The aerosol deposition method

— For production of high performance micro devices with low cost and low energy consumption —

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[Translation from *Synthesiology*, Vol.1, No.2, p.130-138 (2008)]

AD (aerosol deposition) method is one of newly developed technologies for spray coating powder materials. It is a revolutionary coating technology in which high-density consolidation of ceramic powder can be obtained at room temperature, without sintering at high temperature as in conventional ceramic formation. By using AD, it is expected to improve device performance, to greatly reduce energy consumption and to decrease the number of steps during fabrication process that ultimately result in cutting production costs. How the characteristics of AD method are positioned from the perspective of technological competitiveness and reduction of environment load, as well as its potential, is investigated from the viewpoint of Full Research, along with description of principles and specific case studies.

Keywords : Aerosol deposition, AD method, optical scanner, on-demand, energy conservation, electronic ceramics, piezoelectric, MEMS

1 Introduction

The circumstances surrounding the manufacturing process of electronic devices and their implementation are rapidly changing due to industrial globalization and concern for environmental overload. Shortening product(ion) cycle and multi-product variable production have become non-negligible issues. Currently, product specifications are rapidly becoming diverse in the market, and this is affecting mounted products such as connectors, sensors, and actuators. Multi-product variable production with extremely short delivery time is now in demand, in contrast to the age of single-product mass production. The demand in the manufacturing industry is changing greatly due to diversification of market requirements. For example, over 1 billion yen investment in manufacturing line is required to mass produce MEMS device starting from the R&D phase, even when existing LSI manufacturing line is used. Usually, long time is needed for product development, and substantial production volume is required to lower the cost through mass production at device level. For these reasons, the business risk for commercialization is considerable even for a major corporation. It is also the basis for the adage: “killer application is necessary to commercialize MEMS.” On the other hand, MEMS devices are considered as parts (components), and flexibility for multi-product variable production is needed when considering practical application. Although only a hypothesis first, this trend is expected to increase as integration level of modular functional parts increases. Demand for multi-product low-volume production develops when black boxing and customization are conducted to control commoditization of product to maintain its competitiveness. To lower cost in such conditions, further evolution of process technology from perspective of manufacturing will become necessary.

Considering the manufacturing process of advanced devices in the future, demand for high performance by achieving thinning and high integration of oxide electronics material with multiple functions is expected to increase. In the integration process of electronic devices such as MEMS, various R&Ds are conducted using vacuum thin film processes including sputter and CVD methods due to their manufacturing application potential. However, there are surprisingly few cases where thin film technology has reached a practical level through integration of semiconductor parts. This is due to the fact that, as, for example, in the cases of capacitor and filter parts fabrication, the property of material and the cost of production process in device application are at trade-off, and at this point, ingenious utilization of bulk material is more feasible in terms of cost, facility, and energy consumption. Highly pure raw material and ultra vacuum environment are necessary and

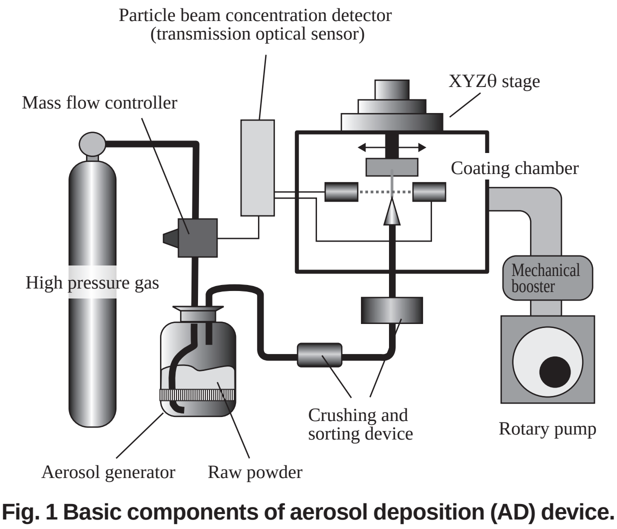

Fig. 1 Basic components of aerosol deposition (AD) device.

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there are several issues that must be tackled including facility cost, energy consumption, and environment load to realize a mass production level. Making breakthroughs to solve these issues will be important. Therefore, construction of on-demand manufacturing process and system that can address these needs is expected to become important in the future from the perspectives of strengthening industrial competitiveness and reducing environment load. Investigations of such issues are made using small-scale cell production systems at assembly level including implementation of circuit substrate for sensor device[1].

In the background of high performance device manufacturing described above, the R&D stance of not only "How do we realize the function?" but also "How should it be made to ensure resources and low costs?" will become more important. In this paper, the potential for on-demand manufacturing process based on aerosol deposition method is investigated along this stance.

2 The aerosol deposition (AD) method

The aerosol deposition method (hereinafter AD method)[2] is a technology in which fine or ultra-fine powder is mixed with gas to form an aerosol, that will be sprayed through a nozzle to form a film coat on a substrate. The motion energy of material particle accelerated by gas carrier is converted to local heat energy by colliding with the substrate, and substrate-particle and particle-particle bonds are achieved. However, the mechanism of energy conversion has not been sufficiently understood.

