Manufacturing of Two and Three-Dimensional Micro/Nanostructures by Integrating Optical Tweezers with Chemical Assembly

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Abstract

This paper proposes a novel micro/nano scale manufacturing system using optical tweezers and chemical linkages for manufacturing two- and three-dimensional micro/nanostructures. A holographic multiple trap optical tweezer system is first used to trap particles in a desired pattern. The particles are then connected to form rigid units using suitable chemistry. Connection schemes based on gold seeding, complimentary-DNA linkage and streptavidin-biotin chemistry are presented and possible applications are explored.

1. Introduction

For future nanotechnology, biotechnology, and information technology products, micro/nano-manufacturing systems are indispensable. Robotics researchers have been focusing to develop such systems [1] using Scanning Probe Microscope probes, optical tweezers, micro/nanogrippers, etc. Main unsolved issues in these systems are high throughput by fast/parallel and autonomous manipulation, bonding, 3-D micro/nanoassembly, repeatability, and being limited to specific materials, environments, and sizes. This paper is especially aimed to propose a novel manufacturing method for the high-throughput, bonding, and 3-D assembly issues.

Manufacturing methods can be broadly classified as either top-down or bottom-up. The top-down approach provides for precision and can be used for controlled fabrication and assembly. However, it is not easy to parallelize it at small scales. The bottom-up approach on the other hand uses a few simple building blocks and can be massively parallel but the main problem is in process control. A hybrid approach that combines the advantages of both precision as well as chemical assembly is proposed here. This method uses optical tweezers and chemistry to fabricate micro/nano-structures. An overview of single and multiple tweezers is given in Sec. 2 and this is followed by the details of the fabrication process in the following sections.

2. Optical Tweezers

Laser tweezers have been used extensively in biological systems for in-vivo manipulation of cells and single molecule studies [2][3]. However, not much attention has been paid to using them as a tool for fabrication. Holmlin [4] used a scheme for making assemblies using coated polystyrene beads and erythrocytes. Korda [5] used a multiple-trap system to get permanent particle-pattern by gelling the surrounding fluid. Tweezers can be used to trap particles of sizes from about 100 nm to 20 μm. Trapping metallic or absorbing particles [6] is tougher than transparent particles but can be done using a donut shaped TEM_{01} Laguerre-Gaussian mode beam [7]. This mode can also be used to spin and rotate particles near the focus [8].

2.1. Multiple Trap Systems

The simplest way to generate multiple beams is to use multiple light sources. Ogura [9] used an addressable 8x8 VCSEL array to generate multiple traps. Visser et al. [10] created multiple optical traps using a single fast scanning trap. An acousto-optic modulator [11] can be used to scan beams to generate multiple beam traps [12]. However, these approaches with multiple beam paths or raster type mechanical beam steering require complicated mechanical systems.

Multiple traps can also be generated dynamically using computer generated holograms and a spatial light modulator (SLM) [13][14]. This method is attractive for the proposed fabrication techniques as it can trap both dielectric and metal particles in 2D or 3D patterns.

2.2. Holographic Optical Tweezers (HOT)

The key element in the Holographic Optical Tweezer system is a computer-generated hologram, which is created by reducing a calculated interference pattern to a series of phase or amplitude masks. The computed phase mask is then written to a spatial light modulator, which uses nematic liquid crystals to do phase-only modulation of light [15]. For a given pattern of traps, there exists a unique phase mask, which is computed using Fourier optics. The trap pattern can be changed dynamically by using a computer to continually refresh the mask on the SLM.

Fig. 1 shows a holographic tweezer system, where an input beam is split by the SLM and the resulting beams are focused into an array of optical traps. The phase masks can be modified easily to get a 3D pattern of traps or to change the beam profile e.g. a TEM_{00} mode Gaussian beam can be converted into a Laguerre-Gaussian TEM^{*}_{01} donut shaped beam at a trap site. A single Gaussian source can yield a combination of

different mode beams, which enables simultaneous trapping of metallic and dielectric particles.

