PHOTONIC CRYSTAL NICKEL AND ALUMINUM OXIDE MICROMECHANICAL DEVCIES HAVING 3D INVERSE OPAL MICROSTRUCTURE

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ABSTRACT

This paper reports a method to fabricate photonic crystal nickel and alumina micromechanical devices having three dimensional (3D) inverse opal microstructure. The 3D photonic crystal microstructure is fabricated using the polystyrene opals self-assembly process on gold coated silicon chips, followed by nickel electroplating. The volume fraction of these 3D nickel micromechanical devices can be controlled over the range 10% to 80%. The resulting nickel structure can be coated with an alumina shell and then sacrificed, to produce an alumina shell devices with volume fraction near 1%. To our knowledge, these are the first micromechanical devices made from a 3D inverse opal structure.

INTRODUCTION

Materials having a regular microstructure are of great interest for their novel optical properties including their application as photonic crystals [1]. Some published papers describe the fabrication of microelectromechanical systems (MEMS) devices from photonic crystals. By integrating a two dimensional (2D) photonic crystal cavity at the end of a silicon nitride atomic force microscope (AFM) cantilever, De Angelis [2] combined surface plasmonics, Raman spectroscopy and atomic force microscopy. Lee fabricated microcantilevers with nanochannels through the thickness of the cantilever [3]. Another study proposed a silicon cantilever having an integrated 2D photonic crystal microcavity resonator where the cavity resonant frequency was governed by the cantilever bending [4].

Published research on MEMS devices integration with photonic crystal materials has been limited to 2D structures, with little, if any, work published on the integration of 3D photonic crystal structures into MEMS devices. This paper reports micromechanical devices made from a 3D photonic crystal structure. These devices are realized as either nickel or alumina shell photonic crystal microcantilevers. The 3D nickel microcantilevers have a regular 3D inverse opal microstructure and the volume fraction can be tuned by further electropolishing or electroplating. To make the volume fraction of the devices even smaller, we use a 3D nickel photonic crystal microcantilever as a template to fabricate a microcantilever with 3D alumina shell structure. Because the alumina shell can be extremely thin, the resulting microcantilevers with alumina shell structure have extremely low volume fraction. Mechanical properties and Fourier transform infrared (FTIR) measurements of these devices are also presented in this paper.

FABRICATION

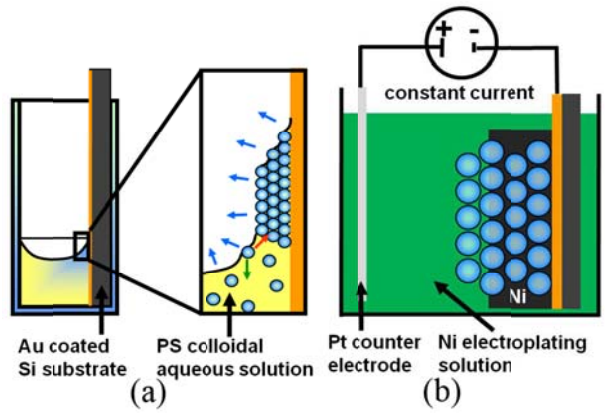

Figure 1: Fabrication process of nickel inverse opal microstructures. (a) Polystyrene microspheres self-assembled on a gold coated silicon chip surface. (b) Electroplated nickel on the chips with polystyrene microspheres.

A brief fabrication process of the 3D nickel inverse opal microstructure is shown in figure 1(a). To start, a thin gold seed layer is prepared on a silicon wafer, which is then soaked in the polystyrene colloidal aqueous solution. As the solution dries, a regular array of polystyrene microspheres is stacked onto this substrate in a self-assembly process [5]. The polystyrene microspheres are about 2 μm in diameter and stack in a regular face-centered cubic lattice. Nickel is then electroplated on the metal seed layer through the polystyrene opal template, such that the nickel filled the spaces between the polystyrene spheres. After electroplating, the polystyrene spheres are dissovled by soaking in tetrahydrofura, leaving a nickel microstructure that is the inverse of the cubic lattices of polystyrene spheres, hence the name "inverse opal" [1].

