Microassembly Technologies for MEMS

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ABSTRACT

Microassembly promises to extend MEMS beyond the confines of silicon micromachining. This paper surveys research in both serial and parallel microassembly. The former extends conventional "pick and place" assembly into the micro-domain, where surface forces play a dominant role. Parallel assembly involves the simultaneous precise organization of an ensemble of micro components. This can be achieved by microstructure transfer between aligned wafers or arrays of binding sites that trap an initially random collection of parts. Binding sites can be micromachined cavities or electrostatic traps; short-range attractive forces and random agitation of the parts serve to fill the sites. Microassembly strategies should furnish reliable mechanical bonds and electrical interconnection between the micropart and the target substrate or subassembly.

Keywords: MEMS, microassembly, serial assembly, parallel assembly, self-assembly, wafer-to-wafer transfer, packaging

1. INTRODUCTION

Microelectromechanical systems (MEMS) research has been catalyzed by the application of lithography and etching processes to fabricate sensors and actuators. The ability to batch-fabricate complex mechanisms that are pre-assembled *in situ* is a remarkable feature of surface micromachining processes. In contrast to Swiss watch mechanisms, Sandia's reduction transmissions[2] are made in arrays on 150 mm-diameter wafers using a five-level polysilicon surface micromachining technology. They are released simultaneously by etching the oxide sacrificial layers; these layers define the mechanical tolerances of the gears and linkages. Micromechanical systems of impressive complexity can be made without assembly of any kind.

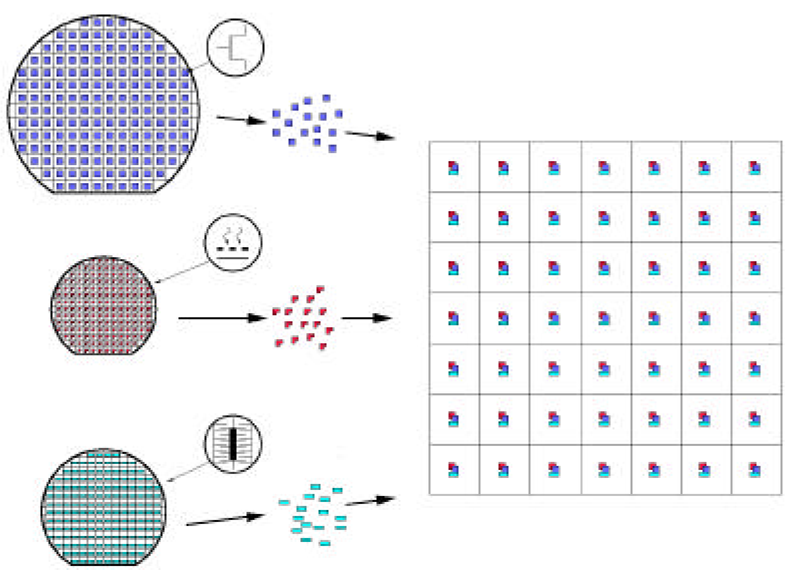

Figure 1: Conceptual description of parallel microassembly, with the upper wafer being standard CMOS electronics, the middle wafer photonic devices, and the lower wafer microstructures.[1]

Why, then, is microassembly of interest for MEMS? One motivation is growing recognition of the limitations of silicon lithography and etching as the universal platform for MEMS fabrication. Monolithic integration of electronics and micromechanics inevitably compromise both subsystems. Even modularized processes suffer from yield losses due to very high mask counts and wafer size differences. Modern CMOS processes use 200 mm diameter wafers and are shifting to 300 mm in the near future; MEMS are still built on 150 mm or 100 mm substrates. In order to co-fabricate CMOS and MEMS on the same substrate, premium CMOS process equipment must be used on smaller wafers – leading to higher production costs and lower-performance electronics. In any event, monolithic MEMS wafers must be diced and the chips packaged in such a way that the microstructures are passivated. These critical "back-end" processes involve assembly and encapsulation steps.

Currently, microassembly is mandatory for sub-cm-scale microsystems that incorporate LEDs or diode lasers and silicon microstructures. Material incompatibilities impede co-fabrication of micro-opto-electro-mechanical systems (MOEMS). Figure 1 presents a conceptual vision of microassembly: microstructures, microelectronics, and optical elements are harvested from their respective substrates and distributed on a target substrate with micron-scale precision.

Microassembly is also required for the “pop-up hinges” used to build three-dimensional structures from surface-micromachined thin films.[3] The interface between the existing cm-scale mechanical world and MEMS is another motivation for developing microassembly processes. Finally, electronic packaging technology is not directly applicable to creating mechanical or fluidic “feedthroughs” to microsystems. Inevitably, “some assembly is required” for any real-world MEMS application.

This paper surveys recent research in microassembly, beginning with serial methods, or “micro pick and place.” Micromachining techniques can furnish both manipulators and assembly pallets for organizing microparts. In order to pick up and release microparts, however, the scaling of physical forces must be carefully considered. Conventionally microfabricated elements can sometimes be designed with the ability to either assemble by self-actuation upon release or by means of electrical actuation. The major research thrust, however, has targeted parallel processes that enable large numbers of parts to be assembled simultaneously with micron-scale precision. These processes are categorized as either deterministic or stochastic, depending on whether the microparts are initially organized. Impressive results have been achieved in the past few years using both approaches. Deterministic parallel assembly has similarities to the rapidly evolving chip-scale packaging technologies, but concerns microstructure-on-substrate placement rather than chip-on-board assembly. Stochastic or self-assembly processes are being applied successfully to fabrication of LCD substrates with embedded silicon electronics. The traps for the microparts in this case are wells etched in the glass substrate. Chemical and electrostatic energy wells are also useful for trapping microparts. All types of microassembly require processes that bond the micropart to the substrate after assembly. Finally, we assess the implications for MEMS of recent progress in microassembly.

2. SERIAL MICROASSEMBLY

Efficient microassembly of parts less than 100 μm in size requires an infrastructure of microtools and microparts designed to interface with each other and, ultimately, with the macroscopic world. The same rules of kinematic fixturing used in the macro world must be applied to the micro world; however, new constraints and phenomena must be taken into account. It is more difficult to make the desired shapes with the necessary tolerances given the technology of micromachining available today. For example, the verticality of sidewalls and the ratio of the magnitude of irregularities to the total size of the part are much poorer than for conventionally fabricated macroscopic parts. *Design for assembly* is a well-known concept in manufacturing: the assembly process of an aggregate product is streamlined by a clever design of its components (for example, if all components can be assembled without moving or rotating the substrate). This concept is even more important at the micro scale.

For microassembly, the relative importance of the forces that operate is very different from that in the macro world. Gravity is usually negligible, while surface adhesion and electrostatic forces dominate[4,5]. This important topic is discussed later in this section.

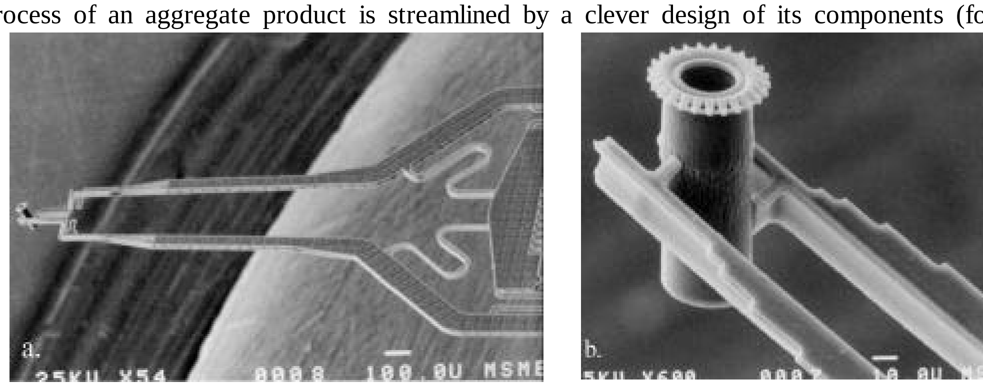

Figure 2: SEMs of Hexsil molded polysilicon microtweenzers gripping a Hexsil gear.[19] (a) the overall structure is 5 mm in length, but the gripper contains features that are smaller than 10 mm.

2.1. Recent Research in Serial Microassembly

One possible approach to microassembly is to improve the performance of conventional automated assembly systems. Commercial robotic systems with resolution and repeatability of a few microns are available (e.g.; from MRSI in Chelmsford, Mass. or from Sysmelec in Switzerland). Even higher precision prototype systems have been described by Quaid and Hollis,[6] Zesch,[7] and Dual,[8] among others, who use stepping motors and inertial drives to obtain sub-micrometer motion resolution. However, this approach requires increasingly sophisticated technology.

