Stabilizing Fiber Optic Pressure Sensor Measurements by Fabricating an Enclosed Photonic Crystal Cavity

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Abstract:

Fiber optic pressure sensors are optical microelectromechanical systems (MEMS) devices used in a variety of industrial applications. Current sensors are assembled by affixing a silicon photonic crystal (PC) chip near an optical fiber-tip with a glass ferrule, which forms a Fabry-Perot (FP) cavity. However, environmental factors beyond human control decrease the sensor's overall measurement stability by inducing fluctuations in the cavity length. A potential method to reduce this variability is to incorporate the FP cavity construction into the fabrication stage of the PC itself. To accomplish this, a silicon wafer was patterned and etched downward to form PCs, which were etched radially outward to create overlapping spherical cavities. Silicon oxide was deposited by low pressure chemical vapor deposition (LPCVD) to seal off the air cavities, after which their reflectivity was measured. Many PCs were fabricated with different diameters to determine the optimal parameters that will yield the highest PC reflectivity. Based on our measurements, PCs with higher photolithographic exposure (larger diameters) are optimal. By successfully implementing this design into the fabrication process, this compact pressure sensor's measurement reproducibility will significantly improve for its industrial applications.

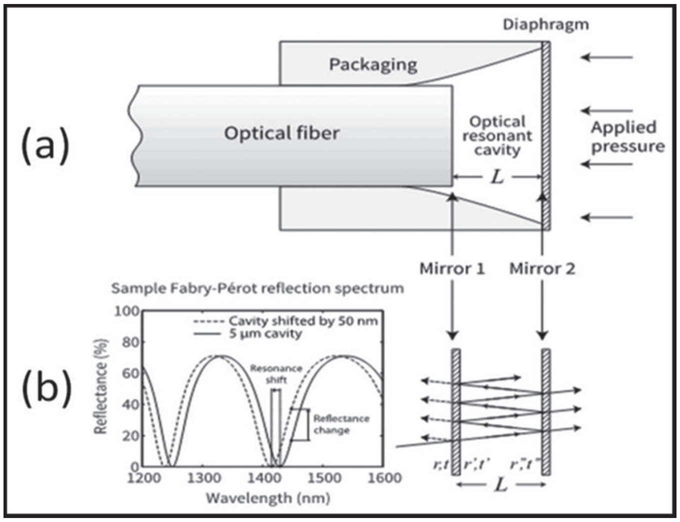

Figure 1: (a) Structure of fiber optic pressure sensor. (b) Applied pressure varies cavity length (L), and thus, shifts the reflection spectrum.

Introduction:

Fiber optic pressure sensors are used for their compactness and measurement sensitivity. Current sensors are comprised of a silicon PC chip near an optical fiber-tip, which forms the FP cavity, a cavity between two highly reflective mirrors (see Figure 1(a)). These sensors function by propagating light through the fiber, which is partially reflected from both mirrors. These reflections interfere to create the total optical reflected power as a function of wavelength (see Figure 1(b)).

However, because the FP cavity is usually assembled after fabrication, environmental factors decrease the sensor's overall measurement stability by fluctuating the cavity length during periods of constant applied pressure. To reduce measurement variability and increase measurement stability, a procedural modification was developed and implemented where an external FP cavity is constructed and sealed during the fabrication stage of the PC itself, which is confirmed by the scanning electron microscope (SEM) and PC characterization.

Photonic Crystal Fabrication Process:

To investigate the parameters that affect the reflectance performance of the FP cavity, three initial silicon wafers were prepared by undergoing oxidation. They went through photolithography, which involved patterning and developing the mask design of 2D PCs. For each PC, a square lattice of circular holes spans over 500 μm by 500 μm. The three wafers were uniformly exposed to 180 mJ/cm^2, 210 mJ/cm^2 and 240 mJ/cm^2, respectively. Once patterned and developed, they were anisotropically and isotropically etched to form overlapping spherical cavities that form the PC cavity. To seal off the finished cavity, silicon oxide is deposited via LPCVD (see Figure 2).

