Embossed Foil Microfluidics for the Classroom

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Abstract – Microfluidic (MF) devices are gaining popularity for numerous applications due to their minimal reagent/sample use and the ability of researchers to tightly control the microenvironment, among other important reasons. Fabrication of devices has historically involved expensive laboratory equipment and methods that are not easily extensible to the classroom – thus presenting an obstacle to undergraduates learning the technology. We present methods for designing and fabricating bona fide (linear dimensions less than 1mm) MF devices using inexpensive materials and methods that are adaptable to a classroom environment. We have found that the method strongly engages students by featuring their own designs from the beginning and can be accomplished by most students in 2-3 class periods with minimal setup and cleanup time. The method enables demonstrations of laminar (low Reynolds number) flow, chemical diffusion, microorganism growth and other microscale fluidic phenomena at little expense. Advanced students may benefit from learning fabrication methods that are applicable in research projects outside of the classroom.

Keywords: Microfluidics, Lab on a chip, Engineering Education, Bioengineering, Engineering Innovation

INTRODUCTION

Microfluidic (MF) devices can be roughly defined as channel networks with cross-sectional dimensions beneath 1 millimeter that allow fluid flow along pressure gradients. Their complexity may range from very simple single channel devices to elaborate multi-layer, interconnected networks with active switching components and pumps that resemble the layout of an electronic circuit. MF devices are being developed for many applications and promise to reduce reagent costs and reaction times and increase measurement complexity and repeatability[1]; for example, in more sophisticated and sensitive lateral flow assays for diagnostics and "organ-on-chip" efforts to recapitulate human organ function for *in vitro* drug and toxin testing. Applications involving study of bioremediation have been examined by civil engineers[2, 3], and there are many mechanical engineering applications including actuators such as valves[4] and pumps[5] and we have found that electrical engineering students are strongly attracted to microcontroller based microfluidic control systems and related applications. Manufacture of the devices is accordingly complex and often requires extended protocols carried out in specialized facilities with expensive and temperamental equipment. This presents a barrier to entry into the field of research for many faculty whose primary focus is undergraduate education, but also an opportunity for a creative process involving undergraduate students to remove, surmount or circumvent elements of the barrier. In the context of a microfluidics workshop conducted by members of our research group over the past five years at conferences and neighboring schools, and always with a complement of undergraduate students, we have systematically explored alternatives to expensive, time-consuming or otherwise intractable difficulties with the design, manufacture and use of microfluidic devices for research. Although the process is still ongoing, we describe here our latest methods using a variant of Repoussage embossing of aluminum (See **Figure 1**) for producing sophisticated devices and our experiences using them in a classroom environment. Our estimates of initial and recurring expenses to perform this workshop and lecture series are $1250 and $175, respectively (See **Table 1**).

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Research with microfluidic devices requires three phases of work: design, fabrication and implementation. We have found that lectures on the topic work well if they access the students' inherent creativity from the very beginning. Even a design as simple as a student's signature or initials, jotted down with a Sharpie® marker, represents an investment and ownership of the process that tends to invigorate his or her participation in subsequent steps – some of which may be challenging. A natural tendency for participants to compare their designs invariably begins an iterative design process among some students that is excellent training for higher-level design using CAD software. This approach contrasts with lectures in which the student is given an existing design to fabricate or study. In this way the creative process is not initiated and the design may represent something foreign and perplexing, or worse a threat of failure if an attempt at fabrication does not go well. A nice side-effect of using original student designs is the wonderful display of creative work including every shape imaginable (See **Figure 6**). Speculation invariably ensues regarding "how the fluid will flow" through the devices, and where the entry and exit ports should be placed, which is a perfect invitation to broach the topic of fluid dynamics and computer simulation, as well as the importance of experimental verification. For these reasons we like to begin a workshop or lecture by asking each participant to create a design using a Sharpie® marker and a blank index card which is then used throughout the remaining fabrication steps.

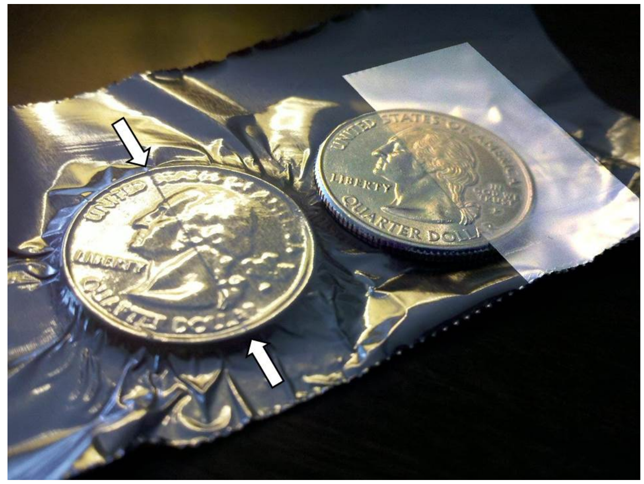

Figure 1: A U.S. quarter with Scotch® tape adhered to the right half (right) and the embossed pattern from the coin and tape in Reynolds® aluminum foil (left). Note the line in the embossed pattern (white arrows) showing the ability of the foil-embossing to replicate feature heights on the order of 50 microns (tape thickness). In this image the author's thumb was used as the compliant layer; in the method described, molten hot glue serves this purpose. Image was enhanced to better see Scotch® tape.

