MEMS for Heterogeneous Integration of Devices and Functionality

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Abstract— **Future MEMS systems will be composed of larger varieties of devices with very different functionality such as electronics, mechanics, optics and bio-chemstry. Integration technology of heterogeneous devices must be developed. This article first deals with the current development trend of new fabrication technologies; those include self-assembling of parts over a large area, wafer-scale encapsulation by wafer-bonding, nano imprinting, and roll-to-roll printing. In the latter half of the article, the concept towards the heterogeneous integration of devices and functionality into micro/nano systems is described. The key idea is to combine the conventional top-down technologies and the novel bottom-up technologies for building nano systems. A simple example is the carbon nano tube interconnection that is grown in the via-hole of a VLSI chip. In the laboratory level, the position-specific self-assembly of nano parts on a DNA template was demonstrated through hybridization of probe DNA segments attached to the parts. Also, bio molecular motors were incorporated in a micro fluidic system and utilized as a nano actuator for transporting objects in the channel.**

Index Terms— **MEMS, micromachining, self assembly, printing, nano technology**

I. INTRODUCTION

The root of MEMS research can be found in the research of silicon sensors. A noticeable turning point from sensor research toward MEMS research was the demonstration of micromachined movable parts [1], gears and turbines [2] made on a silicon chip in 1987. Since then, development has continued in micromachining processes, material varieties, micro actuators, and the applications of MEMS as shown in Fig. 1. The development [3] was so fast and wide in variety that many new products have been and will be introduced to the market. Both the progress in fabrication technology (technology-push) and the expansion of application fields (application-pull) urge larger varieties of devices with very different functionality to be integrated in the future MEMS system. This article deals with the current development trend of new fabrication technologies and the concept towards the heterogeneous integration of devices and functionality into micro/nano systems.

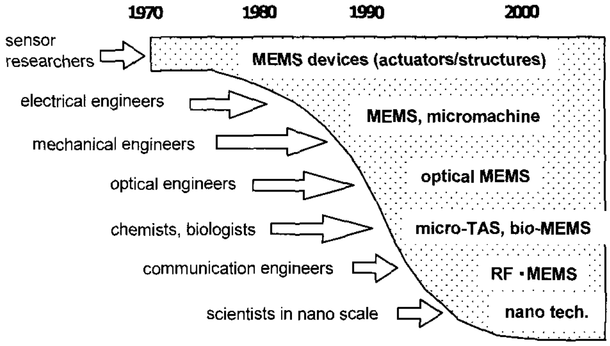

Fig. 1. Development of MEMS research.

II. CURRENT STATUS OF MICROMACHINING

Current Status of Micromachining processes [4] are based on silicon integrated circuits (IC) technology to build three-dimensional structures and movable parts. Therefore, the same technology base that enabled miniaturization and large-scale integration of electronics offers three

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distinctive features defining micromachined devices and systems: miniaturization, multiplicity, and microsystem integration [5]. In order to realize those prospects, researchers have improved the fabrication, design and integration methods of MEMS. As an example, let us follow the historical change of technology for sensor fabrication:

(1) Pressure sensors, one of the first MEMS products, are composed of KOH etched thin membranes and ion implanted piezoresistors.
(2) Integrated accelerometers depend on the surface micromachining to have moving masses and circuits on a chip. Detection of very small capacitance change and electrostatic servo feedback enable the sensor of high sensitivity, linearity and wide dynamic range.
(3) Angular velocity sensors (gyroscopes) are intensively developed recently; the deep reactive etching technology plays a key role to make high-aspect-ratio resonating structures of the sensor. Wafer bonding technology is also used to make a vacuum package for low mechanical loss.

In summary, we have experienced the improvement in etching accuracy and minimum dimension to a few tens of nanometers, and the freedom of making 3-D shapes. The integration of actuators/circuits, the replication process of 3-D structures, and the bonding technology, have also significantly advanced. Deposition and patterning of more materials are performed in micromachining than in VLSI technology. Mechanically active materials, i.e. PZT, ZnO, TiNi, TbFe and quartz, are used for actuators. Bio materials are coated and patterned on glass or plastic substrates for micro fluidic devices. Self-assembly of parts has been demonstrated; this technique is useful when the parts fabrication is incompatible with the process for fabricating structures on the substrate. Fig. 2 shows the fluidic self-assembly of chips on hydrophobic patches on a substrate [6]. Each chip has a particular side hydrophobic that is attracted to the patch. PZT actuator chips were self-assembled on a micromachined silicon substrate to drive micropumps. In addition, wafer-scale encapsulation of MEMS devices is possible by sealing cavities by poly-silicon deposition and epi-growth. Electrical contacts can be routed to the device through the encapsulation layer. Integrated circuits can be made on the wafer surface after encapsulation [7].

