A SILICON-BASED GALINSTAN MAGNETOHYDRODYNAMIC PUMP

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Abstract: This paper presents the design, fabrication and characterization of a novel Magnetohydrodynamic (MHD) pump engineered to actuate Galinstan; a non-toxic liquid metal alloy of gallium, indium and tin. The MHD micro-pump is fabricated using Silicon MEMS fabrication technology. MHD µ-pump design and fabrication has been demonstrated before. While previous research has focused on actuating ionic solutions only, the research presented in this paper demonstrates for the first time micro-actuation of Galinstan. Such an actuation scheme has wide ranging applications from micro-cooling to reconfigurable liquid metal RF-MEMS.

Keywords: Liquid metal, Galinstan, Magnetohydrodynamic, MHD, micropump

INTRODUCTION

Liquid metal promises efficient micro-cooling as well as superior power handling. Under high RF power operation solid metal structures (beams, cantilevers etc.) often suffer electromigration and excessively high contact temperature that result in premature failure and poor reliability. On the other hand, liquid metal has none of these shortcomings and may prove a promising solution for high-power applications. The key to using liquid metal in high power devices is micro-actuation; the ability to control its movement. The choice of liquid metal is crucial since most of the actuation details are material-dependent. Galinstan is widely used as a non-toxic liquid metal alternative to mercury in thermometers. It also has favorable material properties such as good heat transfer coefficient, heat capacity and low viscosity. This makes it particularly suitable for µ-cooling applications as illustrated in Figure 1.

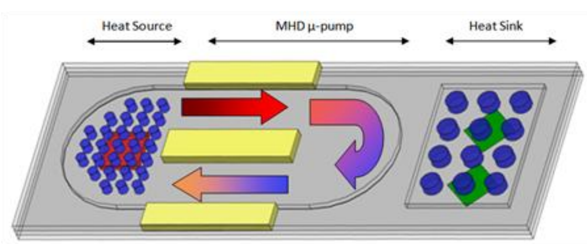

Figure 1: CAD depicting the configuration of a micro-cooling system using the MHD µ-pump

THEORY

MHD µ-pump is based upon Lorentz Force which asserts that when a current-carrying conductor (Galinstan) is subjected to a magnetic field (**B**) normal to the current (**I**), it will experience a force **F** which is perpendicular to both the **I** and **B**. The magnetic field is provided by an external permanent magnet placed directly under the device and the biasing current is applied by vertical electrodes. MHD micro-pump can be biased by AC or DC. Since electrolytic solutions (such as salt solutions) undergo electrolysis when subjected to direct current, alternating current and magnetic fields are used to avoid this. The first MHD micro-pump was demonstrated by A. V. Lemoff et al [1]. Subsequently published papers on the topic improved upon actuation of electrolytic solutions [2, 3, 4], which is not applicable to Galinstan due to its intrinsic chemical properties. Since Galinstan is a liquid metal, electrolysis is not a concern and the micropump detailed in this paper is biased by direct current and steady magnetic field. There are several literary resources on microfluidics and micropumps [5, 6, 7, 8, 9, 10] which aided this research.

DESIGN

Galinstan Adhesion

Galinstan has an undesirable affinity for oxidation, which renders actuation challenging and thus requires special conditions. It oxidizes upon contact with air and forms a viscous oxide coating that adheres to almost any surface. The Galinstan µ-pump demonstrated in this paper resolves these issues by employing oxygen-free quasi-hermetic packaging and novel anti-stiction coating techniques. A thin layer of Teflon is deposited and patterned on the microfluidic channels to minimize friction (anti-stiction layer) and this is crucial to microfluidic actuation. This MHD µ-pump is specifically designed to actuate Galinstan and is unique in this sense.

Galinstan Handling

It is a complicated task to handle Galinstan since even slight oxidation may be detrimental to MHD performance and stiction needs to be controlled to allow for low power-consumption. A trace amount of dilute Hydrochloric acid (HCl) is used as a reducing agent and SOG based packaging is employed in a controlled Nitrogen environment to avoid instantaneous oxidation. The reducing agent reverses any oxidation that may have occurred during handling and exposure to atmosphere. However, the HCl must be removed from Galinstan prior to injection into the micropump since it electrolyses under direct current and the microfluidic volume shrinks once the electrodes are biased. This can result in an open-circuit and MHD micropump will not function. A direct current is passed through the Galinstan sample to remove the HCl and is subsequently injected into the device inside a Nitrogen box (almost oxygen-free). The device employs a quasi-hermetic packaging using an epoxy. The injection-port is then sealed as well. The device is then ready for testing and measurements, which are conducted outside the nitrogen box.

FABRICATION

The key enabling technology used in fabricating the MHD micro-pump is Deep Reactive Ion Etching (DRIE). Figure 2 shows the fabricated MHD µ-pump presented in this paper. Silicon micro-pins serve as efficient heat-exchangers by significantly increasing the surface-area to volume ratio [11].

Starting with an oxidized 2-mm thick high-resistivity Silicon wafer, the etch pattern is defined by photolithography (using the AZ-9260 photoresist). This is followed by an oxide etch (using Buffered Hydrofluoric Acid). Only the exposed patterns are stripped of the oxide (masked by photoresist). Both the photoresist and oxide layer are used to mask the DRIE pattern. Subsequently the DRIE process is utilized to achieve the patterns shown. Metallization (Ti/Au) is achieved using a Si shadow-mask (hard mask), which is also fabricated by DRIE. Lithography techniques to pattern metal (wet-etch or lift-off) can also be used but give significantly lower yields. The most common issue with cavity lithography is the weak definition of photoresist at sharp edges and vertical side-walls. Shadow masking is used to completely avoid these issues and also provides near-perfect yield. Since DRIE is an expensive tool, yield is crucial to device prototyping and measurement.

