Detection of Specific DNA Sequences Using Porous Silicon Photonic Crystal Nanobeams

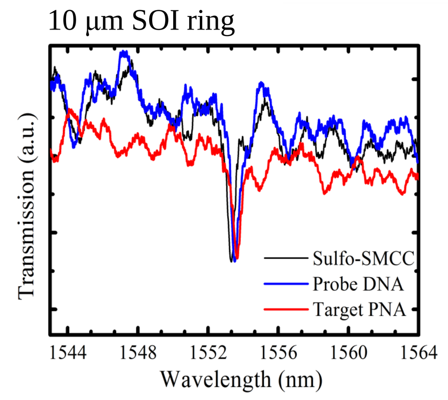
Alyssa P. Cartwright[1], Gilbert A. Rodriguez[2], Kelsey R. Beavers[3], and Sharon M. Weiss[2, 3]

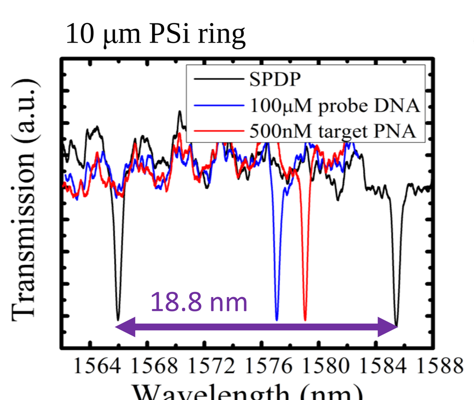
1. *Electrical Engineering and Computer Science Department, Massachusetts Institute of Technology, Cambridge, MA*
2. *Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN*
3. *Interdisciplinary Materials Science Program, Vanderbilt University, Nashville TN*

Introduction

Motivation

- Biosensors promote safety through early detection of hazardous chemical or biological agents in military, environmental, medical, and food industries.
- Photonic devices such as ring resonators and photonic crystal (PhC) nanobeams are promising biosensors due to their compact size, ability to cascade multiple biosensors in a small area, and label-free detection through simple refractometric measurements.

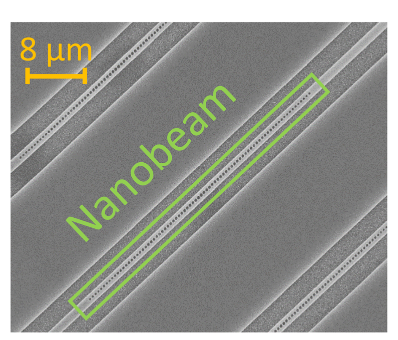


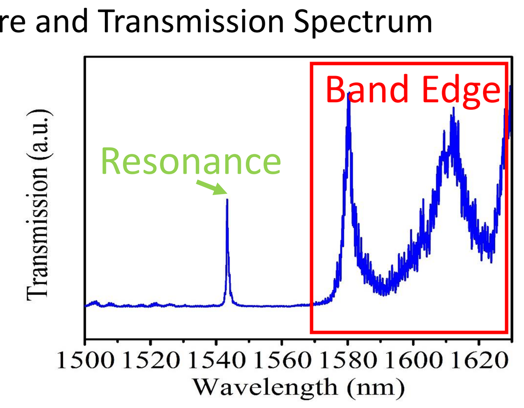


Porous Silicon (PSi) Nanobeams

- A recent PSi ring resonator* reports a 40-fold sensitivity improvement over commercial silicon-on-insulator (SOI) technology; however the device was limited to detecting small concentrations of molecules due to multiple resonances.
- The objective of this work is to capture specific DNA sequences using a high quality factor PSi PhC nanobeam with a single resonant mode to overcome the spectral overlap limitation of PSi ring resonators.

