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Approaching Programmable Self-Assembly from Nanoparticle-Based Devices to Integrated Circuits

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This paper reports on two methods to enable the manufacturing of hybrid nano and micrometer sized systems: (i) electrostatically directed self-assembly of nanoparticles and nanowires to form nanoparticle and nanowire based devices, and (ii) surface tension driven self-assembly of micrometer sized components to form multi-component hybrid microsystems. Both self-assembly techniques are programmable and reconfigurable by applying external voltages to surface electrodes. We demonstrate that directed self-assembly can be used to position 5-100 nm sized nanoparticles with 50 nm resolution, fabricate electrically functional microsystems, integrate III/V semiconductors on silicon, fabricate cylindrical displays, and program the hybrid integration of optoelectronic components in three dimensions.

1. Introduction

Fabrication strategies that rely on mechanisms of self-assembly are widely recognized as inevitable tools in Nanotechnology. Self-assembly is not limited to the nanometer length scale. Strategies that are based on self-assembly are projected to have a major impact in the manufacturing of systems on both, the micro, and nanometer length scale[1-3]. The focus of this paper is programmable self-assembly and self-assembly by design on the micro and nanometer length scale. Programmable self-assembly involves the design of "intelligent" components that undergo self-assembly to form a desired device or microsystem. Programmable self-assembly has the potential to overcome the limitations of existing manufacturing concepts. Currently the incompatibility of Si, GaAs, GaN, InP, and III-VI semiconductor-based processes results in the assembly of systems that are connected with long interconnects on separate substrates. Such systems are typically assembled using robotic assembly. Conventional robotic methods and assembly lines, however, fail as components become smaller, because of the difficulty in building machines that can economically manipulate components in three dimensions. Programmable self-assembly has the potential to overcome these limitations and enable non-robotic manufacturing of hybrid micro and nanometer-sized systems with new functionalities, short interconnects, and superior performance.

Here we report on two methods to enable the manufacturing of hybrid systems: (i) electrostatically directed self-assembly of nanoparticles and nanowires to form nanoparticle and nanowire-based devices, and (ii) programmable surface tension driven self-assembly of micrometer sized components to form multi-component hybrid microsystems. Both self-assembly techniques are programmable and reconfigurable by applying external voltages to surface electrodes and heater arrays. Figure 1 illustrates the basic concept of the two approaches. Our goal is to enable "hybrid systems" manufacturing.

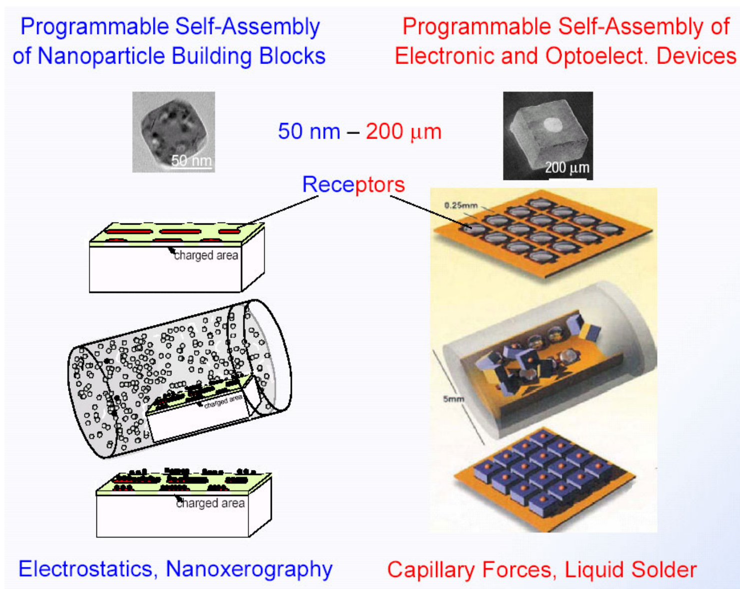

Fig. 1. Concept of Programmable Self-Assembly; programmable/reconfigurable receptors are used to direct the assembly of 50 nm - 200 µm sized components.

