NEW TRENDS OF MEMS/NEMS BASED ON HETEROGENEOUS PROCESS INTEGRATION - TOWARDS LIFE/GREEN INNOVATION -

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ABSTRACT

The technological revolution is essential for providing future innovation. With the saturation in the miniaturization of microelectronics as well as the maturity of MEMS, now further advance in MEMS/NEMS technology is required. Here, a heterogeneous integration technology combining various fabrication methods is proposed. We can utilize micromachining, VLSI technology, compound semiconductor technology, nano technology, bio technology, organic/inorganic chemistry, printing and molding to create a versatile manufacturing technology. Each technology offers the capability to realize specific functionality in different scales with different materials. This talk deals with the concept towards the heterogeneous integration of devices and functionality into micro/nano systems, the current development trend, and its potential contribution to life and green innovation.

KEYWORDS

MEMS, NEMS, bio technology, printing

INTRODUCTION

From late 1980's when first MEMS devices were demonstrated, the development of research has continued in micromachining processes, material varieties, and microactuators. The development was so fast and wide in variety that many new products have been and will be introduced to the market.

Both established and emerging products seem to fall in two categories. The first category is for products having simple function, e.g. sensors, printer heads, RF switches, and AFM cantilevers. For those devices, micromachining technology offers small and precise shaping and batch production capability.

The second category is for products requiring more functional integration. A typical example is the DMD display; the chip itself consists of many microactuated mirrors integrated with CMOS circuits. Embedded circuitry enables sub-ms individual control of a-few-million mirrors. Accelerometers integrated with CMOS circuits can be included in this category, too. High sensitivity, temperature compensation, servo-feedback, and self testing are realized by electronics. Integrated micro fluidic systems that are composed of micro channels, valves and pumps may also fall in the category.

Figure 1 represents those categories as a roadmap. The first generation, which corresponds to the first category, includes the present MEMS products; they are utilized in automobiles, measurement instruments, communication networks, and IT apparatus for miniaturization and higher performance. Current research and development focus on the second generation. The advanced integration technology in a system level is under intensive investigation. We can expect that the multi-functional system-on-chip (SOC) or system-in-package (SIP) MEMS will be introduced to the market quite soon.

I would like to propose the third category that will come to the market in 10 or more years from now. The expansion of application fields urge wider varieties of devices with very different functionality to be integrated in the future micro and nano systems. I believe the third generation needs revolutionary change in concept and technology.

The combination of two disciplines, i.e. semiconductor microfabrication and mechanical engineering, is the origin of MEMS technology. Learning from this lesson, why don't we study how to combine even more technologies for creating a new paradigm? Organic and inorganic chemistry as well as bio technology can provide functional materials for sensing, energy conversion and actuation. The self-organization of crystals, nano particles, and biological cells/materials, can make patterning and 3-D assembly in nano scale easy. Printing can be an inexpensive way to have micro patterns on a meter-size substrate or film. If we can pattern and functionalize thin and long fibers, a smart textile may be made by weaving them. The application areas will be widened to environment and energy conservation, health-care, and security in daily life. Because MEMS in the third generation will include much wider technology bases, I would like to propose naming it as "BEANS" that stands for bio electromechanical autonomous nano systems. BEANS will contribute to life and green innovation.

In this paper, the concept of heterogeneous integration will be proposed first. Next, I will discuss the features of the approach, using the examples from my own laboratory and a Government-supported BEANS project.

