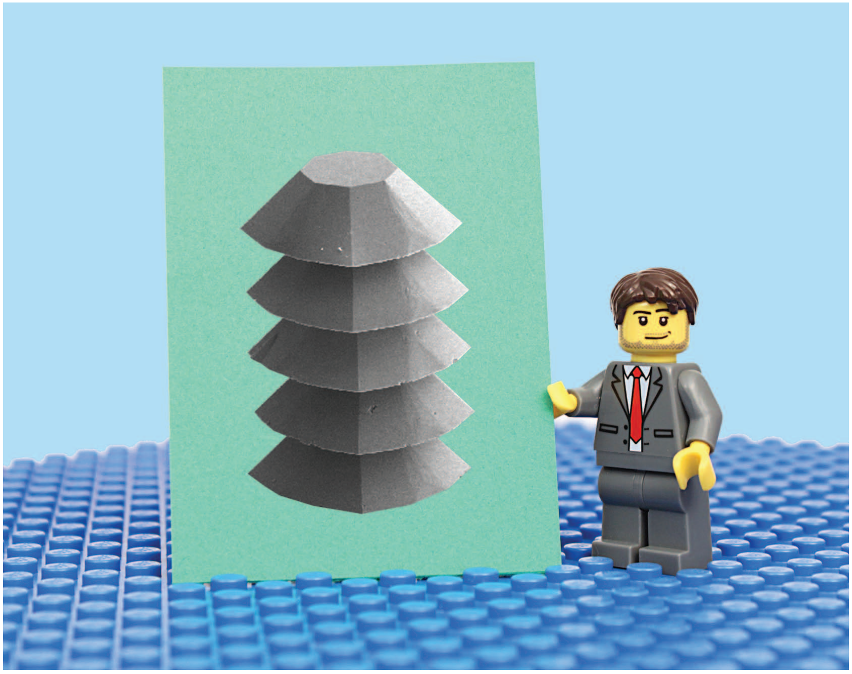
LEGO-like microassembly using reversible dry adhesion

Seok Kim

When I was a kid, I was fascinated by watching water striders glide on the water and would wonder: why do they not drown but instead play, standing effortlessly on the water? This is undoubtedly a common question among curious children. The simplest answer would be "because the insect is very small and light." So then, why are smaller things better able to float on the water? An aircraft carrier can easily float on the sea too, although it is extremely large.

As I got older, I gradually learned that things in different sizes are governed by different external forces. For example, a water strider floats dominantly due to surface tension, while buoyancy lifts and allows an aircraft carrier to cruise. Indeed, surface tension is one of the most dominant and often the most troublesome force at the micro- or smaller scale, unless things are so small that classical mechanics are no longer valid.

Consider the following example: Body weight or buoyancy is linearly proportional to body volume, i.e., its length cubed. In the same way, surface adhesion or friction increases linearly as surface area, or length squared, increases. Surface tension



is just directly proportional to length. Thus, if a body is doubled isometrically, its length, surface, and volume would increase by factors of two, four, and eight, respectively. This implies that buoyancy or body weight would be more dominant than surface tension or surface adhesion at larger scale, and vice versa.

Different scales need different manufacturing methods

Once this conclusion is reached one may imagine that common macro world manufacturing methods may not necessarily be suitable for small-scale manufacturing. At the microscale, sawdust or drill debris would tend to stick to saws or drill bits because of the vanishing ratio of inertia to surface adhesion, and as a result, cutting or coring would be more difficult at smaller scale. This is why common manufacturing approaches at the microscale rely on a diverse set of electrochemical process sequences to build microscale structures.

Microfabrication is a popular, all-encompassing name to describe

Digital Object Identifier 10.1109/MPOT.2016.2540042
Date of publication: 20 July 2016

0278-6648/16©2016IEEE

these many processes. Typical microfabrication involves multiple process cycles starting with a thin film (from submicron to a few micrometers) of material deposited on a flat substrate under vacuum conditions. Since the target material film covers the entirety of the substrate, a lithography step follows to form a patterned photoresist layer that acts as a masking layer for the subsequent thin-film etching step, thus defining the thin film's desired shape. This may be the first of many similar process cycles to be conducted sequentially on the substrate until an intended structure is completed.

As all processes are done on a single substrate, this form of microfabrication can be defined more specifically as *monolithic microfabrication*. Microfabrication has been a very successful high-precision micromanufacturing method for mass production of integrated circuit (IC) chips and microelectromechanical systems (MEMS) devices, which are composed of micro- or nanoscale constituents.

