# Development of laser-assisted inkjet printing technology

## — Wiring technology to achieve high throughput and fine patterning simultaneously —

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A new technology that can be easily adapted to various circuit designs and production in small lots has been requested in electronic device manufacturing where low cost device fabrication on large area is required. We have developed a laser-assisted inkjet printing technology which can achieve high throughput and fine patterning simultaneously. To realize fine patterning with low resistivity, ejected ink-droplets have been dried by laser irradiation to suppress expansion on a substrate, a problem often observed in a conventional inkjet process. Drawing of fine wiring with aspect ratio of 1 or above with line width of 10 μm or less has been achieved using this new approach. In this paper, the achievements of laser assisted inkjet printing technology is shown based on the needs that triggered this research and the solutions used to overcome the problems met during the R&D process.

*Keywords* : Ink-jet printing, throughput, fine pattern, wiring technology, low cost

## 1 Background

As the industrial structure becomes globalized, the electronic technology has become one of the major fields that support the Japanese economy and industry. Several new electronic devices are developed and produced with the advancement of technology. With this background, the price competition is becoming even fiercer, as there are differences in the values for quality and performance in Japan and abroad. Technological innovations are needed to ensure the competitiveness of the Japanese makers in the years to come I nthe world market.

As seen in the built-to-order (BTO) (system where the products are manufactured after receiving the order from the customer), customizations and differentiation of the electronic devices are done according to demand, and various tailor-made electronic devices and products are manufactured to meet the demands of the users throughout the world. As a result, an innovative manufacturing technology that enables high-diversity low-volume or high-diversity variable-volume production as well as shortened product cycle is becoming important. At the sites of development and production, efforts are spent on the diversification of functions, downsizing, further cost reduction, and high throughput by integrating the electronic devices with various functions. At the same time, small-lot production and short delivery time are achieved by the horizontal division of labor of the manufacturing process[1].

On the other hand, from the perspective of sustainability of industry, there is a high demand for technologies that are using minimum resources, minimum energy consumption and low environmental impact for the “manufacturing process” in the 21st century. The National Institute of Advanced Industrial Science and Technology (AIST) propose the concept of “minimal manufacturing”, which is a concept for a production process that simultaneously solves the three elements that often contradict each other: “energy and resource saving”, “high performance/new function”, and “high productivity, low cost”. By achieving minimal manufacturing, AIST aims to contribute to the sustainable development of Japanese manufacturing through environmental harmony and international competition.

The situation is no different in the field of electronics mounting. In the wiring technology that is the core of electronics product manufacturing, there is rising demand for high diversity and customization of the mounting of electronic circuitry and parts. Since photolithography technology used in silicon micromachining is a relatively high cost process, it is difficult to achieve high diversity using this technology. In the wiring for displays with large surface areas such as the flat panel display (FPD), achieving larger surface area is difficult because there are issues in the alignment of mask due to the fine-sizing, increased surface area, and multiple layering of the mask. Moreover, the photolithography process is a multistep process that involves among other steps the formation of the conducting metal film ,deposition and removal of the photoresist material, removal of the excess conducting metal, and washing. Large volume of waste liquid containing precious metals and harmful substances is produced, and energy and resource savings in these processes are necessary[1].

The inkjet printing technology that we are developing can form the desired conductive film only on the areas needed avoiding in this way the production of waste. With its on-demand and energy saving characteristics, it is a technology at the core of “minimum manufacturing” proposed by

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AIST. Since the waste liquid produced in the manufacturing process makes a heavy load on the environment, there are high expectations for the wire mounting process through the inkjet printing technology to achieve reduction of fabrication costs and reduce the production of waste[2][3].

But, before implementing the inkjet printing technology to wiring, there are problems that had to be solved, such as the high resistance of the conductor in the ink and the decreased throughput as the wiring became finer. In this paper, we report our research and progress toward the realization of a practical inkjet wiring under the minimal manufacturing concept.

## 2 Situation of the manufacturing technology for high-diversity production and the selection of technology to be developed

### *2.1 Integration of the IC chip in multiple function devices and the flow of technological development*

To achieve downsizing, high function and low power consumption of the IC chip, the "system on a chip (SoC)"concept where various functions are integrated on a single chip was actively developed.

In the SoC, to integrate the functions on a single chip, the new process technology "system in package (SiP)" is used to realize the multiple functions. Here, the IC chips are inserted in a single package, or the module is created by combining the developed IC chips with the package. Currently, further downsizing and multiple functions are attained for the electronic products, and 3D integration is done by IC stacking where the IC chips are stacked inside the IC package to reduce the mounting surface area (Fig. 1). The 3D mounting technology for connecting the stacked IC chips is the key technology.

Until now, electric connection by flip chip mounting was done for the 3D mounting of the IC chips. Specifically, the solder ball and soldered pad are set on the input-output terminal of the IC chip, and the solder is melted by heating in a furnace to connect the electrode terminal (ball grid array). Another way to connect the electric terminals is by heating and supercharging the space between the IC chips.