HETEROGENEOUS INTEGRATION

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. Similar to the way "micro" machining has been developed from microelectronics over past decades, "nano" machining should follow the miniaturization trend of electronics. Fast, ultra-precise and low-damage fabrication methods for high-aspect-ratio nano structures must be developed as

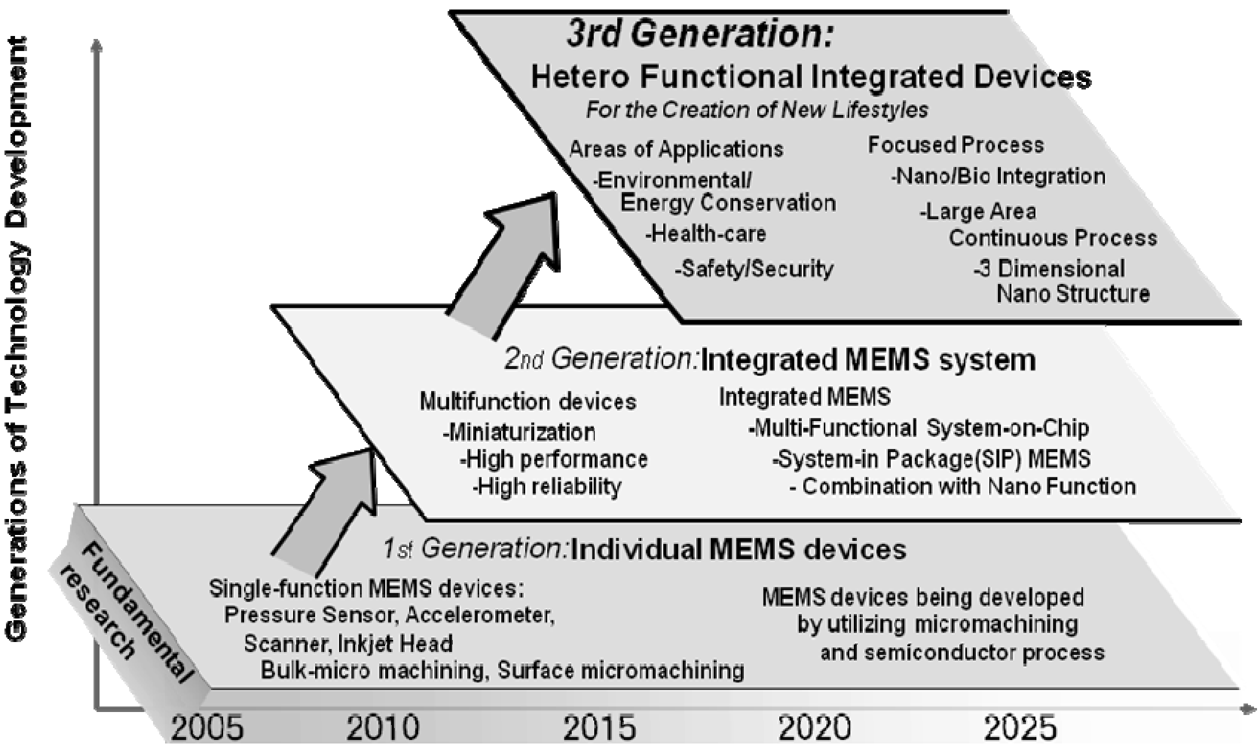

Figure 1: Three generations of MEMS development.

the extension of existing techniques. In addition to the conventional top-down method, so-called a bottom-up method will be incorporated as novel approach.

The top-down method 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, functional nano elements are constructed from atoms and molecules with the bottom-up method. Carbon nanotubes (CNT) and bio molecules are among such elements. CNT can serve as a transistor, a conductive wire and a nano torsion bar [1].

Those nano elements exhibit peculiar functionality in nano-scale such as quantum effects and molecular level specific 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. Individual nano elements are placed at proper locations in a structure fabricated by VLSI/MEMS technologies. The structure provides interconnections among nano elements to organize their functionalities for satisfying the system specification. It also serves as an interface between nano and macro worlds and as a control mechanism of system operation.

Figure 2 represents typical scales where each technology works efficiently. By utilizing them seamlessly together, various heterogeneous functions will be integrated in a nano system; those include electronic, mechanical, optical, quantum, chemical, and biological functions. 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 [1]. Bundles of carbon nano tubes can be grown in via holes of an advanced VLSI chip to have superior conductivity [2]. Bio functional molecules were already incorporated as selective sensing materials for bio sensors.