It has been observed that smaller parts require larger machines to handle them (and microscopic parts require huge machines). Therefore, there is now increased interest in MEMS assembly tools that are at the same scale as the parts to be assembled. Micromachining processes have been used to fabricate a micro air table for parts handling.[9] Residual stress gradients are the basis for "self-adjusting" structures that self-actuate to reduce critical dimensions upon release from the substrate.[10] Hinged polysilicon structures are being applied to fabricate micro optical components; in some cases these structures have been observed to assemble due to turbulence in a rinse bath.[11] Assembly is also feasible by means of integral actuators (either comb-drive or scratch-drive), combined with ohmic heating to fix the structure in its assembled position.[12] Recently, Gonzaléz and co-workers at UC Davis have reported a suite of microfixturing and assembly concepts ("MicroJoinery") that uses microfabricated dovetail joints for easy precision assembly.[13]

Microassembly can require unconventional approaches to the pick-and-place paradigm. For example, Arai and Fukuda have built manipulators with heated micro holes.[14] When the holes cool, they act as suction cups whose lower pressure holds appropriately shaped objects in place. Heating of the cavities increases the pressure and causes the objects to detach from the manipulator. The surface tension of low viscosity fluids has been used to pick and center micro parts.[15] Langen has introduced techniques for achieving precision machining and assembly in the same machine tool, through use of self-alignment.[16]

Tweezers with integrated actuators and force sensors are a fundamental tool for teleoperated assembly of systems made up of independently microfabricated parts. Optical tweezers are widely used to manipulate bacteria, cells, and latex microspheres. There are many diverse niches requiring different microgrippers Conventional machining done with high precision on millimeter scale parts (e.g., Bartels Mikrotechnik GmbH, Germany) has produced working milliscale tweezers. Thermally actuated single crystal silicon micro-grippers have been fabricated by bulk etching.[17] Electrostatically actuated polysilicon microgrippers have been used to handle bacteria.[18] Ultimately, the diversity in microgripper designs should rival that found in biology.

High aspect molded polysilicon (HexSil) processes are suitable for making microtweezers.[19] An initial demonstration of a micro pick and place task has been performed on surface micromachined oxide beams. HexSil tweezers are mm-scale instruments that are removed from the wafer they were made on and are mounted on conventional positioning systems; they are suitable for handling parts from a few µm to 1000 µm in size. The resulting assembly system provides a mechanical interface between the macro world and the micro world, with appropriate dimensions and stiffnesses at each end (Figure 2).

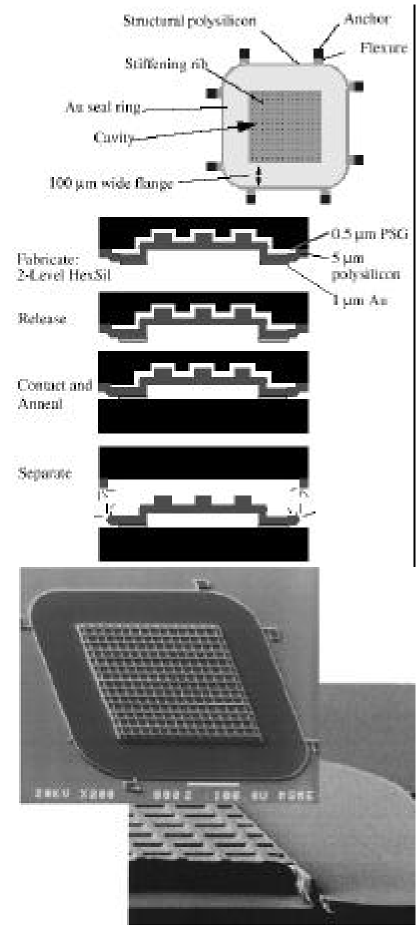

Figure 3. Process flow for wafer-wafer transfer of vacuum lids (above). Seal formed by Au/Si eutectic weld. SEM of transferred structure, cleaved cross-section (below).

2.2. Adhesion

Models based on classical mechanics and geometry are often used to describe small and micro scale robotics. However, there are severe limitations to this approach. Due to scaling effects, forces that are insignificant at the macro scale become dominant at the micro scale (and vice versa).[20] For example, when parts to be handled are less than one millimeter in size, adhesive forces between gripper and object can be significant compared to gravitational forces. These adhesive forces arise primarily from surface tension, van der Waals, and electrostatic attractions and can be a fundamental limitation to part handling. While it is possible to fabricate miniature versions of conventional robot grippers (Figure 2b), overcoming adhesion effects for the smallest parts will be difficult.

The adhesion of particles to substrates has received substantial attention for problems such as particulate contamination in semiconductor manufacturing.[21] Recent developments in MEMS, disk drives, and microassembly have stimulated the study of friction effects at the micron scale. The normal Coulomb friction effects seen at the macro scale are quite different at the micron scale, since unpassivated surfaces exhibit large adhesive components. To grip microparts and then attach them to the workpiece in the desired orientation, it is essential that a hierarchy of adhesive forces be established. Electrostatic forces due to surface charges or ions in the ambient must be minimized. Adhesion of the micro part to the unclamped gripper surfaces (with zero applied force) should be less than the adhesion of the micro part to the substrate, to allow precise positioning of the part in the gripper. In order to release the part, the target spot on the workpiece must have a surface coating that provides sufficiently strong adhesion to exceed that between the micro part and the unclamped gripper.[4] The recent use of surface tension as a means to grip micro parts is an interesting application of this particularly strong force in the micro domain.

3. PARALLEL MICROASSEMBLY

The throughput of serial microassembly is limited by the number of micromanipulators in the array and their bandwidth. Given that microfabrication processes can yield millions of devices, it is intriguing to consider whether large ensembles of microparts can be assembled simultaneously. This class of microassembly is termed "parallel." There are two basic approaches, one based on the massively parallel transfer between wafers of arrays of microcomponents (*deterministic parallel microassembly*) and one utilizing various approaches to orient an initially random array of microparts (*stochastic parallel microassembly*.) These topics will be considered in separate subsections.

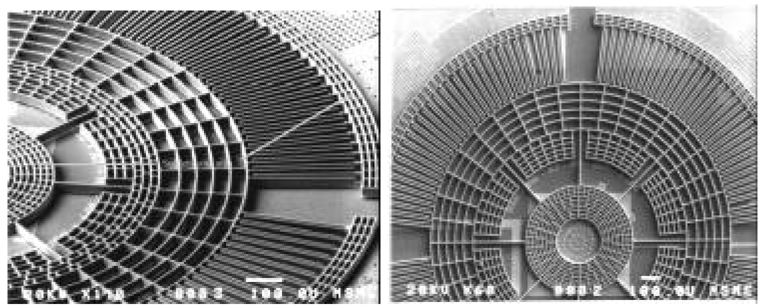

Figure 4. Two-piece HexSil microactuator transferred onto glass substrate using indium solder bonding.

3.1. Deterministic Parallel Microassembly

Deterministic parallel microassembly refers to direct, wafer-to-wafer transfer of microstructures. Since the placement of the structures is predetermined by their layout on the donor wafer, the challenge lies in bonding structures to the target. The process is analogous to rubber-stamp printing, with pre-fabricated microstructures taking the place of the ink. While other structure-transfer processes have been demonstrated, wafer-wafer transfer is distinguished by two key features: *compatibility* and *throughput*.

Compatibility with existing CMOS and MEMS processes is highly desirable. An ideal process would allow devices to be transferred to or from standard foundry wafers without requiring any "back-end" modifications. Other approaches, such as epitaxial lift-off (ELO[22]) and Lucent's SEED[23] include a substrate removal step, which is time-consuming and creates difficulties associated with handling unsupported device layers. Use of an intermediate substrate addresses this problem and facilitates alignment.[24] Ultimately, a transfer process sufficiently fast to allow step-and-repeat transfer – akin to lithography – would have a major impact on MEMS technology.

The initial demonstration of wafer-to-wafer transfer involved vacuum micropackaging.[25] Shells are fabricated on a handle wafer using the Hexsil process,[19] and transferred over resonators. The seal is based on a Au/Si eutectic solder joint. As shown in Figure 3, a typical structure has a top-hat cross-section, with stiffening ribs on the "roof." The metallization on the target substrate may be Au or, if thermo-compression bonding is employed, aluminum. The sealed packages tolerate external pressures in excess of 1,000 PSI.

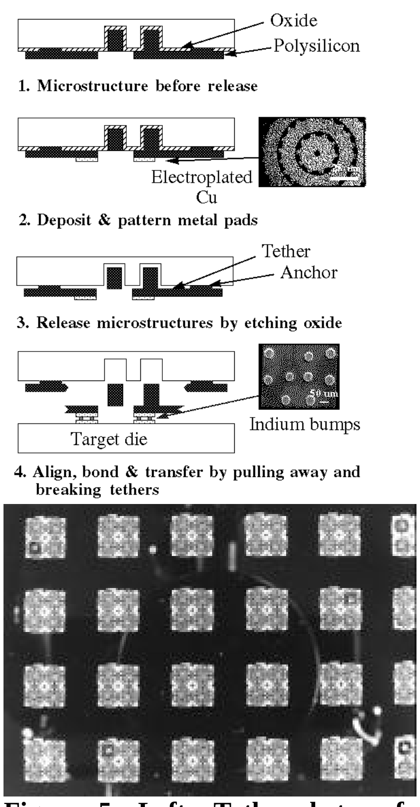

Figure 5. Left: Tethered transfer process using indium solder bonding. Right: Target wafer with transferred HexSil microactuators.

3.2. Wafer-wafer transfer using solder bumps

Since the 1960's, flip-chip bonding has been used to connect ICs to printed circuits and packages[26]. In one of the earliest MEMS applications, solder bumps were used to bond MEMS chiplets to electronics[27]. Chip-to-chip transfer of high-aspect (HexSil) polysilicon structures was demonstrated by Singh et al.[28] Transfer was achieved using an indium solder bonding process, as outlined in Figure 5. Figure 4 shows transfer of a 40 μm thick, two-piece electrostatic actuator. The rotor and stator, though anchored separately, displayed no observable misalignment on transfer. The actuator was fabricated using the HexSil process[29]. Design and operation of such actuators has been described by Horsley[30]. Direct transfer onto CMOS has also been demonstrated by Singh et al.[31] The tensile strength of the indium-copper bond has been measured at approximately 3,000 PSI[64, 106].

