☐ **Poster Presentation** ☐ **Oral Presentation** ☐ **Student presentation**

FANO RESONANT POROUS SILICON METASURFACES OPERATING AT VISIBLE WAVELENGTHS

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SUMMARY

We present the design, fabrication, and experimental analysis of Fano resonant porous silicon metasurfaces operating on the principles of guided mode resonance. These structures are shown to exhibit attractive properties for dynamic structural coloration and sensing.

1. INTRODUCTION

Porous silicon (pSi) is a versatile platform enabling a wide variety of photonic devices which take advantage of its tunable optical properties and high surface area. Common examples of pSi optical components include thin film Fabry-Perot interferometers, multi-layer devices including Bragg mirrors, Rugate filters, and microcavities [1]. These structures utilize the capability to manipulate the refractive index n(z) in a "bottom-up" fashion through varying current density J(t). Structures which utilize additional "top-down" device patterning before or after anodization offer enhanced control over the light matter interaction and resulting optical device characteristics. Selected examples of mesoporous silicon based "hybrid" devices combing top-down and bottom-up processes include: gratings, waveguides, ring resonators, micro-lenses, patterned Bragg reflectors, and volumetric optics [2]–[6].

While pSi based optical devices are promising for several applications – optical biosensing in particular – there are numerous challenges faced by existing approaches. For example, optical microcavities require many layers and are limited to confining light deep inside the structure, which may hinder performance due to the required analyte diffusion. Another example, to name a few, conventional waveguide based devices require sophisticated and costly measurement techniques involving tunable laser sources and/or precisely aligned coupling optics.

In this work, we report Fano resonant pSi metasurfaces operating at visible wavelengths. These structures operate on principles of guided mode resonance and contain multiple degrees of freedom originating from both the device geometry/patterning in addition to the anodization parameters. This enables widely tunable resonant properties to be achieved in a thin metasurface form-factor, which can enhance light-matter interactions very close to the surface (e.g. < 250 nm). The pSi metasurfaces are readily interrogated at normal incidence via reflectance spectroscopy or by monitoring variations in structural color. This eliminates the need for complex, expensive, and/or bulky coupling optics. Here, we demonstrate, and study structures realized in both mesoporous silicon and oxidized mesoporous silica. We further investigate their potential suitability in structural colorimetric devices and sensors.

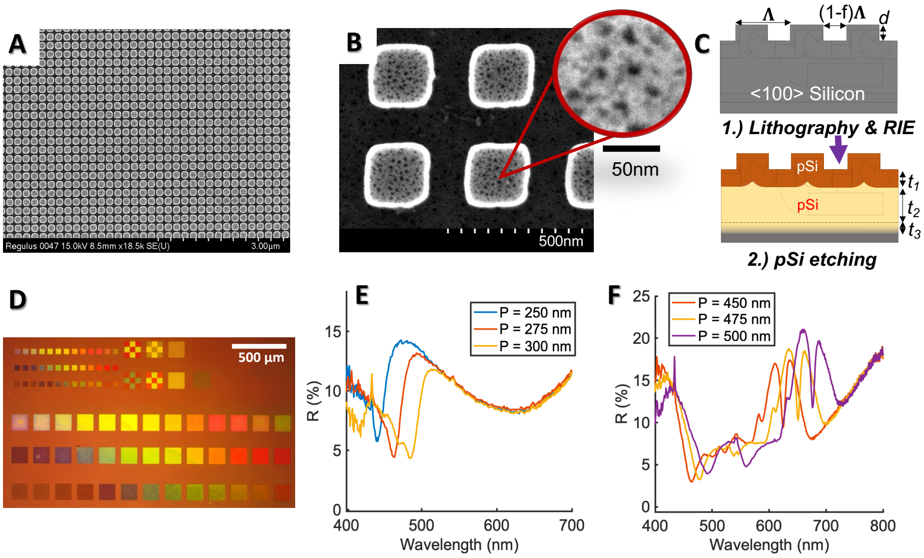
2. EXPERIMENTAL RESULTS

The mesoporous silicon metasurfaces (Fig. 1a,b) were made using <100> silicon (0.01-0.02 Ω-cm) wafers, by first performing top-down lithographic patterning and reactive ion etching (RIE) of silicon, followed by subsequent anodization as shown in Fig. 1c. The top-down processes were performed in a clean room at the Center for Nanophase Materials Science (CNMS), at Oak Ridge National Laboratory. Specifically, electron-beam lithography followed by chrome hardmask deposition, metal lift-off, and RIE of silicon to an etch depth near ~200 nm was performed. The overall device pattern (Fig. 1d) consisted of various meta-arrays and test patterns, with different periodicities and duty cycles. To engineer visible wavelength resonances, the periodicities were varied in the range Λ = 200 – 500 nm. Guided mode resonance occurs under the phase matching condition $\lambda_0 = \Lambda n_{eff}/m$, where is the effective index of the guided mode, and *m* is the diffraction order.

