MULTIFUNCTIONAL PAPER MICROFLUIDIC DEVICES FOR ENVIRONMENTAL ANALYSIS

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ABSTRACT

Individuals are exposed to many different pollutants in the air, water, and even solid surfaces on a daily basis, with the exposures linked to many diseases, including cancer and cardiovascular disease. As a result, there is interest in monitoring exposure but reliance on traditional analytic methods is cost prohibitive. We propose microfluidic paper-based analytical devices (mPADs) as an alternative to traditional analysis methods because of their low cost and simplicity of operation. Here, new fabrication methods are reported along with application to monitoring persistent environmental pollutants.

KEYWORDS: microfluidic paper-based analytical devices, environmental analysis, device fabrication

INTRODUCTION

Common cellulose (paper) has been used for analytical measurements for over a hundred years with applications as simple as pH monitoring and as important as home pregnancy testing. In 2007, Martinez et al reinvigorated this field by patterning paper devices using simple concepts normally associated with semi-conductor manufacturing to create multifunctional microfluidic devices [1]. mPADs have several advantages for chemical analysis including power-free flow generation via capillary action, low substrate material costs, the ability to store reagents for long periods of time, and better than expected detection limits for colorimetric detection as a result of the high contrast provided by the background paper.

While initial fabrication methods used photolithography, its cost and the contamination of paper led to the development of alternative fabrication methods using wax printing or screen-printing and/or physical paper cutting to define channels and devices [2]. While these methods are simple and effective, there are limitations. Wax has low stability in the presence of both organic solvents and surfactants while very small structures generated by cutting methods lack physical stability. We report an alternative fabrication method that relies on bonding of filter paper to Parafilm M to create modified mPADs. Structures are readily defined either prior to or after bonding using a 30W CO_2 laser cutter [3]. The approach is advantageous relative to other fabrication methods because it has higher solvent compatibility and allows for definition of smaller features in mPAD. We have used these hybrid devices for measurement of a variety of environmental pollutants, including perfluorinated surfactants as well as transition metals.

EXPERIMENTAL

Whatman #1 chromatography and Whatman #4 filter papers were used as the base porous substrate material and bonded to Parafilm M under a combination of heat and pressure using a laboratory press. Depending on the overall temperature and pressure, two different materials were generated (Figure 1). Typically, an infused material was generated at 75°C and 8.6 kgf/cm^2 where the entire pore space of the cellulose was filled with wax. At 45°C and 2.2 kgf/cm^2, only a portion of the cellulose is permeated with wax, generating a laminated structure. In laminated devices, the exposed cellulose remains hydrophilic and supports flow while the remaining Parafilm layer resists solvents.

After modification, paper was patterned using a 30W CO_2 laser. Device structures were created in CorelDraw software and uploaded to the laser cutter. Vector cutting programs were used because they gave the best image resolution and smoothest wall structures. Two different structure types were generated based on laser power. At lower laser power with laminated parafilm-paper devices, only the paper was removed (ablation). At higher laser power with infused parafilm-paper, the devices were cut through leaving gaps that could be subsequently modified with additional cellulose or other materials.

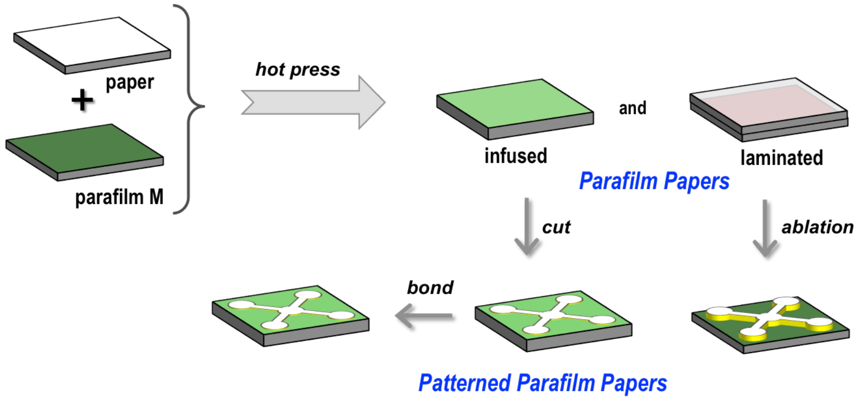

Figure 1: Schematic showing fabrication process for generating infused and laminated parafilm paper.

RESULTS AND DISCUSSION

Alternative fabrication methods are needed with mPADs to allow for enhanced functionality while still maintaining low device cost. Our approach addresses these concerns by combining two common and inexpensive laboratory materials (cellulose and Parafilm M) with a simple, commercial CO_2 laser for fabrication. In total, our equipment cost less than $10,000 to purchase new and can be used to produced thousands of devices per week if needed. Furthermore, a wide range of device structures can be made using our approach. Figure 2 shows a range of structures created using the laminated Parafilm-paper modified using the ablation method. Using these devices, we established minimal feature resolution. The smallest size structure we could fabricate with our system was 180 ∝m with this size largely determined by the spot size of our laser system. We next determined the smallest printed structure that could constrain liquids. Figure 2B shows a series of concentric circles where the inner circle was set to print at the size value listed on the left column. Structures printed as 125 ∝m or greater were all 100% successful at constraining the liquid to the inner circle. Finally, we demonstrated the ability to create flow conduits of different sizes by creating elongated flow channels in two formats (Figure 2C).

