Low-Power Magnetically-Actuated Microvalves for Highly Parallel Microfluidic Automation

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Abstract—This paper presents the design and actuation of low-power, magnetically-actuated microvalves fabricated with CMOS-compatible technology. A prototype chip comprised of 64 microvalves within $2.2 \times 2.2 \text{ mm}^2$ and requiring $< 50 \text{ mW}$ to actuate is demonstrated. Each valve consists of a microcoil and a paramagnetic bead as the valve seat, and is used to address a 50 picoliter well to enable highly parallel biochemical sensing and analysis operations.

I. INTRODUCTION

Miniaturized microfluidic devices offer the potential to replicate the functionalities of an entire lab at the chip scale. Integrating microfluidic devices with existing computing systems yield greater control over microliter reactions in sensing and analysis endeavors to the user. Microvalve control and automation of fluidic transport is essential in microfluidic devices, but successful actuation may require macroscale external support [1] and complex fabrication process steps.

One simple valve design is the ball valve. Manipulation of micron-scale magnetic spheres has been demonstrated but required high current levels [2, 3], raising heating issues when large numbers of valves are simultaneously actuated. Recent magnetically-actuated micro ball valves are bulky and consume $> 0.5\text{W}$ [4, 5].

Here, we use 100 µm paramagnetic spheres to seal each picoliter well, reducing actuation power below 50 mW (10-fold) to enable large-scale microfluidic automation to perform highly parallel biochemical operations such as simultaneous synthesis of hundreds of DNA structures.

II. MICROVALVE DESIGN AND FABRICATION

Fabrication of prototype planar microcoils is completed in a two-metal process. A thermal oxide is grown on a silicon substrate wafer. Photolithography is used to pattern the two Ti/Au metal layers, which are deposited via e-beam evaporation. SiO$_2$ is deposited as a dielectric insulation layer between the two metal layers. The 46 µm diameter wells are etched via silicon DRIE. A 1 µm Parylene C layer is applied by vapor phase deposition to insulate the device for fluidic operation, and a PDMS gasket seals the finished chip to a glass coverslip. Fig. 1 shows an optical image of a completed 64 microcoil array.

Microvalves are self-assembled by magnetically capturing paramagnetic spheres dispersed in DI-H$_2$O flushed across the chip surface. Two different paramagnetic beads were used in experiments: FeSi powder from Höganäs, and Fe$_3$O$_4$ beads in soda lime glass shells (glass/Fe$_3$O$_4$) with a 50% vol. to vol. ratio from MoSci. An external biasing magnetic field magnetizes the spheres. The polarity of the current applied to each microcoil determines the direction of the local field gradient, allowing bidirectional actuation to open and close each valve at a modest current level. Fig. 2 shows an illustration of the microvalve.

III. EXPERIMENT

The experimental setup is shown in Fig. 3. The finished chip is wirebonded to a chip carrier package and tested on a printed circuit board (PCB). A LabVIEW-generated analog voltage signal is sent from a National Instruments data acquisition (NI-DAQ) card to the board through a bipolar power amplifier. The biasing field is provided using either a permanent magnet or a Helmholtz coil pair. The coil requires an additional power supply but enables adjustment to the bias.

Fig. 1. Optical image of completed 64-microvalve array. Inset is an SEM image of an etched well at the center of a microcoil.
field during characterization experiments. A digital camera with an optical zoom is utilized for capturing microvalve switching between open and closed states.

FeSi and glass/Fe$_3$O$_4$ paramagnetic beads were actuated in both DI-H$_2$O and in air. The beads were actuated on microcoil chips with and without etched wells. The magnetic properties of the two bead types (FeSi and glass/Fe$_3$O$_4$) were characterized with a Vibrating Sample Magnetometer (VSM). We weighed a sample of each type of bead and scattered them on top of glass slides coated with a thin layer of rubber cement. Each glass slide was mounted on a sample glass rod for VSM measurements.

IV. RESULTS

A. Bead actuation on devices without wells

Actuation experiments were conducted using FeSi spheres with diameters ranging from 24 µm to 110 µm on devices without wells. Current pulses of positive and negative polarity open and close each valve. The threshold current, defined as the minimum current required for achieving the full 75 µm actuation stroke, was measured as a function of bead diameter and is plotted along with the minimum actuation power in Fig. 4. For sphere diameter < 70 µm, the observed threshold current has a quadratic dependence on bead diameter, suggesting that while magnetic force scales with volume, the opposing stiction force increases with diameter.

The maximum switching frequency of a 108 µm sphere on a microcoil was 33 Hz, measured by applying a bipolar 3 mA signal to the microcoil and sweeping the frequency until bead motion stopped. This measurement agrees well with the typical switching time of 15 ms observed for 108 µm spheres.

