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Melt-and-mold fabrication (MnM-Fab) of reconfigurable low-cost devices for use in resource-limited settings

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ABSTRACT

Interest in low-cost analytical devices (especially for diagnostics) has recently increased; however, concomitant translation to the field has been slow, in part due to personnel and supply-chain challenges in resource-limited settings. Overcoming some of these challenges require the development of a method that takes advantage of locally available resources and/or skills. We report a Melt-and-mold fabrication (MnM Fab) approach to low-cost and simple devices that has the potential to be adapted locally since it requires a single material that is recyclable and simple skills to access multiple devices. We demonstrated this potential by fabricating entry level bio-analytical devices using an affordable low-melting metal alloy, Field's metal, with molds produced from known materials such as plastic (acrylonitrile–butadiene–styrene (ABS)), glass, and paper. We fabricated optical gratings then 4 × 4 well plates using the same recycled piece of metal. We then reconfigured the well plates into rapid prototype microfluidic devices with which we demonstrated laminar flow, droplet generation, and bubble formation from T-shaped channels. We conclude that this MnM-Fab method is capable of addressing some challenges typically encountered with device translation, such as technical know-how or material supply, and that it can be applied to other devices, as needed in the field, using a single moldable material.

1. Introduction

The rapidly increasing global population faces threats of new diseases, scarcity of clean water, and, costs of living rising to crippling heights as global resources are strained to unmanageable limits [1]. This strain will have especially devastating consequences for developing/emerging nations [1,2]. Providing adequate food, clean water, and healthcare is difficult because the necessary tools to diagnose diseases, measure nutrient content, detect food toxins, or assess the quality of water are not always available, especially in resource limited settings [2,3]. The lack of reliable supply of good quality and efficient diagnostic tools in the developing world, is partly due to poor infrastructure (such as roads and bridges) necessary for uninterrupted supply. This breakdown in supply-chain of prefabricated disposable analytical devices makes it challenging – and expensive – to deliver care to populations in resource-limited settings who are also the most in need. The availability of cellular communication, however, has allowed for an influx of information, often free via the web, to almost every region of the world. New approaches to diagnosis and analytical measurements can therefore take advantage of the growing global connectivity and transfer some responsibility of device fabrication to those who need them most. This approach has been applied successfully in agricultural applications [2,4]. It allowed the integration of better farming practices, such as strip farming, contour farming, and gabion construction, in many parts of rural Africa. Similarly, formal education and industrialization principles have been adopted in most parts of the world, not through material transfer, but predominantly through information sharing and local customization.

Recent developments in low-cost diagnostic and bio-analytical devices are driven, in part, by the availability of affordable materials coupled with low-cost fabrication techniques [5]. One example is the emergence of paper-based microfluidics (μ-pads) – an effort spearheaded by Whitesides and co-workers [6–21]. Although affordable wax-printing, 3D printing, and similar technologies that enhance the quality and complexity of paper-based devices are readily available in the developed world, they are almost non-existent in remote villages and other resource-limited

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environs [10,11,18,20,22]. These low-cost diagnostic and bio-analytical devices have to overcome, and/or selectively exploit, the inherent hydrophilicity of paper to control aqueous bio-fluid movement [6,12,20,23]. Paper technologies developed so far are often not adaptable for use in regions without electricity or where the requisite processing technology is unavailable. A practical technology that can be applied in these regions should not necessarily require grid-based electricity, should be simple, and can be accomplished with locally available resources (materials and personnel). Such restrictions are met by reliable and easy to understand techniques such as replica molding, by using reusable materials, applying simple sources of energy (e.g flames for heat) and globally available reagents like water. We believe that although the use of a low-cost, abundant material such as paper is desirable, other approaches are needed to introduce new materials in the development of low-cost, bio-analytical devices.

We therefore envision a new form of ‘ or ’ that involves the user as an active technology participant in not only running and interpreting the assay, or reporting the data over the cellular bandwidth but also in device fabrication. To achieve this goal, the requisite diagnostic and/or device(s) should: (i) mainly be derived from locally available materials (abundant and reliable local supply), (ii) use cheap (with respect to the immediate cio-economic setting) materials, (iii) be easy to fabricate and use, (iv) be powered using locally available resources, and (v) be from an affordable reconfigurable material that can be reprocessed (see Supporting information Table S1). This paper reports our initial development of analytical platforms/devices derived from soft, point alloys that are examples of reconfigurable, easy to process and materials. We hypothesize that the use of low melting point (T_m) metal(s) will allow the fabrication of various devices from the same piece of material using well established processes while utilizing some locally available resources for manpower and molds. To illustrate this capability, we fabricated basic devices such as , optical gratings, and microfluidic devices, from a metal (Fig. 1). The high surface energy of the metal allows the use of both polar and solutions without affecting the behavior of the channel in microfluidic devices. To illustrate the adaptability of our approach, molds were made from plastics, glass, aluminum, and readily available materials even in the developing world.

