Supporting Information for

Co-Fabrication of Electromagnets and Microfluidic Systems in Poly(dimethylsiloxane)

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Materials. We used the following materials and equipment: Sylgard 184 (Dow Corning), 100% In solder (AIM Solders, mp = 156 ºC), 52% In, 48% Sn solder (AIM Solders, mp = 117 ºC), 3-mercaptopropyltrimethoxysilane (Gelest), Micro-mate glass syringe (10 mL) wrapped in silicone heating tape (52 W, 0.5" × 2"), Digital hotplate (PMC Datamate 720), copper wires (Digikey, 200 μm diameter), photocurable polyurethane (Norland NOA81), Nanograbber™ alligator clips (Pomona), DC power supplies (BK Precision 1715 and Agilent E3630A), function generator (Agilent 33120A), superparamagnetic beads (Bangs Laboratories, 5.91 μm diameter, polymer: COMPEL™ magnetic, COOH modified), and a Harvard syringe pump (Harvard Apparatus, flow rate ~10 μL/hr).

Fabrication of Microfluidic Channels. We fabricated microfluidic structures according to the procedure illustrated in Figure 1A. The master of the microfluidic channels was fabricated in SU-8 photoresist (MicroChem, Inc) on a silicon wafer using a procedure described previously by Duffy et al.[21] The master was silanized with (tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane overnight. PDMS (Sylgard 184, mixed at a ratio of 10:1 base:curing agent) was poured on the master, cured thermally, and peeled away. Inlet and outlet holes were punched into the layer of channels using a needle (16 Gauge = 1.65 mm diameter).

We exposed the PDMS and a glass or PDMS substrate to an oxygen plasma for 1 min, and brought the PDMS and substrate in contact to form a permanent seal. Within 15 min of plasma oxidation, we flowed a solution of 3-mercaptopropyltrimethoxysilane in acetonitrile (0.1 M) into the network of microfluidic channels and stored the device at 22 ºC until the solution had evaporated out of the microfluidic channels (~1 hr). This

process coated the inside surface of the microfluidic channels with a silane that reduced the surface free energy and made it possible to wet the walls with liquid solder.

Injection of Liquid Solder. We filled a glass syringe (10 mL, MicroMate Inc) wrapped in silicone heating tape (Daigger Inc) heated to ~200 ºC, with liquid solder (5 g, 100% In or 52% In, 48% Sn, AIM Solders Inc). We placed the device with microfluidic channels on a hotplate set to 200 ºC. Solder was injected into the microfluidic channels of the device by inserting the tip of the syringe into one inlet of the microfluidic channel and applying pressure to the syringe. Liquid solder quickly filled the channels (< 1 sec).

Cooling the solder forms electrical wires. We inserted copper wires (Digikey Inc, 200 μm diameter) into the inlet and outlet holes of the solder channels when the solder was still liquid. We then removed the device from the hotplate and cooled it to 25 ºC on a glass plate. The solder solidified into the shape of the system of microfluidic channels; this process also fixed the copper wires into place at the inlets and outlets of the channels. We applied and cured a photocurable polyurethane (NOA81, Norland Products, Inc) to the point of contact of the electrical wires and the solder to reinforce the mechanical connection between the copper wires and the solder wires. We attached nanograbber™ alligator clips (Pomona Inc) to the copper wires in order to connect the external electrical wires and the network of solder structures embedded in the PDMS.

Electronic Setup. Figure S1 shows a schematic diagram of the electronic circuit used to drive the electromagnets for the experiments in this paper. A 10 V power supply (BK

Precision, Inc), and a dual 6V, 10V power supply (Agilent, Inc), were connected to the circuit. A signal of variable amplitude and frequency was applied to the circuit using a function generator (Agilent, Inc). An increase in the amplitude of the signal increased the current through the electromagnets and increased the intensity of the magnetic field.

Temperature Characteristics of Electromagnets. Electrical current passing through a metallic wire produces Joule heating, causing the temperature of the wire to increase. The increase in the temperature of the wire can be calculated from Equation (S1), where T_{max} is the maximum temperature of the wire (ºK), T_{ref} is the temperature of the glass substrate (ºK), p is the thickness of the substrate (m), σ is the conductivity of the wire ($1/\Omega \cdot m$), k is the thermal conductivity of the substrate ($W/m \cdot ºK$), t is the thickness of the wire (m), and w is the width of the wire (m).

$$T_{max} - T_{ref} = \frac{pI^2}{\sigma k t w^2} \quad \text{(S1)}$$

We devised a model based on Equations (3) and (S1) to determine the width of a wire that would generate the maximum force upon a superparamagnetic bead without exceeding a maximal steady state temperature. Using an average bead diameter of 5.9 µm, $\chi = 0.170$, x = 30 µm, p = 700 µm, $\sigma = 1.20*10^7$ $1/(\Omega \cdot m)$, k = 1.12 W/(m ºK), t = 40 µm, a substrate temperature T_{ref} = 22 ºC, and a maximum steady state temperature T_{max} = 50 ºC, we determined a maximum force of 1.71 pN for a wire approximately 120 µm wide (Figure S2). We constructed all of the electromagnets in this paper using wires with this optimal width.