Wafer-scale transfer of HexSil microactuators was demonstrated by Singh et al.[32] Figure 5 shows a portion of the target wafer with transferred actuators. Since most of the failures appear to be due to bump non-uniformity, increase in yield is expected with optimization of the electroplating and bonding processes.

4. STOCHASTIC MICROASSEMBLY

4.1. Motivation

While conventional assembly techniques have been successfully adapted from the macro world, the molecular regime offers many examples of efficient assembly processes. Crystal growth,[33] antibody-antigen recognition, and most other chemical and biological behaviors[34,35] are mediated by thermal motion and interparticle forces. In contrast to the macroscopic concepts of manipulators and path planning, a molecular system may be analyzed as an *ensemble* of particles evolving toward a state of *minimal potential energy*. The lure of this thermodynamic approach is that when parts must be redistributed or reoriented, a single complex manipulator may be replaced by an array of lithographically-defined *binding sites*. Such sites might consist of electrostatic traps, or simply etched wells on a substrate. Thermodynamic analysis shows the potential for massively parallel operation, forming assemblies of 10^6 or more elements in seconds, with placement tolerance limited by lithographic accuracy.[38,64,106]

In biochemical systems, assembly behavior is characterized by a high degree of selectivity for position, orientation, species, and conformation. An antibody molecule, for instance, can select for one out of a possible 10^{11} antigens.[37]

To harness self-assembly for manufacturing processes, three criteria must be met. First, the desired, assembled state of the system must represent a minimum of potential energy. Second, in order to allow assembly within a reasonable period of time, any energy barriers E_A must be small in comparison to the driving potential DH. The latter should be viewed as the potential difference between the ground and next-lowest state. As shown in Figure 7, an unfavorable scenario would include one or more low-lying local minima, separated by large barriers. The system must be given enough average kinetic energy (thermal or other random motion) to jump the barriers at some reasonable rate; only after a large number of such jumps can the system be expected to approach the ground-state equilibrium. If, as Figure 7D., the energy difference between the two states is very small, an extremely large number of jumps is needed to achieve the ground state with reasonable certainty. The number of jumps, and thus the required assembly time, increases exponentially in the quotient E_A/DH [38].

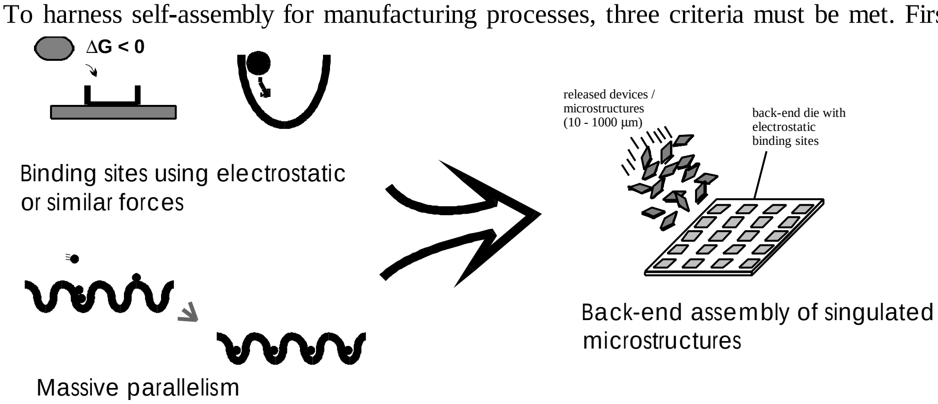

Figure 6. Self-assembly concept [36].

Third and finally, a source of random kinetic energy must be provided. In the molecular systems described above, the thermal bath fulfills this need. While thermal (i.e. Brownian) motion is observable for objects at the extreme low end of the micron scale, it is not sufficient to break the surface forces present in typical silicon microsystems. For this reason, fluidic agitation and ultrasonic vibration have been investigated, as described below.

Historically, stochastic assembly precedes MEMS by several decades. One of the best illustrations is the work of Yando[39]. A 1969 patent discloses an array of magnets on which particles with magnetic coatings are placed, vibrated, and trapped so as to form a matching array. Each particle is described as a microelectronic device, such as a diode. One problem with this scheme is that the magnet arrays are composed of laminated sheets stacked perpendicularly to the plane of the array, so that many laminations are needed to achieve an array of appreciable extent.

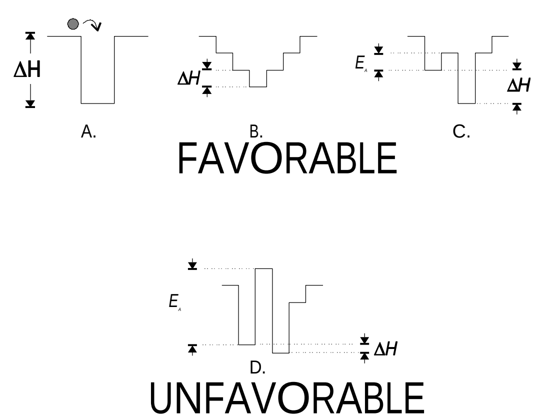

Figure 7. Comparison of favorable and unfavorable potential energy functions for self-assembling systems. [64, 106]

The APOS parts feeder is described by Hitakawa[40]. The feeder uses an array of “berths” cut into a vibrating plate. Parts are fed over the plate, and the berths are designed, like the track of the bowl feeder, to accept only parts in a given orientation. Eventually, all the berths are filled. Similar techniques have been described for creating pin-grid arrays and connectors.

4.2. Wet processes

Yeh, Hadley, and Smith[42,41] (Figure 8) have demonstrated *fluidic self-assembly*, in which micron-scale parts are suspended in a liquid and flowed over a substrate. Etched pits in the substrate serve to trap the parts, which come to rest in a predictable orientation due to their trapezoidal shape. The driving potential is thus gravitational in origin, though fluid and surface forces are thought to play a significant role. The technique has demonstrated 99.5% yields in arrays of 10,000 elements. In addition, arrays may be designed with redundant elements. Both the parts and traps are bulk-micromachined with complementary trapezoidal shapes.

Electric fields have been employed to trap and manipulate small objects such as cells. Generally, these techniques take advantage of the fact that neutral matter is attracted to maxima of the electric field. “Optical tweezers” trap micron-scale particles at the focus of a laser beam[43]. “Optical matter” has been formed by trapping latex micro-spheres in a three-dimensional interference pattern. In this case, the effect is actually cooperative, and the mutual scattering of light among the spheres serves to bind them together[44].

Perhaps more applicable to manufacturing is the work of Kaler[45], Jones[46], Fuhr[47], Washizu[48], and others. Generally, this group has investigated the use of microfabricated electrodes to manipulate particles. In the basic case, field sources may be used to attract a particle, as with optical tweezers. This effect is termed dielectrophoresis, to denote the interaction of the electric field with dielectric materials.

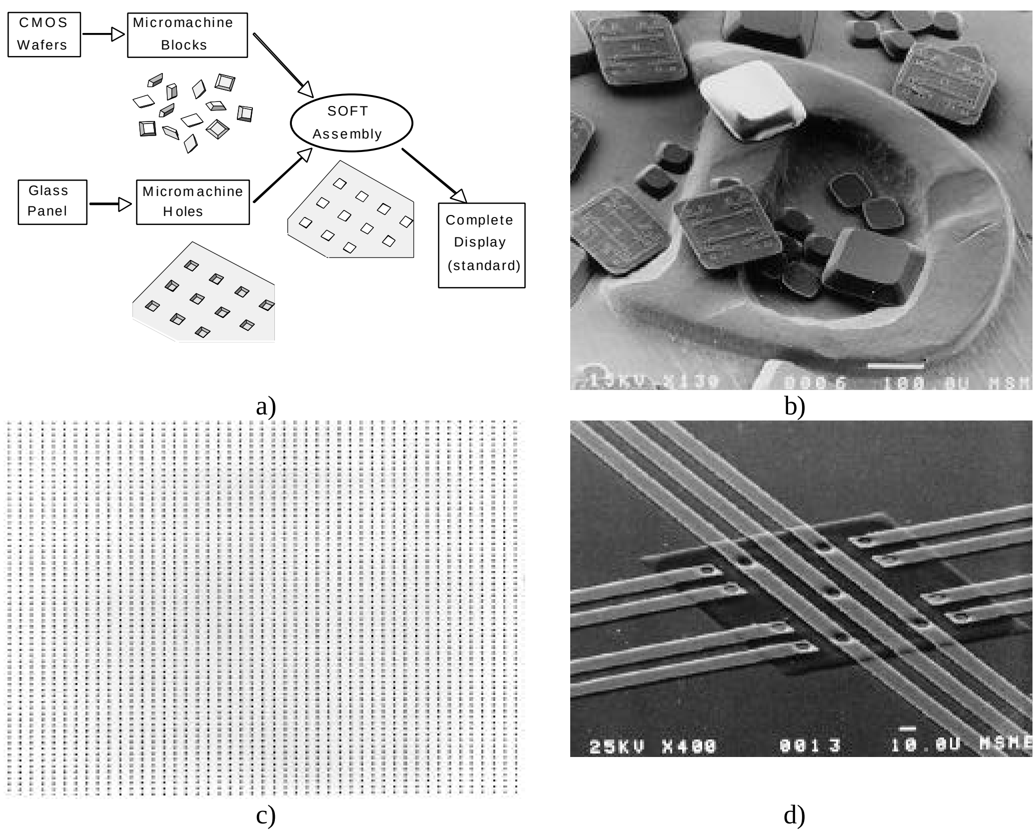

Figure 8: (a) Fluidic self-assembly concept. (b) Chemically diced “nanochips” containing MOS switching transistors for flat panel displays, shown on the Denver Mint mark on a U.S. dime, (c) array of wells etched on glass panel, filled with nanochips after “self-orienting fluidic transport (SOFT)” assembly process. (d) Nanochip with electrical interconnects.[41]

Dielectrophoresis (DEP) is a compelling approach to stochastic assembly. Trap electrodes can be fabricated in array form, using standard VLSI technology. Also, non-contact levitation traps can be created (in liquid media).[49, 64, 106, 50]. The non-contact feature is extremely attractive for self-assembly, since it eliminates the great majority of energy barriers, such as van der Waals and other “stiction” forces.

