LOW GAS PERMEABLE AND NON-ABSORBENT RUBBERY OSTE+ FOR PNEUMATIC MICROVALVES

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ABSTRACT

In this paper we introduce a new polymer for use in microfluidic applications, based on the off-stoichiometric thiol–ene-epoxy (OSTE+) polymer system, but with rubbery properties. We characterize and benchmark the new polymer against PDMS. We demonstrate that Rubbery OSTE+: has more than 90% lower permeability to gases compared to PDMS, has little to no absorption of dissolved molecules, can be layer bonded in room temperature without the need for adhesives or plasma treatment, can be structured by standard micro-molding manufacturing, and shows similar performance as PDMS for pneumatic microvalves, albeit allowing handling of larger pressure.

BACKGROUND

OSTE+ is a polymer system developed specifically for lab-on-a-chip applications. It has the potential to bridge the gap between research prototyping and commercial manufacturing [1-3] due to a number of attractive characteristics, including a fast turn around fabrication process, Young's modulus similar to common thermoplastics, tunable surface properties, and adhesive-free low temperature bonding to a large range of substrates [4-5]. Moreover, OSTE+ has demonstrated preferable material properties for nucleic acid amplification detection compared to PDMS and PMMA [6]. However, large-scale integration of microfluidic devices often uses on-chip integration of actuators such as valves and pumps, most often accomplished by integrating a rubbery membrane material as actuator; and macro to micro fluid connectors, often sealed by a rubbery material. In academia, PDMS is commonly used as the device material [7] because of its rubbery properties and ease of fabrication. However, PDMS is severely limiting in many applications, due to its high gas permeability, sample absorption and the need for plasma treatment prior to bonding to glass or itself. Similar limitations were seen in the PDMS-based off-stoichiometry thiol-ene (OSTE) rubbery material previously integrated in OSTE devices [1].

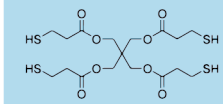
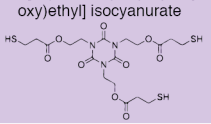
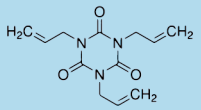
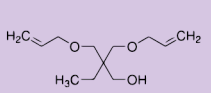
In this paper we introduce a new polymer, based on the OSTE+ polymer system, with a modified monomer composition that allows for obtaining rubbery properties while avoiding some of the limitations of PDMS. We will refer to previously demonstrated OSTE+ polymers with high Young's modulus as "stiff OSTE+" and to the new polymer as "rubbery OSTE+".

DESIGN

Rubbery OSTE+ formulation

To create the rubbery properties, compared to previous OSTE+ mixtures [2, 3], we lowered the crosslink density of the new polymer by reducing the amount of functional groups per monomer and by substituting the epoxy monomer with a rubbery copolymer variant, as shown in table 1: comparing the monomers between rubbery and stiff OSTE+, the thiol monomers are tetra- instead of tri-functional; the allyl monomers are tri- instead of di-functional; and the epoxy monomer is Albipox® 1000, which is a copolymer consisting of long rubbery segments and short epoxy functional group segments that bind into the polymer matrix upon cure. The mechanical properties were further tuned by modifying the stoichiometric ratio and with the use of a stabilizing tri-azine ring on the thiol instead of on the allyl as used in the stiff OSTE+.

Table 1: Monomer composition of stiff OSTE+ and rubbery OSTE+

	Stiff OSTE+	Rubbery OSTE+
Thiol	Tetrakis(3-mercapto-propionate) 	Tris[2-(3-mercapto-propionyl oxy)ethyl] isocyanurate 
Allyl	Triallyl-1,3,5-triazine-2,4,6-trione 	Trimethylolpropane diallyl ether 
Epoxy Epoxy eq. weight Viscosity	D.E.N. 431 172-179 g/eq 1100-1700 mPa•s	Albipox 1000 330 g/eq 200 000 mPa•s
Initiators	TPO-L & photolatent DBN	TPO-L & photolatent DBN
Stoichiometric ratio	1,5:1:0,5 (allyl:thiol:epoxy)	1,2:1:0,2 (allyl:thiol:epoxy)

Valve design

Pinch valves [7] were designed as a pneumatic control channel and a liquid flow channel, each in a different microfluidic layer, separated by an elastic membrane at the position where they cross each other. The pressure in the pneumatic channel controls the valve state: a pressurized control channel deflects the membrane and closes the flow channel; a non-pressurized control channel results in an open valve. As a test device, (see figure 2a) a device with several flow channels closed by the same control channel was designed.