However, as the IC chips are stacked, the bump became smaller and several problems became apparent, such as the difficulty of checking the connection fault, increased cost of bump installation, difficult installation of the fine Si through-via needed for interlayer connection, and the need for ultra-thin processing of Si substrate to keep the IC stack thin.

On the other hand, there are methods where the electric connection between the IC chip and the interposer or lead frame is done by wire bonding, (or) where the input-output terminal is brought to the surface by creating a step on the IC chip. However, there are several issues in wiring that are very difficult to solve. One such example is that is difficult to realize a densifications in the wire connection lines to the IC chip so that there is a limit in high-speed transmission due to increased inductance in the wires[4].

The developments of the 3D mounting technology that allows electric connection over the steps between the chips and the wires on the lateral side of the stacked IC chips are immediate concerns.

### *2.2 Characteristics of process technologies and the technological issues of the inkjet printing*

With the recent integration, the design rule inside the IC chip was reduced from about 100 μm to submicron level, and the fine-sizing of wiring in the 3D mounting technology has become important. At the same time, high performance, energy and resource savings, increased production efficiency, and decreased cost are in demand for the wiring technology.

Figure 2 is a comparison of the wiring technologies that are put to practice or are expected to be put to practice, including the photolithography process technologies, micro contact printing (μCP) nano-imprinting, and screen printing, and the mask-less technologies, such as microchip integrated processing technology (MIPTEC) and inkjet printing.

In the photolithography process, the photosensitive organic substance is exposed in patterns to create a resist film, and the metal film formed on the substrate is etched to fabricate the desired pattern. The fine patterning depends on the diffraction limit of the mask that depends on the wavelength of light used for exposure, and this must be considered to

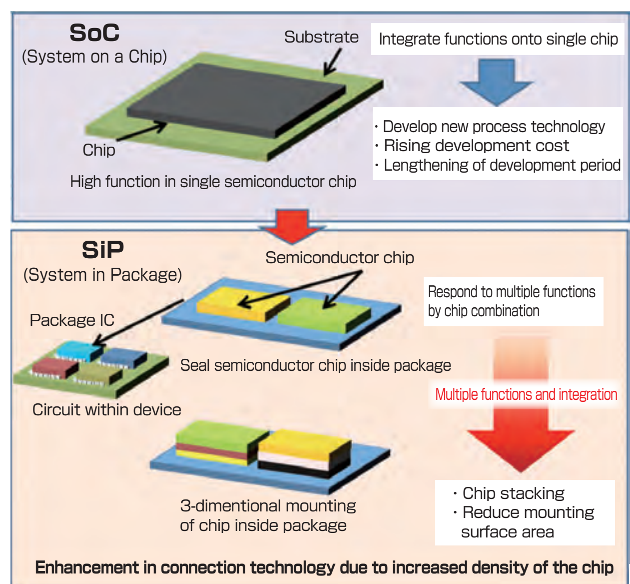


**Fig. 1 Flow of high-density integration of IC chips to achieve multiple functions**

the wide-ranging design rule from semiconductor chips to printed circuit boards (PCB). In μCP nano-imprinting, fine structures can be fabricated easily by transferring the mold plate to the resin substrate, and new developments are possible. In screen printing, the desired wiring pattern can be created by printing the conductive paste onto the PCB substrate using a screen. Screen printing is used as surface mounting technology[2]. Since these process technologies use masks or molds, the 3D mounting on uneven substrate is extremely difficult.

On the other hand, in the maskless process MIPTEC, the pattern can be changed easily simply by rewriting the program. Since the metal film wires formed by electroless plating are transferred by ablation with YAG or YVO4 laser to create three dimensional patterns, it is expected that this 3D mounting technology will allow high-diversity production necessary in creating structures such as 3D connectors. Another maskless process, the inkjet printing technology that is being developed in the organic electronics technology field[5] is using ink, in which the conducting nanosize metal particles are dispersed, to form the desired pattern by applying the necessary amounts in the pattern areas. The inkjet printing allows formation of patterns on uneven substrates. Moreover, recently, it has become possible with this technology to form wirings stably at about 50 μm in width and this make this process suitable for the application to 3D mounting technology.

A comparison of the characteristics of the process technology and the technological elements are shown in Fig. 3. The photolithography technology, which is the most practical process technology at this point, was developed heavily due to the important advantages offered by of fine-sizing, high throughput, and high yield. The mounting technologies were developed utilizing the characteristics of μCP nano-imprinting technology for its fine-sizing capability, the screen printing for its high throughput, and MIPTEC for its high-diversity capability and the superiority of maskless process.

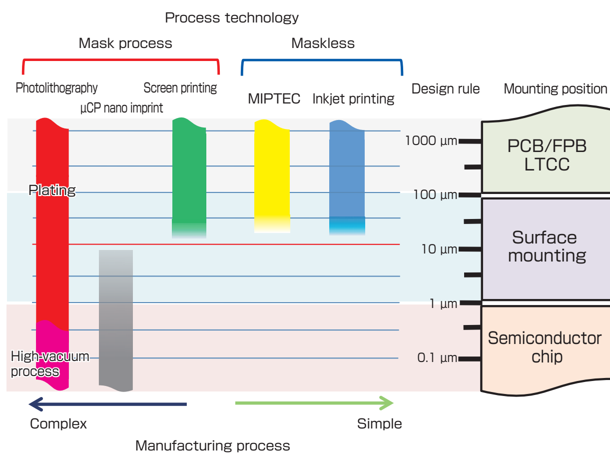


**Fig. 2 Wire width corresponding to mounting position and wiring technology**

In the same time, inkjet printing has other important advantages such as high-diversity, low cost, and energy and resource savings that are unseen in other process technologies, and it shows the potential to become the core of minimal manufacturing. However, there are technological issues that must be overcome, such as the low throughput needed to realize high productivity and low yield.