Figure 1 shows the basic structure of the coating device. The device is composed of an aerosol generator connected to a narrow delivery tube and a coating chamber, which is vacuumed to 50~1 kPa using a vacuum pump. The dried fine or ultra-fine powder that makes the raw material is stirred and mixed with gas in the aerosol generator chamber, carried to the coating chamber by gas flow caused by pressure difference between the two chambers, accelerated through the slit nozzle, and sprayed onto the substrate. Normally, mechanically grounded sintered ceramic powder with particle diameter 0.08~2 μm is used as raw material. The gas carrying the ultra-fine powder can be easily accelerated to several hundreds m/sec by passing through a nozzle with micro opening of 1 mm or less. Since coating speed and density of film coat depends greatly on particle diameter, aggregation state, and dryness of ceramic fine powder, crushing and sorting devices are installed between the aerosol generator and the coating chamber to ensure high quality powder flow.

Recently, using ceramic powder in AD method and selecting appropriate coating condition as well as adjusting particle diameter and its mechanical properties, room temperature impact consolidation (RTIC) was observed. This is a phenomenon where high density, transparent ceramic film was formed at room temperature at high speed, as shown in Figure 2[2][3]. The substrate was not heated when the powder material was sprayed onto the substrate, and no heat processing was required after coating. This phenomenon occurred not only for ceramic materials but was also observed for metals.

Amorphous layer or heterophase between crystalline particles in the microstructure of ceramic film formed by RTIC using the AD method was not observed and the dense films obtained at room temperature consist of non-oriented microcrystal with size 10~20 nm or less. Clear lattice image has been observed in microcrystals 10 nm or less in diameter. Although some distortion occurred in the interior of the film, the texture of the films remained the same from substrate interface to film surface. The powders used in AD deposition have monocrystalline structures with average particle diameter 80~100 nm or more; however, smaller fine crystal texture was observed in the coated films. From the results of XRD and EDX analyses, the coated film maintained the crystal structure of material powder with small compositional variations. From measurement of particle speed and assessment of motion energy, it is considered that the material powder crystals are mechanically crushed by collision, become finer by plastic deformation, and nanocrystal thin film is formed as bonds between particles[1]-[3]. These are not seen in the conventional coating method using particle collision.

Compared with the conventional thin film processes, the AD method shows the following unique characteristics:

1. Binderless, dense coating/film are obtained at room temperature;
2. High coating rate of 5~50 μm/min (conventional method: 0.01~0.05 μm/min);
3. Film coat of same composition and crystal structure as powder used for complex composition system can be obtained with substantially different pressure;
4. Wide variation of film thickness can be obtained (0.5 μm~1 mm);
5. Without etching process, micro pattern can be obtained using direct rendering, mask method, or lift-off method;

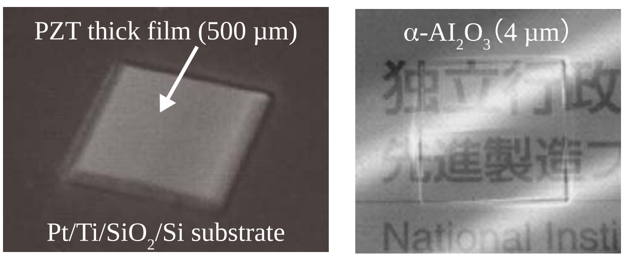

Fig. 2 Ceramic film created at room temperature using the AD method.

6. Film formation is possible even at low vacuum (several hundred Pa ~ atmospheric pressure).

During the film formation by RTIC using the AD method, absolutely no increase in substrate temperature due to collision was observed. Macroscopically, ceramic material was consolidated at room temperature. Since it did not undergo firing process, AD consolidation process could be considered as binderless, ultra high-density ceramic green fabrication process.

3 Comparison with current thin film technologies and energy conservation

3.1 Difference in principle with conventional thin film technologies

If ceramic film with high density and good crystallization can be formed accurately at low temperature, at low cost, and at high speed, the issue of mass production discussed in Chapter 1 can be solved. The AD method is a non-heat equilibrium process, and unlike thermal spraying, the material powder is bonded and a thin film is formed in solid state at room temperature. Compared to the conventional thin film method, the coating speed is extremely fast since it is a build up process at a particle level, and the crystal structure of material powder is almost completely preserved in the film coat. Therefore, one major characteristic of AD method is that it can be used for film coating on any substrate material, and film coatings from powders with complex compositions such as composite oxides can be formed. Due to the characteristics of the AD method, drastic reduction in process temperature can be expected compared to other coating technologies. Moreover, the AD method is also readily applicable for compounding and integration of different ceramic, metal, and polymer materials, as well as for development of nanostructure compound materials.

From the perspective of process energy conservation, coating with conventional technologies is normally possible only in vacuum environment of several hundred Pa or less, while, with AD method, coating can be done in atmospheric pressure depending on the material and use. In conventional thin film technology, material is broken down to atomic and molecular levels, and then crystallized on the substrate. Therefore, to obtain highly pure crystal formation without defects and with high-performance film properties, it is necessary to maintain ultra high vacuum to control adhesion and bonding of contaminating atoms before reaching the substrate. As shown in Figure 3, in the AD method raw powder material is already in crystallized form. AD method has a fast powder supply speed to the substrate and, because the surface of material powder is inactive before collision with the substrate or the coated film and the activation for bond formation occurs only due to collision with the substrate, the need of ultra high vacuum is not necessary to control inclusion of impurities during the coating process. Since adhesion of impurities can occur on the surface of material powder, it is necessary to clean the surface before use to obtain ultra pure crystals. However, in the NEDO Nanotechnology Program / Low Temperature Formation and Integration Technology of Nano level Electronic Ceramics Material Project (FY2002~FY2006)[4], film property equivalent or better than that achieved with current vacuum thin film technology was demonstrated in many electronic ceramic materials without the cleaning process.

