Direct Circuit Formation Technology using Electrophotography

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Abstract

The application of printing technologies such as screen printing and ink jets should be an alternative for circuit formation technology in photolithography. We conducted work on the electrophotography method, which is one of these printing technologies used for laser printers and copiers, among other devices. This technology can achieve mass production with a continuous process and can form a large area pattern. Moreover, this technology is advantageous for producing many different kinds of limited pattern areas because changing the pattern is easy. In addition, the technology is also highly advantageous for forming a high-density pattern because the stroke width depends on not the drops (e.g., ink jet) but on an electrostatic latent image and the particle size.

Metallic wiring by electrophotography has problems with electrification of metallic particles and conductive wiring because of low temperature heating. We examined a method of direct patterning of metallic nanoparticles that were ion electrified in liquid by liquid development. Afterwards, the pattern was baked at a low temperature to make it a conductor. The results were that we achieved a formation and transcription of a fine metallic wiring pattern with a width of 10 μm on an organic substrate.

Background

There has been a great deal of interest in screen printing [1] and inkjet printing [2] as possible replacements for photolithography in forming fine-line circuit interconnects. Technologies for creating electrically conductive paths by depositing and curing conductive inks have excited tremendous interest in new processes that substantially reduce manufacturing costs through simpler processes and more efficient use of materials. Yet all the methods investigated so far have unresolved issues. For example, screen printing requires a different plate for each pattern, so modifying a pattern becomes very cumbersome. With inkjet printing, modifying a pattern is easy enough, but the productivity is poor. Furthermore, the resolution of both these methods is dependent on ink droplets, which suggests they will have physical limits when they are used to form fine-line pattern circuits.

In this paper, we discuss the potential of electrophotography as a technology for forming fine-line circuit interconnects. This method is not only capable of supporting large-scale production and large-area pattern deposition, it also allows for easy modification of patterns. Therefore, it is ideally suited for a limited production of diverse circuit products. Moreover, because the resolution with this method depends on the size of the particles and not ink droplets, it can achieve far better resolution than other technologies can.

One method for depositing fine-line patterns by electrophotography has already been proposed. It involves metal patterns being formed by internally adding resin toner from fine-line circuit interconnects by electroless plating [3]. However, a serious drawback of combining electroless plating with electrophotography is that this would seriously complicate the processing, and probably also increase the fabrication time. This led us to pursue an alternative approach of direct circuit formation for conductive particles without a resin layer, and we developed a procedure for fabricating fine-line circuit interconnects that does not require a electroless plating step.

Principle

Electrophotography is essentially an image forming technology that uses a copier. The printing process involves charging a photoreceptor, producing a latent image through exposure, making the image visible through static absorption of a developer, transferring the image to the target medium, and finally fixing the image with heat.

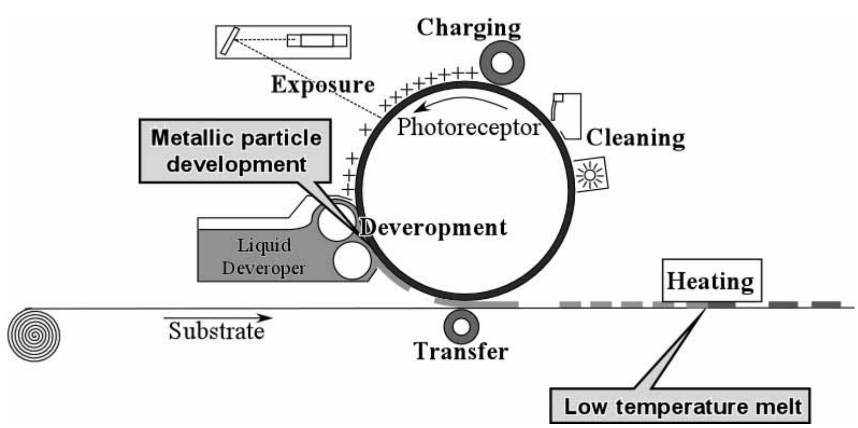

***Figure 1**. Direct circuit formation by electro-photography*

Figure 1 shows a schematic of a direct pattern formation system based on this approach. The basic configuration is similar to that of an ordinary copier, but since our objective is the formation of electrically conductive patterns, the developer must provide conductive particles. Implementation of direct circuit formation, the goal of this work, raises two important issues: (1) charging the discrete conducting particles, and (2) low-temperature melting of the conducting particles to form a good conductor.