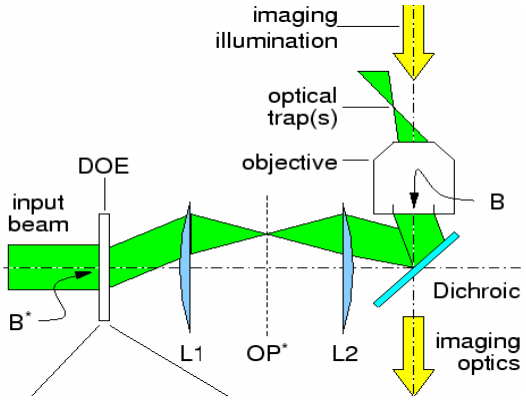

Fig. 1. Holographic optical tweezer system [13].

Curtis et al. [16] developed a dynamic trap system, which is also commercially available [17]. They used a Hamamatsu X7550 SLM with 480x480 array of pixels, each of which is 40 μm wide with 150 distinct phase shifts from 0 to 2π. They were able to trap 1μm beads using just 1mW and also demonstrated 3D trap patterns and combinations of TEM_{00} and TEM_{01} beams.

2.3. Advantages of HOT

The holographic method seems the most configurable and can generate both 2D and 3D patterns of traps for both metallic and dielectric particles without any complex mechanical elements.

The main problem with holographic tweezers is that the power of the input beam is distributed over all the traps but this is remedied by using a higher power laser. Calculating the phase hologram is a complicated process and limits the bandwidth of the system but the manufacturing process does not require a high refresh rate and existing rates (5-10 Hz) are sufficient. Hence holographic tweezers provide an excellent platform for trapping particles stably in arbitrary patterns.

3. Process Overview

The fabrication process consists of two major parts as shown in Fig. 1. An optical tweezer system is first used to trap particles in a pattern by selectively turning on certain traps. The particles are flowed under the traps and excess particles are rinsed away. A set of trap configurations and corresponding particle patterns are shown in Fig. 2. This requires a multiple trap system that can be reconfigured dynamically so that different shapes may be obtained. The focal depth must also be configurable if three dimensional trap patterns are desired. Different tweezer systems and the advantages of the holographic system are described in Sec. 3.

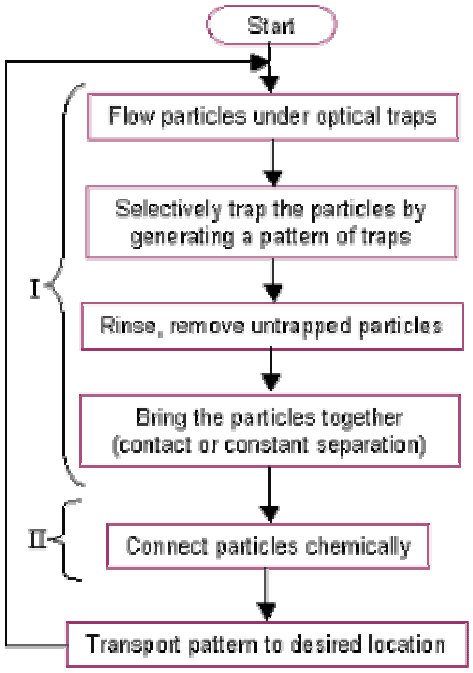

Fig. 2. Process flow of the fabrication method.

Once the particles are trapped, they can be connected chemically to give the final rigid structure. The various schemes shown in Fig. 3 can be used depending on whether the particles are in contact or not. Each of these schemes is described in detail in Sec. 4. These techniques can be used to make 2D and 3D structures.