After pre-patterning the silicon, samples are anodized using an optimized HF-electrochemical etching recipe to create three layers each with different porosity levels and purposes (Figure 1). The first layer is a higher refractive index, lower porosity layer, prepared with an electric current density of 25mA/cm^2 applied for ~8 s to reach a depth of ~105 nm. The second layer is a lower refractive index, higher porosity layer, prepared by a current density of 47.2mA/cm^2 for ~3000 s. This thick cladding layer (~100 μm) aids in attenuating Fabry-Perot interference arising from reflection at the substrate interface. As for the third layer, we applied a varying electric current having the form of a half-cycle cosine between 47.2 mA/cm^2 and 0 mA/cm^2 arc to serve as a gradient index anti-reflection layer, further suppressing the pSi-Si substrate reflection. Selected devices were then oxidized in air ambient at 800C for 10 to 30min. The results of the fabrication process as well as the spectrum exhibited by the device are illustrated in Figure 1.

Reflectance spectra were collected in a microscope configuration at 5x magnification, with the measurement spot size reduced <0.15 mm to enable probing of individual meta-arrays. Spectra from selected meta-arrays for an oxidized sample are reported in Fig.1 e&f, which reveals both asymmetric (Fig. 1e) and symmetric (Fig. 1f) Fano resonances at wavelengths proportional to the local period Λ. In general, the exact Fano line shape is sensitive to the optical thickness of the guiding layer, grating etch depth, and resonance wavelength. In addition to studying the passive spectral properties of the Fano resonant pSi metasurfaces, we investigated their sensitive and dynamic response to refractive index stimuli. An example experiment is depicted in Fig. 2, which shows dynamic structural coloration in response to water vapor adsorption. Here the sample is illuminated with multi-chromatic RGB laser light to enhance the color change, and the observed colorimetric response of each meta-array is unique depending upon the alignment of the Fano resonance with the illumination wavelengths.

Figure 1: (A, B) SEM images of a pSi metasurface. (C) Schematic of the fabrication process. (D) Optical microscope image of the meta-arrays after anodization, showing vivid structural coloration under white light illumination. (E) Asymmetric and (F) symmetric Fano resonances observed in reflectance spectra for selected meta-arrays with varying periodicities.



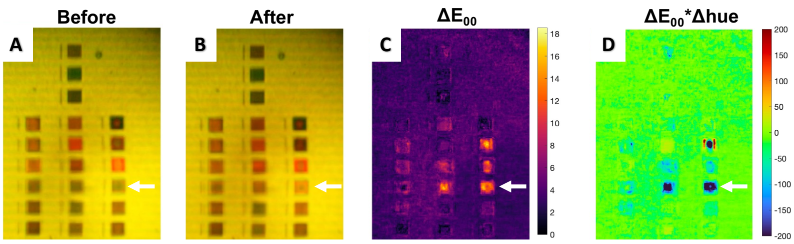


Figure 2: Dynamic structural color from a pSi metasurface exposed to water vapor. (a) Microscope image of porous silicon meta-arrays with varying periods and duty cycles under multi-chrome (RGB) laser illumination at t = 0 seconds, and (b) t = 10 seconds. (c, d) Measured color differences between images in (a) and (b).

3. CONCLUSIONS

We have demonstrated Fano resonant mesoporous silicon and silica metasurfaces operating at visible wavelengths. In addition, we have investigated their potential utility in both passive or dynamic structural color devices and sensors. These structures are straightforward to fabricate and characterize. The resonance characteristics can be tailored through many degrees of freedom originating from both the top-down patterning and bottom-up porosification. By supporting normal incidence interrogation, visible wavelength resonances (colorful response), and shallow surface confinement, these metasurfaces offer a promising and versatile platform for dynamic structural color devices and surface based biosensors.

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