INTEGRATION OF POLYMER MICROFLUIDIC CHANNELS, VIAS, AND CONNECTORS WITH SILICON PHOTONIC SENSORS BY ONE-STEP COMBINED PHOTOPATTERNING AND MOLDING OF OSTE

Carlos Errando-Herranz^{1,2}, Farizah Saharil¹, Albert Mola Romero^{1,3}, Niklas Sandström¹, Reza Zandi Shafagh¹, Wouter van der Wijngaart¹, Tommy Haraldsson¹, and Kristinn B. Gylfason¹

¹ KTH Royal Institute of Technology, Micro and Nanosystems, Stockholm, SWEDEN

² UPV Polytechnic University of Valencia, Valencia, SPAIN

³ University of Barcelona, Barcelona, SPAIN

ABSTRACT

We demonstrate a method for the fast and simple packaging of silicon sensors into a microfluidic package consisting of the recently introduced OSTE polymer. The microfluidic layer is first microstructured and thereafter dry-bonded to a silicon photonic sensor, in a process compatible with wafer-level production, and with the entire packaging process lasting only 10 minutes. The fluidic layer combines molded microchannels and fluidic (Luer) connectors with photopatterned through-holes (vias) for optical fiber probing and fluid connections. All the features are fabricated in a single photocuring step. We report measurements with an integrated silicon photonic Mach-Zehnder interferometer refractive index sensor packaged by these means.

KEYWORDS

Silicon photonics, microfluidics, wafer-level packaging, photopatterning, molding, Off-Stoichiometry Thiol-Ene, OSTE

INTRODUCTION

Silicon-based sensors have recently demonstrated good performance in terms of biological and chemical analyte detection. Silicon-based photonic ring resonators [1], DNA sequencing devices [2], and nanowire sensors [3] are examples of high performance silicon sensors, featuring low detection limits, high scalability, and mass production capability in dense arrays at low cost. However, for chemical and biological applications, silicon sensor fabrication faces a bottleneck: the integration of liquid sample handling.

Casting of microchannels (soft lithography) in *Polydimethylsiloxane* (PDMS) is the prevalent polymeric solution for microfluidics in academia [4]. However, long curing times, adsorption of small molecules into the PDMS [5], and lack of robust bonding techniques compatible with surface biofunctionalization [6] make industrial application of PDMS questionable (Figure 1).

Moreover, because of the difficulty of producing vertical vias by soft lithography, external connections are normally created in a final step by punching [1]. Since the minimum footprint required for ensuring leak-tight fluidic connections is large, space consumption of PDMS based microfluidics is critical, to the extent that one-to-one wafer scale fabrication is not economical.

Figure 1: For commercial uptake of Si based biosensors, economical integration of microfluidics is needed. We present a simple method, compatible with wafer level integration of complete fluidic circuits.

To address PDMS' limitations, the *Off-Stoichiometry Thiol-Ene* (OSTE) polymer was introduced [7] and microfluidic integration on silicon demonstrated [8]. By a UV-initiated thiol-ene reaction, vias can be photopatterned within a few seconds [9]. The OSTE surface properties allow low-temperature dry bonding of the polymer, without adhesives or surface activation using plasma or reactive chemicals, thus enabling bonding to biofunctionalized silicon [10]. Table 1 summarizes the main benefits of OSTE compared to PDMS.

Table 1: A comparison of the polymer characteristics of the prevalent microfluidic material, PDMS, and OSTE. The OSTE characteristics allow fabrication, at wafer scale, of dense microfluidics in the same size scale as silicon devices.

	PDMS	OSTE
Curing process	Thermal	UV
Curing time	1 h	15 s
Photolithographically defined vias	No	Yes
Bonding to biofunctionalized silicon	No	Yes

Here, we present the fast and simple integration of microfluidics onto silicon photonic sensors, with the key features:

- The definition, in a single step, of horizontal channels by molding, and vertical vias by photomasking, during the UV curing of the OSTE.
- The fabrication of fluidics in the same small scale as the silicon sensor arrays, by photolithography of vias both for fluid connections and optical fiber probing. Thus the necessary wafer area is reduced.

We demonstrate measurements using a silicon photonic refractive index sensor fabricated by this process.

FABRICATION

Figure 2: The OSTE based integration scheme: A glass mask with chromium patterns for via formation and SU8 reliefs for channel molding, and a PDMS mold defining the chip outline and fluid connectors, enable OSTE microfluidic layer fabrication. After dry-bonding of the microfluidic layer to the photonic Mach-Zehnder interferometer sensor chip, the integrated chip is ready for measurements.