PSi Nanobeam Structure and Transmission Spectrum



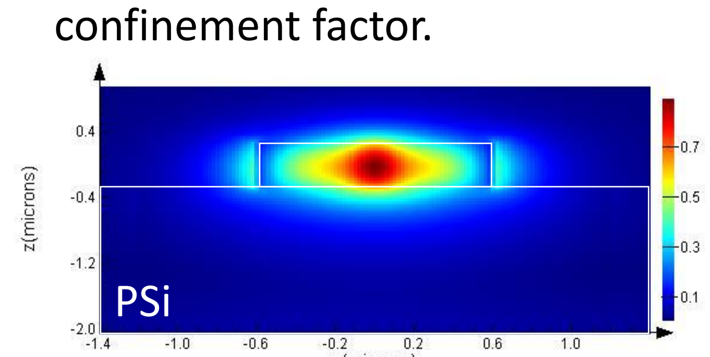


*Gilberto A. Rodriguez, Shuren Hu, and Sharon M. Weiss, "Porous silicon ring resonator for compact, high sensitivity biosensing applications," Opt. Express 23, 7111-7119 (2015)

Simulation

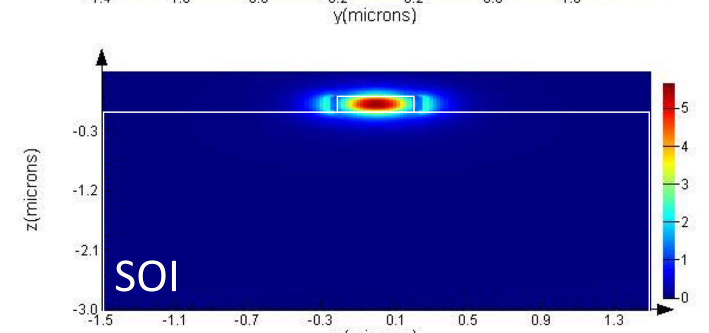
- The sensitivity of a PhC nanobeam is directly related to the light matter interaction defined by the field confinement factor.

$$\Gamma_s = \frac{\iint_s |\mathbf{E}(x,y)|^2\, dxdy}{\iint_\infty |\mathbf{E}(x,y)|^2\, dxdy}$$



PSi Nanobeam

- Γ_s = 40.54%
- Sensing area is entire cross-section plus evanescent field (considering 59% porosity).



SOI Nanobeam

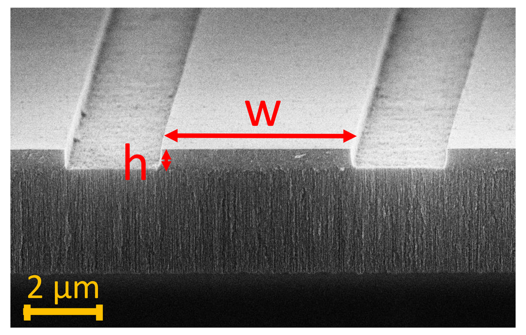
- Γ_s = 1.15%
- Sensing area is only evanescent field.

The improved Γ_s in PSi is due to its large internal surface area promoting light matter interactions within the material. PSi nanobeams demonstrate a 35 fold sensitivity improvement over SOI nanobeams.

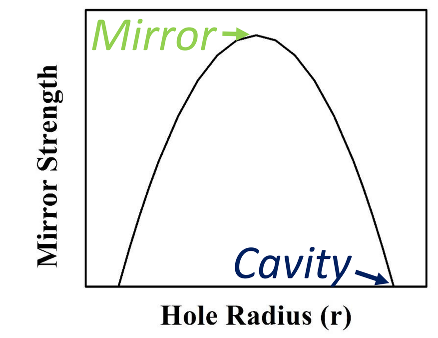
Design

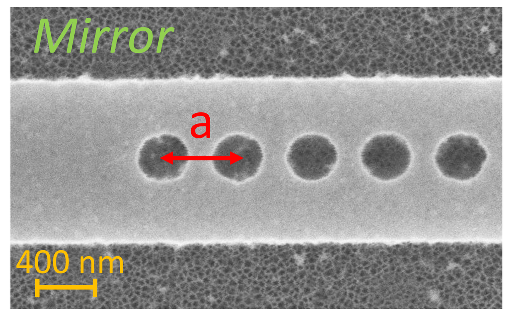
Deterministic Design*

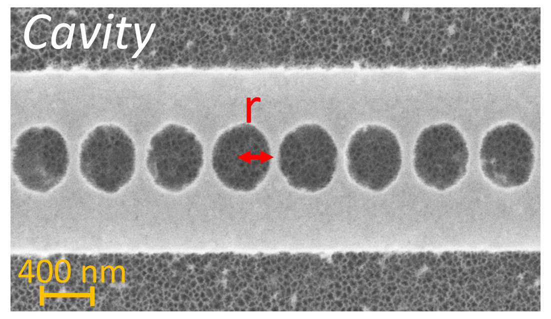
- PSi ridge waveguide parameters (n, h, w) optimized to maximize confinement and reduce scattering loss.
- Periodicity (a) determines resonant wavelength (λ_0) based on n_{eff} of waveguide.
- Hole radius (r) determines mirror strength. A quadratically tapered cavity (low mirror strength) brings rise to the resonant nanobeam mode within the photonic band gap created by the high mirror strength segments.