Figure 2 is a schematic showing how we addressed these issues. To meet the first challenge of charging discrete conducting particles, we used the liquid development method that develop latent images through electrophoresis of the particles that are dispersed in the liquid. This way, the particles are charged by ion absorption, so even discrete conducting particles without resin coating can be charged. We used metallic nanoparticles to address the second issue of low-temperature melting to form a good conductor. Metallic nanoparticles with a 1 – 100 nm diameter have remarkable physical and electrical properties. Most significantly for our purposes, the melting point of metallic particles in the nano order decreases as the diameter decreases. For example, the melting point of silver (Ag) nanoparticles is reduced to under 200ºC [4]. This means that, by using the liquid developer made of metallic nanoparticles, good conducting interconnects can be formed by melting at low temperature. Our work exploits these approaches to create a direct circuit patterning method using the liquid developer that consists of metallic nanoparticles.

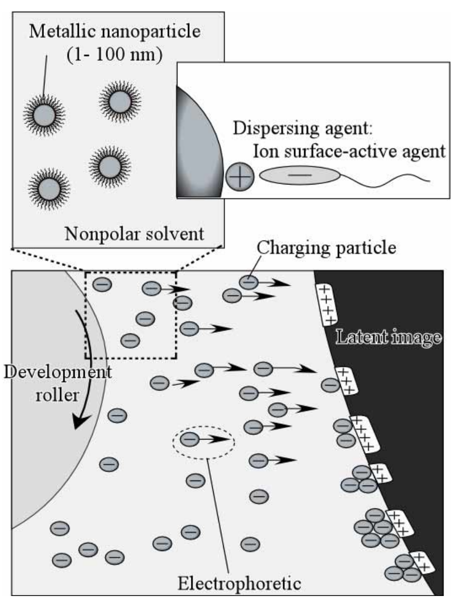

***Figure 2**. Liquid development and metallic nano-particle*

Liquid Developer OF Metallic Nanoparticles

A number of requirements must be met to enable metallic nanoparticles to be used as the liquid developer. First, the liquid developer must support electrophoresis and good latent image retentivity. Second, the metallic nanoparticles must be covered with the dispersant layer [polymer shell] to prevent the particles from agglomerating when in the liquid phase. Moreover, this layer should have a low molecular weight so that it readily melts and evaporates during the low-temperature sintering to form the conductor. Therefore, we used the liquid developer in which low molecular weight ionic surfactant metallic nanoparticles are dispersed in a nonpolar solvent. For this work, we developed a stearic acid (ionic surfactant) based silver nanoparticle dispersant layer using a fatty acid salt pyrolysis method [5] that is both simple and amenable to quantity synthesis.

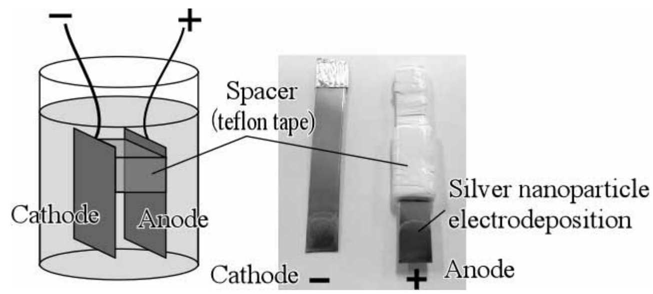

***Figure 3**. Results of examination that shows electrophoretic migration.*

When voltage is applied to this liquid developer of the silver nanoparticles, the silver nanoparticles are electrodeposited onto the anode, as shown in Figure 3. This demonstrates that the silver nanoparticles suspended in the developer do exhibit electrophoresis and have negative charge.

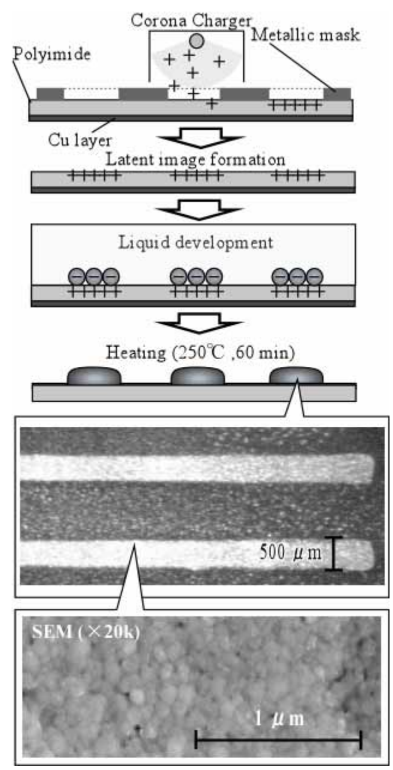

***Figure 4**. Principle of liquid development and conductive wiring by heating*

Next, we used this liquid developer to make latent image patterns, and performed low-temperature melting to produce good fine-line conducting patterns. Figure 4 illustrates the experimental procedure and the results. First, the charge was applied through a mask, and a positive latent image pattern was obtained on polyimide. As a result of immersion in the liquid developer, we found that the silver nanoparticles formed development pattern through electrostatic adsorption in the latent pattern. We also found that a good silver electrically conducting pattern was obtained by heating the pattern at 230°C for one hour. Scanning electron microscopy (SEM) was used to determine that a continuous metal conductor with few gaps between sintered particles was produced. The conductive pattern had a volume resistivity of 14 μΩ ·cm.