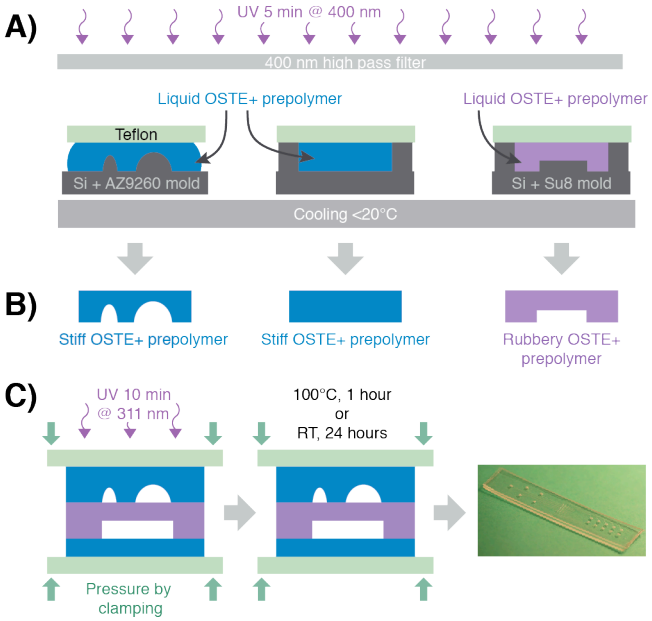


Figure 1: Fabrication process and final device. A) The 1st cure, which mold the prepolymers. B) Layers demolded after 1st cure. C) The 2nd cure for bonding of assembled layers (left and middle) and photography of final device (right).

FABRICATION

Molds were fabricated using photoresist on silicon. Square pneumatic control channels were defined in 50 µm thick SU-8 and the 60 µm membrane thickness was obtained using spacer structures. The liquid flow channels were defined in AZ-9260 photoresist that was reflowed at 125°C for 2 min to define channel molds with circular cross-section [8]. The height of the flow channels was measured to be between 20 and 30 µm, depending on the channel width. The molds were coated with a thin (<100 nm) layer of Teflon AF 1600 (DuPont™, USA) to facilitate demolding.

The stiff OSTE+ prepolymer was prepared using Triallyl-1,3,5-triazine-2,4,6-trione (Mercene Labs, Sweden), Tetrakis(3-mercapto-propionate) (Sigma-Aldrich), and D.E.N. 431 (Dow, Germany) at a stoichiometric ratio of 1,5:1:0,5. The rubbery OSTE+ was prepared using Trimethylolpropane diallyl ether (Sigma-Aldrich), Tris[2-(3-mercapto-propionyloxy)ethyl] isocyanurate (Sigma-Aldrich), and Albipox 1000 (Evonik) at a stoichiometric ratio of 1,2:1:0,2 (table 1). Both stiff and rubbery OSTE+ polymers used TPO-L (BASF) and photolatent DBN as photoinitiators, both at 1% (w/w).

OSTE+ chips containing an array of pneumatic test valves with different footprint size were fabricated by sandwiching a rubbery OSTE+ layer between two stiff OSTE+ layers (figure 1) using the OSTE+-typical dual cure mechanism [4]: 1) molding of the liquid prepolymer and first curing by UV illumination (collimated 12 mW cm-2 @ 365 nm near-UV short arc mercury lamp from OAI, Milpitas, USA) for 5 min above 400 nm wavelength (glass filter: GG400 Longpass, Schott), and cooled to below 20°C; 2) manually aligning and contacting of the three layers; 3) bonding during second cure by 10 min UV illumination (without filter) under clamping followed by 1 h at 100°C (temperature accelerated bonding). An additional valve was manufactured using the same method as above, but substituting the 1h 100° to 24h in room temperature (room temperature bonding). For comparison, microvalves in two PDMS layers on top of a glass microscopy slide were fabricated with standard PDMS casting, curing and plasma bonding, using the same molds.