For industrial application, the innovative point added by AD method is that although high performance material is involved, coating can be accomplished in low vacuum. Compared to the conventional vacuum thin film process, it is expected to reduce cost of building manufacturing facility, energy consumption, and environment load.

3.2 Energy conservation by using the AD method in electrostatic chuck manufacturing process

Investigation has been conducted on how much energy could be conserved in the whole product manufacturing process and to what degree product function would be improved by employing the AD method in the NEDO Energy Research and Development Project for Core Technology for Efficient Energy Use (Leading Energy Conservation Research FY2001~FY2003)[5] through joint research with a private corporation. The subject of investigation was electrostatic chuck, which is currently used to lift up wafers by adsorption in semiconductor manufacturing, and product with high adsorptivity is in demand to support large wide size Si wafers or heavy components such as flat panels. Electrostatic chuck has a structure consisting of a ceramic thin plate added on as isolator to generate static electricity on a metal jacket that acts as radiator and electrode, as shown in Figure 4. The thinner the ceramic plate is, the higher the adsorptivity per applied voltage. Aluminum nitride material with good heat conductivity is generally used due to its radiation property. In

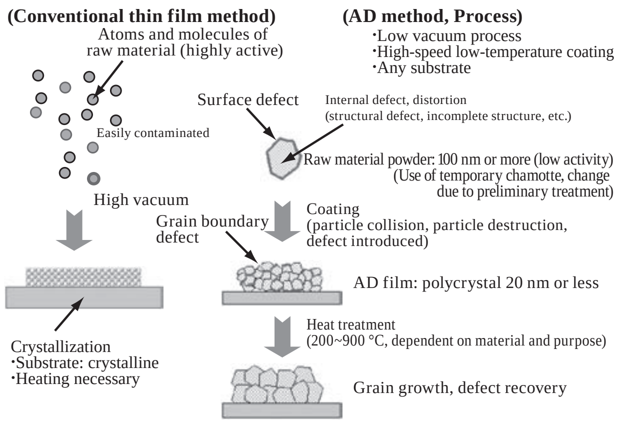

Fig. 3 Difference between the processes of AD method and conventional thin film method.

the NEDO Project, aluminum nitride thin plate was replaced with ceramic coating on a metal jacket using the AD method, and the improvement in performance and energy consumption reduction throughout the entire manufacturing phase were investigated. By replacing the insulation layer with AD coating, thickness was reduced to 1/10 or less, adsorption per applied voltage increased about 20 times, and heat conductivity and speed of adsorption response to a metal jacket also increased dramatically. Since heat conductivity can be improved by replacing aluminum nitride with other materials, ex. yttria, new functional improvements such as increasing corrosion resistance against plasma can be expected.

For the manufacturing of electrostatic chuck through introduction of the AD method, approximately 80 % reduction in energy consumption could be achieved for the entire manufacturing process, as shown in Figure 4. The manufacturing process time was also reduced to 1/10 or less. For this particular application, the energy reduction was obtained not only by the removal of sintering process that is required in conventional manufacturing to be performed at high temperatures, but also for further removal of other fabrication process steps present in the conventional manufacturing process. Particularly, the reduction in energy consumption of polishing process needed to gain evenness of adsorption surface, which determines the performance of electrostatic chuck, contributed greatly to the reduction of total energy consumption. When ceramic thin plate is made using conventional ceramic process, there is substantial contraction and warping during firing, and energy consumption needed for planarization is quite substantial. Using ceramic coating by the AD method, sufficient pressure resistance can be obtained since the film is dense even if it is thin, and warping of adsorption surface is greatly reduced because of its thinness. The energy reduction in manufacturing process is relevant to mass production design, and we believe that the efficacy of the AD method in energy conservation should be further investigated.

Although the above case study was for the particular case of electrostatic chuck, energy conservation can be achieved by employing AD method in ceramic coating in many other ceramic products, when ceramics with properties such as corrosion resistance, insulation, and hardness are demanded.

Improvement of resistance to plasma corrosion by using yttria film coated using the AD method in inner walls of chamber and components in semiconductor manufacturing device is currently in the process of commercialization. Because by using CVD, separate devices are needed for each material and/or process step, an alternative method using a single device needs to be investigated. It may eventually become possible to optimize scale, facility cost, and energy consumption of semiconductor manufacturing plant according to production volume.

