Self-Assembly for Microscale and Nanoscale Packaging: Steps Toward Self-Packaging

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***Abstract*—The packaging of microelectromechanical systems (MEMS) and nanoscale devices constitutes an important area of research and development that is vital to the commercialization of such devices. Packaging needs of these devices include interfaces to nonelectronic domains; integration of structures, devices, and subsystems made with incompatible fabrication processes into a single platform; and the ability to handle a very large numbers of parts. Although serial, robotic assembly methods such as pick-and-place have allowed significant manufacturing feats, self-assembly is an attractive option to tackle packaging issues as the size of individual parts decreases below 300 μm. In this paper, we review advances made in the usage of self-assembly for packaging and potential directions that growth in this area can assume. In the micrometer scale, we review the use of capillary forces, gravity, shape recognition, and electric fields to guide two- and three-dimensional self-assembly processes. In the nanoscale, we survey the usage of self-assembled molecular monolayers to solve current packaging issues, DNA hybridization for guiding self-assembly processes of nanoscale devices, and methods used to package nanowires or nanotubes into electronic circuits. We conclude with an example of a nanoscale biosensor which directly incorporates the concept of its package into its fabrication process. Even though the idea of a fully self-packaging system has not been demonstrated to date, the body of work reviewed and discussed here presents a solid foundation for the pursuit of this goal.**

***Index Terms*—Microelectromechanical systems (MEMS), nanomanufacturing, parallel manufacturing, self-assembled monolayers (SAMs), self-assembly, self-packaging.**

I. INTRODUCTION

THE progress of solid-state microfabrication technology has enabled massively parallel manufacturing of large numbers of components. Extensive capital investment and research has yielded a mature and efficient packaging industry for integrated circuits. The packaging picture is quite different for microelectromechanical systems (MEMS), where the packaging requirements are much more stringent. In MEMS packaging, the interface with the external world is not necessarily only electrical, but also thermal, mechanical, optical, or fluidic among others. Many MEMS devices use unconventional fabrication materials and consist of subsystems that are made with incompatible microfabrication technologies. The packaging geometry can also be important for a MEMS device, and specific positioning of system parts in a three-dimensional (3-D) configuration could be essential for proper device operation.

A variety of packaging solutions have been developed for specific MEMS devices. However, considering the wide range of packaging requirements in MEMS, it is unlikely that a universal packaging solution, similar to that for integrated circuits, can be found. Thus, if MEMS devices can participate in their own packaging (self-packaging), the infrastructure needed to support the packaging processes for a MEMS production line can be greatly simplified. At the nanoscale, packaging a device and providing an interface for it to the outside world is even more challenging. The ability to efficiently manipulate single parts diminishes quickly as the size of objects reaches the nanoscale and the need for a parallel manipulation/packaging method arises. By comparing the requirements for packaging a MEMS or a nanoscale device, one can compile a wish list of attributes for an effective packaging technology. This packaging technology has to be able to perform the following:

1) handle many parts and be parallel in nature;
2) integrate multiple devices made from different materials and incompatible technologies into a single platform;
3) position and interconnect parts on planar and nonplanar geometries.

Modern robotic assembly methods have fulfilled many of these requirements and have compensated for nonparallel methods with shear speed. Modern pick-and-place machines are capable of handling up to 26 000 or more surface mount electrical parts per hour, with part sizes ranging from 300 μm to 75 mm as shown by the upper horizontal bar in Fig. 1. This is more than adequate for typical consumer electronics. For example, a cell phone in 2000 contained some 380 electrical parts, including 15 IC chips and 322 passive electrical components [1]. At 26 000 parts/h, one pick-and-place machine can turn out half a million cell phone circuit boards per year, assuming it is operational for 20 of every 24 h. A personal computer board contains some 1285 electrical parts, including 1066 passive components [1], and a comparable robotic assembly system can assemble tens of thousands of boards per year.

These numbers are indeed impressive; however, it is instructional to note trends in the rate of assembly as component size varies. As demonstrated by examples in Fig. 1, the assembly rate increases as the component size is reduced from meters to centimeters and then millimeters. This is primarily due to the fact that inertia plays a less significant role in smaller scales, and that many of the systems in the smaller scale require less complex assembly geometry (primarily two-dimensional (2-D) rather than 3-D). The peak of this curve indicates state-of-the-art pick-and-place assembly. It is interesting to note that as component size continues to scale down, the trend in assembly

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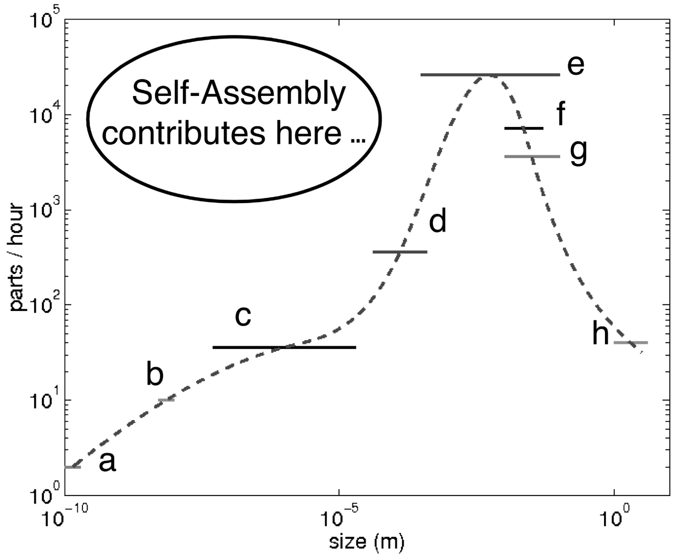

Fig. 1. Approximate speed (parts per hour) versus approximate range of part size for a variety of serial assembly methods. The enclosed zone identifies the area in which self-assembly can have significant contributions. Sources are as follows: a, individual atom placement by STM [2]; b, polymer memory storage device [3]; c, optical tweezers assembly [4]–[6]; d, 3-D microassembly [7]; e, robotic pick-and-place printed wiring board assembly (model HLX8100, Essemtec, Switzerland); f, robotic assembly of a grease gun coupler (Innovation, Inc., Birmingham, AL); g, robotic assembly of automobile wheel bearings (Capitol Technologies, Inc, Niles, MI); h, robotic assembly of an automobile body and chassis (Profibus International case study: OPEL Germany).

rate reverses direction. For small components, the difficulty to handle and correctly position the parts greatly increases which results in a decreased assembly rate. Although the peak of serial, robotic, assembly methods in Fig. 1 has not been firmly established, based on our current understanding of the state-of-the-art, we anticipate it to be located at approximately 300 μm. The diminishing rate of assembly as component size decreases poses a major packaging challenge. Although some research groups have shown remarkable progress with serial handling techniques for microscale and nanoscale prototyping applications [4]–[7], the scalability of such techniques is limited. Clearly, as technology moves toward smaller components sizes, alternative technologies need to be explored. Self-assembly is one such alternative method.