Following metallization, liquid Teflon AF is spin-coated at 500 RPM and subjected to the following temperatures for 10 minutes each; 50ºC, 112ºC, 165ºC and 300ºC. This gives a thick robust layer of Teflon (solidified by the bake cycle) on the microchannels. However, Teflon is a dielectric and tends to insulate the electrodes. This is remedied by performing a quick 30 second Oxygen RIE-etch to pattern the Teflon layer. The shadow-mask used for metallization is once again aligned and attached to the wafer to pattern the Teflon layer. In a similar way, Teflon is also patterned on the Pyrex cover piece (not shown in the figure). Once the active surfaces are coated with Teflon, the cover is sealed with the Si device using epoxy. Spin-On-Glass (SOG) has also been successfully used to package the MHD micropump.

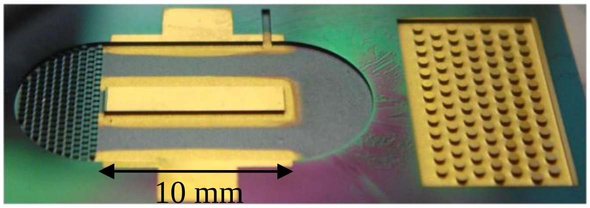

Figure 2: MHD µ-pump fabricated using Silicon MEMS technology with Gold electrodes and micro-pin heat-exchangers

RESULTS

High-speed photography is used to capture the micro-actuation of Galinstan using the MHD pump. The individual frames are subsequently extracted from the video files and linear velocity was estimated in Figure 3. The MHD µ-pump has been tested and linear flow-rate of up to 10mm/s has been measured on 4-mm wide and 0.5-mm deep µ-channels when subjected to 0.4-T B-field and 0.5 V.

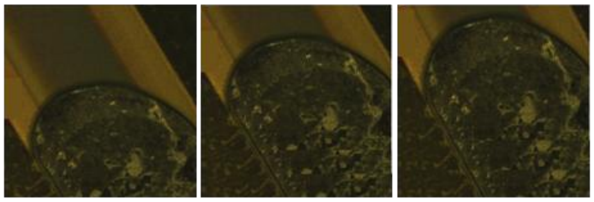

Figure 3: Video Frames showing Galinstan

As expected, a stronger magnetic fields results in faster actuation, as depicted in Figure 4.

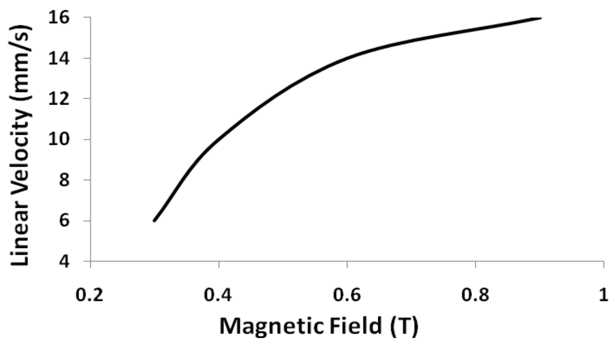

Figure 4: Linear Velocity vs. B-Field

These measurements were taken with power consumption limited to 2 W. The Silicon micro-pins were fabricated to exemplify a configuration where Galinstan micro-actuation could be used for micro-cooling. Since the focus of this paper is actuating Galinstan, the measurements were carried out on devices without the micro-pins. Devices with micro-pins required higher actuation voltages (power) due to the greatly increased microfluidic impedance.

DISCUSSION

It is worth noting that early iterations of this micropump did not have the anti-stiction layer (Teflon) and Galinstan would not move from its original point of injection. The adhesive forces were too strong to overcome. The affinity for oxidation and stiction are strongly correlated with Galinstan. Oxidation will lead to stiction issues. It is therefore crucial to handle Galinstan in an oxygen-free environment and provide hermetic packages for devices that incorporate Galinstan. Performance varies due to changes in surface chemistry, quality of Teflon coating, degree of oxidation, smoothness of the microchannels and a variety of other factors. Reliability is certainly a concern since avoiding oxidation is difficult. Our current research endeavors are targeted to improving reliability of the Galinstan MHD micropump by employing a variety of techniques to combat friction, oxidation and changes in surface chemistry. Power consumption is directly correlated to friction. Hence reducing friction will automatically lower power consumption as well. Lifetime measurements will be conducted to characterize these effects and will be published in our future papers on this topic. We are also developing liquid-metal RF-MEMS devices for high-power applications. These devices will be enabled by the Galinstan micro-actuation technique detailed in this paper.

CONCLUSION

We have demonstrated a novel MHD micropump capable of actuating Galinstan, without any moving parts that are subject to degradation over time. The fabrication has been simplified and optimized for high yield. Linear velocity of up to 10 mm/s has been observed in our experiments using strong permanent magnets, on 4-mm wide and 0.5-mm deep microchannels.

ACKNOWLEDGEMENT

This work has been supported by the National Science Foundation under CAREER Grant No. 0747766.

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