4 Possibility of lower cost and energy conservation by application to MEMS optical scanner

4.1 Application to Si-MEMS scanner and simplification of process

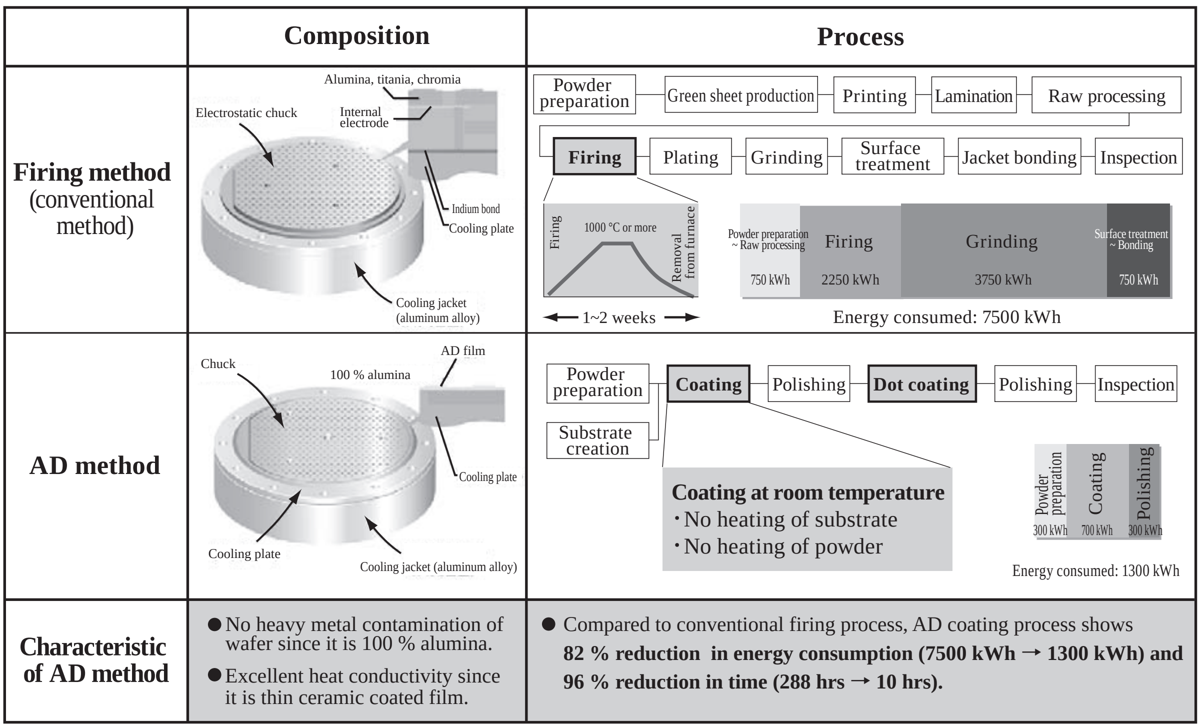

Fig. 4 Structure of electrostatic chuck and comparison of energy consumption in manufacturing process using AD method.

In response to demands for "necessary amount at necessary places" or "multiple product variable volume," we investigated the on-demand application of process and manufacturing system. Since the AD method is a nozzle spray process, it has the potential for an on-demand process similar to the ink jet technology.

As case study, we investigated the application of the AD method to piezoelectrically actuated Si-MEMS optical scanner, as shown in Figure 5. This scanner is expected to be used in next-generation laser printers, barcode readers, and ITS laser radars, and will become a key component of next-generation display devices such as micro projectors and retinal projection displays. Therefore, requirements include high-speed scanning of tens of kHz, scanning angle of over 20°, millimeter size mirror, reduced distortion during motion, and low voltage drive[6].

In the manufacturing process the scanner structure was formed using Si micromachining, and an active film, which would be the driving source, was coated only in required areas. Conventionally, to create such actuator structures, upper and lower electrode layer and piezoelectric layer were deposited using the sputter method, CVD method, or sol-gel method after forming the structure by bulk micromachining using wet and/or dry etching. The substrate has to be heated to crystallize the piezoelectric layer and the patterning is usually done by etching. An expensive microfabrication device, a coating device, and processes involving over 20 steps were necessary. In contrast, using the AD method, the piezoelectric layer could be formed accurately only in necessary areas of the microfabricated Si scanner structure. The etching process for piezoelectric and electrode layers became unnecessary and this enabled drastic reduction of processes and facilities along with improved coating speed. Device performance has been also improved, scanning frequency of 33.4 kHz and optical beam scanning angle of 30° were obtained, and the resulting optical scanner had higher speed and larger amplification than conventional electrostatic driven, electromagnetic driven, and piezoelectric driven MEMS optical scanners[7]. These results were possible because the thickness of the piezoelectric film was easily thickened in the process, and as a result, the generative force of drive source was increased and a Si torsion beam structure with high rigidity could be employed.

4.2 Application to metal base MEMS scanner and reflection in device design

Because high performance piezoelectric film could be formed on any substrate material using the AD method, we investigated the fabrication of a metal base device for a less expensive, highly impact resistant, and practical small-size actuator[8]. Figure 6 shows the manufacturing process of Lamb wave resonance type high-speed micro optical scanner that was created by replacing Si with stainless steel

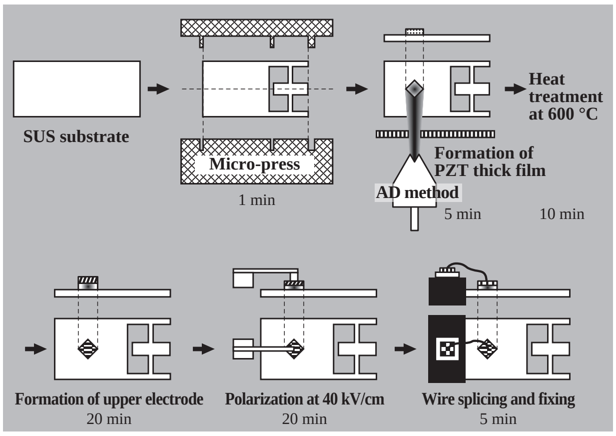

Fig. 6 Metal-base optical scanner driven by AD piezoelectric film and manufacturing process.

