The use of Digital Microfluidics for a Silicon Photonic Sensors Platform

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Label-free biosensing with silicon nanophotonic microring resonator sensors has proven to be an excellent sensing technique for achieving high-throughput and high sensitivity. However, this platform requires a fluidic component which allows the continuous delivery of the sample to the sensor surface. The use of microdroplets in a digital microfluidic system, instead of continuous flows, is one of the recent trends in the field. This technique allows micro-sized droplets to be manipulated on reconfigurable paths without any complex microfluidic structures such as channels or valves, and has great potential for high-throughput liquid handling, while avoiding on-chip cross contamination. We present the combination of these two technologies: label-free silicon nanophotonic microring resonator sensors and digital microfluidics.

Introduction

Monitoring of molecular interactions provides critical information for medical diagnosis, drug development and environmental protection. Because of the complex nature of these biological interactions, sensor arrays capable of multiplexed measurements are often required. Miniaturization, low cost and portability are desirable attributes for such sensing systems.

Silicon-on-insulator (SOI) is a material system with many assets for these applications. First of all, it has a high refractive index contrast permitting very compact sensors of which many can be incorporated on a single chip, enabling multiplexed sensing. Secondly, silicon-on-insulator photonic chips can be made using CMOS-compatible process steps, allowing for a strong reduction of the chip cost by high volume fabrication [1].

A crucial component in most of these photonic biosensors is the transducer that can transform a refractive index change in its environment to a measurable change in its optical transmission. Microring resonator sensors stand out as prime candidates for such transducers for achieving high performance in a robust manufacturable manner.

However, not only the transducer but also the microfluidic system is an essential element for such sensing systems. The use of microfluidic channels for delivery of the sample in continuous flow to the sensor surface is one of the most critical steps in the integration of biosensors and microfluidics for point-of-care applications. This integration is not straightforward, since the interface with the outside world needs special attention, and care needs to be taken to avoid leaks and channel clogging.

Digital microfluidics is an emerging technology similar to the more established technology of microfluidic channels but unique because all elementary fluidic operations (droplet dispensing, splitting, merging, transport, and mixing) are performed

on reconfigurable paths of buried actuation electrodes with high flexibility without the need of moving parts such as pumps or valves.
Here, we demonstrate how digital microfluidics can be used for effective fluid delivery to nanophotonic microring resonator sensors fully constructed in SOI.

Digital microfluidic system

The cross-section of the EWOD lab-on-a-chip is shown in Figure 1.

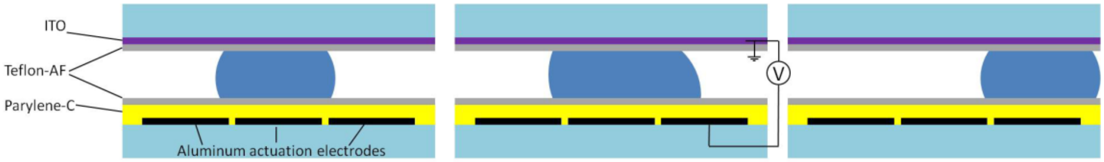

Figure 1. A diagram of the cross-section of an EWOD lab-on-a-chip and the electrowetting principle. When a voltage is applied to an actuation electrode, the droplet is attracted toward this activated region due to the generated imbalance in interfacial tension near the surface above the actuated electrode [2].

The digital microfluidic platform was produced by means of standard photolithographic techniques. For the bottom part of the chip, a 100-nm thick aluminum layer was sputtered on a glass wafer and subsequently patterned using standard photolithographic techniques. All electrodes were 1.4 x 1.4 mm². The aluminum layer was covered by a 2.8 µm dielectric Parylene-C layer deposited using chemical vapor deposition. This insulating layer was rendered hydrophobic by spin-coating a layer of Teflon-AF (300 nm thickness) on top. The top part of the digital lab-on-a-chip consisted of a glass plate coated with a 120 nm layer of transparent indium tin oxide (ITO) which was made hydrophobic with a Teflon-AF layer of approximately 300 nm. Standard tape with a thickness of 80 µm was used as spacer between top and bottom plates.
Droplets were sandwiched between the two plates. To activate the electrowetting-on-dielectric mechanism, a 130V DC actuation voltage was used, while the electrode actuation sequence, activation time and relaxation time were controlled by means of homemade programs in MATLAB and LabView. When a voltage is applied to the system, a surface tension gradient at the droplet surface is evoked which attracts the droplet towards the activated region.