Charging, Exposure, and Development Processes

We constructed an experimental liquid development system and used the system to produce fine-pattern circuits to assess the electrophotography-based charging, exposure, and developing processes with the liquid developer of the silver nanoparticles. Figure 5 shows a schematic of the experimental system. As shown in the figure, the photoreceptor was first subjected to a uniform positive charge from the corona charger. A fine-line latent image pattern was then formed on the photoreceptor using light passing through a glass mask with fine patterns and a projection lithography lens to reduce the patterns. Finally, the liquid developer of the silver nanoparticles develop the latent pattern. Amorphous silicon (a-Si) was used for the durable solvent- and heat-resistant photoreceptor.

The nanoparticle pattern results are shown in Figure 6. The experimental liquid development system and the liquid developer of the silver nanoparticles demonstrated that good silver nanoparticle patterns were formed on the photoreceptor. The finest pattern resolution obtained in the trials was a 10μm line-and-space pattern.

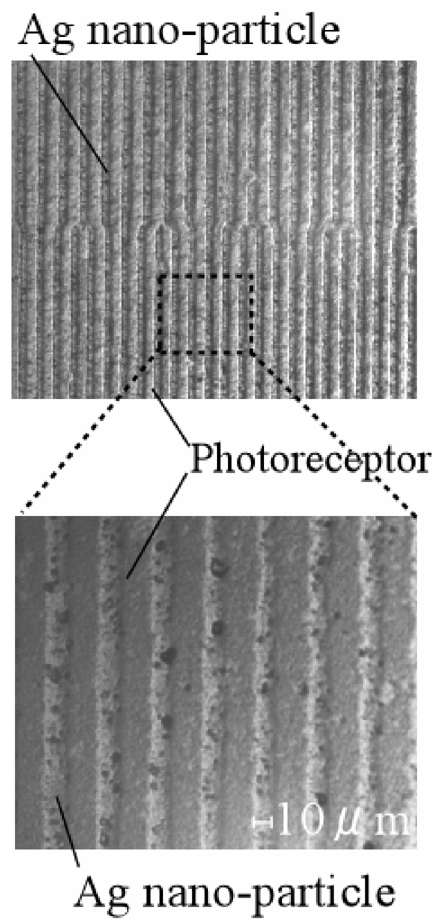

Figure 6. *Formation of Ag nanoparticle pattern on a-Si photoreceptor.*

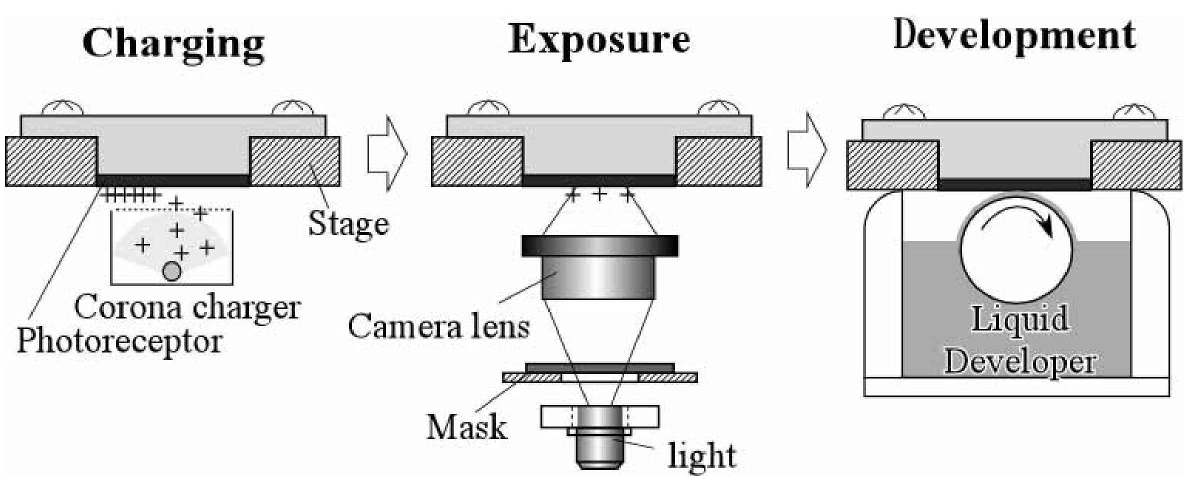

Figure 5. *Liquid development system (charging a photoreceptor, producing a latent image through exposure, making the image visible through static absorption of the liquid developer).*