Self-assembly is the spontaneous formation of higher ordered structures from basic units. Such processes abound in nature, and they can consitute an engineering approach to packaging MEMS and nanoscale devices. In this approach, parts that constitute the final system are made independently and then induced to self-assemble/self-package to form the final system. In addition to their function as a part of the final system, each component in this method has to be equipped with a mechanism that aids in its process of self-assembly. The self-assembly process in general involves recognition and making connections to the other parts of the system.

We identify three fundamental packaging conditions at which self-assembly can significantly extend the capabilities of current robotic assembly methods.

1) The process involves a very large number of parts ($>\sim 10^4$).
2) The parts are small ($<\sim 300 \mu$m.
3) The parts or package require a complicated final geometry (3-D, nonplanar, etc.) to be realized.

Even though a complete self-packaging system has not been demonstrated to date, efforts have been made with various degrees of success to use self-assembly in packaging processes.

In this paper, we review recent works using self-assembly in the microscale and nanoscale for packaging. In the microscale, we will survey the use of self-assembly for the integration of hybrid systems and 3-D packaging. In the nanoscale, we review the use of self-assembled molecular monolayers in aiding microscale and macroscale packaging. We also review use of DNA hybridization for nanoscale device integration, and examples of packaging nanotubes and nanowires into electrical circuits. Self-assembly is the critical concept in all these nanoscale applications that allows for interfacing the nanoscale device to the outside world. Finally, we conclude with an example of a nanoscale biosensor that directly incorporates the concept of its package into its fabrication process. The last example is an indicator of a trend that merges device fabrication and packaging into a single process as the system size is reduced to submicrometer scales. We expect that for many stand-alone nanoscale devices and systems of the future, fabrication and packaging processes will be inseparable and indistinguishable.

II. MICROMETER-SCALE SELF-ASSEMBLY FOR PACKAGING

In a typical microscale self-assembly procedure, parts that participate in the process are fabricated separately and then introduced in a common medium. The parts should have the ability to recognize (self-assembly programming mechanism) and connect (self-assembly binding/driving force) to the proper adjacent part or template. The binding events between the components drive the system toward a lower energy state and occur with a finite error rate due to the statistical nature of the process. In order to drive the system from a local energy minimum to a global minimum that corresponds to the correct self-assembly, an external agitation mechanism is needed. The design and implementation of a self-assembly/self-packaging procedure for a collection of parts not only involves the construction of more complicated parts that incorporate the recognition and binding mechanisms for self-assembly but also the proper design of the self-assembly procedure, including the external agitation, to arrive at a high yield process.

Two main issues have been targeted in micrometer-scale packaging to be solved with the aid of self-assembly: 1) the construction and packaging of hybrid systems that require the integration of parts microfabricated with incompatible microfabrication processes [8] and 2) construction and packaging of devices with geometrical requirements that cannot be realized with inherently 2-D conventional solid-state microfabication. Table I summarizes some select self-assembly applications, charting the driving force, the component size range, and the assembly rate. As shown, two-dimensional (2-D) self-assembly processes are capable of achieving a very high assembly rate, demonstrated especially by Alien Technology's industrialized process. Their reported assembly speed of up to 2 000 000 parts/h clearly indicates that self-assembly has enormous potential when large numbers of parts are involved.

TABLE 1

COMPARISON OF SELECTED SELF-ASSEMBLY APPLICATIONS. INDUSTRIAL PROCESSES HAVE DEMONSTRATED VERY HIGH ASSEMBLY RATES; PROCESS UNDER INVESTIGATION IN ACADEMIC LABORATORIES ARE SLOWER BUT EXAMINE COMPLEX SELF-ASSEMBLY SCHEMES, SUCH AS 3-D ASSEMBLY

	Ref. No.	Structures Formed	Driving Force	Self-Assembly Programming Mechanism	External Agitation	Part Size Range	Estimated Speed (parts/hour)
2D Self-Assembly	see note[1]	ICs into RFID tags	Gravitational	Shape / Size Recognition	Mechanical Vibrations	10µm to >100µm	2,000,000
	[9]	AlGaInP/GaAs LED packages	Capillary Forces of Solder	Shape Recognition	Hydrodynamics	200µm	18,000
	[10]	Freestanding Si parts onto Si and quartz substrates	Capillary Forces of Polymer	Shape Recognition	Hydrodynamics	~200µm	6000
	[11]	Si FETs onto flexible plastic substrates	Gravitational / Capillary Forces of Solder	Shape Recognition	Mechanical Vibrations, Hydrodynamics	100-300µm	500
3D Self-Assembly	[12]	3D arrays of polyhedral plates	Capillary Forces of Polymer	Pattern of edge/face adhesive	Axial rotation of assembly vessel	10-30µm	~500
	[13]	3D aggregates of mesoscopic objects	Capillary Forces of Polymer	Component Shape	Axial rotation of assembly vessel	~1mm	~500

[1] Alien Technology Corporation, http://www.alientechnology.com

As the self-assembly process complexity increases toward 3-D assembly, the assembly rate decreases, but the assembled architectures are very appealing nonetheless.

Currently, most 2-D self-assembly applications share a common goal in that they aim to improve upon traditional pick-and-place part-to-substrate packaging operations. The 3-D self-assembly applications investigated provide examples of creating geometries or architectures at the microscale that current robotic techniques cannot yet address.

