The Eccentroid as a Universal Shape for Driving 3D Self-Assembly

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Abstract:
Creating three dimensional (3D) structures with a specific architecture remains a scientific goal far from being achieved [1]. Inducing the spontaneous association of microscopic building blocks into macroscopic structures seems to be a promising way to create these new materials. Such fabrication processes require interactions between microscopic building blocks. For depletion or deoxyribonucleic acid (DNA) interaction [2,3], the attractive energy between the particles is proportional to the overlapping surface between the colloids. Controlling the positions and orientations of the microscopic building blocks is a critical issue in such processes. To address this issue, we are looking for a shape that has the ability to align in a single configuration when it interacts with a similar shape.

Summary of Research:
The shape must be such that the aligned configuration corresponds to the only existing minimum in the energy landscape: the shape has to be carefully chosen such that the energy landscape does not exhibit any metastable configuration. A schematic example is shown with two colloids of complex shapes in Figure 1. When the two colloids overlap, they interact and orientate in order to maximize the overlapping surface and therefore minimizing the energy. The shape chosen in Figure 1 is not a good one as we can see that configuration 1b is an obvious metastable position in which the two colloids may be trapped. This shape is a typical example of a shape we are not looking for. Preliminary studies have shown that the shapes, called eccentroids, shown in Figure 2 should automatically align. The simplest shapes we could figure out so far are simple circular disks with a hole inside. We found that the hole has to be off-center and its radius cannot exceed some critical ratio of the outer circle diameter. These shapes have only one stable point in their energy landscape, which is obtained when the inner holes are aligned.

Let’s consider the shape on the left, which simply consists of a disk with an off-centered hole in it. One can prove that two identical particles having such shapes translate and rotate to find a minimum of energy when they interact. We can qualitatively explain why such a shape works. Consider two eccentroids which are perfectly aligned and centered. We displace one center of a small distance $\varepsilon$. Such a displacement induces a decrease in overlapping area equal to $2\pi\varepsilon R$, where R is the radius of the disk. Clearly, such a change cannot for sure exceed a gain in overlapping area equal to $4\pi\varepsilon r$, where r is the radius of the inner hole. This proves that the position for which the centers of the outer circles are aligned corresponds to a maximum of overlapping respective to any translation of the shapes. Proving that there is a unique minimum is however not obvious and requires some more computations. Once the centers are aligned, it is clear that the position for which the holes are perfectly aligned corresponds to a maximum of overlap and therefore to a minimum of energy.

We synthesized microscopic colloids using the equipment in Cornell NanoScale Facility (CNF) [4]. So far, by using an i-line AutoStep, we have been able to make particles of external diameter ~ 5 $\mu$m and inner hole of radius of 2 $\mu$m. On a 4” wafer, we can process of the order of $6 \times 10^7$ particles at a time.
So far we have printed the colloids on a thin layer of SU-8 (~ 400-500 nm). This is performed at the CNF. Within two days of work, 20 wafers could be prepared.

After release from their substrate, the colloids are centrifuged and washed in water with SDS. The final solution is very stable. We couldn’t obtain depletion. Particles were further characterized using atomic force microscopy (AFM) and scanning electron microscopy (SEM). SEM pictures obtained from particles before the lift off show some halos next to the edges (Figure 3). Particles seem to have rounded edges and not sharp edges, according the SEM pictures. These observations are confirmed by using AFM and environmental SEM on eccentroids after the lift-off process. We found that the particles have small spots on their surface and that there are some very rough peaks just next to the edges of the particles (Figure 4a and Figure 4b). We could also detect the presence of some impurities located at the surface of the particles (see white spots on the SEM pictures). Another interesting fact is that the size of the hole seems to be much smaller than the size measured by SEM or optical microscope.

We have found a shape which should be able to uniquely determine the orientation and the positions of colloids in 3D. We have shown that the shape would work at the macroscopic scale using the capillary interaction as attractive interactions. In order to prove the generality of our finding, we want to find an equivalent illustration at the microscopic scale using the depletion interaction as an attractive interaction. So far, it looks like the colloids we are able to make have some roughness defects which are now our limitation.

References: