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Field Configured Assembly: Programmed Manipulation and Self-assembly at the Mesoscale

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ABSTRACT

Field configured assembly is a programmable force field method that permits rapid, "hands-free" manipulation, assembly, and integration of mesoscale objects and devices. In this method, electric fields, configured by specific addressing of receptor and counter electrode sites pre-patterned at a silicon chip substrate, drive the field assisted transport, positioning, and localization of mesoscale devices at selected receptor locations. Using this approach, we demonstrate field configured deterministic and stochastic self-assembly of model mesoscale devices, i.e., 50 μm diameter, 670 nm emitting GaAs-based light emitting diodes, at targeted receptor sites on a silicon chip. The versatility of the field configured assembly method suggests that it is applicable to self-assembly of a wide variety of functionally integrated nanoscale and mesoscale systems.

Mesoscale devices and components are an important class of functional objects whose dimensions span a range of length scales intermediate between that of individual molecules (nanometer scale) and that of macroscopic objects (millimeter scale).¹ Typical examples include macromolecular polymers, supramolecular assemblies, nanocrystals, nanowires, micron-scale colloidal particles, biological cells, and discrete semiconductor components such as resonant tunneling diodes, light emitting diodes, vertical cavity surface emitting lasers, and micro-opto-electro-mechanical devices with dimensions of up to several hundred microns.

Recent technological advances have led to the development of many novel "bottom-up" synthetic and "top-down" fabrication strategies capable of creating ordered meso-

scale component arrays with a wide variety of tunable properties. To achieve molecular self-assembly, chemists often exploit biologically inspired interaction paradigms such as shape-complementarity, hydrophobic, or hydrogen-bonding effects.² Self-assembly of mesoscale component arrays with length scales on the order of several microns or more have also been demonstrated using these principles by pre-programming the structure and functions of mesoscale components during synthesis so that components self-assemble into ordered 1-, 2-, and 3-D architectures under appropriate conditions.³ Other alternative types of mesoscopic phenomena, operative on length scales characteristic of the dimensions of larger submillimeter components, for example, have also been exploited to assemble ordered mesoscopic architectures. These include electromagnetic, fluidic, and capillary effects.⁴

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Figure 1. (a) Schematic representation of the field configured assembly (FCA) process: Electrical biasing of a selected receptor electrode on a silicon chip assembly substrate initiates electric field assisted transport and assembly of a mesoscale device at that site. (b) Lateral view of the layer structure of a FCA chip. (c) Optical micrograph of a 4×4 receptor array ($100 \mu\text{m}$ diameter, $250 \mu\text{m}$ pitch). Receptor electrode interconnection tracks are discernible beneath the overlying metal shield and polymer planarization layers. The four corner counter electrodes (diameter $500 \mu\text{m}$) are omitted for clarity.

However, for many future applications of mesoscale devices and components, demonstration of organization and self-assembly approaches to ordered mesoscopic architectures alone will not suffice. New combined manufacturing approaches to assembly *and* functional integration of mesoscale components are required whereby components may be manipulated and integrated into multifunctional arrays on active substrates that permit direct interfacing between each of the components and the external macroscopic world.

To this end, silicon might be considered as the substrate of choice for assembly and electronic addressing of mesoscale components given the maturity of microelectronic device very large-scale integration technologies. Approaches to the integration of mesoscale devices at active silicon substrates include flip chip assembly, microrobotic pick-and-place, and, more recently, fluidic self-assembly and electric field induced transport.^{5–7} However, these techniques suffer from potentially serious limitations such as, for example, requirements for pre-assembly structural or chemical modification, lack of location configurability during assembly, process cost and speed of assembly, as well as constraints on the numbers and sizes of devices that may be integrated.

To address some of these limitations, we recently reported initial development of a programmable force field method, field configured assembly (FCA), for “hands-free” manipulation and assembly of mesoscale devices.⁸ The principle of the FCA method is that electric fields, configured by selective addressing of receptor and counter electrode sites pre-patterned onto a silicon chip, should drive the field assisted transport, positioning, and localization of mesoscale devices at each of the selected receptor locations. See Figure 1a for a schematic representation of the FCA process. In this letter, we demonstrate that FCA may be applied to both deterministic and stochastic self-assembly and integration of model mesoscale devices, namely, sub- $100 \mu\text{m}$ diameter, 670 nm

Figure 2. (a) Simulation of on-chip electrical field distribution following checker-board addressing. (b) Optical micrograph of the receptor array following addition of $1 \mu\text{m}$ diameter carboxylate-modified latex beads in water (pH 8); zero applied field. (c) Optical micrograph showing the effect of checker-board addressing of the receptor array ($+1.5 \text{ V DC}$). The negatively charged beads concentrate at locations of high positive field as intended. (d) Optical micrograph showing “cleaning” of the receptor electrode sites following negative biasing of the receptor array (-1.5 V DC versus the counter electrodes). Scale bar is $100 \mu\text{m}$.

emitting GaAs-based light emitting diodes, at silicon chip substrates.