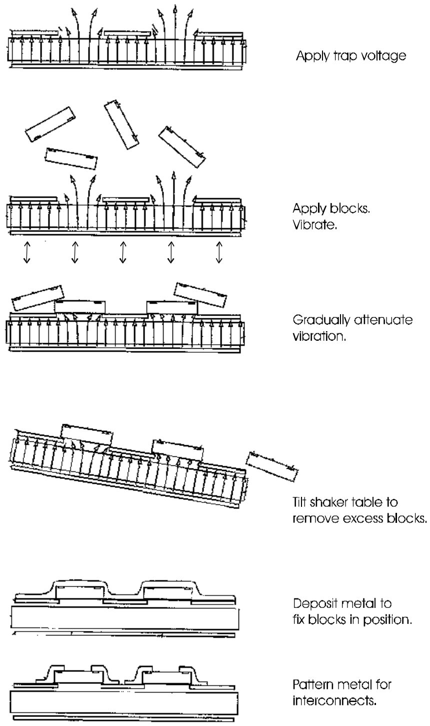

Figure 9. Process flow for dry electrostatic self-assembly.[51]

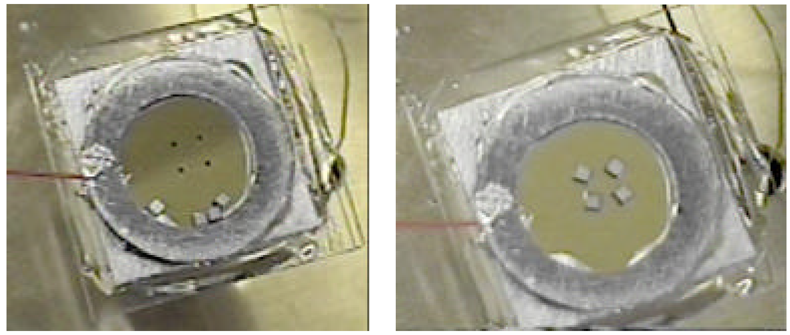

Figure 10: Dry stochastic assembly with electrostatic force fields: Left: Parts are placed on patterned electrode. Friction is overcome by ultrasonic vibration. Right: Voltage is applied to the electrode; parts are attracted to the apertures (dark squares) and trapped there.

Whitesides[52] has described several molecular self-assembling systems. For example, an "ink" composed of a self-assembling molecular monolayer has been demonstrated for lithographic pattern transfer, using a rubber stamp to achieve 0.1 µm resolution. Self-assembly of millimeter-scale, three-dimensional objects has also been demonstrated by the same group[53], and was also described by Cohn[54]. In this case, hydrophobically coated surfaces of small parts suspended in an aqueous medium come together when the parts are agitated.

4.3. Dry processes

In 1991, Cohn, Kim, and Pisano described stochastic assembly using vibration and gravitational forces to assemble arrays of up to 1000 silicon chiplets[38]. Subsequent work demonstrated the use of patterned electrodes to assemble parts in arbitrary 2D patterns (Figure 9 - Figure 10). Recent results by Böhringer, Goldberg, and the above authors have demonstrated the ability to break surface forces using nanometer-amplitude vibration in vacuum[55]. Both squeeze-film levitation and intermittent "hopping" behavior were observed, depending on vibration frequency and amplitude. These results promise a sensitive technique for positioning parts, as well as discriminating part orientation, shape, and other physical properties.

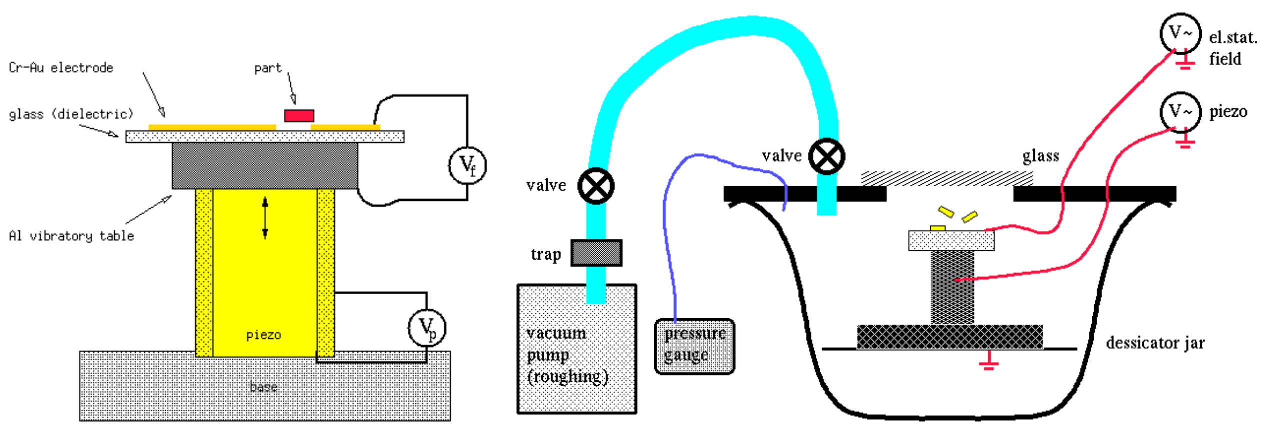

Figure 11: Experimental apparatus for self-assembly with electrostatic traps. (a) A vibratory table with a gold-coated dielectric is attached to a piezoelectric actuator. The aperture in the upper electrode creates a fringing field that causes polarization in the part. The part is attracted to the aperture. (b) Self-assembly experiments in vacuum. The vacuum provides a controlled environment that minimizes surface sticking effects due to capillary forces and reduces squeeze-film effects.

4.4. Actuator Arrays and Programmable Force Fields

Several groups of MEMS researchers have designed and built MEMS actuator arrays, which usually consist of a regular grid of "motion pixels" that can generate force or motion in a specific direction. Devices were built, among others, by Pister et al.[9], Fujita et al.[56, 57], Böhringer et al.[58], Kovacs et al.[59, 60], and Will et al.[61, 62]. Actuation was provided by a wide variety of methods such as electrostatic forces, ultrasonic vibration, air jets, thermo-bimorph, or magnetic actuation. A general model for actuator arrays was introduced by Böhringer et al.[58] who describe them as programmable force fields (PFFs). In contrast to the well-known concept of artificial potential fields in the robotics literature, these fields are physical and thus do not require sensing or feedback. It was shown that useful micromanipulation and assembly tasks can be performed with PFFs. In joint experiments with Suh and Kovacs, they successfully demonstrated these open-loop strategies for translating, orienting, and centering[63] of silicon chips with micrometer accuracy (Figure 12). This force field concept extends beyond MEMS actuator arrays, and can e.g. also be applied to electrostatic fields[64, 65] (Section 4.3). Parts are moved in parallel in these fields until they reach a site with minimal potential energy.

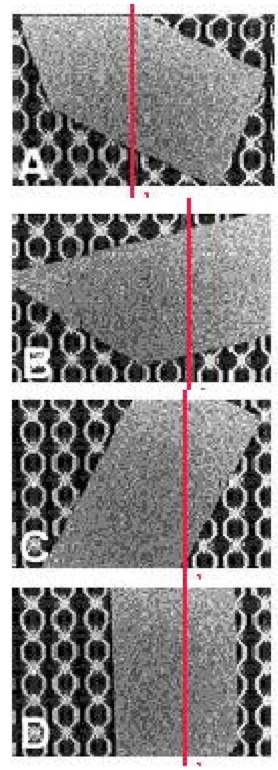

Figure 12: Open-loop positioning and orienting of a silicon chip on a MEMS cilia array. The chip is centered and aligned with µm accuracy.[63]

5. ELECTRICAL/MECHANICAL BONDING PROCESSES

Many joining techniques with potential application to microassembly are known in the literature. These include *soldering*, *welding*, *ceramics*, *polymer adhesives*, *wafer bonding*, *electroplating*, and *mechanical fasteners*. The first five are well established in the clean room as assembly techniques. The last two are beginning to emerge more specifically in connection with MEMS assembly processes.

5.1. Solder

Solder processes may be divided into two groups: solder bump bonding and die attach. Bump bonding[66] is employed in surface-mount and *flip-chip* processes; the latter is the most relevant to MEMS. This technique was first demonstrated by IBM in the 1960s with the C4 (*C*ontrolled *C*ollapse *C*hip *C*onnection) process[67]. An important consideration for MEMS assembly is that the bumps provide a vertical standoff, which relieves the thermal expansion mismatch between chip and substrate. Moreover, the solder bumps form spherical droplets, which act as compliant springs in the molten state. Without this compliance, it would be difficult to guarantee bonding across the substrate, due to warpage of the mating surfaces.