Incorporating this technique into microcantilever fabrication, we developed a method to fabricate microcantilevers with 3D nickel inverse opal structure. Figure 2 shows this microfabrication process. It starts with a 4 inch double-sided polished silicon wafer. First, a 300 nm thick thermal oxide is grown on the wafer (figure 2a). This silicon dioxide layer serves as an insulation layer between the silicon substrate and the metal seed layer and it is also a dry etch stop layer for the microcantilever release process. Next, chromium/gold (10nm/50nm) layers are sputtered on the wafer and patterned to the cantilever

geometry by photolithography followed by metal etch (figure 2b). The wafer is then diced into 1 cm by 3 cm chips. After growing the polystyrene opals on the chip by the self-assembly process described in Figure 1, nickel was electroplated (figure 2d) and polystyrene opals were removed in tetrahydrofura (figure 2e). The resulting nickel MEMS device has the lateral size and shape of the metal seed layer, thickness based on the electroplating, and microstructure based on the originally assembled polystyrene spheres. To release the cantilevers, the silicon substrate is etched through from the back side in an inductively coupled plasma machine. Then a 20 sec dip in hydrofluoric acid removes the silicon dioxide layer underneath the free standing cantilever (figure 2f).

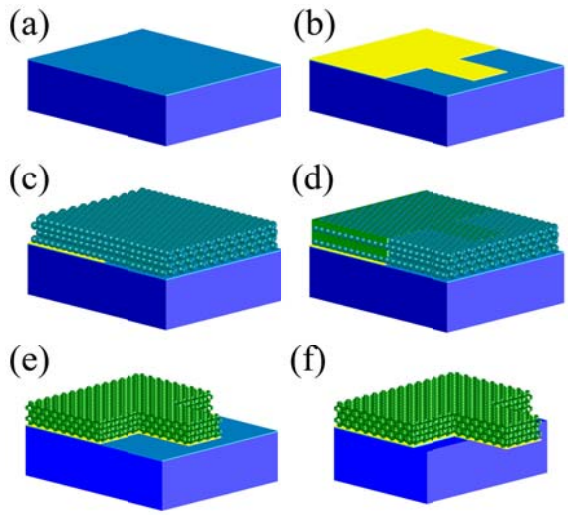

Figure 2: Microfabrication process of a 3D nickel photonic crystal microcantilever. (a) Start with a double-sided polished silicon wafer with 300 nm silicon dioxide. (b) Sputter 10nm/50nm of chromium/gold seed layers and pattern them to the cantilever shape. (c) Self-assemble polystyrene microspheres on the chips. (d) Electroplate nickel on the chips. (e) Remove polystyrene microspheres in tetrahydrofura. (f) Release the cantilevers.

Figure 3 shows scanning electron microscope (SEM) images of a released 3D nickel photonic crystal cantilever including its surface structure and its side view. The inverse opal microstructure produces a regular monodisperse porosity that extends through the extent of the cantilever in three dimensions. Using either electropolishing to remove nickel, or electrodeposition to add nickel, we have been able to control the volume fraction of these microcantilevers over the range of 10% to 80%.

Making a very soft cantilever with relatively high resonant frequency is a key for high-speed AFM applications. To change the spring constant or resonant frequency of a traditional cantilever, the standard approach is to modify the cantilever cantilever length, width or thickness. For example, a cantilever will be softer when the cantilever is thinner or longer. The same design goal can be achieved by lowering the volume fraction of a 3D photonic crystal cantilever. The normalized shift of resonant frequency can be written as $\Delta f/f \approx -\Delta m / 2m_{eff}$, where m_{eff} is the effective mass of the cantilever. To have higher normalized sensitivity in mass sensing, the cantilever needs to be made with small mass. In this case, it is desirable to have the volume fraction to be as small as possible. The minimum volume fraction of a 3D nickel photonic crystal cantilever is around 10%. To make a cantilever with even smaller volume fraction, we developed a new 3D photonic crystal microcantilever with shell structures.

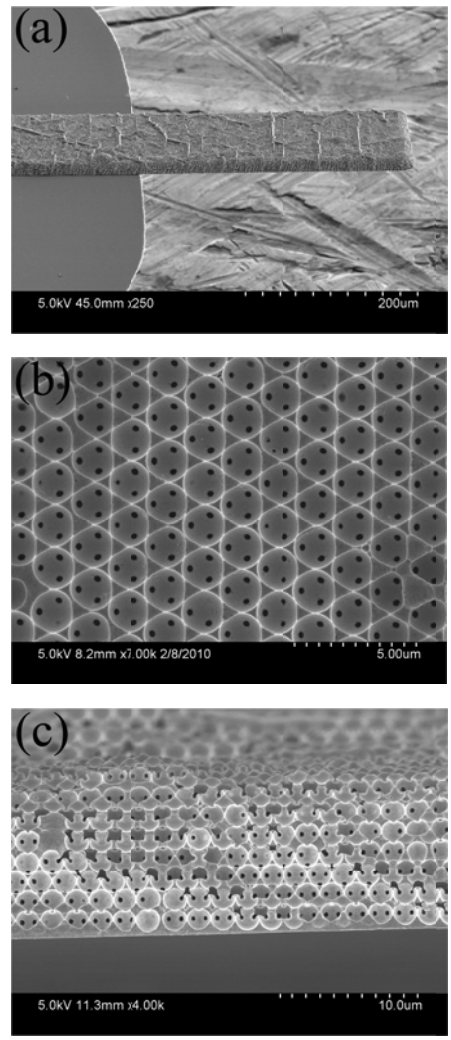

Figure 3: (a) SEM image of a 3D nickel photonic crystal cantilever. (b) Zoomed-in top view of a 3D nickel photonic crystal cantilever showing inverse opal lattice structure. (c) side-view of a nickel photonic crystal cantilever.

