Magnetic connectors for microfluidic applications

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Supplementary information

Materials

(Tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane was bought from United Chemical Technologies)

The annular grooves in connector E were milled with a MicroMill 2000 from MicroProto Systems. The NdFeB magnets as obtained were coated with a metal or resin to prevent exposure of the material to oxygen and degradation of its magnetic properties. The magnets were machined for the O-Ring configuration as proof of principle. However, the proper way to develop the magnets would be to send the design to the vendor and have the magnets fabricated with the proper geometry and coated, because the NdFeB is prone to oxidation and corrosion after milling. Oxidation is not a problem with Samarium Cobalt Magnets (SmCo), but they have less energy density than NdFeB magnets. The magnets used in Connector E are half the height of those used for connectors A, B, C and D. Thus, we stacked two magnets together to have a final connector E of the same dimensions (h=6.4 mm).

Placing the connectors

Note: Special care should be taken when handling NdFeB magnets as they may rapidly collapse together pinching anything in between.

Connector A, B, C or D. These types of connectors have a sticky sealing gasket that makes them especially simple to align and assemble. First, the connector is placed on top of the wafer aligned with the inlet and pressed gently into position over the inlet; the adhesive gasket maintains the connector's position. Second, the backing magnet is placed on the back of the wafer (around 1 cm from the site of the connector) and brought gently to its position. While the backing magnet tends to slide directly to the bottom of the connector, the connector does not slide due to the adhesive sealing gasket. At this point the connection is ready to be used.

To place a second connector the same steps need to be done. We found no problem in placing a second connector if the spacing between connectors is 1 cm or more. Less than that (up to 7 mm), one needs to be careful when bringing the second connector close to the first one. Still, if they collapse, the first one will remain in place and the second one is easily removed.

Connector E. This connector has non-sticky O-rings as sealing gasket. For the application of liposome formation we glued the backing magnets to a supporting stage and then placed each top connector individually. The spacing between connectors was ~1.5 cm, and we had no problems assembling or disassembling the connectors.

Simulations of magnetic force

Simulations of magnetic force between magnets were performed with Comsol Multiphysics (version 3.4). The models used in the simulations were validated by measuring the magnetic field between two magnets with three different configurations using a tesla meter (620, FW Bell) and a probe (STB4-0404, FW Bell). The results agreed to within 10%, as shown in table 1.

Table 1 shows the results of the simulated and measured densities of the magnetic field density between two magnets (KJ magnets, D84) separated by different distances . The field density distribution at the airgap was initially obtained from simulations using the Magnetostatics module of COMSOL. Once the model was validated (the results were within the tolerance of 10% given by the vendor for the remnent magnetic induction, Br), the attraction force between magnets was simulated using the AC/DC module of Comsol.

Airgap	Diameter	Height	B_{max} simulated	B measured
1 mm	12.7 mm	6.35 mm	0.86 T	0.95 T
2 mm	12.7 mm	6.35 mm	0.78 T	0.84 T
3 mm	12.7 mm	6.35 mm	0.71 T	0.75 T

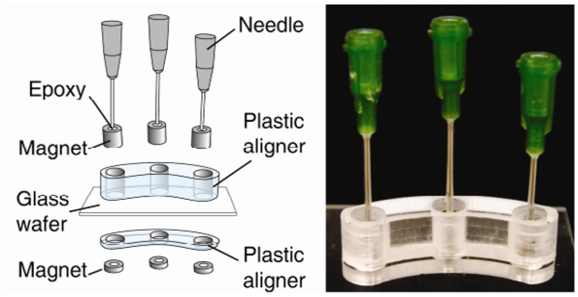

Fig. S 1. A plastic aligner can help to keep magnets in place against the forces exerted by neighboring connectors. Two pieces of plastic with drilled holes were used to maintain the magnetic connectors vertically and to avoid connector tipping due to magnetic interactions.

