Characterization of planar photonic crystals using surface coupling techniques at large wavelengths

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We report a non-destructive characterization of planar two-dimensional (2D) photonic crystals (PhCs) made in silicon on insulator (SOI) wafers using ellipsometric or Fourier transformed infrared (FTIR) spectroscope. At large wavelengths, devices behave as homogeneous isotropic materials defined by an effective filling factor. The experimental results related to the PhC limited dimensions confirm this characterization.

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Determination of the band structure of photonic crystals (PhCs) is important in order to take advantage of their unique properties of dispersion, reduced group velocity or modification of emission around the bandgap frequencies[1]. As their effective characteristics are often far from the nominal ones, it is interesting to determine them experimentally, using non-destructive methods, among which optical ones which have become standards of process monitoring in semiconductor technology in recent years.

In the case of non-optically active materials, surface coupling techniques can be used. According to the parameter to be determined, various methods are available. To characterize properties associated with the structure period, diffractive optics measurements at wavelength λ close to the material period Λ are chosen, which allows the dispersion curve mapping and white-light interferometric[2] or transmission/ reflection measurements selected[3,4]. The determination of the effective characteristics (index) of a layer considered as a homogeneous material induces measurements at large wavelengths ($\lambda \gg \Lambda$) where diffraction is negligible and spectroscopic ellipsometry[5] or polarimetry measurements are performed.

In the following, characterization of planar PhCs using both types of measurements at large wavelengths is presented.

We have studied two-dimensional (2D) triangular PhCs, named CP_i, made of air holes etched in the 0.3-μm-thick Si layer of a silicon on insulator (SOI) wafer. Four structures have been drilled in the same wafer, using deep ultraviolet (UV) (193 nm) optical lithography and reactive ion etching (RIE). They exhibit the same period $\Lambda = 0.5$ μm, but various air-filling factors f (see Figs. 1(a) and (b)). This procedure eliminates spurious changes in the refractive index or thickness of each layer and has a single parameter f to be determined for each PhC.

Spectroscopic ellipsometry measurements have been performed in the range of 1.5 μm $\leq \lambda \leq$ 2 μm (i.e. $\lambda \geq 3\Lambda$) using an ellipsometer with rotating polarizer and micro-spots, for various incident angles θ and incident planes (containing either the ΓK or ΓM direction of the PhCs). Both ellipsometric angles (tgψ and $\cos\Delta$) exhibit sharp maxima whose characteristics depend on θ and on the index and thickness of each layer.

Measurement sensitivity can be increased for specific values of θ or specific optical thicknesses which optimize the contrast of interferences linked to reflection on the various interfaces. Measurements outside the etched regions allow the determination of the thicknesses and complex refractive indices of the wafer layers. In the etched parts, ellipsometric angles tgψ have been measured within the 4 PhCs and in the unetched region for $\theta = 75°3'$ and in the ΓK direction, as shown in Fig. 2(a).

Similar measurements have been performed either in reflection or in transmission using a Fourier transform infrared (FTIR) spectrometer. For various incident angles, planes, and polarizations, tgψ in Fig. 2(b) is obtained from ellipsometric or reflection measurements within

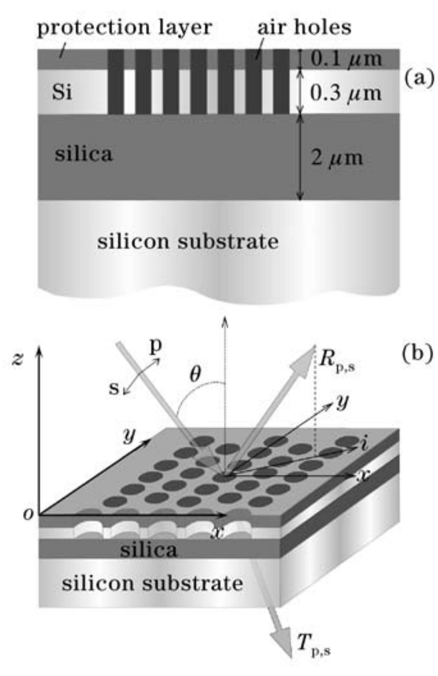

Fig. 1. (a) Schematic diagram of the etched SOI wafer; (b) experimental geometry for reflection measurements.