A potential difficulty with solder bumps is the need for flux. [68] In most solder alloys, a tenacious surface oxide is present and will re-grow within seconds on a freshly cleaned surface. Fluxes contain weak acids that become activated at the re-flow temperature, effectively performing an *in-situ* clean of the solder surface. Fluxes also reduce solder surface tension, and thus, facilitate wetting. Following re-flow, flux residue must be removed[66]; evolved vapors often lead to voids in solder joints. For many MEMS applications, such as hermetic micro-packaging, these are serious problems.

Plasma-activated dry soldering[69] offers one possible solution. Another approach relies on the unique properties of gold. As an interconnect and assembly material, gold does not form surface oxides. In thin-film applications, materials cost is negligible. Finally, while gold poses a potential hazard to CMOS, it has long been part of back-end processing, especially in high-performance and high-reliability products. In solder processes, gold may be used either as a capping layer[70], to prevent oxide growth, or as a component of the solder itself. [71] Gold-based solders find application in packaging of GaAs devices [72, 73], tape-automated bonding (TAB), and package lid sealing. [74, 75, 76, 77] Solders may be deposited by sputtering, evaporation, silk-screening, or CVD. Reliable solder joints require an appropriate choice of *base metal*. The base metal acts as a barrier between the solder joint and the substrate. It must be wettable by – and insoluble in – the solder. Typical choices are Cu, Ni, and TiW [78].

5.2. Welding

The term *welding* is used to characterize metal-to-metal joints formed without an intermediate material.[79] In macroscopic applications, the region of the joint is typically melted to accomplish bonding. In microelectronics, however, ultrasonic, thermosonic, and/or compression bonding are usually employed. In welding, as in etching, "dry" processing allows improved control by avoiding re-flow and surface tension effects. Applications include wire-bonding and flip-chip bonding [80, 81, 82]. Common materials include aluminum and gold.

Welding, in the more conventional sense, has been demonstrated in MEMS applications by Fedder.[83] Aluminum tethers were melted and reflowed by ohmic heating. The surface tension forces were used to assemble and actuate polysilicon structures. One problem with this approach is that the welds could not actually be used to join two objects that were initially separate. Moreover, due to the high current requirements, it was difficult to parallelize more than four welds in a single circuit.

Finally, a tack-welding technique has been demonstrated by Cohn[64,106] using evaporated metals, solders, and ceramics. The advantage of this technique is that vacuum-deposited materials are highly reactive, bonding to metals, oxides, and other materials. The substrate temperature need not rise above ambient. Moreover, the deposition is capable of bridging a gap, providing tolerance for substrate non-planarity. This is a potential approach for assembly of fragile or complex structures, such as stacked HexSil. Bartek has demonstrated a similar technique, using aluminum deposition to seal a polysilicon micro-cavity [84].

5.3. Ceramics

Non-metal-based techniques have also been demonstrated. Glass frits consist of a low-melting glass powder in a resin binder, which may be applied by silk-screen. Typical applications include ceramic-to-metal joints and hermetic packaging.[85] Limitations include resolution and hermeticity, as well as relatively high re-flow temperatures (usually > 300°C for high-quality materials). Current MEMS applications include hermetic packaging of microsensors.

Hermetic encapsulation of microstructures by surface micromachining techniques has been demonstrated by several research groups. In this case, a micro-shell is fabricated and sealed by high-temperature deposition of thin films.[86,87,88,89,90]

5.4. Polymer adhesives

Polymer adhesives are also used for flip-chip type interconnection, whether as a component of solder fluxes or pastes, or Z-axis conductive adhesives [91,92]. UV-curable adhesives are seeing increased use in wafer bonding and epitaxial lift-off applications[93]. However, adhesives may be difficult to pattern and may have undesirable characteristics such as high vapor pressure, limited temperature tolerance, and low modulus. An advantage, however, is adhesion to a wide range of materials, such as metals, ceramics, and other polymer. Solid polymer films may be laminated conformally over microstructures for planarization of high-aspect topography, or to provide enclosed fluidic channels. Recently, autoclavable packaging has been demonstrated using polymer materials.

5.5. Wafer bonding

Interest in wafer bonding for micromachining applications dates to the work of Lasky [94] and Shimbo [95]. Schmidt [96] and Farrens [97] provide reviews and bibliographies relevant to MEMS. Principal wafer bonding methods include anodic bonding and fusion bonding. Initially, anodic silicon-to-glass bonding predominated, though more recently GaAs-Si, Si-Si, and Si-SiN bonding have been demonstrated.[98] Applications of wafer bonding have been in the production of SOI wafers, power devices, and MEMS such as pressure sensors. With the increased application of deep-trench RIE to MEMS [99], exotic multi-layer SOI substrates are expected to become more prevalent.

In the area of microstructure-level assembly, however, wafer bonding displays several limitations. Primarily, since the bonding mechanism is van der Waals bonding, the substrates must be brought very close together – preferably less than 1 nm – so particulates, roughness, and wafer curvature must be carefully controlled. A single micron-sized particulate can lead to cm-sized bond defects.[100] Farrens has reported that handling of wafers with metal tweezers can lead to bond defects. Wafers must meet stringent criteria for overall roughness and curvature to assure successful bonding. Initially, wafer bonding was confined to high temperatures, e.g. 800-1000°C. Recently, however, processes have been demonstrated at 300°C, and even room temperature.[101] The mechanical performance of these bonds is expected to be excellent, since there are no adhesive or bonding materials used that may exhibit creep.

5.6. Electroplating

Aside from its application to solder bump deposition described above, electroplating can be used directly to join two pieces of material. Wise describes the mechanical and electrical interconnection of a 3D neural probe structure [102]. The advantage of this technique is that the deposition is defined by lithographically fabricated features on the 2D components. Following the initial lithography, there are no precision assembly steps. Electroless processes may also be employed, avoiding the need to make electrical contact to the workpieces. Electroplating requires a cathode connection to the intended deposition surface, which may not be practical when there are multiple, complex, or electrically discontinuous structures. Electroless plating simply requires an appropriate metallic seed surface, such as gold, copper, nickel, or platinum. Kim has recently demonstrated the use of electroplated nickel plugs or “rivets” to join two bulk silicon structures [103].

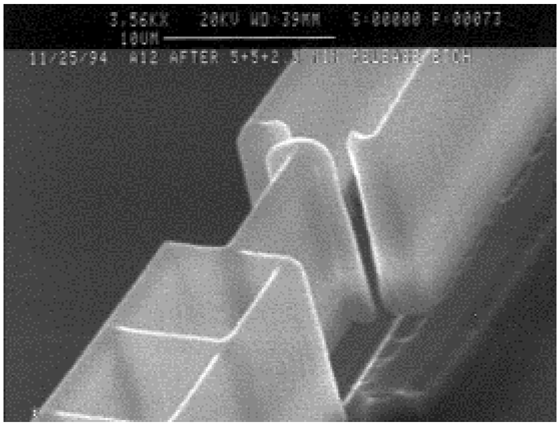

Figure 13: Single-crystal silicon snap fastener.[105]

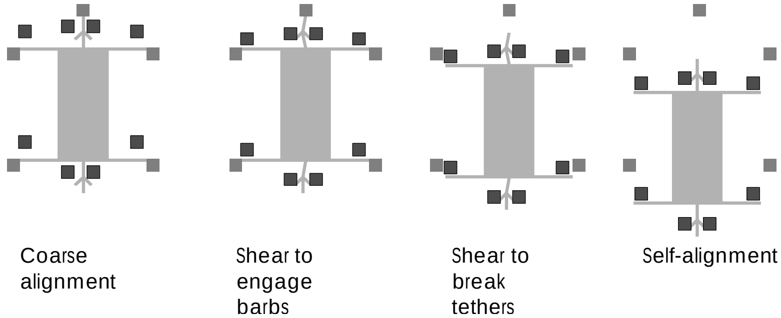

Figure 14. Shear-lock mechanism.

Increased use of plating techniques is expected in the microassembly area. Other than standard sputter or evaporation apparatus for seed layer deposition, no special equipment is required. Moreover, deposition is selective and may be masked. Perhaps the only limitation of the technique lies in the area of vacuum packaging – there is no obvious way to form an evacuated cavity, as might be done by vacuum deposition. Also, materials deposited by electro- or electroless plating tend to out-gas over time. In addition, it may be more difficult to apply these techniques for selective bonding; spatial control would seem more easily achieved in a heat- or pressure-driven process.

5.7. Mechanical Fasteners

Micromechanical fasteners include Reed's "micro Velcro"[104] as well as the snap fastener demonstrated by Prasad and Böhringer[105]. These are intriguing in that they avoid the problems of thermal cycling, surface wettability, and other materials compatibility problems inherent in welding processes. At the same time, they afford the potential for self-alignment and, in the case of the snap fastener, integrated actuation. Cohn has described a "shear-lock" transfer mechanism[106], based on the snap fastener, allowing self-aligned wafer-wafer transfer of individual microstructures. The shear-lock mechanism uses laterally-engaging barbs, in conjunction with break-away tethers. The barbs cold-weld to pylons on the target wafer, providing electromechanical interconnection. This mechanism offers sub-micron alignment precision, using non-precision equipment and relatively low aspect-ratio micromachining.

