Electrically tunable porous silicon active mirrors

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We demonstrate tunable mirrors that consist of a porous silicon microcavity infiltrated with liquid crystal molecules. We show theoretically that by utilizing the electro-optic properties of liquid crystals and the sensitivity of the microcavity resonance position to small changes in optical thickness, the porous silicon active mirror can be switched on (high reflectance) and off (low reflectance) by simply applying a voltage. We discuss the issues of obtaining uniform infiltration of liquid crystal molecules in the constricted geometry of the porous silicon microcavity and determining the necessary change in the liquid crystal orientation to achieve a high reflectance contrast. We also present preliminary experimental results showing a greater than 40% change in the reflectance of our active mirror with the application of voltage.

1 Introduction

Passive and active components consisting of silicon may provide the key to the next generation of optoelectronic technology. Passive components, such as waveguides, have been successfully demonstrated in silicon [1]. Active elements remain a challenge to fabricate since the optical properties of silicon are not sensitive to electric fields. The demonstration of an electrically tunable porous silicon active mirror provides a first step toward the realization of a system architecture capable of manipulating optical signals using silicon-based technology for computing and communications applications [2].

The properties of porous silicon microcavities are well known [3, 4]. The porous silicon microcavity is an efficient geometry for the active mirror for two main reasons. First, the microcavity resonance is highly sensitive to slight changes in the effective refractive indices of its constituent layers. Second, the morphology of porous silicon makes it a receptive host for substances that respond to electric fields. By incorporating liquid crystals into the porous silicon microcavity, the reflectance spectrum can be modulated on demand by applying a voltage to the device.

The ability to infiltrate a variety of materials into a porous silicon matrix, including polymers [5] and biological species [6], has already been demonstrated. Moreover, a slight modulation in the reflectance spectrum of a synthetic opal with liquid crystals infiltrated into the 300 nm void spaces was recently observed [7]. Thus, the foundation has been laid for our electrically tunable porous silicon active mirrors.

2 Experimental conditions

Detailed procedures for the fabrication of the porous silicon microcavities are published elsewhere [8]. Briefly, the porous silicon microcavity structure is formed electrochemically on p+ (~0.01 Ω cm) silicon by introducing a defect layer between two Bragg reflectors, which creates a narrow resonance in the reflectance stopband. The resonance location and stopband shape can be con-
trolled by appropriately modifying the thickness and porosity of each layer. Our structures, as shown in Fig. 1, consist of either 4 or 5 period Bragg mirrors with alternating layers of 50% porosity (165 nm) and 70% porosity (190 nm). The defect layer has a porosity of 75% and a thickness of 205 nm. After anodization, the structures are thermally oxidized in oxygen for 10 minutes at 900 °C to stabilize their properties over time.

2.1 Liquid crystal infiltration E7 nematic liquid crystals from Merck are infiltrated into the oxidized microcavities under vacuum. This particular liquid crystal mixture was chosen for its high birefringence of approximately 0.2 ($n_0 \approx 1.5, n_e \approx 1.7$). Based on the resulting reflectance spectra, we found that infiltrating the liquid crystals under vacuum resulted in the most uniform distribution of liquid crystals throughout the porous silicon matrix. Previous techniques for infiltrating liquid crystals into single layer and multilayer porous silicon structures involved simply dropping the liquid crystals onto the sample and allowing them to flow into the pores over time by means of capillary forces \[9, 10\]. After infiltrating the

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The sample is placed in a chamber with a syringe containing the liquid crystals coupled into a feed-through port in the top of the chamber. After evacuation of the chamber, the liquid crystals are dropped onto the sample. The absence of air in the pores allows the liquid crystals to be more efficiently infiltrated into the microcavity.
liquid crystals into the microcavities, we remove the excess liquid crystals from the surface by dropping a
small amount of hexane on top of our samples while spinning them at 3000–4000 rpm. In this manner, the
liquid crystals are rinsed off of the surface without being removed from the pores of the microcavities.

The uniform infiltration of a material inside the void space of the porous silicon microcavity increases
the effective refractive index of each layer and red shifts the resonance. Figure 2 shows the reflectance
spectrum red shift following the infiltration of liquid crystals into the porous silicon microcavity. We
find a high level of agreement between the experimental and simulated spectra. We therefore conclude
that we have uniformly infiltrated the liquid crystal molecules throughout the porous silicon microcavity.

