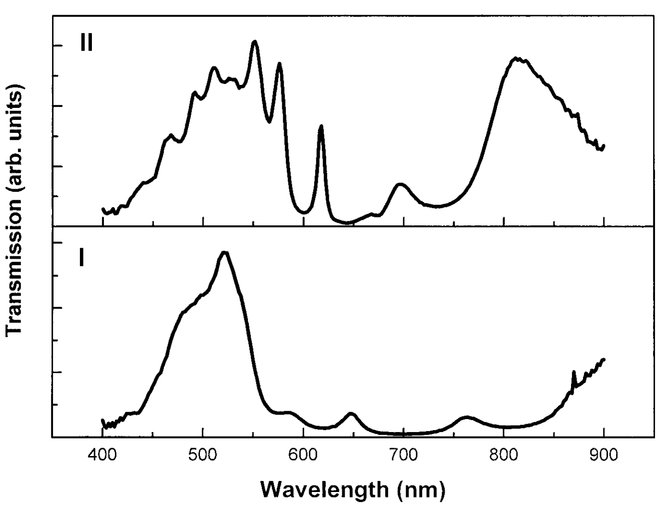

FIGURE 4 Transmission spectra of the $(AB)_5/(CD)_5$ heterojunction structure (I) and the $(AB)_5/(CD)_5/(AB)_5$ photonic quantum-well structure (II)

4 Summary

In summary, one-dimensional porous-silicon photonic quantum-well structures, formed by sandwiching a photonic well between two photonic barriers, have been constructed by using the pulsed electrochemical etching method. Such structures are characterized by the appearance of discrete states in both reflectance and transmission spectra, in a way similar to the electronic states in semiconductor quantum-well structures. It is found that sharp peaks appear only in the photonic bandgap of the photonic barrier. These peaks are associated with the quantized states resulting from the photon confinement effect in the photonic quantum-well structures. The number of confined photonic states can be increased simply by increasing the number of periods of the well PC in the PQWS.

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