2. Electrostatically Directed Self-assembly of Nanoparticles and Nanowires to Form Nanoparticle and Nanowire Based Devices

The first "hybrid systems" approach is geared to the integration of nanoparticles and nanowires to enable the manufacturing of nanoparticle and nanowire-based devices and systems. Nanoparticles and nanowires are considered the building blocks of future nanotechnological devices. The ability to assemble nanoparticles and nanowires in two and three dimensions will enable the fabrication of a whole range of quantum-effect-based devices including single electron transistors [4], quantum-effect-based lasers [5], photonic bandgap materials, filters, wave-guides [6], and high-density data storage devices [7]. The use of nanoparticles and nanowires as building blocks, however, requires novel assembling strategies. Single particle/wire manipulation and random particle/wire depositioning have been used to fabricate first-device prototypes. Strategies that use single particle manipulation and random particle deposition are considered as straightforward methods to fabricate and explore new device architectures. For example, a "nanorobot" [8, 9] would position nanoparticles with *nm* resolution to fabricate a certain device. Most commonly, such a "nanorobot" consists of a modified scanning probe microscope where the probe is used as a tool to position the nanoparticles [10-13] or makes use of nanotweezers [14, 15] for pick and placement. Both single particle manipulation and random particle deposition enable the fabrication of device prototypes at an early stage and are therefore important strategies. However, inherent disadvantages such as the lag in yield and speed will have to be overcome to enable the manufacturing of nanotechnological devices. Fabrication strategies that rely on mechanisms of self-assembly may overcome these difficulties.

We and others have begun to use self-assembly and directed assembly to assemble components and nanoparticles onto substrates. Most actively investigated areas currently use protein recognition[16], DNA hybridization [17], hydrophobicity/hydrophilicity[18], and magnetic interactions[7]. In our own work we have investigated the use of surface tension[19] and electrostatic interactions[20] to drive the assembly process. In the area of electrostatics, we have developed a method to pattern charge with sub 100 *nm* resolution[20] and a number of different systems to enable the parallel integration of nanoparticles from a gas or liquid phase [21-23]. The advantage of using electrostatic forces compared to other strategies is that it is long-range and non-material specific (any particle can be trapped).

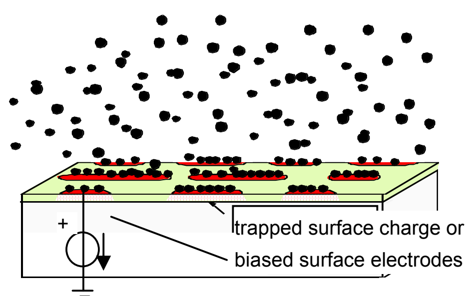

Fig. 2. Principle of Electrostatic directed self-assembly.

The basic principle of the electrostatically directed self-assembly process of nanoparticles is illustrated in Figure 2. Electric fields and charged areas are programmable by applying external bias voltages to surface electrodes. We refer to this process as electrostatically directed self-assembly or nanoxerographic type printing. We have developed a number of different systems to enable the parallel integration of nanoparticles from a gas or liquid phase [21-23].

Figure 3 illustrates the realization of a gas phase system that creates, size-selects, and positions nanoparticles with 50 nm resolution [21, 23]. Particles of silicon and other solid materials are created in the gas phase by homogeneous nucleation. This particular system generates metallic and semiconducting nanoparticles by a vapor-liquid-solid solidification technique. The technique allows us to integrate 5 - 100 nm sized nanoparticles onto surfaces with 50 nm resolution. The nanoparticles are created using a tube furnace by evaporation and condensation. Vapor, which contains atoms of the evaporated material, forms within the furnace. The carrier gas transports the atoms out of the furnace where they nucleate and condense into particles due to the change in temperature. The gas flow carries the nanoparticles into the differential mobility analyzer (DMA) where they are size-selected. Particles that pass the DMA enter the particle assembly module. The particle assembly module