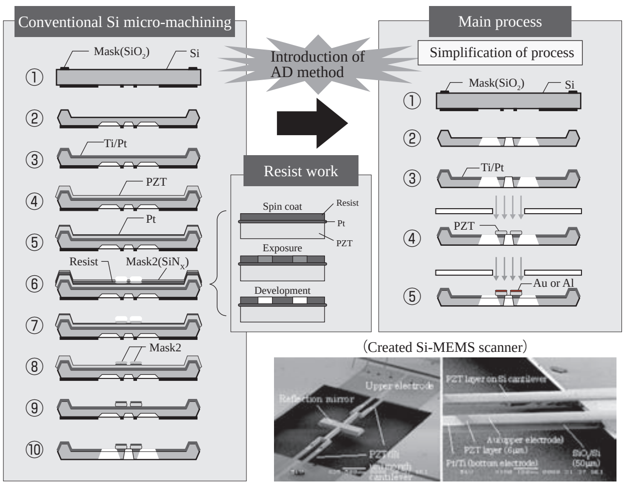

Fig. 5 Comparison of Si-MEMS optical scanner driven by AD piezoelectric film and conventional manufacturing process.

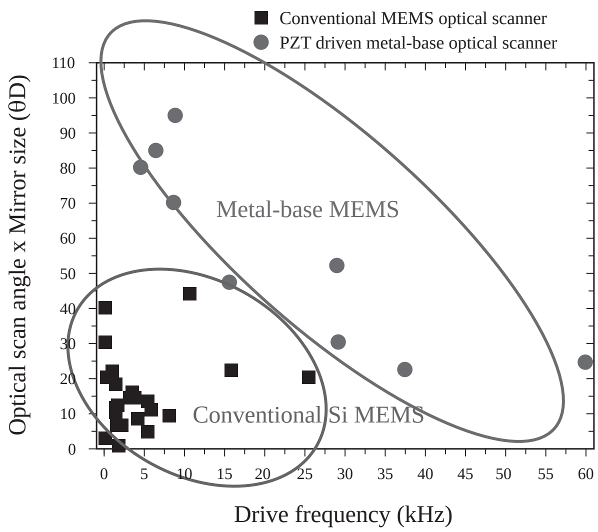

Fig. 7 Comparison of performance of metal-base optical scanner based on Lamb wave resonance principle and conventional Si-MEMS scanner.

material for the body of MEMS optical scanner shown in Figure 5. The whole scanner structure including mirror and torsion beam was formed by a punching process, and the piezoelectric film was directly formed on the structure using the AD method. As the AD piezoelectric film formed on the substrate undergoes expansion and contraction by external electric field, bending deflection is induced in the entire substrate (function as uni-morph actuator), Lamb wave is produced, mirror is excited by resonance, and laser light reflected by the mirror is scanned at high speed. Figure 7 shows the performance comparison with an optical scanner manufactured by conventional Si-MEMS when same driving voltage has been used. The horizontal axis shows the resonance frequency and the vertical axis shows the mirror size x scanning angle of light beam as standard assessment index for the deflection angle of the mirror. The resonance frequency could be designed at wide range between 100 Hz ~ 90 kHz in air, and maximum 95° was obtained as scanning angle of the light beam. Also, by using stainless steel material that was treated by ultra-precise polishing process, punch processed mirror achieved flatness of about $\lambda/4$ ~ $\lambda/8$ for 1 by 1 mm^2 mirror size, making it applicable for this optical scanner. When Si wafer is used, it is impossible to achieve mirror scanning angle at 10 kHz or more, because the torsion beam is damaged when the yield limit is surpassed and resonance frequency decreases. As shown in Figure 8, as a result of continuous motion test at maximum scanning frequency of 61 kHz and at maximum light beam scanning angle of 75° for over one year, there was no decrease of resonance frequency or deterioration of light beam scanning angle, confirming that practical durability was achieved from perspective of metal fatigue. Also, impact resistance was significantly improved by using stainless steel material, making possible its implementation in mobile devices and vehicle-mounted devices. Moreover, the stainless steel structure allowed the scanner itself to be used as a lower electrode, manufacturing process being greatly simplified compared with Si-MEMS or other optical scanners that require the fabrication of lower electrode. Since the initial cost for facility could be kept lower compared to conventional Si microfabrication facility, the cost of a device is expected to be also reduced.

These results indicate that, for realizing high-speed optical scanner with large scanning angle, both high performance and cost reduction could be achieved when conventional design philosophy based on silicon micromachining could be exceeded by maximizing the advantage of the AD method which enables direct formation of excellent quality piezoelectric films[9] on metal substrate, and by combining this advantage with conventional mechanical processing technology.