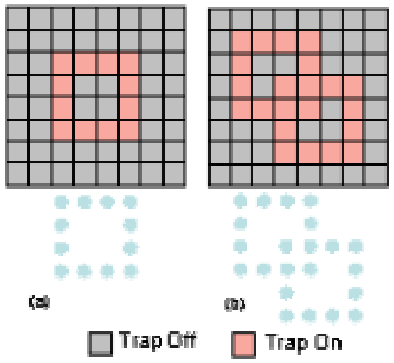

Fig. 3. Optical trap configuration and the corresponding pattern.

4. Connection of Trapped Particles

Once the particles are trapped they need to be connected rigidly. We propose to use polystyrene or gold microspheres as the starting particles. These particles can be easily modified by coating their surfaces with chemical or biological molecules such as proteins and DNA. This process holds the key to the connection process since they can now be made to respond to specific chemistry. Several companies [18]

sell micro/nano particles with size ranging from 1 nm to 20 µm with or without surface coatings.

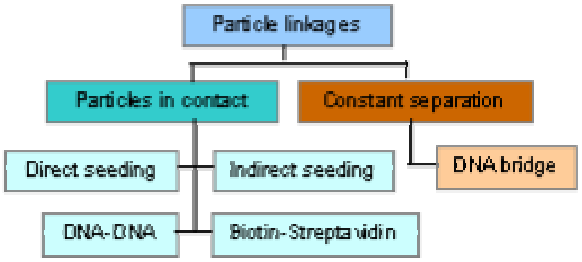

Fig. 4. Classification of the different connection mechanisms.

The different particle connection methods mainly depend on whether the particles are in contact or not. For the case where the particles are in near or full contact, the feasible connection schemes are shown in Fig. 5. They rely on either a gold seeding process (A) or biotin-streptavidin chemistry (B) or DNA linking (C). Details about the various connection processes are explained in the following sections.

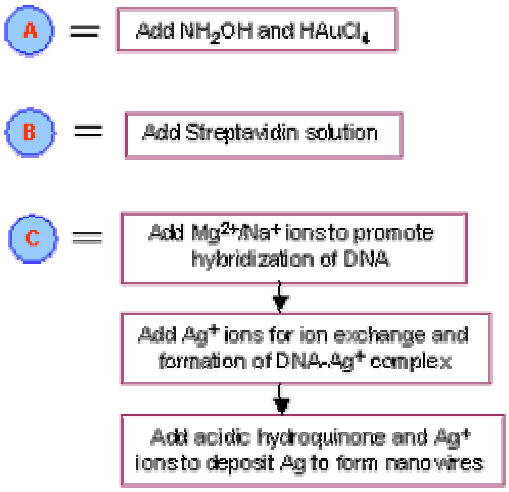

Fig. 5. Connection methods for particles in contact.

4.1. Direct Gold Seeding (A)

Hydroxylamine (NH_2OH) seeding of gold (Au) nanoparticles has been successfully demonstrated for increasing the size of the particles and also for forming micro/nano structures. Brown et al. [19] describe the seeding process for increasing the size of gold nano particles using NH_2OH. NH_2OH is capable of reducing Au^{3+} ions to form bulk metal, and this reaction is strongly accelerated by the presence of Au surfaces. Consequently, no nucleation takes place in solution and all the Au goes into the production of larger Au particles. Meltzer [20] used this technique to form gold nano structures on SiO_2 substrates.

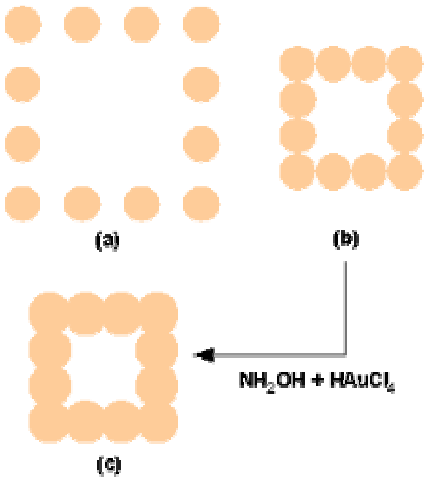

Fig. 6. Micro/nanostructure formed using direct seeding.