Enzymatic assays are useful for detecting environmental toxins because many toxic compounds inhibit enzymatic activity. Once demonstrating successful fabrication of Parafilm-paper devices, we set about demonstrating their analytical utility by carrying out a series of enzymatic assays for glucose, lactate, uric acid, and ethanol using glucose oxidase, lactate oxidase, uric acid oxidase, and alcohol oxidase. While these enzymes are not used for screening environmental toxins, they serve to demonstrate the potential of the fabrication method for creating multifunctional devices. To demonstrate proof-of-principle, we fabricated a series of well-based devices of varying size (3-5mm). Our new method lends itself to rapid fabrication of these types of devices, and the variation in well size allows for different linear ranges to be achieved. Figure 3 shows photographs of devices used for glucose assays (3A) and the resulting calibration curve (3B). These results clearly show that devices containing multiple well sizes can be easily fabricated and can provide multiple working ranges for enzymatic assays.

CONCLUSION

Here, a new fabrication method for creating mPADs was presented. The devices are made using a combination of ordinary filter paper with Parafilm M fused together in a laboratory press. Using a simple CO_2 laser cutter, a variety of structures can be created with size resolutions down to 200 ∝m. Finally, it is possible to carry out enzymatic reactions using these devices with the added advantage that a single device can contain multiple size structures leading to enhanced coverage of testable concentrations.

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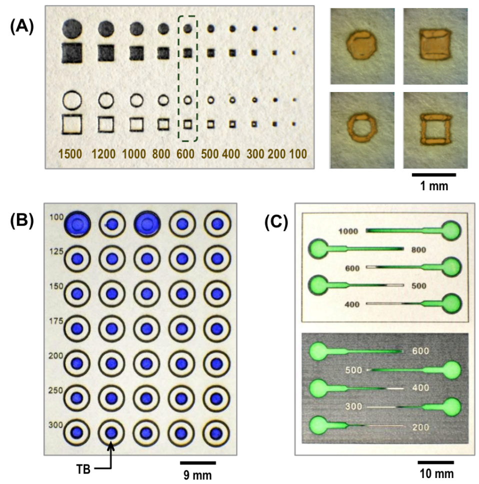

Figure 2. Photographs of devices made from Parafilm-paper patterned using the ablation process. A) Structures showing feature resolution (left) as well as photographs of individual structures (right). B) Effective size resolution needed to constrain liquids. C) Flow channels created by either patterning lines (top) or etching all removable material except the flow channel (bottom).

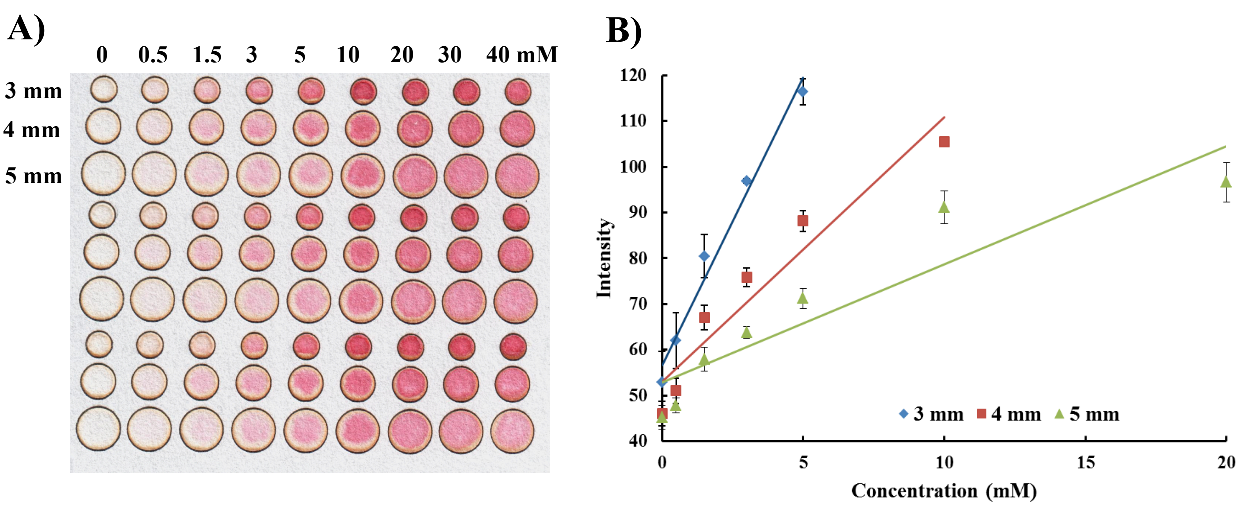

Figure 3. Results for enzymatic assays done using Parafilm-paper devices. A) Results for three different size structures as a function of glucose concentration. B) Resulting calibration curves obtained from A as a function of spot size showing linear range variability achievable with this method.

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