Particle Integration across Scales Using Self-Assembly and Transfer

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The integration of functional particles into planar devices facilitates a more efficient use of material, the definition of very small features, the use of otherwise incompatible materials and possibly also the fabrication of novel device types that take advantage of the unusual properties of nanoparticles.

Bulk synthesis is the most efficient way to produce such particles. However, in general the products are disordered, whereas devices usually require ordered arrangements. Self-assembly processes can order large numbers of particles in parallel on surfaces, but require specific chemistry and patterned substrates, both of which often conflict with other fabrication requirements. In addition to particle order, also the particle-substrate junction is often crucial for device performance, and the reliable creation of well-defined particle-surface interfaces remains a challenge.

This work shows how templated self-assembly can be combined with a transfer step (Figure 1). The combined process, called "SATI" for "Self-Assembly, Transfer and Integration", maintains the advantages of self-assembly but relaxes the requirements on the substrates, and is more flexible than single-step self-assembly.

Directed transport of particles using self-assembly. For very small particles or very large numbers of particles, it becomes prohibitively time-consuming to place them using a serial approach. A much more efficient method is directed assembly, a type of self-assembly that uses a template with user-defined structures. In this contribution we show that through careful control of particle transport, yield and reproducibility of directed assembly can be increased towards the levels needed for a fabrication technology.

Particles having diameters of 100 μm, 500 nm and 60 nm were assembled in templates using different methods: Large particles were fluidized and trapped in holes by gravitational assembly; smaller latex particles were forced into position by capillary forces. To increase yield and precision, particle transport was controlled accurately by

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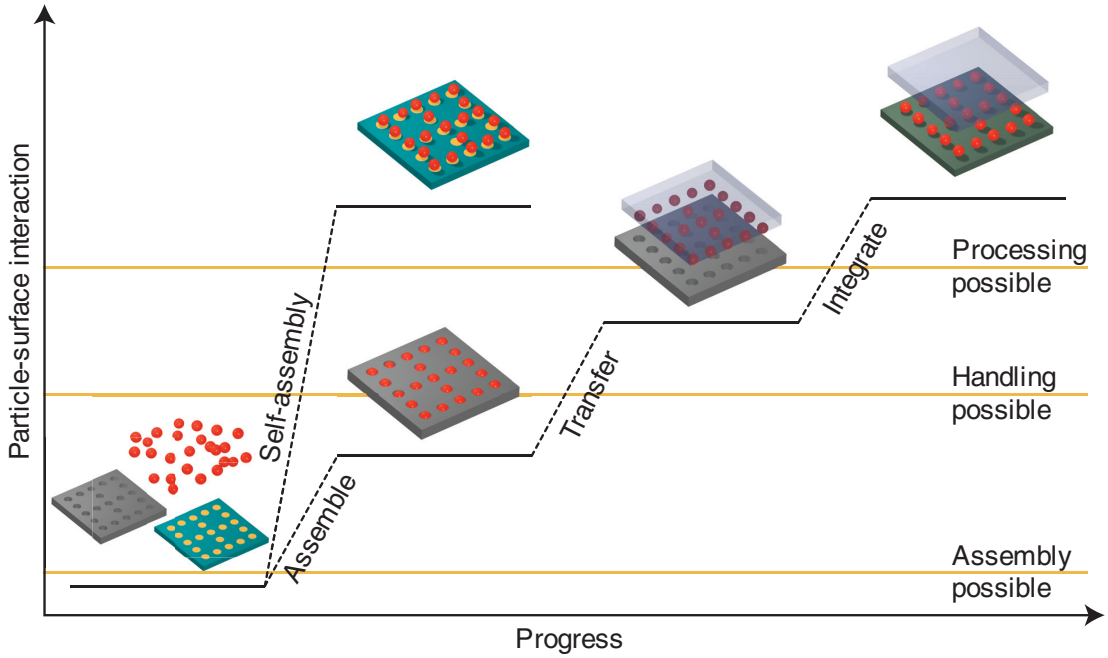

Figure 1: The multi-step SATI process.

means of the template geometry and the process parameters, such as temperature, velocity and suspension properties. The yield reached unity even in extended sparse arrays, as shown in Figure 2.

In most directed assembly processes, yield and reproducibility are largely determined by transport phenomena. However, the transport in directed assembly is different from that in many familiar problems: while it is meaningful and useful to treat particle transport from the bulk towards the assembly region using diffusion models, the actual assembly has to be analyzed at a greater level of detail. The integration of particles into the binding sites of the template is probably better viewed at Fokker-Planck-time scales, and, compared with other surface processes such as molecular adsorption, the number of events is small. This leads to small-number statistics that can exhibit considerable fluctuations, affecting yield, maximum throughput and quality.