$$a = \frac{\lambda_0}{2n_{eff}}$$

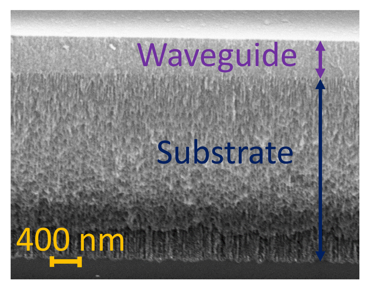






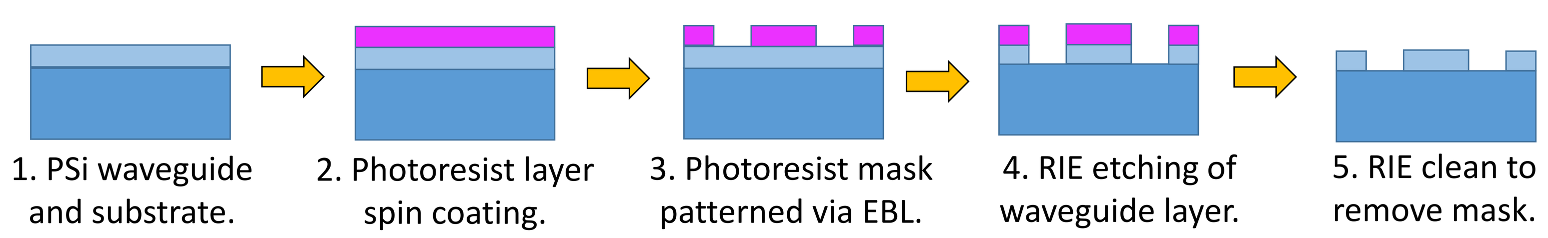
*Qimin Quan and Marko Loncar, "Deterministic design of wavelength scale, ultra-high Q photonic crystal nanobeam cavities," Opt. Express 19, 18529-18542 (2011)