Nanophotonic ring resonator sensors, chip layout and setup.

The photonic chip was fabricated in silicon-on-insulator with 2 µm buried oxide and a 220-nm silicon top layer with CMOS-compatible 193-nm optical lithography and dry etching [1]. The resonators consist of 450-nm-wide single-mode waveguides, with 5 µm bend radius, 2 µm long directional couplers and a gap of 180 nm between the waveguides. The layout of the chip is illustrated in Figure 2 [3].

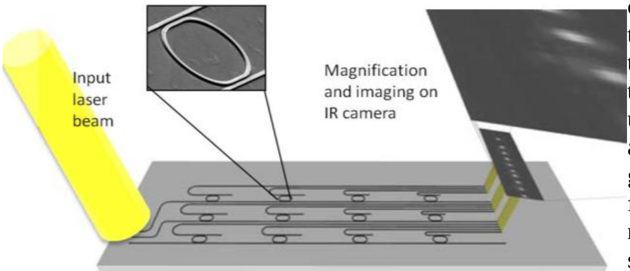

Figure 2 Chip layout top view. Four rings are connected to one common input waveguide, each of them having a dedicated drop signal port. Three of these four ring series are placed independently next to the other. A SANTEC TSL-510 tunable laser was used as a light source. The three input waveguides are simultaneously addressed through vertical grating couplers with a 2 mm-wide collimated beam from a tunable laser source. The output signals of the ring resonators are near-vertically coupled to free space by means of integrated grating couplers and are imaged with an infrared camera. [3]

Integrating both technologies

The SOI chip containing the array of ring resonator sensors described above was incorporated into the digital microfluidic system by replacing the top glass plate of the platform. Figure 3 illustrates how the chip was placed up-side down, squeezing the liquid droplets against the bottom plate containing the buried electrodes.

In order to guarantee the hydrophobicity of the SOI chip surface, which is crucial for performing droplet manipulations efficiently, and at the same time ensure the contact of the sensors with the droplets, a layer of Teflon-AF (300 nm thickness) was coated on the SOI chip and subsequently patterned. Hereto, the Teflon-AF surface was activated with O_2-plasma to allow photoresist to be spincoated on top. This thin layer of photoresist

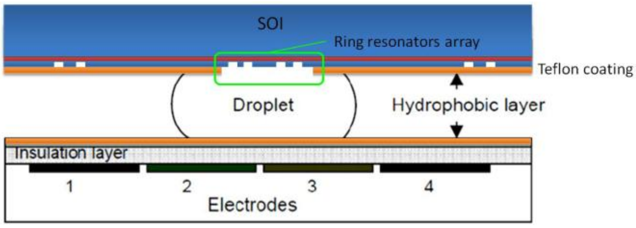

Figure 3: Incorporation of the SOI chip containing an array of microring resonator sensors into the digital microfluidic system by replacing the top glass plate of the platform.

was then patterned by using standard photolithography to expose the regions covering the ring resonators. Next, the Teflon-AF covering the ring resonators was locally removed with reactive ion etching using O_2-plasma. Some ring resonators were left covered with Teflon-AF in order to provide a reference to compensate for environmental drift.

Grating couplers were used to couple the light from a tunable laser into the chip and couple it out to be detected by an infrared camera. A new aspect with respect to our previous work [3] is that now, since the chip is placed up-side down, light needs to be coupled in and out through the 750-µm thick silicon substrate. Silicon is considered practically transparent for the wavelength used (1.55 µm).