6. CONCLUSIONS

Extending MEMS beyond the confines of IC-based processes will inevitably involve some form of assembly. An early application of microassembly may be the placement of microstructures onto CMOS substrates, followed by their encapsulation with transferred package lids. Such "batch assembled" MEMS may include inertial sensors and RF signal processing elements; their performance may equal that of their monolithic counterparts, since unmodified, state-of-the-art CMOS electronics can be used. In contrast to traditional hybrids, parasitics in microassembled MEMS could be comparable to those seen in monolithic equivalents. Microphotonics or MOEMS is another "technology driver" since a monolithic solution is impractical due to materials incompatiblility between photonic devices and micromechanical mirrors and mechanisms.

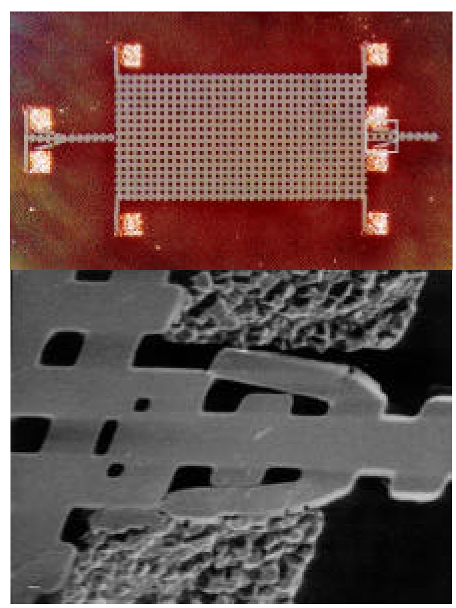

Figure 15. Transferred shear-lock structure.

Serial assembly using micro pick and place has been demonstrated in the laboratory, in some cases using MEMS micromanipulators. In order for serial processes to have a commercial impact, large arrays of manipulators and associated control algorithms are needed. By micromachining its key components, it may prove feasible to make a cost effective "micro assembly line" for MEMS and other applications. Further research is needed into the control and exploitation of the relatively large surface tension and electrostatic forces encountered in micro parts handling.

Parallel assembly processes are generally less mature. However, they have the greatest potential for fundamentally changing MEMS and other microfabrication technologies. If microparts can be "batch assembled" on substrates with very high yields, parallel assembly may become an alternative to conventional lithography and etching. Deterministic parallel assembly strategies involve the transfer of microstructures from a donor wafer to a target wafer. Initial research has focussed on using metal-based bonds to make electrical and mechanical contact between the donated microstructure and the substrate. This approach draws on the large body of knowledge in solder bumps for flip-chip attachment. Much additional study is needed to develop a variety of bonding processes, with adhesive-less bonding likely to demand careful surface preparation. Yields and the limits to precision of wafer-to-wafer transfer processes using full wafers have yet to be established, but initial results are promising using compression bonding. The tolerance to wafer warpage is a primary question that remains to be resolved.

Stochastic parallel assembly is a rich area for research, with various systems being investigated in both dry and liquid ambients. With proper design of the trapping mechanism and the microparticles, theory predicts that high assembly yields are feasible for ensembles with 10^7 or more elements. The fluid-based assembly of silicon "nanochips" into glass wells with etched particle traps has demonstrated yields of higher than 99.5%. Micromachining plays a key role in this process, since the chemical dicing of the silicon CMOS substrate is necessary for formation of the nanonchips, in addition to the precise shaping of the holes in the glass substrate. Successful assembly of large arrays is yet to be demonstrated for the case of vibrationally excited dry micropart ensembles with electrostatic particle traps. Tighter control of the surface properties of the microparts and the substrate is likely to improve the reproducibility of this process.

Given the rapid progress of microassembly technology over the past five years, it is quite plausible that it will soon be making an impact in MEMS manufacturing. Regardless of the particular assembly strategy used, the implication is that dense "quasi-monolithic" microsystems will be much easier to realize. One fallout is that integration of MEMS with electronics in a merged, monolithic process sequence will not be as compelling for many applications. Further in the future, microassembly processes will likely prove instrumental in the development of 3D microsystems.

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8. REFERENCES

[1] K. F. Böhringer, K. Goldberg, M. Cohn, R. Howe, and A. Pisano, "Parallel microassembly with electrostatic force fields," *Int. Conf. on Robotics and Automation*, Leuven, Belgium, May 1998. Figure after M. B. Cohn, "Self assembly using electrostatic particle traps," Ph.D. Qualifying Exam, Dept. of EECS, Univ. of Calif. at Berkeley, May 1995.

[2] S. M. Rodgers and J. J. Sniegowski, "5-level polysilicon surface micromachine technology: application to complex mechanical systems," *Solid State Sensor and Actuator Workshop*, Hilton Head, S.C., June 1998, pp.144-149.

[3] Pister, K.S.J.; Judy, M.W.; Burgett, S.R.; Fearing, R.S. Microfabricated hinges. Sensors and Actuators A (Physical), vol.A33, (no.3), June 1992. p.249-56.

[4] R. S. Fearing, "A survey of sticking effects for micro parts handling," *IEEE/RSJ Int. Workshop on Intelligent Robots and Systems*, Pittsburgh, Penn., 1995.

[5] C. G. Keller and R. T. Howe, "Hexsil tweezers for teleoperated microassembly," *IEEE Micro Electro Mechanical Systems Workshop*, Nagoya, Japan, Jan. 1997, pp. 72-77.

[6] A. E. Quaid and R. L. Hollis. Cooperative 2-dof robots for precision assembly. *IEEE Int. Conf. on Robotics and Automation*, Minneapolis, Minn., Apr. 1996.

[7] W. Zesch. *Multi-Degree-of-Freedom Micropositioning Using Stepping Principles*. PhD Thesis, Swiss Federal Institute of Technology, Zurich, Switzerland, 1997.

[8] G. Danuser, I. Pappas, B. Vögeli, W. Zesch, and J. Dual. "Manipulation of microscopic objects with nanometer precision: Potentials and limitations in nano-robot design," submitted to *Int. Journal of Robotics Research*, 1997.

[9] K. S. J. Pister, R. S. Fearing, and R. T. Howe, "A planar air levitated electrostatic actuator system," *IEEE Micro Electro Mechanical Systems Workshop*, Napa Valley, Calif., Feb. 1990, pp. 67-71.

[10] M. W. Judy, Y.-H. Cho, R. T. Howe, and A. P. Pisano, "Self-adjusting microstructures (SAMS)," ," *IEEE Micro Electro Mechanical Systems Workshop*, Nara, Japan, Jan.-Feb. 1991, pp. 51-56.

[11] K. S. J. Pister, M. W. Judy, S. R. Burgett, and R. S. Fearing, "Microfabricated hinges: 1mm vertical features with surface