The particles have to be either made of gold or coated with a layer of gold ((a) in Fig. 6). Once the particles are in contact ((b) in Fig. 6), a solution of NH_2OH and $HAuCl_4$ is introduced at the trap location using suitable micro/macro fluidics ((c) in Fig. 6). The individual particles grow in size due to gold deposition and fuse together to form a single microstructure.

4.2. Indirect Gold Seeding (A)

The direct seeding process requires gold particles, which are difficult to trap using optical tweezers. Polystyrene beads are much easier to trap but they must be coated with a gold layer for the seeding process to occur. Gold coating on polystyrene particles makes them opaque and similar to metal particles unless the coating is very thin (a few angstroms), which is very difficult to make. An alternate approach to make these particles compatible with the seeding process is to coat them with gold nano particles (Fig. 7). The density of gold nano particles and their sizes can be tailored such that they do not affect the transparency of the poly particles drastically. To make such particles, solutions containing streptavidin coated polystyrene particles and biotin coated gold nanoparticles (1-5 nm diameter) are mixed. The gold nanoparticles then assemble on the polystyrene particles as shown in Fig. 7(a) due to the binding between streptavidin and biotin. Biotin and streptavidin are bio-molecules that have a very strong affinity for each other and their bond strength is similar to that of a covalent bond.

The nanoparticle coated polystyrene particles are then trapped, brought into contact and the seeding agent is added. The gold nanoparticles grow in size due to the Au deposition and fuse together and thereby bonding the polystyrene particles as shown in Fig. 15 (b),(c).

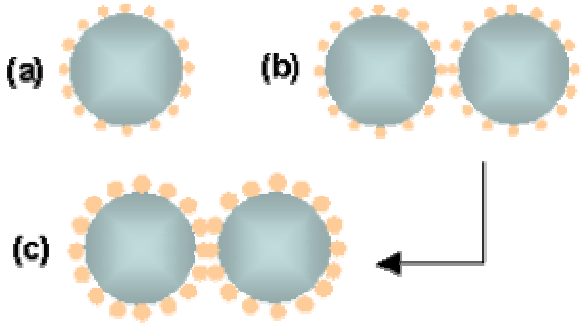

Fig. 7. Microstructure formed using direct seeding.

4.3. Biotin-Streptavidin Linkage

In this process, the starting material is biotin-coated particles (gold or polystyrene) and streptavidin molecules are used to link them together. Once the particles are trapped, streptavidin is introduced in solution at the trap location and bond with the biotin on the particles. This forms a linkage between the trapped particles as shown in Fig. 8.

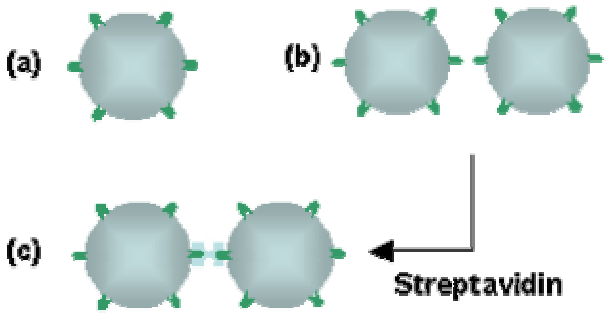

Fig. 8. Microstructure formed using biotin-streptavidin linkage. (a) A single biotin coated polystyrene particle, (b) two such particles brought into contact, (c) streptavidin linkage formed between particles.

4.4. DNA-DNA linkage

The affinity of the single strand DNA molecules to their complementary strand can also be exploited to link microparticles. Complementary single strands of DNA hybridize to form a double stranded molecule in the presence of ions like Na^+ or Mg^{2+}. The connection process differs a bit for polystyrene and gold particles.