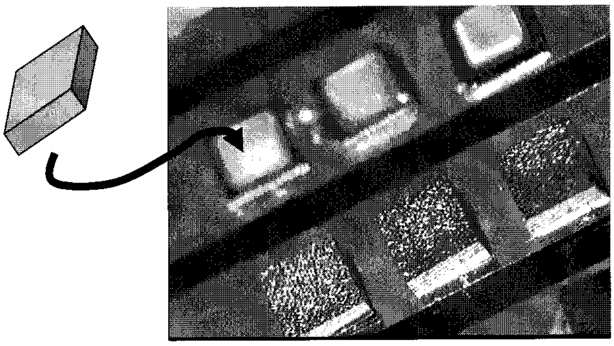


Fig. 2. Fluidic self-assembly: small parts with hydrophobic surface treatment are assembled on hydrophobic patches. The parts were permanently bonded after assembly step by curing the organic lubricant. [6]

III. EMERGING MEMS PRODUCTS AND HETEROGENEOUS INTEGRATION

Following successful cases in inkjet printers, automobile sensors and projection displays, many MEMS products have been or will be introduced to the market:

(1) Optical MEMS including variable optical attenuators (VOA) and optical switches.
(2) IT sensors including TV-game controller sensors, microphones, uncooled infra-red cameras, robotic sensors, taste sensors, and odor sensors.
(3) RF MEMS includes RF switches, integrated resonators, and variable capacitors/inductors with a high-Q factor.
(4) Nanotechnology tools including AFM cantilevers and handling tools for atoms and molecules.
(5) Micro fluidic systems including DNA analysis chips, micro reactors, medical diagnosis chips and environmental monitoring chips.
(6) Many other products utilizing 3-dimensional microstructures fabricated by MEMS related technologies.

Table 1 summarizes the correspondence between MEMS products and technologies. You may notice how the technological development is essential for new successful products. This is why the heterogeneous integration technology of devices and functionality is necessary. Fig. 3shows how such integration is achieved. For the purpose, we can utilize various technologies; those include micromachining, VLSI (very large scale integration) silicon

Table 1. Relation between MEMS products and technology.

	wet anisotropic etching	surface micromachining	dry anisotropic etching	circuit integration	nano machining	microactuator	fluidic device	surface treatment	bonding
pressure sensor	thin membrane								
accelerometer		movable mass & capacitive electrodes		high		servo feedback			
angular speed sensor			thick structure	sensitivity detection		electrostatic actuator			vacuum encapsulation
ink-jet printer head						micro heater	arrayed nozzle	hydrophobic surface	sealing channel
digital micromirror device		arrayed movable mirror		array control		electrostatic actuator		anti-sticking	hermetic sealing
optical scanner			flat mirror			electrostatic actuator			
VOA			flat mirror			electrostatic actuator			
electrophoresis chip							separation channel	separation, anti-absorption	sealing channel
AFM probe	cantilever, sharp tip				nano tip				

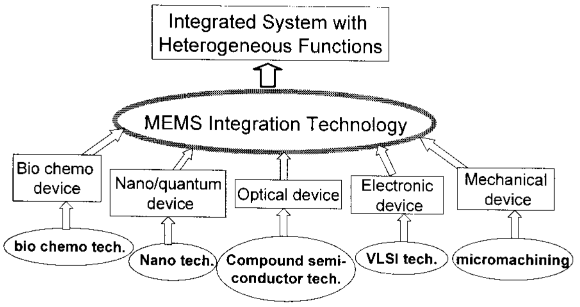


Fig. 3. MEMS technology for heterogeneous integration of devices and functionality.

microelectronic technology, compound semi-conductor technology, nano technology and bio/chemo technology. Each technology offers different devices with specific functionality. The MEMS integration technology can combine those and enable us to build a micro/nano system having multiple functions.

