



Plasma-assisted building and coating of multi-layered microfluidic devices

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^aFraunhofer USA's Center for Manufacturing Innovation has collaborated with ^bPlasmaTreat USA to develop protocols for the plasma-based activation of polymer and glass surfaces, allowing the assembly and functionalization of multi-layered microfluidic devices.

INTRODUCTION

Portable and low cost devices that allow for the use of small sample volumes have become a focus for the development of novel point-of-care technologies. Due to its biocompatibility, chemical inertness, low cost, and optical clarity, PDMS is the polymer material of choice for a significant portion of microfluidic devices [1]. Pre-polymer material exists in a stable liquid form and upon mixing with a cross-linker takes the shape of the underlying rigid mold surface. Imprinting leaves the bottom of the device with features fully open, therefore the PDMS layer needs to be bound to another layer for sealing. Due to the chemical inertness of PDMS, bonding to another layer requires an activation step conventionally performed with gas plasma [2].

Exposing surfaces to gas plasma leads to the formation of highly reactive species, activating inert surfaces for periods of time. Specifically in the case of PDMS, highly reactive hydroxyl groups are formed on the polymer surface. This surface activation can facilitate both bonding and long-term changes of the material surface properties.

In this white paper, we discuss two protocols developed for building multi-layer microfluidic devices from and changing the long-term wettability of polydimethylsiloxane (PDMS) using Plasma Technology Systems' low-pressure plasma apparatus.

BUILDING MULTI-LAYER PDMS-BASED DEVICES

Developing the method

The presented device consists of three layers: 1) a chemically modified glass slide with active chemical groups (epoxides) on the surface, 2) a fluidics-defining PDMS layer, and 3) PDMS-based fluidic adaptors for tubing attachment (Figure 1). This device is used to localize bacteria on the floor of the microfluidic channel via covalent attachment to the epoxide-functionalized surface. Once immobilized, bacterial survival is monitored in the presence of antibiotic and fluid stress to rapidly assess their antibiotic susceptibility [3]. Due to the high rates of fluid flow and the small dimensions of the device, significant forces are applied at the interfaces between layers; therefore, strong bonding is required.





Figure 1. Microfluidic device components.1. Coated glass slide. 2. Channel-defining PDMS layer 3. Fluidic adaptors

To bond PDMS to glass, both materials are typically activated with oxygen plasma before bringing the surfaces together to form a bond. However, in this case, the epoxide coating is required to immobilize the bacteria to the glass slide, and must not be destroyed by plasma treatment. Because of this, only the PDMS layer can be plasma treated. Following activation, the PDMS is then immediately placed on the coated glass slide and baked at 100 °C (Figure 2, Steps 1–3). The plasma induces oxidation of the upper molecular layer of the PDMS, and the baking step helps to remove H_2O to bond the layers covalently. The second PDMS layer acts as a tubing-to-channel adaptor on top of the already bonded PDMS-layer, and is attached with an additional plasma treatment step (Figure 2, Steps 4–5). Note, that the epoxide layer is largely protected from plasma, which does not penetrate into the microfluidic channels.



Figure 2. Microfluidic device assembly. Step 1: Plasma-activate channel-defining surfaces. Step 2: Place activated PDMS layer on the epoxy coated glass slide. Step 3: Bake at 100 °C to remove H_2O and bond the surfaces covalently. Step 4: Plasma-activate PDMS fluidic adaptors and topside of channel-defining PDMS. Step 5: Push two PDMS layers together.

Thus, three-layer microfluidic devices can be built. In principle, additional layers could be added to the device in the same manner, enhancing both the complexity and functionality of the device.

Optimizing the bonding protocol

Successful implementation of the bonding protocol required careful preparation of the device components and optimization of the experimental parameters.

Plasma is a surface-based activation technique and the bonding outcome depends on the number of active sites available on the surface at the time of bonding. Because of this, any surface contaminants present before or after activation may prevent the formation of a strong bond. All surfaces must be



clean prior to and following the surface activation. The PDMS and glass slide should be touched only on the edges with a gloved hand. Low pressures in the Plasma Technology apparatus minimize contamination during the activation step.

In low-pressure plasma systems, surface reactivity is affected by the concentration of ionizing gas, and the power level and duration of the plasma treatment [4]. For example, PDMS-to-PDMS bonding cannot occur if power levels greater than 300 W or durations over 2 min are used. Literature-derived values can serve as guidelines for adjusting protocols for a specific plasma system.