A. Two-Dimensional Self-Assembly of Microstructures

The primary objective of most 2-D self-assembly applications is the integration of prefabricated microcomponents at prescribed locations onto a substrate via part-to-substrate self-assembly. Most of these processes require a fluidic media for transporting the microcomponents during assembly, although "dry" self-assembly techniques are also under investigation. In a typical process, premicrofabricated parts suspended in a liquid flow past a series of prescribed binding sites on a template. Shape recognition, gravitational forces, and capillary forces (among others) are then used to guide the self-assembly of parts onto the binding sites. In [14], for example, components slide over a template and fall into wells at the assembly sites; whereas in [15]–[17] the components assemble after making contact with an adhesive or solder. The fluid flow provides a constant supply of parts that are available for binding and removes unbound or incorrectly bound parts. Fluidic self-assembly differs from traditional robotic packaging methods because of its stochastic nature. Large numbers of components are typically suspended in a liquid media over a substrate, which contains a much smaller number of active binding sites. Spontaneous assembly occurs at random, and the large number of parts available for assembly insures high yield as well as rapid assembly. Parts that do not assemble are often recycled in subsequent self-assembly processes. The result is a rapid and cost-effective integration and packaging technique.

1) Fluidic Self-Assembly Driven by Gravitational Forces: Gravity, although a relatively weak force in the microscale, has been successfully used as a driving force in fluidic self-assembly. In a typical scheme, components are agitated to move across the substrate until they fall into recesses or wells. Van der Waals and capillary forces between the part and the substrate then help to hold the part in place once assembled. Depending on the application, post processing may be necessary to give electrical connection between the part and the substrate.

Thin GaAs blocks [18] and optoelectronic devices [19] have been assembled in this manner. In [19], about 100 multiple-sized laser diodes are assembled on silicon wafers with 100% efficiency at high speed and accuracy of less than ±2-μm precision. In similar work, Smith and coworkers have developed a process that employs gravity and hydrodynamic forces to guide components into recesses on a substrate [14], [20], [21]. Fig. 2(a) illustrates the fluidic self-assembly process. In their approach, trapezoidal semiconductor devices ranging in size from 10 μm to several hundred micrometers are suspended in a fluid, and flowed over a substrate with correspondingly shaped recesses (holes) at the binding sites. After the parts have assembled, van der Waals forces act with gravity to keep the parts in place for subsequent metallization and post-processing. Successfully assembled devices include GaAs LEDs, InGaAs photodetectors, and microelectronic devices produced with standard CMOS IC processes. This process can use a large array of substrates ranging

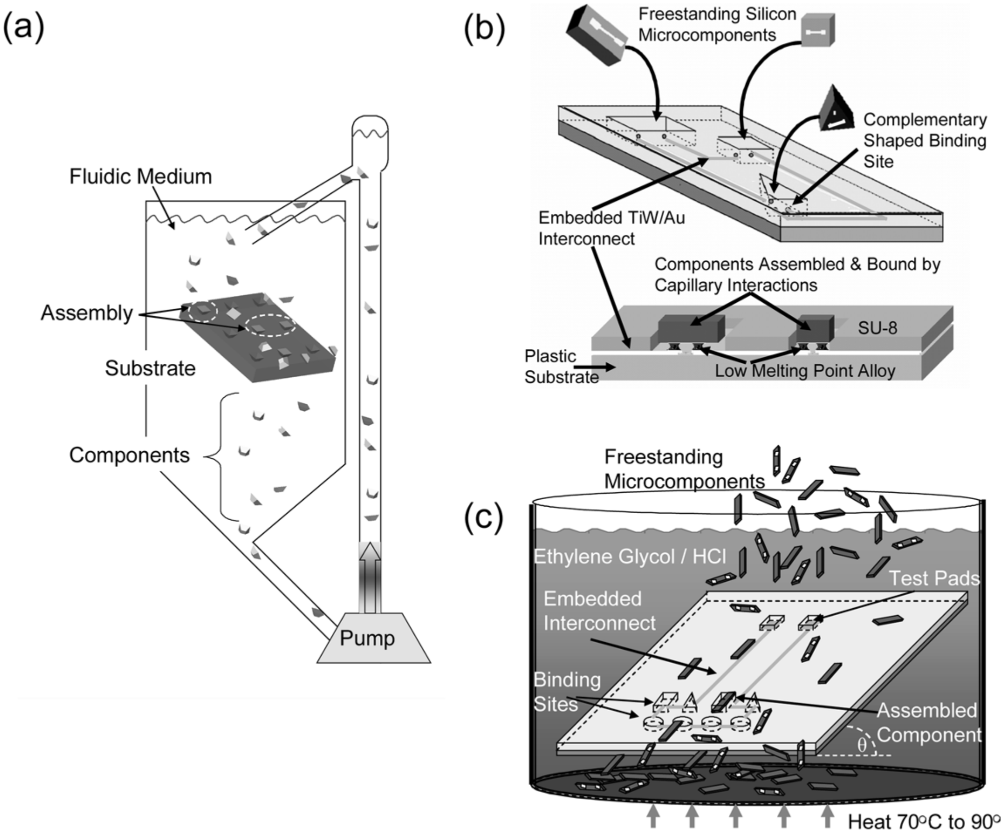

Fig. 2. Illustration of fluidic self-assembly using gravitational forces. (a) Assembly chamber showing device and fluid flow for trapezoidal devices to assemble at recesses in the substrate (b) using shape-recognition and capillary forces to guide the self-assembly. (c) Illustration of assembly chamber shows angle at which substrate is tilted, microcomponents only assemble at complementary shaped recesses. (a) Adapted from [14], (b), and (c) from [11].

from rigid materials such as glass to flexible materials such as polyester, polyimide, and polycarbonate.

Shape recognition can be used to selectively control or program the assembly. We have demonstrated the selective self-assembly of silicon circuit components onto plastic substrates, wherein each component assembled only at a binding site with a complementary shape. Once assembled, the capillary forces of molten solder bound the component to the substrate as well as provided electrical connection to underlying interconnect, as illustrated in Fig. 2(b) and (c). In this manner, p-channel, n-channel, and diffusion resistors can assemble individually in a predetermined manner on the substrate [11].

Gravitational force-based assembly methods have demonstrated the highest assembly rate to date. Alien Technology Inc. has developed this fluidic self-assembly process into a mass manufacturing scheme. In perhaps the most successful application of self-assembly for industrial-scale packaging to this date, it has successfully demonstrated the assembly of electronic devices onto flexible plastic films, placing tens of thousands of devices in a single step.[1]

2) Fluidic Self-Assembly Driven by Capillary Forces: Capillary forces have proven to be a reliable and effective means to induce the self-assembly of microscale devices [22]. With capillary force-based methods, the overwhelming power of surface forces at the microscale is exploited to guide the assembly. Assembly and alignment occur due to interfacial surface energy minimization between devices and an adhesive liquid at binding sites on the substrate. Studies have demonstrated that capillary force-based assembly processes are capable of arranging thousands of components per minute with submicrometer precision [10], [15].