## 3 Technological issues and the selection of methods to solve them

### *3.1 Wet-spreading of ink that causes decreased wire formation speed*

In the inkjet printing technology for wire formation, the wires are formed by connecting the dots, and the process factors are different from the home-use inkjet technology in which the dots are placed at even intervals. Specifically, the state-of-dot connection changes and the form of wiring pattern is greatly affected by factors such as the wire forming speed and ejecting frequency, ink viscosity and surface tension, and wet-spreading of ink onto the substrate.

In the conventional inkjet printing technology, the ink that lands on the substrate spread in the planar direction, the width of the wire spread further than the diameter of the droplet even with controlled surface tension, ink viscosity, or the wetness of the substrate. For example, under the conditions of stage speed 100 mm/s and ejecting frequency of 30 kHz, when the droplet with a diameter of 15 μm lands onto a substrate at contact angle of about 60°, the wire width will expand to about 50 μm or several times larger than the droplet diameter[6]. To achieve fine wiring of about 10~20 μm of width, it is necessary to reduce the droplet size to 10 μm or less.

This means that when the wire resistance is kept constant, or when the ink supply per unit length of wire is kept constant yet maintaining the throughput, the ejecting frequency depends by factor of 3 on the reduced droplet diameter.

| | Functionality | | Productivity | | Production cost | | Environmental friendliness | |
|---|---|---|---|---|---|---|---|---|
| | Fine-sizing | High diversity | High throughput | Large surface area | Manufacturing cost | Reduced manufacturing procedure | Energy and resource savings | High yield |
| Photolithography technology | ◎ | × | ◎ | △ | × | × | × | ◎ |
| μCP nano-imprinting | ○ | △ | △ | × | △ | △ | △ | △ |
| Screen printing | △ | △ | ◎ | △ | ○ | ○ | ○ | ○ |
| MIPTEC | △ | ○ | ○ | ○ | △ | △ | △ | ○ |
| Inkjet printing | △ | ◎ | × | ◎ | ◎ | ○ | ◎ | × |

**Fig. 3 Wiring technology and characteristics of the technological elements**

However, as the ejecting frequency of the inkjet head is increased, the meniscus (boundary between the ink and air) formed at the nozzle orifice vibrates during discharge making the continous discharge very unstable. Moreover, problems such as unstable discharge at various vibration modes occur due to the pressurization and decompression of the ink in the injector of the inkjet head. Therefore, it is necessary to simultaneously optimize the various parameters such as the droplet diameter, orifice diameter, volume change of the actuator, and physical properties of the ink (surface tension, viscosity, etc.). In the current inkjet technology, it is extremely difficult to significantly increase the ejecting frequency to several ten kHz without altering the pattern formation[7].

In the conventional inkjet wiring technology, the fine-sizing of the wires and the throughput have a trade-off relationship, and, to overcome this, a breakthrough in the technology to control the wet-spread after the droplet lands on the substrate was needed.

### 3.2 Conventional methods for controlling the wet-spread

Our research was also focused to control the wet-spreading of ink that lands on the substrate, which is an essential issue of inkjet printing technology. Summarized below are the methods for controlling the wet-spreading of ink in the R&Ds so far, and why the throughput cannot be further improved by further optimizations of these methods(Fig. 4).

1) Reduction of resistivity by improvements of ink
Before considering the methods to control the wet-spreading of ink, it may be possible to decrease the wire resistance by replacing the ink material with one with lower resistivity. However, it is clear that the ink resistivity cannot be lowered below the resistivity of the metals contained in the ink. Specifically, the resistivity of the currently commercially-available nanoparticle silver ink is $2-5 \times 10^{-6}$ Ω·cm, which is higher than the $1.6 \times 10^{-6}$ Ω·cm of silver metal. The room for reducing resistivity by improvements in ink material is relatively small. Therefore, we did not set the reduction of wire resistance through ink improvement as our development approach.

2) Use of ink with high viscosity; decreased diameter of droplets
When high viscosity ink is used, as mentioned before, there are reductions of the ejecting frequency or decreased throughput, because of the meniscus issue and the vibration mode that inhibits the stable discharge. There is also the problem of nozzle getting clogged easily. By reducing the nozzle diameter in order to reduce the droplet size decreased throughput cannot be avoided and the possibility of nozzle clogging increases.