Replication of micro molds has been investigated over twenty years. However, there are two new developments recently. One is nano imprinting. Structural size below 100 nm can be obtained with typical aspect ratio of 1-2. Hot embossing is one way for nano imprinting. Also UV-cured resin is used to replicate transparent nano molds; this is called photo nano imprinting. The other is the roll-to-roll printing process. As shown in Fig. 4, the idea is to apply different process on films continuously; these processes include sputtering of films, off-set or gravure printing of patterned ink, hot embossing, and lamination. Although the minimum feature size and alignment accuracy are approximately 10 micrometers, the technology enables us to process meter-wide and hundreds-meter-long film with very low cost. Not only dyes and insulators but also metal conductors and organic/inorganic semiconductors can be printed. Printed transistors [8], LEDs [9], power transmission sheet [10], and tactile sensors [11] have been demonstrated. We may envision that thinned silicon IC-chips are surface-mounted at certain places on the sheet. Therefore, inexpensive large-area fabrication of heterogeneous microdevices and MEMS will be realized by printing technology.

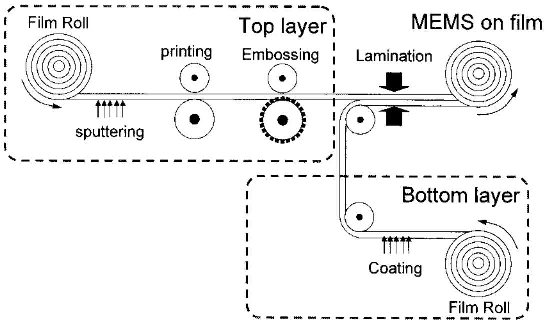


Fig. 4. Roll-to-roll MEMS fabrication. (prospected)

IV. TOWARDS NANO SYSTEM INTEGRATION ON A CHIP

1. Combinations of Top-down and Bottom-up Methods

The minimum feature size of MEMS has decreased to a few tens of nanometers owing to the downsizing of VLSI technology. Further miniaturization becomes more

Table 2. Top-down technologies and bottom-up technologies.

Method	Technology	Typical dimension
Top down	VLSI technology	- 45 nm(design rule)
	MEMS	- 100 nm(structural width)
	Two photon/FIB deposition	- 100 nm(feature size)
Bottom up	Atom manipulation	Sub-nm
	Molecular synthesis	1-100 nm (molecular size)
	Protein engineering	10-100 nm (molecular size)
	Carbon nano tube	2-100 nm (diameter)

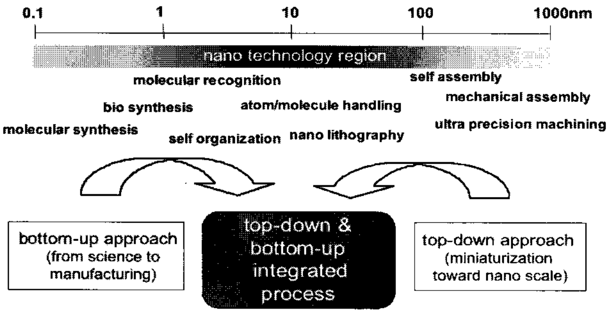


Fig. 5. Combination of top-down & bottom-up technology.

and more difficult. In order to overcome the difficulty, a novel approach as compared to the conventional top-down method, so-called a bottom-up method will be incorporated. The major technologies and associated typical dimensions are listed in Table 2 for both top-down and bottom-up methods.

The top-down method in the table is capable of building a system from millions of elements according to our design; a good example is a VLSI processor. However, its miniaturization is limited to tens of nanometers. On the contrary, with the bottom-up method functional nano elements are constructed from atoms and molecules. Carbon nanotubes (CNT) and bio molecules are among such elements. CNT can serve as a transistor, a conductive wire and a nano torsion bar [12]. Those nano elements exhibit peculiar functionality in nano-scale such as quantum effects and specific molecular recognition. Many elements may be synthesized simultaneously through chemistry or biotechnology. They may also organize themselves in an ordered form; this is called self-organization. However, precise control of such assembly towards a complete engineered system is almost impossible now. Therefore, it is still out of our capability to build a complicated system, e.g. an integrated memory chip, by (self) assembling only nano elements, e.g. CNT transistors.

In order to solve the problem, the combination of both methods to realize a nano system seems to be practical.

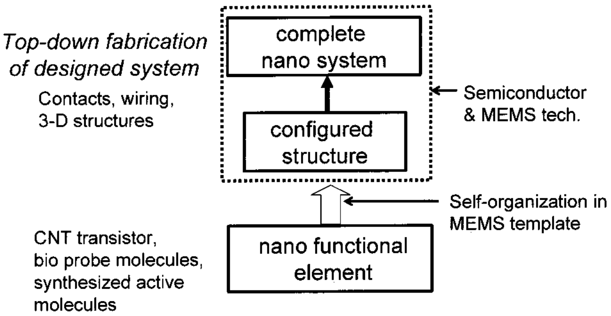


Fig. 6. Nano systems made by combination of a MEMS structure and nanoelements.