For example, in capillary assembly a convective flux of liquid brings the particles into the assembly region, where the concentration increases locally. The particles are trapped in specific locations due to capillary action only when the contact line finally breaks up. We investigate the dynamics in detail both by direct observation and by analyzing the yield depending on template properties.

Adhesion-based transfer. To separate the assembly process and the actual integration, we rely on adhesion forces that commonly govern particle behavior in the dry state. Adhesion holds assembled particles in position at the end of any self-assembly process.

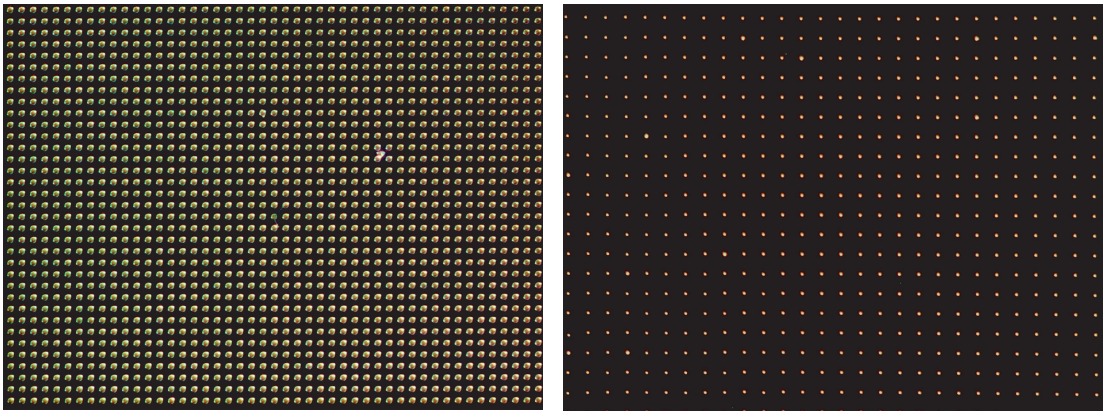

Figure 2: Sparse arrays of 100-μm glass beads (left panel) and 500-nm polystyrene particles (right panel).

If the adhesive forces are properly tailored, they can be strong enough to hold the ordered particles after assembly and allow their inspection, cleaning or modification, but at the same time weak enough to release the particles onto a target substrate when the particles and the substrate are brought into intimate contact (see Figure 1). Thus the assembly process does not have to be carried out on the actual target substrate, but can be done on a specialized template.

This separation gives us access to the surfaces that will later form the particle-substrate junction, so that we can tailor the junction properties for each application envisaged. For example, adhesion layers on the substrate provide adhesion between particle and substrate during transfer. For the final integration, the layers can be removed, replaced or converted into a functional particle-substrate junction. If an adhesion layer is not an option, surface energy differences between the carrier and the target substrate can be sufficient to effect a transfer. Thanks to all these options, the SATI process is rather comprehensive in terms of materials and interfaces.

Functional integration. Figure 3 shows at its top 100-μm-diameter glass and, below, tin-coated beads. The glass beads were integrated using a spin-on glass layer to provide a transparent connection, whereas the tin beads were transferred onto a sacrificial polymer layer that was later removed. Shown below are 500-nm-diameter polystyrene beads that were transferred onto a heated substrate, so that they softened and formed a circular connection having a well-defined area of contact. Capillary assembly was used to order the beads, permitting a variety of particle arrangements. Finally, the last row of Figure 4 shows 60-nm gold nanocrystals that were transferred onto a silicon oxide substrate without surface modification.