3) Substrate surface treatment to control the wet-spreading after landing
Although the method of substrate surface treatment may possibly control the wet-spreading of ink while reducing the width of wire, the surface treatment agent may reduce the adhesiveness of the ink and wire. For example, when the wire is formed using the aqueous-solvent conducting ink on a flexible substrate such as water-repellent polyimide, the adhesiveness may be greately affected by the surface treatment[8]. To avoid this and to increase the adhesiveness of ink, patterning is done on the hydrophilic and hydrophobic surfaces using a mask, and then applying the ink only to the hydrophilic surface[9]. However, this causes an increase in the manufacturing process steps and the total improvement of throughput cannot be achieved.

4) Increased drying speed of ink by heating the substrate
When the substrate is heated, there are serious problems such as the nozzle drying due to the heat radiation from the substrate which causes clogging, and cracks and gaps are formed in the wire as bumping occurs when the ink lands on the substrate. Therefore, this method has no good practical applications.

The fine-sizing of the wire width by controlling the wet-spreading of ink and the achievement of high throughput of the wiring process were at a trade-off relationship. This was a technological issue that could not be overcome with conventional technology.

### 3.3 Ink drying method using the laser energy

To realize both the fine-sizing of the wire width and high throughput that were in trade-off relationship, we developed a process technology from a totally new approach. As the method to control the wet-spreading of ink, we did not select the methods that were extensions of conventional solutions such as the use of high viscosity ink, small nozzle bore, or substrate surface treatment, but we selected the method of providing energy assistance to the discharged droplet to

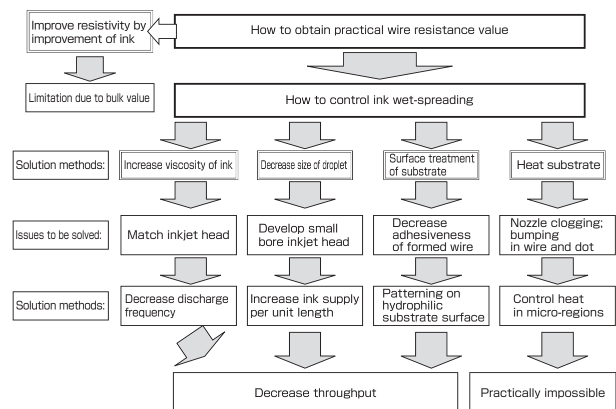


**Fig. 4 Conventional methods to control the ink wet-spreading and the effect finally obtained**

increase the drying speed.

As a method of injecting the energy directly into the discharged droplet without drying the nozzle or causing bumping, we devised a simple method in which drying is promoted by focusing the laser to the droplet and controlling the wet-spreading of ink (laser-assisted inkjet technology).

The laser-assisted inkjet technology is a method where the ink solvent is evaporated and dried instantly by heat energy, as the focused laser beam is irradiated onto the droplet and the substrate at the same time the droplet discharged from the inkjet head lands on the glass substrate.

Through the local assistance by laser energy, it was possible to reduce the nozzle clogging and damage to the substrate and to control of wet-spreading of ink through drying and higher viscosity.

In this research, the droplet of about 25 μm ~ 50 μm diameter was discharged from the single head, and the area around the discharged droplet was irradiated using the carbon gas laser with wavelength of 10.6 μm at continuous wave (CW) mode to form the wires.

### *3.4 Objective of the technological development and its aim*

In the wire forming technology using the inkjet, to reduce the wire resistance, it is necessary to control the wet-spreading and increase the wire thickness, or in other words, to improve the aspect ratio of the wire. Therefore, to solve both the high throughput and wire resistance reduction, we wanted to establish a process technology that enables formation of wire with high aspect ratio without recoating (Fig. 6).

In the wire forming technology using the inkjet, the setting of the diameter of the discharged droplet is important. In the conventional inkjet technology, when the generally used droplet of 20 μm is used for wire forming, the ink spreads out, and the width of the formed wire would be about 30~50 μm even with substrate surface treatment[2]. Since recoating is necessary to reduce the wire resistance, the total time required to complete the patterning process is relatively high not only because of repeating coting process but also because of the waiting time necessary for the ink to dry before the next layer can be applied.

If wire formation is done at droplet diameter of 10 μm or less[10], the contribution of the surface area per unit volume increases according to the decreased size of the droplet[9], and the evaporation speed increases non-linearly during the flight of the droplet discharged from the inkjet head, making possible the control of the wet-spreading of the landed ink on the substrate surface and the wire formation of several μm or less width can be realized. But, because of the thin thickness of the wire, recoating must be performed several times to reduce the wire resistance, and this decreased the throughput.

To overcome the limitation of the conventional technology, the objective of laser-assisted inkjet technology was set to maintain the high throughput while realizing the wire width of 10 μm or less that was considered impossible with conventional technology.