Bio integration to artificial devices

Biological cells and molecules are of particular importance for the medical and environmental monitoring. Those will be incorporated in MEMS devices because they are capable of highly sensitive detection [3], producing bio functional materials, self-assembly and temporal growth. The study on micro fluidics systems has made remarkable progress in handling, culturing and characterizing cells. Furthermore, integration of bio molecules in individual molecular level is emerging. In the different approach DNA molecules can serve as the template for nano devices [4] and two/three dimensional structures [5].

The highly-sensitive, biostable, long-lasting, and injectable fluorescent microbeads were fabricated in a

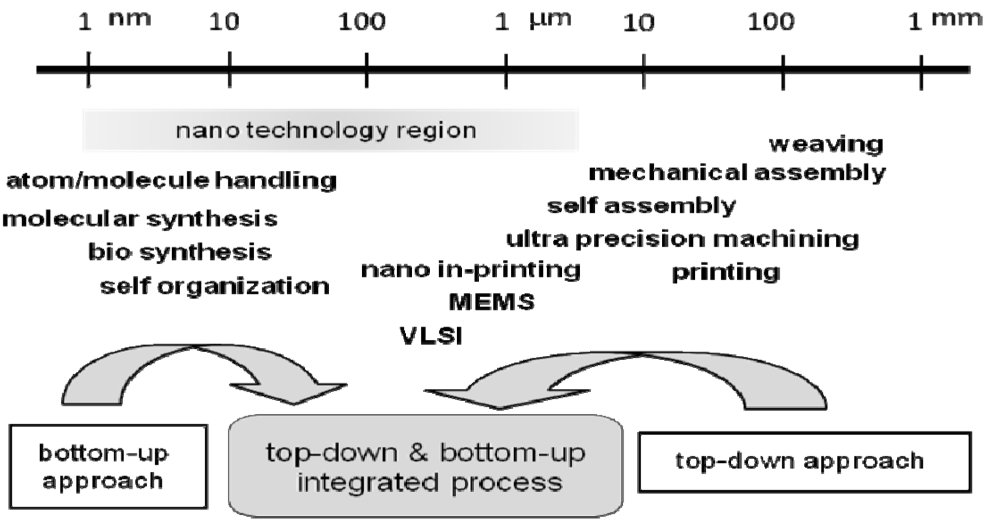

Figure 2: Heterogeneous integration of various processes over scale

microfluidic device for *in vivo* continuous glucose monitoring [6]. The fluorescent monomers of high responsiveness to glucose were shaped into fluorescent polyacrylamide hydrogel beads of a few hundred micrometers in diameter with high uniformity and high throughput. After injection under the skin, Fluorescent beads provide sufficient intensity to transdermally monitor glucose concentrations *in vivo*. The fluorescence intensity successfully traced the blood glucose concentration fluctuation. This method has potential uses in highly-sensitive and minimally invasive continuous blood glucose monitoring.

Microfabrication over large-area

Now, precise 3D structures can easily made by micromachining of silicon. The typical devices have structural dimensions down to tens of nanometers and chip sizes of millimeters to reduce the fabrication cost on a silicon substrate. There is a class of MEMS devices, however, that requires implementation over a large area; this class includes displays, smart skins, and smart textiles. Fortunately, the flexible electronics is rapidly emerging. We can learn from this development in the same manner as we adopted silicon technology for micromachining in 30 years ago. Ink-jet printing, roll-to-roll printing, molding and embossing are usually used to make patterns of tens of micrometers in definition on flexible sheets. Printed transistors [7], LEDs [8], power transmission sheet [9], and tactile sensors [10] have been demonstrated.

I believe the roll-to-roll printing is particularly interesting. A sheet is running between rolls while different processes are applied on it 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.