Nevertheless, microfabrication inherently suffers from a variety of challenges, such as the high cost originating from vacuum processes; difficulty with the recycling of etched materials, which often constitute a majority of a deposited film; complications with creating three-dimensional architectures; and significant limitations when attempting to combine different classes of materials. These challenges originate from the layer-by-layer thin-film processing of a single substrate and the fact that dissimilar materials often require different and incompatible techniques to process. Consequently, the development of novel micro-devices with improved performance or new functionality often requires independent fabrication of constituents followed by microassembly, rather than monolithic microfabrication.

Microassembly combined with microfabrication advances micromanufacturing

Microassembly is generally classified into two categories: 1) robotic pick-and-place including contact and noncontact modes and 2) self-assembly relying on the principle of minimum total potential energy. Robotic pick-and-place commonly uses microgrippers, such as mechanical tweezers or other end effectors operated by electrostatic, magnetic, capillary, optical, or vacuum effects. This approach can perform very complex handling tasks utilizing machine vision, force sensing, and feedback control. However, it is very difficult to release a micro-object once gripped with a contact mode microgripper, since surface adhesion dominates over body weight at the microscale. Without proper strategies to overcome surface adhesion between a micro-object and microgrippers, releasing processes are very tedious and time-consuming, if not impossible.

The development of such novel microsystems with improved performance or new functionality often requires independent fabrication of constituents followed by microassembly, rather than monolithic microfabrication.

Moreover, microgrippers may damage micro-objects, and such manipulations are not easily preformed in parallel, thus scaling the approach to allow for mass production is generally not feasible.

Self-assembly is performed by designing the system with the desired assembling positions of micro-objects that correspond to the minimal potential energy of the system. Therefore, the assembly naturally forms using gravitational, capillary, or electrostatic forces as the driving potential. Since self-assembly uses the minimum total potential energy principle, it can be done in parallel for higher throughput. While self-assembly is well suited for multi-batch processes, it suffers from poor design flexibility and often poor yield due to the misassembly of parts when the system is stuck in its local potential energy minimum.

Each approach has different advantages and disadvantages so that each one can be used for different needs or purposes. However, the need remains for a manufacturing approach that can allow for both strong flexibility of design and scalable manufacture.

Transfer printing using reversible dry adhesion

To enable deterministic and parallel manipulation of micro-objects, transfer printing, involving the use of smart dry surfaces with highly reversible adhesion (i.e., reversible dry adhesives) has been studied in many different forms for the last several years. Among these, a microstructured elastomeric surface designed using strategies of biomimetic dry adhesives provides extreme, reversible levels of switchability of nonspecific, generalized adhesion. This design turns out to be highly effective for controlling surface dry adhesion to pick and place micro-objects and possibly in parallel mode for process scalability.

This microstructured elastomeric surface can repeatedly switch its dry adhesion as a function of drastic contact area change upon mechanical loading. Figure 1 presents the surface with a microplatelet in its strong and weak adhesion states (i.e., adhesion ON and OFF), which corresponds to pick and place modes, respectively. When the microplatelet is in contact with a receiving surface and their intermolecular interaction is sufficient, the microstructured surface in its adhesion OFF state can release the microplatelet.

How to join adjacent micro-objects

While transfer printing has shown enormous potential toward highly scalable heterogeneous materials integration, it natively addresses

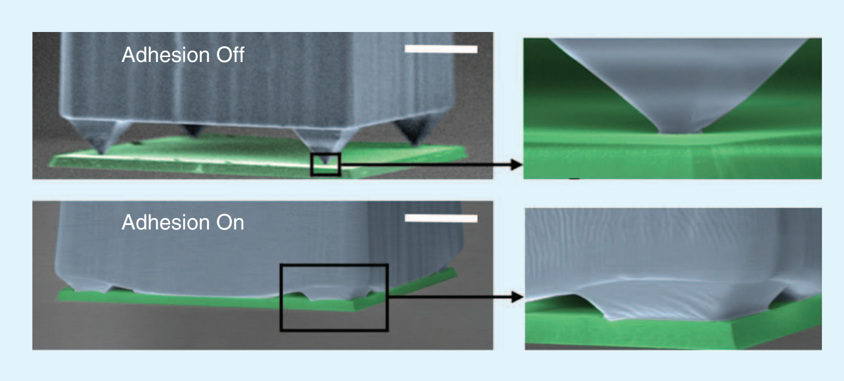


FIG1 The colored scanning electron microscope (SEM) images of a microstructured elastomeric surface representing its strong and week adhesion states (i.e., adhesion ON and OFF), in which microplatelets appear green. Scale bars are 20 μm. (Reproduced with permission from S. Kim et al., 2010.)

only manipulation of micro-objects from the microassembly point of view. Microassembly-enabled functional devices may only be considered complete when the manipulated objects are finally joined together, not only mechanically but also electrically, thermally, and optically, as each application requires. Strategies of material joining have been extensively studied in the MEMS field, where two wafers of homogeneous or heterogeneous materials are brought together, pressed to enhance their intimate contact, and annealed to cause direct bonding that forms covalent bonds at the atomic level.