1 mm and 0.5 mm thick unstructured rubbery OSTE+ membranes were fabricated for mechanical and gas permeability characterization, respectively, using the same dual cure mechanism as described above.

PDMS membranes for characterization (1 and 0.5 mm) and devices were all fabricated using a ratio 1:10 of curing agent:base (Sylgard 184, Dow Corning, USA), degassing, and curing at 70°C for 3 h. For PDMS valve structure manufacturing, the PDMS layers were bonded using a treatment with oxygen plasma (Femto, Diener, Germany) prior to layer contacting, and 10 min on a 70° C hotplate after contacting.

EXPERIMENTS

Material characterization

Storage moduli and loss factors in PDMS and Rubbery OSTE+ were measured at room temperature using a Dynamic Mechanical Analysis Q800 instrument from TA instruments on fully cured samples measuring 15 mm x 5 mm x 1 mm using the vertical tension film mode DMA instrument configuration, 15 µm oscillation amplitude, and 1 Hz frequency.

Water vapor permeation was measured by weight loss of water enclosed in a container, created by clamping membranes (500 µm thick PDMS and Rubbery OSTE+, and 1 mm thick glass for reference) with O-rings of area 1100 mm^2 area, for 72 hours at 40°C (figure 2).

Permeability to small molecules was tested by fluorescence microscopy of PDMS and OSTE+ channels, bonded to glass and stiff OSTE+ respectively, and filled with Rhodamine B (dissolved in ethanol) for 30 min.

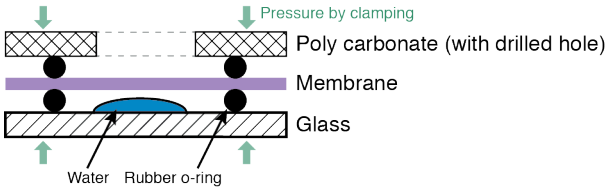


Figure 2: Gas permeability measurement setup. Membranes tested were rubbery OSTE+, PDMS, and glass for reference, all at 40°C for 72 hours.

Valve testing

The PDMS and OSTE+ valve devices were tested using relative air actuation pressures between 0 and 300 kPa (limited by failure of the pneumatic port connectors at

higher pressures) and monitored using optical microscopy. The flow channels were filled with red dye for improved visibility of the threshold actuation pressure, and were left at atmospheric pressure. The valves were characterized as closed when a discontinuation of red fluid in the flow channel direction could be observed.

RESULTS AND DISCUSSION

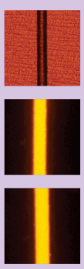
Material characteristics

Dynamic mechanical analysis (table 2) revealed similar storage modulus and loss factor for rubbery OSTE+ and PDMS: 2.8 MPa vs 2.0 MPa, and 0.35 vs 0.18, respectively. I.e., the materials are very similar, with rubbery OSTE+ being slightly less elastic and with slightly more viscous losses.

Water vapor permeation (table 2) was measured to be 5.2 mg/h for PDMS but only 0.4 mg/h for rubbery OSTE, i.e. a reduction in excess of 90%. The reduced permeability to gases allows better control in devices with long incubation times and need for a controlled environment.

In the images of Rhodamine B incubated channels (table 2) an increased fluorescence outside the channel can be observed for PDMS while no increase in fluorescence can be observed for rubbery OSTE+. This confirms that PDMS is very permeable to small molecules while the rubbery OSTE+ has a significantly lower permeability to small molecules, possibly none. This property can avoid detrimental events such as analyte depletion, increased sample dispersion and contaminations between sequential liquid samples.

Table 2: Material characterization results, showing an order of magnitude reduction of gas permeability for rubbery OSTE+ compared to PDMS and no absorption of small molecules for OSTE+.

