Reconfigurable Logic Devices Connected with Laser-Sintered Liquid Metal Nanoparticles

Edward L. White, Jennifer C. Case, and Rebecca K. Kramer
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana, USA
rebeccakramer@purdue.edu

***Abstract* — In this paper we demonstrate the use of liquid metal nanoparticles as electrical traces between logic gates. When first deposited, films of nanoparticles are non-conductive, despite their metallic composition. Nanoparticle films can be coalesced into conductive traces using an infrared laser. We demonstrate the utility of this approach by using laser-patterned films to connect NAND gates in different circuits, creating an OR gate and a light-sensitive thermostat. We also show that patterned films can be removed, making the devices re-usable and re-programmable. Liquid metal nanoparticle-based devices may be used to create environmentally responsive devices in the future.**

Keywords—flexible electronics; liquid metal electronics; re-configurable logic

I. INTRODUCTION

Although many different types of sensors exist for different physical phenomena, the information collected by these sensors is generally processed by fixed logic devices. In contrast to this approach, we hypothesize that a new class of environmentally-responsive electronic circuits that adjust functionality and programming in response to changes in environmental conditions are possible [1]. Our research is based on liquid-metal alloys, which can be used to create electrical connections in highly deformable systems [2,3]. Multiple approaches to patterning liquid metals have previously been demonstrated, including injection into microchannels, ablation of a film of native liquid metal, and extrusion of liquid metal onto a surface [4]. Reconfigurable devices made from liquid metals have also been demonstrated [5,6]. These devices use the movement of liquid metals within microchannels to achieve adjustable functionality.

Instead of using pre-patterned channels, we sought an approach that would allow for the rapid fabrication of arbitrary conductive pathways. Further, we sought a patterning method that would be responsive to external stimuli. We have previously demonstrated that particle-filled inks based on organic carrier solvents [7] can be deposited on a surface in a non-conductive state using ink-jet printing [8] and spray printing [9]. During synthesis, the metal particles develop an oxide layer that insulates the particles from one another. This oxide layer remains on the particles after they are deposited onto a substrate, producing a non-conductive film of particles. To convert the film of non-conducting particles into a continuous conductive trace, this oxide layer must be removed or ruptured, allowing the liquid metal within the particle to contact its neighbors.

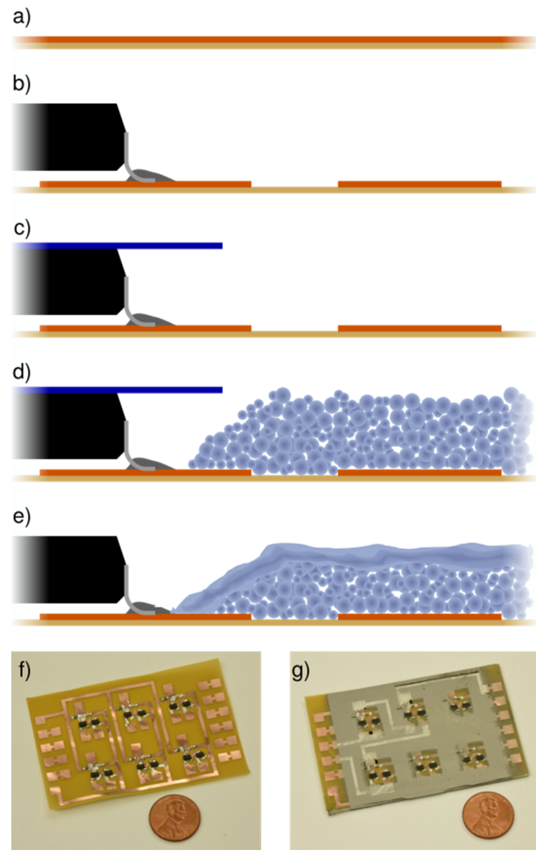

Fig. 1. Illustrations and images of the fabrication sequence. a) A copper-clad polyimide film (Pyralux). b) A copper pattern is etched into the film and electrical components are soldered to the circuit. c) Blue painter's tape is applied over the electrical components to mask them during the nanoparticle dispersion application. d) The liquid metal dispersion is applied. e) An IR laser is used to coalesce the liquid metal nanoparticles into a conductive film. The laser does not penetrate completely through the full thickness of the particle layer, maintaining a high resistance between copper traces (>10KΩ) relative to the trace on the right. f) Photograph of flexible PCB with electronic components attached, corresponding to the illustration in b). g) Final laser patterned device, corresponding to the illustration in e).

Previously, we demonstrated mechanical sintering of liquid metal particles via application of pressure to the particle film surface [8,9].