Fabrication of microfluidic devices in the classroom poses some challenges that should be considered before making the attempt. Provisions should be made for adequate power outlets and work stations with enough room for foot traffic between stations, and time should be allowed for setup and clean up. It is important to consider how to capture and answer students' questions and how much time can be devoted to the workshop. We have found that most equipment can be kept in hard-sided suitcases and transported easily on a cart. Deputized students can help set up and break down the stations quickly and help answer other students' questions at each fabrication stage. The only potentially messy part of the process (involving liquid silicone elastomer) we have been able to contain reasonably well on a designated desk or table that can be cleaned with isopropyl alcohol. Most important, the instructors should be reasonably experienced in the methods themselves – but by no means must they be absolute experts. Often the best opportunities for learning occur when instructors and students are both unsure and decide to try an experiment.

METHODS

The basic setup for embossed foil MF devices is illustrated in **Figure 2**, and each step of the embossing is shown in **Figure 3**. MF devices are commonly fabricated by replica molding from a master device[6]. A common feature of nearly all MF devices is their planarity, which they inherit from the master device. The channels of the MF device lie on a plane, or multiple planes in the case of layered devices. This planarity partly results from manufacturing methods using patterned light, but also from the need to conform to existing inexpensive glassware such as microscope slides and Petri dishes. Although there is no theoretical requirement for planarity, planar devices lend themselves well to microscopic examination and experimentation and may lead to interesting and advantageous situations. For instance, colony expansion of microbes is necessarily confined to a planar slab and thus easier to measure and quantify. Loss of planarity is among the most frequent causes of fabrication failure in the classroom and may occur at a macroscopic or microscopic scale. Wrinkles, bends and surface roughness that are ordinarily not noticed may be severely detrimental to the function of a device.

Materials – Adhesive-backed material (ABM) such as vinyl or Mylar is a two-layered laminated product with an adhesive coating in between the layers that can be patterned and cut with a knife and peeled. When the patterned ABM is peeled from the backing and discarded, the remaining structure can assume a two-tiered, adequately planar configuration. Common aluminum foil wrap is easily embossed against a pattern with moderate pressure from a compliant source. The combination of patterned ABM, aluminum foil and compliant pressure represents the core method for fabrication of MF master devices described here. A very quick demonstration of this replica molding may be made in the classroom using Play-Doh® and coins, and a slightly more convincing one with aluminum foil and a U.S. quarter partially masked with Scotch® tape, as illustrated in **Figure 1**. In fact, the thickness of Scotch tape makes a reasonable height for a microfluidic device at about 0.002” or 50 microns, and we have done some experiments with Scotch tape on acetate (transparency) films as an ABM. The pressure required to emboss foil is not great, and aside from some issues with surface roughness that can be overcome, Reynolds® heavy duty foil makes an excellent substrate for building MF master devices. In this case the foil is replica molded from the ABM to create the master, which is itself replica molded with an elastomer such as polydimethylsiloxane (PDMS) to create the usable MF device. The ABM master may be used several times to generate foil masters, but in practice we have found that after about a dozen compressions the ABM begins to deform slightly and patterning new ABM may be required. The foil master is usually used only once.

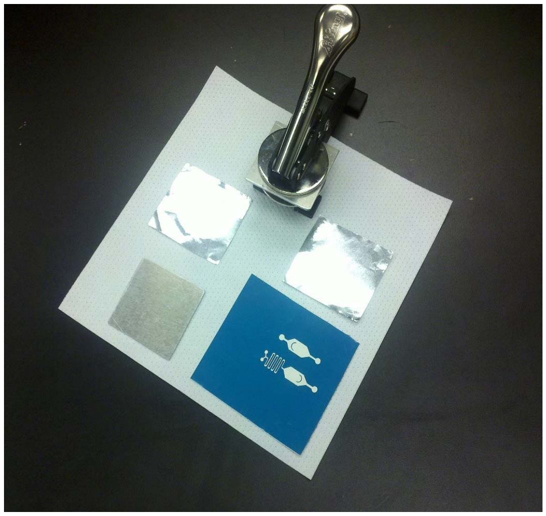

Figure 2: Clockwise from top. The hand-embosser with custom top pressure plate affixed. Top foil layer (backing). Cerulean vinyl (ABM) with Silhouette-cut pattern peeled, revealing white backing. Bottom pressure plate not affixed. Bottom foil layer (embossed layer).