Results and Discussion:

In Figure 3(a), the oxide deposition mostly sealed the 240 mJ/cm^2 PC holes from the 710 nm pre-deposition diameter to the 95 nm remaining hole, but is capable of completely sealing the holes given a longer deposition. The low exposure post-

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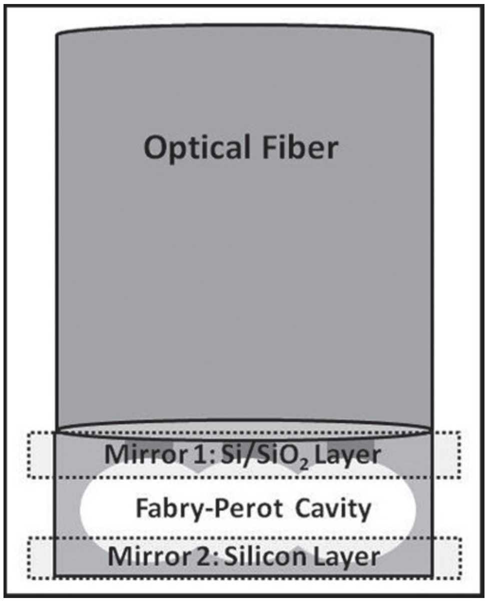

Figure 2: Cross-section of the pressure sensor. For mirror 1, grey is Si and white is SiO_2.

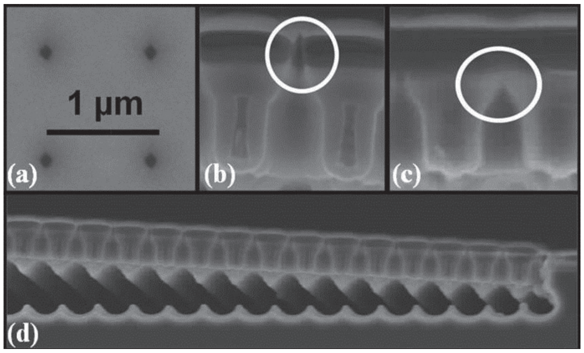

Figure 3: Post-deposition SEM images. (a) 240 mJ/cm² PC's top view. (b) 240 mJ/cm² and (c) 180 mJ/cm² cross-sectional view of PC. (d) Zoomed-out image of FP cavity from (b).

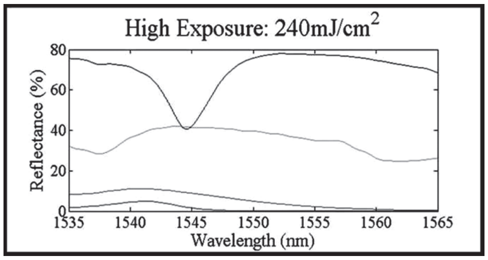

Figure 4: A single 240 mJ/cm² photonic crystal characterization, a representative reflectance spectrum for the three exposure levels of inconsistent reflectances.

deposition image (not displayed) had a remaining blur, suggesting that those holes were successfully sealed with a substantial oxide layer on top. This is confirmed in the circled portion of Figure 3(c) that indicates the 180 mJ/cm² holes closed as opposed to the 240 mJ/cm² holes. The stress that the silicon PC chip endured from oxide deposition caused the evident "buckling" (i.e. bending) effect in Figure 3(d) because of the compressive stress that the silicon oxide imparts on the silicon. The formed FP cavity has varying lengths across the entire cavity, which made the light behavior and ultimately the reflectance power spectrum inconsistent.

The freespace reflectances were measured by focusing a laser onto the PC chips and coupling the reflection into an optical spectrum analyzer. In Figure 4, each of the four curves is the reflectance recorded from four different locations on a single photonic crystal, which illustrates the inconsistent reflectance measurements observed for any PC at any of the given exposure levels by the evident dissimilar curves and reflectance values across each curve. Even though there is high measurement variability amongst the reflectances for a given photonic crystal, the higher exposure PCs have better reflectances.

Comparing the lowest and highest exposure photonic crystals (180 mJ/cm² and 240 mJ/cm²), their reflectances reached up to 21% and 80%, respectively. The higher photolithographic exposure produced a better photonic crystal reflectance most likely due to the larger holes.

Conclusions:

A fabrication method was developed that successfully seals the FP cavity, as indicated by SEM imaging. We found there is a direct relationship between the PC's reflectance and the photolithographic exposure, despite the "buckling" effect. While the low exposure PCs exhibit higher sealing capability, the high exposure PCs exhibit higher reflectance, which allows for sensors with higher sensitivity. For future work, we recommend performing pressure sensing measurements and finding methods to handle the silicon oxide "buckling."

Acknowledgments:

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