In the present work, we replace mechanical force with infrared (IR) laser radiation to sinter the liquid metal particles and create conductive traces by rupturing the electrically-

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insulating oxide shells. As a demonstration of this technique, we used laser radiation to coalesce particles deposited on a flexible PCB substrate, connecting traditional semiconductor NAND gates to create multi-gate logic devices. NAND gates are universal logic elements, and any other logic function can be made from combinations of NAND gates. This concept is a stepping stone towards a broader goal of building electronic components that not only sense changes in environmental conditions, but can alter their basic functionality in response to external stimuli.

II. Fabrication

Fabrication of the devices occurred in four phases. First, standard electronic components were soldered to a patterned flexible PCB substrate, as shown in Fig. 1(a,b,f). Second, liquid metal nanoparticle ink was prepared according to the procedure previously described by Boley, *et al.* [8]. To summarize this procedure, a room temperature alloy of gallium and indium was sonicated in ethanol to create nanoparticles. The resulting ink retained the physical properties of the ethanol, making it spray-printable. Third, masking tape was used to cover the electronic devices, and the nanoparticle ink was sprayed onto the circuit. The ink was sprayed onto the surface at a density of 0.07mL/cm^2 using multiple passes to prevent pooling, as shown in Fig. 1(c,d). The masking tape was not adhered to the flexible substrate, and instead had an "overhang" off of the top of the electronic components, as shown in Fig. 1(c). Fourth, an IR laser (VLS 2.30, Universal Laser Systems) was used to activate the nanoparticles, causing the individual particles to coalesce into a conductive trace as shown in Fig. 1(e,g).

Key to this process were the feathered edges of the dispersion film. A gradually decreasing thickness of nanoparticle ink was deposited under elevated masking tape, as shown in Fig. 1(d). The laser did not penetrate completely through the full particle layer, maintaining a high resistance between copper traces (>10KΩ), but a low resistance through the trace (<100Ω). The thinner film thickness at the feathered edges allowed the laser to connect the conductive traces on the upper surface of the dispersion to the copper substrate.

After laser patterning, the dispersion could be removed from the surface using a caustic bath, as shown in Fig. 2. Soaking the dispersion film in 1.0M sodium hydroxide for a few seconds removed the oxide layer from the nanoparticles, causing them to detach from the surface [1]. Sodium hydroxide was selected because it is able to quickly strip the nanoparticle film without damaging the underlying copper traces and electronic components. After cleaning, the logic device can be re-sprayed and re-patterned according to the sequence described above.

III. Results

A. Simple Example: OR Gate

As an example of how NAND gates can be used to emulate any other logic unit, we wired the device as an OR gate. The functionality of an OR gate can be re-written using the NAND operator:

$$A \vee B = (A \barwedge A) \barwedge (B \barwedge B) \tag{1}$$

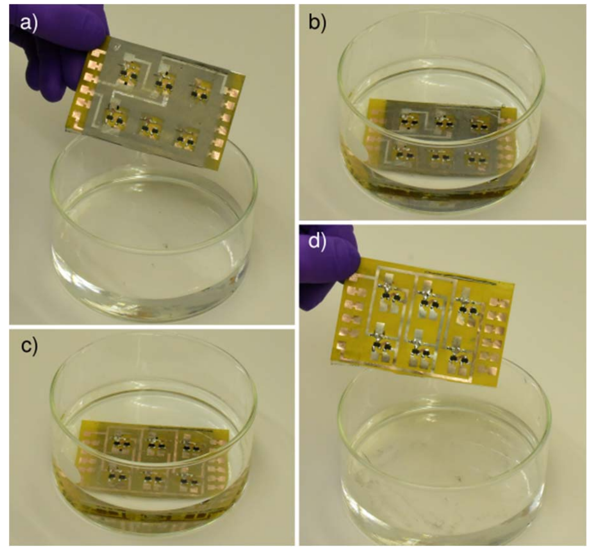

Fig. 2. Cleaning process to remove the nanoparticle film. a) A laser-patterned device showing conductive patterns. b) The device is placed in 1.0M NaOH bath. c) After a few seconds, the dispersion has detached from the surface and formed into a few small liquid metal balls. d) Cleaning is finished by wiping the surface with a paper towel with NaOH, followed by rising with water and drying. The device is now ready to be re-sprayed with nanoparticle ink.

where A and B are the two inputs. The operation of the programmed device is shown in Fig. 3. In this configuration, only three of the six NAND gates on the device were utilized. The remaining unused NAND gates could have been used to construct an additional OR gate, or any combination of gates requiring three NANDs.