PDMS is commonly used to replicate MF masters and offers many advantages. It is safe, non-toxic and not very expensive. It is optically clear at visible wavelengths and elastomeric. It is capable of covalently bonding to itself (in cured solid form) and to glass, enabling the construction of permanent structures. Much has been written about the use of PDMS, and the scientific literature may be explored to augment the information provided here. Briefly, the product is mixed from two components referred to as the base and curing agent. The standard mixing ratio is 10:1 base to curing agent. A higher ratio (more base) leads to a more pliable and elastic solid and a lower ratio to a stiffer solid. The curing may occur at room temperature over a period of days, or at elevated temperatures with faster completion. A solid may be obtained in approximately 10 minutes at 150 ˚C but is more commonly cured at 60 ˚C for several hours. The liquid components can be adequately mixed with a plastic fork in a small drinking cup and vigorous frothing action, keeping in mind that the curing agent needs to be uniformly distributed among the base for an appropriate cure. Bubbles introduced from dissolved gases or the mixing action can cause mild to severe distortions in the MF device and some effort to remove them is worthwhile. This is conventionally done with a vacuum pump and chamber, but we have had success using a heavy gas such as R134a and a gas chamber formed from large drinking cups or disposable Glad® food containers.

Although manual ABM patterning is certainly possible, machines that cut the ABM according to a design created on a computer (or collected with an electronic camera) exist and enable more elaborate designs in less time with ease of replication. We have used the Silhouette Cameo® vinyl cutter with both vinyl and Mylar and have found that if care is taken to determine the limits of obtainable line thicknesses, the devices perform robustly and with little trouble. Briefly, the principle of operation is similar to early computer plotters in which the paper is moved by means of rollers, thus defining the x-axis. A drag knife is moved on a rail with stepper-driven belts to define the y-axis. A compensation for the radius of the drag knife is automatically included, but very sharp turns in a cut path may be problematic (more so with thicker material) as the knife must rotate while it is embedded in the material. Very satisfactory facsimiles of the original design are easily achieved and may in fact be used as MF devices themselves, although results are better with Mylar than with vinyl as some adhesives may interfere with PDMS curing.

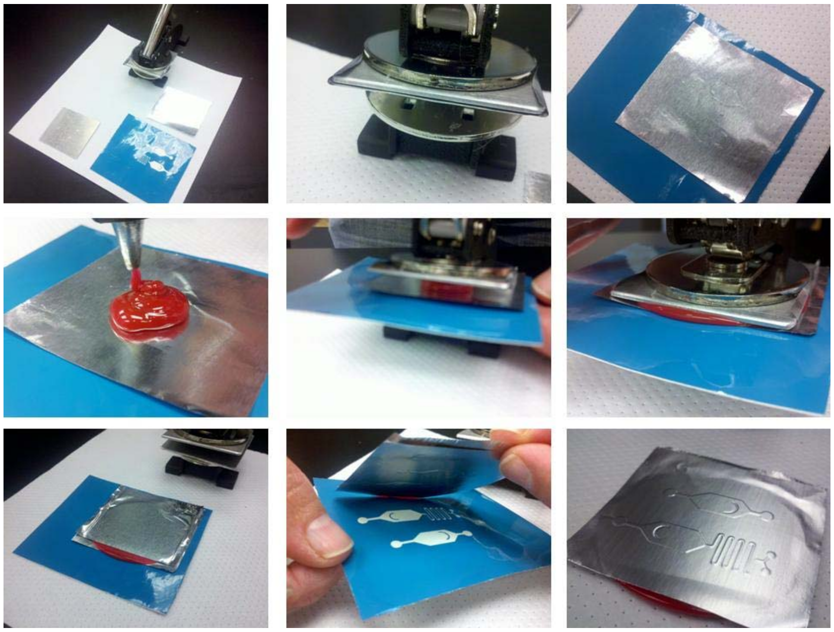

Figure 3: Embossing procedure. Top Row: Assembly with top foil loosely attached to top pressure plate. Close-up of top foil on pressure plate. Bottom foil on ABM vinyl with light embossing of ABM pattern showing through. Middle Row: Dollop of hot glue directly on pattern. Assembled sandwich of ABM, hot glue, and two foil layers in the embosser. Compression of the embosser with hot glue extruding from edge. Bottom Row: Fresh embossed sandwich cooling on bench. Parting embossed foil master from ABM vinyl. Embossed foil master, feature side up. Device design by Cameron Togrye.

Sketching – Begin by having each student design a MF device using a Sharpie marker and a blank (non-ruled) white index card. No limitations are necessary, but some advice regarding sufficient line widths and spacing and the overall size and complexity of the device may prevent common fabrication difficulties. Starting simple and increasing complexity is always a good way to begin. Alternatively, students may use the MS PowerPoint scribble tool to generate a design on a PowerPoint slide – especially useful with tablet PCs and a stylus, or other drawing software such as AutoCAD or Inkscape (open source). When design involves a computer, plan for additional time to train students in the software if they do not already know it from prior work or classes.