Hydrophobic and hydrophilic interactions provide the basis for many fluidic self-assembly processes. These forces have proven valuable to drive both part-to-substrate and part-to-part assembly. With part-to part assembly, devices are immersed entirely in a solution or are suspended at an air–fluid interface, as shown in Fig. 3 [23]. Upon agitation, the parts minimize their surface energy by forming agglomerations in the solution or at the interface. With part-to-substrate assembly, a typical self-assembly process involves the preparation of parts and a template with hydrophobic pads. The template is submerged in an aqueous environment, and a hydrophobic liquid is preferentially dewetted onto the hydrophobic binding sites. Parts are introduced in the aqueous environment and the system is agitated. The free-standing parts preferentially bind to the hydrophobic binding sites on the template by minimizing the total interfacial surface energy of the pad–liquid–pad system. This method has been demonstrated to accurately position freestanding silicon parts onto a template with submicrometer precision [17]. Difficulties encountered with alignment precision, such as tilting or rotation of parts at a binding site, have been addressed through changing parameters such as adhesive lubricant thickness and shape of the binding site.

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[1] Alien Technology Corporation. http://www.alientechnology.com.

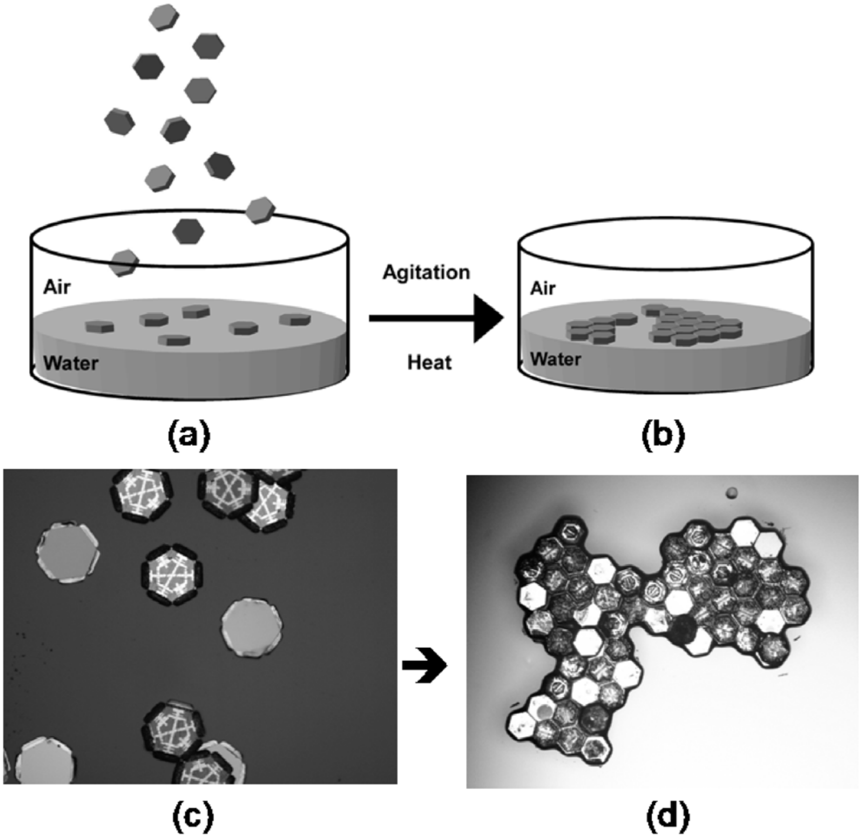

Fig. 3. Self-assembly of silicon elements floating at a fluid interface. (a) Schematic showing the introduction of the elements to the air-water interface. (b) Schematic showing the pattern formation after heat and agitation were introduced. (c) Optical microscope image of released silicon components supported at the air–water interface prior to self-assembly. (d) Optical microscope image of a collection of parts at the interface after self-assembly. The side of each hexagon is 100 μm (from [23]).

Controllability and selectivity in the assembly process allow for more complex integration between multiple types of components and the substrate. Shape recognition [17], [24] and electrochemical modulation of the hydrophobicity of specific binding sites [25], [26] are methods that give selectivity between binding sites and components. With shape recognition, the potential energy minimum of a component is located at binding sites with corresponding shapes. Electrochemical modulation of the hydrophobicity of binding sites, on the other hand, disallows or allows binding at specific sites according to the site's hydrophobicity. Therefore, assembly of multiple types of components on the same substrate is achieved.

Molten solder can be used instead of a hydrophobic liquid to provide both a guiding mechanism for self-assembly to sites on a template and to provide electrical connections between them. LEDs integrated onto a cylindrical display [9] and the assembly of high-performance inductors [27] both realize electrical connections between the devices and substrate. A two-step assembly process is demonstrated in [27]; first the "inductor chiplets" assemble at the binding sites which are coated in a layer of hexadecane, and second, the hexadecane is evaporated, causing the inductors to contact solder pads which are then reflowed for assembly. In a different approach, a combination of shape recognition and solder surface tension-driven self-assembly is used to bind components selectively and provide electrical connectivity [28]. As shown in Fig. 4, heterogeneous microsystems are assembled after the introduction of multiple types of components to the assembly solution.

3) Guided Self-Assembly for Packaging Driven by Electrostatic Forces: The ability to dynamically control the self-assembly process can aid in the realization of more complex packages. Ideally, dynamic control could enable self-assembled configurations that are actively controlled or programmed to change or grow according to specific input signals. Self-assembly driven by electrostatic forces presents an intriguing candidate for dynamic control because of the ease at which the driving electric force can be applied and manipulated. Techniques using electrostatic forces have demonstrated the ability to position and align parts [29], [30], and a combination of dielectrophoresis and electrohydrodynamics contribute to the self-assembly of silicon resistors [31] onto a template. This technique could be extended to the heterogeneous integration of microdevices for flexible displays and electronics, power electronics, and MEMS applications [31]. A major barrier toward the use of dynamic electrostatic forces in assembly, however, is the difficulty in controlling the charge on individual freestanding microcomponents.