One set of particles are coated with single stranded DNA molecules of Type A and an another set is coated with molecules of type B, which is complementary to type A. The DNA molecules need to be modified at one end to attach them to the particles. If gold particles are used, a thiol (-SH) group is attached to one end of the DNA, and this bonds to the gold surface through the gold-thiol bond. If polystyrene beads are used, the beads are first coated with streptavidin and one end of the DNA is modified with biotin, which attaches the DNA to the surface by the biotin-streptavidin bond as seen in Fig 9(a) and 9(b).

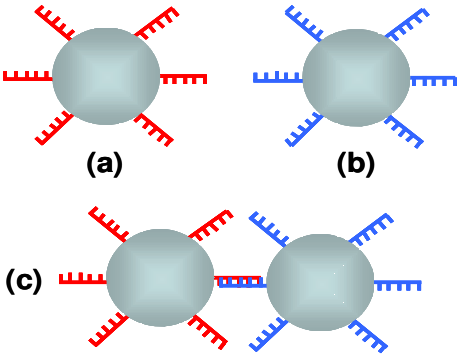

Fig. 9. DNA-DNA linkage. (a) Polystyrene particle coated with single strand DNA (type A), (b) Polystyrene particle coated with single strand DNA (type B), (c) Particles linked as a result of hybridization between the single strands.

The pattern in this case is made in two steps. First, the type A particles are trapped and the type B particles are trapped such that they form an alternating pattern. Once the particles are brought into contact, a salt solution is added to facilitate hybridization, thus linking up the particles as shown in Fig. 9(c). The salt solution is added last to prevent random hybridization from occurring during the trapping process. The bond formed by the DNA hybridization is weak and can be easily broken by changes in the pH or by shear forces. Hence it must be strengthened. One way of doing so is to use the silver (Ag) staining process as shown in Fig. 10.

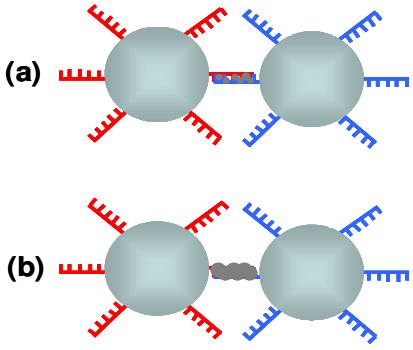

Fig. 10. Silver staining process (a) Ag deposits on DNA to form nanometer size aggregates, (b) Development using acidic hydroquinone solution, Ag^+ ions forms the nanowire.

The process of silver deposition on a DNA strand to form nanowires has been successfully demonstrated by Braun et al [21]. The silver staining process involves three main steps. The first step is the exchange of ions in the vicinity of the DNA with Ag^+ ions and the formation of DNA-Ag^+ complex. This is followed by the deposition of silver on the DNA strands to form

nanometer-sized aggregates (Fig. 10a). The final step is the development of the silver, much as in the standard photographic process, using an acidic solution of hydroquinone and silver ions under low light conditions. The deposition is limited only to the silver line formed over the DNA (Fig. 10b).

5. Connection of Separated Particles

This method is used when the particles cannot be brought into physical contact with each other. This may be due to the limitations of the optical trap array, the optics system used, or the particles themselves. In such a case a DNA bridge can be used to link up the particles. As described earlier, the DNA bridge can be strengthened by using the silver staining process. The process again depends on whether polystyrene or gold particles are used.

In the case of polystyrene beads, the starting material is streptavidin-coated polystyrene beads. After trapping the particles in the desired pattern, a solution with long DNA molecules like λ DNA with biotin molecules attached to both ends is introduced in the vicinity of the trap. These molecules attach to the surface of the beads as shown in Fig. 11.

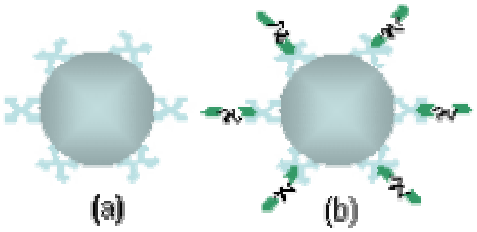

Fig. 11. (a) Single streptavidin coated polystyrene particle, (b) Assembly of biotinylated DNA molecules on the surface of the polystyrene particle.