Photography/Digitization – The sketched design can be photographed with a webcam connected to a designated computer, or with a student's cell phone camera, and sent by email or other internet file-sharing software (Google Drive, Dropbox, etc.). Care should be taken to ensure good background lighting without glares, steep brightness gradients or blurring. The ultimate objective of digitization is a truly black and white image with no grayscale. Some digital cameras or smartphone apps may be capable of producing this type of image at the time of acquisition by over-saturation effects, which would be helpful in saving time in vectorization.

Vectorization – The image or design must be in vector form for automatic cutting. This is most easily accomplished by importing it into the Silhouette software and automatically tracing it using the trace feature. Alternatively, Inkscape and other software may be used to threshold the image (set all pixels to zero or full saturation) before importing to Silhouette for more accurate pattern reproduction. The silhouette software is free to download and install and fairly simple to learn and use. A reasonable requirement for a classroom with some prior notice and assistance would be the finished Silhouette pattern, ready to be cut and emailed to the instructor in the Silhouette file format or drawing exchange format (.dxf) or other transferable format. It would then be left to the student to choose from among several options to arrive at the design. This would not be amenable to a workshop format in which students arrive with no prior preparation.

ABM Master Creation – Automatic cutting with the Silhouette Cameo® or other computerized cutter is interesting for students to witness as many have not seen this sort of apparatus and will be surprised at how well it works. We recommend that the patterns be grouped into a single file and cut in the classroom from one sheet of ABM in order to minimize material waste. It is important to include wide margins around each student's pattern. Narrow margins lead to difficulties downstream, and wide margins can be trimmed when necessary. A paper cutter or large scissors are useful to cut out each student's pattern with margins. The student must then peel away the part of the ABM that represents his or her device. There are two ways to peel each device, which may be thought of as a positive or negative image of the design. Either way is acceptable and the quality of the resulting ABM master should be the guiding light as to how to proceed. For instance, with a student's initials the interior portion or letters are removed, which make a nice decoration for a cell phone or notebook, increasing interest in the topic. At this stage it is not crucial to be especially careful or clean about the work, but the goal is a relatively tidy, planar pattern that satisfies the student's requirements. Our testing indicates a minimum line width of 100-300 microns for vinyl and Mylar depending on the complexity of the design. More complex designs and designs using tight radius curves will require wider (300 micron) lines where simple designs using large radius, sweeping curves may allow narrower line widths (100 microns). Vinyl measures between 70-100 microns thickness with a dial indicator and Mylar measures 50 microns with the same method. This suggests a minimum cross-sectional area of 50x100 microns and minimal channel volumes of approximately 5 picoliters per micron of length or 5 microliters per millimeter.

Embossing – Aluminum foil can be embossed using very simple tools (a thumb, a large book or a C-clamp) or more elaborate equipment like a heated press. It is important to provide a consistent source of uniform pressure across the entire surface of the pattern at the same time. Rolling or brushing can also work but may lead to curling and a loss of planarity depending on the circumstances. We have had good success using a hand embosser (Stamp-connection.com, Shiny EZ Pocket Seal) with a blank insert onto which we hot-glued two pieces of 1/8" aluminum plate (approximately 2" square) to increase the embossing area. Blank circular inserts up to 2" diameter can be obtained from stamping companies and may be good alternatives. In the case of a custom modification, it is important to choose the right thickness such that at full compression the two pressure plates are parallel. This calculation should include the thickness of the material being embossed. For the methods described here, 1/8" inch plates are adequate. Equally important is a uniform compliant layer such as rubber, cured PDMS or certain papers to fill the ABM pattern while under pressure and deform the aluminum foil. A poor choice of compliant material will result in lack of fidelity between the ABM pattern and foil, and low resolution of features. Notice the loss of resolution and blurring on the taped side of the embossed U.S. quarter in **Figure 1**. In this case the compliance of the author's thumb was reduced or limited by the presence of the relatively non-compliant tape so that the pressure could not fully deform the foil around the coin's lettering. We use molten hot glue along with a second piece of foil backing as a pattern filler, which also provides stability and maintenance of planarity when the glue has hardened. To accomplish this it is necessary to build a layered sandwich of ABM pattern, aluminum foil, dollop of hot glue and aluminum foil backing, in order from bottom to top, being sure to place the dollop on the center of the ABM pattern. To find the center of the pattern on the first foil layer some light finger pressure can be applied. It is important to be fairly quick but not hasty about getting the assembled layers into the embossing device since the hot glue will begin to congeal and harden in room air and its high temperature will start to melt the ABM pattern. Different glue formulations will have their own potting times. We have studied high temperature glue (polyamide, glu-stix.com) with a melt temperature of approximately 253 ˚C and more ordinary hot glue with softening at 173 ˚C. For each we have found a setting time of about 30 seconds. Upon compression with the cool and thermally conductive plates of the embosser the glue typically hardens in less than 10 seconds. It may be possible to carefully remove the foil master sooner and set it aside until it is completely cooled – a possible benefit for a workshop with many students and limited time. The edges of the cooled, hardened master can often be carefully folded upward to form a reservoir for PDMS casting, eliminating the need for a separate vessel such as a Petri dish. If the compressed glue has leaked out one of the sides or there is not enough foil to fold, it may be necessary to use a separate casting vessel, although even these devices can be shaped if one is very careful. IMPORTANT: the feature side of the foil master will be cast in PDMS and should be kept very clean. Wearing gloves and being careful not to shed dust or skin flakes onto the surface will help. If the foil was not clean going into the embosser it will not be clean coming out. We find it best to carefully pre-cut foil squares and leave them stored out of the way until they are ready for embossing, and then to handle them only by the corners and edges. A cutaway view of each layer of the material involved in the embossing step is shown in **Figure 4**.

