3D Structures Integrated with MoS_2

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Abstract: Photonic crystals (PC) are fabricated using a polymer 3D structure coated with a thin molybdenum disulphide (MoS_2) layer resulting in a polymer-high refractive index composite. A two-step process is used; 3D polymer woodpile structures are fabricated by direct laser writing (DLW) followed by chemical vapour deposition (CVD) of MoS_2. The high refractive index contrast between polymer-MoS_2 and air results in a photonic band gap for centre wavelength=1.27um at normal incident.

Introduction: Periodic crystal structures interact with light, creating a full photonic band gap (PBG), stopping the propagation of a specific wavelength (similar to the periodicity) in all directions. Inserting a defect into a PC creates an optical micro-cavity with confinement exceeding 2D slabs/waveguides due to reduced scattering and out-of-plane radiation losses [1].

Inserting an emitter into the cavity creates a single photon source, if the photon wavelength emitted is equal to the PBG. With strong coupling between cavity photons and two-level systems, cavity quantum electro dynamics (cavity-QED) is achieved.

Fabrication: Previously, 3D PCs are fabricated using a 2D layer-by-layer lithographic technique, with limited number of stacks [2]. More recently 3D structures are fabricated using a two-photon polymerisation (2PP) technique using DLW.

In this work we demonstrate 3D PC structures fabricated initially from polymer using 2PP, on a Nanoscribe Photonic Professional DLW system. A body-centred-cubic woodpile structure is fabricated, consisting of layers of parallel dielectric rods, with perpendicular layers, with and without walls [1]. CVD is then used to coat the structure in MoS_2; a high refractive index transition metal di-chalcogenide (TMDC). Firstly, a chlorine-based precursor ($MoCl_5$) is reacted with H_2S at room temperature. A second annealing step converts the film into MoS_2, reducing excess sulphur and Cl [3]. Due to polymer temperature constraints, 250° C is chosen. Conformal coverage was achieved throughout the structures as seen in Figure 1, with no damage.

The MoS_2 thickness is 10.0nm, measured by surface profiling and ellipsometry, as shown in Figure 2, with n=3.0 and k=0.78 at 632.8nm. Raman spectra, shown in Figure 3, reveal the two MoS_2 characteristic vibrational modes.

Photonic Band Gap Measurements: Figure 4 shows the measured photonic band gap before and after 10nm MoS_2 coating. The reflectance is measured using S-polarized white light source. A broadening and red shift of photonic band is observed. The measured reflectance at normal incident is shown in Figure 5. The full width at half maximum (FWHM) of photonic band gap is increased by 34nm after coating with MoS_2. The reflectance at a higher incident angle 11^o before and after MoS_2 is illustrated in Figure 6.

References:

[1] Taverne M et al., 2015 *J.Opt.Soc.Am.B* **32**, 639-648
[2] Deubel M et al., 2004 *Nat.Mat.* **3,** 444-447
[3] Huang C-C et al., 2014 *Nanoscale* **6,** 12792-12797

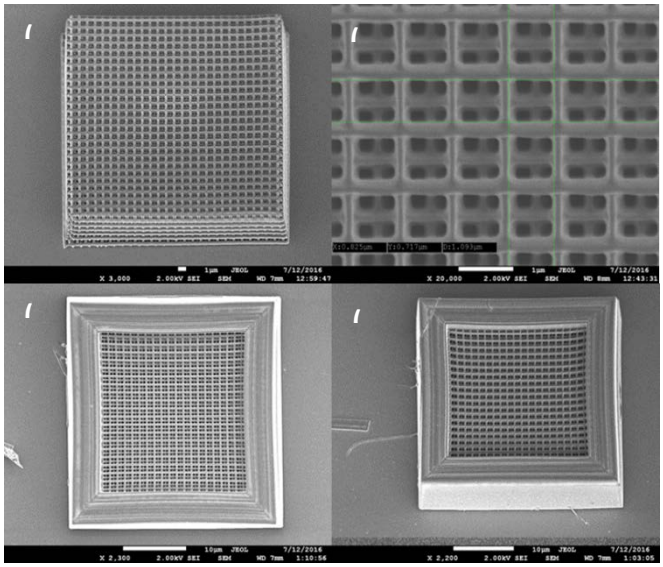

Figure 1. SEM images of BCC Woodpile Structures coated in 10nm of MoS2 with (a) no walls with tilted view, (b) higher magnification to show woodpile structure, (c) structure with walls for structural support and (d) structure with wall with tilted view.