Implementing the bonding protocol

The PDMS layer is placed on a piece of clean aluminum foil with the open channels facing up. The optimized process settings are 40 W, 125 sccm (standard cubic centimeters per minute) of oxygen and 50 mTorr base pressure for 30 s of plasma treatment (Figure 3). Immediately after the treatment, the PDMS layer is placed on the epoxide-coated glass slide and pressed firmly from left to right to avoid creating air bubbles. Once the PDMS has touched the glass, its position should not be adjusted. Another piece of clean aluminum foil should be used to press the PDMS onto the glass. This two layer chip is then baked for 30 min at 100 °C. Once at room temperature, the bonding can be confirmed by trying to gently pry the corner of the PDMS from the glass.



Figure 3. Microfluidic device assembly. 1. PDMS layer is activated in the plasma chamber on a piece of aluminum foil with channel cavities facing up. 2. PDMS layer is placed on an epoxide-coated glass slide inside a fixture to facilitate alignment. 3. Covalently bonded glass slide and PDMS layer.

To bind the adaptors on the existing two-layer device, both pieces are plasma activated. The plasma will not destroy the epoxide substrate inside the channels. Two adaptor pieces and the PDMS-glass slide are placed in the plasma chamber with the clean surfaces up and the same plasma process is run. Following the plasma treatment, the tunnels in the adaptor pieces are aligned exactly with the holes of the device (Figure 4.2). The adaptors should be pushed firmly on the slide for some seconds (Figure 4.3).



Figure 4. PDMS adaptor bonding. Step 1: Cutting the adaptors out of the dish. Step 2: Aligning one adaptor piece to the channel holes following activation. Step 3: Pushing the adaptor on the PDMS layer. Step 4: Flow cell; multilayer device ready to use.

The resultant microfluidic device is able to sustain flow rates up to 70 mL/min for the channel crosssections of 0.2 by 0.4 mm, which corresponds to interface pressures of 250 Pa. Its performance is an order of magnitude better than previously used mechanical sealing, in which the PDMS and glass slide were brought together via externally applied mechanical force.



PLASMA-ASSISTED, LONG-TERM PDMS WETTABILITY

Building the assembly

In the following application, PDMS with two through holes needs to be bonded over a microchannel etched on a silicon chip (Figure 5.1–3). A liquid-tight seal between the PDMS and the silicon chip then forms two reservoirs. Electro-osmotic flow then moves the liquid through the microchannel (Figure 5.4).



Figure 5. 1. Silicon chip measuring 13.5 x 13.5 mm 2. PDMS with two through holes 3. PDMS bound to silicon chip forms reservoirs 4. Schematic of the electro-osmotic fluid flow.

The silicon chip surface is covered with a deposited oxide at high temperatures, forming a silicon oxide layer on the surface. The simultaneous treatment of the oxidized silicon chip surface and the PDMS leads to the formation of silanol groups on both surfaces, which react upon bringing the two in contact, as shown in Figure 6 [5].



Figure 6. Reaction of PDMS with silicon oxide layer following plasma treatment [6].

Coating PDMS

PDMS is a hydrophobic polymer, which has inherently poor wetting properties. This makes sample buffer introduction into the device difficult. Plasma-treated PDMS becomes hydrophilic only temporarily [7]. To increase its long-term wettability, the PDMS piece was treated (coated) with polyethylene glycol (PEG) [7]. PDMS treatment with PEG takes place before bonding it to the silicon chip via the protocol described above.

First, the polymer piece is activated in oxygen plasma for 15 s (chamber pressure 30 mTorr, oxygen flow rate 30 sccm, plasma power 30 W). Following activation, the piece is incubated in a 10 mg/mL

PEG solution for 10 h on a shaker. The piece is rinsed with DI water and dried with filtered compressed air. The PDMS piece is exposed to oxygen plasma a second time for 90 s to facilitate PEG polymerization (chamber pressure 30 mTorr, oxygen flow rate 30 sccm, plasma power 30 W). The silicon chip is activated together with the PDMS during the polymerization step. The two are then



pressed together to form a bond. As illustrated in Figure 8, plasma-assisted PEGylation enhances the long-term wettability of PDMS, and the sample buffer fills the reservoir entirely.



Figure 6. Changing the wettability of PDMS. 1. PDMS before polyethylene glycol (PEG) treatment 2. PDMS after PEG treatment

Therefore, PDMS treatment with low-pressure plasma in Plasma Technology Systems' apparatus allows one to build multi-layered and multi-material devices and alter their surface properties.

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