The microfabrication process of a photonic crystal cantilever with shell structures starts with a 3D nickel photonic crystal cantilever. First, the 3D nickel photonic crystal cantilever is coated with 75 nm thick alumina in a Cambridge NanoTech atomic layer deposition (ALD) tool.

Because the thin film deposited by ALD is extremely conformal, the alumina film covers not only the outside surface of the 3D nickel photonic crystal cantilevers, but also entire inner surfaces. Next, a focus ion beam (FIB) tool is used to cut off the cantilever edges to expose the nickel. The cantilevers were then soaked in nickel etchant until only the alumina shell remained. Figure 4 shows the SEM images of a cantilever with alumina shell structure and the zoom-in image of its cross-section. In figure 4(b), we can clearly see the alumina shell structure and the nickel between the shells is completely removed. Because the nickel etchant etches alumina very slowly, we can make the alumina shell structure as thin as 10 nm. This means that the volume fraction can go down to as low as 1%. Besides making cantilevers with alumina shell structure, the same method may be applied to make shell structure with other materials. The only condition is that the new materials can be deposited in ALD and not etched by the nickel etchant. This method opens a wide range of application opportunities for the cantilevers with 3D photonic crystal structure.

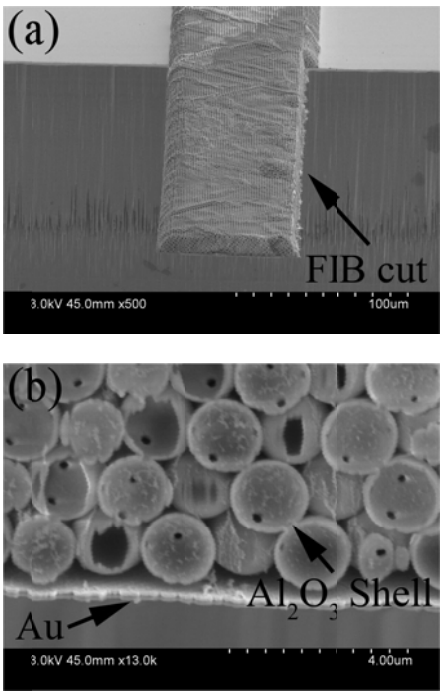

Figure 4: SEM images of (a) an alumina *photonic crystal cantilever and (b) the regular lattice structure made of 75 nm thick* alumina *shell.*

CHARACTERIZATION

Mechanical properties of the 3D nickel photonic crystal cantilevers were measured in our Asylum MFP3D atomic force microscope (AFM) and Agilent Nanoindentor. To measure the spring constant, the 3D nickel photonic crystal cantilevers are deflected at different positions from the end of cantilevers in the Nanoindentor. Based on the measurement of load and the displacement curves, spring constant of the cantilever was calculated. Typical load vs. displacement measurement of a cantilever is shown in figure 5(a). The load depends linearly on the Z displacement, which is expected for small displacements. The spring constant of a cantilever can be obtained by fitting these measurements with the theoretical model, where the spring constant k is proportional to $1/L^3$. Once we know the spring constant and the dimension of the cantilever, Young's modulus of this cantilever can be calculated using equation $E = 4kL^3 / Wt^3$, where k is the spring constant, L, W and t are the length, width and thickness of the cantilever, respectively. Figure 5(b) shows the measurement of the Young's modulus of 3D nickel photonic crystal microstructure with different volume fractions. The Young's modulus decreases as the volume fraction decreases. For a 3D nickel photonic crystal microcantilever of length 375 μm, width 150 μm, thickness 13 μm and volume fraction 0.22, typical spring constant is 35 N/m and resonant frequency is 42 kHz. For a solid cantilever with similar dimension, typical spring constant is 200 N/m and resonant frequency is 55 kHz. The quality factor of both cantilevers with these dimensions are around 450.