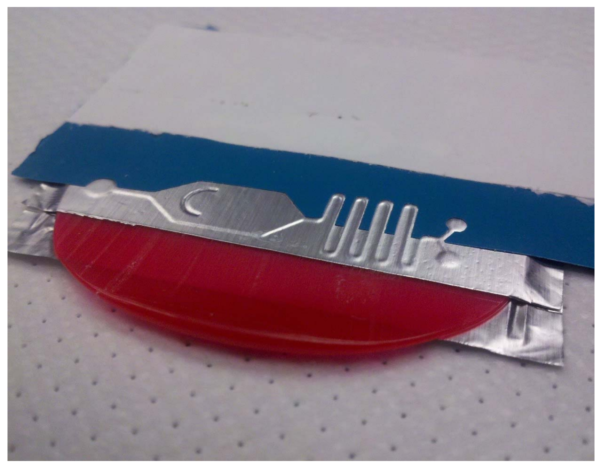

Figure 4: Cutaway view of embossed device and ABM master from **Figure 3.** Top white ABM backing paper, Cerulean ABM vinyl, feature-side foil, red hot glue ingot, backing foil. ABM vinyl is between 70-100 microns, which closely matches the height of the resulting features in foil as measured by a dial indicator. Very fine machine marks from foil manufacturing can be seen transverse to the long axis of the device. These present a loss of planarity and can interfere with plasma bonding. Treatment with PVA prior to PDMS casting mitigates the difficulty significantly.

PVA Coating – Reynolds® aluminum foil is not perfectly smooth on a microscopic scale. Tooling marks that look like fine unidirectional scratches appear on both sides. This represents a lack of planarity at the microscopic level that can interfere with plasma bonding by reducing the bond density in the plane formed by the joint between the two surfaces. The effect can be mitigated by use of a greater base ratio such as 15:1, but a more general and useful method is to coat the foil with the mold-release agent polyvinyl alcohol (Amazon/Fiberglass Evercoat). The PVA coating is applied at 4% concentration by dripping onto a nearly vertical master and allowing the droplets to roll down and off the end. Two coats made in this way and allowed to dry completely in an oven in between coats have the effect of smoothing the foil surface and increasing the contact area of the resulting PDMS cast and greatly improving the plasma bonding. Alternatives include polishing the foil before embossing. We have done limited testing of this using a simple polishing compound and rotary tool (Dremel) as well as manual polishing with a fine grit metal polish. High pressure, as may be achieved with a smooth metal roller on a smooth hard surface, may also be effective. Finally, if a high speed (high temperature) PDMS cure is not required, Mylar may be used in place of the feature-side aluminum foil. The Mylar conforms well under pressure, maintains the features with the hardened hot glue, maintains planarity, but loses its shape at 150 ˚C. An alternative we have not yet tested is the use of high temperature hot glue with Mylar and a high temperature cure.

PDMS Casting – The desired ratio of PDMS can be easily obtained volumetrically using 10mL and 1mL syringes to draw up the base and curing agent. Care must be taken not to draw bubbles into the base syringe since the high viscosity makes bubble removal difficult and the bubbles will cause volumetric error that will change the mixture ratio. Although a scale is typically used in the lab, inexpensive scales with sufficient precision are not readily available for the classroom. Gloves and an absorbent work-mat of paper towels are recommended for this procedure as it can become somewhat messy with repeated use of the same syringe. A small plastic drinking cup and plastic fork can be used for mixing – which should be continued until the mixture is pearlescent (about five minutes) from air bubbles in the mixture. R134a is a refrigerant that can be purchased from online vendors or local auto parts stores. It is heavier than air and when gently dispensed into the drinking cup it will settle and form a head above the PDMS. It is best to cover the top of the cup with paper or a lid to protect the heavy gas from room air currents. After 5-10 minutes the air from the PDMS will have diffused into the R134a and formed a lake near the top of the cup. When the PDMS appears clear, with no bubbles, it is ready to cast. A word of caution: the diffusivity of R134a into PDMS is not known, but is probably not zero. After long periods the R134a may begin to saturate the PDMS and could coalesce and form bubbles during the curing phase. Be sure to degas as long as necessary and not longer to prevent unwanted bubbles. The degassed PDMS can be dispensed directly onto the foil MF master from the previous step, as shown in **Figure 5**. The cast foil master can then be placed at elevated temperature for curing. A used toaster oven works very well, although its temperature should be monitored independently with a meat thermometer or thermistor device because the thermostat may not correspond closely with actual temperature in inexpensive ovens. The elastomer will cure to a solid at a range of temperatures including ~48 hours at room temperature, 45 minutes at 100°C , 20 minutes at 125°C, and 10 minutes at 150°C[7]. We have noted that curing at the highest temperatures sometimes causes warping of the bulk PDMS upon removal from the oven – a flat disk shape becomes concave and bowl-like. If sustained, this loss of planarity can make plasma bonding impossible. It may be avoidable with less dramatic temperature changes. An intermediate cooling hotplate, set on its lowest setting, may be used to slow down the cooling process and prevent thermal warping. After a complete cure the foil master can be carefully peeled away from the PDMS and discarded. Some trimming of the PDMS edges with an anvil cutter or knife may be desired.