The technological issue set was to reduce the wire width to smaller than the discharged droplet size by promoting drying with energy assistance, for droplets of about 25 μm ~ 50 μm in diameter. If the droplet size can be increased, the current inkjet head can be used, long-term stability and reliability can be obtained, the effect of airflow is reduced since the kinetic energy of the droplet increases, and the precision of the flying droplet landing on the substrate is increased. Moreover, by improving the landing precision, it would

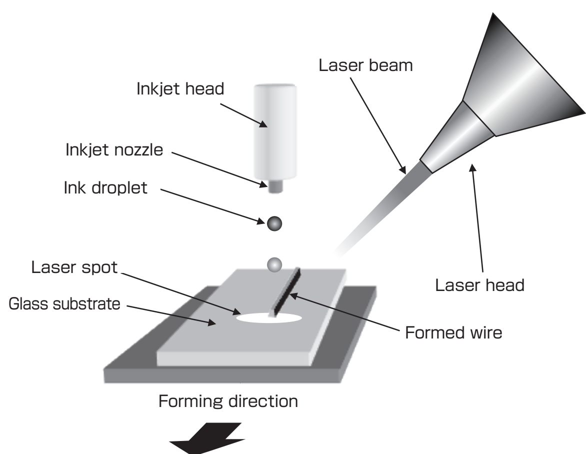


**Fig. 5 Wire formation method by laser-assisted inkjet technology**

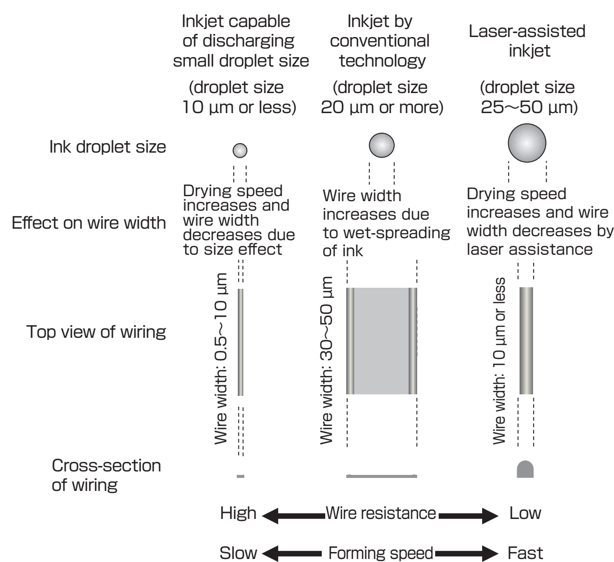


**Fig. 6 Droplet size and wiring pattern targeted in the laser-assisted inkjet**

become possible to widen the distance between the substrate and nozzle, and this will enable formation on materials with large step structures.

The technological issues of the conventional industrial inkjet technology were organized and the essential issues were extracted, to set the direction, technological issues, and objectives to be achieved for the laser-assisted inkjet technology.

## 4 Effect of the laser-assisted inkjet technology

### 4.1 Achievement of high aspect ratio of wire by laser assistance

Figure 7 shows the results of the formation on non-surface treated glass plate to study the effect of laser assistance on the wire width, to form fine wire with high aspect ratio.

When the formation was conducted under conditions of droplet diameter size of 25 μm, ejecting frequency of 3 kHz, and stage speed of 60 cm/min, the wires formed by the laser-assisted inkjet technology have a width of 10μm and a thickness of 11 μm. Compared to the wire forming without laser assistance, the wire width decreased from 230 μm to10 μm, or 1/20 time less, and the wire thickness increased from 0.8 μm to 10 μm, or about 12.5 times more. An extremely large improvement was observed.

Figure 8 shows the 3D configuration obtained by laser microscope. The wire formed by laser assistance was very different from the wire formed by conventional inkjet printing. The uneven wire formations such as the coffee stain phenomenon where the grooves are formed on both sides of the wire[9][11] and the bulge phenomenon where the wire width bulges out in some places[12] were not seen, and the wire had an even, smooth surface with a “semi-cylinder structure”.

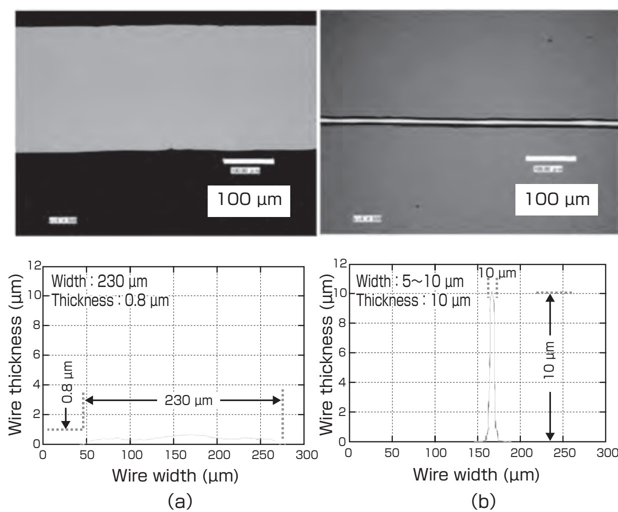


**Fig. 7 Effect of laser assistance on wire width**
(a) Without laser assistance (b) With laser assistance

It was possible by this approach to form a wire with high aspect ratio of 1 that is much higher than in che case of using the conventional inkjet method. Moreover, a wire with width smaller than the droplet diameter could be formed on untreated substrate surface using our approach.