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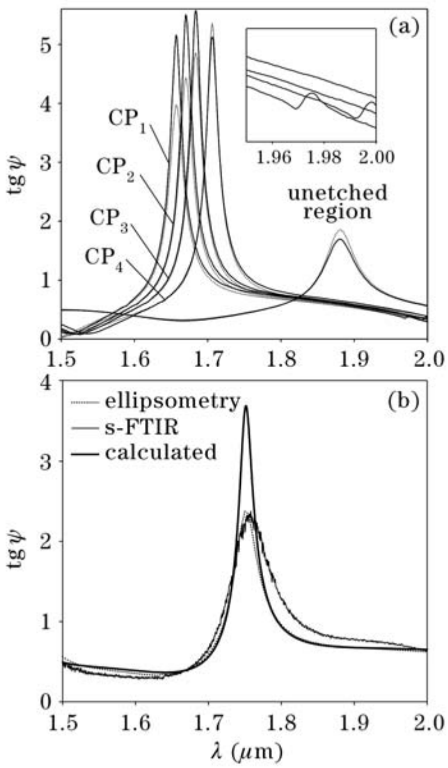

Fig. 2. Ellipsometric angle tgψ. (a) Measured within the 4 PhCs and in the unetched region (solid lines) and calculated with optimized air-filling factor f (dotted lines) for incident angle $\theta = 75°3'$, and in the ΓK direction. (b) Measured in CP_3 using ellipsometry (dotted), s-FTIR reflection measurements (thin line), and calculated with optimized air-filling factor f (thick line), for $\theta = 60°$, in the ΓK direction.

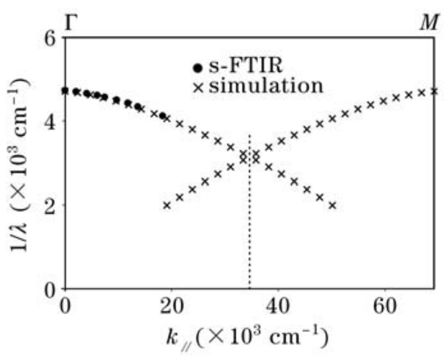

Fig. 3. Dispersion curve determined from Fano resonances observed on the FTIR transmission spectrum in the ΓM direction as θ varies (circles) and 3D simulation with an adjusted value of f (crosses).

the same device (CP_3), the same incident angle $\theta = 60°$ and incident plane direction (containing ΓK): they give analogous results.

Moreover, for larger wavelengths ($\lambda \geq 2$ μm), diffractive phenomena and Fano resonances have been observed for both types of measurements (see inset of Fig. 2(a)). The associated dispersion curves are reported in Fig. 3 for device CP_1 and three-dimensional (3D) simulations allow a new determination for f which corroborates the previous ones. In Fig. 4 the various determinations for f are shown and compared with nominal values.

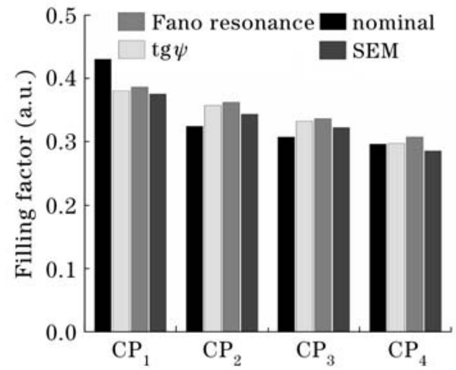

Fig. 4. Air-filling factor f deduced from tgψ, Fano resonances, scanning electron microscopy (SEM) in the 4 PhCs, and the nominal values.

Proper description of experimental results requires careful modelling of the electromagnetic (EM) fields reflected and transmitted by the structured material. The most spread rigorous method is the rigorous coupled-wave analysis (RCWA)[6−8], but its application needs long computation time. The effective medium approximation (EMA) often provides efficient description of sub-wavelength structures[9]. It assumes that the propagating wave is nothing but a zero-order diffraction mode propagating in a homogeneous medium. This assumption is all the more valid as higher diffracted orders have smaller amplitudes (as $\lambda \gg \Lambda$). That amounts to consider a Bloch mode as a plane wave (with wave vector $\mathbf{k}$ and frequency ω), which is the case when dispersion curves $\omega(\mathbf{k})$ are drawn. Within this approximation, analytical formulas for the medium effective permittivity diagonal elements are the weighed average of constitutive material permittivities and reciprocal permittivities[10]. Experimentally, at large wavelengths, we have checked that PhCs behave as isotropic materials (ellipsometric measurements were identical whatever the incident plane). We have then associated to each PhC a homogeneous layer with the same thickness, an effective index n_{eff} (with $n_{\text{eff}} = \sqrt{\varepsilon_{\text{eff}}}$) and an effective permittivity $\varepsilon_{\text{eff}} = \varepsilon_{\text{air}} f + \varepsilon(1 - f)$, where f is the effective air-filling factor adjusted for each PhC (more precisely, ε_{eff} is defined in each drilled layer i with permittivity ε_i). In Fig. 2 the theoretical curves of the ellipsometric angle tgψ are obtained for homogeneous materials with the adjusted values of f. In addition, the use of devices with finite dimensions and of an incident beam which enlightens the PhC edges induces new boundary conditions for the EM field and its wavevector: it allows the excitation of diffracted orders under the light cone, otherwise evanescent, with non-zero amplitude and the emergence of membrane eigen modes which can be observed.

In conclusion, diffractive optics methods, usually used in the short wavelength range to draw dispersion curves above the light cone[3,4], can operate in the long wavelength range to characterize actual PhCs. We shall use them in the same way to check the filling of the PhC air holes by other, possibly nonlinear, materials.

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