	PDMS	Rubbery OSTE+
Mechanical properties Storage modulus Loss factor	2.0 MPa 0.18	2.8 MPa 0.35
Gas permeability H_20 diffusion rate	5.2 mg/h	0.4 mg/h
Absorption Empty channel 1 min incubation of Rhodamine B 30 min incubation of Rhodamine B		

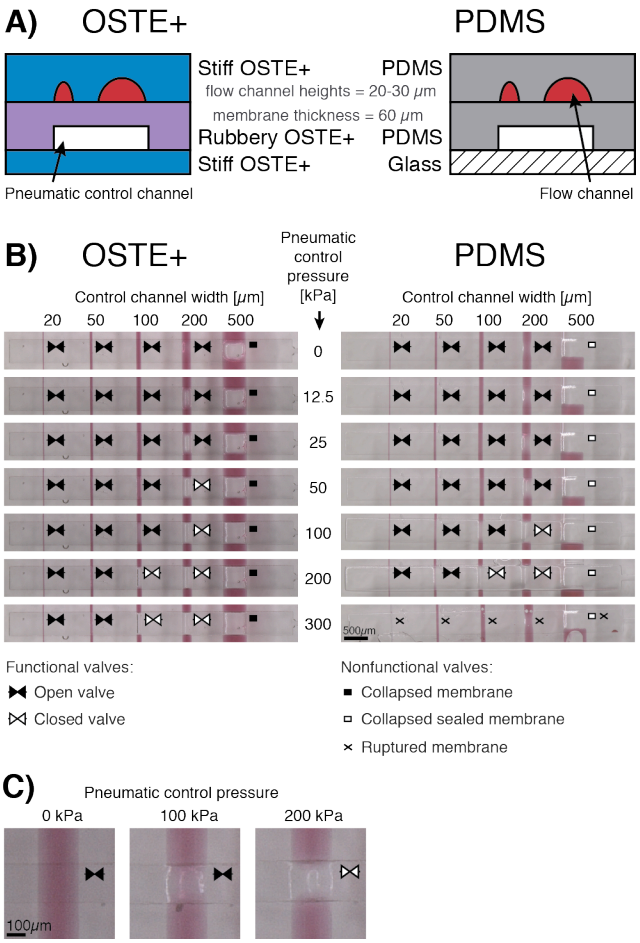


Figure 3: Pinch valve testing of OSTE+ (left) and PDMS (right) microvalves, flow channels filled with red dye. A) Cross-sectional schematic of valve devices. B) Photographs of valves under different control pressures. Valve footprint areas are 500 x 500, 200 x 500, 100 x 500, 50 x 500, and 20x500 μm^2. The OSTE+ device was fabricated with temperature accelerated bonding and the PDMS device was fabricated using standard micromolding and plasma bonding. C) Photographs of a 200 x 200 μm^2 pinch valve manufactured using room temperature bonding, actuated at different control pressures.

Valve performance

Valve structures were intact after manufacturing, except for rubbery OSTE+ and PDMS valves with 500 x 500 μm^2 membranes, which spontaneously collapsed. For PDMS, the membrane collapse occurred already during plasma bonding, hence no fluid could pass the valve in the 500 μm PDMS channel. The valve pressure test (see figure 2b) shows that valves made of PDMS and OSTE+ close at very similar control pressures. Several PDMS membranes ruptured at 300 kPa, whereas all OSTE+ membranes remained intact, indicating higher durability for high-pressure applications. After use, all valves returned to the normally open state when removing the pneumatic pressure.

The 200 x 200 μm^2 room temperature bonded OSTE+ valve in figure 2c closes with an actuation pressure between

100 and 200 kPa and withstands at least 300 kPa pressure (300 kPa not shown).

Discussion

While long term use and response time remains to be tested, the performed characterization indicates that rubbery OSTE+ has the potential of being used for valving and pumping in similar applications as PDMS components, but with the benefit of withstanding higher pressures. The lower gas permeability of Rubbery OSTE+ would prevent air bubble injection during operation of thinner membranes as described in [9], i.e. allowing pressurized gas as control medium in pneumatic membrane valves for thinner membranes and at higher pressures. The possibility to combine stiff and rubbery materials makes it easier to design valves that are completely leak tight and ensures that a complete microfluidic device withstands handling without deformation. The ability to bond layers of OSTE+ using room temperature bonding is especially useful in bio applications with sensitive functionalization inside of micro channels.

