Optimized Porous Silicon Bloch Surface and Sub-surface Wave Structure for Simultaneous Detection of Small and Large Molecules

John D. Lonai[1], Gilberto A. Rodriguez[2], and Sharon M. Weiss[2]

[1] Department of Engineering and Physics, Northwest Nazarene University, Nampa, ID

[2] Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN

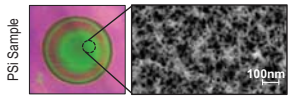
Introduction

Motivation

❖Growing medical, food, security, and environmental industries require faster, more accurate, and portable devices for the detection of small and large molecules including biotoxins, viruses, and drugs.

❖ Porous silicon (PSi) based biosensors offer several advantages:

- Label-free sensing
- Large internal surface area
- Tunable optical properties
- Inexpensive, quick fabrication



❖The Bloch surface and sub-surface wave (BSW/BSSW) biosensor design adds an additional size selective detection capability to PSi biosensors.

Objectives

❖ Fabricate and optimize BSW/BSSW PSi sensors for the simultaneous detection of large and small molecules.

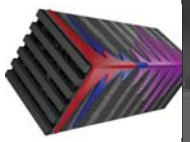
Background

❖The BSW/BSSW structure consists of a Bragg mirror (multilayer) with a reduced optical thickness surface layer.

BSW: electric field confined near the interface between the surface of the structure and the external medium.

BSSW: spatially localized electric field in designed region of the structure based on a given step/gradient refractive index profiles in the Bragg mirror

Band edge: electric field distributed deep within the multilayer.



❖The BSW/BSSW modes result in distinct resonance peaks in the angle-resolved reflectance spectrum.

❖Molecular interaction with the confined electric fields results in an angular resonance shift proportional to the number of molecules present.

❖The BSW/BSSW detect surface bound and small molecules within pores, respectively.

Fabrication

Sample Production

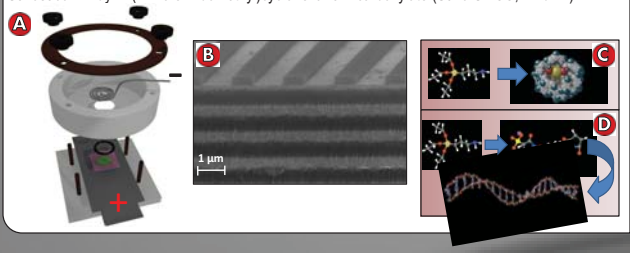
A) PSi structures are fabricated via electro-chemical etching in hydrofluoric acid

B) ZEP resist gratings are patterned using Electron Beam Lithography

Molecule attachment methods

C) Large carboxyl terminated 60 nm latex nanospheres immobilized using 3-aminopropyltriethoxysilane (3-APTES, 0.8 nm)

D) Medium-sized 40 mer DNA (13.2nm) immobilized using 3-APTES and the cross-linker Sulfosuccinimidyl-4-(N-maleimidomethyl)cyclohexane-1-carboxylate (Sulfo-SMCC, 1.26nm).

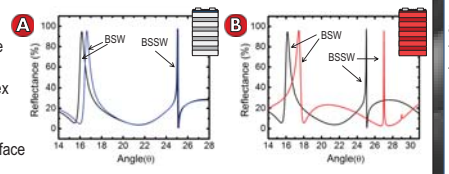


Simulation

Molecule attachment

Rigorous coupled wave analysis simulations show expected resonance angle shifts due to the specified change in refractive index during molecule attachment

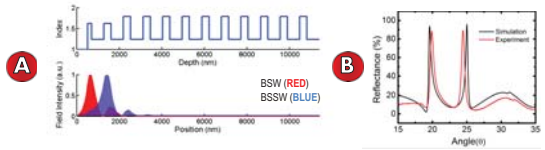
A) Δ n = 0.03 for the top-most layer. Notice only the BSW shifts for the surface attachment of large molecules.