However, to reduce the scattering of the rough substrate surface and to facilitate the alignment of the laser beam and the detection of the light coupled out from the chip, a few simple processing steps were done in advance: the silicon substrate was thinned down to 300 µm by chemical mechanical grinding and afterwards a chemical mechanical polishing step was performed in order to attain a smooth surface.

Bulk sensing experiments

As a proof-of-principle to show the capabilities of the combined system, we measured the sensitivity for refractive index changes of aqueous solutions and compared it with previous measurements for the same array of sensors using typical microfluidics based on microchannels [4] and the simulations for bulk refractive index changes done in Fimmwave. Three sets of experiments were performed with sodium chloride, glucose and ethanol. For each of these compounds, 3 different droplets with different concentrations were prepared.

The measurements were performed as follows, e.g. for the sodium chloride solutions: a droplet of DI-water was transported on the digital microfluidic platform to the sensors area. Our system started measuring. Subsequently, the droplet of water was moved, leaving a free route for the second droplet with a first sodium chloride concentration. Since the read-out system performs continuous measurements in time, we measured in

air during the switching of droplets, causing a big shift in the resonance wavelength, which was discarded. When the second droplet reached the sensing area, the measured signal will shift again to a similar wavelength as measured during the previous droplet, since the refractive index of different watery solutions does not differ to a large extent.
This same process was repeated for measuring glucose and ethanol concentrations in DI-water in order to confirm the behavior of the system for different refractive index materials and samples, while guaranteeing reproducibility.
Analyzing these shifts as a function of the refractive index unit (RIU) of the droplets, we observed a very close correspondence between the simulations and the measurement results (Figure 4). 78 nm/RIU is the sensitivity that these ring resonators show for refractive index change simulations, which was also measured and proved in [4] using the typical microfluidcs system based on microchannels. The measurements performed in this digital microfluidic system show a sensitivity of 77±0.6 nm/RIU, which shows that the performance of the transducer does not suffer from being integrated in a digital microfluidics system.

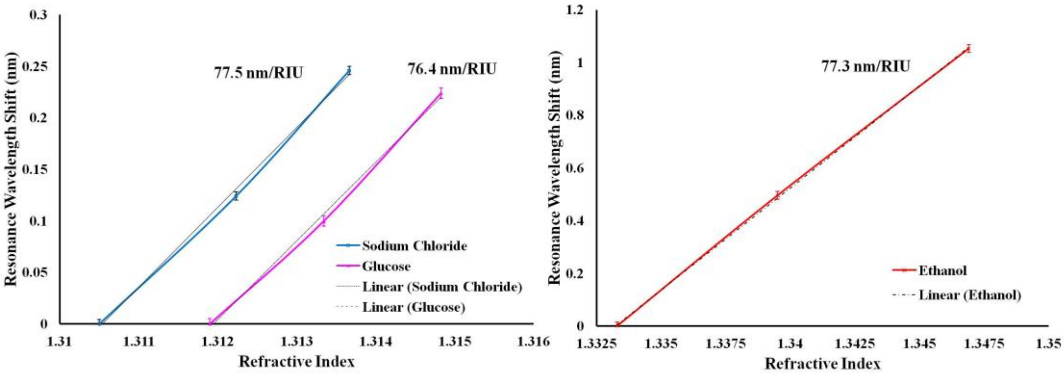

Figure 4. Three experiments with different sodium chloride, glucose and ethanol concentrations were performed. Each line corresponds to one of these experiments. Error bars indicate the standard deviations based on 3 repetitions. The sensitivity is determined to be 77±0.6 nm/RIU [4].

Conclusions

We have presented the combination of label free-silicon nanophotonic microring resonator sensors in SOI with digital microfluidics, providing an alternative to the typically costly and complex microfluidic system based on microchannels.
The presented integration of SOI microring resonators enables plug-and-play ease of use, as no physical connection is needed between the optical chips and the light source and detection unit, while SOI chips can be fabricated in mass production volumes. This combination allows for multiplexed real-time detection and analysis. Its great flexibility, portability and disposability make it ideal for easy and fast use in any laboratory.

References

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