A MEMS controlled paperlike transmissive flexible display has been demonstrated using roll-to-roll printing process [11]. This device takes advantage of Fabry–Perot interferometer concept for switching RGB color pixels and was realized on flexible polymer substrate with low operation voltage of 20 V. We have confirmed the fabrication capability of each step in the prospected process flow shown in Figure 3.

For fast and complicated electronic control, we may envision that thinned silicon IC-chips can be surface mounted at certain places on the sheet. Therefore, inexpensive and heterogeneous fabrication of large-area MEMS will be realized by printing technology.

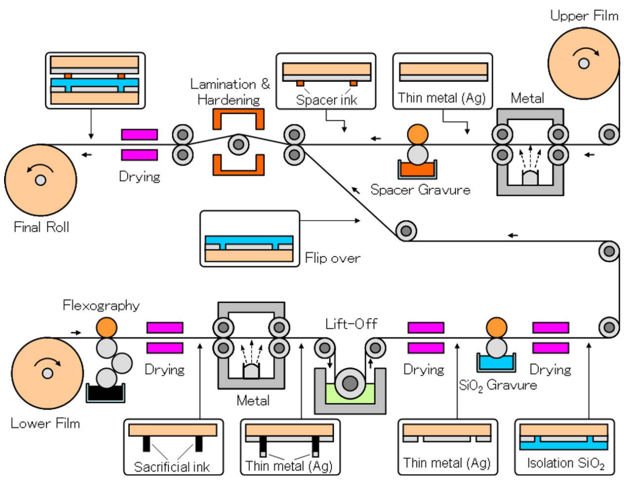

Figure 3: Prospected Roll-to-Roll process flow of MEMS controlled flexible display [11]

Government supported BEANS project

In order to develop manufacturing technologies for hetero-functional devices, a national research and development project of the Ministry of Economy, Trade and Industry was initiated in July, 2008 for a 5-year term. We named the hetero-functional devices as Bio & Electromechanical Autonomous Nano Systems (BEANS), the revolutionary devices of the future. BEANS will provide fabrication platform for the third-generation MEMS devices. The goal of the project is the integration of technologies in different fields (Figure 2), e.g. combining MEMS with nanotechnology and biotechnology. Also printing and weaving techniques are employed for the fabrication of large-area flexible MEMS sheets. Future BEANS devices will be useful to solve important social issues such as healthcare, environmental protection, food safety, and conservation of energy.

There are five research centers in the BEANS project, covering three major targets: Life-BEANS, 3-D BEANS and Large-Area BEANS. More than 120 researchers from about 10 universities, 20 companies and 2 research institutions are involved in the project. Roughly US$ 50 million will be supported. Please visit http://www.beanspj.org/ for more details.

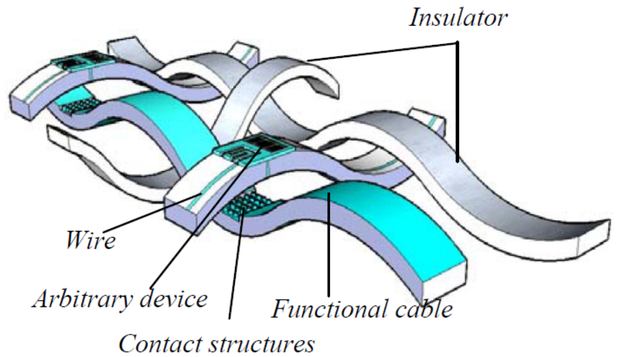

Figure 4: Schematic of weaving fiber components for flexible sheet device applications [13]