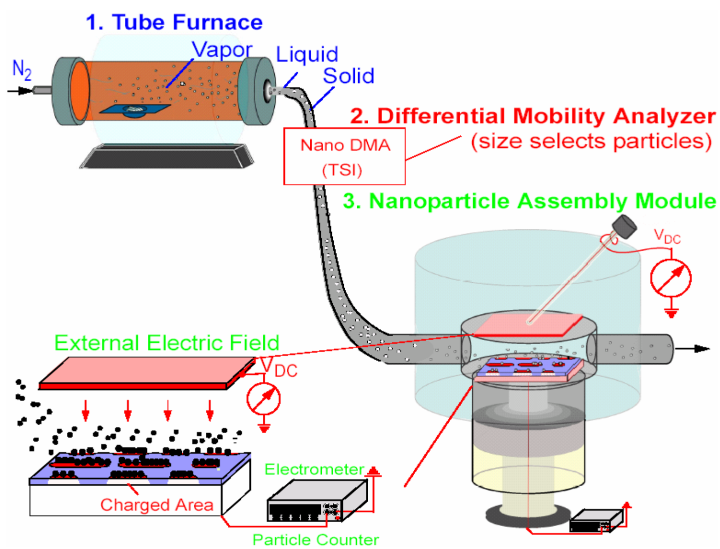

Fig. 3. Principle of nanoxerographic printing from the gas phase. (1) A constant flow of nanoparticles is generated by evaporation of matter in the tube furnace, transport of the atoms to the outlet by the N2 gas, and condensation. (2) Particles are size-selected in the DMA. (3) The directed assembly of the nanopaticles occurs in the particle assembly module.

directs incoming charged particles towards the sample surface. *Figure 4* shows a representative image of silver nanoparticle that was created and positioned with this system. A process is also being developed to enable the patterning of any organic and inorganic material with sub 100 nm resolution. We are working on a number of different semiconductors nanoparticles and nanowires. Planned nanoparticle-based devices include nanoparticle based transistors and nanoparticle-based light emitting diodes.

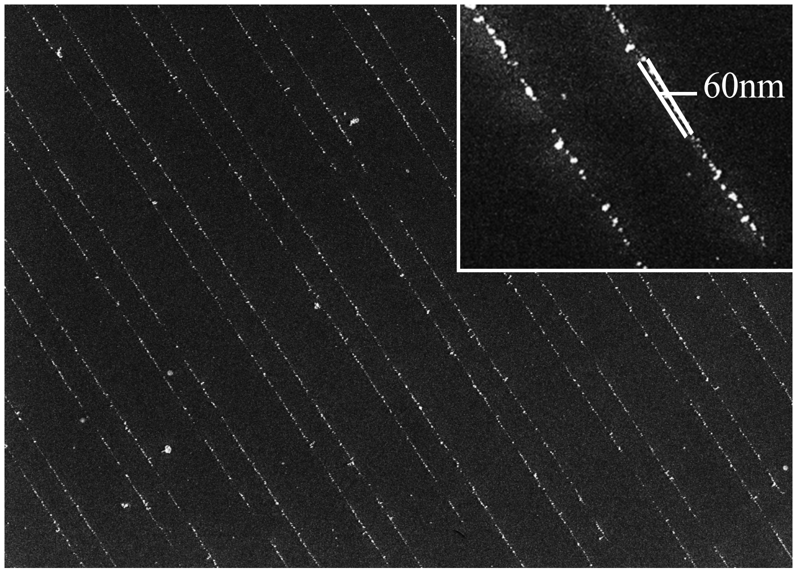

Fig. 4. A Scanning Electron Microscope (SEM) image of 60 nm wide lines of silver nanoparticles assembled using electrostatically directed self-assembly.