A silicon chip comprises 4×4 arrays of circular receptor electrodes ($100 \mu\text{m}$ diameter, $250 \mu\text{m}$ pitch) with counter electrodes ($500 \mu\text{m}$ diameter) located at the four corners of each array. Conducting interconnection tracks connect each electrode to a unique contact pad located on the chip periphery; see Figures 1b and 1c. On-chip electric fields are configured using a DC power supply connected to a custom-made multiplexer unit, which, via probe card connection to the peripheral contact pads, allows programmed electrical addressing of the receptor array and counter electrodes under PC control. To demonstrate that the electric field distribution around a receptor electrode site or set of sites may be successfully configured using this approach, a comparison is first made between simulated electric fields and actual field distributions measured on-chip using electrostatically charged latex beads as electric field markers.

Simulation of on-chip electric fields resulting from application of a checker-board electrical bias configuration to the receptor electrodes (Maxwell 3D field simulator, Ansoft Corp.), by biasing every other receptor electrode positively versus the counter electrodes and leaving each nearest neighbor electrode unbiased, indicates that a corresponding checker-board configured electric field distribution is formed across the receptor electrode array; see Figure 2a. To ascertain whether such a field configuration can be actually achieved in situ, a droplet of an aqueous suspension (pH 8) of $1 \mu\text{m}$ diameter carboxylate-modified latex spheres is dispensed onto the surface of a silicon chip mounted and electrically interfaced as described above; see Figure 2b. A checker-board electrical bias configuration is applied to the receptor electrode array by biasing every other electrode positively, i.e., at $+1.5 \text{ V}$, versus each nearest neighbor and versus the counter electrodes.

Figure 3. (a) Simulation of on-chip electrical field distribution following addressing of a single receptor electrode location versus the counter electrodes. (b) Video image frame of a 50 μm diameter, 670 nm emitting LED pre-localized at a selected receptor electrode site (acetonitrile medium). (c)–(j) Video image frames showing that the LED may be manipulated or “driven” around the receptor array in a programmed manner by sequential electrical addressing of each target receptor electrode in turn (−20 V DC versus the counter electrodes). Scale bar is 100 μm .

In response to electrical addressing of the electrode array in this manner, the initially randomly distributed, negatively charged latex beads are observed to concentrate at the positively biased receptor electrode sites, thereby confirming the configurability of the on-chip electric field distribution; see Figure 2c. Further, the field distribution may be easily reconfigured by applying, e.g., a negative bias to the entire receptor electrode array (−1.5 V versus the counter electrodes), which causes the previously concentrated latex beads to be subsequently repelled from the area of the receptor array; see Figure 2d. Note that integration of a metallic (TiW) shielding layer into the silicon chip substrate during fabrication prevents any electric fields associated with the underlying receptor electrode interconnection tracks from adversely interfering with the configured on-chip field distribution (see chip fabrication details in Supporting Information).

To achieve field configured assembly of functional meso-scale devices, 50 μm diameter, 11 μm thick, 670 nm emitting LEDs are immersed in a nonaqueous medium (acetonitrile) and dispensed in a dropwise manner onto a silicon chip, whereupon the devices rapidly settle at random onto the chip surface in response to gravity. Concerning the feasibility of on-chip field-configured device manipulation and transport, the electric field simulation of Figure 3a indicates that electric fields, sufficient in magnitude to effect field assisted device transport, may indeed be generated between a uniquely addressed receptor electrode site and the four-corner counter electrodes on the silicon chip. Figure 3b shows a video image frame of a single 50 μm diameter 670 nm emitting LED pre-localized at a single receptor electrode location at top right. The video image frames in Figures 3c and 3d show efficient field assisted transport of this device from its initial location to a neighboring receptor site at bottom right following application of a −20 V electrical bias to this electrode site versus the counter electrodes (resulting in an average electric field strength, $E \sim 6.66 \times 10^3$ V/m, between the electrodes). As such, the devices exhibit a net positive charge in the acetonitrile medium, and transport appears to be electrophoretic in nature; see Supporting Information for further details. In real time, the 50 μm diameter device traverses the 250 μm center-to-center distance between the adjacent receptor electrode sites and localize at the target

receptor site in seconds. In fact, rapid on-chip field-assisted device transport over distances of up to several millimeters is achievable.