B. Bead actuation on devices with wells

Actuation experiments performed on devices with etched wells show that valve opening and closing occur at two threshold currents, $I_{\text{OPEN}}$ and $I_{\text{CLOSE}}$. For a 134 µm FeSi bead that was actuated with a square wave, $I_{\text{CLOSE}} = 18.9$ mA and $I_{\text{OPEN}} = -10$ mA. Once the valve is closed, it remains sealed when subthreshold current pulses are applied, as illustrated in Fig. 5.

The repeatability of opening and closing of the microvalve was also investigated. Beads were actuated multiple times over the same microcoil, and $I_{\text{OPEN}}$ and $I_{\text{CLOSE}}$ were noted for each sequential cycle. Both $I_{\text{OPEN}}$ and $I_{\text{CLOSE}}$ magnitudes decreased slightly over time for FeSi beads in DI-H$_2$O, as seen in Fig. 6. The first and second $I_{\text{OPEN}}$ and $I_{\text{CLOSE}}$ values are quite large compared with the later switching values. Measurements conducted in DI-H$_2$O show more repeatable threshold currents than measurements in air due to the increased damping provided by the fluid which prevents the bead from overshooting the edge of the coil.
Glass/Fe$_3$O$_4$ actuation experiments in DI-H$_2$O and in air also reflect the above trends. Fig. 7 indicates that $I_{\text{OPEN}}$ and $I_{\text{CLOSE}}$ for air and DI-H$_2$O are comparable and have a downwards trend, but $I_{\text{OPEN}}$ and $I_{\text{CLOSE}}$ have a wider range when sequentially switching in air. Since the glass/Fe$_3$O$_4$ beads have a protective soda lime glass shell surrounding the magnetic material, the beads do not corrode in H$_2$O. As a result, we can switch a microvalve open and close a larger number of times with glass/Fe$_3$O$_4$ beads compared to microvalves assembled with FeSi beads.

V. FEM Modeling and Discussion

Based on experimental data and measured magnetic characteristics from the VSM measurements, we performed Finite Element Method (FEM) modeling using COMSOL 4.3a to approximate the amount of force the microcoil exerts on the bead.

We use a 2D model to map out the magnetic flux surrounding the 10-turn microcoil when the microcoil is driven by experimental threshold currents. The radial force exerted by the microcoil on the bead is approximated using

$$F_{\text{R,COIL}} = \chi H_{\text{ext}} V \frac{dB}{dr}$$

(1)
where $\chi$ is the susceptibility of the bead, $H_{ext,z}$ is the external biasing field, $V$ is the volume of magnetic material in the bead, and $dB_z/dr$ is the radial magnetic flux gradient created from the microcoil. Assuming the bead center is one radius above the 10-turn coil, we evaluate $dB_z/dr$ at that height above the microcoil using the experimentally measured threshold currents, and multiply that with the susceptibility of the bead obtained from the VSM measurement, the external biasing field applied to the microvalve during the experiment, and the measured bead radius to calculate the in-plane radial force.

Fig. 8 illustrates the radial forces, $F_{R,\text{CLOSE}}$ and $F_{R,\text{OPEN}}$, applied to a 114 µm FeSi bead in DI-H$_2$O to close and open the microvalve. The threshold currents for this bead are $I_{\text{CLOSE}} = 7.4$ mA (43 mW) and $I_{\text{OPEN}} = -5.2$ mA (21 mW), and the external biasing field is 9 mT. We use the FEM force model to model the forces for different-sized beads actuated in DI-H$_2$O and in air, and plot the peak $F_{R,\text{CLOSE}}$ against bead diameter in the inset of Fig. 8.

Fig. 8 shows that the force required to close the valve scales with bead diameter. The major forces opposing bead motion in the experiments are viscous (Stokes) drag force and stiction, both of which have a linear dependence on bead radius. However, since the peak $F_{R,\text{CLOSE}}$ are similar for beads actuated in air and in DI-H$_2$O, it appears that viscous drag force is minimal and that stiction is the dominant force.

VI. CONCLUSIONS

We have demonstrated the feasibility of magnetic actuation of large paramagnetic beads using low-power microcoils and formation of large array of microvalves that can be independently controlled in a highly parallel fashion. We have actuated two types of paramagnetic beads of various diameters and in dry and wet settings. While we can approximate the forces applied to the beads by the microcoils using FEM modeling, the actual forces exerted on the beads remain to be investigated in greater detail. For the future, we will further evaluate the magnetic microvalve in leakage experiments.

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REFERENCES