4.3 Application to multi-product variable production system

To investigate the efficiency of the AD method in the above-mentioned optical scanner manufacturing at production level and, as an attempt for application to sensor and actuator parts for custom-made medical micro-devices for which multi-product variable production is required, we developed

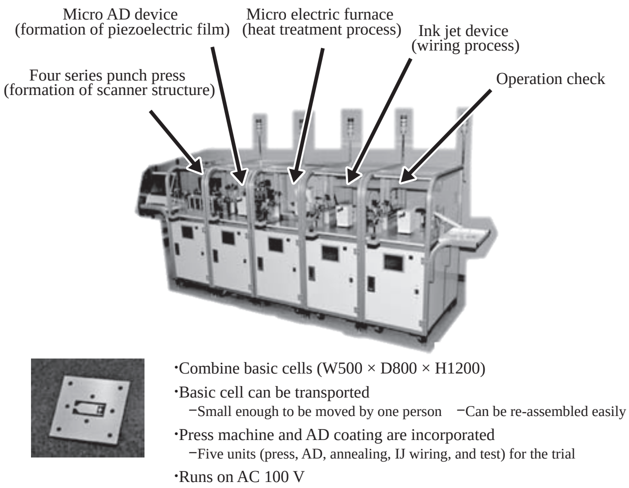

Fig. 9 On-demand MEMS manufacturing system.

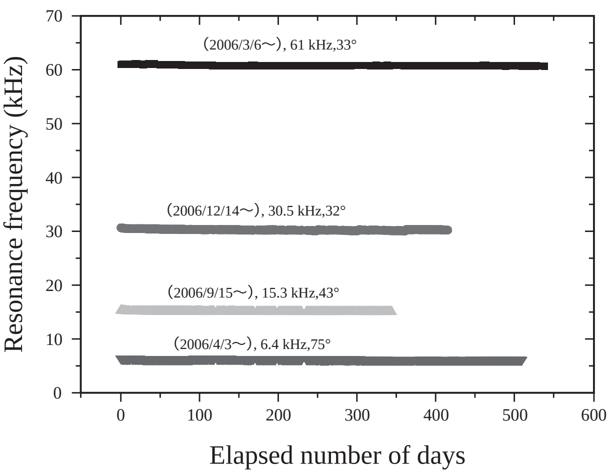

Fig. 8 Durability of metal-base optical scanner.

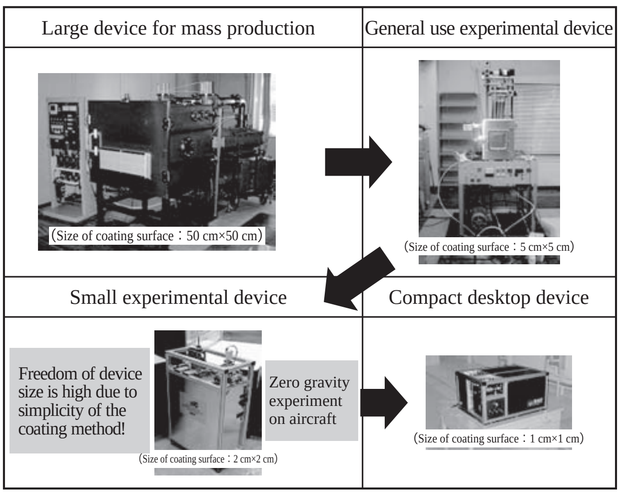

Fig. 10 AD devices in various scales.

a manufacturing system using forming and processing technologies for functional material with immediate demand which includes the AD method, laser process, and ink jet method, that allows speed and diversity of mechanical processing as shown in Figure 9. We aimed for a manufacturing process that can handle multi-product variable production masklessly even though the manufacturing process was for electronic functional devices. Below are described the results of these investigations.

Due to simplicity of its principle, the AD method holds potential of shifting the scale of device from role-to-role to desktop. Figure 10 shows some AD device prototypes at various scales. Currently, the largest size is a device with coating surface of 50 cm square, while the smallest is less than 1 cm^2 in size. A small AD device has performed successfully in trial coating in zero gravity aircraft for potential use in a space station.

For the equipment that includes AD created as prototype for manufacturing of aforementioned metal base optical scanner (Figure 9), the chamber size was optimized so as a single device would fit into 2 cm square area. In the actual production system, as shown in Figure 11, since mechanisms for automatic delivery and automatic alignment of sample must be added, the sample holder was installed in the chamber lid to enable reduction of tact time for transfer and positioning of the samples. The chamber lid with holder can be moved vertically by piston cylinder driven by compressed air. This allows the conveyor arm to set the sample, the lid to close, and vacuuming to start in less than 0.2 sec. The prototype system seem to be advantageous since high vacuum level is not required for coating using the AD method; and evacuation and vacuum leak time of the coating chamber are significantly reduced by down-scaling the coating device.