Note that, in contrast to the simple disk electrode structures employed during the latex bead manipulation experiments of Figure 2, the receptor electrode structure utilized in this experiment is an integrated “disc-and-torus” type. This electrode format is employed in order to confine the electrical field that arises following exclusive biasing of the inner disk electrode, close to the center of a receptor electrode site, and to thereby maximize the assembly process yield. Further, the video image frames shown in Figure 3e to 3j show that the LED may be successfully manipulated or progressively “driven” from receptor site to adjacent site by individual electrical addressing of each target receptor electrode in turn. Therefore, using the FCA approach, sequential reconfiguration of on-chip electric field distributions permits rapid programmed serial manipulation and assembly, i.e., deterministic self-assembly, of discrete functional mesoscale devices at targeted receptor sites on a silicon chip substrate.

To extend the FCA process to the parallel assembly of multiple devices, 50 μm diameter LEDs immersed in an acetonitrile support medium are dispensed in a dropwise manner onto a silicon chip substrate. As expected, the deposited devices settle at random across the chip surface; see video image frame of Figure 4a. Following parallel application of a −20 V electrical bias, versus the counter electrodes, to the entire receptor electrode array, the initially randomly distributed GaAs-based devices simultaneously migrate toward the biased receptor sites; see Figure 4b–4i. In contrast to the programmed or deterministic assembly approach employed in the experiments of Figure 3 above, the process of device assembly is, in this case, stochastic in that the relationship between a given device and its final destination, i.e., receptor electrode site location, is unknown or random.

However, this process of electric field driven stochastic self-assembly of devices at receptor sites is susceptible to defects. Since the diameter of the devices, 50 μm , is substantially smaller than the diameter of the receptor sites, 100 μm , it is possible that more than one device may migrate

Figure 4. (a) Video image frame of 50 μm diameter, 670 emitting LEDs randomly distributed across the receptor array (acetonitrile medium); zero applied field. (b)–(i) Video image frames showing field assisted self-assembly of the GaAs-based devices at the receptor electrode sites following negative biasing of the receptor array (-20 V DC versus the counter electrodes). Scale bar is 100 μm .

toward and localize at a receptor site in response to the applied field. This is particularly likely for the receptor electrode structures employed in the present experiment, i.e., simple disk electrodes equal in diameter to the receptor site recess. In this case, devices tend to localize at the electrode edges rather than in the center of the electrodes due to the more intense electric fields present at the sharp lithographically defined edges.

Since the localization of a device at a receptor electrode site tends to shield that electrode, the probability of co-localization of a second device may be somewhat reduced. If, however, a second device does co-localize, the electric field associated with a neighboring vacant receptor electrode site tends to attract one of the co-localized devices to that site. This effect is apparent in Figures 4g and 4h where one of the devices co-localized at a given receptor site migrates to an adjacent electrically addressed vacant receptor site (out of image view). The incorporation of sacrificial receptor sites into a receptor array may therefore be a useful means for minimizing or annealing assembly defects; see Figure 4i. Likewise, matching of mesoscale device geometry and dimensions to those of the target receptor sites will permit complete self-termination of the assembly process through shielding, and consequently minimize defect formation while maximizing assembly process yield.

Following field configured assembly of GaAs-based LEDs, chip level device integration is completed by transport medium evaporation and bottom metal contact formation by reflowing the Sn/Au solder layers underlying the localized devices. Measured device electrical characteristics indicate standard GaAs p–n junction behavior with a voltage threshold of just over 1.7 V for light emission typical of that obtained from fully operational 670 nm emitting LEDs; see Figure S1 (Supporting Information). These results confirm that FCA may be successfully employed as a tool for combined assembly and integration of mesoscale devices at technologically relevant substrates.

In conclusion, this paper describes a programmable force field method, field configured assembly (FCA), which is applicable to the rapid tweezer-less manipulation, assembly and integration of functional mesoscale devices at electrically addressable receptor locations. FCA may be implemented in a serial or parallel manner to assemble discrete devices at various levels of integration density without the need for pre-assembly structural or chemical device modification. The method has been successfully applied to deterministic and stochastic self-assembly of model mesoscale devices, i.e., sub-100 μm diameter, 670 nm emitting GaAs-based light emitting diodes, onto silicon chips. Future work will focus on application of FCA to assembly of functional nanoscale

electronic and photonic devices within more complex integrated architectures.

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Supporting Information Available: Details concerning silicon assembly chip and mesoscale device fabrication. Experimental protocol for field configured assembly. Experimental protocol for on-chip integration and electrical characterization of assembled devices. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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