B. Three-Dimensional Self-Assembly

Recently, self-assembly methods have been demonstrated which may apply to fabrication and packaging of 3-D microstructures. Forming higher order structures from previously

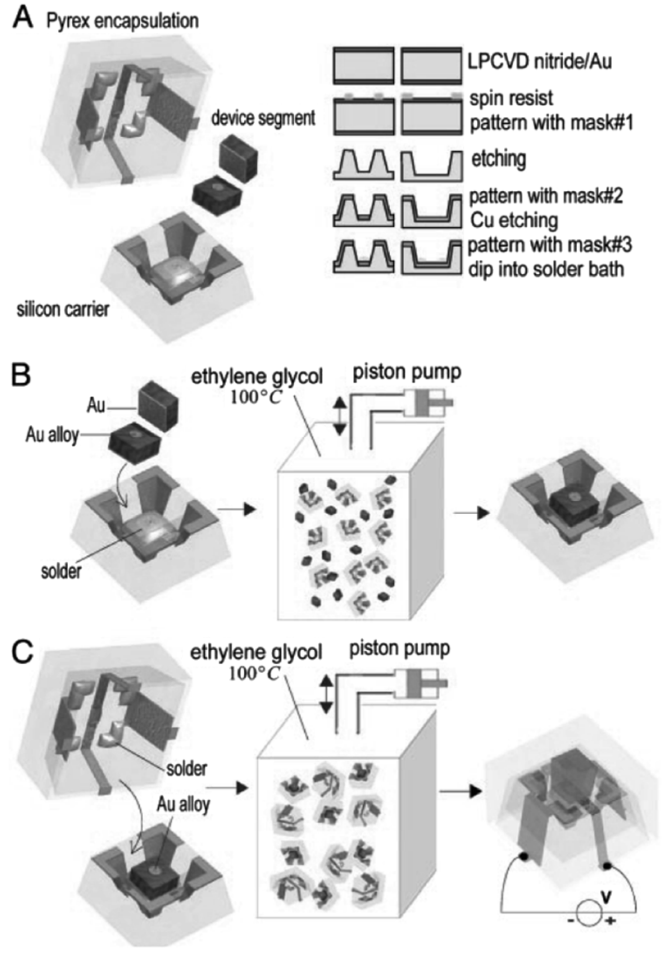

Fig. 4. Sequential shape-and-solder-directed self-assembly is used to package AlGaInP/GaAs LEDs. (a) Surface micromachining defines silicon carrier and encapsulation units. (b) Assembly of LED device to silicon carrier. (c) Encapsulation of units (from [28]).

fabricated microstructures is a baseline objective in many 3-D self-assembly applications. Although the technology is young and no established products have yet been realized, the potential to "grow" microstructures and electrical circuits has great appeal. Multiple components such as microactuators, microsensors, microcontrollers, and micropower sources can be integrated and packaged together into 3-D structures to create complex, powerful microstructures or even micromachines [32].

As in 2-D self-assembly, a common platform for 3-D self-assembly involves the assembly of microcomponents while suspended in a liquid medium. In one application, polyhedral metal plates are assembled into large arrays resulting in assembled structures using hydrophobic–hydrophilic interactions [12]. Rendering the specific faces of parts hydrophobic or hydrophilic followed by the deposition of a thermally curable hydrophobic adhesive results in a capillary force-based assembly process when the parts are immersed in water. Consequently, different structure geometries such as monolayers, multilayers, and rods, can be realized with control of the geometry of the metallic plates and the surface treatment on the polyhedra. A similar method does not require the use of a hydrophobic adhesive to bind the components together, but solely relies on the interactions between hydrophobic or hydrophilic component surfaces [33]. In addition, an approach using dry self-assembly demonstrates the assembly of micromotor arrays [32]. The use of capillary forces to assemble 3-D structures has been demonstrated with larger objects such as millimeter-sized silicone cubes [13] and octahedra and tetrahedra [34]. With these techniques, self-assembly yields multicomponent crystalline structures. Components self-assembled in a similar process to form shapes such as "doughnuts," "footballs," and cylinders [35]. Self-assembled crystalline structures can serve as the platform or backbone in 3-D electrical networks. Although still in their infancy, these experiments point toward the potency of self-assembly as a means for producing 3-D structures and packages.

C. Using Material Reflow Surface Tension Forces to Guide Packaging

The surface tension forces of molten materials can be used to drive and align microstructures that require out of plane rotation. The assembly process begins by melting a material and using the resultant surface tension forces to guide the movement of the structure to a new configuration. Upon cooling and solidifying the material used to guide the self-assembly, the newly formed structure can be fixed in its new configuration.

These forces have been used to assemble complex microstructures with 3-D features, such as micromirrors [36] and inductors [27] that have been rotated out of the substrate plane. A number of materials including solder, photoresist, and borophosphosilicate glass have been successfully used for surface tension-powered self-assembly [37]. The surface tension properties of molten solder, for example, have been exploited to power the assembly of many microstructures, including optoelectronics [36], [38]–[41] and the alignment of optical fibers in photonic devices [42]. We refer the reader to Syms *et al.* [43] for a comprehensive review of the use of surface tension forces for this type of self-assembly.

III. NANOSCALE SELF-ASSEMBLY FOR PACKAGING

The need to explore new methods for packaging nanoscale devices has been previously identified [44]–[46]. Packaging a nanoscale device has all the complexities associated with MEMS packaging plus the issue of its interface and interconnection to objects that are orders of magnitude larger. To illustrate this point, consider molecular electronics, where molecules that constitute a device are constructed via chemical synthesis. The packaging problem is how to connect electrical leads to the molecules and enable their use as single or interconnected devices [47]. Extremely small device sizes and the large numbers involved rule out the use of techniques such as pick-and-place, and call for alternative technologies to be explored.