Similarly, micro-objects may be joined based on covalent or metallic bonds simply by annealing after transfer printing. Whereas the bonding of large wafers is highly sensitive to surface defects, which ruin intimate surface contact and therefore bond quality, the likelihood of surface defects tends to decrease as an object becomes smaller, particularly when its surface is small compared to the surface defect density. Once micro-objects are placed, they can be annealed and joined without any pressing step to enhance intimate contact in most circumstances. Intermolecular force between the micro-object and substrate is enough to form their intimate contact.

Microassembly of heterogeneous materials relying on transfer printing and thermal annealing, so called *micro-LEGO*, is a new approach that complements monolithic microfabrication.

Different joining mechanisms are adopted for different material pairs at the interface of two micro-objects. For example, two silicon objects are joined through fusion bonding, while a silicon-to-gold interface is formed through eutectic bonding, each process involving its own processing conditions of temperature and duration.

LEGO-like microassembly

Microassembly of heterogeneous materials relying on transfer printing and thermal annealing, so called *micro-LEGO*, is a new approach that complements monolithic microfabrication. This assembly is referred to as *micro-masonry* or *micro-LEGO* due to the similarities in the aspects of stacking and joining of disparate classes of building blocks while at different scales. Target materials are processed into transferrable micro-objects, assembled into spatially organized three-dimensional (3-D) architectures via reversible adhesion-based transfer printing and thermal annealing-based material joining.

Figure 2 depicts the general procedure of micro-LEGO, where micro-objects are first formed such that they are weakly tethered to a donor substrate and they can be retrieved by a microstructured elastomeric surface, i.e., a reversible dry adhesive. Those micro-objects are repeatedly retrieved, delivered, and placed onto a receiving substrate, then joined through thermal annealing. This approach has allowed not only the construction of teapot-, pagoda-, and motor-like 3-D silicon microstructures, but also the assembly of a micromirror device with silicon platelets and conductive elastomers as demonstrated in Fig. 3. These 3-D heterogeneous

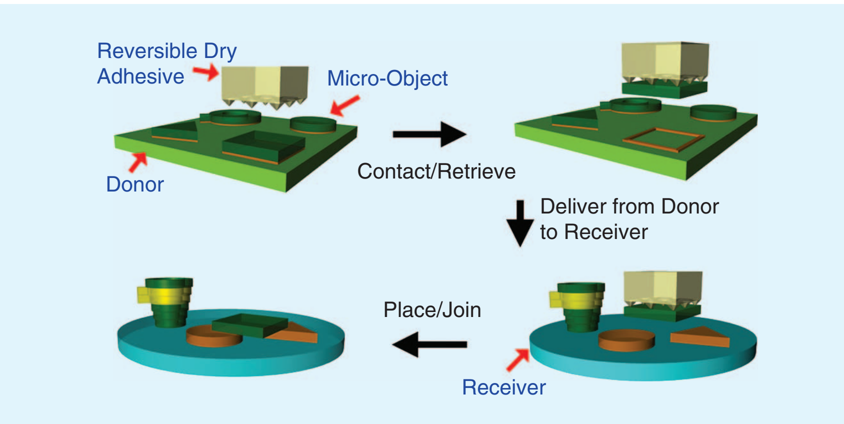


FIG2 The procedure of LEGO-like microassembly including micro-object retrieval using a microstructured surface with reversible dry adhesion, delivery to the target location of a receiver, and placing and joining of the micro-object on the receiver.