In the conventional technology, even if the substrate surface treatment was done, wire thickness of about 290 nm[6] was the limit for one coating for a wire with width of 10 μm formed on the substrate with contact angle of 90°. Therefore, assuming the resistivity of the conductor at 2.0 μΩ·cm, the resistance per 1 cm of formed wire would be about 70 Ω/cm for wire formed with conventional technology with surface treatment. But the actual resistance value was about 6 Ω/cm for a wire obtained onto an untreated surface using laser assistance. The improvement observed in the wire resistance is over 10 times that of the conventional approach when laser assistance is used.

To get the same wire resistance by concentional inkjet methods, 13 or more recoatings are necessary. The potential for dramatic improvement of throughput by using laser assistance can be easely deduced from this comparison.

Moreover, since high precision in positioning and landing were required for recoating, laser-assisted method may solve these issues also.

### 4.2 Electric property of the wire

To develop the laser-assisted inkjet technology as the surface mounting technology specifically for the wires on the IC chip, we investigated the properties for the high frequency transmission line of the formed wire. The high frequency transmission property of the wire is affected greatly by the cross-sectional form and the precision of pattern. Therefore, the pattern of the coplanar transmission line, where the central conductor and ground conductor are arranged on the

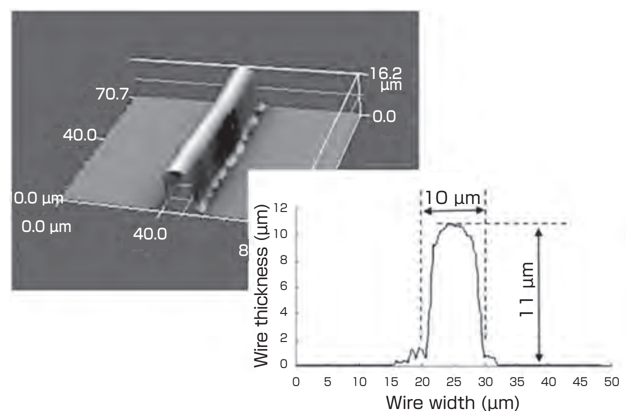


**Fig. 8 3D configuration and cross-section of the wire formed by laser-assisted inkjet technology**

same plane, was formed using only the laser-assisted inkjet technology and the high frequency transmission property was measured.

When the transmission line and the package were considered by the parameter measurement of the transmission property (S21) and the reflection property (S11) in the high frequency region using the Thru-Reflect-Line (TRL) calibration method by the network analyzer, it was possible to accurately observe which frequency could be used.

Figure 9 shows the results of the experiment and the simulation of high frequency transmission property to 1 GHz ~ 40 GHz, for the rectangular wire with resistivity of 3 x $10^{-6}$ Ω·cm, length of 4 mm, and width of 30 μm. In the conventional inkjet wire formation, the high frequency transmission of the wire was difficult because the wires had dot configuration. However, in the wire formation by the laser-assisted inkjet technology, the theoretical calculation values and the actual values matched well, and the wire capable of high frequency transmission is easy to be realized.

From the results of S11, slight discrepancies between the transmission gain of the calculated and experimental values was seen as the frequency increased. This is thought to be because the disorder on the wiring side of the coplanar transmission line pattern fabricated by the laser-assisted inkjet technology that may be affecting the impedance matching of the electromagnetic field. On the other hand, from the results of S21, good transmission property was obtained in the wire formation by the laser-assisted inkjet technology, since it was possible to transmit signals up to 40 GHz, and the attenuation was small up to about 10 GHz.

From the above results, the possibility of high-speed transmission, which was considered difficult by inter-chip connection and wire bonding in the 3D mounting, was shown to be possible for the high frequency region at about 10 GHz using the laser-assisted inkjet technology.

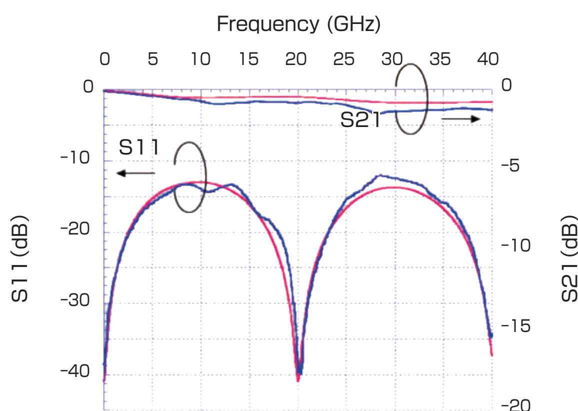


**Fig. 9 High frequency transmission property of the formed wire**
(<40 GHz; blue - actual value; pink - theoretical calculation value))

### *4.3 Overcoming the step structures*

To check the possibility of formation to uneven surface and the control of the wet-spreading of ink on the rough-surface substrate with the laser-assisted inkjet technology, the wires were formed on a glass substrate ground in concave form with depth of about 200 μm. Figure 10 shows the electron microscope image of the wire pattern formed on the stepped, rough-surface substrate. When laser assistance was not used and the substrate surface was very rough, the formed pattern was spread out significantly due to the capillary force in the in-plane direction of the unevenness on the substrate surface. Conduction was not obtained when the wire resistance was measured on both ends of the grinding groove.