Similar to MEMS, it is unlikely that there is a single solution to the packaging of nanoscale devices due to the diversity of their functions and interface requirements. Here, we review two classes of self-assembly applications relevant to nanoscale

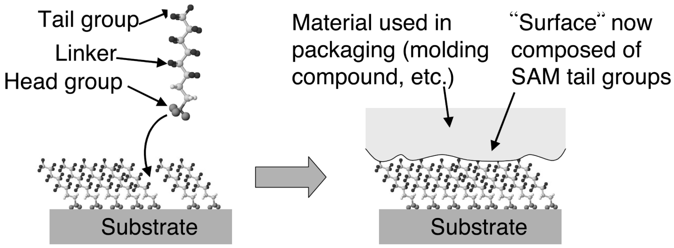

Fig. 5. Depiction of how SAMs serve to replace the surface properties of a substrate material with those of the SAM's tail group.

packaging. We will first briefly look at the use of self-assembled molecular monolayers (SAMs) to aid current integrated circuits (IC) and MEMS packaging issues, which is an example of applying nanoscale assembly to solve macroscale problems. Then, we will in more depth review self-assembly methods that interface between nanoscale electronic devices such as carbon nanotubes (CNTs) or nanowires (NWs), and the micrometer-sized world and beyond. We end our discussion by considering a future direction of nanoscale packaging: a lab-in-a-sphere concept.

A. Self-Assembled Monolayers (SAMs) for Antistiction, Wear Resistance, and Adhesion Promotion

This section focuses on examples which use the nanoscale phenomena of SAMs to aid in the packaging of microscale or macroscale devices. A molecule capable of forming a SAM typically consists of a head group with preferential binding to a particular material, a tail group, and a linker (for example a chain of sigma-bonded carbon atoms) connecting the two, as shown in Fig. 5. The chemical self-assembly of the monolayer results in a surface having properties similar to those of the tail group. This tail group will directly affect surface-dependent phenomena such as contact angle or adhesion. The robustness of certain SAM systems have been investigated for several decades, making SAMs a good solution to many engineering packaging problems.

Stiction of released MEMS devices, often cantilever beam-like structures, is one of several hurdles preventing a universal packaging solution for MEMS. The situation is reviewed in [48] and the use of SAMs to solve the problem is given in a review from the year 2000 [49]. The head group of these SAMs is trichlorosilane, which reacts and binds with silanol groups present on the native oxide of Si. One barrier to the commercial use of this SAM is the lack of reproducible results from one research group to the next, owing primarily to the difficulty of working with this SAM molecule because of its affinity for trace amounts of water. Vapor phase deposition in a reaction chamber appears to be a promising way to improve its reproducibility [50], [51]. Another barrier may be the poor adhesion of gold wirebonds to the SAM-treated Si surface, although Al wirebonds were successful [52].

In macroscale electronic packaging, SAMs with a thiol head group (S–H) have been studied for some applications. Molecules with this head group do not suffer from the same affinity for water and tend to yield more reproducible results. The delamination of epoxy molding compounds (EMCs) from metal interfaces such as copper is one of the weakest links in modern packaging processes. Wong *et al.* [53] recently demonstrated a thiolate SAM which bonds readily with copper and forms a surface of carbonyl groups, improving adhesion to EMCs. Nöel *et al.* [54] report results describing the corrosion-resistance of methyl (-CH3) terminated SAMs deposited on nickel, a material which is normally prohibited as a packaging material because poorly conducting corrosion layers readily form. Another recent use of thiolate SAMs is a ten-fold increase in the conductance of anisotropically conductive adhesive (ACA) joints [55], [56]. The SAM allowed chemical bonds to form between bonding pads and metal particles in the ACA, and facilitated the flow of electrons between them.

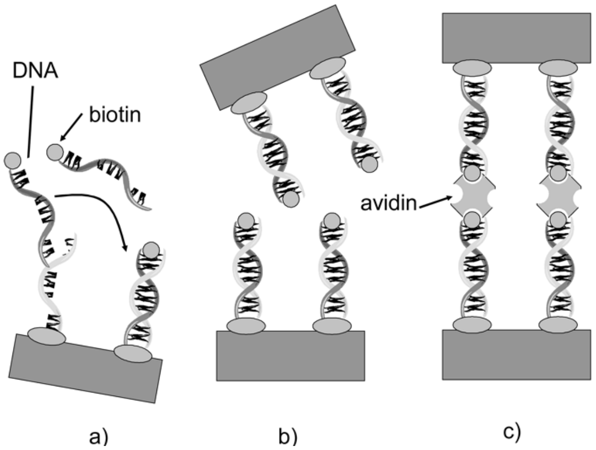

Fig. 6. Nanoscale self-assembly method for microscale parts using avidin–biotin interactions for binding and DNA for selectivity.

B. Packaging Nanoscale Devices With Self-Assembly

1) Self-Assembly by DNA Hybridization: Self-assembly abounds in biological systems, where amino acid sequences encoded by DNA produce the 3-D structures of enzymes and proteins. The process of DNA base-pair binding is known as hybridization. This is a parallel programmable fabrication process that generates 3-D structures with nanoscale precision. It is no wonder that there has been much work using DNA hybridization to guide the self-assembly of electronic devices.

Most work can be classified as development of DNA-based methods to integrate different inorganic materials into a single package. Bashir and coworkers propose [57], [58] and later demonstrate [59]–[61] a method for attaching DNA molecules to 5–10-μm Si microfabricated parts. The parts were attached to each other using DNA and an avidin-biotin system, which is one of the most specific of protein-small molecule bindings. As shown in Fig. 6(a), single-stranded DNA (ssDNA) is attached on one surface, and the complimentary ssDNA strand with a biotin molecule is introduced to hybridize with the first ssDNA, forming double strand DNA (dsDNA) in Fig. 6(b). Avidin is a large protein with four highly selective binding sites for biotin molecules and is introduced to form bonds between the biotin on the ends of the dsDNA on the part and that on another corresponding silicon part [Fig. 6(c)]. Thus, a system for highly selective self-assembly is demonstrated, with ssDNA sequences controlling which parts assemble in a particular

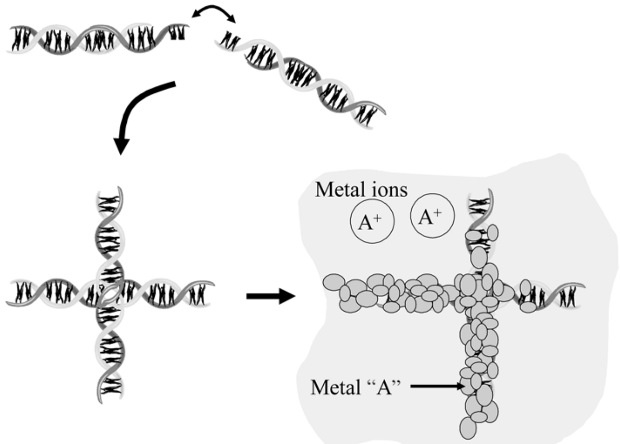

Fig. 7. Schematic showing DNA-based scaffolding for nanowire assembly. First, specific sequences of DNA having unbound ends ("sticky ends") are allowed to hybridize with other predetermined sequences to form structures. These structures form a template, and a chemical reduction of metal ions serves to coat the template with metal.