micromachining," 6th Int. Conf. on Solid-State Sensors and Actuators, San Francisco, Calif., June 1991.
[12] Y. Fukuta, D. Collard, T. Akiyama, E. H. Yang, and H. Fujita, "Microactuated self-assembling of 3D polysilicon structures with reshaping technology," *IEEE Micro Electro Mechanical Systems Workshop*, Nagoya, Japan, Jan. 1997, pp. 477-481.
[13] C. Gonzaléz, R. L. Smith, D. G. Howitt, and S. D. Collins, "MicroJoinery: concept, definition, and application to microsystem development," *Sensors and Actuators A (Physical)*, **66**, 315-332 (1998).
[14] F. Arai and T. Fukuda, "A new pick up and release method by heating for micromanipulation, *IEEE Micro Electro Mechanical Systems Workshop*, Nagoya, Japan, Jan. 1997, pp. 383-388.
[15] C. Bark, T. Binnenböse, G. Vögele, T. Weisener, and M. Widmann, "Gripping with low viscosity fluids," IEEE Micro Electro Mechanical Systems Workshop, Heidelberg, Germany, Feb. 1998, pp. 301-305.
[16] H. H. Langen, "A study on micromachining/assembly," Ph.D. thesis, Univ. of Tokyo, 1994.
[17] W.-H. Chu and M. Mehregany, "Microfabricated tweezer with a large gripping force and a large range of motion," *Solid State Sensor and Actuator Workshop*, Hilton Head, S.C., June 1994, pp. 107-111.
[18] C.-J. Kim, R. S. Muller, A. P. Pisano, and M. G. Lim, "Polysilicon microtweezers," *Sensors and Actuators A (Physical)*, **33**, 221-227 (1992).
[19] C. G. Keller, "Microfabricated silicon high aspect ratio flexures for in-plane motion", Ph.D. Thesis, Dept. of Materials Science and Mineral Engineering, Univ. of Calif. at Berkeley, 1998.
[20] I. Shimoyama, "Scaling in microrobotics," *IEEE/RSJ Int. Workshop on Intelligent Robots and Systems*, Pittsburgh, Penn., 1995, pp. 208-211.
[21] R. A. Bowling, "A theoretical review of particle adhesion," in K. L. Mittal, ed., *Particles on Surfaces I Detection, Adhesion, and Removal*. New York: Plenum, pp. 129-155.
[22] E. T. Yablonovitch, J.P. Harbison,; R. Bhat, "Extreme selectivity in the lift-off of epitaxial GaAs films." *Applied Physics Letters*, **51**, 28 Dec. 1987, pp .2222-4.
[23] K. W. Goosen, et al, "GaAs MQW modulators integrated with silicon CMOS," *IEEE Photonics Tech. Lett.*, **7**, 360-363 (1995).
[24] Camperi-Ginestet, C.; Hargis, M.; Jokerst, N.M.; Allen, M., "Alignable epitaxial liftoff of GaAs materials with selective deposition using polyimide diaphragms," IEEE Photonics Technology Letters, vol.3, no.12 p.1123-6 Dec. 1991.
[25] M.B. Cohn, Y.-C. Liang, R.T. Howe, A.P. Pisano, "wafer-to-wafer transfer of microstructures for vacuum packaging," *1996 Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, USA, June 2-6, 1996.
[26] L.S. Goodman, "Geometric optimization of controlled collapse interconnections," *IBM J. Res. Devel* 13(3): pp. 251-265, 1969.
[27] K.W. Marcus, V. Dhuler, D. Roberson, A. Cowen, M. Berry, S. Nangalia, "Smart MEMS: Flip Chip Integration of MEMS and Electronics," SPIE Smart Materials Conference, Feb 1995.
[28] A. Singh, D.A. Horsley, M.B. Cohn, A.P. Pisano, R.T. Howe, "Batch Transfer of Microstructures using flip-chip solder bump bonding", Technical Digest, Transducers'97, Chicago, June, 1997.
[29] C.G. Keller and M. Ferrari, "Milli-Scale Polysilicon Structures," Solid-State Sensor and Actuator Workshop, Hilton Head SC, pp. 132-137, June 1994.
[30] D.A. Horsley, A. Singh, A.P. Pisano, R. Horowitz, "Angular Micropositioners for Disk Drives," Intl. Workshop on Micro Electro Mechanical Systems, Nagoya, Japan, pp. 454-459, 1997.
[31] Horsley D.A.; Cohn, M.B.; Singh, A.; Horowitz, R.; Pisano, A.P. Design and fabrication of an angular microactuator for magnetic disk drives. Journal of Microelectromechanical Systems, vol.7, (no.2), IEEE, June 1998. p.141-8.
[32] A. Singh, D.A. Horsley, M.B. Cohn, A.P. Pisano, R.T. Howe, "Batch Transfer of Microstructures using flip-chip solder bonding", in the *Journal of Microelectromechanical Systems* submitted 5/98.
[33] S. Wolf and R. N. Tauber, Silicon Processing for the VLSI Era, Volume 1: Process Technology, Lattice Press, Sunset Beach, CA, 1986, p. 8 ff.
[34] J. Darnell, H. Lodish, D. Baltimore, *Molecular cell biology* / New York: W.H. Freeman, 1986.
[35] C. Cantor, *The behavior of biological macromolecules* / San Francisco : W. H. Freeman, 1980.
[36]. M. B. Cohn, R. S. Fearing "Self-Assembly in Microfabrication," Seminar Presented to the Berkeley Sensor and Actuator Center, Nov. 22, 1992.
[37] H. Lodish, D. Baltimore, A. Berk, S Zipursky, P. Matsudaira, J. Darnell, *Molecular Cell Biology*, Third Edition, / New York: W. H. Freeman, 1995, p. 1322.
[38] M. Cohn, C. J. Kim, A.P. Pisano, "Self-Assembling Electrical Networks: An Application of Micromachining Technology," *Transducers '91 International Conference on Solid-State Sensors and Actuators, Digest of Technical Papers*, San Francisco, June 24-27, 1991 / New York: IEEE, 1991, p. 493.
[39] S. Yando, *Method and Apparatus for Fabricating an Array of Discrete Elements*, U.S. Patent No. 3,439,416, Assigned to

GTE Laboratories, Inc., 1969.
[40] H. Hitakawa. "Advanced parts orientation system has wide application," *Assembly Automation*, 8(3), 1988.
[41] M. A. Hadley, "Self-orienting fluidic transport (SOFT) assembly of liquid crystal displays," presentation at *the Defense Manufacturing Conference*, Palm Springs, Calif., Dec, 1-4, 1997.
[42] H. J. Yeh, J.S. Smith, "Fluidic self-assembly of microstructures and its application to the integration of GaAs on Si," *Proceedings IEEE Micro Electro Mechanical Systems*, Oiso, Japan, 25-28 Jan 1994 / New York: IEEE, 1994. p.279-84.
[43] A. Ashkin and J.M. Dziedzic, *Science* **235**, 1517 (1987).
[44] M. M. Burns, J. M. Fournier, J. A. Golovchenko, "Optical Binding," Physical Review Letters 63:12, p. 1233 ff. (18 Sept 1989).
[45] K.V.I.S. Kaler and H.A. Pohl, "Dynamic dielectrophoretic levitation of living individual cells," *IEEE Trans. IAS*, vol. IA-19, 1983, 1089-1093.
[46] T.B. Jones, *Electromechanics of Particles* / New York: Cambridge University Press, 1995.
[47] G.Fuhr, W.M. Arnold, R. Hagedorn, T. Muller, W. Benecke, B. Wagner, and U. Zimmermann, "Levitation, holding, and rotation of cells within traps made by high-frequency fields," *Biochim. Biophys. Acta*, **1108**, 1992, 215-223
[48] M. Washizu, T.B. Jones, and K.V.I.S. Kaler, "Higher-order DEP effects: Levitation at a field null," *Biochim. Biophys. Acta*, **1158**, 1993a, 40-46.
[49] T.B. Jones and J.P. Kraybill, "Active feedback-controlled dielectrophoretic levitation," *J. Appl. Phys*., **60**, 1986, 1247-1252.
[50] M.B. Cohn, R. T. Howe, A. P. Pisano, "Self-Assembly of Microsystems Using Non-Contact Electrostatic Traps," *Proc. ASME International Mechanical Engineering Congress and Exposition (IMECE)*, San Francisco, California (November 1995), p. 893-900.
[51] Cohn, M.B., "Self Assembly of Microfabricated Devices," US Patent No. 5,355,577, October, 1994.
[52] Berggren, K.K.; Bard, A. Wilbur, J.L.; Gillaspy, J.D.; Helg, A.G.; McClelland, J.J.; Rolston, S.L.; Phillips, W.D.; Prentiss, M.; Whitesides, G. M. "Microlithography by using neutral metastable atoms and self-assembled monolayers." *Science* v269, n5228 (Sept 1, 1995):1255
[53] A. Terfort, N. Bowden, and G.M. Whitesides, "Three-dimensional self-assembly of millimetre-scale components." *Nature 386*, 6621 (March 13, 1997):162.
[54] M. Cohn, U.S. Patent No. 5,355,577, issued 10/1994.
[55] K.-F. Böhringer, M. Cohn, K. Y. Goldberg, R. Howe, A. Pisano, Electrostatic Self-Assembly Aided by Ultrasonic Vibration, Presented at AVS'97 - American Vacuum Society National Symposium on Micro Electro Mechanical Systems (MEMS) , San Jose, CA (October 1997).
[56] H. Fujita. Group work of microactuators. In International Advanced Robot Program Workshop on Micromachine Technologies and Systems, pages 24--31, Tokyo, Japan, Oct. 1993.
[57] S. Konishi and H. Fujita. A conveyance system using air flow based on the concept of distributed micro motion systems. In Transducers --- Digest Int. Conf. on Solid-State Sensors and Actuators, pages 28--31, Pacifico, Yokohama, Japan, June 1993.
[58] K.-F. Böhringer, B. R. Donald, R. Mihailovich, and N. C. MacDonald. A theory of manipulation and control for microfabricated actuator arrays. In Proc. IEEE Workshop on Micro Electro Mechanical Systems (MEMS), pages 102--107, Oiso, Japan, Jan. 1994.
[59] C. W. Storment, D. A. Borkholder, V. Westerlind, J. W. Suh, N. I. Maluf, and G. T. A. Kovacs. Flexible, dry-released process for aluminum electrostatic actuators. Journal of Microelectromechanical Systems, 3(3):90--96, Sept. 94.
[60] J. W. Suh, S. F. Glander, R. B. Darling, C. W. Storment, and G. T. A. Kovacs. Combined organic thermal and electrostatic omnidirectional ciliary microactuator array for object positioning and inspection. In Proc. Solid State Sensor and Actuator Workshop, Hilton Head, NC, June 1996.
[61] C. Liu, T. Tsao, P. Will, Y. Tai, and W. Liu. A micro-machined magnetic actuator array for micro-robotics assembly systems. In Transducers --- Digest Int. Conf. on Solid-State Sensors and Actuators, Stockholm, Sweden, June 1995.
[62] W. Liu and P. Will. Parts manipulation on an intelligent motion surface. In IEEE/RSJ Int. Workshop on Intelligent Robots & Systems (IROS), Pittsburgh, PA, 1995
[63] K.-F. Böhringer, B. R. Donald, N. C. MacDonald, G. T. A. Kovacs, and J. W. Suh. Computational methods for design and control of MEMS micromanipulator arrays. IEEE Computer Science and Engineering, pages 17--29, January--March 1997.
[64] M. B. Cohn. *Assembly Techniques for Microelectromechanical Systems*. Ph.D. thesis, University of California at Berkeley, Department of Electrical Engineering and Computer Sciences, 1997.

[65] K.-F. Böhringer, K. Goldberg, M. B. Cohn, R. Howe, and A. Pisano. Parallel microassembly with electrostatic force fields. In Proc. IEEE Int. Conf. on Robotics and Automation (ICRA), Leuven, Belgium, May 1998.