Methods

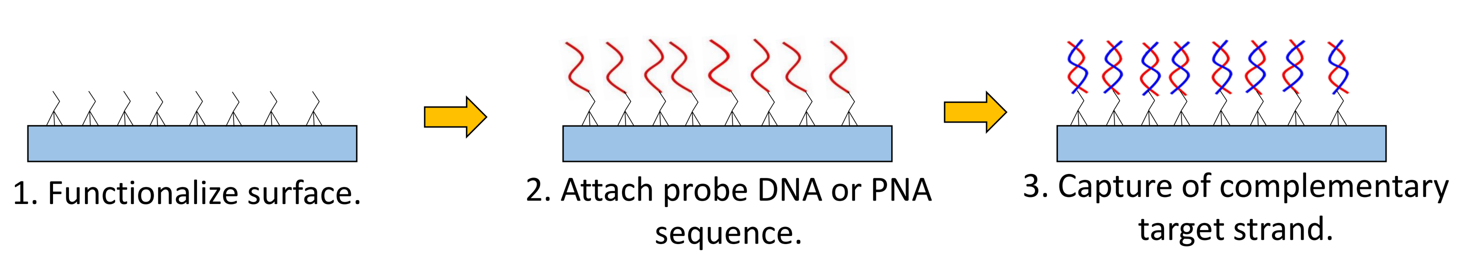


Fabrication

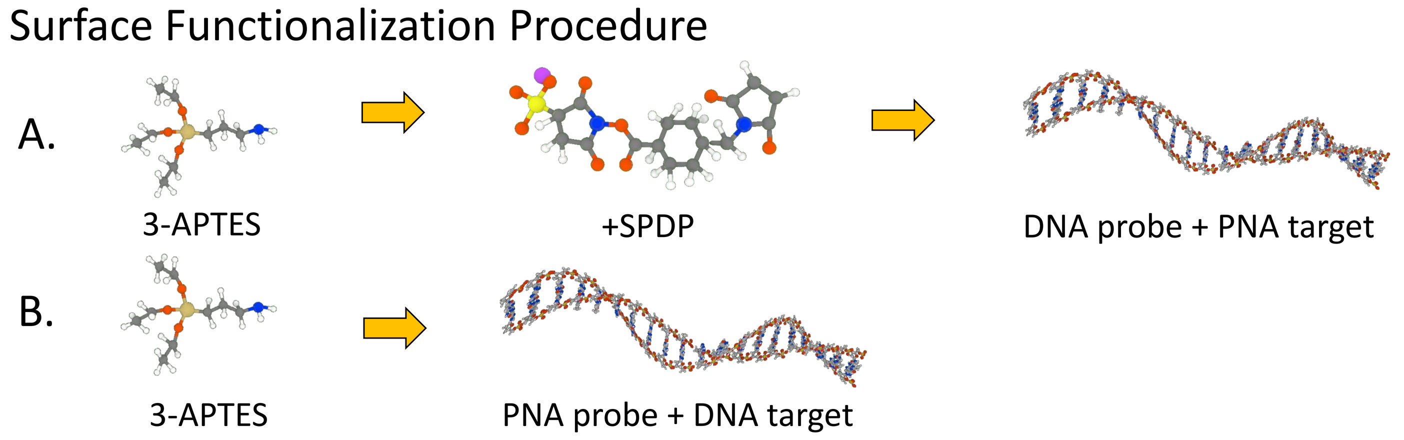
- PSi two layer waveguide fabricated by electrochemical etching of p-type silicon in HF-based electrolyte.
- Nanobeam design lithographically etched into wafer.



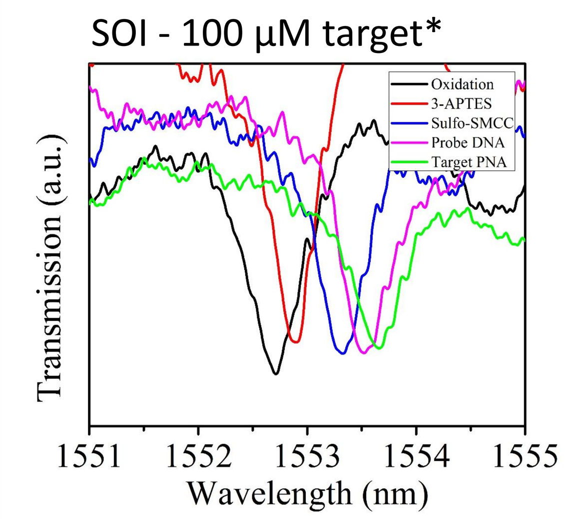
Label-free Detection of Target 16 Base PNA and DNA Sequences