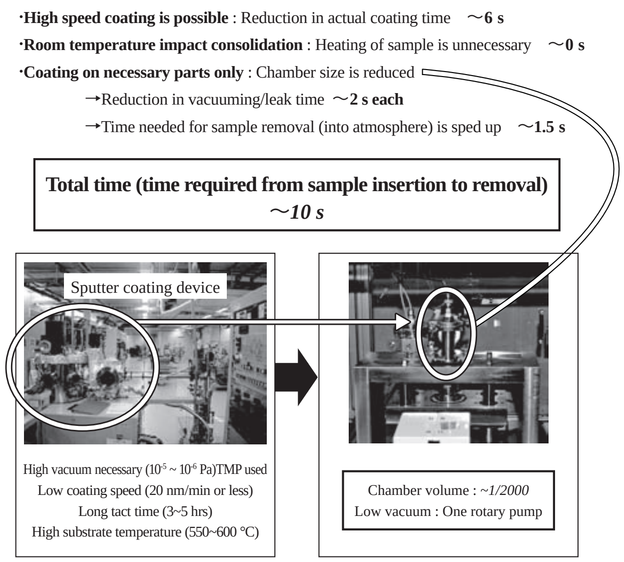

Fig. 11 Improvement of tact time by downsizing.

Since the vacuum level necessary in AD method was about 100 Pa (during coating), high-speed evacuation at low vacuum range was necessary. By designing the whole chamber volume (up to gate valve) at extremely small scale, about 75 cm^3, to match the sample size, coating became possible in about 3 sec after using a single small size rotary pump with 15~20 m^3/min throughput to achieve 2 Pa. Atmospheric pressure after AD deposition was reached in 0.7 sec from about 0.1 Pa. Coating speed depends on the performance of the aerosol chamber. Although it is not satisfactory at this point, a coating rate of around 1 μm/sec can be achieved under current conditions.

In the above design, for coating PZT thick film of 3 micrometers on 5 mm square surface area, time required for the processes of substrate insertion → evacuation → coating → vacuum leak → substrate retrieval was reduced dramatically to about 10 sec, as shown in Figure 12. This revolutionizes the conventional understanding that vacuum process must be done as a batch process, and is a major point in achieving on-demand production.

In the punching process for forming the scanner body structure, 4 progressive divisions were set for mirror, torsion beam, entire scanner frame formation, and positioning holes. 4 micro-press mechanisms punched out the stainless steel

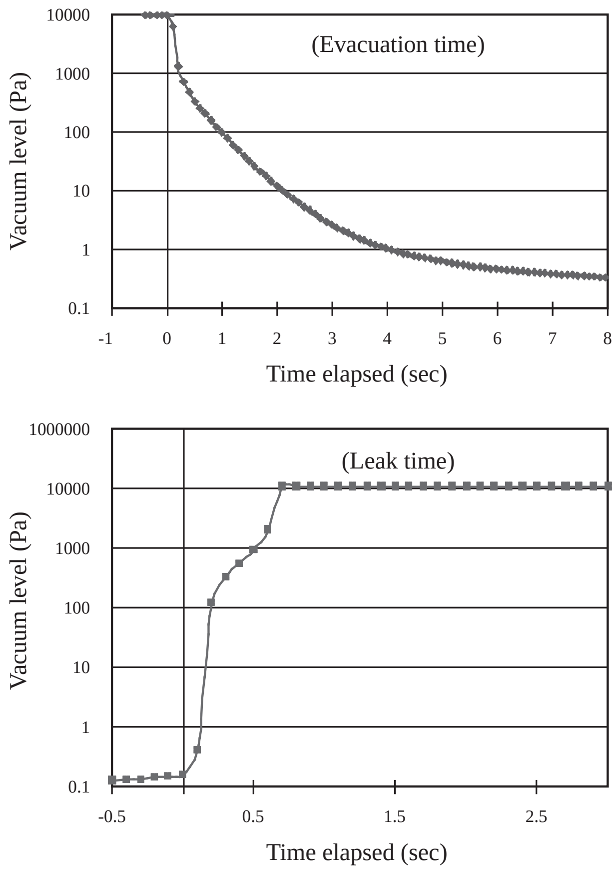

Fig. 12 Speed required to reach vacuum level where coating is possible, and leak time in a small AD device.

hoop material. This construction allowed exchanging the molding parts and selection of several kinds of combinations for manufacturing of scanners with different resonance frequency and different mirror size for relatively low cost production. Prototypes for process unit for small heating processing device and ink jet device for wiring were also created, and we were able to construct a system that enabled manufacturing from material to device. Currently, several revisions and improvements are necessary before the unit can be used for practical manufacturing, but we believe there is an advantage in simultaneous optimization and evolution of manufacturing facility development and device design.

The metal based optical scanner discussed in the previous section was optimally designed and created by trial-and-error using the prototype production system and computer simulation. As a result, production speed of 1 device/min per line has been achieved. This means that a production level of about 20 ~ 30,000 units per month can be easily obtained. By replacing the conventional Si microfabrication facility manufacturing process with the one described above, great reduction of energy consumption, facility surface area and manufacturing time has been confirmed and the reduction in environment load became possible, as shown in Table 1.

5 Summary and future prospect

Maximizing the characteristics of the AD method, we investigated the construction of on-demand manufacturing technology with low environmental load that realizes both high product performance and cost reduction. The AD method is making possible coating at room temperature, has a high coating speed, and allows localized coating of functional materials without the need for etching to achieve the desired pattern. In the investigation of manufacturing of electrostatic chuck and optical scanner, simplification of device structure and manufacturing process, improvement of process tact time, and simplification of process device worked effectively. By reviewing the device design from material level, improved function, cost reduction, and decreased environment load were realized in the manufacturing process. Moreover, increase in as mass production device was obtained, and simultaneous optimization of manufacturing facility development and device design can be achieved. This is an example of the vision of "minimal manufacturing" with least input (resource and energy consumption) yet with high practicality (high productivity, low cost) and maximum function (new function, high performance). Of course, MEMS device used as example here cannot be effectively optimized by introduction of the AD method alone, but large-scale optimization (minimization) is possible for wider use if there are further advances in currently known elemental processes.