[66.] J. S. Hwang,. *Modern solder technology for competitive electronics /* New York: McGraw-Hill, 1996.

[67.] L.S. Goodman, "Geometric optimization of controlled collapse interconnections," *IBM J. Res. Devel* 13(3): pp. 251-265, 1969

[68]. M. M. Schwartz, "Fundamentals of Soldering," in ASM Handbook, 10^{th} Edition, Volume 6: Welding, Brazing, and Soldering / Materials Park, OH; ASM International, 1990, p. 129-30.

[69.] S. M. Bobbio, N. G. Koopman, S. Nangalia, *Fluxless soldering sample pretreating system*, U.S. Patent No. 5,499,754, MCNC Corporation, Research Triangle Park, NC. ISSUED: Mar. 19, 1996

[70.] Y. C. Chen, C. Y. Wang, and C. C. Lee, "Directly deposited lead-indium-gold composite solder," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol.16, (no.8), Dec. 1993. p.789-93.

[71.] T. Nishikawa, M. Ijuin, R. Satoh, Y. Iwata, M. Tamura, M. Shirai, "Fluxless soldering process technology," *1994 Proceedings. 44th Electronic Components and Technology Conference*, Washington, DC, USA, 1-4 May 1994 / New York, NY, USA: IEEE, 1994. p.286-92.

[72.] C. H. Lee, Y. M. Wong, C. Doherty, K.L. Tai, E. Lane, D. D. Bacon, F. Baiocchi, and A. Katz, "Study of Ni as a barrier metal in AuSn Soldering Application for Laser Chip/Submount Assembly, *J. Appl. Phys*. 72 (8), 10/15/1992, pp. 3808-15.

[73.] M.A. Hadley, *Vertical-cavity surface-emitting laser diodes: design, growth, mode control and integration by fluidic self-assembly*, Ph.D. thesis, EECS Dept., UC Berkeley, 1994.

[74.] G. S. Matijasevic, C. C. Lee, C. Y. Wang, "Au-Sn phase diagram and properties related to its use as a bonding medium," *Thin Solid Films*, 223 (1993), 276-87.

[75]. T. Kawanobe, K. Miyamoto, M. Hirano, Proc. *33^{rd} IEEE Electronic Components and Technology Conf*., 1983, IEEE, New York, 1983, pp. 221-26.

[76]. W. H. Ko, J. T. Suminto, G. J. Yeh, in C. D. Fung, P.W. Cheung, W.H. Ko, and D.G. Fleming (eds.) *Micromachining and Micropackaging of Transducers*, Elsevier, Amsterdam, 1985, pp. 41-61.

[77]. C.A. Mackay and S.W. Levine, *IEEE Trans. Compon., Hybrids, Manuf. Technol.*, 9 (1986) pp. 195-201.

[78.] C.H. Lee, Y.M. Wong, C. Doherty, K.L. Tai et al, "Study of Ni as a barrier metal in AuSn soldering application for laser chip / submount assembly," *J. Appl. Phys.* 72:8 (15 Oct 1992), pp. 3808-15.

[79.] American Welding Society. *Welding handbook*, Charlotte Weisman, editor. 7th ed. Miami, Fla.: American Welding Society, 1984.

[80.] R.R. Tummala, E. J. Rumaszewski, A.G. Klopfenstein, *Microelectronics Packaging Handbook. Technology Drivers. Part 1*, Chapman & Hill, 1997.

[81.] H. Yatsuda and T. Eimura, "Flip-chip assembly technique of SAW devices," *1995 International Symposium on Microelectronics*, Los Angeles, CA, USA, 24-26 Oct. 1995.) SPIE, 1995. p.365-70.

[82] D. Gupta, "Evaluation of alternative processes for Au-Sn-Au flip chip bonding of power devices. 1995 International Symposium on Microelectronics, Los Angeles, CA, USA, 24- Oct. 1995.) SPIE, 1995. p.371-7.

[83.] G.K.Fedder, J.C. Chang, R.T. Howe, "Thermal assembly of polysilicon microactuators with narrow-gap electrostatic comb drive," *Technical Digest. IEEE Solid-State Sensor and Actuator Workshop,* Hilton Head Island, SC, USA, 22-25 June 1992, New York, NY, USA: IEEE, 1992. p.63-8.

[84] Bartek, M.; Foerster, J.A.; Wolffenbuttel, R.F. Vacuum sealing of microcavities using metal evaporation. Sensors and Actuators A (Physical), vol.A61, (no.1-3), (EUROSENSORS X, Leuven, Belgium, 8-11 Sept. 1996.) Elsevier, June 1997. p.364-8.

[85.] Ajluni, C. Silicon accelerometer targets airbag restraint systems. *Electronic Design*, vol.43, (no.21), 13 Oct. 1995. p.143-4. (Motorola MMAS40G accelerometer with glass frit hermetic package)

[86] K. Ikeda, et al, "Three dimensional micromachining of silicon resonant strain gauge, 7^{th} Sensor Symposium, Tokyo, Japan, May 1988, pp. 193-196.

[87] C. H. Mastrangelo and R. S. Muller, Int. Electron Devices Meeting, San Francisco, Calif., Dec. 1989, pp. 503-506.

[88] Guckel, H.; Rypstat, C.; Nesnidal, M.; Zook, J.D.; Burns, D.W.; Arch, D.K. Polysilicon resonant microbeam technology for high performance sensor applications. Technical Digest. IEEE Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, USA, 22-25 June 1992. New York, NY, USA: IEEE, 1992. p.153-6.

[89] Lin, L., McNair, K.M., Howe, R.T., and Pisano, A.P., "Vacuum Encapsulated Lateral Microresonators," Digest of Transducers '93, International Conference on Solid-State Sensors and Actuators, pp. 270-3, 1993.

[90] K. S. Leibouitz, A. P. Pisano, and R. T. Howe, "Permeable polysilicon etch-access windows for microshell fabrication," 8^{th} Int. Conf. on Solid-State Sensors and Actuators, Stockholm, Sweden, June 1995, vol. 1, pp. 224-227.

[91.] Alpha Metals, Advanced Products Division, Jersey City, NJ. Alpha-Bond anisotropically conductive film preliminary data sheet. 10/94.

92. P. H. Singer, "Die bonding and package sealing materials," Trans. on Electron Dev., ED-26, 12, pp. 1896-1905 (1979).

93. Norland Products, Inc., New Brunswick, NJ (908)545-7828.

94. J.B. Lasky, S. R. Stiffler, F.R. White, J. R. Abernathey, "Silicon-on-insulator (SOI) by bonding and etch-back," *Technical Digest, 1985 IEEE International Electron Devices Meeting*, p. 684, Dec 1985.

95. M. Shimbo, K. Furukawa, K. Fukuda, T. Tanzawa, "Silicon-to-silicon direct bonding method," *Journal Of Applied Physics*, Vol. 60, No. 8, P. 2987, Oct 1986.

96. M. A. Schmidt, "Silicon wafer bonding for micromechancal devices," *Solid-State Sensor and Actuator Workshop*, Hilton Head, SC, June 13-16, 1994, pp. 127-131.

97. J. A. Folta, C. E. Hunt, S. N. Farrens, "Low-temperature wafer bonding of surfaces using a reactive sputtered oxide," *Journal of the Electrochemical Society*, vol. 141, (no.8), Aug. 1994. pp. 2157 - 60.

98. R.W. Bower, M. S. Ismail, and B. E. Roberd, "Low temperature Si_3N_4 direct bonding," *Appl. Phys. Lett.*, vol. 62, no. 26, pp. 3485-7, 1993.

99. T.J. Brosnihan, J.M. Bustillo, A.P. Pisano, R.T. Howe, "Embedded interconnect and electrical isolation for high-aspect-ratio, SOI inertial instruments." *Tranducers 97. 1997 International Conference on Solid-State Sensors and Actuators.* Chicago, IL, USA, 16-19 June 1997. New York, NY, USA: IEEE, 1997. p. 637-40 vol. 1.

100. Q.-Y. Tong, U. Gosele, "Semiconductor wafer bonding: recent developments." *Materials Chemistry and Physics*, vol.37, (no.2), March 1994. p.101-27.

101. Q. Y. Tong, G. Cha, R. Gafiteanu, U. Gosele, "Low Temperature Wafer Direct Bonding," *Journal of Microelectromechanical Systems*, vol. 3, no. 1 (March 1994), pp. 29-35.

102. Hoogerwerf, A.C., Wise, K.D., "A three-dimensional neural recording array," *Transducers '91 1991 International Conference on Solid-State Sensors and Actuators*, San Francisco, CA, 24-27 June, 1991, pp. 120-123.

103. B. Shivkumar and C.-J. Kim "Microriveting - A New Wafer Joining Method" *IEEE Micro Electro Mechanical Systems Workshop*, Nagoya, Japan, Jan. 1997,pp. 197-202.

104. H. Han, L.E. Weiss, M.L. Reed, "Design and Modeling of a Micromechanical Surface Bonding System," *Transducers '91*, pp. 974-77.

105. R. Prasad, K.-F. Böhringer, N. C. MacDonald, "Design, Fabrication, and Characterization of SCS Latching Snap Fasteners for Micro Assembly," *Proc. ASME International Mechanical Engineering Congress and Exposition (IMECE)*, San Francisco, California (November 1995).

106 M. B. Cohn, *Assembly Techniques for Microelectromechanical Systems*, Ph.D. Thesis, Department of Electrical Engineering and Computer Science, University of California, Berkeley, 1997.