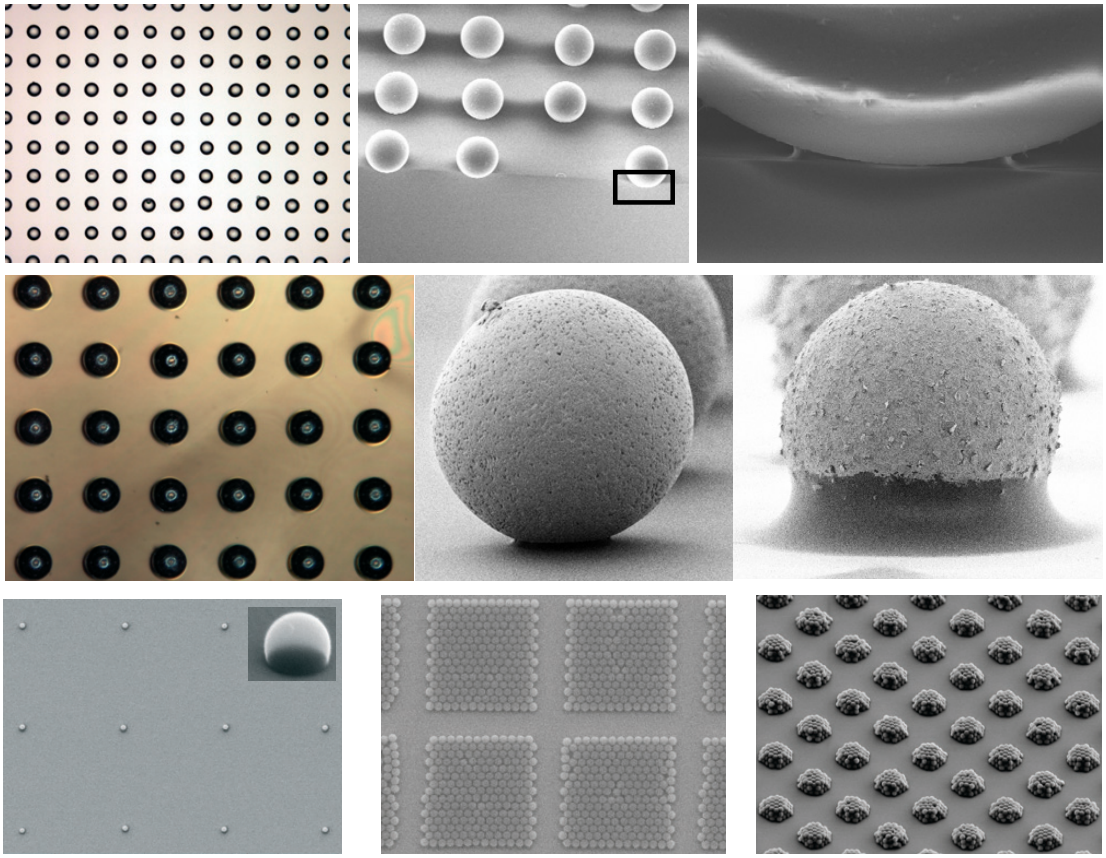

Figure 3: Arrays of 100-μm glass beads (top row), 100-μm tin-coated beads (second row) and 500-nm polystyrene particles (third row), assembled and printed using the SATI process.

The above examples show how SATI can enable particle integration into electronic devices. Another field of interest is the synthesis of multilayer coatins from particles. When applied multiple times, SATI can produce multilayer structures (Figure 4). This could open new routes to the construction of synthetic materials consisting of different particles, with control over both the lateral and the horizontal arrangement.

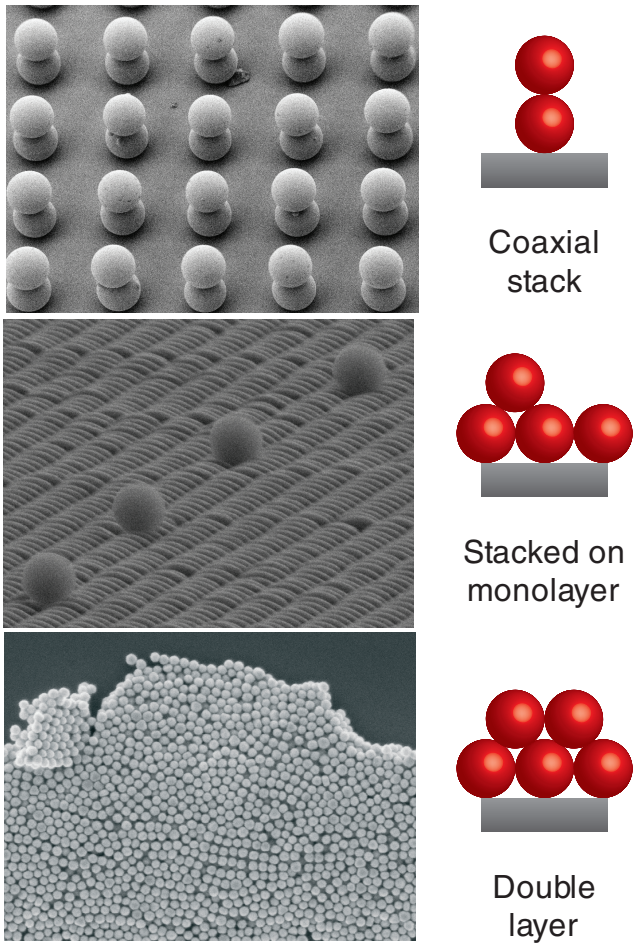

Figure 4: Stacks of 100-μm glass, 500-nm polystyrene and 60-nm gold particles (from top to bottom).