To get directional assembly, the DNA are stretched out in a particular direction using either flow [21] or a high frequency electric field [22][23]. Drag forces due to the flow can cause particles to escape the trap but the electric field doesn't affect the particles and is hence preferred. The field can be applied using an external source or by micro-fabricated electrodes. The electric field causes the DNA to stretch in one direction and the other end of the biotinylated DNA can attach to the neighboring particles as seen in Fig. 12. If the pattern needs to be connected in two directions, electric field can be applied sequentially in both directions.

The process using the gold microspheres is similar to the one described above, except that the linkage chemistry is different. The DNA molecules are modified so that they have thiol groups at both ends and they attach to the gold particles by the thiol-gold bond.

The DNA bridge between the particles is compliant and is made rigid using the silver staining process described in Sec 4.4 and is illustrated in Fig. 13.

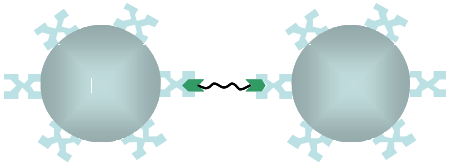

Fig. 12. Stretching of the DNA molecules using an electric field, to link the particles together.

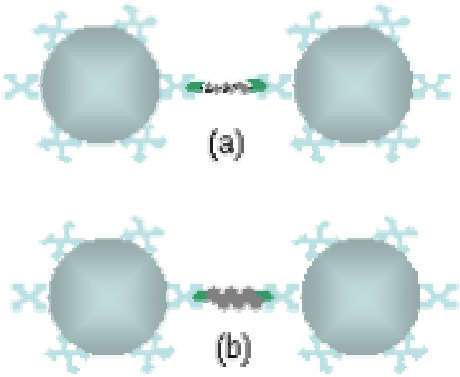

Fig. 13. Strengthening of the linkages using silver staining.

6. Discussions

The simplest methods for joining particles in contact are the direct seeding and biotin-streptavidin binding since they do not need elaborate preparation of the beads or DNA. The approach with complementary DNA is complicated since it requires trapping different types of particles. Connecting separated particles by stretching DNA is an exciting prospect since networks of nanowires can be obtained using this approach. 3D connected nanowires can be obtained by applying electric field in the desired direction though the application of generalized 3D fields in the setup is not yet clear.

The main advantage of this method over conventional lithographic techniques is that it does not require the use of masks. The tweezer array is dynamically configurable and can be used to make different shapes just by using software to define a new pattern. The critical dimensions of the pattern are influenced mainly by the size of the particles, which in turn is limited by the capabilities of the tweezer array like laser power, grating resolution, etc. Structures made using this technique are free floating and this could pose some handling problems once the structure is released. Finally, the usable starting materials are limited by requirements of refractive index though

other beam modes could be used but with some loss in stability.

7. Applications

The simplest application is in making motifs and patterns. These small building blocks could then be assembled into super assemblies since they are large enough to be individually manipulated. Micro-wires formed in this process can be used to connect up micro devices or link components of assemblies. Since the trap system is dynamic and easily reconfigurable, this method is well suited for rapid prototyping, where flexibility and speed are desired without need for any mask making. This method could also be used to engineer the properties at the microscale by building custom films or sheets by spatial ordering of particles with different properties.

8. Conclusions

A novel micro/nanomanufacturing method combining the advantages of the top-down and bottom-up approaches was presented. The holographic tweezer system is best suited for making structures because of its flexibility and diverse particle trapping capabilities. Different chemical schemes for connecting particles were described and further investigation is being pursued to test them in a tweezer system. This process would be very promising for rapid prototyping and other low volume pattern fabrication at the micro/nanoscale.

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