On the other hand, with laser assistance, there was no effect of the rough substrate surface, wire was formed having the same width in the stepped area, and conduction was obtained when the wire resistance was measured on both ends of the grinding groove. From these results, it was shown that the laser-assisted inkjet technology could be applied to the wire between the substrates with different wetness or lateral connection without using bump or fine through-via for the connection between IC chips.

### *4.4 Improvement of adhesiveness of the wire by rough-surface substrate*

The wire was formed by the laser-assisted inkjet technology on the mirror-surface and rough-surface substrates, and the adhesiveness of the wire was checked by the peeling test using cellophane tape, as indicated by the peeling test for plating (JISH8504). Figure 11 shows the results of the tape peeling test on the mirror-surface and rough-surface substrates.

As a result, the wire on the mirror-surface substrate adhered to the tape, and the entire wiring peeled off the substrate. On the other hand, the wire on the rough-surface substrate did not peel off with the adhesiveness of the cellophane tape. From this result, it was indicated that the adhesiveness with the substrate could be increased if roughening treatment is applied to the substrate surface, due to the physical anchoring effect.

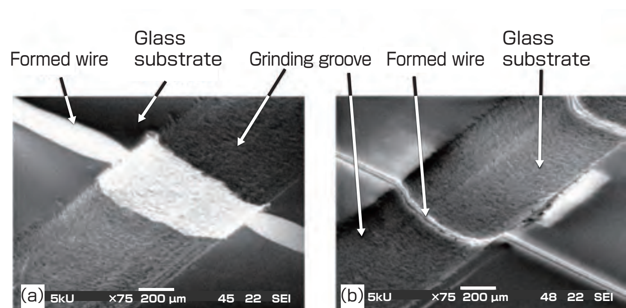


**Fig. 10 Wiring on stepped structure and rough-surface substrate**
(a) Without laser assistance (b) With laser assistance

However, the method for quantitatively measuring the adhesiveness of fine wiring with thickness and width of tens of μm has not been established, and new development is necessary to evaluate the adhesive strength of the wires.

## 5 Technological potential of the laser-assisted inkjet and its future prospect

In this paper, the possible solution to the problems that were considered difficult with conventional inkjet printing technology was indicated by using the laser-assisted inkjet technology in the wiring process for the diverse-type variable-volume production of electronic devices.

By setting and solving the technological issue of controlling the wet-spreading of ink, it was shown that the improvement of inkjet printing technology throughput and low wire resistance were possible. By controlling the wet-spreading of ink using the laser-assisted inkjet technology, the possibility of handling high frequency transmission needed for 3D mounting, wire formation on nonplanar substrate, and wire formation onto flexible substrate becomes a reality.

The positioning and possibility of the laser-assisted inkjet as a mounting technology are as follows:

(1) Achieving high frequency for the IC chip: fabrication of high frequency transmission line and good high frequency property at 1 GHz ~ 40 GHz

Possibility of high frequency transmission without shortening the distance of wiring between elements

(2) 3D wiring technology: capable of wiring onto uneven, stepped, and rough-surface substrate

Simplification of electric connection as well as flip chip mounting

(3) Durability of wiring: improved adhesiveness of the wiring

Applicability to the wiring of device that must be environment-resistant

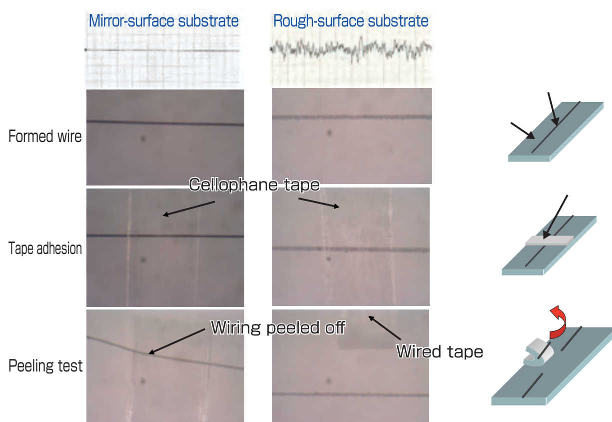


**Fig. 11 Tape peeling test for wires on mirror-surface and rough-surface substrates**

It is necessary to solve several other technological issues to establish this technology as a practical 3D mounting technology based on these results. It is also important to clarify the basic mechanism of the laser-assisted inkjet method and the phenomenon of gaining high aspect for the wire.

This means it is necessary to conduct a dual development into *Type 1 Basic Research* and *Product Realization Research*, using the *Type 2 Basic Research* as the entrance.

The principles of the mechanism by which wire with width less than the droplet diameter can be formed and the phenomenon by which high aspect ratio is obtained are not clarified, and to further improve the performance, the basic research to clarify the phenomena or *Type 1 Basic Research* is necessary.

On the other hand, to greatly minimize the time needed for practical application, the technological development for multiple functions and increased yield should be the central issue of the increased production efficiency, which is an area that is not a stronghold of the inkjet printing, and can be positioned as the *Product Realization Research*.

As the technological issue to improve the production efficiency, the advancement of multiple nozzle and post-annealing process technology are necessary. As technological issues of multiple functions, the development of functional ink, understanding of applicability of various substrate materials, and control of forming conditions are needed.