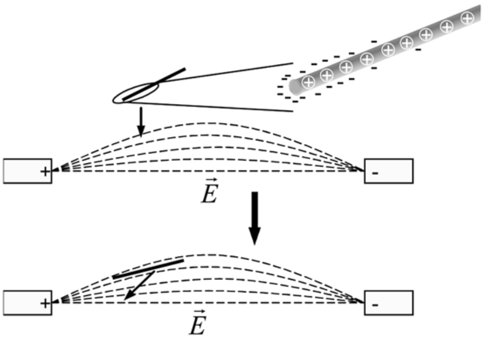

Fig. 8. Schmatic showing how a long nanoscale object (a CNT, for example) with mobile electrons acquires an electric dipole in an ac field, which serves to align the object with the field and draw the object toward the electrodes.

step. The idea is extended to part-to-substrate assembly in [62]. Although DNA provides an excellent candidate for programming a self-assembly processes at the nanoscale, the resultant hybridization forces may not be sufficient for extending the technique to the micrometer domain. In the aforementioned experiment, the forces experienced by microfabricated Si parts during subsequent liquid handling procedures, which include gravitational and fluidic drag, are larger than the forces resulting from DNA hybridization. In [60], future work pointed toward reducing the size of parts in order to increase the relative strength of DNA binding forces. Wang *et al.* motivate the development of on-chip optical waveguides based on nanoscale quantum dots, along with a method to package such devices into useful optical circuits [63]. The proposed method is similar to that shown in Fig. 6. Acrydite–DNA binding to one substrate is facilitated by a SH-terminated SAM on silicon oxide, patterned by e-beam lithography. A biotinated-cDNA is allowed to hybridize with the strand that has been covalently bound to the subsrate. Quantum dots 4–6 nm in diameter are functionalized with streptavidin to recognize and bind to the biotin sites, completing the construction process [64].

There is great potential for DNA self-assembly to directly form nanoscale circuits and systems. Periodic, 2-D arrays of DNA based on the crossed Holliday junction (see Fig. 7) allow for the creation of addressable locations at which components may self-assemble [65], [66]. A primary challenge has been to enhance the electrical conductivity of DNA via metallization, and several groups have demonstrated an electroless deoposion method onto DNA [67]–[72], creating templated nanowires (Fig. 7). LaBean and coworkers report the formation of curled DNA arrays and subsequent metallization to form wires [73], [74]. We have reported on the metallization of individual strands of DNA, aligned in one and 2-D arrays [75], [76]. In a significant step toward using DNA-templated device packaging, Keren *et al.* [77] report on the actual assembly of a DNA-templated field-effect transistor. Although the metallization process is prone to irreproducibility, and may ultimately limit the integration of large number of nanoscale components, DNA-templated self-assembly and subsequent metallization allows the fabrication of a simple circuits with a finite number of devices in an extremely small space. DNA hybridization is one of the most promising methods for construction, programming, and packaging of nanoscale devices.

2) Electric Field Directed Nanoscale Self-Assembly: Nanoscale parts such as CNTs are produced via chemical synthesis which is typically incompatible with many other microfabrication processes, and the packaging challenge for these devices is, thus, their proper integration. Much work has been done in the area of CNT self-alignment using electric fields between previously-patterned electrodes. Yamamoto *et al.* [78] apply the principles of dc electrophoresis to the handling of CNTs: particles acquire a positive charge in a solvent such as isopropanol, and the charged particles migrate toward a negatively-charged electrode. The same group later demonstrates ac electrophoresis [79], wherein clusters of CNTs are aligned between electrodes in an ac field. The alignment occurs when the ac frequency exceeds the ability of negatively charged ions (which normally surround the positively charged CNTs in isopropanol) to travel the length of a CNT, and the mobility-limited situation results in each CNT acquiring an electric dipole, as shown in Fig. 8. Parallel networks of CNTs are shown to form perpendicular to parallel electrodes on a glass substrate. Taking the idea further, Smith and Nordquist [80] describe the use of nonuniform ac fields to self-align single metallic NWs between two predefined metal pads. With sufficiently small pads, the electric field in the vicinity of a NW is reduced once it assembles and screens the effect of the field on other NWs [81]. Alignment of nanotubes using similar techniques is also shown in [82], reporting that the nanoscale wiring self-assembles within seconds.

Examples of devices packaged using electric field self-alignment include a biosensor consisting of a silicon NW that is functionalized with different molecules to provide a recognition mechanism for proteins or antibody–antigens [83]. Duan *et al.* [84] report on parallel and cross-arrays of indium phosphide NWs packaged by electric-field mediated alignment and demonstrate functional nanoscale field-effect transistors, p-n junctions, and light-emitting diodes. Recent work by Kamat *et al.* [85] demonstrates the crossed assembly of CNTs through the use of dc amplitude modulation. While these methods seem promising, a limitation seems to be the scale at which electrodes may be patterned prior to nanoscale CNT or NW assembly. The electrodes tend to be much larger than the device being assembled, often resulting in the assembly of not one but many devices across the same region. Similar to the case for the self-assembly of micrometer-scale parts, the use of electrical field generated easily by application of a voltage immediately creates the opportunity to dynamically control the self-assembly process. This is an appealing prospect; however, the need to individually address each pad in the self-assembly process can significantly limit the utility of this approach.