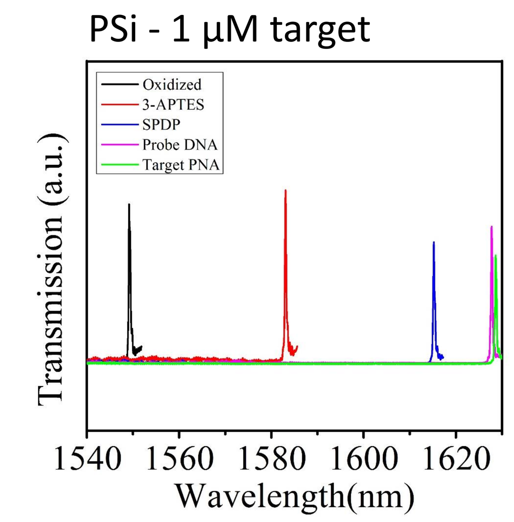


Surface Functionalization Procedure



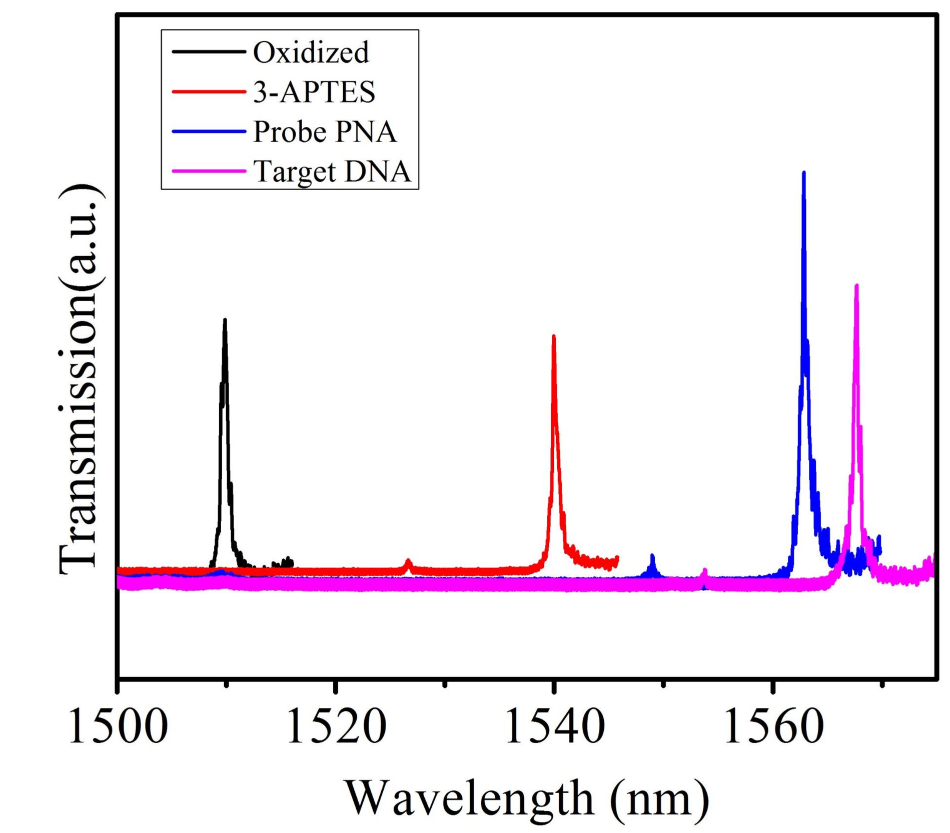
Results





- PSi nanobeams demonstrate over a 40-fold experimental sensitivity improvement over a SOI 2D PhC biosensor in the detection of small chemical molecules and a 5-fold sensitivity improvement in the detection of target PNA.

- First demonstration of an in situ synthesized probe PNA capturing a target DNA sequence in a PSi nanobeam.
- In situ synthesis of probe increases the number of available binding sites and improves target capture by 4 times over pre-synthesized probes.



*Enhancing the Sensitivity of Label-Free Silicon Photonic Biosensors through Increased Probe Molecule Density. S. Hu, Y. Zhao, K. Qin, S.T. Retterer, I.I. Kravchenko, and S.M. Weiss, *ACS Photonics* **2014** *1* (7), 590-597, DOI: 10.1021/ph500075g

Conclusions

- Porous silicon nanobeams have successfully been demonstrated for detection of a target DNA strand using an in situ synthesized PNA probe.
- PSi nanobeam biosensors promise a significant improvement in sensitivity for small molecules over their SOI counterparts, as well as lower cost of production.
- The improved stability and sensitivity of the PSi nanobeam results in nanomolar detection limit of target nucleic acid sequences.
- The specificity these nanobeams offer is promising for detection of DNA in genetic testing and DNA disease markers.

Future Work

- Demonstrate application of PSi nanobeams in sensing explosives, cancer markers, etc.
- Attachment of microfluidic cells to cascade PSi nanobeams and detect multiple analytes simultaneously.

Acknowledgements

This work was supported in part by the National Science Foundation (REU grant DMR-1263182 and grant ECCS-1407777) and the Army Research Office (grant W911NF-09-1-0101). Lithographic etching of the nanobeams was conducted at the Center for Nanophase Materials Sciences, which is a DOE Office of Science User Facility. EBL images were obtained in Vanderbilt Institute of Nanoscale Science and Engineering facilities. PNA synthesis was conducted by Kelsey Beavers in Dr. Craig Duvall's laboratory. I would like to thank the members of the Weiss group for their support and feedback throughout this project.