The technological development issues from *Type 1 Basic Research* to *Product Realization Research* become varied with the progress of R&D. Of course, there are limits in terms of human and monetary resources to engage in practical technology for a single research institute like AIST. It is mandatory to effectively appeal the technological concept of the results from the *Type 2 Basic Research*, and to continue the industry-academia-government collaboration to integrate the researchers and engineers of various fields.

Through such development of R&D, we wish to take the laser-assisted inkjet technology toward practical use and to establish it as the core technology of minimal manufacturing.

## 6 Summary and future prospect

This paper is a report of the R&D process of the laser-assisted inkjet technology, which is a development of the wiring technology using inkjet printing and has the potential to become the core technology for practical high-diversity variable-volume production. Comparison with other wiring technologies currently in practice, extraction of issues for

high-diversity variable-volume production, selection of the solution method, and research results and positioning of the results are summarized. The issues that may become important in the future and the flow of the technological development are described.

In the future, we wish to develop additional multiple functions, to enable custom-made production that instantly provides function demanded by the user, to expand the market, and to create a new market for electronic device with new functions. By increasing the throughput of the laser-assisted inkjet technology, we plan to develop a technology that can handle devices with large surface areas that could not be handled with the conventional inkjet printing technology.

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## Authors

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## Discussions with Reviewers

### 1 Overall comment

**Comment (Yasuo Hasegawa, Energy Technology Research Institute, AIST)**

I think the developed technology is excellent, but to make this paper suitable for Synthesiology, please revise the following two points.

### 2 Clear statement of the technological issues

**Comment (Yasuo Hasegawa)**

For the titles of the subchapters, please revise them so the technological issues to be overcome can be readily seen.

**Answer (Akito Endo)**

In response to your comment, I revised the text so that the summary of the subchapters became the titles of the subchapters.

### 3 Solution to the ejecting frequency

**Comment (Yasuo Hasegawa)**

You indicate the issue of ejecting frequency, but can you describe how, after all, the authors solved the issue?

**Answer (Akito Endo)**

Until now, to reduce the width and the resistance of the formed wire, we reduced the size of the discharged droplet and reduced the ink supply per unit length, or in other words, we tried to increase the ejecting frequency of the inkjet. However, since we could increase the ink supply per unit length by forming the wire with small width using large droplets, we were able to solve the problem without greatly increasing the ejecting frequency.

### 4 Comparison with the conventional approaches

**Comment (Yasuo Hasegawa)**

For the conventional approaches compared with this research, please explain logically why those approaches were not appropriate, what kind of breakthroughs were necessary, and how you solved the problems. I think it will be easier to understand if you itemize the problems of high viscosity ink.

**Answer (Akito Endo)**

The following four methods are efforts to even out the wiring pattern and to reduce the wire resistance:

(1) Decrease resistivity of ink → limit of low resistivity
(2) Discharge high viscosity ink and reduce size of droplet → nozzle clogging and limit of ejecting frequency
(3) Formation of even pattern through surface treatment → reduced throughput by making the process complicated
(4) Increase drying speed by heating → breaks in wire due to bumping caused by rapid drying

1 and 2 greatly affect the narrowing of the wire width, and 3 and 4 the formation of even patterns. There were issues that were difficult to solve in using the inkjet as a practical process technology.

These four methods were not ways to deal with the essential issues of drying droplets in the process where the droplet discharged by the inkjet wet-spread at the moment it landed and dried. From the viewpoint of improving throughput, we set our topic as the control of wet-spreading of the droplet. As a result, we used the idea of locally applying the heat energy necessary for drying to the ink droplet by laser irradiation. This enabled the formation of wire with high aspect ratio with width smaller than the droplet diameter, without greatly increasing the ejecting frequency and with large droplet diameter, by optimizing the drying speed.

### 5 Size of droplet and value of the wire width

**Comment (Yasuo Hasegawa)**

Please indicate what were the droplet size and wire width in the conventional inkjet method. Since this is related to the development goal set in this research, please state them clearly.

**Answer (Akito Endo)**

The droplet size used in the conventional industrial inkjet method was about 15 μm (1.8 pl) ~ 40 μm (33.5 pl) in diameter. Therefore, the wire width was about 30 μm ~ 50 μm since it became larger than the droplet size, and the thickness was thought to be limited to several tens nm to several hundreds nm. When recoating was done several times to thicken the wire to about several μm, bulges occurred and formation of even wires was difficult.

### 6 Reason for setting the droplet size

**Comment (Yasuo Hasegawa)**

Please state clearly the logic of setting the droplet size. Did you decide on the droplet size after setting the target thickness from the target wire width and the target resistivity when it was formed?

**Answer (Akito Endo)**

In the conventional inkjet technology, the discharge of droplets of 10 μm or less was difficult. Therefore, the target values we set were wire width 10 μm or less and forming speed of several mm/sec to several tens mm/sec per nozzle. As technological issue needed to achieve the goal, it was necessary to form the wire width smaller than the droplet diameter. Therefore, we set the droplet diameter at 10 μm or more.