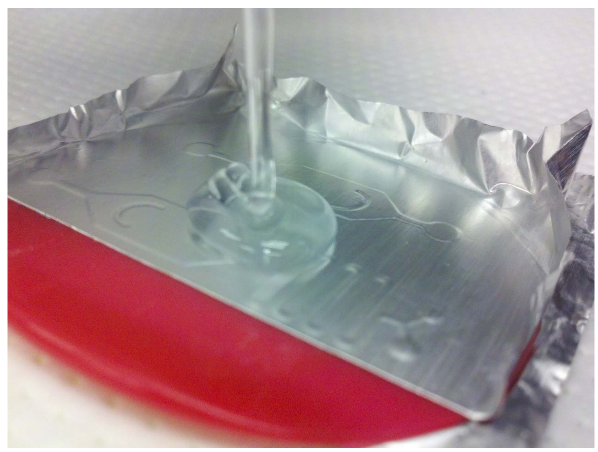

Figure 5: Cutaway view of foil master with PDMS. The PDMS is typically poured closer to the master surface to avoid entraining air bubbles. The turned edges of the foil on all sides form a vessel to contain the liquid PDMS during the curing stage.

Punch Making and Hole Punching – The steps up to this point should have produced a relatively flat solid slab of clear elastic PDMS with a clear impression of the device design on the bottom surface. If bonded to glass at this point the device would be plainly visible due to the varying refractive indices of PDMS and air and the close indices

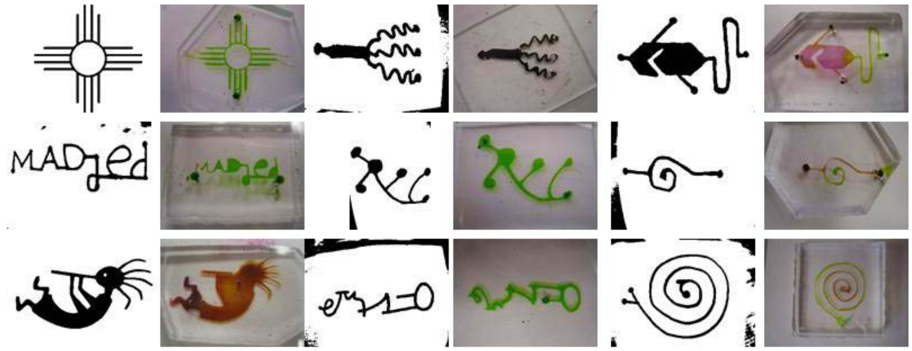

Figure 6: Selected student designs and the resulting fluidic devices from a recent workshop using the methods described. Patterns can be filled with multiple dye colors to study fluid dynamics.

of PDMS and glass. However the channel network of the design would be sealed and not accessible to the outside world. Entry and exit holes for fluid flow must be provided, and this is typically done by punching holes with blunt-end stainless steel dispensing needles, often with the edges sharpened. An assortment of dispensing needles (McMaster-Carr 75165A791 or Amazon/CML Supply) is usually best for a classroom so that students may choose the size they prefer. The needles can be sharpened by hand against fine grit sandpaper by rotating them while moving back and forth to achieve a beveled outer edge. The needles can be mounted in a rotary tool for a more consistent edge if one is available. Most of them can also be used unsharpened, but perhaps with less success. Punching is accomplished by carefully positioning the punch where an entry or exit hole is desired, starting from the patterned side and simply driving the punch completely through the PDMS as if sewing with needle and thread. Using a scrap piece of PDMS that has been cut from the original casting as a punch pad can improve the quality of the punched hole. Punching from the non-patterned side of the PDMS can also be done, but with careful aim to be sure the channels and punch hole intersect. The major problem to be avoided with hole-punching is PDMS splitting. This occurs when the punch rate is too rapid, the punch lumen is clogged, the punch cutting edge is deformed or very dull or when the PDMS is very stiff, old or brittle. Rather than being a clean, cylindrical-shaped thru-hole, a split punch hole is either a hole with a torn segment, a hole that transitions into a tear midway through or a tear from top to bottom of the PDMS. A good example of a torn punch hole can be obtained for study by pushing a thumb tack, straight pin or needle through the PDMS and withdrawing it. It will leave a discernible crack, but not a clean hole. Torn punch holes can most often be avoided by using larger punches (1 mm ø or greater) and using a stylus fashioned from a paper clip to clear the punch of all debris prior to punching. Again, care must be taken to protect the feature side of the device from skin oils and dirt. It may be cleaned with isopropyl alcohol and/or contact-cleaning with Scotch® tape before bonding.