Derivation of the time to move a superparamagnetic bead across a microfluidic channel

Two forces act on a superparamagnetic bead in a microchannel: the magnetic force, F_x, [Eq. (3)] and the Stokes force, F_s, due to the viscous drag exerted by the suspending liquid [Eq. (S2)]. In Equation (S2), η is the dynamic viscosity of the suspending medium (10^{-3} kg·(m·s)$^{-1}$), v is velocity of the bead (m·s^{-1}), and R is radius of the bead (m):

$$F_s = -6\pi\eta v R \tag{S2}$$

The balance of forces (in the x-direction) acting on a superparamagnetic bead in the microchannel is given by Equation (S3):

$$ma = F_s + F_x \tag{S3}$$

Neglecting the inertia of the bead ($ma = 0$) and substituting the equations for the magnetic force F_x [Eq. (3)] and the Stokes force F_s [Eq. (S2)] produces Equation (S4):

$$0 = 6\pi\eta v R - V\chi\mu_0 \frac{{I_{wire}}^2}{2\pi^2 x^3} \tag{S4}$$

For a superparamagnetic bead moving in the negative x-direction (towards the electromagnet), Equation (S4) can be simplified into Equation (S5).

$$V\chi\mu_0 \frac{{I_{wire}}^2}{2\pi^2 x^3} = 6\pi\eta R(-\frac{dx}{dt}) \tag{S5}$$

Separating the independent variables in Equation (S5) and expressing the volume of bead in terms of its radius produces the Equation (S6).

$$\frac{1}{9}\frac{\chi\mu_0}{\pi^2\eta} R^2 {I_{wire}}^2 \cdot dt = -x^3 \cdot dx \tag{S6}$$

Integrating Equation (S6) from the initial position of the superparamagnetic bead, *b*, to the position of the sidewall of the microfluidic channel, *a*, produces Equation (S7).

$$\frac{1}{9}\frac{\chi\mu_0}{\pi^2\eta}R^2{I_{wire}}^2\cdot\int_0^{t_{cap}}dt=-\int_b^a x^3dx \tag{S7}$$

Solving Equation (S7) for t_{cap} produces an equation [Eq. (S8)] for the time required to move a bead across a microfluidic channel.

$$t_{cap}=\frac{9}{4}\frac{\pi^2\eta}{\chi\mu_0R^2}\cdot\frac{(b^4-a^4)}{{I_{wire}}^2} \tag{S8}$$

Magnetic capture experiments. Superparamagnetic beads were suspended in buffer (2% bovine serum albumin, 0.05% Tween 20, 0.1% NaN_3 by volume) at a concentration of approximately 5×10^8 beads/mL before adding them to the channel. The suspension of beads was injected into the microfluidic channel using a syringe; the beads were motionless and dispersed uniformly throughout the channel prior to the start of the experiment.

Figure S1: Schematic diagram of the electronic circuit used to drive the pair of electromagnets in the experiments in this paper.

Figure S1

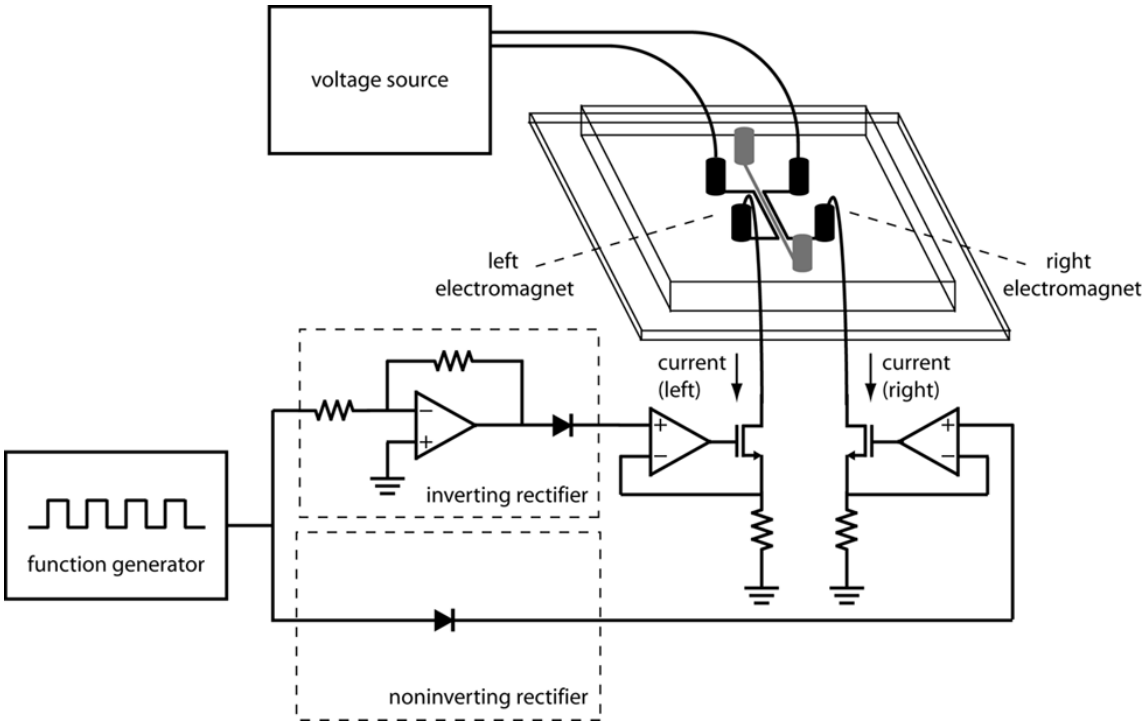
voltage source
left
electromagnet
right
electromagnet
current
(left)
current
(right)
inverting rectifier
function generator
noninverting rectifier

Figure S2: The a) maximum current, b) magnetic field, and c) force upon a magnetic bead calculated from equations (1), (3), and (S1). We assume the following parameters: bead diameter = 5.9 μm, $\chi = 0.170$, x = 30 μm, p = 700 μm, $\sigma = 1.20*10^7$ mhos/m, k = 1.12 W/(ºK m), t = 100 μm, a substrate temperature T_{ref} = 22 ºC, and a maximum steady state temperature T_{max} = 50 ºC. Using these parameters, we determined a maximum force of 1.71 pN for a wire width of approximately 120 μm.

Figure S2