Transfer Process

Next we studied the process of transferring the developed patterns on the photoreceptor to a target substrate. We concluded that, because the silver nanoparticle developer used in this work does not contain resin, an adhesive transfer process would be ill suited for pattern transfer in our system. This led us to use an electrostatic image transfer method in which the pattern was electrostatically attracted to the substrate. Note, however, that we had to use an electrophoretic migration transfer method mediated by solvent between the photoreceptor and the substrate to enable our electrostatic image transfer because silver nanoparticle patterns cannot be charged in air.

Figure 7 shows a schematic representation of the electrostatic transfer system. As illustrated in the figure, a sheet of substrate was superimposed onto the developed patterns on the photoreceptor, then they were pressed together using a transfer roller on the back of the substrate. The gap between photoreceptor and substrate was filled by nonpolar solvent and by applying a positive bias of approximately +1,000 volts to the transfer roller. The developed pattern on the photoreceptor was transferred to the substrate by electrophoretic migration. A polyimide sheet was used for the substrate.

The transferred nanoparticle pattern results are shown in Figure 8. A close examination of the patterns transferred from the photoreceptor by the electrostatic transfer system revealed that the resolution was preserved and that the patterns were faithfully transferred to the polyimide surface by the silver nanoparticles.

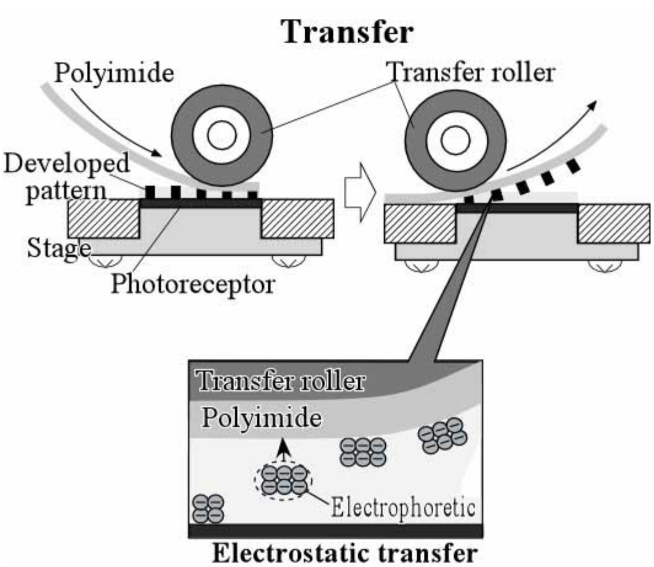

***Figure 7**. Electrostatic transfer system for Ag nanoparticle pattern*

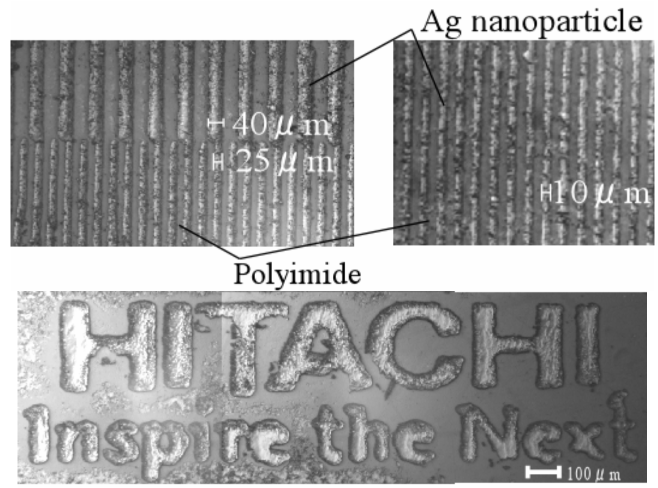

***Figure 8**. Transferred Ag nanoparticle pattern on polyimide.*

Conclusions

This study demonstrated the viability of a direct circuit formation technology based on electrophotography. First, we developed 10μm line-and-space silver nanoparticle patterns onto a photoreceptor using the liquid developer based on silver nanoparticles and using ionic surfactant as a dispersant. Then, we transferred the pattern to a substrate using an electrostatic image transfer method. Building on the technologies reviewed here, we plan to enhance the development and transfer accuracy further, to continue to study low-temperature melting for forming electrically conductive patterns, and to incorporate these technologies in a series of powerful fine circuit metallization pattern systems.

References

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Author Biography

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