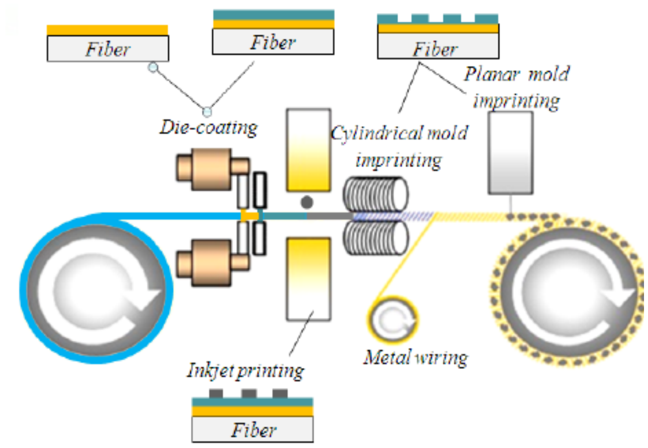

Figure 5: Schematic diagram of reel-to-reel continuous fiber process and equipment [13]

FEATURES OF BEANS

The heterogeneous integration technology has three features:

- Hetero-scale integration from nanometer to meter scale
- Hetero-material integration from bio and organic materials to semiconductors
- Hetero-process integration of bottom-up and top-down processes

As for the hetero-scale integration, an infrared filter with two pass-bands is developed for satellite remote sensing. Sub-wavelength structures of a few hundred nm in size were fabricated on top of the interferometer structure of micrometers [12]. This is a novel combination between conventional light-wave elements and nanophotonic elements. Another research topic is the micromachining

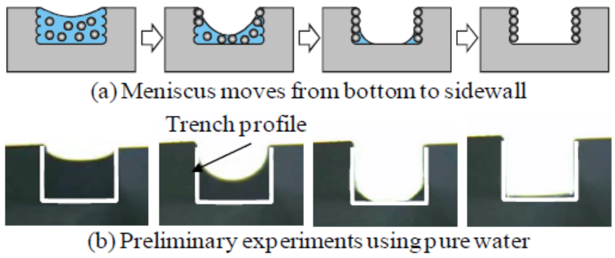

Figure 6: (a) Schematic cross-sectional images of a particle suspension spreading in a trench, (b) observed cross sectional images of a silicon trench with pure water instead of the suspension. [16]

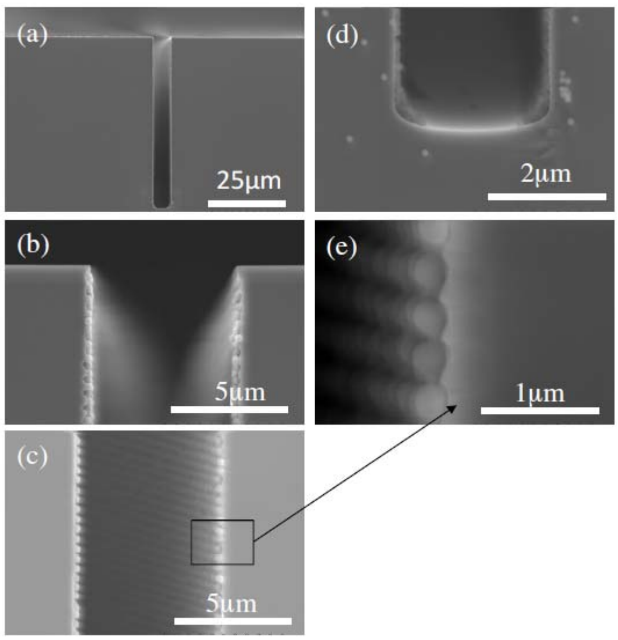

Figure 7: SEM images of self-assembled particles (300nm in diameter) on trench sidewalls. (a) An overall view. Close-up images at (b) upper, (c) middle, (d) bottom part of the trench. (e)A further close-up image of the middle part. [16]

on flexible fibers [13]. A flexible array of MEMS may be fabricated by weaving such fibers and interconnecting them. Figures 4 and 5 show the concept. This is a novel way towards large area woven MEMS textile.