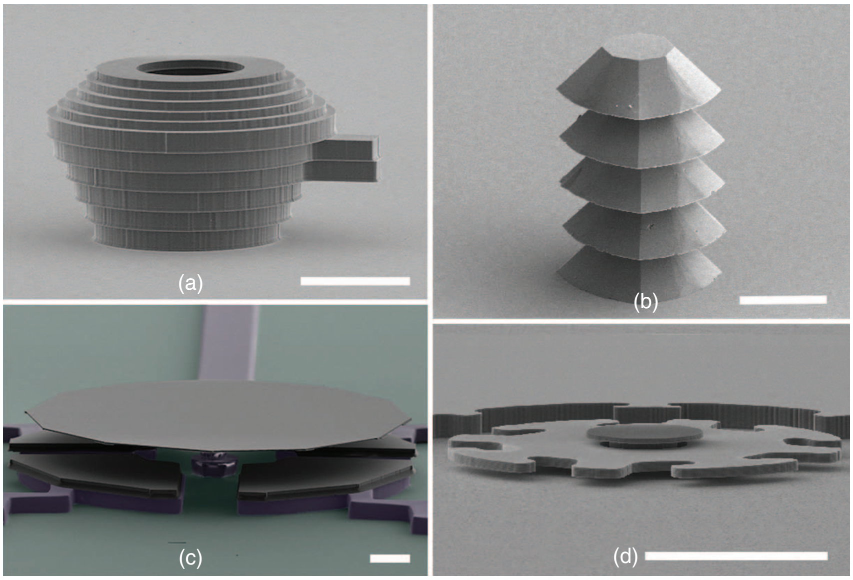


FIG3 Exemplary microstructures and a microdevice fabricated by LEGO-like microassembly. Micro-teapot, (b) a micro-pagoda, (c) a micro-mirror device, and (d) micromotor structures. All are made of silicon (gray) and conductive (purple) or nonconductive (green) elastomers. Scale bars are 100 μm. (Reproduced with permission from H. Keum, et al., 2012; J.D. Eisenhaure, et al., 2016; and Z. Yang, et al., 2015.)

architectures of assembled structures and devices are extremely challenging, if not impossible, to reproduce via conventional monolithic microfabrication or other microassembly techniques, such as those based on robotic pick and place and self-assembly.

While miniaturized electronic device manufacturing has and will continue to rely on monolithic microfabrication, further advances to enable 3-D integration of active and passive components, 3-D architectures for MEMS, and others necessitate alternate manufacturing methods.

Future of micro-LEGO

Transfer printing natively supports mass production since it involves an elastomeric surface that may deliver micro-objects in parallel or roll-to-roll fashions, yet micro-LEGO based on transfer printing has yet to be demonstrated with any significant degree of parallelism. Furthermore, for the improvement of process flexibility selective manipulation of micro-objects is desired. In this regard, the grand question of transfer printing is how to achieve process parallelism and selectivity simultaneously.

In addition, quick and selective material joining processes must also be developed to enable scalable and flexible microassembly. The use of reversible dry adhesion of responsive materials, such as shape memory polymers, in place of elastomers, and local thermal annealing techniques including laser raster scanning are being actively researched to meet these needs.

While miniaturized electronic device manufacturing has continued and will continue to rely on monolithic microfabrication, further advances to enable 3-D integration of active and passive components, 3-D architectures for MEMS, and others necessitate alternate manufacturing methods including deterministic robotic pick and place and stochastic self-assembly. In addition, transfer-printing-based microassembly, i.e., micro-LEGO, would be the third axis to complement monolithic microfabrication due its potential for assembly scalability and flexibility.

Read more about it

- V. Sariola, Q. Zhou and H. N. Koivo, "Hybrid microhandling: A unified view of robotic handling and self-assembly," *J. Micro-Nano Mechatronics*, vol. 4, nos. 1–2, pp. 5–16, 2008.
- S. Kim, J. Wu, A. Carlson, S. H. Jin, A. Kovalsky, P. Glass, Z. Liu, N. Ahmed, S. L. Elgan, W. Chen, P. M. Ferreira, M. Sitti, Y. Huang, and J. A. Rogers, "Microstructured elastomeric surfaces with reversible adhesion and examples of their use in deterministic assembly by transfer printing," *Proc. Natl. Acad. Sci*, vol. 107, no. 40, pp. 17,095–17,100, 2010.
- H. Keum, A. Carlson, H. Ning, A. Mihi, J. D. Eisenhaure, P. V. Braun, J.A. Rogers, and S. Kim, "Silicon micro-masonry using elastomeric stamps for three-dimensional microfabrication," *J. Micromechanics Microeng.*, vol. 22, no. 5, p. 055018, 2012.
- J. D. Eisenhaure, S. I. Rhee, A. M. Al-Okaily, A. Carlson, P. M. Ferreira, and S. Kim, "The use of shape memory polymers for MEMS assembly," *J. Microelectromech. Syst.*, vol. 25, no. 1, pp. 69–77, 2016.
- Z. Yang, B. Jeong, and A. Vakakis, and S. Kim, "A tip-tilt-piston micromirror with an elastomeric universal joint fabricated via micromasonry," *J. Microelectromech. Syst.*, vol. 24, no. 2, pp. 262–264, 2015.

About the author

Seok Kim (skm@illinois.edu) is an assistant professor at the University of Illinois at Urbana–Champaign. His current research interests include biomimetic-engineered surfaces for reversible dry adhesion and tunable wetting, transfer printing-based microassembly, and 3-D MEMS fabrication technologies.