Plastic aligner for multiple connections

A 6 mm thick poly(methylmethacrylate) (PMMA) stock (McMaster-Carr) was milled and holes were drilled to seat the magnetic connectors in the desired geometry (Fig. S1). This aligner served to confine the magnets against forces between the magnets or other external lateral forces (e.g., torque from stiff tubing) that could cause the magnetic connectors to tip and leak. Such forces would be most detrimental for magnets having large height to diameter ratios.

Leakage tests set up

Magnetic connectors sandwiching two glass slides (1 mm thickness each) were connected to an in-house air pressure system and immersed in a tank with water. The pressure was ramped at different time intervals until bubbles appeared around the connector. The pressure was monitored with a general purpose digital gauge (690 kPa max, Ashcroft).

Initially, we used 1 mm thick glass slides as the substrate material, but we were unable to experimentally determine the rupture pressure due the limitations on the in-house air pressure system, which had a maximum pressure of 550 kPa (a pressure to low to induce leakage). Therefore, all the experiments were conducted with two stacked glass slides with total thickness s = 2 mm.

Leakage tests using connectors C and D

Initially, we tried to cure a PDMS gasket directly to the magnet. These gaskets delaminated easily from the magnets, though these connectors withstood pressures of up to 414 kPa (60 psi) if the PDMS stayed sandwiched between the magnet and the substrate. Even if leakage did not occur, the gasket detached from the magnet after repeated use. Gluing the PDMS to the magnet did not improve the seal, and the best results were obtained using double-sided polyimide tape between the PDMS gasket and magnet.

Liposome Synthesis: Methods

Phosphate buffered saline packets (pH 7.4, PBS) were purchased from Sigma Aldrich. Isopropyl alcohol (IPA) was purchased from J.T. Baker, Inc. Dimalitoyl phosphatidylcholine (DMPC) and cholesterol were obtained from Avanti Polar Lipids, and dicetyl phosphate (DCP) was obtained from MP Biomedicals. The 100 mm diameter silicon and borosilicate glass wafers were obtained from UniversityWafer.com.

The free terminus of the tubing epoxied to the magnetic connector with O-Ring was pressure fitted into 0.2 µm filters attached to a syringe. Five of these syringes were placed in syringe pumps (Harvard Apparatus, Model 11 Pico Plus) that controlled the flow rates. The microfluidic channels were etched in a ~550 µm thick Si wafer using deep reactive ion etching to obtain a width of 65 µm and a depth of ~260 µm. A 500 µm thick borosilicate glass wafer with ~1 mm diameter drilled access holes aligned to the ends of the channels was anodically bonded to the Si wafer. The volumetric flow rate was 200 µL/min with buffer:IPA flow-rate ratios of 49:1, 29:1, and 19:1. The IPA contained a 5:4:1 molar ratio mixture of DMPC:Cholesterol:DCP at a total concentration of 5 mM. The size distributions of the liposomes were obtained using asymmetric flow field-flow fractionation with multi-angle laser light scattering (DAWN EOS, Wyatt Technology, Santa Barbara, CA) as described previously[8, 9], except using the Berry plotting formalism to fit the angular static light scattering data.