2. Materials and methods

2.1. Materials

Bismuth indium tin (Field's metal, Bi/In/Sn at 32.5:51:16.5 wt%, Alfa Aesar), bismuth tin eutectic (99.95%, Bi/Sn at 58:42 wt%, Alfa Aesar), indium (99.9%, Alfa Aesar), and gallium (99.99%, Strem Chemicals) were used as received. Polydimethylsiloxane molds (PDMS, Sylgard) were made by mixing the elastomer with the curing agent at a ratio of 10:1. Diffraction gratings with 1800 grooves/mm (556 nm spacing) and 2400 grooves/mm (417 nm spacing) were purchased from Edmund Optics and used as received. All other chemicals were obtained from Sigma-Aldrich and used as received.

2.2. General MnM method

Field's metal, a low melting alloy, was melted using either a Bunsen burner or a laboratory heating gun in a ceramic crucible and poured over the molds at ambient conditions. For comparison purposes, we also fabricated devices from other low-melting metals (pure metals of bi- and tri-component alloys) to illustrate the versatility and simplicity of the MnM Fab approach.

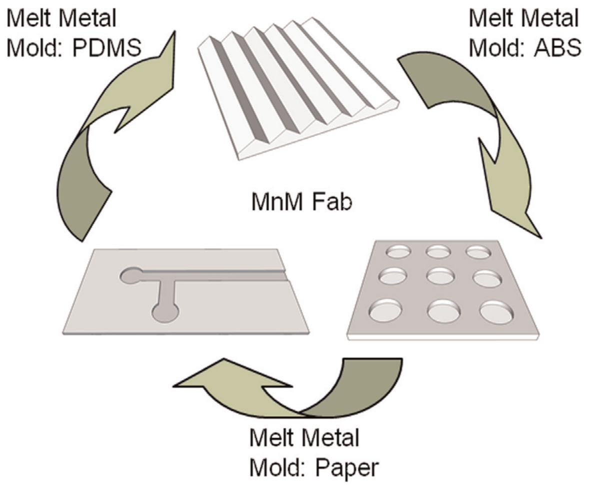

Fig. 1. Diagram of Melt-and-mold fabrication (MnM-Fab) of diffraction gratings, microfluidic devices, and well plates all using the same piece of metal and various molds.

2.3. Fabrication of well plates using plastic molds

Models of the desired well plate molds were created using SketchUp software, then molds were printed using a MakerBot Replicator 2X and an ABS filament. Molten Field's metal was then poured directly in the 3D-printed mold and left to cool at ambient conditions for at least 10 min. The cooled metal easily separated from the plastic molds providing well-plates with an inner diameter of 7 mm. Well-plates were filled with different polar and non-polar liquids of various volumes to demonstrate they can be used with either liquid in contrast to plastic well plates.

2.4. Fabrication of gratings in elastomeric molds

The PDMS elastomer and curing agent were mixed at a ratio of 10:1. The desired diffraction grating was covered in the PDMS mixture, degassed, and then cured in an oven at 70 °C for 2 h. The grating was then removed from the cured PDMS, leaving a negative of the original in the PDMS. The metal of choice (Field's metal, Bi/Sn, Ga, or In) was heated until molten, then poured into the PDMS mold at ambient conditions. The metals were released from the molds after cooling to ambient conditions (> 10 min). Negative replicas of plastic double diffraction gratings were made by pouring molten Field's metal over plastic diffraction gratings that had 13,500 lines/in. and pulled off after cooling to room temperature.

2.5. Light diffraction by replicated gratings

A bright white light source was shone onto the molded gratings at ambient conditions. Diffracted light was directed onto a white background and the resulting diffraction pattern was photographed using a Nikon D7100 camera.

2.6. Fabrication of microfluidic devices using paper molds

Cardstock paper molds of the microfluidic device were created using a Cameo Silhouette craft cutter and accompanying software (similar molds were also made using scissors). The paper molds were then placed on a glass support, metallic fluid inlets were attached, and the re-molten Field's metal was poured onto the molds (with the inlets already positioned). The devices were allowed to cool at ambient conditions for 10 min. The paper mold was then removed from the metal devices, which were subsequently immersed in an aqueous 1 M H_2SO_4 solution (95–98%