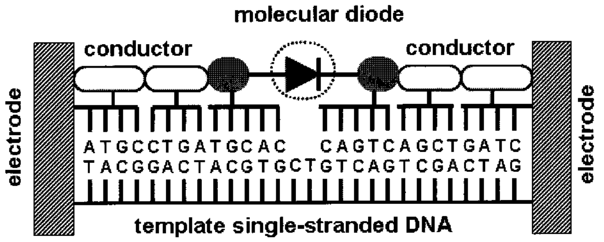


Fig. 7. Conceptual drawing of DNA-based molecular construction. Stretch-and-positioned single stranded DNA serves as a template for molecular assembly.

Fig. 5 represents the way both approaches are used in combination. Individual nano elements are placed at proper locations in a structure fabricated by VLSI/MEMS technologies. The structure provides interconnections among nano elements to integrate their functionalities into a target system. It also serves as an interface between nano and macro worlds and as a control mechanism of system operation. Fig. 6 represents how such a system, named nanosystem, can be obtained. Various heterogeneous functions will be integrated in a nanosystem; those include electronic, mechanical, optical, quantum, chemical, biological, etc. There are already some preliminary examples. A metal piece was suspended by a torsion bar made by a carbon nano tube and rotated by electrostatic force[12]. Bundles of carbon nano tubes can be grown in via holes of an advanced VLSI chip to have superior conductivity [13]. Kobayashi and Washizu proposed to use a stretched single-strand DNA as a template to align nano parts with DNA segments having complimentary sequences to the template DNA (see Fig. 7) [14]. They stretched single-strand DNA molecules between electrodes and introduced DNA probes of a particular complimentary sequence. The probes attached to a designated position in the template by hybridization.

2. Nano Conveyance Device Composed of Bio Molecular Motor in MEMS

In order to realize the concept of the nanosystem, we incorporated bio functional molecules, i.e. kinesin and microtubules for linear motor, in a micro fluidic system and utilized them as a nano actuator. On a glass chip, we attached long chain molecules [15], named microtubule, that work as rails to direct the motion according to their polarity. Small structures such as polymer beads and silicon microstructures were coated with kinesin molecules. When micro beads or structures are placed on the microtubule, kinesin generates force and convey those objects. We have successfully carried micro objects on the immobilized rail molecule. ATP molecules in water served as the energy supply for bio motors. On and off control of the motion of micro beads was successfully demonstrated by adding ATP molecules and removing them from the solution. We also oriented microtubules in the same polarity and carried many beads toward one direction [16].

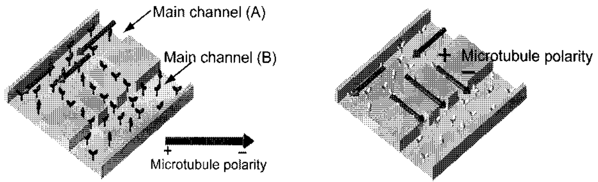
Furthermore, we tried to manipulate a single microtubule in micro fluidic channels [17]. The device and the experimental procedure are shown in Fig. 8.

(1) Sub-micrometer channels (50 micrometers in length, 500–2000 nm in width, and 4 micrometers in height) connect two access channels (10 mm in length, 300 micrometers in width, and 4 micrometers in height). The bottom surface of channels was coated with kinesin. Microtubules are immobilized on the kinesin-coated access channel (A).

(2) Microtubules start gliding by ATP injection and are guided into sub-micrometer channels. The sub-micrometer channel is so narrow that only a single microtubule is allowed to come into the channel.

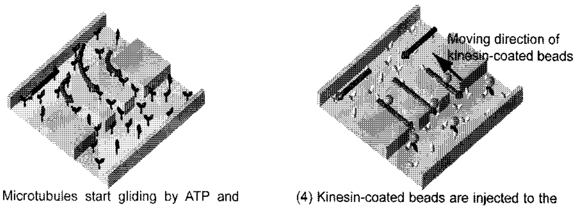
(3) Microtubules in the sub-micrometer channels are immobilized by mercury lamp exposure (wavelength of 420–500 nm).