3 Programmable Surface Tension Driven Self-assembly of Micrometer sized Components to Form Multi-component Hybrid Microsystems

The second "hybrid systems" approach is geared to the integration of existing functional nanoscale and microscale (electronic and photonic) devices into large mesoscale systems. The goal is to develop a technology to enable the hybrid integration of functional components with a component size between 100 nm - 100 μm in two and three dimensional systems.

Previous demonstrations of directed self-assembly to generate functional electrical microsystems include the coplanar integration of segmented integrated circuit (IC) devices into 2D "superchips" using capillary forces [24, 25], shape-directed fluidic methods that position electronic devices on planar surfaces using shape recognition and gravitational forces [26, 27], liquid-solder-based self-assemblies that use the surface tension between pairs of molten solder drops to assemble three-dimensional electrical networks, ring oscillators, and shift registers [28, 29], capillary force-directed self-assembly that uses hydrophobic-hydrophilic surfaces patterns and photo curable polymers to integrate micro-optical components, micromirrors and semiconductor chips on silicon substrates [3, 30, 31] and solder-receptor-directed self-assembly to realize hybrid microsystems and flexible displays where metal contacts on segmented semiconductor devices bind to liquid-solder-based-receptors to assemble and electrically connect devices on planar and non-planar surfaces [19].

The basic principle of our programmable solder-receptor-directed self-assembly process is illustrated in Figure 5. Metal contacts on segmented semiconductor devices bind to liquid-solder-based-receptors to assemble and

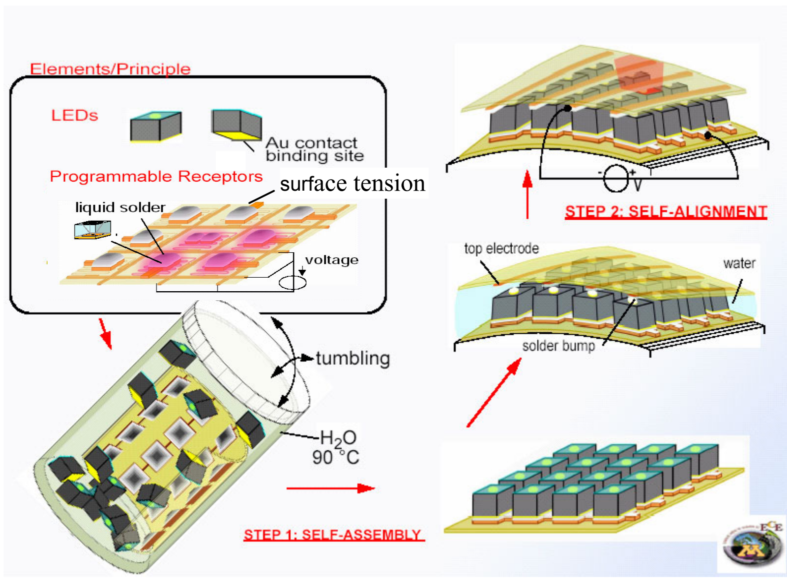

Fig. 4. Programmable solder-receptor directed self-assembly.

electrically connect devices on planar and non-planar surfaces. Our liquid metal coated templates provide three key requirements: they can (i) act as receptors for subunits during the assembly (no manipulator is needed), (ii) they form rigid bonds upon solidification (no adhesive needed), and (iii) they provide electrical input/output-connectors to operate the final device (no wirebonder needed). We have used solder-receptor-directed self-assembly to realize flexible cylindrical displays and hybrid microsystems.

Cylindrical Displays. Figure 6 illustrates the realization of an electrically functional cylindrical display [19, 32]. The components were

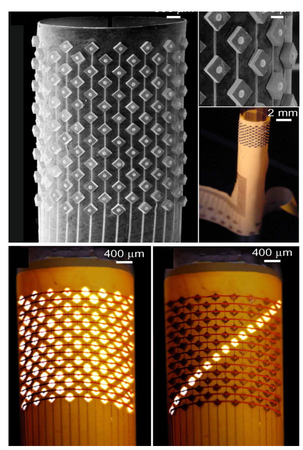

Fig. 6. Self-Assembled Cylindrical Display.

fabricated using standard surface micromachining. The display was then assembled in two steps: (i) the self-assembly of LEDs on the bottom electrode and, (ii) the self-alignment of the top electrode. The surface tension of liquid solder was the driving force in both steps. The self-assembly took only 3 minutes [19].