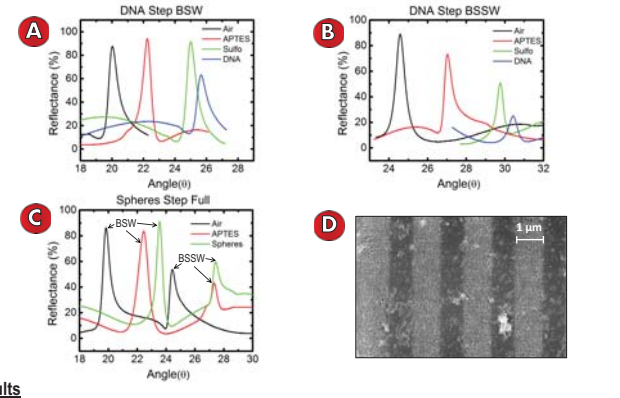
B) Δn = 0.5 for 10nm above surface and Δ n = 0.03 all layers. Both the BSW and BSSW experience resonance shifts. A theoretical BSSW sensitivity for this device is calculated as 66.0°/RIU.

Step Profile

A step increase in the high refractive index layers of the Bragg mirror results in a single well-defined BSSW peak in the reflectance spectrum. **A)** Step refractive index profile and electric field distributions. **B)** Step simulation shows good agreement to PSi experimental results.



Results



Results

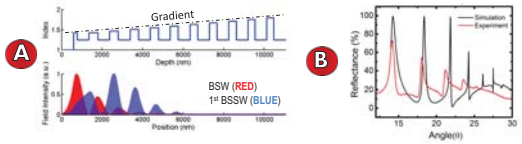
A) and B) The resonance peaks for the BSW and BSSW are shown shifting with each progressive molecule attachment. The similarity in the BSW and BSSW shifts represents the successful molecule infiltration and surface attachment of all molecules.

C) The BSW and BSSW both shift during 3-APTES application, but when the large spheres are attached only the BSW shifts. The BSSW senses no spheres infiltrating the pores and remains unchanged in position. This demonstrates the size-selectivity of the device.

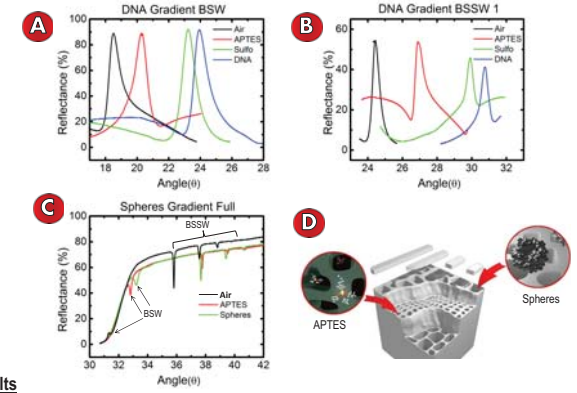
D) Top view of grating coated with nanospheres.

Gradient Profile

The gradient refractive index profile has been found to occur naturally during the PSi etching and treatment process. The gradient is further increased via varying current densities to optimize the locations and intensities of the BSSW modes. **A)** Gradient refractive index profile and electric field distributions **B)** Gradient simulation shows good agreement to PSi experimental results.



Results



Results

A) and B) The functionality of the device was demonstrated by detecting 40 mer DNA and observing successive shifts in the BSW/BSSW modes due to each molecule.

C) Prism coupling configuration was used as an additional measurement technique. The BSW/BSSW are manifested as reflectance dips. During the large molecule (spheres) attachment there is no shift in the BSSW despite the shifting BSW. This represents the size-selectivity of the device.

D) Latex nanospheres attach to the surface and 3-APTES molecules infiltrate the porous matrix.

Conclusions

❖**The shift in BSW during nanosphere attachment without a shift in BSSW position demonstrates successful size selective capabilities—only the BSW could detect the spheres which were incapable of penetrating the porous matrix.**

❖This project yielded results that show promising correlation between simulation and experiment, suggesting an efficient fabrication process.

❖The DNA sensing experiments showed that the devices could operate successfully and maintain resonance peak definition for progressive molecule attachments.

Future Work: Optimization of designs to work in fluidic solutions to allow the monitoring of molecular diffusion within the porous membrane.

Acknowledgments: I would like to thank the members of the Weiss group for their instruction and feedback. This work was supported in part by the NSF and REU Grant **DMR-1005023**