OSTE with 70% thiol excess [7] is poured onto a PDMS mold, defining Luer connectors, and then sandwiched with a glass mask. The glass mask has chromium patterns defining vias, and SU8 reliefs defining microchannels, thus simultaneously acting as a mold and as a photolithography mask (Figure 2). After UV-exposure (15 s at 13 mW/cm^2), the polymer layer is released and developed in butyl acetate for 30 s. During development, the unexposed regions dissolve, and the vias for optical and fluidic connections are opened. The thiol functional groups on the OSTE allow covalent bonding of the fluidic layer to an isocyanate functionalized silicon optical chip, in a reaction that takes 10 min (Figure 3). Bonding in 5 min at 37°C was shown in [4].

Figure 3: A schematic cross-section of the fabrication process: (a) OSTE with a 70% thiol excess is poured onto a PDMS mold. (b) A 15 s UV exposure through a glass mask polymerizes exposed parts via a thiol-ene reaction. (c) The fluidic and optical vias are developed in butyl acetate. (d) An isocyanate coated photonic silicon chip is then aligned and bonded to the fluidic layer and cured for 10 min at 70°C . Bonding in 5 min at 37°C was shown in [4].

EVALUATION AND DISCUSSION

The devices were first evaluated for leaking, and thereafter the photonic response was characterized.

We obtain leakage free dry-bonding of the OSTE-70 microfluidic layer both to flat silicon and glass.

Furthermore, we dry-bonded OSTE-70 microfluidics onto a silicon photonic sensor chip with 220 nm thick protruding waveguides. Our fluidic design includes critical structures, such as microchannels defined by thin and long bond surfaces ($0.12 \times 10 \text{ mm}^2$, Figure 4). The dry-bonding is enabled by a click reaction between the thiol excess of the OSTE-70 and the isocyanate on the surface of the silicon chip.

Figure 4: (a) A top view photograph of the Mach-Zehnder interferometer chip. In the magnified inset, the surface grating couplers of two of the 12 interferometer photonic devices are visible. (b) The design of one of the photonic interferometers fabricated in the silicon chip, showing the critical alignment between the interferometer and the microchannel.

To demonstrate the usefulness of the integrated chips for refractive index based sensing, we measured the interference wavelength shift of a silicon waveguide based Mach-Zehnder interferometer sensor, upon the injection of air, isopropanol, and ethanol.

The measurement setup is shown in Figure 5. One fluidic port (molded Luer connector) is connected by rubber tubing to a syringe pump in suction mode. Sample is introduced by pipetting into the second upstream Luer connector. Optical fibers were aligned and inserted in the optical vias, positioned above the on-chip grating couplers. Light from a tunable laser source was coupled in and out of the chip via these fibres. The interference pattern is observed on a wavelength domain component analyzer (Agilent Technologies 86082A).

Figure 5: (a) Setup for the optical measurements. The photograph shows the optical fibers aligned with the grating couplers of the interferometer sensor through the optical vias, and the input and output fluidic tubes in the Luer connectors. (b) Enlarged schematic of the design of the Mach-Zehnder interferometer array showing 3 of the 12 devices present on the chip.

Figure 6 shows the measured shift in the interference wavelength with the introduction into the microfluidic channel of air, ethanol, and isopropanol, with refractive indexes ranging from 1 to 1.38. Since the interference pattern shifts multiple interference orders upon such a large change in refractive index, the absolute refractive index sensitivity of the sensor cannot be determined from this simple experiment.

Figure 6: Transmitted optical power through the Mach-Zehnder interferometer sensor. By changing the fluid in the microchannel, a shift in the interference wavelength is observed. The large change in index shifts the spectrum several interference orders.

CONCLUSION

We demonstrated a one-step microfluidic integration technique for silicon photonic waveguide based sensors with surface grating couplers.

We replace the prevalent microfluidic integration solution (PDMS) with one based on the OSTE polymer, and thus, by combined lithography and molding, we enable the integration of photolithographed vias for

optical probing with grating couplers (Figure 5). Moreover, dry bonding of OSTE to silanized silicon photonic chips overcomes the limitations of PDMS in bonding to biofunctionalized surfaces.

We show leakage free bonding of microfluidic layers to patterned silicon (Figure 4), together with refractive index measurements using a grating coupled Mach-Zehnder interferometer sensor chip, fabricated by these means (Figure 6).

Our demonstration of a functional photonic sensor, packaged by a fast single-step microfluidic layer integration extendable to wafer-level fabrication, illustrates that our novel approach has the potential to accelerate the commercial uptake of silicon based biosensors.

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CONTACT

*K.B. Gylfason, tel: +46-8-790 9231;
kristinn.gylfason@ee.kth.se