(4) Kinesin-coated beads are injected into the access channel (B), and transported from the (B) side to the (A) side.



(1) Microtubules are immobilized on the kinesin-coated main channel (A).

(3) Gliding microtubules are immobilized by mercury lamp exposure (λ=420-500 nm).



(2) Microtubules start gliding by ATP and are guided into nano channels.

(4) Kinesin-coated beads are injected to the main channel (B), and transported from (B) side to (A) side.

Fig. 8. Process to align and capture individual microtubules in micro channels.

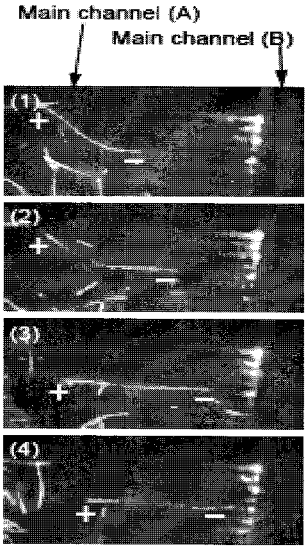


Fig. 9. Experimental result to align and capture individual microtubules in micro channels. A single microtubule was orientated and fixed in a micro channel. After the process, kinesin coated bead successfully traveled from minus (-) to plus (+) direction on a microtubule.

Fig. 9 shows fluorescent microtubule guidance into sub-micrometer channels. Fig. 9(1)–(4) are sequential pictures (15 s interval) of a microtubule gliding into a channel (750 nm in width). The gliding speed was 690 nm/s. A microtubule was immobilized in each channel as shown in Fig. 9 (4). The transportation of a kinesin-coated bead was demonstrated (Fig. 10). The bead was introduced from the access channel (B); it traveled along the single microtubule towards the channel (A) as expected.

In the latest experiment, a direct molecular sorting device is investigated [18]. We use tow kinds of beads; one kind of beads has specific affinity to the first kind of target molecules and the other to the second kind of target. Those beads captured their own target molecules from the solution and conveyed them toward the destination separately by the force of motor molecules.

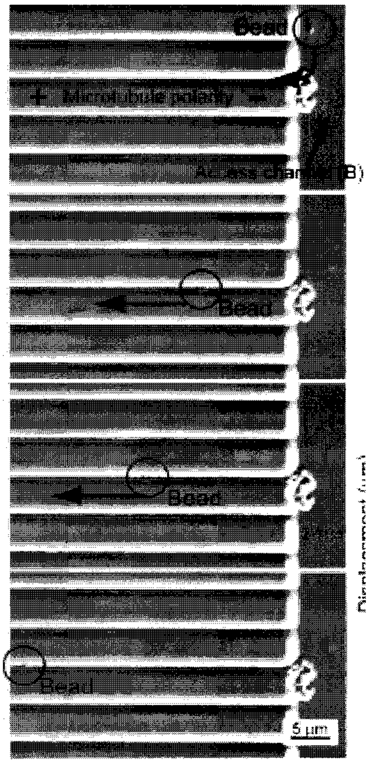


Fig. 10. Unidirectional transportation of a bead in a channel. Sequential pictures (20 s interval) of a kinesin-coated bead (747 nm/s, bead diameter = 320 nm) transported on a microtubule (not visualized) immobilized in a sub-micrometer channel of 500 nm in width.

The unidirectional conveyance of target molecules in the cells is conducted by the microtubule network on which vesicles coated with kinesin move around. Therefore, our device that imitates the intracellular nanotransport system is the first step to transport individual target molecules in a nano-channel.

V. CONCLUSIONS

The MEMS research has shown remarkable development. Micromachining capability in micrometer scale has reached its maturity. Such technological advance enabled MEMS commercial products. In the future, MEMS technology will include printing/replication processes and will be capable of integrating nano elements into the system; with this development, further expansion of MEMS application area is expected. In the long run, the combination of nanotechnology and MEMS will be fruitful. MEMS will evolve into nano systems that have heterogeneous multiple functionalities. I believe the most practical way to build nano systems is utilizing and controlling nano functional elements placed at proper locations in MEMS/VLSI structures. Some preliminary examples of such approach were described in the article. In the same way as past development of MEMS technology pushed commercialization, such new development will lead to new products to solve problems in the future society.

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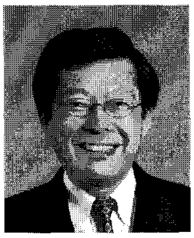

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