As for the hetero-material integration, an array of lipid bilayers was formed on the mouths of micro chambers. After membrane proteins were introduced in the bilayer, ion channel activity was successfully measured [14]. The membrane proteins are responsible for the communication between intra and extra cellular environments. Because many of them are a good target for medicine, the chip will be useful for understanding mechanisms as well as a quick screening tool.

We have also integrated motor proteins in microfluidic devices. A single strand of microtubules was placed in a nanochannel. Submicron beads attached with kinesin transported successfully via the interaction between microtubules and kinesin [15]. The bead may also capture a specific kind of molecules by molecular recognition and transport them to a designated point; a mechanical sorter for molecules may be realized.

Another research aims at the high performance nano electric devices based on combined use of organic and inorganic materials. Nano pores in anodic oxidized aluminum film were utilized for fabricating nano pillars of organic materials. It is expected that such nano pillars of 50 nm in diameter are useful for improving conversion efficiency of thermoelectric or photovoltaic devices for energy harvesting.

There are many attempts on nano patterning based on self-assembly. Regular nano patterns in the order of 10 nm are obtained by anodic oxidization, crystalline structure of block copolymers, and nano water droplets condensed on a substrate just below dew point. One target in hetero-process integration is the combination of such self-assembly with top-down patterning methods. For example, a regular and dense array of SiO_2 submicron particles was formed on the vertical walls of a silicon trench by surface tension and evaporation of suspension liquid [16]. Its concept and results are shown in Figures 6 and 7, respectively. Attached with functional molecules, beads on side-walls may interact with materials in the fluid that runs in the trench with small flow resistance.

In the bio related research, the controlled self-assembly and culturing of living cells in micromachined structure is intensively investigated; this is the way to produce well regulated 3D cell structures for future tissue engineering. Adhesive cells, which are very difficult to handle, were encapsulated in gel beads. By molding cell beads in a PDMS mold and culturing them, 3D structures packed tightly with cells were obtained [17]. In the other work, liver cells were sandwiched and cultured between a gel layer and the PDMS film which is permeable to O_2 and CO_2. When trenches or recesses were patterned on the gel surface, liver cells collect themselves in the space and formed a large cavity, resembling a bile duct, filled with cell metabolic product. This may lead to the artificial reconstruct of liver tissue.

FUTURE IMPACT

BEANS will contribute solving social issues such as environmental/energy conservation, healthcare, and security in daily life. Thus, it will enable life and green innovation.

The BEANS technology can create a smooth transition interface from inorganic materials to organic and bio materials. Resulted biocompatible surface due to functionalization and nano patterning ensures reliable long-term operation of embedded healthcare device. The glucose responding gel bead is a good example [6]. Controlling growth and assembly of cells of different kind may be achieved in microstructures engineered by BEANS technology, although the current cell structures were composed of a single type of cells [17]. Heterogeneous reconstruction of cell assembly has significant impact on tissue engineering. It also opens the way to mimic a certain function of an organ by reconstructing its key part. Demonstration of the fine regulation of polarity in a hepatocyte culture [18] is the first step towards this goal. I have a dream concerning BMI (brain-machine interface). Neurons are cultured in a microfluidic system which has electronic readout circuits. After controlled neuron growth, they establish connection to both electronic circuits and brain neural network, providing an ideal BMI. If realized, such a method is regarded as spatio-temporal (4D) fabrication technology.

As for the green innovation, inexpensive energy harvesting is very important. Large-area BEANS process can provide the fabrication platform for such a purpose. In the future we might be able to spread a large sheet of photovoltaic or thermoelectric cell array to generate electric power in any place. They must be composed of nano structured highly-efficient converters [19]. In addition, the cellular based sensor [3] is well suited for the environmental monitoring because it can directly indicate the environmental effect to the living organisms.

CONCLUSION

The future MEMS technology will be the heterogeneous integration of processes that can handle inorganic/organic/bio materials over scales from nanometer to meter. With this development, further expansion of MEMS application area is expected. MEMS will evolve into BEANS that have multiple functionalities. 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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