In the future, we will continue the investigation of the effect of introducing new processes, while reconsidering the manufacturing process from the material to device levels.

Table 1. Comparison of MEMS manufacturing systems.

	Silicon lithography MEMS factory	On-demand factory
Floor area	300 m^2 (1000 m^2 including ancillary facilities)	10 m^2 (*1/30〜1/100*)
Electrical power (kWh/year)	360000	8000 (*1/45*)
Manufacturing time	About 12 min/piece (process time/number per wafer) About 1.2 min/piece (10 per batch)	Designed target value 1 min/1 piece (*1/10〜1/1*)
Environmental load	Disposed material such as resist Process gas Cleaning process	Hardly necessary **(big reduction!)**

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Received original manuscript January 29, 2008
Revisions received March 14, 2008
Accepted March 14, 2008

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Joined Mechanical Engineering Laboratory, Agency of Industrial Science and Technology in 1989, and has worked on development of micromachine technology using ion injection technology and others. Investigated useful function of material surface. After working at NEDO (New Energy and Industrial Technology Development Organization) in 2001, has been involved in aerosol deposition method, and worked on microgravity experiment and developed on-demand manufacturing technology. Doctor of Engineering from The University of Electro-Communications in 2003. In this paper, worked mainly on development of device for on-demand manufacturing system including small AD device.

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Joined AIST in 2004. Works on practical application research for ultra high-speed micro MEMS scanner and development of on-demand MEMS small-scale manufacturing device for this optical device, by conducting R&D for transparent nano-composite for magneto- electro-optics using AD method for the development of new optical material and for its application to optical device. Completed electronic information engineering course at Graduate School, Toyohashi University of Technology in 2003. For this paper, worked mainly on development of metal base optical scanner.

So Baba
Joined AIST in 2003, after working as researcher of pre-venture business, Japan Science and Technology Corporation. Has worked on development of laser aided aerosol deposition method to create high performance piezoelectric film actuator on metal substrate, which was very difficult to achieve, in NEDO project. Currently working on development of on-demand manufacturing and process enhancement technology using aerosol deposition method. Completed doctorate in material application engineering, Graduate School of Engineering, Osaka University in 2001. For this paper, worked mainly on development of heat processing (laser aided AD method) for on-demand manufacturing system.

Kiwamu Ashida
After receiving doctorate from Graduate School, Chiba University in 1998, joined the Mechanical Engineering Laboratory, Agency of Industrial Science and Technology, Ministry of International Trade and Industry. Based on concept of “micro factory” where “small things are made with small machines,” works on developing prototypes of “small processing machines” such as portable factory. Also works on micro nano-scale machine processing technology for “small machine processing.” In this paper, designed system architecture and delivery device, where production line can be freely constructed and reconstructed by joining small unit cells, in the on-demand manufacturing system. Also worked on micro-press processing cell that was the initial process.

Discussion with Reviewers

1 Overall composition

Question (Kazuo Igarashi)

This paper describes how the AD method and its application will lead to innovation in manufacturing, and it is appropriate for the objective of this journal. However, the subtitle and the content do not necessarily match, and this hinders understanding. I think by selecting an appropriate subtitle, the relationship to low cost and energy conservation manufacturing stated in the title will become clearer.

Answer (Jun Akedo)

It is exactly as you indicated. I revised the subtitle according to your indications.

2 Problems in introduction and practical application of AD method

Question (Kazuo Igarashi)

In the manufacturing of electrostatic chuck, it is stated that by using the AD method, 80% reduction in energy consumption and 1/10 of manufacturing time was achieved, but how is this technological innovation actually used in actual manufacturing line? If it is being employed somewhere, I think you should mention this. If it is not being employed, what are the factors that prevent that from happening?

Answer (Jun Akedo)

As mentioned in the text, major commercialization is about to be started in the plasma corrosion resistance coating material (announced in The Chemical Daily, April 13).

Reduction in process energy consumption and shortening of process time cannot be assessed easily because they are dependent on production volume and number of AD devices installed. Here, we give estimates based on initial facility cost and production volume projected by the company. For energy conservation, it is extremely complicated since other factors such as product yield are involved, so practical use will depend on the final product cost.

Also, for introduction and deployment of new manufacturing process without previous record like our AD method, substantial time must be taken on sample production to confirm reliability, even if it is satisfactory in terms of performance and cost. Therefore, it took time before practical application. The optical scanner discussed here took about a year and a half for durability tests.

3 Relationship to minimal manufacturing concept

Question (Kazuo Igarashi)

In “Summary and future prospect,” you refer to “totally optimized (minimal)” and “drastic optimization (minimization),” but I feel that the meaning of “minimal” cannot be understood well. If this is referring to minimal manufacturing, I think you should add a note to clarify.

Answer (Jun Akedo)

As you indicate, this research aims for minimization. Therefore I added the sentence: “This is an example of vision of “minimal manufacturing” with least input (resource and energy consumption) yet with high practicality (high productivity, low cost) and maximum function (new function, high performance).”