Plasma Bonding – Plasma is generated by ionizing a gas (such as air). It activates the surface chemistry of glass and PDMS, creating –OH groups on each surface that when brought into close contact will form Si-O-Si covalent bonds through a condensation reaction. If a sufficient number of bonds can be formed per unit area, the surfaces will be essentially permanently bonded. The plasma treating in the lab is typically done with a Harrick plasma treater, but we have had good success in our workshop with a hand-held plasma leak detector device, Model BD-20AC (Electro-Technic Products) in room air. The product comes with several tip shapes of which the T-shaped wire lead works best. The corona from the tip glows purplish pink, clearly visible in the dark. The method is simply to expose the entire surface to be bonded to the corona (glass and feature side of PDMS) for 20-40 seconds each and then put them in contact with each other and place them in an oven for five minutes. Planarity of the PDMS relative to the glass is critical for a good bond. Loss of planarity in prior steps of fabrication will show clearly here as regions that do not contact the glass and thus have layers of air refractive indices. These regions will also be open to fluid perfusion, which may be detrimental to the function of the MF device design. There are some alternatives to plasma bonding. Devices made with 15:1 PDMS ratios are much more compliant and tend to auto-adhere more completely and may be sufficient for simple perfusion. Clamping devices to glass is a known viable method, but requires a clear plastic clamp with thru-holes for fluidic connections. A partial-cure bond of PDMS to other PDMS (such as a thin layer of PDMS on glass) may also be very useful. The partial cure is accomplished by partly curing each piece, then placing them in contact and finishing the cure at ?? temperature. The subtlety lies in choosing the time point carefully for each piece so that channel structure is maintained but enough fluidity remains to achieve the bond. Less initial cure time may be required for the thinner layer than for the thicker.

Item		Supplier or Mfr.	Alternate Supplier	Approximate Cost
Silhouette Studio software		Silhouette America		Free
Silhouette Cameo cutting device		Silhouette America	Local Craft Store	$300
Vinyl ABM sheets 12” x 24”	*	Silhouette America	Amazon.com	$50
Mylar ABM sheets 27”x 20”	*	McMaster Carr	-	$3 pc.
Aluminum foil	*	Local Grocer	Amazon.com	$6
Scissors		Local Craft Store	Amazon.com	$5
Hot glue gun		Surebonder	Amazon.com	$20
Hot glue (170 ºC melt)	*	Local Craft Store	Amazon.com	$5
Hot glue (275 ºC melt)		Glu-stix.com	-	$100
Hand embosser		Stamp-connection.com	-	$45
4% PVA solution		Local Craft Store	Amazon.com	$16
PDMS Sylgard 184	*	Amazon.com	Ellsworth.com	$50
12 mL syringe for PDMS	*	Amazon.com	-	$9 (10 pcs.)
1 mL syringe for PDMS	*	Amazon.com	-	$5 (10 pcs.)
Plastic forks to mix PDMS	*	Local Grocer	Amazon.com	$4 (400)
Plastic cups	*	Local Grocer	Amazon.com	$5 (100)
Desiccator (optional)		Bel-Art	Amazon.com	$50
Programmable toaster oven with timer		Local Goodwill	Target	$5-25
Scalpel	*	Amazon.com	McMaster Carr	$12 (10)
Tweezers		Amazon.com	McMaster Carr	$3
Scotch tape	*	Local Drugstore	Amazon.com	$3
Punches		McMaster Carr	Amazon.com	$14
Sandpaper (800 grit)		Local Hardware	Amazon.com	$8
3” x 2” Large slides 1 Gross	*	Amazon.com	-	$14
Isopropyl Alcohol	*	Local Drugstore	Amazon.com	$5
Kimwipes (or paper towels)	*	Local Grocer	Amazon.com	$5
Plasma Leak Detector		Electro-technic	-	$500

Table 1: Parts list for embossed foil microfluidics. Frequent recurring costs are shown with an asterisk.