3) Self-Assembly Using SAMs: Another method to self-assemble CNTs is the definition of self-assembled monolayer patterns through either previously patterned (usually metal) regions or through direct SAM patterning with e-beam lithography. The local situation is then analogous to that shown in Fig. 5, where the SAM molecule tail group defines the surface and encourages the binding of a nanoscale device (instead of the bulk material depicted in Fig. 5. For example, charged tail groups such as amino ($-NH_2/-NH_3^+$) or carboxyl ($-COOH/-COO^-$) groups have been shown to drive the assembly of CNTs [86], [87]. Burghard *et al.* [88] demonstrate CNT assembly by first patterning nanoscale metal electrodes with e-beam lithography, then forming a thiol-based SAM on the electrodes which attracts surfactant-covered CNTs. Liu *et al.* [89] used e-beam lithography to directly pattern self-assembled monolayers of trimethylsilyl and then followed a similar procedure. Choi *et al.* [90] patterned a PMMA mask with e-beam lithography, and a deposited amino-silane SAM and subsequent surfactant-covered CNTs were patterned by lift-off. Valentin *et al.* [91] present CNT-based field-effect transistors using similar self-assembly methods followed by metal lithography.

Fabrication methods used to pattern SAM regions tend to be an order of magnitude or more larger than the diameter of the nanoscale devices themselves. Still, such methods are and will continue to be useful for the experimental study of individual nanoscale electronic components.

C. Lab-in-a-Sphere: The Future of Nanoscale Packaging

As the size of the components and the overall system enters the nano domain, the process to construct the parts and the procedure to package them into a functional system become exceedingly intertwined. Lab-in-a-sphere demonstrates this point clearly.

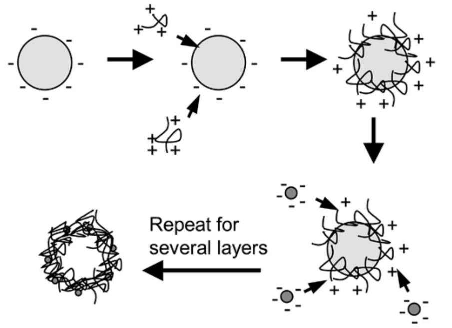

Fig. 9. Schematic of lab-in-a-sphere layer-by-layer sensor construction, adapted from [94]. First, a negatively charged latex or silica template is placed in a solution, allowing positively charged particles (such as proteins) to self-assemble onto the sphere surface. Next, negatively charged magnetite particles (for example) self-assemble onto the now-positively charged surface. After repeating the process several times, the template is dissolved and allowed to diffuse out of the structure, and the finished device has encapsulated biological probes which allow free interaction with an analyte through nanosized pores.

Fig. 9 shows a biosensor device that interfaces directly with its intended application [92]–[94]. Rather than packaging this device onto a substrate such as a chip carrier with wire boards, the freestanding device is its own package. This represents an example of a self-packaging system, where the layer-by-layer fabrication process results in a finished, packaged device. It also exemplifies an application where it was necessary to have an extremely small final device size, and where a very large number of devices fabricated in a low-cost fashion was necessary. We believe this example points toward the future direction of packaging for nanoscale systems in which fabrication and packaging are codesigned and coperformed, the final system is multifunctional and retains a submicrometer overall size, and the fabrication/packaging cost per unit should be kept extremely low due to the need to construct a very large number of systems. Note that the level of system integration in such systems goes well beyond what the current MEMS technology can offer.

IV. CONCLUSION

We have reviewed several accomplishments, as well as some aspirations, on the use of self-assembly to package microscale and nanoscale systems. Recalling the fundamental areas where self-assembly can improve upon traditional packaging techniques—extremely large numbers of parts, very small parts, and difficult geometries—these accomplishments make evident that self-assembly is a viable packaging technology. Many groups have demonstrated self-assembly processes that handle between hundreds and tens of thousands of devices for placement with other devices or on substrates. Devices made from different materials such as group-IV semiconductors, optical fibers, and carbon nanotubes have been successfully self-assembled to CMOS-compatible silicon substrates, and other types of substrates. A significant contribution from self-assembly is likely to be in packaging 3-D micrometer-scale functional systems. For example, although the current MEMS technology allows for the microfabrication of microactuators, sensors, telemetry circuits, and even microscale power sources, there is no parallel packaging technology available capable of putting the above parts together to construct a functional μm-scale robot. Currently, self-assembly is perhaps the only candidate technology that can meet this challenge in the near/mid future.

One of the main drawbacks of self-assembly is the increase in the complexity of elements that constitute the final system. In a self-assembled/self-packaged system, it is likely that parts carry sections and features that are used only once to put the system together and do not contribute to the actual intended operation of the system. The extra requirement of incorporating the ability to recognize and bind to other parts in a predetermined fashion can significantly complicate the construction process of parts. This issue has been faced by our group in all the self-assembly experiments.

Programming the self-assembly/self-packing process of a system is still an unresolved issued. Although various methods have been implemented both in the nanoscales and microscales to program the self-assembly of parts, a clear advantageous method has yet to emerge. Using methods such as electric field to dynamically control the self-assembly process pose both challenges and promises. The ability to speedily reconfigure the assembly processes of a system with known parts is certainly desirable; however, the requirement of actively addressing each binding site, especially in the nanoscale where the number of sites can be extremely large, can significantly reduce the rate of the assembly process. Many of the self-assembly processes demonstrated to this date take advantage of only a few types of parts. Heterogeneous self-assembly of many different types of parts into a functional system is an area that has not been explored. Based on our preliminary experimental results in this area we believe that hierarchical self-assembly is the proper approach to tackle this problem. Another less explored area is self-assembly across the size scale. The question of how to start the self-assembly process at the nanoscale with discrete components and proceed to construct a mm-scale or a cm-scale self-packaged functional system promises to remain a challenging one for a number of years to come. This problem is complicated even further by considering the fact that the dominant forces at different size-scales vary and hence such a self-assembly/self-packaging scheme need to rely on multiple types of physical interactions between the parts. A finite assembly error rate is expected when working with a large numbers of parts. Although phenomena such as electric field screening by an assembled nanowire may be considered error correction because it prevents other nanowires from assembling to the same site, more elaborate fault-tolerant and self-repairing techniques may be necessary such as those found in biological systems. Alternatively, device and system designs should be modified to accommodate a packaging process with a finite error rate.

We believe that self-assembly holds great promise for packaging, both at microscales and nanoscales and there is clear indication and justification that it will be one of the key packaging technologies of the future for small-scale systems. The pioneering works performed by many research groups reviewed here provide a strong basis for the pursuit of self-assembly toward the establishment of a technology that allows for design and construction of truly self-packaging systems.

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