3 Active mirror
3.1 Microcavity structure  The porous silicon microcavity serves as the basis for the electrically tun-
able mirrors. By careful control of the optical thickness of each microcavity layer, we have achieved very
deep and narrow resonances. As shown in Fig. 3, the peak reflectance is near 1.0 and the minimum re-
flectance of the resonance is close to 0.1. It is critical for the active mirror to have a sharp resonance to
allow a small shift in the reflectance spectrum to translate into a large reflectance contrast at a specific
wavelength.

3.2 Simulated reflectance modulation  Simulations based on interference effects were performed to
determine how the reflectance spectrum changes when the orientation of the E7 liquid crystals inside the
pores is altered. Assuming a uniform infiltration and a complete change in the orientation of the liquid
crystals from one extreme (perpendicular to the pore walls) to the other extreme (parallel to the pore
walls), a shift of nearly 100 nm is predicted as shown in Fig. 4. The refractive index of the liquid crystals
varies as the liquid crystals rotate, causing the reflectance spectrum to shift. Taking into consideration
the complex and constricted geometry of the interconnected network of pores, a complete change in
orientation of all of the liquid crystals inside the pores may not be achievable. Nevertheless, a large
change in the reflectance of the active mirror at a particular wavelength can be attained without utilizing
the full anisotropy of the liquid crystals. For example, based on the simulation in Fig. 4, a 30 dB contrast
in reflectivity can be achieved by simply applying a sufficient voltage to shift the resonance position
from 1.424 microns to 1.408 microns, a distance equal to the full width at half maximum of the reso-
nance. This shift corresponds to a change in the refractive index of the liquid crystals from 1.535 to
1.500. We can gain some insight into the angle by which the liquid crystals must rotate to accomplish

![Fig. 3](image1.png)  (Experimentally measured reflectance spectrum of porous silicon microcavity containing 5 period
Bragg mirrors. The resonance has a full width at half maximum value of 15 nm with the peak reflectance
near 1.0 and the minimum reflectance near 0.1.)

![Fig. 4](image2.png)  (Simulated reflectance spectra of porous silicon microcavity (containing 5 period Bragg mirrors) infil-
trated with E7 liquid crystals aligned perpendicular to the pore walls and parallel to the pore walls. When the
alignment of the liquid crystals is switched, the reflect-
ance at the design wavelength of 1500 nm undergoes a
large change in magnitude.)
this index change by referring to the index ellipse for uniaxial crystals:

\[ \frac{1}{n^2(\theta)} = \frac{\cos^2(\theta)}{n_o^2} + \frac{\sin^2(\theta)}{n_e^2} \]  

(1)

where \( n_o \) is the ordinary refractive index, \( n_e \) is the extraordinary refractive index, and \( \theta \) is the angular deviation from the optic axis. We can therefore estimate that, on average, the liquid crystals must rotate by 27° to achieve a 30 dB contrast in reflectivity. We should note that the liquid crystals in the center of the pores undergo a higher degree of rotation than the liquid crystals next to the pore walls due to surface anchoring effects [11].

**3.3 Device operation**  
Contact to the bottom of the microcavity is made by direct connection to the backside of the crystalline silicon wafer. ITO-coated glass is used as a top contact. In order to provide an efficient contact between the ITO and the microcavity, a small amount of polyethylene glycol (PEG 200) is dropped onto the sample before the ITO-coated glass is attached. The electrical conductivity of PEG 200 is similar to that of the porous silicon [12].

In theory, when voltage is applied, the directors, or long axes, of E7 liquid crystals align in the direction of the applied electric field. The degree of rotation of the liquid crystals is directly related to the strength of the field. Consequently, the location of the microcavity resonance can be continuously tuned by modulating the applied electric field strength.

Preliminary experiments indicate a reversible 12 nm shift of the reflectance spectrum after the application of voltage. As shown in Fig. 5, a greater than 40% change in reflectance was observed at a wavelength near the resonance minimum, where the microcavity is most sensitive to changes in the amplitude of reflectance. Independent experiments in which the device is heated with only PEG in the pores showed a comparable spectral shift. Further experiments are needed to distinguish the effect of the electric field on the liquid crystals from the heating of the PEG.

**4 Conclusions**  
The modulation of reflectance spectra of porous silicon active mirrors has been demonstrated. Porous silicon microcavities with deep and narrow resonances have been fabricated and serve as the basis for the active mirrors. E7 liquid crystal molecules were uniformly infiltrated into the porous silicon microcavities in vacuum. Simulations suggest that a large reflectivity contrast is achievable without utilizing the full rotation of the liquid crystals in the porous silicon matrix. By applying voltage to the
device, we have observed a significant change in reflectance, which may be due to the liquid crystal rotation and heating effects.

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