B. Complex Example: Light-Sensitive Thermostat

As an example of a multi-gate logic system that can be fabricated with this approach, we created a light-sensitive thermostat. In this example, the device used two different temperature set points depending on the illumination condition. In practice, this might represent a case where it is desired to keep a room warmer during the day than at night. Thermal and light sensors were implemented on a daughterboard attached to the logic device. The desired truth table is shown in Table I. Using

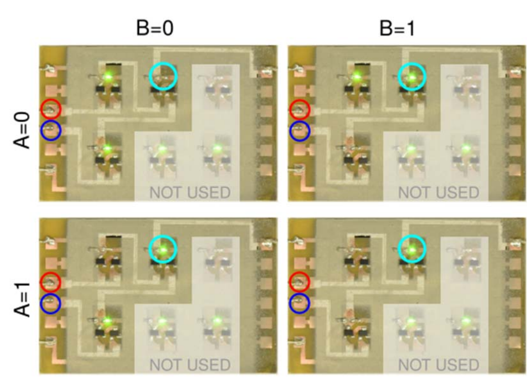

Fig. 3. Operation of the device as a two-terminal OR gate. Three NAND cells are required to form an OR gate. In this case, the three gates in the upper left triangle of the device are used. Input A (highlighted with a red circle) drives the upper left NAND cell, input B (highlighted with a blue circle) drives the lower left cell, and the output (highlighted with a cyan circle) is driven by the upper middle cell. The output state of each cell is shown with an LED.

TABLE I. DESIRED OUTPUT STATES OF A LIGHT-SENSITIVE THERMOSTAT. THE DEVICE IS PROGRAMMED TO HOLD A HIGHER TEMPERATURE WHEN EXPOSED TO LIGHT.

T_H	T_L	L	O
L	L	L	H
L	H	L	L
H	H	L	L
L	L	H	H
L	H	H	H
H	L	x	N/A

both AND and OR functions, the output F of the circuit needs to be:

$$F = (\neg T_L \wedge \neg L) \vee (\neg T_H \wedge L) \tag{2}$$

where T_L is the lower temperature set point, T_H is the higher temperature set point, and L is the state of the light. Since NAND gates are universal, the equation above can be recast into an expression using only NANDs:

$$F = \big((T_L \barwedge T_L) \barwedge (L \barwedge L)\big) \barwedge ((T_H \barwedge T_H) \barwedge L)$$

Noting that the temperature terms only appear in negated form, we designed the thermistor circuit such that the output is high when the temperature is below the set point and low when it is above. Because of the circuit design, we also had a negated light input. Thus, we simplify the logic function into the final form:

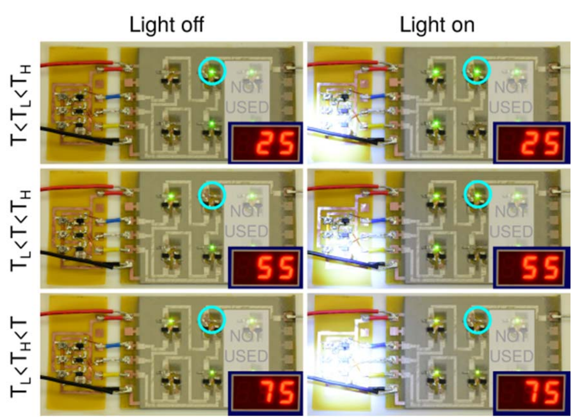

Fig. 4. A programmable logic device with corresponding thermistor/photoresistor daughterboard. The left column shows the operation of the circuit with light off, the right column shows operation with light on. The lower set point, T_L, was set to 40°C and the upper set point, T_H, was set to 60°C. The actual temperature is shown in the inset in each figure in °C. In the top row, the temperature is below both set points, and the "heater" output, highlighted with the cyan circle, is on in both illumination conditions. In the middle row, the temperature is between the two set points, and the output is only on in the illuminated condition. In the bottom row, the temperature is above both set points, and the output is off in both illumination conditions. The connections from the daughterboard to the logic device are, from top to bottom $\overline{T_L}$ (blue), $\bar{L}$ (white), and $\overline{T_H}$ (yellow).

$$F = (\overline{T_L} \barwedge \overline{L}) \barwedge (\overline{T_H} \barwedge (\bar{L} \barwedge \bar{L})) \tag{3}$$

From this expression, it can be seen that four NAND cells were required to implement the desired operation. The patterned dispersion and circuit operation are shown in Fig. 4. This example demonstrates how to transition from a general Boolean formulation of a logic device to a NAND-only formulation, and how the resulting logic operation is implemented in a working device using laser-patterned conductive traces in a nanoparticle film.

IV. CONCLUSION

In this paper, we have demonstrated the deposition and patterning of a liquid metal nanoparticle ink to create reconfigurable laser-activated conductive traces. As an example, we have demonstrated using nanoparticle ink as a laser-programmable conductive layer between NAND logic gates, and have demonstrated how an array of NAND gates can be used to construct a useful logic device. This same approach could be applied to arbitrary types and numbers of devices, creating both functionally and physically flexible electronics. In the future, we propose to use alternative coalescence mechanisms, besides laser activation, to create environmentally-responsive electronic devices.

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