Hybrid Parallel Integration on Silicon. Figure 7 shows GaAs/GaAlAs light emitting diodes that have been assembled onto silicon wafers. We coated the top contact with photoresist to prevent upside down assembly before we diced the wafer in the clean room. A flexible copper-polyimide composite (Pyralux LF 9110, DuPont) was used to connect the top contact to operate the assembly (inset).

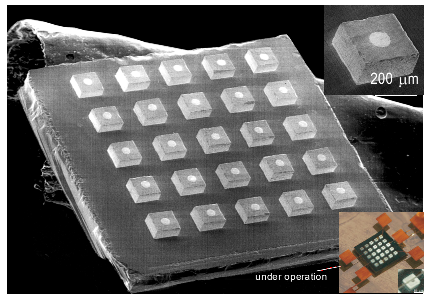

Fig. 7. *Hybrid Parallel Integration - Batch transfer of GaAs/GaAlAs LEDs on Si.*

Programmable Reconfigurable Liquid Solder-Directed Self-Assembly. Current self-assembly strategies are most suitable to handle large numbers of identical components. Their disadvantage is that they provide insufficient selectivity to assemble non-identical components to form multicomponent hybrid systems. Programmable reconfigurable liquid solder directed self-assembly is a self-assembly concept that enables parallel hybrid integration of non-identical components. Programmability is implemented using solder-based receptors that can be switched on and off electrically using integrated heaters.

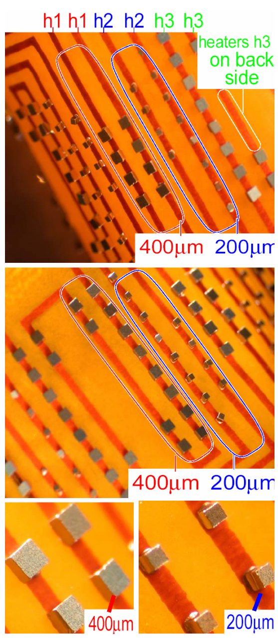

Fig. 9. Hybrid *batch integration.*

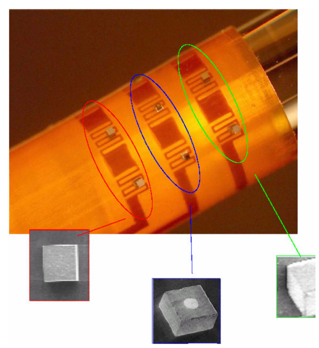

Fig. 8. Non Identical Component assemblies.

The first biggest advantage of programmable liquid solder-directed self-assembly is that it enables reconfigurable self-assembly rather than static assemblies. The user can select the form of assembly without fabrication of a new structure. The second biggest advantage is that it forms electrical interconnects during the assembly procedure. This enables the fabrication of electrically functional assemblies. The third biggest advantage is that it allows the assembly of microsystems that contain non-identical parts – the integration of non-identical devices to form multi-component microsystems is difficult to accomplish with existing self-assembly due to insufficient power of recognition. *Figure 8* illustrates programmable reconfigurable liquid solder-directed self-assembly using integrated heaters on flexible substrates. Three different types of light emitting diodes were self-assembled into rows around a cylinder. The assembly was programmed using a meander type heater array. *Figure 9* shows 200 and 400 μm sized silicon segments that form an "M" type pattern. The 200 μm sized components self-assembled onto 200 μm sized receptors with the heater *h2* being switch "ON", whereas the 400 μm sized components self-assembled onto 400 μm sized receptors with the heaters *h1* and *h3* switched "ON". All components found their target site. The self-assembly was programmed using 200 μm wide copper heaters that are located on the back side of the flexible polyimide film.

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