CONCLUSIONS

We have presented a rubbery, low gas permeability off-stoichiometric thiol–ene-epoxy (OSTE+) polymer fully compatible with standard micro-molding manufacturing. We demonstrated its use in pneumatic pinch microvalves for microfluidic applications. This is the first OSTE+ material with rubbery properties (similar to PDMS). The material shows low permeability to gases (magnitude orders less than PDMS) and low or no absorption of small molecules from the sample gases (magnitude orders less than PDMS). It can be bonded in room temperature without the need for adhesives or plasma treatment (unlike PDMS).

Thus, rubbery OSTE+ forms a viable alternative to PDMS, especially in applications where low temperature bonding or low permeability to gas and small molecules in solution are desired.

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REFERENCES

[1] C. F. Carlborg, T. Haraldsson, K. Öberg, M. Malkoch, and W. van der Wijngaart, “Beyond PDMS: off-stoichiometry thiol–ene (OSTE) based soft lithography for rapid prototyping of microfluidic devices,” *Lab Chip*, vol. 11, p. 3136, 2011.

[2] X. Zhou, C. F. Calborg, N. Sandstrom, A. Haleem, A. Vastesson, F. Saharil, W. van der Wijngaart, and T. Haraldsson, “Rapid Fabrication of Of Oste+ Microfluidic Devices with Lithographically Defined Hydrophobic/Hydrophilic Patterns and Biocompatible Chip Sealing,” in *MicroTAS'13*, Freiburg, October 27-31, 2013, pp. 134–136.

[3] A. Vastesson, X. Zhou, N. Sandstrom, F. Saharil, O. Supekar, G. Stemme, W. van der Wijngaart, and T. Haraldsson, “Robust microdevice manufacturing by direct lithography and adhesive-free bonding of off-stoichiometry thiol-ene-epoxy (OSTE+) polymer,” in *Transducers'13*, Barcelona, June 16-20, 2013, pp. 408–411.

[4] F. Saharil, L. El Fissi, Y. Liu, F. Calborg, D. Vandormael, L. A. Francis, W. van der Wijngaart, and T. Haraldsson, “Superior Dry Bonding of Off-Stoichiometry Thiol-Ene Epoxy (OSTE (+)) Polymers for Heterogeneous Material Labs-on-Chip,” in *MicroTAS'12*, Okinawa, October 28 - November 1, 2012, pp. 1831–1833, 2012.

[5] F. Saharil, F. Forsberg, Y. Liu, P. Bettotti, N. Kumar, F. Niklaus, T. Haraldsson, W. van der Wijngaart, and K. B. Gylfason, “Dry adhesive bonding of nanoporous inorganic membranes to microfluidic devices using the OSTE(+) dual-cure polymer,” *J. Micromech. Microeng.*, vol. 23, p. 025021, 2013.

[6] F. Saharil, A. Ahlford, M. Kuhnemund, M. Skolimowski, A. Conde, M. Dufva, M. Nilsson, M. Brivio, W. van der Wijngaart, and T. Haraldsson, “Ligation-based mutation detection and RCA in surface un-modified OSTE+ polymer microfluidic chambers,” in *Transducers'13*, Barcelona, June 16-20, 2013, pp. 357–360.

[7] M. A. Unger, “Monolithic Microfabricated Valves and Pumps by Multilayer Soft Lithography,” *Science*, vol. 288, pp. 113–116, 2000.

[8] “Product Data Sheet: AZ 9200 Photoresist,”, AZ Electronic Materials, 2001.

[9] M. Johnson, G. Liddiard, M. Eddings, and B. Gale, “Bubble inclusion and removal using PDMS membrane-based gas permeation for applications in pumping, valving and mixing in microfluidic devices,” *J. Micromech. Microeng.*, vol. 19, p. 095011, 2009.

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