Liposome formation in a platform using magnetic connectors

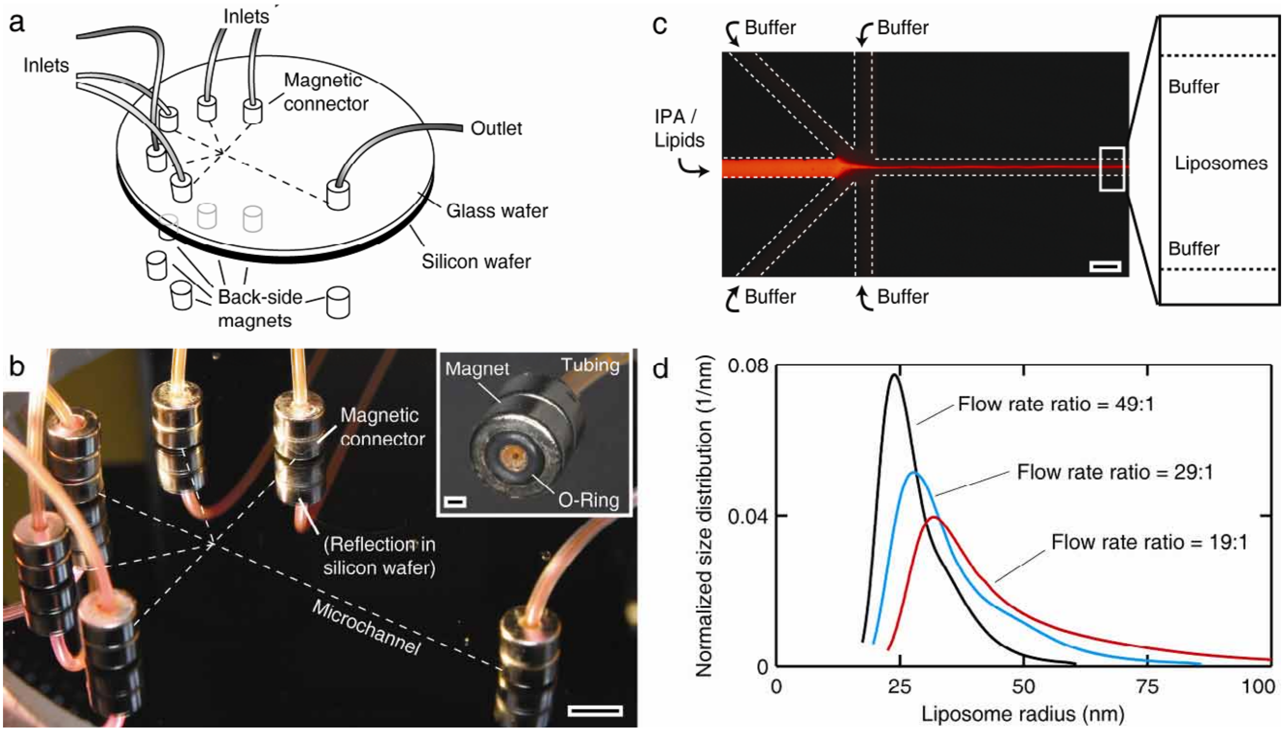

Fig. S 2. Generation of liposomes in a chip using magnetic connectors. **a-b** The chip has five inlets and one outlet, with all inlets connected to syringe pumps via tubing and magnetic connectors. The inset in (b) shows the bottom contact surface of a single connector: the first magnet has a machined semi-circular annular groove where an O-ring is placed (not glued). When the connector is placed on top of the chip, it aligns to a magnet on the other side of the wafer. The magnetic force seals the O-ring to the wafer, which prevents buffer and IPA (Isopropyl Alcohol) from leaking. **c** Lipids (and Rhodamine B) suspended in IPA are introduced in the chip through the center inlet. Buffer is introduced through the 4 outlying inlets, which hydrodynamically focuses the IPA/lipid stream. The buffer and IPA/lipid streams mix through controlled diffusion, resulting in the self-assembly of lipids into liposomes. **d** Liposome size distributions at different flow-rate ratios of buffer to IPA/Lipids. The displayed curves were normalized to have an area equal to 1. These results demonstrate the generation of liposomes in a microfluidic device using magnetic connectors for world-to-chip interfacing. Scale bars: **b** 5 mm, **b** inset 1 mm, **c** 100 µm

Liposome formation was achieved in the device shown in Fig. S2. The liposome formation process diffusively mixes two miscible liquids (phosphate buffered saline and IPA) and is not to be confused with microdroplet formation, microemulsions, and water-in-oil emulsions, which all use immiscible liquids. As lipid dissolved in IPA is mixed with buffer, the amphiphilic molecules self-assemble into thin bilayer membranes, which close into spherical shells called liposomes. The bilayer membrane sequesters the internal aqueous volume from the external surrounding volume.