***Perfusing* –** Once a device has been bonded several options are open for perfusing. We most often use food dye because it is inexpensive and readily available (even in neon colors). Water color paints or even oil-based paints may also be appropriate. What is important in the classroom is good contrast so that the channels may be clearly seen to have fluid in them. Water is not a good choice for this reason, but even water can be seen to perfuse a channel in the correct light and background. A 1 mL syringe with perfusion solution can be held against the inlet and gently depressed to inject into the device. WARNING: anything but gentle depression may lead to spraying the perfusion solution at table-top level in lateral directions – and food dye can stain clothing. An apron or just a paper towel barricade is strongly advised. Alternatively, if a vacuum chamber is available, the inlet holes to the device can be covered with perfusion solution while alternately increasing and decreasing air pressure, which will act to pump fluid into the channels. It is always a pleasing sight when the pattern fills seemingly by itself.

RESULTS & DISCUSSION

We have allowed this method to evolve naturally over the course of many workshops, beginning with full photo-resist UV lithography on silicon wafers requiring ventilation, air filtration and literally a van-load of equipment. Foil fluidics can also be made by writing directly with a ball-point pen and casting the reverse side. Planarity is difficult to achieve and maintain with this method, leading to a high failure rate. We have attempted several methods involving plastics, including Dymo® labelers and Mylar as the feature side in the present method – only to be disappointed when the plastic re-melts at the higher PDMS cure temperatures, leading to little or no patterning on the PDMS side. For several workshops, we used Shrinky-Dinks® as masters with good success, but had some difficulty keeping the shrunken devices planar and thus could not reliably plasma bond the resulting PDMS MF devices[8]. Shrinky-Dinks® can also be a little expensive as training material (at least as compared with aluminum foil), so we continued looking for alternatives.

We believe the present method is applicable for devices with much larger surface areas than the two square inches used here and well beyond the typical 3” wafer used in traditional photolithography. This may allow large-scale integration of small-featured devices on a single monolithic ship – akin to the concept of a printed circuit motherboard that houses any number of integrated circuit microchips to achieve a higher overall function. Our group has been working in this area for some time and has recently pioneered pumps and valves that may be easy to manufacture using methods described here. **Figure 7** illustrates a device that is almost six square inches with line widths and inter-line spacing of approximately 500 microns produced with a heated press at 200 °C and about 200 psi. The heated press causes some difficulties with the adhesive layer of the ABM, but we are still in the early stages of this effort.

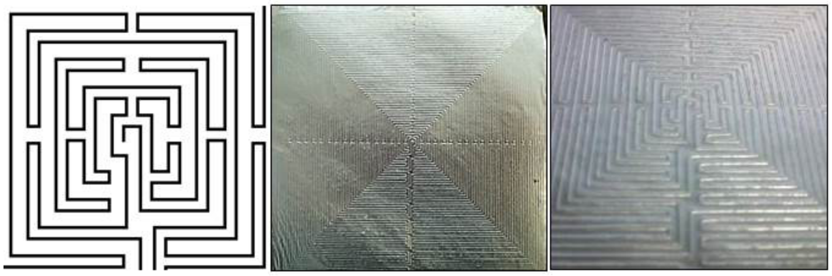

Figure 7: Large area emboss pattern. Center section of an AutoCAD drawing of seven nested Chartres-like labyrinths occupying a 5.75 inch^2 area (Left). The embossed labyrinth pattern using a modification of the methods described on a heated Carver® press, also 5.75 inch^2 (Middle). A zoomed view of the middle of the nested labyrinth more clearly showing the channels, which are approximately 500 microns wide.

The evolution of the workshop at conferences and in classrooms from high school age to aging faculty has been a tremendously exciting activity. As many faculty already know, interacting with students over research matters can be incredibly rewarding, especially when the students are able to relax, share their thinking and attempt some experiments and share results. The methods presented here enhance such interactions because they have tended to have a high success rate, which increases student confidence in their own research abilities.

CONCLUSIONS

Making microfluidic devices has historically required a rather complex and expensive infrastructure that involves many hours of specialized training, making it a difficult technology to utilize in the typical classroom. The embossing methods described here bring MF technology within the reach of nearly any classroom setting with very little investment in equipment and very little training required for each individual student. Devices capable of demonstrating important physical, chemical, and biological concepts are easily achieved during just a few classroom sessions and can be integrated into existing curricula.

ACKNOWLEDGEMENTS

We acknowledge generous support from the Systems Biology and Bioengineering Undergraduate Research Experience (SyBBURE-Searle), a program funded by Gideon Searle and operated by the Vanderbilt Institute for Integrative Biosystems Research and Education (VIIBRE); microfabrication workshop participants and venues, including meetings and conferences of the Engineering in Medicine and Biology Society, the Biomedical Engineering Society, q-bio, the Advanced Laboratory Physics Association, the American Society of Engineering Education Southeastern Section, Lipscomb University and the School for Science and Math at Vanderbilt. We also thank Philip Samson for kindly suggesting the use of the Silhouette Cameo and Julia Warner and Allison Price for proof-reading and edits.

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