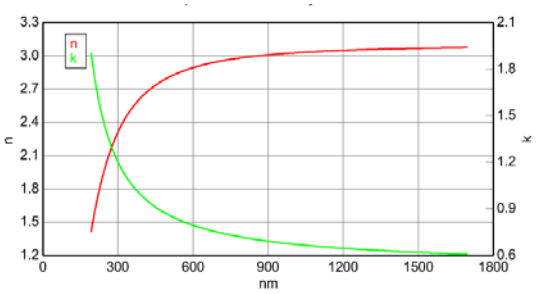

Figure 2. Refractive index and absorption vs. wavelength measured by ellipsometry for MoS_2 on 300 nm SiO2/Si.

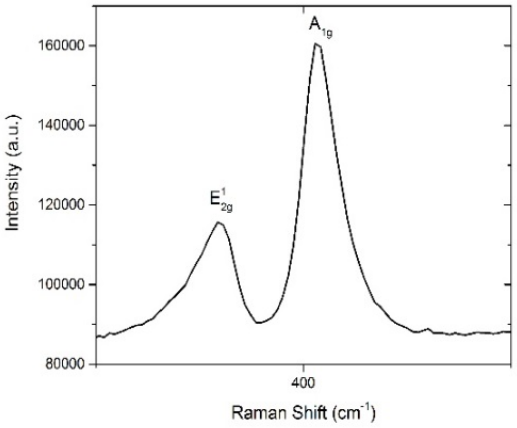

Figure 3. Raman spectra of MoS_2 vibrational modes, on quartz substrate. Peak separation is 23.4 cm^{-1}.

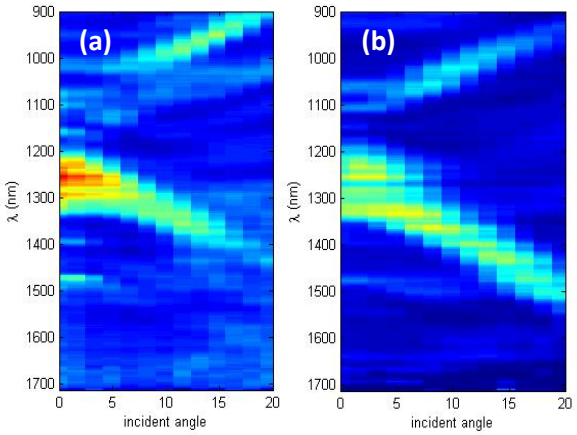

Figure 4. Measured angular reflectance of BCC woodpile structures (a) before coating (b) after coating

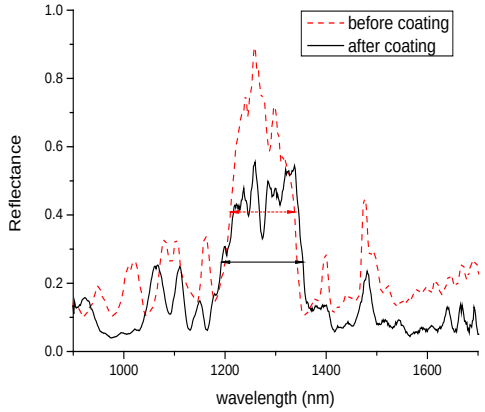

Figure 5. Measured reflectance at normal incident angle before and after coating.

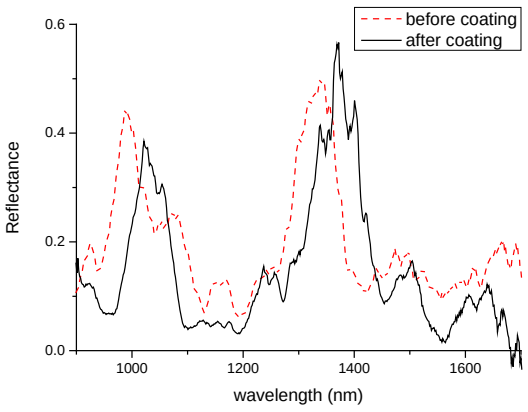

Figure 6 Measured reflectance at incident angle 11° before and after coating.