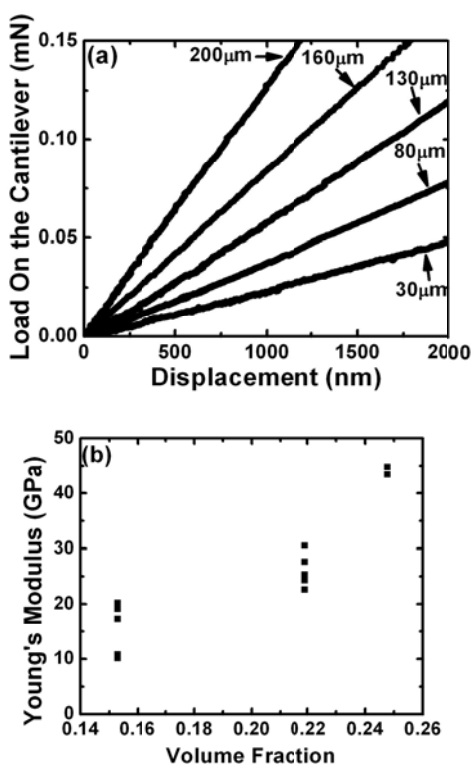

Figure 5: Mechanical property measurements of 3D Ni photonic crystal cantilevers. (a) Load and Z displacement measured at different position from the end of a cantilever in a Nanoindentor. (b) Dependence of Young's modulus on the volume fraction of 3D photonic crystal cantilevers.

Previous work has demonstrated that 3D photonic crystal microstructures can be used to modulate the absorption and thermal emission of a metal [1]. Figure 6

shows data from an FTIR measurement on the top surface of a 3D nickel photonic crystal cantilever, which agrees well with previous measurements [1]. The reflectivity of the photonic crystal cantilever surface is close to 0.2, which is much lower than the typical value of electroplated solid nickel, which is typically at about 0.6.

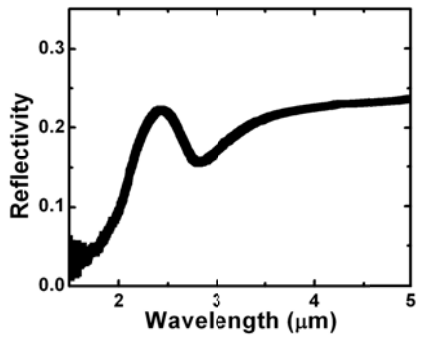

Figure 6: Reflectance of the top surface of a three-dimension nickel photonic crystal microcantilever measured by FTIR. The reflectivity of smooth electroplated nickel is significantly higher, at about 0.6.

This type of 3D photonic crystal cantilevers can be made with any metal that can be electrodeposited, such as gold or copper. While this paper demonstrates a cantilever structure, many other ther micromechanical structures could also be fabricated, with the requirement being metal plating from the lithographically defined seed layer. Finally, other materials could be merged with the photonic crystal structure, for example layers on top of or below the phtononic crystal.

CONCLUSION

We have successfully fabricated three-dimensional photonic crystal micromechanical devices having an inverse opal structure. These devices have tunable volume fraction with a regular lattice microstructure. The volume fraction can be tuned from 10% to 80% for a three-diemensional nickel photonic crystal microcantilever and it can be as low as 1% for a three dimensional alumina shell microcantilever. Slight modifications to the process could result in similar micromechanical devices from other materials.

REFERENCES

[1] X. D. Yu, Y. J. Lee, R. Furstenberg, J. O. White, and P. V. Braun, "Filling Fraction Dependent Properties of Inverse Opal Metallic Photonic Crystals," *Advanced Materials,* vol. 19, pp. 1689-1692, Jul 2007.

[2] F. De Angelis, G. Das, P. Candeloro, M. Patrini, M. Galli, A. Bek, M. Lazzarino, I. Maksymov, C. Liberale, L. C. Andreani, and E. Di Fabrizio, "Nanoscale Chemical Mapping Using Three-Dimensional Adiabatic Compression of Surface Plasmon Polaritons," *Nature Nanotechnology,* vol. 5, pp. 67-72, 2010.

[3] P. S. Lee, J. Lee, N. Shin, K. H. Lee, D. Lee, S. Jeon, D. Choi, W. Hwang, and H. Park, "Microcantilevers with Nanochannels," *Advanced Materials,* vol. 20, pp. 1732-1737, May 2008.

[4] C. K. Lee, J. Thillaigovindan, C. C. Chen, X. T. Chen, Y. T. Chao, S. H. Tao, W. F. Xiang, A. B. Yu, H. H. Feng, and G. Q. Lo, "Si Nanophotonics Based Cantilever Sensor," *Applied Physics Letters,* vol. 93, 113113, Sep 2008.

[5] N. D. Denkov, O. D. Velev, P. A. Kralchevsky, I. B. Ivanov, H. Yoshimura, and K. Nagayama, "2-Dimensional Crystallization," *Nature,* vol. 361, pp. 26, Jan 1993.